GROWING CROPS WITH RECLAIMED WASTEWATER

Editor: Daryl Stevens

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Preface

The Australian horticultural industry comprises cut flowers, fruits, extractive crops, nursery products, nuts, sports turf and vegetables. The benefits of horticulture to Australia are enormous. Many Australian communities depend to varying degrees on the social, environmental and economic benefits of horticulture. The supply of high quality fresh horticultural produce to the Australian consumers is arguably one of the best in the world. The Australian horticultural industry employees about 97 000 people with a benefit to the Australian economy that can be estimated at between $10 billion and $20 billion per year (2001/02).

For any horticultural enterprises a guaranteed supply of the appropriate water quality is crucial for their success. However, as urban and environmental demands for water increase and rainfall patterns change, altering our water harvesting capabilities, water supplies which were once considered as certain are now under threat. In some cases already, across Australia, horticultural areas cannot secure sufficient water to continue the current rate of production. Any expansion will be futile without securing a guaranteed supply and quality of water.

Reclamation and reuse of water from our urban and industrial wastewater (sewage) treatment plants (reclaimed water) offers the opportunity for horticulturalists to secure a water supply, indefinitely. However, there is a reluctance of the horticultural industry to embrace the use of reclaimed water due to concerns about its quality. These concerns are generally regarding the chemical, physical and pathological qualities of reclaimed water, which potentially affects the sustainability of the farming operation, yield or quality of produce, and its market acceptance.

The concerns when irrigating with reclaimed water are generally no different to other traditional water sources (surface or groundwater). However, there is an enormous amount of *historical proof* that the use of traditional water sources, with current horticultural practices, produces goods that are of saleable/acceptable quality to wholesalers, retailer and consumers. This historical proof develops a trust and confidence in this practice and ultimately acceptance from society. The trust and confidence in the use of reclaimed water is questionable in many societies because of the lack of historical proof, and that our excreta (sewage) has been responsible historically for the outbreak and/or spread of devastating diseases — we are trained from childhood to avoid contact with our urine and faeces.

Interestingly, humans have recognised the value of returning human and animal wastes to the soil for crop production for thousands of years. However, during recent centuries, the linkage of disease with sewage has lead to its treatment and disposal, generally by dilution (eg at sea where possible). In some cases, the treatment process may include well-managed land treatment (eg historically what Melbourne Water's wastewater treatment facility at Werribee practised), where the primary aim is wastewater treatment and disposal. Over the last decades, as demands for water have increased, both from the agricultural and urban perspectives, the potential value of reclamation and reuse of the wastewater has been recognised. This realisation, coupled with developments in water treatment, have lead to hundreds of research projects since the 1950s worldwide to determine if reclaimed water can be used sustainably and without the fear of sacrificing quality or quantity of produce, and ultimately, human health.

This research has culminated in the development of state, national and international guidelines for the use of reclaimed water in agriculture. These guidelines have led to the successful development and continued operation of hundreds, if not thousands, of agriculturally based reclaimed water schemes around the world (eg USA, Israel and Australia). Now the historical proof for the successful use of reclaimed water in horticulture has been acquired. Where appropriate, the use of reclaimed water should be embraced by society as the environmentally responsible method for recycling water and nutrients from society's waste.

This book aims to provide the user with a historical background of water treatment, use and disposal from Australian wastewater treatment facilities, the technologies now utilised to treat our wastewater, and provide a background in the fundamentals required to ensure a reclaimed water scheme is developed that addresses the environmental, economic and social requirements of society today.

Most importantly, the use of reclaimed water is complicated by the complexity of drivers (political, social, scientific, environmental and economic), that almost wish schemes to be developed. However, these drivers must never be allowed to override the sound science (social and physical) and site-specific knowledge that is essential to assess the practicality and feasibility of individual reclaimed water schemes.

We hope this book helps Australians and people around the world to make the right decisions when establishing and managing reclaimed water schemes.

A special thanks

This book would not have been possible without the foresight of Horticulture Australia Limited (especially Jonathon Eccles) and their financial support for research and development projects for the Virginian Pipeline Scheme (Northern Adelaide Plains, South Australia). The Australian horticultural industry is also indebted to the horticulturalists across Australia who risked their livelihoods to embrace the initial Australian reclaimed water schemes and helped provide the historical proof required to overcome many misconceptions associated with reclaimed water use in horticulture. Also the unconditional effort of many scientists, regulators and health department officers involved with these initial schemes has unquestionably assisted in this process.

In today's time-poor society, we would also like to thank all those who have volunteered their time to contribute to this book.

Reclaimed water

The terminology suggested by Radcliffe (2004) has been used in this book. 'Reclaimed water' is defined as 'water reclaimed from the effluent of sewage treatment plants'. However, many of the principles discussed apply to the reclamation and reuse of any wastewater source.

'Water reclamation' is the treatment of wastewater to make it reusable for one or more applications. This process produces 'reclaimed water'.

'Water reuse' is the beneficial reuse of reclaimed water or treated water for specific purposes such as irrigation, industrial or environmental uses.

'Water recycling' is a generic term for water reclamation and reuse.

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1 Reclaimed water use in Australia

An overview of Australia and reclaimed water

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The country

Australia lies between the South Pacific and Indian Oceans, between latitudes of 10°S and 44°S and longitudes of 113°E and 154°E. It covers an area of 7 682 000 km^2, about five-sixths that of the United States of America, but is sparsely populated, with only about 20 million people. A high proportion of the population lives in urban centres in high rainfall areas on the temperate southern strip of the continent between latitudes 25°S and 43°S. Sewerage systems were initially designed to gravitate as much of the flow as possible, naturally leading to ocean outfalls. Turning that effluent back (ie pumping it against gravity) in hindsight generally poses a distance and topography barrier, ruling out cost-effective reuse in many coastal communities.

Australia is a federation of six States and two Territories, with a federal system of government. Federal and State legislatures operate under the Westminster parliamentary system and constitutional responsibility for water resource management, environmental protection and public health rests with the States and Territories. Regulation of water recycling is also a State responsibility. Usually, an Environment Protection Agency/Authority (EPA) has prime responsibility with varying involvement of health and water resource management agencies. Local government operates under State government legislation and has been delegated some planning approval functions.

As a very old, flat continent, Australia has equally old, depleted soils, which lack the organic matter common to younger soils, but has overlaying aquifers which contain millions of years of accumulated salts.

For all of these reasons, the practice of irrigation is often problematic. When the water being used for irrigation is treated effluent (reclaimed water), the level of concern increases, as salts in the water can exacerbate soil problems. Over-enthusiastic irrigation with reclaimed water can also mobilise salts, raise water tables and lead to saline outflows.

Water resources

Australia has climates ranging from subtropical, through temperate, to arid. The northern parts of the continent receive predominantly summer rainfall from tropical weather systems, while the southern parts receive predominantly winter rainfall from southern ocean weather systems. These systems are strongly influenced by the El Niño/La Niña ocean circulation and sea surface temperature phenomena in the Pacific Ocean. Although the average annual rainfall across the continent is 455 mm, it varies from over 3000 mm in the tropics to less than 200 mm in central Australia. About 63% of the continent has less than 400 mm average annual rainfall. Because of high evaporation rates, runoff and groundwater recharge equate to only 12% of average rainfall. As well as geographical variation, temporal variability of rainfall is greater in Australia than on any other continent. Consequently, runoff is also highly variable and much of the country is prone to drought. Hydrologists rate Australia's river flow variation coefficient equal to the world's highest, alongside Southern Africa.

Australia is among the driest countries on Earth, having 5% of the global land area, but only 1% of global river runoff. Mean annual runoff is about 50 mm, a total of 400 million megalitres (ML). About 70% of this occurs as floods. About half of the 120 million ML of divertible water occurs north of the Tropic of Capricorn and in Tasmania, remote from the main centres of population, and only about 24 million ML (12%) is harvested for agricultural, industrial and urban use.

Most water is used on a ‘once-through’ basis before it is returned to the natural water cycle by discharge or evaporation. About 18% is used for urban and industrial uses, 74% for irrigation and 8% for stock and domestic use in rural areas. Over 50% of irrigation use occurs within the Murray-Darling Basin in south-eastern Australia where the available surface water resources are almost fully committed to irrigation.

Australia has been extremely liberal in its approach to water rights and water use, and available water is now very heavily committed in several river basins. Some of these are showing signs of environmental stress, manifest through declining water quality. The rivers of the Murray-Darling Basin have deteriorated markedly since European settlement late in the 18th century, principally because of agricultural land use practices and diversion of water for irrigation. Nutrients in urban wastewater and stormwater discharges have also made their mark. Similar deterioration has occurred in the Hawkesbury-Nepean Basin, which drains western Sydney, caused principally by urban diversions and urban runoff. These two cases highlight the impact of water use that approaches or exceeds the limits of sustainability in individual catchments. Compared to the Murray-Darling Basin, the level of regulation in the Hawkesbury-Nepean is a relatively modest 30%. This highlights the possible constraints imposed on the use of water resources by the combined impact of water diversions and urban runoff.

Development of sustainable water management policies

Concern over declining river water quality has led to new public policy measures to work toward sustainable management of Australia’s water resources. Federal measures include funding of capital works to reduce nutrient discharges, a cap on irrigation diversions in the Murray-Darling Basin, and a requirement for the States to introduce environmental flows. State governments have introduced water reform measures. For example, one of the most far reaching is the water reform package introduced in New South Wales, which includes the following.

- Establishment of a Healthy Rivers Commission to set water quality and river flow objectives in priority catchments.
- Development of a Water Management Plan for each catchment that incorporates environmental water quality objectives, and river flow objectives which share water between users and the environment.
- Development of integrated water planning for urban areas incorporating water conservation and recycling.
- Consolidation of existing water legislation into a new *Water Management Act* 2000 No. 92. The primary objective of the Act is to ‘provide for the protection, conservation and ecologically sustainable development of the water resources of New South Wales’. This Act:

  (a) sets aside water allocations for the environment;
  (b) classifies rivers and aquifers according to levels of stress and conservation values and nominates water source protection zones; and
  (c) clearly defines licensed water access rights under volumetric allocations, which may be reduced in dry times.

- Load-based licence fees for discharges with rebates for water recycling.

Matters still to be resolved are whether reclaimed water return flows of acceptable water quality can be:

- credited against town water allocations;
- credited against the environmental flows required by water access licences; and
- traded in the water transfer market.

There are several incentives for water reuse in agriculture. Chief among these, as an external driver to the industry, has been a widespread perception that reusing effluent is intrinsically better, under almost any circumstances, than discharging it directly into waterbodies. That view has probably passed its peak, in light of some bad experiences, but its impact lingers in policies and regulations.

In arid areas of Australia the availability of a reliable supply of reclaimed water is very attractive to irrigators, and thus many inland towns have been supplying water to farmers for periods of up to decades, either formally, by a pipeline, or informally, through downstream extraction.

The last 30 years of reuse for agriculture in Australia has been shaped by these forces. This book outlines how the forces for and against reclaimed water use have been played out in the various jurisdictions. Each reuse opportunity should be viewed in the light of its whole-of-life-cycle merits, economically, environmentally and socially. However, the methodology to achieve this is still in its infancy, so practitioners, operators and regulators have to make do with whatever analyses they have available. The range of experience given in this book is wide and run from very positive to seriously problematic. This information is important to assist the next generation of reuse projects in achieving environmental and economic sustainability, as well as satisfying community aspirations.

Apart from any other challenges and opportunities, irrigating with reclaimed water requires a high level of multidisciplinary collaboration. Simplistic models of water availability and rainfall, coupled with crop factors, are nowhere near sufficient to empower a project. Engineers, health professionals, chemists, operators and agricultural scientists must understand one another's issues and constraints, so that each project is firmly rooted in practicalities, improving the chance of success.

Future directions

Trends in Australia

The following are some of the emerging trends in Australia.

- Better water resource planning at river basin, catchment and subcatchment levels including specific accounting for water recycling.
- Better water cycle management by individual users, including the development of integrated water, sewerage and drainage planning for individual urban areas.
- Water reforms which will increase the market value of recycled water.
- In some rivers the river flow objectives may encourage return of recycled water to streams to improve flows and water access.
- Water quality objectives will encourage higher standards of treatment and greater reuse.
- Load-based licensing fees will:

  (a) encourage ocean discharge rather than river or estuary discharge;
  (b) encourage consumptive reuse rather than discharge to improve river flows;
  (c) encourage higher treatment standards to reduce fees, particularly in inland areas; and
  (d) reduce incremental costs of all forms of reuse.

- Higher standards required for discharge to the environment will also reduce the incremental cost of all forms of reuse, including potable reuse.
- Some reuse schemes may be inhibited or prevented by groundwater protection measures.
- Developments in technology will:

  (a) reduce water reclamation and reuse costs;
  (b) make neighbourhood and on-site reuse systems more cost-effective; and
  (c) make urban potable reuse increasingly cost-effective relative to non-potable urban reuse.

- Development of clearly identifiable reuse grades and products.
- Development of national guidelines in place of State guidelines.
- Investment in higher grades of recycled water to reduce risks and simplify operating and monitoring arrangements.

Decentralised treatment and recycling

The move, about one century ago (1905), from individual to community-wide water and sewerage systems, was the most beneficial public health initiative in the history of Australia. The introduction of safe, reticulated water supplies between 1880 and 1920 cut the death rate in half and reduced the incidence of infectious diseases and infant mortality by a factor of ten. There is now a movement, promoted by environmental groups, for a return to individual household systems in the interests of conservation.

Individual systems may provide appropriate solutions for large, rural residential allotments with adequate areas for irrigation. Except in very dry areas, there is insufficient space on a typical urban residential allotment to recycle all wastewater without external runoff and environmental impacts. Considerable technological improvement would be needed on current individual household systems to achieve acceptable public health and environmental outcomes in urban areas.

Individual household systems have the advantage of low pipework costs. Locating water reclamation plants closer to the point of reuse would reduce pipework costs for community systems. Community systems are likely to be better than individual systems in terms of performance, reliability and treatment costs. Neighbourhood treatment and recycling systems might provide the right balance in the long term.

Community education

There seem to be obvious gaps in community knowledge of human interaction with the water cycle. This includes an almost total lack of awareness of how water supply and wastewater systems work. This is compounded by community inhibitions relating to bodily functions (urination and defecation) and unfounded community concerns about health risks. Much of the available information on water issues is too technical for the average person. Community consultation processes on water and wastewater projects are often delayed and sometimes frustrated because of this lack of knowledge. There is more likely to be informed and rational debate about proposals if the community is well informed on water issues before the start of community consultation processes. A water education project to improve community understanding on water issues (Bovill and Simpson 1998) has become the 'We all use water' suite of documents and education aids. This came to fruition in 2002 and training courses were on offer around Australia, to give the necessary community education skills to relevant workers.

Recycled water products and grades

A necessary ingredient of community education is the use of understandable terminology. There is an active debate in Australia on appropriate terminology for grades of recycled water based on quality. An alternative proposal is to describe recycled water products in terms of their end use. It may be possible to combine these two ideas to produce a clear and workable system. Developing simple and easily understood terminology will also assist in community education. An example of a user-friendly rating system was developed by Jenifer Simpson (2002).

Economics and sustainability

Dual reticulation, residential, non-potable reuse projects have been costed for various schemes and are generally in the range of A$2.50/kL to A$5.00/kL reclaimed water supplied. Law (1993) demonstrated that an indirect potable reclamation system returning water to a reservoir would cost less than a dual reticulation, non-potable reuse scheme.

Much work is being done to evaluate water recycling projects in terms of their economics and environmental sustainability. A recent example is the Sydney Water Corporation's December 1999 Water Recycling Strategy which evaluates potential projects in terms of levelised annual costs in A$/m^3 and greenhouse gas impacts expressed as equivalent kWh/m^3 energy use. The levelised annual cost approach has been described by White and Howe (1998). White and Howe (1998) have reported that the following (Table 1.1) reuse costs were derived during the recent Sydney Least Cost Planning Study.

The results of these analyses indicate the following.

Table 1.1 Reuse costs derived from the Sydney Least Cost Planning Study.

Option	Levelised cost A$/kL
Wollongong industrial reuse (non-potable)	0.53
Kurnell industrial reuse (non-potable)	0.65
Indirect potable reuse (116 ML/d)	0.77
Bondi STP reuse (non-potable)	0.93
Golf course reuse (non-potable)	1.47
Rainwater tanks (80% of houses)	2.11
Grey water reuse systems (80% of houses)	2.44

Source: White and Howe (1998).

- Selected large industrial reuse projects and urban landscaping projects which are located close to treatment plants are more economical than dual reticulation residential schemes.
- Indirect potable reuse would be more cost effective than many non-potable reuse options but would have higher greenhouse gas impacts.
- Decentralised treatment and recycling systems may warrant further examination.
- Australia still has substantial scope to implement low cost water conservation measures, most of which cost less than A$0.40/m^3 to implement. Such measures provide a 10-year to 20-year window of opportunity in which to make informed decisions about the safety, economics and sustainability of advanced water recycling applications and to further improve the technology.

National guidelines for water recycling

Although good progress is being made with establishing uniform guidelines across Australia, there is concern in the water industry that State regulatory agencies have not provided the level of leadership required to establish a satisfactory water recycling framework. Delays in delivery of the new National Guidelines for Water Recycling: Managing Health and Environmental Risks (NRMMC and EPHC, in draft) have led to the State agencies continuing to deliver their own guidance documents reflecting local environmental values. In some cases the latter produces inconsistent regulatory decisions and project uncertainty. For example, New South Wales has lost some worthwhile beneficial reuse initiatives because the project approval process is too onerous and costly for small projects. In other cases the wording rather than the intent of the current guidelines has been used to frustrate projects. These cases would be permissible under the current Californian regulations,

Table 1.2 Annual water reuse from water utility treatment plants in Australia, 1996–99 and 2001–02.

Region	1996–99			2001–02		
	Effluent (GL/year)	Reuse (GL/year)	%	Effluent (GL/year)	Reuse (GL/year)	%
Qld	328[B]	38[B]	11.6	339[C]	38[C]	11.2
NSW	548[A]	40.1[A]	7.3	694	61.5	8.9
ACT	31[B]	0.25[B]	0.8	30	1.7	5.6
Vic	367	16.9	4.6	448	30.1	6.7
Tas	43	1	2.3	65	6.2	9.5
SA	31[B]	9[B]	9.9	101	15.2	15.1
WA	109	5.5	6.1	126	12.7	10.0
NT	21[B]	1[B]	4.8	21	1.1	5.2
Australia	1538	112.9	7.3	1824	166.5	9.1

[A]1996
[B]1998
[C]Subject to revision
Source: Radcliffe (2004).

that most guidelines have been based on (Anon. 1998). There has been a regrettable tendency to require the reinvestigation of issues, which have long since been resolved in California and elsewhere.

Conclusions

Water recycling in Australia is at an interesting stage of development. Events arising during the droughts of 1978–83, 1990–95 and 2001–03 have led to substantial changes in public policy on environmental and water resources management, and have encouraged greater water conservation and recycling (Radcliffe 2004). There are many worthwhile water reclamation and reuse projects in operation or under construction. The level of beneficial reuse in Australia approximately doubled during the decade 1990 to 2000 and is likely to double again from 2000 to 2010. In some States reuse has grown at even higher rates (Table 1.2).

Water reuse in Australia 'came of age' during the 1990s. Prior to this most schemes consisted of small projects using less than 100 ML/yr, whereas we are now seeing the implementation of many schemes with reuse in excess of 1000 ML/yr. The quality of projects, the quality of research and development and the standard of papers being presented at Australian conferences are now worthy of international notice.

Emerging trends include moves towards the development of uniform national guidelines for water recycling. There are concerns about health risks, sustainable irrigation and the protection of groundwater. There are moves towards the adoption of higher grades of reclaimed water to reduce risks, the identification of reclaimed water products/grades and improved community education. As elsewhere, there is active debate on the use of recycled water to supplement public water supplies.

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Reuse in South Australia

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Municipal wastewater management

In South Australia, municipal wastewater management is primarily the responsibility of the South Australian Water Corporation (SA Water) in metropolitan Adelaide, with both SA Water and local governments playing key roles in country areas. SA Water is a statutory corporation owned by the government of South Australia. It is a State-wide organisation with a long history of providing water and wastewater services for the South Australian community.

SA Water provides wastewater services to the capital city, Adelaide, the major regional cities of Mount Gambier, Murray Bridge, Port Augusta, Port Lincoln, Port Pirie and Whyalla, and to a further 12 country townships due to their importance for tourism or industry, or because of the sensitive water resources in their vicinity.

Metropolitan Adelaide is segregated into four major drainage areas for wastewater collection, with each discharging to a wastewater treatment plant (WWTP) which provides at least secondary treatment prior to disposal to the marine environment of Gulf St. Vincent, or for reuse (Figure 1.1). One-fifth of the drainage area, at Aldinga, serves a small population on the southern fringes of the metropolitan area (small section near bottom of the figure, not marked). In total, SA Water serves a population of over 1.1 million people with wastewater services throughout the State.

In other areas of the State, wastewater management for communities is generally based on individual, privately owned, on-site septic tanks, which discharge treated effluent to on-site soakage systems. However, for larger communities, or in places of environmental sensitivity, septic tank effluent is discharged to a common municipal collection/treatment system, referred to as a Septic Tank Effluent Drainage Scheme. Septic Tank Effluent Drainage Schemes are funded by

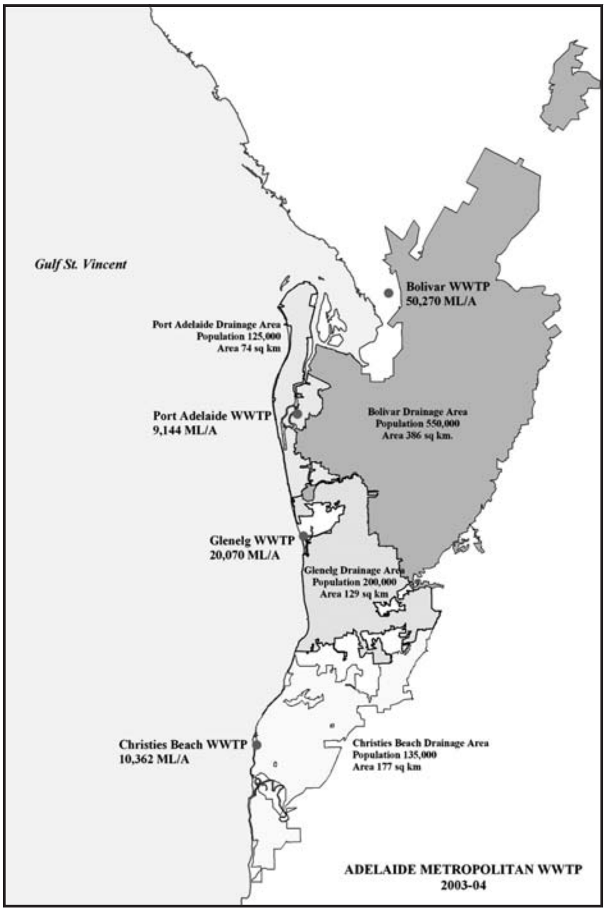

Figure 1.1 Major drainage areas for wastewater in metropolitan Adelaide.

local councils or jointly by the State government and local council, and operated by the local council. There are currently 165 Septic Tank Effluent Drainage Schemes throughout country South Australia, serving about 150 000 people (Local Government Association of South Australia 2002). Further Septic Tank Effluent Drainage Schemes are planned as part of an ongoing program to improve wastewater management in country South Australia.

Background to reuse (1880s to 1990s)

The history of wastewater reuse in South Australia dates back to the early 1880s with the establishment of the first deep drainage system to serve the City of Adelaide and the associated sewage treatment facility (the sewage farm) at Islington. The incoming sewage was screened at the sewage farm before directing it to broadacre irrigation over the 470 acre (about 190 ha) site. By 1888 the farm's main interests were grazing and fattening stock and growth of root crops and fodder plants. Lucerne, Italian rye-grass, marigolds, sorghum, wheat, barley, vines and wattles were all grown (Hammerton 1986). Reuse for dairy products and orchards was originally practiced, but was later abandoned because of public concern about the produce. Although the reuse practiced at the sewage farm would not be acceptable for a modern city today, the success of the sewerage system was heralded by a fall in Adelaide's mortality rate from 23.5 per 1000 in 1881 to 14.3 per 1000 after only five years of operation. Typhoid was virtually eliminated from urban areas which brought high acclaim from both interstate and overseas.

The sewage farm continued operation until 1966 when it was replaced by the newly commissioned, first stage of the Bolivar Treatment Works, and by 1969 the final stage of its construction was complete. The new Bolivar works was designed to cater for the sewage from a population of 600 000 people together with industrial wastewater from the city's major industrial areas. Treatment standards at the Bolivar plant, consisting of secondary treatment and stabilisation lagoons, were far in-excess of what had been practiced at the former sewage farm.

Reuse of the treated wastewater was considered to be a worthwhile objective by plant designers in 1959, particularly since the nitrogen and phosphorus in the water could be valuable for irrigation purposes. However, the high costs of an irrigation project and concerns about the expected high salt content of the treated wastewater (and its potential effect on soil conditions in the area) led to a decision to defer any government-funded irrigation scheme.

Nevertheless, market gardeners in the region lobbied hard for access to the treated wastewater and were eventually rewarded with the opportunity to establish their own private irrigation schemes with restrictions on the use and application of the water to safeguard public health of irrigated crops. Since these schemes were privately funded, most uses occurred close to the 13 km long outfall channel, and reuse was generally small compared to the quantities of treated wastewater which was discharged to Gulf St. Vincent each year.

Reclaimed water from Bolivar was used to irrigate lucerne, pasture and fodder crops such as maize and field peas. It was also used for the production of horticultural crops such as potatoes, carrots, onions, tomatoes, grapes and olives. However, reuse was limited due to the cost and restrictions imposed on use. The reuse experience and associated research provided a valuable demonstration of the viability of using reclaimed water for agricultural activities in the region.

Over the next 40 years (from 1959), the opportunity for the establishment of a government-funded irrigation scheme was intermittently reviewed, but always with the same result – too expensive to justify. It was not until 1999 that extensive reuse became a reality.

In the intervening period (1959–99) reuse was established at other metropolitan and some country WWTPs. Reclaimed water from the Glenelg WWTP has been successfully used since 1933 when on-site lawns and gardens were first irrigated. This success led to the first use by private consumers in 1958 when the West Beach Trust began irrigating eight hectares of playing fields. This was followed in 1972 by the construction of the first government-operated reticulation scheme to supply reclaimed water to private users for irrigation of recreational areas (three golf courses, a school and extensive playing fields) and, parks and gardens of the local council.

In the mid 1970s limited reuse occurred at the Christies Beach WWTP for the irrigation of recreational areas and parklands adjacent to the plant. It was not until 1999 that extended reuse from this plant was established.

No reuse has occurred from the Port Adelaide WWTP due to the elevated salinity levels in the wastewater caused by infiltration of highly saline groundwater into the aged (but still structurally sound) wastewater collection system, and the exorbitant cost which would be necessary to eliminate the infiltration or to reduce the salt content in the reclaimed water through desalination.

Also during the mid 1970s, opportunities for reuse were pursued at several country WWTPs and Septic Tank Effluent Drainage Schemes. An important driver was the introduction of the *Water Resources Act* 1976, and the recognition by State authorities that the sustainability of the environmentally sensitive River Murray required proactive action to eliminate wastewater discharges to the river system, to divert saline groundwater out of the river basin (where practicable), and to licence and regulate abstractions from the river system. The predicament of the River Murray today is testimony to the fact that measures of this nature can only be effective if they are applied across the whole of the river system, not just within one State's jurisdiction.

As a result of these initiatives reclaimed water at the Mannum WWTP was diverted for irrigation of the local golf course. In 1993 at Murray Bridge, reclaimed water was pumped away from the river to a constructed wetland at the nearby Australian Army base and firing range to create a green oasis in the sandy mallee. This oasis provides a habitat for birds and a wide range of flora and fauna, while providing irrigation water to enhance the amenity at the army facilities. At Loxton, reclaimed water from the local Septic Tank Effluent Drainage Scheme was used for woodlot irrigation, avoiding discharge to the river. Reclaimed water projects were also implemented for other Septic Tank Effluent Drainage Schemes serving River Murray towns.

In more arid areas, reclaimed water use provided a cheap source of water for irrigation of community facilities. For example, in the late 1970s, the Port Augusta Golf Club commenced using reclaimed water for irrigating fairways and greens. At Coober Pedy, reclaimed water from the local government wastewater treatment plant is used to irrigate the school oval. Regrettably in other arid coastal areas reclaimed water reuse has not developed due to elevated salinity levels similar to those which afflict the Port Adelaide Plant. Many more examples of reclaimed water use are available for local Septic Tank Effluent Drainage Schemes throughout the State for irrigation of school ovals, passive recreation areas, woodlots, agriculture and wetlands. In total about 3300 ML/yr or 50% of the reclaimed water from Septic Tank Effluent Drainage Schemes is reused (LGA SA 2002).

Despite this wide application of small reclaimed water schemes throughout the State, by the end of the 1980s only about 6% of treated wastewater from municipal treatment systems was being used for beneficial purposes. This low figure was largely caused by the low reuse from metropolitan treatment plants. This situation was not the result of a reluctance to develop reclaimed water reuse applications, but derived from other factors such as the following.

- The geography of the metropolitan area and application of traditional planning principles which result in treatment plants being located along the coastline.
- The location of industry (which potentially could have used reclaimed water) within the Port Adelaide drainage area.
- The location of extensive horticulture at the northern and southern extremities of the metropolitan region, or in elevated areas in the Adelaide Hills.

These factors combined meant that costs for the development of extensive reuse schemes were excessively high and could not be justified in the absence of other drivers.

The last decade (1995 to 2005)

The principal drivers for the development of reclaimed water reuse systems have been environmental, economic and social 'triple bottom line' factors.

Environmental drivers

The introduction of the *Environment Protection Act* 1992, and the establishment of the independent Environment Protection Authority (EPA), provided the framework for regulation, environmental assessment, and management of all wastewater discharges. This initiative established the basis for future discharge requirements and recognised, for the first time in a social and political context, that decisions would no longer be taken solely with a focus on cost or political will.

Concurrently, amendments to the *Water Resources Act* 1976 established new arrangements for the management of surface and groundwater resources based on a whole-of-catchment approach. This saw the introduction of Catchment Water Management Boards (with a strong community representation) to oversee the regulation of water resources and to develop policies for government consideration, based on sustainable practices for a particular catchment.

These two legislative developments have raised the importance of reclaimed water reuse as a means of minimising bulk uncontrolled discharges to the environment, particularly the marine environment, to reduce environmental harm. They have also highlighted the importance of providing alternative water sources as a replacement for overexploited groundwater and surface water resources.

Economic drivers

Demand for water, particularly for agricultural activity, is rapidly increasing in response to commercial and economic development agendas of private companies and of government. For example, the boom in the wine industry, which is founded on the successful push into international markets, is underpinned by access to water. The availability of reclaimed water for this purpose provides a high degree of security of supply. Availability of reclaimed water is not subject to the same variability as other sources, which are under stress due to unsustainable practices, being more highly regulated and at the mercy of a variable climate (see *An overview of Australia and reclaimed water*).

The expansion, or even maintenance, of agriculture to service the needs of increasing populations, locally, nationally and internationally, depends on the application of best practice production methods and the availability of relatively cheap sources of water.

Social drivers

Urban populations are becoming increasingly aware of the environmental, economic and social advantages, and indeed imperative in some circumstances, of recycling. Historically, recycling was seen as the domain of the conservation movement rather than the general public. Whilst the recycle philosophy has been evident in many fields (paper recycling, green waste, even 'pre-loved' goods) and is now far-reaching, it is in the realm of water recycling that this philosophy is likely to provide focus for significant policy change and on-ground developments in the immediate future.

This focus has been sharpened in recent times by prevailing drought conditions throughout Australia, by water restrictions at previously unimagined levels over wide geographic areas, and by the deterioration of the River Murray. All of these have contributed to an ever widening debate on the importance and sustainability of the nation's water resources.

The influence of these drivers in the South Australian context has been responsible for the development of two significant reuse schemes centred on the Bolivar and Christies Beach WWTPs for extensive irrigation in agriculture.

South Australian reclaimed water schemes

Bolivar WWTP (The Virginia Pipeline Scheme)

The coming together of three events in the early 1990s finally led to the development of an expansive irrigation scheme for the Northern Adelaide Plains using treated wastewater from the Bolivar WWTP.

First, the Northern Adelaide Plains had developed into the site of the major horticultural industry providing vegetables and other produce for local and interstate markets. This industry relied on groundwater for irrigation. The groundwater resources in the region had become seriously depleted as a result of overuse, creating a large cone of depression of lower groundwater levels centred around Virginia. This is increasing bore and pumping costs, and also establishing conditions whereby the quality of the groundwater could be adversely affected by incursions from adjacent saline aquifers.

Second, the increasing public sensitivity to environmental issues (which heralded the establishment of the EPA) highlighted the impact of treated wastewater discharges on the relatively shallow marine environment in the Gulf St.Vincent. As a result, the Engineering and Water Supply Department (now known as SA Water) was required to consider and implement changes to the Bolivar WWTP which would significantly reduce the discharge of nutrients to the Gulf (particularly during the critical summer months).

Third, the government secured an A$10.8 million Federal Government grant through the Building Better Cities program to assist in the establishment of an irrigation project for the Northern Adelaide Plains using treated wastewater from the Bolivar plant. The Virginia Pipeline Scheme was the culmination of the need to integrate these three events, and is a cooperative undertaking of the Virginia Irrigation Association (representing market gardeners and other irrigators), SA Water (supported by several State government agencies) and Water Reticulation Systems Virginia (a private sector subsidiary of Tyco International).

SA Water has constructed a A$30 million Dissolved air flotation and granular multimedia filtration (DAFF) plant to treat the lagoon effluent from the existing Bolivar WWTP. The DAFF plant produces a Class A equivalent reclaimed water which can be used for irrigation of agricultural crops without restrictions on the method of irrigation or crops grown, from a food safety and human health perspective (Bosher *et al* 1998). The quality of the water is closely monitored in accordance with procedures set down by the Department of Human Services to ensure that public health standards related to the reclaimed water are continuously maintained.

Water Reticulation Services Virginia (with financial assistance from Building Better Cities funds and SA Water) has constructed an extensive distribution system involving more than 100 km of pipes, costing about A$22 million. The system has a capacity of 110 ML/d and starts at the Bolivar plant, fanning out to provide water to irrigators as far north as the Gawler River. The scheme, shown schematically in Figure 1.2, was commissioned in 1999.

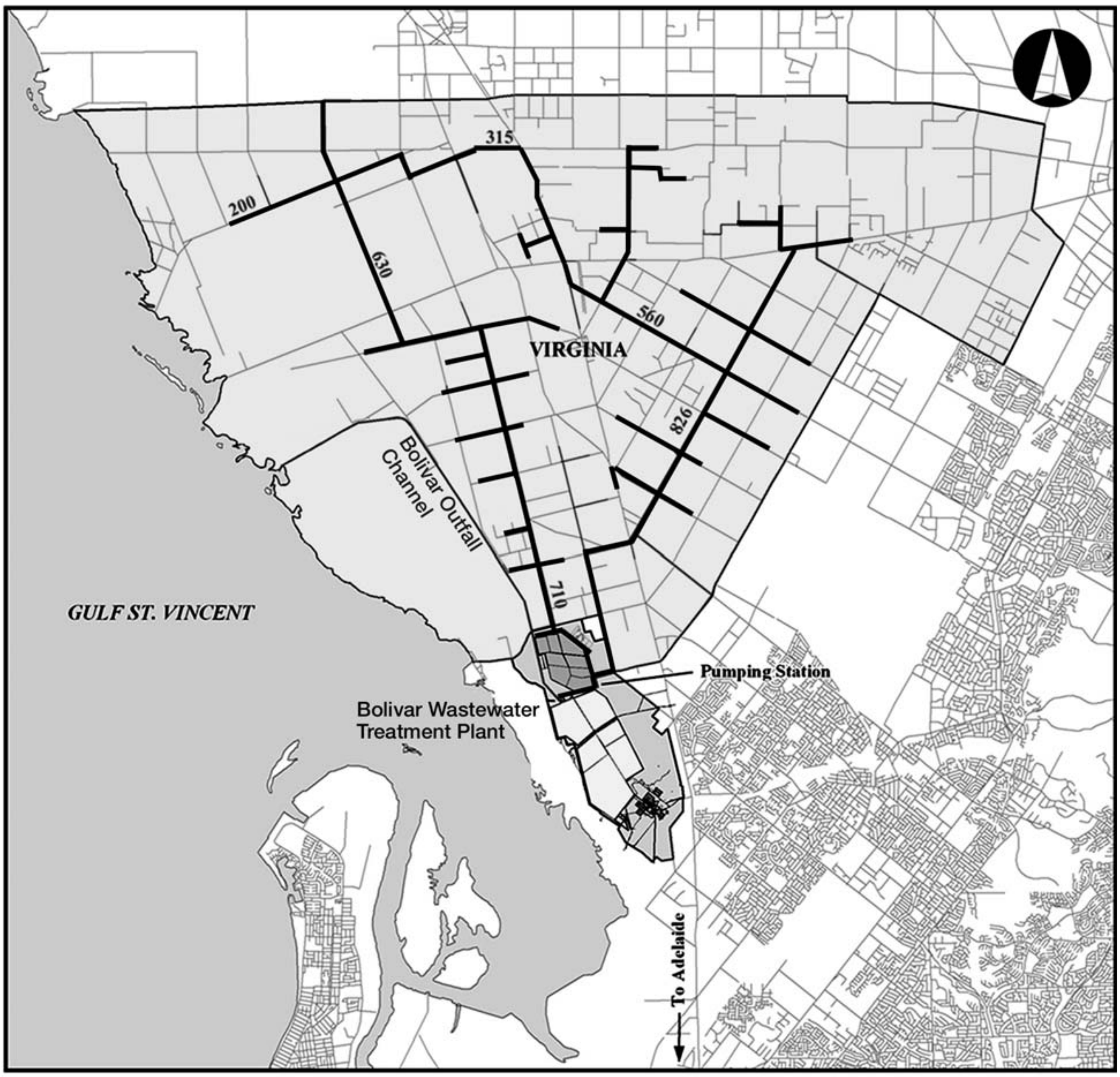

Figure 1.2 Main pipelines (black) of Water Reticulation Services Virginia's reclaimed water scheme.

The scheme boasts some 243 contracts for the supply of reclaimed water for irrigation, totalling some 19 658 ML/yr. Annual use has increased from about 1600 ML in 1998/99 financial year (before the commencement of the Virginia Pipeline Scheme) to 6000 ML in 1999/00, and to 12 100 ML in 2004/05. The use of reclaimed water is expected to increase further as the horticultural industry continues to expand, as groundwater substitution takes place, and as growers establish on-site infrastructure and refine their water usage methods. Ultimately, about 50% (or some 22 000 ML) of flow from the Bolivar plant could be used for irrigation on the Northern Adelaide Plains (Marks *et al* 1998). This could be further increased significantly if Aquifer Storage and Recovery (ASR), which is undergoing field trials, proves to be technically feasible and economically viable (see *Aquifer storage and recovery research*).

The Virginia Pipeline Scheme is the first and largest reclaimed water scheme of its type in Australia. This is, indeed, something which the community of South Australia can be justly proud.

Christies Beach WWTP (The Willunga Basin Scheme)

In 1995 SA Water commissioned a study into the feasibility of using reclaimed water from the Christies Beach WWTP in the Willunga basin south of Adelaide for irrigation of horticultural crops, specifically premium quality wine grapes. The region was already a renowned producer of quality wines but industry expansion was limited due to non-sustainable use of groundwater from underlying aquifers, notwithstanding the availability of nearly 5000 ha of suitable land for viticulture.

At the same time nearly 10 000 ML of Class B (SA Guidelines; see *Chapter 2*) treated wastewater was discharged annually to the marine environment from the nearby Christies Beach WWTP.

The study concluded that up to 600 ha of land could be irrigated using the then summer flow from the Christies Beach plant without the need to construct balancing storages in the Basin. It also concluded that a 2400 ha irrigation scheme could be developed if seasonal storage could be economically provided, thereby diverting nearly 60% of the annual flow from the plant to productive irrigation use.

A licensing agreement was negotiated between SA Water and the Willunga Basin Water Company (a consortium of 18 grape growers, landholders and winemakers) which allowed the company to access all uncommitted Class B (SA Guidelines; see *Chapter 2*) reclaimed water from the Christies Beach plant (Gransbury 2000). The agreement required that the company design, construct, install, operate and maintain the 'pipeline' infrastructure at its own expense and risk. In addition, the company was to comply with any law in respect of its use of the reclaimed water including obtaining and complying with any approval and or consent required from the regulating agencies, particularly the South Australian EPA and Department of Human Services.

The location of resultant reuse scheme (Stage 1) is shown on Figure 1.3 and consists of 13.2 km of pipeline, pumping stations and an intermediate balancing storage, constructed at a cost of about A$7.2 million. The scheme has a capacity of 24 ML/d and was commissioned in 1999.

The use of this reclaimed water has increased to about 2000 ML in 2001/02 and the company is planning to expand the scheme to provide a further 1000 ML/yr,

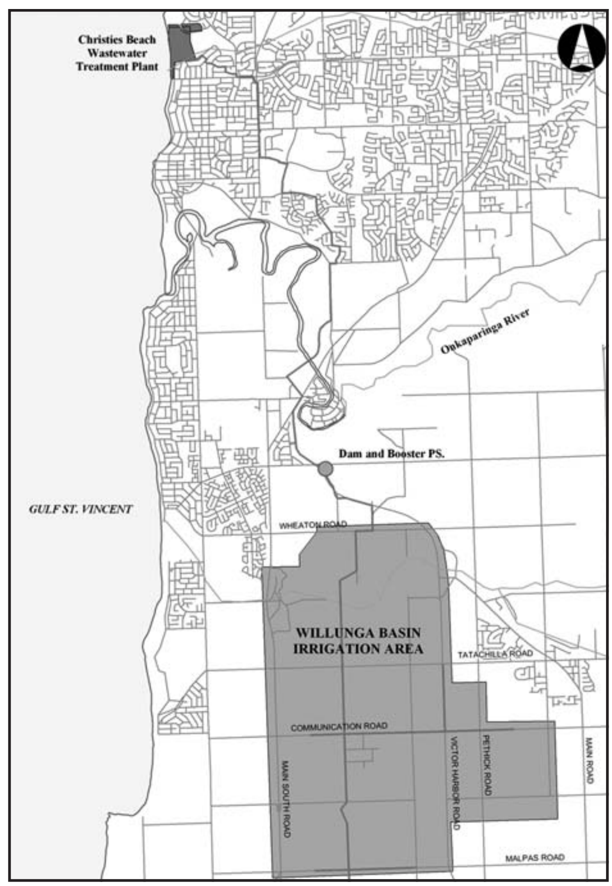

Figure 1.3 Willunga Basin Water Company reclaimed water scheme.

initially through surface storage of winter flows. The potential for ASR is being evaluated by the government to determine the suitability of this technique to store the remaining surplus flows from the Christies Beach plant.

This scheme is an excellent example of the worth of reclaimed water in providing multifaceted benefits for the whole community. In particular, the growers benefit as a result of expanding sustainable horticulture, the State benefits from significant economic development, and the environment benefits from a significant reduction in the amount of treated wastewater being discharged to the sea.

Aldinga WWTP and reuse scheme

The Aldinga Wastewater Treatment Plant and Reuse Scheme, which Henry Walker Environmental began operating in mid 1997, saw the construction of a privately financed, built and operated WWTP, requiring 100% reuse of the reclaimed water produced by the plant.

The plant, which has the capacity for a population of 3500 people, treats wastewater from 1100 existing customers in the Aldinga Beach area and recycles it to irrigate some 20 ha of vines. The 25-year operating contract provides for expanding the plant's capacity as the local population grows, giving it the eventual potential to provide sufficient treated wastewater to irrigate 150 ha of vines.

Because irrigation in the area is generally undertaken in the five months from November to March, the scheme has incorporated the construction of sufficient winter storage lagoons to hold the Class B treated wastewater (SA Guidelines; see *Chapter 2*) until it is required by the vineyard.

Urban reuse

Mawson Lakes is one notable advancement from the more traditional uses of reclaimed water on school ovals, passive recreation areas, woodlots, agriculture and wetlands, mentioned above. Mawson Lakes is an urban development 12 km north of Adelaide City, which is designed to recycle water to provide at least 50% of household water and all open space irrigation water needs from storm and wastewater (Richard Marks, pers. comm., 2002). It is a joint venture between the SA Government and Delfin Lend Lease Consortium (Mawson Lakes Economic Development Joint Venture). Stormwater and wastewater from the development is to be collected and treated onsite to a high standard for distribution. The annual use of recycled water is estimated to be 1000 ML (400 ML wastewater, 600 ML stormwater). All houses will have a mains connection and a recycled water connection, with the recycled water being used for toilet flushing, garden watering, car washing and public open spaces. The development is scheduled for completion in 2009.

Aquifer storage and recovery research

Background

Economic storage of excess flows of treated wastewater in winter when irrigation demand is low is critical if maximum use of water resources is to be achieved. Since the early 1990s ASR has been increasingly used in South Australia to assist in specific surface or groundwater problems that have required innovative solutions (Martin *et al* 2000). The schemes range from harvesting catchment runoff in urban areas to providing safe potable rural water supplies. The focus for ASR in South Australia has expanded recently from single well projects to much more ambitious undertakings. The use of ASR for reclaimed water is being trialed at Bolivar and Willunga to determine the economic and environmental sustainability of this technique. If successful, these trials will provide guidance for the implementation and management of much larger schemes to store all winter excess of reclaimed water in the aquifer.

Bolivar Reclaimed Water ASR project

The purpose of this project is to examine the feasibility of injecting winter flows of reclaimed water from the Bolivar WWTP into the aquifers beneath the Northern Adelaide Plains.

A consortium comprising the Department for Water Resources (DWR), United Water, SA Water, CSIRO, Department of Administration and Information Services (DAIS) Major Projects Group, and the assistance of Natural Heritage Trust funding have combined to undertake a joint feasibility study into the injection of winter excess treated wastewater into the confined aquifer beneath the Northern Adelaide Plains. A four-year A$3 million research project commenced in 1997 to determine the technical feasibility, environmental sustainability and economic viability of ASR using the DAFF treated water from the Bolivar WWTP. The project has been designed to demonstrate that any potential health risks associated with the practice can be controlled effectively within a strict quality regulation and monitoring regime.

The Bolivar ASR trial is at the international leading edge in the design and implementation of deep-well injection of irrigation quality waters into low transmissivity aquifers. This project provides the opportunity to realise significant environmental, economic and social benefits for water dependent activities, through the storage of reclaimed water at costs which are significantly lower than would be expected by providing above-ground storage and without the risk of adverse water quality changes possible with surface storage. Community acceptance in supporting such a possible future scheme is an important prerequisite to the success of such a project.

The risks and immediate benefits of the trial are low, but a successful trial and community acceptance of a full-scale scheme will potentially lead to major benefits. The storage and subsequent retrieval of reclaimed water from the aquifer can also be seen as a long-term solution to the sustainable management of all of the available water resources on the Northern Adelaide Plains if the trial proves that the practice is safe, can be well managed, is both technically and economically viable and will have no adverse environmental effects.

Country WWTP reuse schemes

Schemes for reclaimed water reuse are being progressively introduced to SA Water's country WWTPs where this can be achieved economically. These schemes are associated with a range of agricultural, horticultural or community activities including viticulture, pasture, forestry and recreation. To date, 10 out of 19 country WWTPs support reuse schemes for either total annual flows or summer flow application.

In 2001/02 a total of 1515 ML was reused from these plants, representing some 15% of the total treated wastewater produced at the plants (Table 1.3). This figure is expected to increase to 24% over the next few years. The portion of treated wastewater that is not reused is released to the environment either to coastal marine waters or inland streams.

Summary

SA Water anticipates that use of reclaimed water will gradually increase over the next few years as a result of:

- increasing demand from customers of the Virginia Pipeline Scheme;
- provision of some storage for winter flows within the Willunga Basin scheme;
- expansion of existing schemes subject to economic viability;
- successful demonstration of technical viability of ASR for reclaimed water; and
- implementation of new schemes, particularly at some country WWTPs and Septic Tank Effluent Drainage Schemes.

Continued development of reclaimed water use by SA Water is directed to achieving key environmental outcomes by 2005, namely to increase:

- wastewater reuse at metropolitan WWTPs to 30% of available treated wastewater; and
- wastewater reuse at country WWTPs to 24% of available treated wastewater.

Table 1.3 Summary of reclaimed water use in South Australia (financial year 2001/02).

	Treated wastewater available (ML/yr)	Reuse (ML/yr)	Reuse (%)
Metropolitan			
Bolivar	45 671	9714	21
Glenelg	20 812	1897	9
Christies Beach	10 718	1969	18
Port Adelaide	13 731	0	0
Aldinga	201	201	100
Metropolitan Total	91 133	13 675	15
Country			
Inland	4512	1515	34
Coastal	5870		0
Country – total	10 382	1515	15
Septic tank effluent drainage schemes	6600	3300	50
Total	108 085	18 490	18

Source: SA Water, South Australia.

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Reclaimed water use in Victoria

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The vast majority of Victoria's population resides in the greater Melbourne area and, thus, most wastewater is managed by Melbourne Water through the Western Treatment Plant at Werribee and the South Eastern Purification Plant at Carrum. However, many smaller cities and towns also increasingly face the need to reduce discharge into the marine environment (principally bay and ocean outfall) and freshwater environments through land application or other forms of reuse.

Historical perspective

The Melbourne and Metropolitan Board of Works (MMBW) commenced operation in 1891, and by 1897 the Main Outfall Sewer from Melbourne directed sewerage to the Board's farm at Werribee for treatment prior to the treated effluent being discharged into Port Phillip Bay.

Part of this treatment process included land filtration and grass filtration through overland flow. Since 1900, cattle and sheep have grazed the effluent-treated pastures. After paddocks have drained fully following irrigation, livestock are introduced until the next irrigation is due. A presentation in 1978 on the utilisation of wastewater at Werribee discussed the 'effective and economic use of wastewater by land filtration, grass filtration (overland flow) and lagooning' (Croxford 1978). This report also described research underway to determine the practicability and economics of using treated effluent for irrigation of high value agricultural and horticultural crops including cereal and oilseed, forage crops and various vegetable rotations.

In 1975, the South Eastern Purification Plant was commissioned at Carrum to service the eastern and southern parts of greater Melbourne leaving the Werribee Farm to service the other needs of Melbourne. At the South Eastern Purification Plant the wastewater is treated by an activated sludge process and the secondary treated effluent is principally discharged into Bass Strait at Boag's Rocks near Cape Schank. Some diversion of the secondary treated effluent has been directed onto areas of recreational turf (eg golf courses, parks and gardens) and some market gardens. Restrictions on market gardening use ensured that the reclaimed water (Class C) did not come into direct contact with produce that may be consumed raw (see *Chapter 2*).

Changing environmental and health standards and guidelines

The commencement of the South Eastern Purification Plant at Carrum was a key driver in developing new ideas for wastewater reuse and for creating a framework for environmental and health standards for the use of reclaimed water through legislation and guidelines. Prior to this, a joint committee of the MMBW and the State Rivers and Water Supply Committee (SRWSC) tabled an interim report relating to the organised reuse of wastewater (Bird and Lang 1968). This led to some field experiments on agricultural reuse but work was placed on hold since they depended on the availability of wastewater from the South Eastern Purification Plant.

Following the 1972–73 summer drought, the government appointed a Standing Committee on Water Supply for Victoria with a subcommittee on reclaimed wastewater use. The inclusion of a Commission of Public Health medical officer was an important development because until then, the emphasis was on water reuse in terms of engineering, but now public health was on the agenda. In 1973, a mission to investigate practices in other countries relating to the reuse of wastewater lead to a seminal report with 16 recommendations. The recommendations included the creation of necessary legislation to authorise and control the use of wastewater and establishment of a body responsible for administering applications and managing compliance (Lang *et al* 1977). Up to this stage, there were no regulatory frameworks or guidelines for the use of wastewater in Victoria.

Through the recommendation of the Health Commission, the State Government legislated the use of wastewater in the *Health (Amended) Act* 1977 and Regulations made thereunder, the Health (Use of Waste Water) Regulations 1978. These regulations contained microbiological standards adopted from the Australian Water Resources Council and the National Health and Medical Research Council. The 1978 Regulations were amended in 1985 to qualify the use of reclaimed water in pastures for grazing cattle because of the threat of transmission of beef measles and beef tapeworm. Reclaimed wastewater had to be ponded for 60 days or treated by sand filtration before it could be used on pastures. Other amendments included the introduction of the restriction that spray irrigated crops including vegetables must be cooked, peeled or treated in a manner to destroy any human pathogens.

Preceding this, research undertaken at the Vegetable Research Station at Frankston (see *Frankston Vegetable Research Station*) included the investigation of health and safety aspects of the reclaimed water relating to bacteria, viruses and heavy metals (Kaddous *et al* 1986; Smith *et al* 1972). The positive results led to the first official use of reclaimed water for horticultural crops from the South Eastern Purification Plant in 1981. The use of wastewater was regulated through the issuing of licences permitting the use of wastewater under the Health (Use of Waste Water) Regulations 1981. The permits were for the growing of vegetables that were required to be cooked prior to eating, peeled before being eaten uncooked or processed commercially by a method that would destroy pathogenic organisms. The permit stipulated only wastewater that conformed to a specification was to be used. This specification covered three parameters: faecal coliforms less than 1000 per 1000 mL, biological oxygen demand with a median level of 15 mg/L and suspended solids with a median level of 20 mg/L.

The regulation also specified the use of notices easily legible to farm workers and the public stating the water used was not safe for drinking and the user had to provide a sampling point for the water so Health Commission officers could take samples. Pond location and requirements were also described with emphasis on water runoff and access by stock and the public. Conditions for spray application were clearly stated. Other conditions included the issue of protective clothing to employees and the non-interfacing of wastewater connections with any other water supply system on the property. The permit was conditional on limiting the use of the water to the intended purpose and the condition that the Health Commission could at any time change the conditions of use or revoke the permit.

More recently, the Environment Protection Authority (EPA) released guidelines for the disposal of wastewater to land by irrigation (EPA 1983). The revised EPA 1991 guidelines (EPA 1991) incorporated the Health Commission conditions of use and described the site selection process, wastewater quality in relation to soils, plant growth and public health and management in relation to land use and the environment but they did not apply to the irrigation of crops for human consumption. A less prescriptive EPA guideline was released in 1996 (EPA 1996) that incorporated most of the previous guidelines in an easy-to-understand format with information on potential reuse options, roles and responsibilities, wastewater quality, wastewater treatment, site and system control, performance monitoring and reporting and notification. It also included the use of wastewater in food crop production. It rated water quality into three classes that delineated suitability for use on food crops.

Future of reclaimed water use in Victoria

In 2001, an updated set of guidelines was released for the use of reclaimed water (EPA 2001b) and for disinfection of treated wastewater (EPA 2001a). These new guidelines generally adopted approaches described in the recently released national guidelines for sewage systems (ARMCANZ 2000), but have some variations to reflect Victorian conditions (eg increased restrictions on some horticultural products).

Despite these guidelines, adoption of reclaimed water irrigation in Victoria has been slow, mainly because most of the water available (Class B and C) has restricted usage to a few applications. The trend with Water Authorities has been to establish an internal policy on the reuse of reclaimed water that is often guided by the commercial reality of supplying treated water or by the cost of treating the water.

The Victorian Government has set a target of 20% of effluent to be recycled from the Eastern and Western

Treatment Plants in the greater Melbourne region by 2010 (Metropolitan Water Recycling Committee 2001). In order to address the 20% recycling target, a preliminary 'desk top' study has been undertaken to identify Prime Development Zones suitable for sustainable irrigated agriculture and horticulture. Prime Development Zones must have soils suitable for high value agriculture and horticulture with access to a secure supply of quality reclaimed water ensuring sustainably low environmental impact. The concept of recycling wastewater has been reinforced with the release in June 2004 of the Victorian Government White Paper (DSE 2004). This document sets out policy for the use of alternative water supplies for non-drinking uses and policy related to a reduction of ocean discharges of effluent.

Research into reclaimed water use in Victoria

Frankston Vegetable Research Station

The potential for using reclaimed secondary treated effluent for the production of vegetables has long been recognised in other countries (Day *et al* 1979). Not only was wastewater accepted as a substitute for higher quality irrigation water, the nutrients present in the reclaimed water, principally nitrogen, potassium and phosphorus, were seen as a partial substitute for manufactured fertiliser leading to reduced fertiliser costs even though the potential contamination of groundwater and drainage water with nitrogen and phosphorus (in sandy soils) had environmental implications. However, accumulation of trace amounts of heavy metals in the soil and the retention of bacteria and viruses on vegetables irrigated with wastewater was of concern since it could lead to food chain contamination (Hinesley 1972).

This lead to a research study from 1977 to 1983 at the Frankston Vegetable Research Station on a loamy sand using secondary treated wastewater from the South Eastern Purification Plant at Carrum (Kaddous *et al* 1986). Using equivalent rates and frequencies of reclaimed water to that of bore water previously used by local growers, the total and marketable yields of successive crops of lettuce (first), carrot, cabbage, celery, spinach, lettuce (second) and tomatoes were recorded. Plant uptake and recovery of nitrogen, phosphorus, potassium, cadmium, chromium, copper, iron, nickel, zinc and their accumulation in the soil were also recorded. After balancing the manufactured fertilisers to compensate for the nitrogen, phosphorus and potassium supplied by reclaimed water, a 7% to 18% increase in the marketable yield was measured relative to the use of bore water. Kaddous *et al* (1986) concluded that the increased yields were due to the regular supply of trace amounts of other water soluble nutrients in the reclaimed water that were absorbed through the foliage as well as the plant roots. This contrasts to normal practice where large amounts of manufactured fertilisers are applied to the soil prior to sowing, and a later side dressing, leading to higher leaching losses of nitrogen and potassium.

Kaddous *et al* (1986) calculated that the use of reclaimed water represented approximately a 35% saving in fertiliser costs because reclaimed water saved about 60%, 33% and 40% of inorganic nitrogen, phosphorus and potassium fertiliser, respectively. The boron content in wastewater was sufficient to eliminate the common occurrence of boron deficiency in celery on these sandy soils without having any adverse effects on boron sensitive crops. A further saving from using reclaimed water was the bore water saved; between 0.64 ML and 5.6 ML of bore water depending on the crop and seasonal weather conditions.

No accumulation of heavy metals was recorded for the edible parts of the vegetable crops or the soil receiving wastewater irrigations. Furthermore, total coliforms, *Escherichia coli* and *Salmonella* levels on vegetables that were spray irrigated with wastewater did not differ significantly from vegetables purchased from commercial outlets around Melbourne. The presence and survival of human enteric viruses were studied and the results suggested no health effects from the consumption of the crops were likely. Although viral contamination was seen as a potential problem for crops eaten within two weeks of harvest, no work on parasites was conducted as part of that study (Smith *et al* 1972).

Black Rock Sewerage Treatment Plant, Bellarine Peninsula

During 1999–2000, cooperative trials were undertaken by scientists of the Department of Natural Resources and Environment in conjunction with Barwon Region Water Authority and local growers on the Bellarine Peninsula of Victoria (Harapas and Premier 2000; Premier *et al* 2000).

The first trials were commissioned to establish the growth characteristics of potatoes irrigated with reclaimed water, and to determine the suitability for human consumption, including their suitability for the fresh food market based on their heavy metal and microbiological contaminants.

This research indicated that the yield and size of potatoes produced using reclaimed water were comparable with those obtained with traditional water sources in the area. Disease proneness, postharvest storage life and cooking behaviour were not adversely affected by the use of reclaimed water. Although potatoes are known cadmium accumulators, there were no concentrations of cadmium that exceeded the maximum permissible level for those grown using reclaimed water (ie they were suitable for human consumption). This was expected as the cadmium level in the reclaimed water was significantly lower than the Australian and New Zealand Environment and Conservation Council (ANZECC) maximum recommended limit (ARMCANZ 2000). Potatoes grown using treated wastewater did not have a different microbiological profile than those grown with normal irrigation water even though the high nutrient status of the reclaimed water could encourage the growth of plant pathogens affecting the crop (Premier *et al* 2000).

In 2000, another study was undertaken using reclaimed water (215 faecal coliforms/100 mL) from the Black Rock WWTP for the production of hydroponic tomatoes. Results showed the lack of salmonella, listeria and faecal coliforms and extremely low levels of *E. coli*, indicating insignificant microbiological health risks from eating tomatoes grown with this reclaimed water. Heavy metals concentrations in tomatoes were insignificant from a human health perspective (Harapas and Premier 2000).

Buckland Valley

In 2001, a study was also undertaken for North East Water to examine the feasibility of using reclaimed water in the Buckland Valley. Treated wastewater from the township of Bright was found to have the potential to benefit apple, grape and chestnut growers with only minor modification to current irrigation practices.

Commercial adoption of horticultural production using reclaimed water

Despite the early use of reclaimed water by the MMBW, usage figures have been difficult to obtain until comparatively recent years. Melbourne Water data from the financial years 1995/96 to 2000/01 are shown in Table 1.4.

For the Western Treatment Plant, about 10% of the total volume of effluent discharged into Port Phillip Bay is used for irrigated pasture production. Other water authorities throughout Victoria (eg Barwon Water) also supply reclaimed water to industries for production of vegetables, ornamental flowers, tree lots and grapes (for more detail see Radcliffe 2004).

Summary

In Victoria, treated wastewater has been used in agricultural production systems for more than 100 years at the MMBW farm at Werribee. In more recent times, secondary treated wastewater from authorities such as the South Eastern Purification Plant at Carrum, and Barwon Water at Black Rock Sewage Treatment Plant, has been successfully demonstrated to be safe for use in some vegetable production.

However, even though low risk uses of secondary treated effluent have been identified and access to these wastewaters is assured, the rate of acceptance of this option by industry has not been great relative to the volume of wastewater available. Now there are clear and safe guidelines for the various classes of reclaimed water (wastewater), there is scope for a vast increase in the use of reclaimed water for agricultural and horticultural production. With the increasing price of high quality irrigation waters and progressive water shortages to meet the increasing demands for agricultural and horticultural production, it is anticipated that reclaimed water will be seen as an increasingly viable option for profitable and environmentally sustainable production.

Table 1.4 Historical wastewater discharge and recycling volumes from Melbourne Water.

	2000/01	1999/00	1998/99	1997/98	1996/97	1995/96
Total volume recycled (ML)	4423	1656	1564	1279	1400	0
Total volume discharged (ML)	322 865	295 559	295 304	302 777	304 250	164 250
Total percentage recycled (%)	1.4	0.6	0.5	0.4	0.5	0.0

Source: Melbourne Water.

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Reclaimed water use in New South Wales

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Geographically, the State of New South Wales is quite large (801 600 km^2) but its population of 6.6 million is concentrated along the narrow coastal strip, east of the Great Dividing Range. Although the Range is not very high, it does create a significant rain shadow, so coastal communities are well watered (average rainfall around 1000 mm/yr to 1200 mm/yr) while inland communities are much drier (typically 550 mm/yr to 700 mm/yr). When sewerage systems were installed for coastal communities, most were designed to drain either to an ocean outfall or into a coastal river. The result has been that reuse by coastal communities is limited.

Inland communities, however, typically have had drier conditions and smaller towns, so there have been thirsty agricultural activities nearby. Overall, reuse has been much more extensive in those inland communities. Most early water recycling was small local government projects where reclaimed water was used to irrigate pasture, municipal parklands and golf courses. For example, the City of Wagga Wagga commenced irrigating its lawn cemetery in about 1968 and gradually extended the system to public parklands and sporting fields. For many years one of the mining companies in Broken Hill used reclaimed water for garden irrigation on company-owned properties.

Australia was affected by a severe drought between 1978 and 1983. In many parts of New South Wales, it was the worst drought recorded in over 100 years since the commencement of rainfall records. Many small water supply systems failed, necessitating emergency supply measures, and many of the larger systems required severe restrictions on use. In implementing water conservation measures both during and after the drought, New South Wales drew heavily on experience from California's 1976–78 drought.

In 1982, at the height of the drought, the New South Wales Government appointed a Task Force to report on reuse of treated effluent. In its report, the Task Force identified the Sydney and Hunter Water Boards and more than 50 local government councils supplied reclaimed water for beneficial reuse projects. These projects included irrigation of pastures, golf courses, sporting fields and municipal landscaping, a variety of industrial and some environmental uses.

The Task Force also made several recommendations to increase public awareness of the benefits of reuse, improve guidelines for reuse, and improve coordination of research and development efforts by New South Wales agencies. In 1984, the New South Wales Deputy Premier, Mr Jack Ferguson, established the NSW Recycled Water Coordination Committee, a non-statutory interdepartmental committee with representation from the water authorities and agencies. The NSW Recycled Water Coordination Committee had a charter to pursue the implementation of the Task Force recommendations.

Water recycling has blossomed in New South Wales following the 1978–83 drought. As well as direct beneficial reuse from municipal plants, a considerable amount of the reclaimed water that is discharged to streams is beneficially used by downstream irrigators and other users (indirect reuse). There is also a considerable amount of direct on-site recycling by industrial and agricultural enterprises. Although there is widespread use of recycled water, it is still only a small percentage of total recycled water volumes (Table 1.2). Most recycled or reclaimed water in New South Wales is returned to the natural water cycle by discharge to rivers, estuaries or the ocean. A small proportion is returned to the water cycle by infiltration to groundwater.

Regulatory pressures

In New South Wales, the Environment Protection Authority (EPA) has statutory responsibility for environmental discharges and regulates water recycling through its licensing of treatment plant discharges. Prior to the formation of the EPA, this role was undertaken by the then State Pollution Control Commission. The Department of Health advises on the microbiological parameters for recycled water guidelines.

The NSW Recycled Water Coordination Committee played a key role in developing the New South Wales recycled water guidelines. Its outputs included:

- 1987 State Pollution Control Commission *Water Conservation by Reuse: Guidelines for use of recycled water in New South Wales* (SPCC 1987), where the NSW Recycled Water Coordination Committee helped resolve a debate about appropriate disinfection levels; and
- 1993 NSW Recycled Water Coordination Committee's (RWCC 1993) NSW guidelines for urban and residential use of reclaimed water were developed after a demonstration project at Shoalhaven Heads. The document drew heavily on California's Title 22 regulations and received written endorsement from the NSW EPA and NSW Department of Health before publication.

The 1987 State Pollution Control Commission's guidelines covered three classes of disinfected secondary effluent for irrigation and industrial uses (Table 1.5), specified in terms of typical faecal coliform levels achieved by maturation pond systems.

The 1993 Urban and Residential guidelines provide for unrestricted access for urban and residential use of reclaimed water for activities such as toilet flushing, garden watering, vehicle washing and washing of paths. The required reclaimed water quality was:

- faecal coliforms – <1/100 mL;
- coliforms – <10/100 mL (95 percentile);
- viruses – <2 in 50 L; and
- parasites – <1 in 50 L.

In 1995, the NSW EPA circulated draft guidelines for use of recycled water for irrigation which updated the 1987 guidelines and provided more specific guidance on measures to protect the environment (NSW EPA 1995). These guidelines were finalised and published by the NSW Department of Environment and Conservation in 2004 (NSW DEC 2004). The recycled water quality provisions in the 2004 guidelines are similar to the draft national guidelines. An important advance in New South Wales has been the development of the *Protection of the Environment Operations Act* 1997. This Act provides for a system of load-based license fees for discharges to the environment. Rebates can be obtained by implementing water reuse schemes provided certain standards of environmental protection are met.

Table 1.5 State Pollution Control Commission grades of disinfected secondary effluent, 1987.

Class	Thermotolerant coliforms[A] (cfu/100 mL)[B]	Pond retention time (days)
A	<300	30
B	<750	20
C	<2000	10

[A] Geometric mean; [B] cfu, colony forming units.

By mid 2002, the revision of the NSW reclaimed water guidelines had not been taken up by the relevant agencies. Relevant issues include whether to:

- follow the draft national guidelines or to create an additional recycled water grade by retaining the more stringent current New South Wales urban and residential grade;
- adopt statistical water quality requirements rather than current mean or absolute values; and
- relax virus and parasite requirements in line with Californian practice.

The health risks posed by aerosols from spray irrigation are an issue in Australia. Recent quantitative risk assessment work, by Rynne and Dart (1998) and Vieritz *et al* (1998), suggests that there are potential bacterial and virus risks from spray irrigation using lower grades of recycled water, particularly from rotavirus. Rynne and Dart suggest that the risks can be reduced by withholding periods, and by care with personal hygiene by exposed persons.

Water reclamation and reuse projects in New South Wales involving agriculture

Shoalhaven Regional Effluent Management Scheme

Shoalhaven City Council is developing a long-term scheme to recycle water for irrigation of agricultural land on the Shoalhaven river floodplain near Nowra, on the south coast of New South Wales. Objectives include:

to eliminate discharges to Jervis Bay (a large estuary 160 km south of Sydney) and, as far as possible, to meet expressed community desire to end ocean discharges. The scheme provides for up to 80% reuse of the recycled water from local sewage treatment plants to irrigate dairy pastures, with the development staged in two parts over about ten years. The first stage will irrigate about 700 ha with possible later expansion to about 1800 ha. The initial section to irrigate 350 ha was commissioned in April 2002. Two important lessons learnt were: an 80% reuse in a high rainfall coastal zone is likely to be the maximum practical, and that land irrigation comes at a financial cost which the community must accept and support.

Shoalhaven Water also established the Bomaderry Tea-tree Plantation. Reclaimed water, previously discharged from the Bomaderry Sewage Treatment to the Shoalhaven River, has been used to irrigate a 3 ha demonstration tea-tree plantation where a new species of tea-tree has been trialled. The irrigation system incorporates a solar powered radio control system controlling the section valves, simplifying the installation, control and maintenance of the irrigation system. Control of weeds was a significant issue during the early establishment of the plantation.

Wagga Wagga

The inland City of Wagga Wagga, working with the CSIRO (Divisions of Water, Forestry and Soils) conducted a major woodlot irrigation trial, on a site that became known as 'Flushing Meadows' (Myers *et al* 1992). In 1991, on a 7 ha site, 4544 trees were planted in four blocks: a eucalypt rates trial, a pine rates trial, a pine clone trial and a species trial. The rates trials were aimed at determining the water and nutrient fluxes for stands of *Eucalyptus grandis* (flooded gum) and *Pinus radiata* (radiata pine) which were irrigated with different amounts of reclaimed water or bore water (as a control). The clone trial was directed at identifying an optimum pine species for irrigation with effluent. The species trial evaluated a total of 60 species/provenances, also to identify an optimum choice for effluent irrigation. The trials demonstrated that *Eucalyptus grandis* grew faster and used more water than the pines. Water use reached a plateau once the canopy closed, and nutrient application rates, at the higher irrigation rates, exceeded the ability of any of the trees to take them up. Overall, the study found that there are several *Eucalyptus* species suitable for effluent woodlot applications, but that selection had to be based upon site specific conditions.

The culmination of the Flushing Meadows project was the publication of CSIRO's *Sustainable Effluent Irrigated Tree Plantations – An Australian Guideline* in 1999 (Myers *et al* 1999). The guideline provides the background and tools required to design and manage sustainable effluent-irrigated plantations. It includes an economic evaluation model developed by the Australian Bureau of Agriculture and Resource Economics. Based on extensive scientific research, the guideline provides a deep insight into the role of plantations, their potential benefits and risks, as well as a comprehensive list of references to Australian literature on the subject. It also helps users to:

- design and manage productive plantations;
- evaluate the economics of alternatives;
- select suitable sites and species;
- determine required plantation areas;
- calculate appropriate loading rates;
- schedule irrigation effectively; and
- ensure adequate monitoring standards.

Dubbo

The City of Dubbo is located in the Central West of New South Wales, in an area that receives 580 mm of rain per year. The city operates one scheme at its Troy Junction plant. Depending on annual rainfall, varying amounts of effluent are used to grow fodder crops (lucerne, sorghum, maize and pastures) under centre-pivot irrigation. In one instance, the city's effluent is combined with that from Fletcher International Exports' abattoir/woolscour and the blended effluent is applied to fodder crops. The overall scheme has been in operation since 1986, with the joint venture implemented in 1995.

The City lists the benefits as: a reduction in effluent discharged to the Macquarie River; an environmentally sustainable waste management system; a reduction in the demand for fresh water that would have been used to dilute industrial waste; and the resource in the effluent stream is beneficially reused.

Armidale

Armidale City Council has been applying effluent to pastures for more than 30 years. The reuse scheme was using 50% of total effluent flow by 2000 and the intention was to achieve 100% (2180 ML/yr) ultimately. Flood irrigation is used to apply the water and users are a combination of a lessee and nearby farmers. Use of effluent has resulted in improved pasture growth rates and a careful evaluation of monitoring results has enabled a gradual reduction in the frequency and cost of monitoring.

Albury

The new Waterview treatment plant in Albury supplies effluent to a commercial woodlot which has 75 ha of *Pinus radiata* and 75 ha of *Eucalyptus camaldulensis* (river red gum) and a 60 ha commercial lucerne crop on flood-prone land. Recycled water, which is surplus to irrigation needs, flows to 85 ha of ephemeral wetlands on the River Murray floodplain. The scheme was commissioned in 1999.

Narrabri

Narrabri Shire Council's Federation Farm is part of a A$9.6 million upgrade of the Narrabri Sewerage Scheme. The project uses recycled water from the upgraded Narrabri sewage treatment plant for irrigation of cotton crops. The scheme irrigates 130 ha of cotton by flood irrigation. It also includes a 77 ha dryland cropping area for recycling the biosolids. Due to a high sodium absorption ratio, the Council applied 5 t/ha of gypsum on the reuse site as a soil conditioner. The project incorporates a 450 ML storage, a 150 ML stormwater retention basin and 17 km of pipelines. The system is designed to reuse all of Narrabri's reclaimed water in a 1-in-10-year extreme wet season. The scheme will use about 760 ML/yr in an average rainfall year. Council anticipates a reduction of about A$97,000/year in EPA load-based licensing fees. An interesting feature is the use of the farm as an educational resource by Narrabri High School and the local primary schools. The schools share in the revenue from the farm under an educational trust arrangement.

Sydney 2000 Olympics WRAMS (Water Recycling and Management Scheme)

A water recycling scheme is in operation at the Olympic's site at Homebush Bay, Sydney. Up to 7 ML/d of recycled water from stormwater and treated wastewater sources is recycled for toilet flushing and irrigation of open space areas. The treatment train includes a 7 ML/d microfiltration plant and a supplementary 2 ML/d reverse osmosis plant. The residential reuse section of the system was commissioned in April 2001.

Coffs Harbour

The City of Coffs Harbour, located in semitropical conditions, north of Sydney, has long had highly contentious issues surrounding its effluent disposal practices. While trying to resolve those issues, the City conducted a three-year trial of banana trees irrigation, which are grown extensively in the region. Battye-Smith (1992) reported on the trial, which did not progress to a permanent operation, mainly owing to health concerns over pathogens on the exterior of the banana skins. Tests demonstrated that the bananas themselves were not microbiologically compromised, but local irrigation practices could not be guaranteed to avoid wetting the fruit, and the cost of delivering water microbiologically equivalent to potable water (as stipulated by the Department of Health) was felt to be prohibitive. At the time, it was felt by industry representatives that the position adopted by the Department of Health was overly cautious, as bananas are invariably peeled before eating. Another outcome of the trial was that the cation make-up of the effluent had a deleterious effect on soil quality. Local soils are somewhat acidic, and the sodium absorption ratio was unfavourable. That aspect may have been manageable by a program of gypsum addition, had the project been continued. More recently the City has undertaken a successful trial using reclaimed water for hydroponic growing of tomatoes.

Taronga Zoo

A small water recycling scheme (0.25 ML/d) is in operation at the Taronga Zoological Gardens in Sydney. Wastewater from the zoo is treated in a conventional activated-sludge process followed by microfiltration and disinfection. The recycled water is used for landscape irrigation, moats and the washing down of animal enclosures.

Ulan Mine Wastewater

Drainage water from the underground and open-cut workings at the Ulan Coal Mine has been collected in water quality control ponds prior to discharge to the headwaters of the Goulburn River. In response to a request from the EPA for the mine to reduce discharges, Hassall & Associates of Dubbo developed a 12 ha demonstration area of fodder crops on previously unused scrubland at the mine site. A centre pivot irrigation system was commissioned in August 1999. Four crops were cut in the first 18 months of operation.

Emu Plains Correctional Centre Dairy

This project is the flagship of a statewide Dairy Waste Management Program being implemented by the Department of Agriculture. Washdown water from dairies has been a significant source of pollution in New South Wales. In this project, washdown water from the dairy is collected in a simple solids trap which can be cleaned mechanically. The wastewater drained from the solids trap is treated in a simple two-pond anaerobic/aerobic system to produce reclaimed water which can be used for yard washing and pasture irrigation. The result is reduced pollution and reduced freshwater use. Standard mobile irrigation equipment is used to draw water from the second pond and irrigate the pastures. The system achieves good environmentally sustainable development results and is commendable for its low implementation costs. While each project is small, implementation in the 1700 dairies in New South Wales will result in significant environmental benefits.

Albury Paper Mill

The recycled water from the Norske Skog newsprint mill at Albury NSW is used to irrigate a 310 ha radiata pine plantation. Artificial destratification was used to control algae growth in the wet weather storage. An aeration system has helped to overcome clogging of the drip irrigation system used in the plantation.

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Reclaimed water use in Queensland

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Water reclamation and reuse from municipal WWTPs has been practised in Queensland for many years. The most common applications in the agricultural sector have been for irrigation of pasture and sugar cane and in the urban sector for irrigation of golf courses.

Reclaimed water supplied for these purposes has generally been sourced from the same WWTP effluent that has already been approved by the EPA for discharge to waterways, occasionally with additional treatment in the form of storage or disinfection. In terms of the classification system used in *Queensland Water Recycling Guidelines* this could be described as a Class C reclaimed water [ie thermotolerant coliforms <1000 cfu/100 mL, suspended solids (SS) <30 mg/L and biochemical oxygen demand (BOD) <20 mg/L].

Reclaimed water has been popular for these uses because it has been a cheap, reliable source of water during seasonal water deficits. In some cases, WWTP effluent has been irrigated to land principally in order to reduce discharges to waterways. However, this form of land application of reclaimed water is generally not considered beneficial and, in the long run, is not likely to be supported.

Drivers for reuse

Since the mid-1990s the drivers for more widespread and effective use of reclaimed water have increased substantially. These include:

- recognition of the scarcity of freshwater resources, particularly outside tropical regions of the state, reinforced by the recent severe drought in many parts of Queensland;
- increasing population demands – the population of Queensland is expected to increase by 40% over the next 20 years;
- the need to reduce the impact of WWTP discharges on waterways, especially to sensitive marine environments like the Great Barrier Reef lagoon and Moreton Bay; and
- the search for more sustainable and integrated solutions to problems of water shortage, water pollution and population growth.

These pressures have provided the background to the development of the State Government's Queensland Water Recycling Strategy. This strategy provides a framework to enable Queenslanders to more effectively and efficiently use recycled water, to accommodate an increasing population, and to support sustainable economic growth while protecting the environment and safeguarding human health.

A key deliverable from the Queensland Water Recycling Strategy is the publication of the Queensland Water Recycling Guidelines in 2005 (EPA 2005). These guidelines provide a risk management framework for planning, operating and monitoring the use of recycled water from municipal WWTPs.

Regulation

At present, water recycling is not directly regulated in Queensland. Where the holder of a WWTP licence uses reclaimed water, this will be subject to licence conditions. When a WWTP supplies reclaimed water to a third party, the EPA has generally required that the licence holder sign a formal Third Party Agreement with each user, detailing how the user will meet obligations under the *Environmental Protection Act* 1994. Where there is a risk of environmental harm, the EPA has often applied more prescriptive requirements such as a need for the user to prepare an irrigation management plan. Suppliers of reclaimed water are generally required to maintain a register of reclaimed water users and provide returns to the EPA on quantities supplied.

In recognition of the importance of recycled water as a sustainable, reliable water source for Queensland's future growth, the Queensland Government is considering the development of a new regulatory framework for water recycling. It is hoped that this new framework will be in place by the end of 2006.

Reuse schemes, past and present

There are 241 WWTPs in Queensland, operated by 139 authorities (White 2000). These generate around 340 000 ML of effluent, of which about 12.9% (43 800 ML) is reused (Queensland EPA, unpublished data, 2003). There are significant regional differences in reuse, with drier parts of the State (eg central Queensland) averaging 45% beneficial reuse, and several WWTPs achieving 100% dry weather reuse (see Radcliffe 2004).

The largest single use of reclaimed water in Queensland is for golf course irrigation, followed by pasture and crop use, predominantly sugar cane. Other beneficial uses include public open space irrigation, industrial reuse and groundwater recharge. A small amount of reclaimed water is supplied to nurseries and for irrigation of horticultural crops such as stone fruits.

Many local authorities have plans to commence or increase use of reclaimed water from WWTPs. This can be expected to substantially increase the amount of water that is recycled in Queensland. Proposals for expanded reclaimed water use in horticulture include use for stone and vine fruits, apples, citrus and wholesale nurseries. Some of the main reuse projects are described below.

Gold Coast

The Gold Coast Waterfuture Strategy was finalised in December 2005. This strategy includes a broad range of initiatives to save potable water and increase reuse. Recently included under the Waterfuture Strategy is the Northern Wastewater Strategy and Reclaimed Water Scheme, which commenced in 1996.

Northern Wastewater Strategy is Gold Coast Water's plan for providing wastewater services to meet the demands of future population growth in the northern Gold Coast area, between the Logan and Coomera Rivers. A major component of the strategy is the provision of up to 690 ML of reclaimed water every year from the Beenleigh WWTP to local cane farmers.

Hervey Bay

Wide Bay Water at Hervey Bay is providing reclaimed water from its WWTPs for use on sugar cane, native pasture, woodlands, a turf farm, a golf course and sports fields. It is achieving 90% reuse of reclaimed water with an expectation to increase to 100%.

Maryborough

Maryborough Council supplies reclaimed water to sugar cane growers and plans to extend supply to a diversified horticultural enterprise (Just 2001). This would provide 100% beneficial reuse of reclaimed water from the Maryborough (Aubinville) WWTP.

Mackay

As part of its long-term strategy for the treatment and management of WWTP effluent, Mackay City Council has developed the Mackay Water Reuse Project. This project is intended to provide reclaimed water to sugar cane farmers, replenish groundwater resources to help prevent saltwater intrusion to coastal cane-growing lands and significantly reduce WWTP nutrient discharges to the Great Barrier Reef lagoon.

Stanthorpe

Reclaimed water from Stanthorpe's WWTP is being supplied for irrigation of a golf course and open space irrigation as well as irrigation of tree crops such as stone fruits and apples.

Gatton

At Gatton, three farms growing low-chill tree and vine fruits such as persimmons and passionfruit will be using reclaimed water to irrigate crops using partial root zone techniques. This increases the sugar content in fruits and increases their market value. This is a novel application of reclaimed water for horticulture in Australia. The University of Queensland (Gatton campus) is providing technical support and monitoring soil and water conditions.

Toowoomba

Toowoomba's Water Futures project, which was launched in mid 2005, includes use of reclaimed water for a variety of uses including coal washing, irrigation and indirect potable use.

Lockyer Valley and Darling Downs

Studies have been commissioned into the viability of treating the wastewater from Brisbane and Ipswich and sending it inland to the Warrill, Bremer and Lockyer Valleys and over the Great Dividing Range to the Darling Downs (eg Brennan *et al* 2003).

In the Lockyer Valley, the reclaimed water would be used for production of fruit and vegetables and in the Darling Downs for cotton or other broadacre crops. While benefits could be felt in both production areas and in reduction of wastewater discharges to Moreton Bay, the proposal is still in its feasibility stage. The Queensland Government is working with key stakeholders to ensure the proposal is both commercially and environmentally sustainable.

Other proposals

A range of other major projects using reclaimed water for industrial purposes are proposed or operational in Queensland. These include the following:

- In November 2002 Queensland Aluminium Limited at Gladstone commissioned one of Australia's largest industrial water recycling projects. Effluent from Gladstone's Calliope River WWTP is now used as process water for the refining of alumina. In combination with some reuse by Gladstone Power Station, this has allowed Gladstone to virtually eliminate its discharges of secondary treated effluent to the Calliope River estuary.
- The BP oil refinery at Bulwer Island in Brisbane is now using 10–14 ML/d of reclaimed water from the Brisbane City Council's Luggage Point WWTP. After additional treatment through a continuous microfiltration pretreatment plant, a reverse osmosis plant, disinfection and chemical dosing, the reclaimed water is used at the BP refinery as cooling tower make up, boiler feedwater and in other processes designed to help BP achieve a cleaner fuel.
- Townsville and Thuringowa City Councils in North Queensland are both investigating proposals that would achieve close to 100% dry weather reuse of reclaimed water from their WWTPs.

Research projects in Queensland

In the mid 1990s there was substantial interest in 'disposing' of WWTP effluent using irrigated tree lots in Queensland as an alternative to upgrading sewage treatment plants to tertiary nutrient standards and continuing discharge of effluent to waterbodies. However, there were regulatory concerns that land dumping of effluent could become an alternative to water dumping without a clear understanding of the assimilative capacity of a soil-plant production system to store, transform or volatilise effluent and nutrients on a sustainable basis. However, research by the Department of Primary Industries and Fisheries (DPIF) has shown that using recycled water to establish and irrigate hardwood plantations can be commercially viable, if managed sustainably. DPIF has published a booklet (DPIF 2003) to promote the sustainable use of reclaimed water for irrigation of tree plantations. Several Queensland Councils have shown an interest in developing such plantations.

WC Fields effluent irrigation project

The National Heritage Trust-funded WC Fields effluent irrigation project was initiated in 1995, in partnership with Redland Shire Council, on land adjacent to the Cleveland WWTP treatment plant. Five replicated treatments were established including a pure grass sward (Rhodes grass) irrigated with undiluted effluent – in the remaining four treatments, trees (*Eucalyptus robusta*) were grown with a grass understorey, using effluent containing a range of nitrogen concentrations to encompass values found in Queensland WWTPs (5–40 mg/L N).

The project studied, in considerable detail: water and nutrient balances, biomass production and changes in soil salinity/sodicity from 1995 to 2000 (Moss *et al* 1998). Much of this research has been incorporated into a monograph discussing water, nutrient and salt balances in South East Queensland (QNRM 2003).

Many of the reclamation and reuse schemes (eg Gold Coast, Stanthorpe, Hervey Bay, Maryborough and Mackay) have had extensive environmental impact and consultancy reports completed (eg Arunakumanren and Evans 2003). However, as the value of reclaimed water appreciates, much of these data have become 'commercially in confidence'. This can be interpreted favourably, in the recognition that reclaimed water is a valuable resource, or unfavourably, if it means the results are not available to the public.

Amenity horticulture

The Queensland amenity horticulture industry has a number of producers using reclaimed water provided by local WWTPs as an irrigation source. There are expected to be significant increases in use of reclaimed water within the amenity horticulture industry in the coming years.

Turf

The Department of Primary Industries & Fisheries' Redlands Research Station at Cleveland has access to a permanent supply of reclaimed water from Redland Shire Council for use on turf and other trial plots.

Urban reuse schemes

Research in Queensland has also looked at urban reuse issues. Examples include the Healthy Homes Project, where greywater reuse and rainwater tanks are the major emphasis (Gardner *et al* 2002), and the Springfield Water Recycling Demonstration Project, where highly treated recycled water is being delivered via a dual reticulation pipeline scheme to a few households, road verges and a school for open space irrigation (Gardner 2002).

Summary

Pressure for beneficial use of reclaimed water in Queensland has been growing significantly in recent years. Through implementation of the Queensland Water Recycling Strategy, the Queensland Government has been working to provide a supportive environment to facilitate use of reclaimed water from WWTPs to remove the barriers to water recycling and to improve community understanding and acceptance of recycled water.

Although the largest applications of reclaimed water are for golf courses and irrigation of pasture and sugar cane, there has recently been a substantial increase in the use of reclaimed water for industrial purposes. Significant new proposals have been put forward for both urban and horticultural use of reclaimed water.

These developments reflect a growing awareness of the value of reclaimed water, its reliability as a source of supply and the importance of protecting vulnerable waterways from the impact of nutrient discharges from a growing population.

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Reclaimed water use in Western Australia

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In Western Australia, the Water Corporation operates the WWTPs systems for the highly concentrated population areas centred around Perth and the Swan Coastal Plain, with a population of about 1.7 million people. In the remainder of the State, many small towns and cities totalling about 400 000 people are serviced predominantly by about 90 treatment plants operated by the Water Corporation, with about 30 small WWTPs run by local councils. Outflows from wastewater management systems under the jurisdiction of the Water Corporation are shown in Figure 1.4.

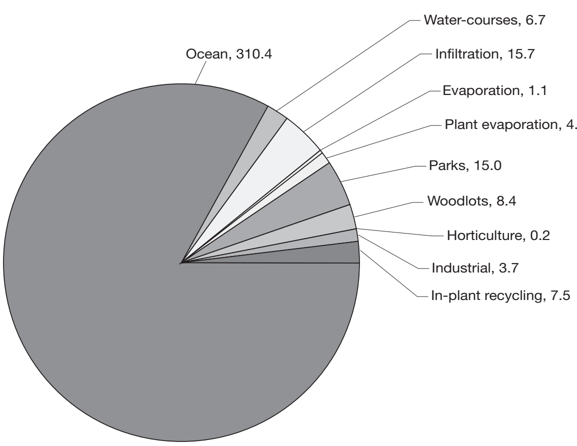

Figure 1.4 Western Australian state wastewater effluent management in the 2004/05 financial year. Data represent average daily outflows (ML/d). Evaporation is the planned disposal of wastewater after treatment; plant evaporation is the water which evaporates *during* treatment, mainly from pond systems.

There are four ocean outfalls in Western Australia, three serving the three large metropolitan wastewater treatment plants of Woodman Point, Beenyup and Subiaco, and one serving the town of Bunbury. The very high flows from the Perth area, in comparison to the rest of the State, are highlighted when compared to reuse for country areas under the jurisdiction of the Water Corporation (Figure 1.5). The much higher percentage of reuse [about 38% of wastewater is reused in the country (Figure 1.5) , compared with 4% in Perth (Figure 1.4)] is also highlighted if country areas are considered in isolation (Figure 1.5).

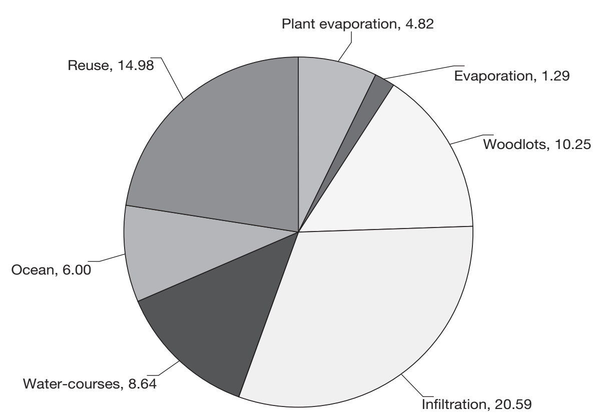

Figure 1.5 Country wastewater effluent management in the 2004/05 financial year. Data represent average daily outflows (ML/d). Evaporation and plant evaporation are defined as in Figure 1.4.

Drivers for reclamation and reuse

Drivers for reclamation and reuse may be summarised as follows:

- **Lack of other suitable water resources in some areas of Western Australia** – Reclaimed water is used for greening of local amenities such as ovals, golf courses, school grounds and parks. Most reuse schemes in Western Australia fall into this category. Obviously, reuse of this kind is practiced where there are limited other options for irrigation water supply, generally due to lack of rainfall, such as the Pilbara, the Goldfields and Murchison regions. High salinity groundwater may be a secondary driver for these schemes, such as in Kalgoorlie, where the natural groundwater is three times more saline than sea water.
- **Environmental impacts of discharges** – This has become a significant driver in the Southwest and Great Southern regions of Western Australia since 1995, and has resulted in establishment of significant reuse schemes in locations such as Busselton, Dunsborough, Bridgetown and Albany. It may also become a driver for the establishment of reuse schemes in the Perth metropolitan area following concerns about nutrient enrichment of coastal waters where ocean disposal is employed. However, Water Corporation WA monitoring of these outfalls indicates that these concerns are largely unfounded.
- **Areas where groundwater is approaching full allocation** – The best example is the Kwinana industrial area, where several major industries have requirements for large quantities of water for processing. Industries include an oil refinery, a fertiliser manufacturer, a power station and a paint manufacturer. This has resulted in the proposed Kwinana Reuse scheme, which is discussed further below. There are few other areas in the State which are at full allocation, though this situation is likely to change within the next few years, particularly in the Perth region.
- **Areas where excessive abstraction has resulted in saline intrusion** – Western Australia is in the fortunate position of being able to manage allocations so saline intrusion is comparatively rare. Mosman Park is a location in the Perth metropolitan area where this is currently a driver – a narrow peninsula is bounded on one side by the Indian Ocean and on the other by a tidal area of the Swan River. The use of reclaimed water as a barrier to prevent seawater intrusion has been investigated for this location, but prices for supply of water are much higher than end users are prepared to pay, and there are concerns about possible environmental impacts on reefs close to the coast from leakage of reclaimed water.
- **Community pressure to maximise reuse** – The community of Western Australia generally considers treated wastewater as a resource that should be reused rather than disposed of. When disposal options are considered for new plants or existing plant upgrades, reuse is consistently identified as the favoured option.

Barriers for reclamation and reuse

Barriers for reclamation and reuse may be summarised as follows:

- **Ready availability of cheap, good quality groundwater in some areas of Western Australia** – Particularly in the Perth metropolitan region and other areas of the Swan Coastal Plain, there is little financial incentive to adopt wastewater reclamation and reuse because good quality groundwater is readily available and cheap to abstract.
- **Cost of direct disposal options** – The cost to establish reuse schemes in the Perth metropolitan area has been compared with upgrades which allow continued discharge to ocean. These are between five and ten times higher than the cost to discharge. Thus, until another driver becomes critical, most treated wastewater in Perth is likely to continue to be discharged to the ocean for at least the next ten years.
- **Costs of wastewater storage over winter** – High rainfall during wet seasons restricts irrigation during these periods. If direct discharge is to be avoided during high rainfall, large storage dams will need to be constructed. The capital cost of storage can exceed that of treatment, as is the case with Bridgetown in the south-west of the State.
- **Concerns about potential health impacts of reuse** – Although reuse schemes have been employed in country areas for some time, it is a practice foreign to the Perth Metropolitan area. Many community members are concerned about the potential effects of recreational contact with reclaimed water. This may be more of a problem in metropolitan areas because of higher population densities and possibly different perceptions between city and country populations regarding reuse. In May 2005, CSIRO produced the report *Predicting Community Behaviour in Relation to Wastewater Reuse*, which gives in-depth analysis on

what may drive a community to accept or reject the concept of an indirect potable scheme for the Perth Metropolitan area (Po *et al* 2005).

- **Low capacity for phosphorus absorption in Swan Coastal Plain soils** – The sandy soils of the Swan Coastal Plain have extremely low capacity for absorption of phosphorus (Hodgkin and Hamilton 1993). Thus any discharge to the catchment enriches groundwater and, in turn, any watercourse which intercepts with groundwater. This has resulted in significant eutrophication of some waterways in the south-west of the State. This includes the Peel/Harvey catchment near Perth, and, to a lesser extent, the metropolitan Swan/Canning catchment. A key driver for the A$800 million infill sewerage program was to eliminate many thousands of septic systems from the Perth metropolitan area, and thus reduce impacts on groundwater and river systems. Regulators are understandably focussed on possible nutrient impacts of any proposed reuse scheme on the Swan Coastal Plain.

Reuse schemes: past and present

In the country areas of Western Australia, the drivers for implementing wastewater reclamation and reuse have been much stronger than any barriers, leading to many reuse schemes adopted in these areas. Until recently, only one small reuse scheme had been adopted in the Perth metropolitan area. However, the Kwinana Water Reclamation Plant has recently commenced operation, and has had a significant impact on total amount of reuse for the metropolitan area.

The past and current reuse situation for Western Australia can be summarised relatively simply, as follows:

- Most schemes involved recycling of water for irrigation of municipal facilities, such as golf courses, ovals, racecourses and school grounds. This is widely practiced in country areas where water resources are scarce.
- There are also a significant number of woodlots irrigated with recycled water. These are more prevalent in the south-west and south of the State, where rainfall is higher and evapotranspiration rates afforded by woodlots reduce land requirements. The largest such scheme is in Albany, where 575 ha of eucalypts, mainly blue gums, are irrigated with about 4.5 ML/d of reclaimed water. Irrigation is by drippers, and nutrients are controlled by a mixture of adsorption by clay surface soils (phosphorus), and take up by the tree crop (nitrogen).
- There is only one reuse scheme in Western Australia using reclaimed water sourced from Water Corporation infrastructure for horticulture. This is in Mount Barker, where about 140 KL/d of reclaimed water is supplied to a winery for irrigation of grapes. Treatment is by a pond system followed by chlorination. Water is added to the storage dam for the winery prior to usage, resulting in about a ten-fold dilution.
- The Kwinana Water Recycling Project (KWRP) represents a significant step in reuse in Western Australia, as it is the first major example of reuse for Perth. Water from the newly commissioned Woodman Point advanced secondary treatment plant is further treated by a two-stage membrane filtration to produce a low total dissolved solids water which is suitable for use by industry in heating and cooling systems. A scheme taking 24 ML/d to produce 17 ML/d of product water and 7 ML/d of concentrated reject water was commissioned in 2005. This is currently supplying a number of industrial customers with over 10 ML/d of product water, and it is anticipated the plant will be at full production capacity by June 2006. Reject water from the system is discharged back into the Cape Peron Outfall. Further, industries supplied with the water will be diverting discharges which flow to Cockburn Sound to the Water Corporation's ocean outfall. This was a significant driver in getting industries to sign up for supply via the scheme.
- A demonstration reuse project uses some of the Subiaco WWTP effluent to irrigate an adjacent sporting complex, McGillvray Oval.

Future developments in reuse

The Department of Environment in Western Australia encourages reuse and recycling, particularly in the case of water, as was identified at the State Water Summit. The Department of Environment recognises that water is an important commodity in Western Australia, and that traditional supplies of water in the State are becoming increasingly unable to match demand. In addition, abstraction of groundwater, which is one of the most significant water sources in the State, can have its own negative environmental consequences. Therefore, substantial efforts to enable and promote wastewater reuse are justified.

The Department of Environment regulates the environmental aspects of wastewater disposal, including reuse of treated wastewater. While there are significant philosophical reasons for the Department to prefer reuse over disposal, this may not always be the case. Groundwater is a particularly important resource in this State, and soils on the Swan Coastal Plain, where most of the population resides, are not good at retaining contaminants. Reuse schemes need to be implemented so that environmental quality is not compromised. Sometimes the environmental risks associated with reuse outweigh those for other forms of disposal (eg to the ocean). In these cases, the Department may choose not to approve such a scheme.

Wastewater reuse needs to be performed in a sustainable manner. This chapter has identified some of the potential economic, environmental and social barriers to wastewater reuse. These need to be considered and mitigated before any reuse scheme can be sustainably adopted. If a reuse scheme has been carefully considered, and potential barriers suitably addressed, it would always be endorsed by the State Government. The Western Australian State Water Strategy has undertaken to achieve 20% reuse of treated wastewater by 2012; noting that water is a precious resource and should be priced accordingly (Gallop 2003). To achieve the objective of 20% recycling by 2012, various proposals are being assessed (Radcliffe 2004):

- industrial use at Kwinana – Stage 1 (5.5 GL/yr), Alcoa (additional 1 GL/yr), and Kwinana – Stage II (2.9 GL/yr);
- golf course, playing fields and park use at Subiaco – Stage I (3.3 GL/yr), Subiaco – Stage II (4.4 GL/yr) and Lark Hill (1.8 GL/yr);
- horticultural use at Gnangara (10 GL/yr), Carabooda (8.8 GL/yr, replacing a current groundwater allocation) and Guilderton (14 GL/yr);
- possible indirect potable reuse by establishing ASR at the Gnangara Mound from the Beenyup STP following microfiltration and reverse osmosis (27 GL/yr); and
- establishing a Western salt water barrier (16 GL/yr).

Recent droughts and possible long-term shifts in weather patterns (Radcliffe 2004) have raised the profile of reuse significantly and the reclamation and reuse of wastewater has the support of the Department of Environment. The most likely opportunities within the next 20 years for the Perth metropolitan area would seem to be use of reclaimed water in place of water that could be used for potable water, either by:

- substitution at source – irrigators using reclaimed water rather than groundwater of potable quality; or
- substitution at point of use – domestic or municipal users using reclaimed water instead of potable scheme supplied water for uses such as irrigation of gardens and parks.

There is also a possibility of replenishment of water resources by injection into confined aquifers after reverse osmosis treatment, where modelling indicates that it would be tens or hundreds of years before water would be abstracted for potable use. The Environmental Protection Authority in conjunction with Health and Environmental regulators and the Water Corporation have recently undertaken a significant public consultation exercise on this possibility. The product of this process is *Strategic Advice on Managed Aquifer Recharge Using Treated Wastewater on the Swan Coastal Plain* published October 2005 (EPA WA 2005). In April 2005, the Water Corporation – against a backdrop of drying climate and a rapidly growing population – released the 'Source Development Plan for the Integrated Water Supply Scheme'. This formally recognised recycled water as a potential source option via replenishment into the Gnangara Mound, with the earliest date of implementation being 2014.

For country areas, the future for reuse is likely to be a steady increase – driven in arid areas by the desire for greening of public spaces, and in environmentally sensitive river catchments by the need to reduce or eliminate discharges to inland waterways.

Summary

In terms of reclaimed water usage, Western Australia can be defined in terms of the Perth metropolitan area and the rest of the State. Over 75% of treated wastewater for the State is derived from the city of Perth, and, until the commissioning of the Kwinana Water Reclamation Plant, only 3% of this was reused. The Kwinana Water recycling project was commissioned in 2005, and will result in about 6% reuse of metropolitan wastewater discharges. It is likely that major increases in reuse for the city of Perth in the near future will be limited to expansions of supply to industry in the Kwinana area. Key factors include: sensitivity of discharge of nutrients to the Swan Coastal Plain; availability of other water sources, in particular, good quality groundwater from confined and unconfined aquifers at a much lower price; and an established, closely monitored and demonstrably sustainable approach of discharge to the ocean after significant levels of treatment.

In the longer term, it is likely that reuse schemes will focus on freeing up allocation of resources for potable scheme water, by substitution at point of supply, point of use or replenishment of groundwater resources where it can be demonstrated that water will not be abstracted for potable use for tens or hundreds of years.

It is likely that current levels of reuse will be maintained or increased slightly over time in country areas, with little change in end use.

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Reclaimed water use in Tasmania

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Unlike the mainland States, Tasmania has a very high proportion (30%) of its population living in rural areas, and consequently the drive for increased wastewater reuse is likely to result in the development of many small, inland agricultural reuse schemes servicing small to medium-sized rural towns. The major population bases of Launceston and Hobart are located on large river systems close to the ocean, with little agricultural land nearby and reuse of wastewater from these major population centres will prove a more considerable challenge.

Tasmania produces around 60 GL of wastewater per year. The annual volume of water allocated for agricultural irrigation was about 770 GL in the late 1990s, making reclaimed water potentially around 10% of the annual volume of water used for irrigation in Tasmania, a tempting source of water in areas with over allocated river systems. In irrigated pasture terms at an irrigation rate of 3 ML/ha per year, Tasmania's reclaimed water could potentially irrigate up to 20 000 ha/yr.

Drivers for reuse in Tasmania

The push for increased use of reclaimed water has come from many sectors. The community and environment sector has placed increasing demands for improved quality of waterways and recreational opportunities. Agriculture needs additional sources of irrigation water, councils are seeking to avoid costly treatment plant upgrades, and State and Federal policies and funding have provided incentives for development of the wastewater reuse industry.

Community and environment sector

Environmental effects of discharge to inland and estuarine waterways have become a significant driver for wastewater reuse in the South Esk Basin, the Derwent Catchment, and the Mersey River where water quality is impaired by wastewater discharges, especially in the drier months. Wastewater reuse would significantly reduce the nutrient load going to waterways, reducing environmental impacts and increasing recreational opportunities. Schemes that are unable to recycle all the wastewater would be able to store water and target discharge events to natural storm flows, to better use the natural hydrological cycle to remove nutrients from river systems. About 80% of Tasmania's wastewater has been discharged into inland, estuarine and bay waters (Figure 1.6).

Councils

Many treatment plants in Tasmania were constructed in the 1970s and 1980s to meet new environmental standards introduced at that time. The environmental requirements and wastewater discharge standards have since increased such that many old plants are unable to treat water to current standards. The cost of upgrading these plants is an economic challenge particularly to some of the smaller municipalities (several councils service only 8000–9000 residents) and, in some places limited due to the original type of technology constructed. Reclaimed water is seen as a low cost means of managing treated effluent out of watercourses, thus avoiding treatment upgrades. The cost to establish reuse is consistently around ten times cheaper than upgrading a treatment plant both in terms of capital and ongoing

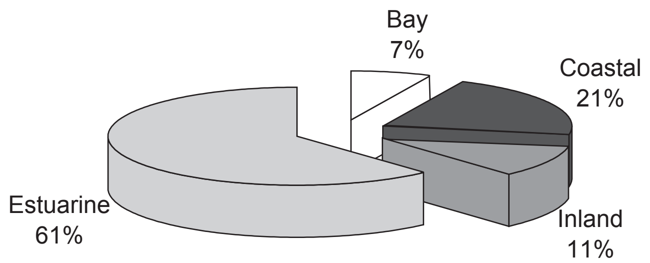

Figure 1.6 Breakdown of Tasmanian wastewater receiving environments by volume.

costs. There is also mounting evidence that on a mass load basis even tertiary level wastewater treatment with 99% nutrient removal may not be sufficient to protect sensitive inland and estuarine water quality year round.

Agriculture

Despite Tasmania's reputation for abundant water supplies, many areas of the State receive less than 600 mm annual rainfall and require irrigation for maximal agricultural production. In many areas, existing surface water sources are over allocated or supply is unreliable, especially during summer. Reclaimed water is in demand for agriculture due to its reliability of supply and affordability when compared to other water sources. Most wastewater reuse schemes are for agricultural land. The major schemes at Brighton and the Coal River Valley in the drier south of the State could use a potential 2500 ML/yr. In some areas of the Coal River Valley, salinity of alternate water sources is higher than the reclaimed water, making reclaimed water a more attractive option to farmers.

State and Federal policies and funding

The Natural Heritage Trust funding has facilitated the development of approximately 30 additional water reclamation schemes between 2000 and 2002 (Figure 1.7).

Regulation and management of wastewater reuse in Tasmania

Unlike many of the mainland States, Tasmania does not have a separate EPA and Department of Environment and/or agriculture. In Tasmania the environmental impacts of wastewater reuse are assessed by the Department of Primary Industry Water and Environment (DPIWE). Wastewater reclamation is undertaken primarily by agriculture with local government under approved environmental

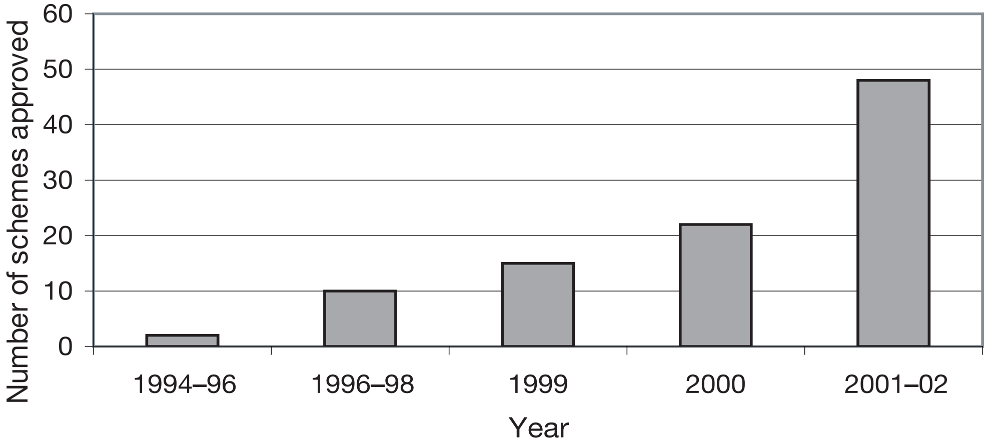

Figure 1.7 Number of water reuse schemes approved in Tasmania.

management plans with user agreements between the end user and the local council or water authority.

In June 1994 the Director of Environmental Management formed the Wastewater Reuse Coordinating Group to facilitate intergovernmental assessment of environmental impacts and approval of wastewater reuse schemes. In December 2002 the Environment Division (DPIWE) published environmental guidelines for Tasmania (Dettrick and Gallagher 2002). Key issues covered in the document are soil sustainability, salinity identification and management, and food safety.

Management of water quality in Tasmania is governed by the State Policy on Water Quality Management 1997 and the *Environmental Management and Pollution Control Act* 1994. Wastewater reuse is a key waste management strategy used by producers of wastewater to reduce the disposal of liquid wastes to aquatic ecosystems. Reduction, reuse and recycling are the main components of the key principles for limiting emissions from point sources under Section 16 of the State Policy on Water Quality Management.

The State Policy on Water Quality Management recognises the need for guidelines for reuse in Section 38, Reuse of wastes by land application. Section 38.2 causes regulatory authorities to not approve schemes to apply wastes to land unless they are satisfied that any proposal meets all of the following criteria:

- can be carried out in an environmentally sustainable manner;
- incorporates the use of best practice environmental management;
- will not compromise the water quality objectives for surface or groundwaters;
- will not give rise to an unacceptable risk to human or animal health; and
- involves less net environmental risk than other strategies for dealing with the wastes (SPWQM 1997, p. 27).

Additionally, in the State Policy on Water Quality Management Section 38.4, the land application of wastewater from sewage treatment plants should be carried out in accordance with the environmental guidelines for Tasmania (Dettrick and Gallagher 2002).

Constraints to reclamation and reuse in Tasmania

The constraints to reclamation and reuse in Tasmania are as outlined below:

- Much of Tasmania's regional wastewater is treated by secondary lagoons. This level of treatment restricts crop suitability as Class B or C reclaimed water which is generally only useful for fodder crops and some horticultural and municipal areas. Food safety is an important aspect of reuse in Tasmania.
- The drier midlands of Tasmania represent the biggest opportunity for reusing wastewater, but also contain 80% of Tasmania's potential and existing areas affected by dryland salinity. Areas around Evandale, Tunbridge and Bothwell, for instance, may have limited areas of land unaffected by salinity for wastewater irrigation.
- With the variable returns from the opium poppy (pharmaceutical) industry, and limits to crops that can be grown without further processing, Tasmanian farmers argue that they have few high-value crops that can be grown with Class B wastewater.
- Areas with established coastal discharge systems will prove more difficult to encourage reuse in. Extended outfalls and ambient environmental modelling, combined with some comparatively high rainfall areas, make reuse less attractive. Until another environmental driver becomes critical (eg the establishment of Marine Protected Areas in the Bass Strait) most treated wastewater produced by the northern coastal cities of Tasmania is likely to be discharged to the sea for the foreseeable future or until an external funding source, such as Water Smart (http://www.nwc.gov.au/water_fund/water_smart_aust.cfm), makes the projects viable. Tasmania's accepted modern technology guidelines for large wastewater treatment systems specify secondary treatment for coastal discharges. This may create another driver in the medium to long term.

Future developments in reuse

Most (70–80%) wastewater treatment systems in Tasmania will probably incorporate some form of reuse by 2005. Under State Policy, all new wastewater systems must include reuse as a central strategy to minimise or avoid discharges to aquatic ecosystems.

In some areas, such as Launceston, it will be a challenge to include changes because of the lack of close agricultural land and increased capital cost owing to pumping distances. Priority may be given to upgrading existing treatment systems in some areas. The higher the level of treatment, the greater the range of potential end uses for the water. This may make urban reuse an increasing share of the reclaimed water market.

The Clarence City Council Coal River Valley Water Recycling Scheme 2002 represents a significant step in reuse in Tasmania, as it is the largest single example of water reuse in the State to date. Water from the Rosny Park secondary treatment plant is to be reticulated to the Coal River Valley Irrigation District with over 500 farms of extensive tracts of horticulture, viticulture and turf growing areas. Farmers will then be able to supplement relatively expensive irrigation district water with cheaper reclaimed water to enhance profitability.

Summary

It is likely that:

- by 2007, 80% of Tasmania's wastewater treatment plants will undertake some form of water recycling;
- 80% of current reuse is by agricultural irrigation onto fodder or seed crops;
- any remaining discharges will be directed into discharge regimes such as storm flows to minimise environmental pollution of aquatic ecosystems;
- future demands from the agricultural sector for higher quality water will require further upgrades to municipal wastewater treatment plants; and
- filtration systems will be used increasingly as a final treatment stage in systems with large amounts of reuse to increase the quality of the water, and hence offer more flexibility in the end use of the water.

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2 Australian and international reclaimed water guidelines: the fundamentals

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Reclamation of water from 'wastewaters' such as sewage is now an established component of sustainable water resource management, providing increased water security and removing the direct discharge of nutrients to our rivers. However, while reclaimed water is a valuable resource, the need to manage potential pathogen and chemical risks has resulted in water recycling being subject to regulatory oversight in most countries.

Effective regulatory oversight is important from a range of perspectives, including ensuring a sustainable water recycling industry by maintaining community and industry confidence, protection of human health and the environment, encouraging innovative approaches and providing stable frameworks for investment.

In this chapter the regulatory requirements and guidelines of key jurisdictions are reviewed, with information provided on the approaches taken for management of reclaimed water. The review covers the State and national requirements in Australia, the guidance in the United States of America (federal) and in the state of California, the World Health Organization guidance and the situation in Israel. These jurisdictions were selected on the basis of having effective water recycling programs and to illustrate the range of regulatory/guidance approaches that are taken.

Regulatory frameworks

Australian regulatory frameworks

National regulatory framework

National guidance in Australia is provided in the *Guidelines for sewerage systems: use of reclaimed water* (ARMCANZ, ANZECC 2000). This document is part of the National Water Quality Management Strategy series. The guideline is intended to provide general direction. However, it notes that differing guidance may be required within individual States and that national guidelines should be used in conjunction with State requirements.

The national water recycling guidelines are being updated. It is anticipated that this will be finalised in 2006.

Victoria's regulatory framework

Sewage treatment plants designed to treat greater than 5 kL/d of sewage are subject to works approvals and licensing by EPA Victoria. Under the Environment Protection (Scheduled Premises and Exemptions) Regulations 1996, an exemption from these statutory processes is provided for effluent reuse schemes that meet the requirements specified in the Victorian guideline, the *Guidelines for environmental management: use of reclaimed water* (EPA Victoria 2003).

The guideline provides a framework for the management of reclaimed water, sets performance objectives, establishes the obligations of suppliers and users of reclaimed water, and suggests best practice measures for treatment, quality, site selection, application, site management, and monitoring and reporting in order to meet the performance objectives (EPA Victoria 2003).

Environment Improvement Plans (EIPs) form a critical component of the guideline framework. EIPs need to demonstrate that the performance objectives of the guideline can be complied with, by detailing the procedures and practices that will be implemented to manage risk and ensure sustainability.

Suppliers and users of reclaimed water must ensure that all reuse schemes have an appropriate EIP. EPA Victoria and Department of Human Services (DHS) approval is required for schemes requiring Class A reclaimed water (highest class of reclaimed water in Victoria). For all other schemes involving greater than 1 ML/d of reclaimed water or industrial process waters, approval from EPA or an appointed auditor is required. Endorsement from the Department of Primary Industries is also required for water with significant quantities of animal effluent (EPA Victoria 2003).

A key supporting document is the *Guideline for wastewater irrigation* (EPA Victoria 1991) which contains guidance on the selection of appropriate irrigation sites and describes irrigation management for protection of soils and waterbodies. This guideline is being reviewed and updated.

All monitoring, reporting and auditing procedures and programs should be documented in the EIP. Reuse schemes that use more than 1 ML/d should be audited every year to verify compliance with the guidelines. Reuse schemes that use less than 1 ML/d must be audited at least every three years (EPA Victoria 2003). Audit programs for schemes that use greater than 1 ML/d should comply with the principles in *ISO 14010:1996 Guidelines for environmental auditing – general principles.* (These principles have since been superseded by ISO 19011: 2003). The proponent of the reuse scheme should ensure that an appropriately qualified independent auditor or internal expert undertakes the audit (EPA Victoria 2003).

At the time of writing this chapter a guideline for managing health and environmental risks in dual pipe water recycling schemes was being developed by the EPA Victoria and DHS, in partnership with the water industry.

South Australia's regulatory framework

Under the *Public and Environmental Health Act* 1987, all reclaimed water schemes require approval by the Department of Health (DH). Under the *Environment Protection Act* 1993, schemes from sewage treatment plants with a capacity exceeding 100 persons in a catchment area or 1000 persons in a non-catchment area also require licenses (AATSE 2004).

The *South Australian reclaimed water guidelines (Treated effluent)* (SA DH, SA EPA 1999) describes measures to manage reclaimed water sustainably. The guidelines are not a prescribed code, but rather compliance is recommended to those proposing to use reclaimed water. Provisions in the publication could be incorporated in a licence pursuant to the *Environment Protection Act* or an approval issued pursuant to the Public and Environmental Health (Waste Control) Regulations of the *Public and Environmental Health Act* 1987 (SA DH, SA EPA 1999).

An irrigation management plan (IMP) must be prepared for all schemes involving the irrigation of reclaimed water. The IMP must include evidence of approval under the Public and Environmental Health (Waste Control) Regulations of the *Public and Environmental Health Act* 1987 (SA DHS, SA EPA 1999).

For irrigation schemes using reclaimed water from SA EPA licensed wastewater treatment plants (WWTPs) and septic tank effluent disposal schemes (STEDS), an independently verified report of the schemes monitoring program must be submitted annually to EPA (SA DH, SA EPA 1999).

For schemes which use reclaimed water from unlicensed WWTPs or STEDS, monitoring may be required by conditions which form part of Public and Environmental Health (Waste Control) Regulations approval (SA DH, SA EPA 1999).

Queensland's regulatory framework

Under the *Environmental Protection Act* 1994, water recycling is not an environmentally relevant activity (ERA) and hence no environmental authority or development permit is required from the Queensland Environmental Protection Agency. However, a sewage treatment works having a peak design capacity to treat the sewage of 21 or more equivalent persons (EP) (about 5 kL/d) is defined as an ERA. Water recycling from these sewage treatment works will be subject to regulation under the current licence, environmental authority or development permit. If the reclaimed water is supplied to a user not subject to the licence, a formal Third Party Agreement is required between the supplier and user (EPA Queensland 2004).

In 2004, the Queensland Environmental Protection Agency released the *draft Queensland guidelines for the safe use of recycled water* for public consultation.

A Recycled Water Safety Plan, or equivalent site-based management plan or irrigation management plan incorporating risk management is required for water recycling schemes using reclaimed water from a sewage treatment plant. The guidelines refer to the *Australian and New Zealand guidelines for fresh and marine water quality 2000* (ANZECC and ARMCANZ 2000) for design of environmental monitoring and assessment programs (EPA Queensland 2004).

Tasmania's regulatory framework

Under the *Environmental Management and Pollution Control Act* 1994 sewage treatment plants treating more than 100 kL/d are regulated by the Environment Division of the Department of Primary Industries, Water and Environment (DPIWE 2002).

Any of these plants planning to undertake wastewater reuse must develop an approved Environmental Management Plan to the satisfaction of the Director of Environmental Management. Reuse from smaller sewage treatment plants is administered by local government.

The *Environmental guidelines for the use of recycled water in Tasmania* (DPIWE, 2002) is the primary reference document for effective management of wastewater reuse. The DPIWE has also established the Wastewater Reuse Coordinating Group to facilitate reuse and assess the sustainability of reuse schemes.

New South Wales' regulatory framework

The *Protection of the Environment Operations Act* 1997 (POEO Act) requires environment protection licences for sewage treatment systems (including the treatment works, pumping stations, sewage overflow structures and the reticulation system) that have an intended processing capacity of more than 2500 persons equivalent capacity or 750 kL/d per day and that involve the discharge or likely discharge of wastes or by-products to land or waters (NSW EPA 2003).

In 2004, the New South Wales Department of Environment and Conservation (which incorporates the Environment Protection Authority) released the *Environmental guidelines: use of effluent by irrigation.* These guidelines provide a framework for developing sustainable irrigation schemes. An environment protection licence is not likely to be required for effluent irrigation schemes operating in accordance with these guidelines, unless specifically required to be licensed under the POEO Act (NSW Department of Environment and Conservation 2004).

Australian Capital Territory's regulatory framework

The ACT Wastewater Reuse for Irrigation Environment Protection Policy 1999 sets out health and planning requirements for wastewater reuse. The health requirements have been developed on advice from the Health Protection Service, ACT Department of Health and Community Care. The guidance is based on the EPA NSW (1995) guidelines (ACT 1999).

Under the *Environment Protection Act* 1997 an Environment Protection Agreement with the Environment Management Protection Authority (EMA) or an Environmental Authorisation is required for the reuse of wastewater in excess of 3 ML/yr or in circumstances where the EMA is concerned that there is a risk of environmental harm. The Agreement must comply with the wastewater reuse guidelines. Approval for any wastewater reuse system is required from the Health Protection Service, ACT Health and Community Care (ACT 1999).

International regulatory framework

United States' regulatory framework

In September 2004, the United States Environmental Protection Agency and the United States Agency for International Development released the *Guidelines for water reuse* (US EPA 2004). This document updates the 1992 *Guidelines for water reuse* to reflect significant technical advancements and institutional developments. The document also addresses new areas, including national reclaimed water use trends, updated contaminant criteria and approaches to integrated water resources management. Rather than proposing standards, the primary purpose of the document is to present and summarise water reuse guidelines with supporting information for use by utilities and regulatory agencies. It is a guidance document that provides a framework for individual States to set their own standards (US EPA 2004).

California's regulatory framework

The California State Department of Health Services (DHS) is responsible for developing regulations for the use of reclaimed water. The California State DHS has established water quality standards and treatment reliability criteria for recycled water. These are written into statute and summarised in '*The purple book*' (DHS 2001a).

In 1984 the California State Water Resources Control Board and University of California published the *Irrigation with reclaimed municipal wastewater –*

a guidance manual (CSWRCB 1984). The focus of the manual is on the beneficial use of reclaimed wastewater for agricultural and landscape irrigation. The guidance provided is applicable to arid and semiarid environments outside of California (CSWRCB 1984).

California Regional Water Quality Control Boards issue water recycling permits that include the health-based requirements from the California DHS regulations. The master reclamation permit needs to include (DHS 2001a):

- waste discharge requirements;
- a requirement that the permittee comply with the uniform statewide reclamation criteria;
- a requirement that the permittee establish and enforce rules or regulations for reclaimed water users, governing the design and construction of reclaimed water use facilities and the use of reclaimed water in accordance with uniform statewide reclamation criteria;
- a requirement that the permittee submit a quarterly report summarising reclaimed water use;
- a requirement that the permittee conduct periodic inspections of the facilities of the reclaimed water users to monitor compliance by the users with the uniform statewide reclamation criteria and master reclamation permit; and
- any other requirement determined to be appropriate by the regional board.

Israel's regulatory framework

Rules governing the treatment of wastewater designated for irrigation of different crops were established by the Ministry of Health in 1981. Regulations setting standards for wastewater treatment were released by the Ministry of Health in 1992 (Israeli Ministry of the Environment 2000a).

National policy calls for the gradual replacement of freshwater allocations to agriculture by reclaimed effluent. It is estimated that by 2020, effluent use will constitute 50% of the water supplied to agriculture. To achieve this target, the Ministry of the Environment has finalised recommendations for effluent quality standards for unrestricted irrigation based on soil, flora, hydrogeological and public health considerations. An agreement in principle has been reached on the new effluent quality standards, and a technoeconomic review of the standard has been conducted (Israeli Ministry of the Environment 2003).

World Health Organization

The *Guidelines for the safe use of wastewater and excreta in agriculture and aquaculture* (WHO 1989) were developed with the intention that they would act as general guidance, with modification according to local conditions. These guidelines have significantly influenced the reuse of wastewater in developing countries, but have had less influence in countries such as Australia and the United States of America.

Microbiological water quality and horticultural uses

All guidelines reviewed operate a multi-tiered approach to managing microbiological water quality, whereby the highest grade water quality specified is required where there is direct contact between irrigation water and food crops consumed raw. Lower grades of water are allowed where additional risk management measures are in place, such as the cooking of food before consumption, or the edible portion of the crop does not contact the reclaimed water. However, while the guidelines operate within a similar structure, there are significant differences in how the jurisdictions define categories of produce such as 'crops consumed raw', and the required water quality and management controls.

For the purpose of this chapter, the produce categories can be crudely broken into three groupings:

1. crops consumed raw with direct contact between reclaimed water and edible portions of the produce;
2. crops consumed raw but without direct contact between edible produce and reclaimed water (through protection of peel or the irrigation method); and
3. crops that are cooked or processed before consumption.

Summaries of key regulatory and guideline microbiological criteria and management controls for each of the produce categories are provided in Tables 2.1, 2.2 and 2.3.

The differences in microbiological water quality are most significant for produce that is consumed raw and in direct contact with reclaimed water. Reflecting the relevance to the horticultural market and the higher potential exposures associated with these crops, reclaimed water quality relevant to these crops is the primary focus of this chapter.

Please note that this chapter provides only summarised information on guidelines. For detailed requirements, readers should refer to the primary referenced documents.

Criteria for direct irrigation of human food crops consumed raw

National guidelines

For direct irrigation of human food crops consumed raw, the Australian national guideline (ARMCANZ, ANZECC and NHMRC 2000) requires use of a grade termed 'Tertiary treatment with pathogen reduction'. This grade is based on a generic requirement for tertiary treatment (eg sand and membrane filtration) coupled to key water quality parameters of:

- <2 NTU (nephelometric turbidity units) as a 24 hour mean and a 5 NTU limit as a maximum;
- a chlorine residual of 1 mg/L after a minimum contact time of 30 minutes;
- less than 10 thermotolerant coliforms/100 mL as a median; and
- helminth removal through 25 days ponding or filtration.

The guidance recommends against establishing virus limits, but notes that monitoring and demonstrated removal of specific organisms such as *Giardia*, *Cryptosporidium* and *Ascaris* may be required. However, water quality limits are not provided.

At the time of writing of this chapter, the national guideline was being updated. The redrafting focuses on the application of hazard analysis and critical control point (HACCP) principles, building from the framework in the *Australian drinking water guidelines* (NHMRC, NRMMC, 2004).

Australian State guidelines

The Reclaimed Water Guideline in South Australia (SA DHS, SA EPA 1999) adopts similar criteria to those adopted in the national document for direct irrigation of food crops consumed raw. However, the South Australian position for Class A reclaimed water has a critical difference, noting that 'Specific removal of viruses, protozoa and helminths may be required'. This provision was significant in water quality verification for the Virginia Pipeline Scheme, where Class A reclaimed water is used for growing vegetables on the Northern Adelaide Plains. The water quality verification included demonstration that the reclaimed water had <1 virus/50 L and <1 parasite/50 L. This was based on monitoring for viruses (enteroviruses, reovirus, adenovirus group, Hepatitis A), protozoa (*Giardia* and *Cryptosporidium*) and helminths (*Ascaris lumbricoides*).

The management of microbiological water quality in Victoria is described in the *Guidelines for environmental management: use of reclaimed water* (EPA Victoria 2003). These guidelines follow the philosophy of the South Australian guideline more closely than the national document, with Class A water quality indicators such as turbidity being listed as 'indicative' and the primary focus on achieving sufficient treatment to reliably achieve:

- <10 *Escherichia coli*/100 mL (median), 40 E. *coli*/100 mL as a maximum;
- <1 protozoa/50 L;
- <1 virus/50 L; and
- <1 helminth/L.

At the time of writing of this chapter, the Class A reclaimed water requirements in Victoria were being updated with an emphasis on treatment process capability. It has been proposed that Class A requirements would be based on treatment processes demonstrating a 7 log reduction of viruses and a 6 log reduction of protozoan parasites. This would be based on reductions from raw sewage and under typical treatment plant operating conditions. Treatment plant operation would also be required to be managed within a risk management framework (such as HACCP), including the development of customised critical control limits.

The criteria used to define 'Class A' in other Australian States with guidelines for reclaimed water do not dramatically differ from the various criteria described above. Proposed Queensland guidance (EPA Queensland, 2003) adopts an approach similar to the proposed Victorian framework, but proposes treatment objectives of 5 log virus removal post primary treatment. New South Wales guidance for urban recycling establishes pathogen criteria similar to the current guideline in Victoria, but also includes prescriptive treatment technology requirements.

United States and Californian guidelines

Overarching guidance in the United States is provided in the federal *Guidelines for water reuse* (US EPA 2004), while individual states, such as California, have prepared detailed guidance, supplemented with a variety of supporting documents.

The highest grade in the United States guidelines is required for direct irrigation of food crops consumed raw. The grade criteria has generic descriptions of the treatment technology requirements (secondary treatment plus filtration and disinfection) with a reliance predominantly on final water quality, with objectives of:

- ≤10 mg/L BOD;
- ≤2 NTU as a 24 hour average, with a maximum of 5 NTU;
- no detectable faecal coli/100 mL as a 7 day median value and a maximum of 14 organisms/100 mL; and
- a total chlorine residual of ≥1 mg/L is required after a minimum contact time of 30 minutes, but it is noted that a higher residual or longer contact time may be necessary to ensure that viruses and parasites are inactivated or destroyed.

Direct pathogen criteria are not provided. However, the guidance notes that the effluent should not contain measurable levels of pathogens, confirmed by testing prior to commencing the reuse program.

The Californian criteria for irrigation for crops consumed raw are arguably the most well-recognised criteria internationally and therefore this approach is covered in a relatively high level of detail in this chapter. In California, the microbiological classification of reclaimed water occurs under the *Californian health laws related to recycled water* (DHS 2001a). The classification is unusual as a recycling guidance document, as it includes highly prescriptive requirements for treatment technologies, linked to relatively detailed criteria for the operation of the treatment plants and final water quality.

The criteria for 'disinfected tertiary reclaimed water' (*Title 22* water) is based on the following.

- Secondary treatment of the wastewater (termed oxidised) followed by prescribed filtration processes of either:
  - coagulation and granular media filtration (within prescribed criteria such as flow rate) to achieve <2 NTU as a 24 hour average and so that the water does not exceed 5 NTU for greater than 5% of the time within the 24 hour period, and 10 NTU at any time; or
  - granular media filtration without coagulation to achieve a water quality of <2 NTU (does not state whether average or maximum), provided the influent turbidity to the filters is continuously monitored and does not exceed 5 NTU for more than 15 minutes, never exceeds 10 NTU and bypass mechanisms or coagulation can begin if these parameters are breached; or
  - microfiltration, ultrafiltration, nanofiltration or reverse osmosis membrane such that filtered water turbidity does not exceed either 0.2 NTU more than 5% of the time within a 24 hour period, and 0.5 NTU at any time.
- Disinfection postfiltration by either:
  - a chlorine contact time (concentration multiplied by time) of not less than 450 mg-minutes with a modal contact time of at least 90 minutes based on Peak Dry Weather Flow; or
  - a process that when combined with filtration, inactivates or removes 99.999% of the plaque forming units of F-specific bacteriophage MS2 or a virus at least as resistant as polio virus; and
  - total coliform bacteria limit of 2.2 most probable number (MPN) organisms/100 mL as a seven-day median – the total coliform bacteria must not exceed 23 organisms/100 mL in more than one sample and no sample can exceed a MPN of 240 organisms/100 mL.

The guidance notes that protozoa and virus monitoring will be required for treatment trains that do not meet the above minimum treatment requirements; however, no associated criteria are provided.

The publication *Treatment technology report for recycled water* (DHS 2003) provides additional information on the specifications for filtration systems endorsed by the Californian State Department of Health Services, while details of engineering reports required prior to the supply of recycled water are provided in the *Guidelines for the preparation of an engineering report for the production, distribution and use of recycled water* (DHS 2001b).

World Health Organization

In contrast to the requirements in the Australian and United States guidelines, the WHO criteria (WHO 1989) for food crops consumed raw are relatively permissive. The required water quality is based on technologies such as a stabilisation pond series, with microbiological water quality required of ≤1 viable intestinal nematode eggs/L (as arithmetic mean of *Ascaris*, *Trichuris* and hookworms) and ≤1000 faecal coliforms/100mL (as geometric mean).

Recently, Blumenthal *et al* (2000) reviewed the WHO standards and recommended that the Class A criteria be modified to include an intestinal nematode limit of ≤0.1 eggs/L.

Israeli guidelines

According to the Israeli Ministry of Health report *Irrigation with effluents standards* (IMH 2001), Israel considered adopting the WHO recommendations of 1989, but decided more stringent guidelines were required due to the risks to travellers and exports. The

Israeli guideline requirements for irrigation of food crops eaten raw are described based on the guidance provided in the Israeli Ministry of Health report.

The Israeli guideline describes requirements for 'Effluents of very high quality' which is a secondary treated effluent (20 mg/L BOD, 30 mg/L SS) that is 'filtered' and disinfected for half an hour with a minimum total residual chlorine of 1 mg/L. A limit of not greater than 10 *E. coli* organisms/100 mL applies to the final water. Three processes are considered to achieve the requirement for filtration:

- granular depth filtration or equivalent producing effluents with less than 5 NTU or 10 mg/L SS;
- detention of effluents by either 60 days detention in pond or detention in lagoon where influent flow is stopped 30 days prior to irrigation; and
- dilution in a pond so that less than 10% of water is effluent.

For unrestricted irrigation, new standards under consideration by the Ministry of the Environment adopt the faecal coliform limit of 10 units/100 mL and residual chlorine at 1 mg/L. The recommended criteria for BOD is 10 mg/L (Israel Ministry of the Environment 2003).

Monitoring

The detail of the monitoring requirements to confirm water quality in the various jurisdictions is not detailed above. However, it typically involves continuous monitoring of critical parameters such as turbidity and chlorine residual. Should the reclaimed water not achieve the required parameters, the water is not allowed to be supplied. Monitoring of bacterial parameters such as *E. coli* is typically weekly or daily depending on the guideline. Direct pathogen monitoring, if required, is primarily during plant commissioning.

Comparison of criteria

With regard to stringency, a ranking of the criteria involves the following:

- As least stringent of the requirements, the World Health Organization criteria are achievable with widely available treatment processes such as stabilisation lagoons.
- Intermediate, in terms of stringency, is the requirements in Israel and the current Australian national guidelines, with requirements for tertiary treatment and reliance on limits of 10 *E. coli*/100 mL and 10 thermotolerant coliforms/100 mL, respectively. Similar criteria for chlorination and filtration are required, although the Australian guidance is more stringent than the Israeli requirements with regard to the necessary turbidity – a potential indicator of filtration efficiency and therefore removal of pathogenic organisms.
- The most stringent of the criteria are the Californian, US EPA, Victorian and South Australian requirements. The Victorian and South Australian guidance includes verification of the removal of pathogen groups such as protozoan parasites, which depending on the treatment processes, may make these guidelines more stringent than the United States and Californian. To illustrate this comparison, there have been some reports of very low levels of parasites being detected in the reclaimed water from selected Californian *Title 22* plants (Gennaccaro *et al* 2003).

As with stringency, there are important differences in the structure of the guidance. The Californian approach is heavily focussed on the use of prescribed technologies, such as filter design and operational parameters, coupled to generic water quality criteria such as turbidity of filter effluent. This approach provides a high level of certainty in designing a treatment plant that will achieve the criteria, but is relatively inflexible.

In comparison, the Israeli and national Australian guideline approaches provide less prescriptive requirements for treatment processes, coupled with relatively generic water quality criteria such as turbidity. A key difficulty with this relatively generic approach is that it relies heavily on a single set of treatment performance surrogates that apply to all processes (eg turbidity <2 NTU). Given the rapid evolution of treatment processes and the diversity of treatment options, it is probably impossible to establish prescriptive, 'one size fits all' process-based criteria.

The approach in the Victorian guidelines is to place a greater emphasis on the removal of specific pathogen groups (eg viruses and protozoan parasites). Treatment process-monitoring criteria, such as a turbidity limit, are then established once the process is operational. This enables flexibility in the technologies that can be used, but has the disadvantage, compared to the Californian approach, of reduced certainty in designing a treatment process that will comply with the criteria.

Table 2.1 Summary of reclaimed water microbial quality requirements for use in horticulture.

Jurisdiction	Grade required for direct irrigation of human food crops potentially consumed raw	Intermediate grade requiring management controls in horticulture – either food processing or cooking or separation from irrigation
Australia – national guideline (ARMCANZ, ANZECC and NHMRC 2000)	**Tertiary with pathogen reduction** Water quality specified as: • <2 NTU (24 hour median); • 5 NTU (maximum); • pH 6.5–8.5 (90%ile); • chlorine residual of ≥1 mg/L for ≥30 minutes (or equivalent disinfection); and • <10 thermotolerant coliforms/100 mL (median). These criteria are supported by generic descriptions of treatment processes. Virus limits are not recommended, but demonstrated removal of organisms such as *Giardia* and *Ascaris* may be required.	**Secondary with pathogen reduction** The criteria for the grade is: • pH 6.5–8.5 (90%ile); and • <1000 thermotolerant coliforms/100 mL. Secondary effluent generally has BOD <30 mg/L and SS <30 mg/L, although SS may rise to >100 mg/L due to algal solids in lagoon systems. Note: Guidance also includes higher and lower grades, with limits of 100 and 10 000 coliforms/100 mL, respectively.
South Australia (SA DHS, SA EPA 1999)	**Class A** Full secondary treatment with tertiary filtration and disinfection to achieve water quality criteria of: • ≤2 NTU (mean); • BOD <20 mg/L; and • <10 thermotolerant coliforms or *E. coli*/100 mL as a median. Specific removal of viruses, protozoa and helminths may be required. Regulatory approvals for horticulture have been based on verification to demonstrate <1 virus/50 L and <1 parasite/50 L.	**Class C** Based on either primary sedimentation with lagooning or secondary treatment to achieve: • BOD <20 mg/L; • SS <30 mg/L; and • <1000 thermotolerant coliforms or *E. coli*/100 mL (median). Disinfection is only required as part of the treatment train where necessary to meet the bacterial limit. Note: Guidance also includes a higher (Class B) and lower grade (Class D), with limits of 100 and 10 000 coliforms or *E. coli*/100 mL, respectively.
Victoria (EPA 2003)	**Class A** Note that this has been currently updated with a focus on log removal of specific pathogen groups, eg viruses and protozoan parasites. However, the current guidelines specify the following water quality objectives: • < 10 *E. coli* per 100 mL (median) and 40 *E. coli*/100 mL (max); • < 1 helminth/L; • < 1 protozoa/50 L; and • < 1 virus/50 L. The guideline also describes an expected treatment train of secondary, filtration and disinfection and indicative water quality criteria of: • <2 NTU (24 hour median), 5 NTU (maximum limit); • pH 6.5–9 (90%ile limits); • <10 mg/L BOD and <5 mg/L SS; and • chlorine residual of ≥1 mg/L for ≥30 minutes (or equivalent disinfection).	**Class C** Based on secondary treatment and disinfection to achieve: • BOD <20 mg/L; • SS <30 mg/L; • <1000 *E. coli*/100 mL (median); and • 4000 *E. coli*/100 mL (maximum). Note: Guidance also includes a higher (Class B) and lower grade (Class D), with limits of 100 and 10 000 coliforms or *E. coli*/100 mL, respectively.

Table 2.1 Summary of reclaimed water microbial quality requirements for use in horticulture (continued).

Jurisdiction	Grade required for direct irrigation of human food crops potentially consumed raw	Intermediate grade requiring management controls in horticulture – either food processing or cooking or separation from irrigation
United States federal recommendations (US EPA 2004)	**Secondary/filtration/disinfection** Generic descriptions of treatment via filtration and disinfection are provided coupled with water quality criteria of: • pH 6–9; • ≤10 mg/L BOD; • ≤2 NTU (24 hour average) maximum of 5 NTU; • no detectable faecal coli/100 mL (7 day median), 14 faecal coli/100 mL (max); • a total chlorine residual of ≥1 mg/L for ≥ 30 minutes is required. A chlorine residual of 0.5 mg/L or greater in the distribution system is recommended; and • secondary treatment should produce <30 mg BOD/L and 30 mg SS/L effluent.	**Secondary with disinfection** Based on secondary treatment and disinfection to achieve: • pH 6–9; • BOD ≤30 mg/L; • SS ≤30 mg/L; • ≤200 faecal coli/100 mL (7-day median); and • 1 mg/L chlorine residual.
Californian guidance (DHS 2001[a])	**Disinfected tertiary reclaimed water** Relatively detailed criteria on treatment processes are linked to the final water quality criteria. The criteria for a disinfected tertiary reclaimed water is based on: • initial secondary treatment of the wastewater (termed oxidised); • filtration through prescribed processes of either: – granular media filtration with coagulation to <2 NTU (24 hour average) and <5 NTU (24 hour 95%ile) and 10 NTU (max); or – alternative limits for granular media filtration without coagulation are specified; or – membrane filtration to <0.2 NTU (24 hour 95%ile) and 0.5 NTU (max); • disinfection postfiltration by either: – a chlorine contact time of not less than 450 mg-minutes with a modal contact time of at least 90 minutes; or – a process that, when combined with filtration, removes 5 logs percent of F-specific bacteriophage MS2 or a virus as resistant as polio virus; and • a total coliform bacteria limit of 2.2 MPN organisms/100 mL as a 7-day median. The total coliform bacteria must not exceed 23 organisms/100 mL in more than one sample and no sample can exceed a MPN of 240 organisms/100 mL. Prescriptive treatment specifications are focussed on the filtration step.	**Disinfected secondary – 23 reclaimed water** Based on secondary treatment and disinfection to achieve: • a median 7-day total coliform bacteria less than 23 MPN organisms/100 mL; and • the limit that the total does not exceed 240 organisms in more than one sample per 30 days. Note: the guidance includes a higher grade of disinfected secondary – 2.2 reclaimed water which has a median 7-day limit of less than 2.2 MPN total coliform bacteria/100 mL. The guidance also includes a disinfected secondary reclaimed water grade that does not include quantitative criteria.

Table 2.1 Summary of reclaimed water microbial quality requirements for use in horticulture (continued).

Jurisdiction	Grade required for direct irrigation of human food crops potentially consumed raw	Intermediate grade requiring management controls in horticulture – either food processing or cooking or separation from irrigation
Israel Israeli Ministry of Health report Irrigation with effluents standards (IMH 2001)	**'Effluents of very high quality'** The grade for unlimited irrigation[A] is based on a secondary treated effluent (20/30 BOD/SS) being 'filtered' and then disinfected for half an hour with a minimum total residual chlorine of 1 mg/L. A limit of 10 *E. coli* /100 mL applies to the final water. There are three processes that are considered to achieve the requirement for filtration: • granular depth filtration or equivalent producing effluents with less than 5 NTU or 10 mg/L SS; • detention of effluents by either 60 days detention in pond or detention in lagoon where influent flow is stopped 30 days prior to irrigation; and • dilution in a pond so that less than 10% of water is effluent.	**Oxidation pond effluents** Oxidation pond effluents are included in the Israeli guideline, requiring an oxidation lagoon that has 15 days retention time, a BOD of less than 60 mg/L and less than 10^5 *E. coli* /100 ml. The guideline also includes: • effluent of high quality – which is a secondary treated effluent (20/30 BOD/SS); and • effluents of medium quality – effluents from aerated ponds and biological-mechanical plants with <60 mg/L BOD, <90 mg/L SS.
World Health Organization (WHO 1989)	**Class A** The water quality is based on technologies such as a stabilisation pond series, with microbiological water quality required: • 1 viable intestinal nematode eggs/L (as arithmetic mean of *Ascaris*, *Trichuris* and hookworms); and • 1000 faecal coliforms/100 mL (as geometric mean). A provision is included that a limit such as ≤100 faecal coliforms/100 mL may been needed for public lawns, especially hotel lawns in tourist areas, where people unaware of risks would come in contact with recently irrigated grass.	**Class B** Expected to be based on technologies such as retention in a stabilisation pond for 8–10 days with microbiological water quality required of ≤1 viable intestinal nematode eggs/L (as arithmetic mean). A faecal coliform limit is not specified. The guidance also includes Class B water, a grade based on ≤1 viable intestinal nematode eggs/L, coupled to retention in stabilisation ponds for 8–10 days or equivalent removal of helminths and faecal coliforms. A lower grade Class C water is specified but lacks microbiological criteria.
Proposed World Health Organization (Blumenthal *et al* 2000)	**Class A** The water quality is similar to described above for Class A; however, the recommendation is that the nematode criteria be reduced to an intestinal nematode limit of ≤0.1 eggs/L.	The water quality is similar to described above.

[A] This effluent can be used for the irrigation of public open space. However, it requires that irrigation is only undertaken if the area is closed to the public or at night, or where there is subsurface irrigation.

Reclaimed water quality with use restrictions

In contrast to the significant differences that can be found in the reclaimed water quality requirements for direct irrigation of food crops consumed raw, the quality requirements are more comparable for irrigation of food crops that are either cooked before consumption or where the reclaimed water doesn't contact edible portions of produce. The requirements in the different jurisdictions are summarised in Tables 2.2 and 2.3.

As a way of illustrating the approach used in linking restrictions in end use with water quality, a summary of the South Australian guideline approach follows below. This guideline describes three classes of reclaimed water that are below 'Class A' and involve restrictions on produce irrigation: Class B, Class C and Class D.

Class B is based on secondary treatment with disinfection to achieve a BOD <20 mg/L, SS <30 mg/L, coupled with a median of <100 thermotolerant coliforms or *E. coli*/100 mL. The accepted uses for Class B are:

- crops consumed raw, but not in contact with the ground, can be flood irrigated although dropped produce cannot be collected; and
- crops protected with a peel can have spray irrigation.

Class C is based on either primary sedimentation with lagooning or secondary treatment (to achieve BOD <20 mg/L, SS <30 mg/L, coupled with a median of <1000 thermotolerant coliforms or *E. coli*/100 mL). Disinfection is only required as part of the treatment train where necessary to meet the bacterial limit. The accepted uses are:

- crops consumed raw, but not in contact with the ground can have Class C water through drip irrigation although dropped produce cannot be collected;
- crops protected with a peel can have Class C if flood, drip or subsurface irrigation is used and the crops are not wet from irrigation when harvested; and
- for crops that are cooked or commercially processed before consumption, Class C water can be used.

Class D is based on either primary sedimentation with lagooning or secondary treatment to achieve BOD <20 mg/L, SS <30 mg/L, coupled with a median of <10 000 thermotolerant coliforms or *E. coli*/100 mL. The accepted uses are relatively restricted. However, crops consumed raw, but not in contact with the ground, can use Class D water provided subsurface irrigation is used and dropped produce is not collected.

Although similar, the treatment grade criteria are not tightly harmonised between the different guidance documents. The US EPA guidance specifies a higher minimum level of treatment than described in South Australia. Californian guidelines include a relatively high quality intermediate classification, while the WHO and Israeli requirements extend below the minimum criteria described (summarised in Tables 2.2 and 2.3).

In addition to the treatment grade criteria not being harmonised, the detail of the acceptable end uses can be quite variable. Israel includes a relatively complex system involving 23 crop categories for matching management 'barriers' (eg separation distances and crop type) with the required water quality. In comparison, the national Australian and Californian guidelines provide relatively generic descriptors of the crop categories linked to the different water qualities.

Managing worker and public safety

The scope of this chapter does not enable a detailed discussion of the guideline controls that apply for managing worker and public safety. However, the controls can be summarised as:

- Restrictions apply on public and worker access during irrigation with reclaimed water, unless the highest grade of reclaimed water for that guideline is being used;
- Requirements exist for buffer distances to sensitive land uses such as residential areas, or drinking water bores. The buffer distances depend on the quality of the water and the irrigation method;
- Identification of reclaimed water irrigation lines and equipment through colouring or labelling, particularly where the pipes are in the proximity of potable lines; and
- Signage on the entrances to properties advising of the use of reclaimed water.

See the specific guideline for more details.

Managing nutrients

Nutrients are essential for plant growth. However, excessive accumulation of nutrients in the soil can cause toxicity to some plants and adverse impacts on surface and groundwater. Of the range of nutrients required for plant growth and expected to be in reclaimed water, phosphorus and nitrogen are the most likely to have potential adverse effects on the environment.

Table 2.2 Linkages between reclaimed water quality and permitted uses where human food crops are in direct contact with reclaimed water but will be cooked or processed before consumption.

Guideline	Lowest treatment grade and water quality parameters permitted	Specified management controls
National guideline (ARMCANZ, ANZECC and NHMRC 2000)	**Secondary + pathogen reduction** Secondary effluent generally has BOD <30 mg/L and SS <30 mg/L, coupled with <1000 coliform/100 mL, pH 6.5–8.5.	Crops for human consumption must be cooked (>70°C for more than 2 minutes) or commercially processed before sale to consumers.
Victorian guideline (EPA 2003)	**Class C** Secondary treatment and disinfection to achieve: BOD <20 mg/L; SS <30 mg/L; and <1000 *E. coli*/100 mL (median).	Produce should not be wet from reclaimed water when harvested. Crops for human consumption must be cooked (>70°C for more than 2 minutes) or commercially processed before sale to consumers.
South Australian guideline (SA DHS, SA EPA 1999)	**Class C** Secondary treatment and disinfection to achieve: BOD <20 mg/L; SS <30 mg/L; and <1000 *E. coli*/100 mL (median).	Crops need to be processed before consumption.
California (DHS 2001)	**Undisinfected secondary reclaimed water** This grade does not include quantitative criteria and is based on wastewater in which the organic matter has been stabilised, is non putrescible, and contains dissolved oxygen.	Must undergo commercial pathogen-destroying processing before being consumed by humans.
US EPA (2004)	**Secondary + disinfection** Defined by: ≤200 faecal coli/100 mL; pH 6–9; BOD ≤30 mg/L; and SS ≤30 mg/L. A total chlorine residual of ≤1 mg/L is required.	Food crops need to be commercially processed (means that prior to sale to the public, crops have undergone chemical or physical processing sufficient to destroy pathogens).
Israeli Ministry of Health guideline (IMH 2001)	**Effluent of high quality** which is a secondary treated effluent (20/30 BOD/SS). Note: low grade could potentially be allowed when coupled with other management controls.	The guidance does not have an individual category for crops cooked or commercially processed, rather it describes barrier credits for different management options linked to specific crops. Cooking of vegetables is included as part of that matrix.

The environmental risk is largely determined by whether the site is in nutrient balance or not (ie the nutrient load, the amount applied by the reclaimed water application and by any other means, such as fertiliser, should be balanced with the crop requirement).

The regulation of nutrients in reclaimed water schemes is based on a risk assessment approach, taking into consideration site-specific conditions including soil characteristics, irrigation scheduling, crop type, depth to groundwater and buffer to surface waters. The appropriate management controls for a reuse scheme are typically determined through this assessment process.

Managing nutrients in Australia

The current national guideline *Guidelines for sewerage systems; use of reclaimed water* (ARMCANZ, ANZECC and NHMRC 2000) states that for a reclaimed water irrigation scheme to be ecologically sustainable, the agronomic system must not become stressed by excessive nutrient loading. However, specific guidance is not provided.

All State guidelines identify the need to undertake a nutrient balance as part of a land capability assessment. For example, the *South Australian reclaimed water guidelines (treated effluent)* (SA DHS, SA EPA 1999) requires an assessment of the wastewater for nutrient concentrations. The Irrigation Management Plan must consider a mass balance of nutrients, particularly nitrogen and phosphorus, with the objective where possible of balancing nutrient loading with crop requirements. If such a balance is not possible, the monitoring program must account for the fate of nutrients.

The guidance available in Victoria, New South Wales and Tasmania provide specific detail in calculating and determining the appropriate nutrient loadings for irrigation schemes. For example, the Victorian reclaimed water guideline requires that in addition to a water balance, a nutrient balance must be completed during the design stages of an irrigation scheme (EPA Victoria 2003). The nutrient balance needs to ensure that nutrients are applied at an optimal rate and load for the specific crop. The nutrient load (the amount applied by the reclaimed water application and by any other means,

Table 2.3 Linkages between reclaimed water quality and permitted uses where the edible portion of human food crops are protected from direct contact with reclaimed water through irrigation method (eg drip irrigation) or through a protective layer (eg peeling).

Guideline	Lowest treatment grade and water quality parameters permitted	Specified management controls
National guideline (ARMCANZ, ANZECC and NHMRC 2000)	**Secondary + pathogen reduction** Secondary effluent generally has BOD <30 mg/L and SS <30 mg/L, coupled with <1000 coliform/100 mL, pH 6.5–8.5.	Where separation through irrigation method is used (eg drip, dropped crops not to be harvested).
Victorian guideline (EPA 2003)	**Class C** Secondary treatment and disinfection to achieve: BOD <20 mg/L; SS <30 mg/L; and <1000 *E. coli*/100 mL (median).	For irrigation barrier, spray irrigation not permitted, crops need to be >1 metre above ground and dropped crops not to be harvested. For protective layer barrier (eg peel) crops must not be wet with reclaimed water at harvest.
South Australian guideline (SA DHS, SA EPA 1999)	**Class C** Secondary treatment and disinfection to achieve: BOD <20 mg/L; SS <30 mg/L; and <1000 *E. coli*/100 mL (median).	For irrigation barrier, crops cannot contact group, spray or flood irrigation not permitted and dropped crops not to be harvested (Class B enables flood irrigation). For protective layer barrier (eg peel) spray irrigation not permitted and crops must not be wet with reclaimed water at harvest. (Class B enables spray irrigation).
California (DHS 2001)	**Undisinfected secondary reclaimed water** This grade does not include quantitative criteria and is based on wastewater in which the organic matter has been stabilised, is non putrescible, and contains dissolved oxygen.	Surface irrigation of orchards and vineyards permitted where the reclaimed water does not come in contact with the edible portion of the crop.
US EPA (2004)	**Secondary + disinfection** Defined by: ≤200 faecal coli/100 mL; pH 6–9; BOD ≤30 mg/L; and SS ≤30 mg/L. A total chlorine residual of 1 mg/L is required.	Surface irrigation of orchards and vineyards permitted.
Israeli Ministry of Health guideline (IMH 2001)	**Effluent of high quality** which is a secondary treated effluent (20/30 BOD/SS). Note: low grade could potentially be allowed when coupled with other management controls.	The guidance does not have an individual category for separation of produce from edible crops; rather it describes barrier credits for different management options linked to specific crops. Crops with edible peel require greater barriers than crops with inedible peel. A distance of 50 cm between drip irrigation and fruits is 'two barriers', whereas 25 cm is 1 barrier.

eg fertiliser) should be balanced annually with the crop requirements, to prevent excessive leaching to groundwater or runoff to surface waters. The companion document *Guideline for wastewater irrigation* (EPA Victoria 1991) provides supporting technical information on irrigation management including indicative nutrient uptake rates for selected crops. The guidance available for reclaimed water use in irrigation is being reviewed.

State guidelines released after the publication of the *Australian and New Zealand guidelines for fresh and marine water quality 2000* (ANZECC and ARMCANZ 2000) borrow heavily from these national guidelines. State guidelines finalised before 2000 typically reference the earlier version of the national guidelines, the *Australian water quality guidelines for fresh and marine waters* (ANZECC 1992). The current national guidelines provide long-term trigger values (LTV) and short-term trigger values (STV) for nitrogen and phosphorus in irrigation water based on maintaining crop yield, preventing bioclogging of irrigation equipment, and minimising off-site impacts (for detailed explanations of trigger values see *Chapter 8*). The trigger values are provided in Table 2.4.

The national guidelines also provide information on nitrogen and phosphorus removal (kg/ha per crop) and mean concentrations in harvestable portions of crops.

For the protection of aquatic ecosystems, the national guidelines also provide trigger values for nutrients in waterways based on key ecosystem types. In broad terms, depending on geographical region and ecosystem type, the trigger values for total nitrogen range from 100 μg/L to 1500 μg/L and for total phosphorus 10 μg/L to 100 μg/L. In addition, trigger values for toxicants,

Table 2.4 Agricultural irrigation water long-term trigger value (LTV) and short-term trigger value (STV) guidelines for nitrogen and phosphorus.

Element	LTV in irrigation water (long-term – up to 100 years) (mg/L)	STV in irrigation water (short-term – up to 20 years) (mg/L)
Nitrogen	5	25–125[A]
Phosphorus	0.05[B]	0.8–12[A]

[A] Requires site-specific assessment; [B] to minimise bioclogging of irrigation equipment only.
Table 4.2.11 from ANZECC and ARMCANZ, 2000.

nitrate and ammonia, are provided. Trigger values for fresh water for nitrate range from 17 μg/L to 17000 μg/L and for ammonia 230 μg/L to 2300 μg/L depending on the required level of environmental protection (ANZECC and ARMCANZ 2000). Specific environmental water quality objectives for the protection of surface waters are provided in state policies.

The discussion below relates to the derivation of the short-term and long-term trigger values (Table 2.4) for phosphorus and nitrogen in irrigation water specified in ANZECC and ARMCANZ (2000).

Nitrogen trigger values

In the *Australian and New Zealand guidelines for fresh and marine water quality 2000*, the LTV for nitrogen has been established to ensure that excessive nitrogen does not result in a decrease of crop yield or quality. In contrast, the STV for nitrogen has been set as a range and focuses on ensuring that nitrogen in surface waters and groundwater do not affect drinking water.

In determining a site-specific STV the national guideline lists the following for consideration: crop uptake, crop sensitivity to excess nitrogen concentrations, irrigation load, removal of nitrogen from the irrigated site in harvestable portions of crops, volatilisation/denitrification losses, and fertiliser nitrogen applied.

The following equation (Eqn 2.1) is provided to calculate the site-specific STV for nitrogen (equation 9.32 from the *Australian and New Zealand guidelines for fresh and marine water quality 2000*). However, it does not consider concentration of soil nitrogen through plant evapotranspiration, soil leaching, or dilution on entering waterbodies.

$$STV_{\mathrm{N}} = N_{\mathrm{es}} + N_{\mathrm{removed}} + N_{\mathrm{gasloss}} \quad \textit{(Eqn 2.1)}$$

where

STV_N represents short-term trigger value for nitrogen (N) in irrigation water (mg/L);

N_{es} represents environmentally significant N concentration potentially toxic to humans (mg/L);

$N_{removed}$ represents nitrogen removed from irrigation water in harvestable portion of the plant (mg/L); and

$N_{gasloss}$ represents gaseous losses through volatilisation and denitrification (mg/L) (ANZECC and ARMCANZ 2000).

Phosphorus trigger values

To prevent bioclogging of irrigation equipment or decreases in product quality as a result of algal contamination on some crops, the LTV has been set low enough to restrict algal growth in irrigation water. In setting this trigger value, it has been assumed that all other conditions for algal growth are adequate (ie light and turbidity) (ANZECC and ARMCANZ 2000).

The STV range for phosphorus has been set as an interim range due to limitations in the available data. The national guidelines suggest further research is needed to refine the understanding of the movement, or potential movement of phosphorus from soils into waterbodies due to phosphorus inputs into soils through the use of fertilisers or irrigation water.

The interim site-specific STV aims to prevent excess phosphorus entering waterways by balancing the phosphorus inputs and output taking into consideration phosphorus in irrigation water, fertiliser use and crop uptake.

The interim method of calculating a site-specific STV (equation 9.35 from the *Australian and New Zealand guidelines for fresh and marine water quality 2000*) (Eqn 2.2) is:

$$STV_{\mathrm{p}} = P_{\mathrm{es}} + P_{\mathrm{sorb}} + P_{\mathrm{removed}} \quad \textit{(Eqn 2.1)}$$

where

STV_p represents phosphorus concentration in irrigation water (mg/L);

P_{es} represents environmentally significant P concentration (ie >0.05 mg/L algal blooms likely) (mg/L);

P_{sorb} represents total phosphorus in irrigation water sorbed by soil (mg/L); and

$P_{removed}$ represents P removed from irrigation water in harvestable portion of the plant (mg/L).

Managing nutrients from an international perspective

United States and Californian guidelines

The *Guidelines for water reuse* (US EPA 2004) recognise that nitrogen in reclaimed water may not be present in concentrations great enough to produce satisfactory crop yields and some supplementary fertiliser may be necessary. The guidelines do not identify a framework for management of nutrients for agricultural applications, but indicate that off-site controls may be required to prevent discharge or a national pollutant discharge elimination system (NPDES) permit may be required for a discharge to surface water.

In California, the *Irrigation with reclaimed municipal wastewater – a guidance manual* (CSWRCB 1984) provides an approach that emphasises the management required to successfully use water of a certain quality, with management controls becoming more critical with increased nutrient levels. With regard to total nitrogen, no special management practices are required for irrigation water having a concentration less than 5 mg/L. The degree of restriction on use is slight to moderate for total nitrogen concentrations between 5 mg/L and 30 mg/L. The restriction on use for total nitrogen concentrations above 30 mg/L is considered severe which means that there may be a restriction on crop choice and special management practices are required to allow successful production (CSWRCB 1984).

With regard to phosphorus, no guideline value is given. However, evaluation of water quality and soil testing for fertiliser planning is recommended. Chapter 12 of the guidelines provides a discussion on the fate of nitrogen and phosphorus applied to soil (CSWRCB 1984).

Israeli guidelines

The Israeli Ministry of the Environment proposes the following maximum levels for nutrients in effluents used for unrestricted irrigation: 20 mg/L for total nitrogen and 5 mg/L for total phosphorus (IME, 2003).

Managing salinity and sodicity

Salinity and sodicity management is often critical for reclaimed water irrigation schemes. Defining an appropriate criteria for the salinity and sodicity of water for irrigation use depends on several factors specific to an irrigation scheme including: water quality, soil properties, plant salt tolerance, climate, landscape (including geological and hydrogeological features) and irrigation management practices. Since the effects of salinity and sodicity are situation-specific, prescriptive water quality criteria are not specified in guidance documents. However, some indicative water quality values are provided.

Sodicity is the presence of a high proportion of sodium ions relative to calcium and magnesium ions in soil or water. This can affect the integrity of the soil structure by making the soil more dispersible and erodible, reducing water infiltration and hydraulic conductivity of the soil, and limiting drainage. This may lead to water logging or build up of salinity (see *Chapters 6 and 7*).

Salinity effects result from accumulation of applied salt and from the mobilisation of existing salt (from subsoils and/or groundwater) as a result of irrigation. The potential impacts of salinity (see *Chapters 7 and 9* for more detail) caused by applied salt include:

- loss in crop productivity due to increases in osmotic pressure and hence reduced ability of the crop to extract water and nutrients;
- direct toxicity due to specific ions (ie chloride, sodium and boron);
- foliar damage; and
- migration to groundwater and surface water systems.

All guidance documents recognise the significance of salinity and sodicity management and there are significant similarities within the Australian and international guideline approaches.

Managing salinity and sodicity in Australia

Most States require an assessment of salinity and sodicity, adopting the recommended guidance provided in the *Australian and New Zealand guidelines for fresh and marine water quality* (ANZECC and ARMCANZ, 2000) or the earlier 1992 guidance document (depending on when the State documents were developed).

The discussion below relates to the process identified in national guidelines to evaluate salinity and sodicity impacts.

In summary, the process entails:

- identifying water quality (including salinity and sodium absorption ratio), soil properties (including clay percentage, cation exchange capacity, exchangeable sodium percentage), climatic conditions and management practices;
- estimating the leaching fraction;
- estimating the average root zone salinity;
- estimating the relative plant yield (taking into consideration crop salt tolerance and management

practices such as application methods, amelioration techniques, variable quality of water supply); and
- consideration of catchment issues such as regional watertables, groundwater pollution and surface water quality.

Salinity assessment

In evaluating salinity impacts of irrigation water quality, ANZECC (1992) focused on providing salinity classes based on Total Dissolved Solids (TDS) and used conversion factors to convert electrical conductivity (EC) to TDS. In contrast, the current national guidelines recommends that only directly analysed electrical conductivity data is used in the assessment of salinity because of the range of relationships between EC and TDS.

The current national guideline provides a water salinity rating for irrigation waters (refer to Table 2.5) that is solely based on electrical conductivity of the irrigation water. However, the guidelines state that these salinity ratings are a general guide only and are not intended to be used on their own to define the suitability of irrigation water.

Table 2.5 Irrigation water salinity ratings based on electrical conductivity.

EC (dS/m)	Water salinity rating	Plant suitability
<0.65	Very low	Sensitive crops
0.65–1.3	Low	Moderately sensitive crops
1.3–2.9	Medium	Moderately tolerant crops
2.9–5.2	High	Tolerant crops
5.2–8.1	Very High	Very tolerant crops
>8.1	Extreme	Generally too saline

Table 9.2.5 from ANZECC and ARMCANZ 2000, adapted from Department of Natural Resources.

Recognising the importance of considering other factors in evaluating the salinity impacts of irrigation water (such as soil characteristics, climate, plant species and irrigation management), the national guidelines provide a risk based framework, detailing the process for predicting the average root zone salinity, which is a more accurate measurement of salinity risk. This process is summarised below.

In determining the suitability of irrigation water salinity for a crop, the following equation (Eqn 2.3) (equation 4.1 from the *Australian and New Zealand guidelines for fresh and marine water quality 2000*) is provided to calculate the average root zone salinity (EC_e) (soil saturation extract) from the EC of irrigation water (EC_{iw}) and the average root zone leaching fraction (LF).

$$EC_e = \frac{EC_{iw}}{2.2 \times LF} \quad \textit{(Eqn 2.3)}$$

The EC_e is defined as the EC of the soil saturation extract and according to the guidelines has been used to relate plant response to soil salinity across a wide range of soil textures.

The leaching fraction (LF) is the proportion of applied water (irrigation and rainfall) that drains below the root zone in the soil profile, expressed as a percentage. The average root zone leaching fraction is provided for the various soil types: sand, 0.6; loam, 0.33; light clay, 0.33; and heavy clay, 0.2. These leaching fractions are indicative only and the national guideline presents several approaches to predicting the leaching fraction of soils.

The predicted average root zone salinity, EC_e, can be compared to the soil and water salinity criteria provided in Table 4.2.4 of the guideline describing plant salt tolerance groupings, or the list of the relative salt tolerances of a limited selection of common field crop, pasture and horticulture species (ANZECC and ARMCANZ 2000) (see also *Chapter 9*).

Sodicity assessment

To determine the risk of soil structure degradation caused by irrigation water quality, the following equation (Eqn 2.4) is provided in the national guideline to calculate the SAR (equation 4.2 from the *Australian and New Zealand guidelines for fresh and marine water quality 2000*). Units for SAR are $(\text{mmol}_c/\text{L})^{0.5}$.

$$SAR = \frac{Na+}{\sqrt{\dfrac{Ca^{2+} + Mg^{2+}}{2}}} \quad \textit{(Eqn 2.4)}$$

where concentrations of cations are expressed in meq/L. To convert from mg/L to meq/L: for sodium, Na (mg/L)/23; for calcium, Ca (mg/L)/20; and magnesium, Mg (mg/L)/12.2. An equation (Eqn 2.5) that combines these conversions factors is given below (concentrations of cations are expressed in mg/L):

$$SAR = \frac{\frac{Na}{23}}{\sqrt{\frac{\frac{Ca}{20}+\frac{Mg}{12.2}}{2}}} \qquad (Eqn\ 2.5)$$

The guideline figure 4.2.2 depicts the relationship between SAR and EC of irrigation water for prediction of soil structural stability.

The sodicity of the soil can be measured by the following methods:

- exchangeable sodium percentage (ESP), being the proportion of sodium absorbed onto the clay mineral surfaces as a proportion of the total cation exchange capacity (CEC, the ability of soil particles to adsorb cations); and
- sodium adsorption ratio (SAR), being the relative concentration of sodium to calcium and magnesium in the soil solution.

A guide to permissible SAR of irrigation water for maintaining a stable soil surface under high rainfall conditions according to clay mineralogy and clay content or soil texture is provided in Table 9.2.6 of the guideline (see *Chapter 7* for details on sodicity).

Major ions of concern for irrigation water quality

The *Australian and New Zealand guidelines for fresh and marine water quality 2000* note that elevated levels of bicarbonate in the irrigation water can affect crop foliage through white scale formation caused by the precipitation of calcium carbonate. The precipitation of calcium carbonate increases the SAR or ESP. However, no trigger value is provided for bicarbonates in irrigation waters.

Elevated chloride levels can cause foliar injury to crops (see *Chapter 9*) and cause increase uptake by plants of the heavy metal, cadmium, from soil (see *Chapter 8*). Therefore the guideline provides trigger values for the prevention of foliar injury due to chloride in irrigation water from sprinkler application and trigger values for assessing chloride levels in irrigation water with respect to increased cadmium uptake by crops.

High levels of sodium in irrigation water can affect plant growth by causing leaf burn (following sprinkler application), soil structural problems, and calcium and magnesium deficiency. The guideline provides trigger values for sodium concentration causing foliar damage and toxicity effects (ANZECC and ARMCANZ 2000).

Managing salinity and sodicity from an international perspective

United States and Californian guidelines

The *Guidelines for water reuse* (US EPA 2004) identifies salinity as the most important parameter in determining the suitability of any water for irrigation. The process for assessing and managing salinity and sodicity effects is similar to the approach identified in ANZECC and ARMCANZ (2000). However, although the assessment process adopts EC, the recommended limits for salinity in the US EPA guideline are expressed as TDS with a conversion factor provided.

The US EPA (2004) recommended limit is 500 mg/L to 2000 mg/L in reclaimed water. The guideline notes below 500 mg/L TDS no detrimental effects are usually noticed, while between 500 mg/L and 1000 mg/L TDS, irrigation water can affect sensitive plants. At 1000 mg/L to 2000 mg/L, TDS levels can affect many crops and careful management practices should be implemented. For above 2000 mg/L TDS, the guideline recommends use only on tolerant plants grown in permeable soils.

The Californian guidance, *Irrigation with reclaimed municipal wastewater – a guidance manual* (CSWRCB 1984), provides water quality criteria for salinity and sodicity based on a wide range of Californian soil conditions. These are comparable to the *Australian and New Zealand guidelines for fresh and marine water quality 2000* and the US EPA guideline. Table 2.6 summarises the guidance provided.

Israeli guidelines

To reduce salinity in wastewater, the Israeli Ministry of the Environment has developed a series of regulations, including prohibition of the discharge of brines from

Table 2.6 Salinity and sodicity criteria for irrigation.

Potential irrigation problem	Degree of restriction on use		
	None	Slight to moderate	Severe
Salinity	None	Moderate	Severe
EC_{iw}[A] (dS/m)	<0.7	0.7–3.0	>3.0
TDS (mg/L)	<450	450–2000	>2000
Sodicity (SAR)	EC_{iw}	EC_{iw}	EC_{iw}
0–3	>0.7	0.7–0.2	<0.2
3–6	>1.2	1.2–0.3	<0.3
6–12	>1.9	1.9–0.5	<0.5
12–20	>2.9	2.9–1.3	<1.3
20–40	>5.0	5.0–2.9	<2.9

[A] EC_{iw} = electrical conductivity of irrigation water.
Adopted from *CSWRCB*.

ion-exchange renewal, from food, tanning and textile industries, and from hospitals, to the municipal sewage system.

The Israeli Ministry of the Environment published Israeli standard (IS 438) on environmental and labelling requirements for washing powders aimed to reduce the boron, sodium and chloride content of detergents (Israeli Ministry of the Environment 2000b).

The proposed new Israeli standards for treatment of sewage effluent for unrestricted irrigation specify the following maximum levels criteria for salinity and sodicity:

- EC 1.4 dS/m
- SAR 5
- chloride 250 mg/L
- sodium 150 mg/L

(IME, 2003)

Metal contaminants

There are significant similarities within Australian and international guideline approaches to the management of contaminants. The guidance has a similar structure, with prescribed concentration limits (or trigger values) for individual contaminants in reclaimed water. The contaminants listed in the guidance are heavily focussed on metals and the concentration limits have some remarkable similarities, considering when the different guidelines were established and the typical differences between regulatory approaches and philosophies. However, there are also differences in approaches, with some jurisdictions listing different limits to distinguish between short-term and long-term irrigation practices and/or establishing soil limits or loading limits in addition to the water concentration limits.

Managing metal contaminants in Australia

In Australia, the *Australian and New Zealand guidelines for fresh and marine waters* (ANZECC and ARMCANZ, 2000) is recognised as the most authoritative guideline for contaminant management in primary production irrigation. The guideline establishes three limits for inorganic contaminants (Table 2.7):

1. soil cumulative loading limit – a loading limit (kg/ha) which, when exceeded on a cumulative basis, should trigger a site-specific risk assessment and associated soil analysis;
2. long-term trigger value – the maximum concentration of contaminant that is acceptable in the irrigation water – this value was established assuming annual irrigation of 1000 mm/yr for 100 years and that the contaminants are retained in the upper 150 mm of soil with a bulk density of 1300 kg/m^3; and
3. short-term trigger value – the maximum concentration of contaminant that is acceptable in the irrigation based on 20 year irrigation with the assumptions otherwise the same for the long-term trigger value.

More detailed discussion on the theory of these trigger level values is presented later (see *Chapter 8*).

The guideline replaced ANZECC (1992) as Australia's national guideline for irrigation water quality. The State guidelines for reclaimed water borrow heavily from these documents and therefore the criteria in State documents primarily reflect when the State documents were prepared. As examples, the South Australian guidance references contaminant limit values from ANZECC (1992), whereas the more recent Tasmanian guidance (2002) is derived from the current guideline (ANZECC and ARMCANZ 2000).

The current metal water quality requirements in Victoria (EPA 1991) were not adopted directly from the ANZECC criteria, but nevertheless are very similar. However, the Victorian requirements include maximum cumulative loadings for key contaminants such as cadmium, copper and zinc, with the loading limits based on the soil cation exchange capacity.

For comparative purposes, the national guideline provisions, Victorian and South Australian guidance is provided in Table 2.7. Limits for stock drinking water in the national guideline are described in Table 2.8.

Managing metal contaminants from an international perspective

The United States reclaimed water guidance (US EPA 2004) includes limit values for both short-term and long-term irrigation with reclaimed water (Table 2.7). The detailed derivation of the values are not described. However, the guidance does note that the maximum concentrations for long-term use are set conservatively. The Californian limit values are very similar to the US EPA guidance; however, several short-term use trigger values are more relaxed.

Canada has recently updated irrigation guidelines for contaminants and therefore the guidance is also included in Table 2.8. The guidance includes limits for inorganic and organic contaminants and for irrigation water and livestock water (CCME 2003).

Table 2.7 Summary of reclaimed water microbial quality requirements for use in horticulture.

Element	ANZECC and ARMCANZ (2000)			Victoria (EPA Vic 1991)	South Aust. (SA DHS and SA EPA 1999)	US EPA (2004)		Canada (CCME 2003)	Israel (IME 2003)
	Cumulative loading limit (kg/ha)	Long-term trigger value (mg/L)	Short-term trigger value (mg/L)	Maximum concentration (mg/L)	(mg/L)	Long-term use (mg/L)	Short-term use (mg/L)	Irrigation water (mg/L)	Threshold (mg/L)
Aluminium	—	5	20	5	5	5.0	20	5	5
Arsenic	20	0.1	2.0	0.1	0.1	0.10	2.0	0.1	0.1
Boron	—	0.5	Table 9.8	0.75	—	0.75	2.0	0.5–6 Depending on crop	0.4
Cadmium	2	0.01	0.05	0.01	0.01	0.01	0.05	0.005	0.01
Chromium	—	0.1	1	0.1	1.0	0.1	1.0	(CR III) 0.0049	0.1
Cobalt	—	0.05	0.1	0.05	0.05	0.05	5.0	0.05	0.05
Copper	140	0.2	5	0.2	0.20	0.2	5.0	0.2–1	0.2
Flouride	—	1	2	1	1.0	1.0	15.0	1	2
Iron	—	0.2	10	0.2	2.0	5.0	20.0	5	2
Lead	260	2	5	5	0.2	5.0	10.0	0.2	0.1
Manganese	—	0.2	10	0.2	2.0	0.2	10.0	0.2	0.2
Mercury	2	0.002	0.002	—	0.002	—	—	—	0.002
Molybdenum	—	0.01	0.05	0.01	0.01	0.01	0.05	0.01–0.05	0.01
Nickel	85	0.2	2	0.2	—	0.2	2.0	0.2	0.2
Selenium	10	0.02	0.05	0.02	0.02	0.02	0.02–0.05	0.02–0.05	0.02
Zinc	300	2	5	2	2.0	10.0	1–5	1–5	2

The guidance for water recycling in Israel includes recommended trigger values for determining whether contaminants may harm fruit and vegetable protection. Exceeding these values should result in testing of produce, controls on discharges to the STP and investigation of the site's capacity for the metals. These trigger values are predominantly referenced from United States sources. However, there are proposals to have stricter limits for key contaminants (Table 2.7).

Managing organic contaminants

The current water recycling guidelines and irrigation management guidelines provide very limited criteria for organic contaminants. As examples, the Tasmanian guidance (DPIWE 2002) does not include specific limits for organic contaminants. However, it notes that if reclaimed water contains more than trace amounts of synthetic organic compounds, then the water is likely to be unsuitable for irrigation. A definition of trace is not provided. The United States recycled water guidance of 2004 does not include discussion or criteria for organic contaminants.

Table 2.8 Summary of the livestock drinking water criteria for metals in the Canadian (CCME 2003) and national Australian guideline.

Parameter	ANZECC and ARMCANZ (2000)	Canada
	Livestock drinking water trigger values (mg/L)	Livestock water (mg/L)
Aluminium	5	5
Arsenic	0.05–5	0.025
Boron	5	5
Cadmium	0.01	0.08
Chromium	1	0.05
Cobalt	1	1
Copper	0.4–5	0.5–5
Fluoride	2	1–2
Iron	—	—
Lead	0.1	0.1
Manganese	—	—
Mercury	0.002	0.003
Molybdenum	0.15	0.5
Nickel	1	1
Selenium	0.02	0.05
Zinc	20	50

Where criteria for organic contaminants in irrigation water are provided, such as in the national Australian and South Australian guidelines, the information is focussed on agricultural chemicals such as herbicides. This contaminant grouping would be expected to be more relevant to water extractions from surface waters in agricultural areas, rather than irrigation with reclaimed waters. The most detailed guidance for organic contaminants in irrigation water is the Canadian guidance of CCME (2003) which includes a range of values, although they are heavily focussed on agricultural pesticides (Table 2.9).

This review could find no regulation or specific water quality criteria focussed on the need to manage organic contaminants in reclaimed water for horticultural uses. However, there is research being undertaken in this area and the issue of organic contaminants has attracted broad interest (see *Chapter 10* for more details). Most regulatory agencies would appear to have ongoing programs to monitor developments and assess whether formal regulation is needed.

Apparent directions in the management of biosolids land application could provide some indications of the organic contaminants that may require particular attention in water recycling. However, in examining the potential implications for water recycling, it needs to be considered that the organic contaminants involved typically partition to the biosolids within treatment processes, rather than entering the reclaimed water streams. As a result, the relative loads of organic contaminants from water recycling may be orders of magnitude lower than the loads expected from biosolids land application.

Table 2.9 Selected organic contaminants referenced in CCME (2003) for agricultural water uses (µg/L).

Parameter	Irrigation water	Livestock water
Aldicarb	54.9	11
Dicamba	0.006	122
Dichloromethane	—	50
Hexachlorocyclohexane (lindane)	—	4
Phenol	—	2
Toluene	—	24

In Australia, limits for organic compounds in biosolids have been long established and have focussed on organochlorine pesticides and polychlorinated biphenyls. Recently, the Victorian EPA established an additional trigger value for compounds with dioxin-like activity (EPA Victoria 2004). In comparison, the US EPA does not regulate any organic contaminants in biosolids, but has been considering establishing a limit for compounds with dioxin-like activity. The United States explored the risks associated with organic contaminants in the large scale so-called Round One (US EPA 1995) and Round Two assessments, completed, respectively, in the early and mid 1990s. Both assessments started with large numbers of candidate chemicals for regulation, but at the completion of the process regulatory intervention was only considered warranted for inorganic contaminants (NRC 2002).

Within Europe, regulatory directions appear to be moving towards specific regulation of organic contaminants, with the redraft of the European Commission directive proposing limits for a range of organic contaminants (Table 2.10) (EU 2001). These limits are contained within a working paper that has not yet had broad consultation within EC member states. Therefore, the proposed limits and regulated compounds could be presented significantly differently in the final directive.

Table 2.10 Limit values for organic contaminants proposed in early drafts of the EC directive for sewage sludge land application.

Contaminant	Limit values (mg/kg DM)
Sum of halogenated organic compounds	500
Linear alkylbenzene sulfonates	2600
Di-(2-ethylhexyl)phthalate	100
Nonyl phenoyl and ethoxylates with 1 or 2 ethoxy groups	50
Polycyclic aromatic hydrocarbons (sum of 9 compounds)	6
Polychlorinated biphenyls	0.8
	(ng TE/kg DM)
Polychlorinated dibenzodioxins/ dibenzofurans	100

Source: EU (2001).
TE, toxic equivalent; DM, dry matter.

Summary

When the Australian and international regulatory approaches are reviewed, it becomes apparent that while there are similarities, there are also important differences in the approaches taken, even among the individual states of Australia. The key aspects of these regulatory approaches and the similarities and differences are:

- Regulatory frameworks.
  All Australian States and countries considered in this chapter have guidance documents for managing potential food safety, health and environmental issues with the use of reclaimed water. Differences in approaches to the regulatory framework become evident with regard to the level of involvement of regulatory agencies, ranging from a system whereby reclaimed water users consider guidance but do not require specific 'approvals', through to a system whereby each user has 'a permit' from a regulatory agency coupled to monitoring, inspection and audit systems.
- Management of microorganisms and produce quality.
  All guidance documents utilise a multi-tiered system for classification of reclaimed water microbiological quality, with the highest grade required for direct irrigation of crops that may be consumed raw. Lower grades of reclaimed water can be utilised for crops such as those consumed after a cooking step, or where management controls such as separation of edible food components is undertaken. The most significant difference among the guidance documents is with regard to the stringency of the water quality criteria and the structure of the criteria. At the lower end of the scale for stringency, the World Health Organization guidance enables reclaimed water from commonly available lagoon technology to be used on raw food crops. At the other end of the scale, the Californian and Australian criteria are focussed on advanced treatment processes such as filtration and chlorine disinfection, coupled with relatively stringent criteria. The structure of the guidance also varies, with the Californian criteria heavily focussed on the use of verified technologies for delivering reclaimed water, while some Australian States place a greater emphasis on establishing microbiological water quality objectives and enabling flexibility in the technologies that can be used.
- Management of nutrients, salinity and sodicity.
  The guidance documents describe the potential effects of nutrients, salinity and sodicity; however, they are not prescriptive on water quality criteria. Recognising that the potential effects of nutrients, salinity and sodicity are largely dependent on factors such as crop type, irrigation practices, soil characteristics and climatic conditions, the guidance generally adopts a site-specific risk-based approach. However, some guidance documents do specify upper limits for water quality parameters.
- Management of metal and organic contaminants.
  There are important similarities within Australian and international guideline approaches to the management of contaminants in reclaimed water or irrigation water. The guidance has a similar structure, with prescribed concentration limits (or

trigger values) for individual contaminants in reclaimed water. The contaminants listed in the guidance are heavily focussed on metals and provide very limited criteria for organic contaminants.

The guidelines found in Australia today for the use of reclaimed water can be seen to be comprehensive and relatively stringent when benchmarked internationally. However, in order to maintain Australia's standing as a world leader in the sustainable use of reclaimed water, there will need to be ongoing research and reviews of the guidelines against advances in scientific knowledge.

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3 Wastewater reclamation processes

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Sewage has been applied to sewage farms for many decades in several countries (eg Germany, UK, USA, France, Australia, Israel, India and Mexico) for irrigation of food crops (Angelakis and Sprydakis 1995; Asano and Levine 1998). In Australia, early reuse of sewage for agricultural irrigation began in 1881 with the application of sewage to a 190 ha sewage farm near Islington in South Australia (Hammerton 1986), followed by well-known sewage farms at Werribee, Victoria, in 1897 (Westcot 1997). The key driving force behind these sewage farms was the protection of the downstream water users from diseases by minimising pollution of the receiving waterbodies. Although application of sewage on land is in itself a form of treatment, it is no longer acceptable to use untreated sewage for agricultural irrigation due to substantial public health and environmental concerns about the safety of food products and the sustainability of agricultural lands. Consequently, stringent standards in many countries have phased out sewage farms and have enforced the treatment of sewage before any reuse can occur (NRC 1996).

Wastewater reclamation refers to the treatment of wastewater (ie sewage) for beneficial uses such as agricultural irrigation, in order to reduce potential health risks and damage to crops and soils, and to prevent nuisance conditions during storage (Asano *et al* 1985). The treated wastewater is commonly referred to as reclaimed or recycled water. The degree of treatment depends upon many factors, including the quality of sewage, required quality of reclaimed water for a particular end use, soil characteristics, crop irrigated, type of distribution and application systems, the degree of human exposure and available funds.

The objective of this chapter is to provide an overview of wastewater treatment processes which have been used successfully for reclaiming wastewater for agricultural irrigation. The term 'wastewater' has been used in this chapter to primarily define sewage. Although this chapter focuses on the treatment of sewage (being the major source of wastewater), many of the treatment processes discussed here could also be used or modified for any source of wastewater.

Wastewater composition and characteristics

Wastewater is the water available after its use from mainly domestic and commercial establishments, although it may also contain industrial discharges and stormwater. It typically consists of 99.9% water and 0.1% of impurities including dissolved and suspended organics, pathogens, nutrients, trace elements, pesticides and heavy metals. The percentage of each of these constituents is varied and dependent on the strength of the wastewater. Wastewater can be classified as high, medium and low strength, with most municipal wastewaters falling into the medium strength category. The typical constituent values for medium strength wastewater for Australian conditions are shown in Table 3.1. The actual flow and concentrations depend on the nature of the water uses (eg domestic or industrial) and thus the values included in this table should be used as a guide only.

Wastewater generation rates in a community typically range from 170 L/d to 260 L/d per capita (Lpcd – Litres per capita day). However, there are seasonal and diurnal variations in the quantity and quality of wastewater flows within a community. For planning purposes, average dry

Table 3.1 Typical composition of untreated wastewater.

Parameter	Units	Range of values	Typical values
pH	—	6.5–8.5	7.5–8.5
Biochemical oxygen demand (BOD)	mg/L	230–450	250
Suspended solids (SS)	mg/L	220–400	300
Total dissolved solids (TDS)[A]	mg/L	500–1500	750
Total nitrogen (TN)	mg/L	35–75	65
Total phosphorus (TP)	mg/L	10–30	12
Microorganisms Escherichia coliforms (*E. coli*)	No./100 mL	10^4–10^9	10^8
Cryptosporidium[B]	No./L	$0.85 \times 10^3 - 1.4 \times 10^4$	—
Giardia[B]	No./L	0.8×10^3–3.2×10^3	—
Virus[B]	No./L	5–10^5	—

[A] TDS as a measure of salinity and note that TDS value can be much higher (eg 22 000 mg/L has been measured at the Port Pirie wastewater treatment plant in South Australia).
[B] Table 14.1, pp. 14-6, WEF, Vol. 2 (1998).

weather flows of 170 Lpcd for smaller rural communities and 230 Lpcd for larger metropolitan communities are often used in Australia.

Need for treatment of wastewater

Wastewaters have the potential to cause odours, health impacts and damage to soil, crops, surface water and groundwater (Table 3.2).

Table 3.2 Constituents of concern in wastewater for agricultural irrigation.

Constituents	Reason for concern
Solids – suspended, colloidal and particulate organic solids	Shield microbes from disinfection. Clogging of irrigation systems. Organic contaminants and heavy metals are adsorbed on particulates. Impart turbidity and colour to wastewater and affects the aesthetic quality.
Dissolved inorganic elements – chloride sulfate, sodium, boron, calcium, magnesium	Chloride, sodium (sodicity, salinity) and boron are toxic to plants and determine the suitability of wastewater for agricultural reuse. Increases hardness leading to scaling and corrosion of irrigation equipment. Imparts colour to wastewater and affects aesthetic quality/public perceptions.
Nutrients – nitrogen, phosphorus, potassium	Stimulates algal/aquatic growth which may adversely affect distribution and irrigation systems. Can cause adverse impact on crops if applied at inappropriate time. When applied at levels greater than crop uptake can potentially affect ground and surface water quality.
Dissolved organics – total organic carbon, stable organics (eg pesticides, chlorinated hydrocarbons, surfactants, refractory organics, pharmaceutical products)	Adversely affect disinfection process. Deplete oxygen and lead to odour. Can be carcinogenic and cause endocrine disruption. Resist conventional methods of treatment, may be toxic to plants and consumers and the presence of stable organics may limit suitability for irrigation.
Heavy metals/trace elements such as cadmium, zinc, nickel, mercury and chromium	Can accumulate in plants, surface and groundwaters and eventually enter the food chain. May be toxic to plants and animals.
Pathogens – bacteria (*E. coli*, *Salmonella*, *Shigella*, *Vibrio cholera*) Protozoa (*Cryptosporidium parvum*, *E. hystolytica*, *Giardia lamblia*). Helminths (*Ascaris lumbricoides*, *Taenia spp*.). Viruses (*Hepatitis A*, Entero viruses).	Human exposure to pathogens in wastewaters may cause various types of diseases including gastroenteritis, typhoid and dysentery (see *Table 12.1*) depending on the type of pathogen, exposure and immune levels of the person exposed. Helminths in reclaimed water applied to pasture may be transmitted via meat products to humans.

Source: US EPA (1992); Asano and Levine (1998); Metcalf and Eddy (2003), table 11.1, pp. 1039); Rowe and Abdel-Magid (1995).

The concentration of contaminants in reclaimed water determines its suitability for agricultural reuse (see *Chapters 5 to 10* for the major factors that need to be considered). In many cases the treatment process can be manipulated to ensure the concentration of contaminants in reclaimed water are suitable for a particular sustainable irrigation application (see *Chapter 2*). Since the focus of this book is on agricultural reuse, the following discussions are based on the use of reclaimed water for agricultural purposes.

Reclaimed water guidelines

Guidelines for reclaimed water irrigation are well-established worldwide and are principally aimed at reducing pathogens, toxicants, nutrients and salts to acceptable levels. The guideline values are set with consideration of the method of application, degree of public access during irrigation, crop type and local environmental factors. One of the first regulations for reuse of wastewater for irrigation purposes was formulated in 1914 in California, USA. This guideline has undergone several revisions since then and is now commonly referred to as 'Title 22' (see Metcalf and Eddy 2003, table 13.9, pp. 1362). Other agencies such as United States Environmental Protection Agency (US EPA), World Health Organization (WHO) and countries including Australia, Israel, France and various States of the United States of America (USA) have subsequently issued regulations to ensure the protection of public health and the environment when implementing wastewater reuse schemes (see *Chapter 2*).

In Australia, a national guideline for reclaimed water use was released in 2000 (NWQM 2000) and State guidelines also exist in all States except the Northern Territory and Western Australia (see *Chapter 2*). All of these guidelines outline the required level of treatment and minimum reclaimed water quality to be met, the method of application, recommendations on the buffer distances to areas of public access and monitoring requirements to ensure the reliability and sustainability of the reuse schemes. The level of treatment is normally specified in terms of primary, secondary and tertiary treatment (see *Wastewater reclamation processes*). These guidelines also specify the reclaimed water quality requirement for different classes of irrigation and outline limits for various contaminants such as biological oxygen demand (BOD), suspended solids (SS), turbidity and pathogens in terms of annual mean, median or 90th percentile values. Limits for nitrogen and phosphorus are normally determined based on site-specific conditions.

These guidelines also classify reclaimed water into different categories (Class A, B, C and D) reflecting their quality and therefore the degree of restrictions placed on their end use. To illustrate this, Table 3.3 shows the different classes of reclaimed water included in South Australian reclaimed water guidelines.

As seen in Table 3.3, Class A is the most stringent of all classes, requiring turbidity levels as low as 2 NTU. Class A quality water is used for growing food crops (consumed raw) for human consumption and essentially must be free of all types of pathogens including viruses and protozoa (*Cryptosporidium and Giardia*), typically <1/50 L, and helminths <1/L (EPA Victoria 2002). Class D is the least stringent of all of the classes and is mainly focussed on dedicated restricted reuse application (see *Chapter 2*).

Table 3.3 Classes of reclaimed water and irrigation water quality requirement.

		Irrigation water quality requirement [A,B]			
Parameter	**Units**	**Class A[C]**	**Class B**	**Class C**	**Class D**
BOD	mg/L	<20	<20	<20	—
SS	mg/L	—	<30	<30	—
E. coli	No./100 mL	<10	<100	<1000	<10 000
Turbidity	NTU[D]	≤2	—	—	—
Typical agricultural application		Human food crops consumed raw	Pastures for dairy cattle grazing	Processed food crops /grazing/ fodder for livestock	Non-food crops including turfs and flowers

Source: DHS and EPA SA (1999).
[A] All values in the above table are mean values except *Escherichia coli* (median values); [B] this table shows the minimum requirement for each class (eg *E. coli* must be less than 10 to meet Class A criteria); [C] specific removal of viruses, protozoa and helminths may be required for Class A, B and C, while helminths need to be considered for pasture and fodder irrigation for Class D. For all the classes chemical contents should match the use; [D] nephelometric turbidity unit (NTU).

Wastewater reclamation processes

Reclamation of wastewater is a process where the concentrations of dissolved and suspended inorganic and organic chemicals, nutrients (such as N and P) and pathogens are decreased by combinations of physical, chemical and biological action via a range of preliminary, primary, secondary and tertiary treatment processes (Figure 3.1) Many of these processes have been used extensively since the late 1970s to overcome socio-technical and economic barriers in reuse schemes (Asano and Levine 1996). Note that a number of novel and innovative proprietary treatment processes, which combine one or more types of treatment process, have been developed for improved removal efficiency and cost effectiveness. For instance, many wastewater treatment plants (WWTPs) built in the last decade or so incorporate nitrogen and sometimes phosphorus removal within activated sludge (secondary process) treatment with no tertiary treatment step.

An overview of the different types of treatment processes is provided in the following sections. More detailed information can be found in Williams (1982); Martin and Martin (1991); US EPA (1992); WEF (1998); Qasim (1999) and Metcalf and Eddy (2003).

Preliminary processes

Preliminary processes are the simplest form of treatment in any reclamation plant. They include screening, grit removal and sometimes prechlorination or preaeration. The main functions of these processes are to protect the downstream process equipment from abrasion and abnormal wear and tear by removing large floating and suspended solids from wastewater and to control odour. Step, bar and rotary screens may be used for screening, while grit removal can be achieved via horizontal flow, aerated or vortex-type grit removal systems (Metcalf and Eddy 2003, pp. 385). Fixed or rotary fine screens are also being used after or in place of primary sedimentation (WEF 1998, Vol. 2, pp. 10–53). The debris such as plastics, rags and leaves retained on the screen are termed as screenings. Screenings and grit are normally disposed of in landfill along with municipal solid wastes, although they may be buried onsite in the case of small treatment plants (Metcalf and Eddy 2003, pp. 330). Mechanised washing of screenings is becoming increasingly common in order to minimise odour and the faecal content prior to disposal.

Primary processes

Primary treatment is based on physical and/or chemical processes for sedimentation of suspended solids in either circular or rectangular tanks referred to as primary sedimentation tanks or primary clarifiers. Primary treatment may not always be carried out in smaller treatment plants as it is not considered economical for small plants. Furthermore, primary treatment also decreases readily biodegradable carbon for the biological nutrient removal in downstream activated sludge processes. Hence, preliminary treatment is often followed by secondary treatment using lagoons or activated sludge.

In order to enhance the sedimentation process and increase removal of phosphorus, chemicals such as alum, ferrous and ferric chlorides have been used. A significant portion of influent heavy metals may be adsorbed onto these primary settled solids. The primary treatment removes the organic and inorganic solids that can be settled (about 50% SS, 30% BOD, 15% organic nitrogen, 10% total phosphorus, TP) including about 50% to 90% of parasitic eggs and 25% of bacteria (which may be attached to settleable matter), but they do not remove colloidal and dissolved constituents (Asano and Levine 1998). Often the primary treated effluent has a BOD of >100 mg/L and SS> 85 mg/L, and hence primary treated wastewater is seldom approved for reuse. However, in countries where infrastructure for further treatment is not available, untreated or primary treated wastewater has been used for agricultural irrigation, exposing workers and consumers to greater risk (WHO 1989). In contrast, most States in Australia require at least secondary treatment for agricultural reuse.

Secondary processes

Secondary processes employ aerobic and anaerobic microorganisms to remove dissolved and colloidal organic matter by biological uptake, oxidation and sedimentation of pollutants in microbial mass. The microbial biomass can be either suspended, as in activated sludge processing, or attached to a medium, as in trickling filters and rotating biological contactors. The most commonly used biological processes are waste stabilisation lagoons (ie ponds), wetlands, trickling filter and activated sludge and these are described below.

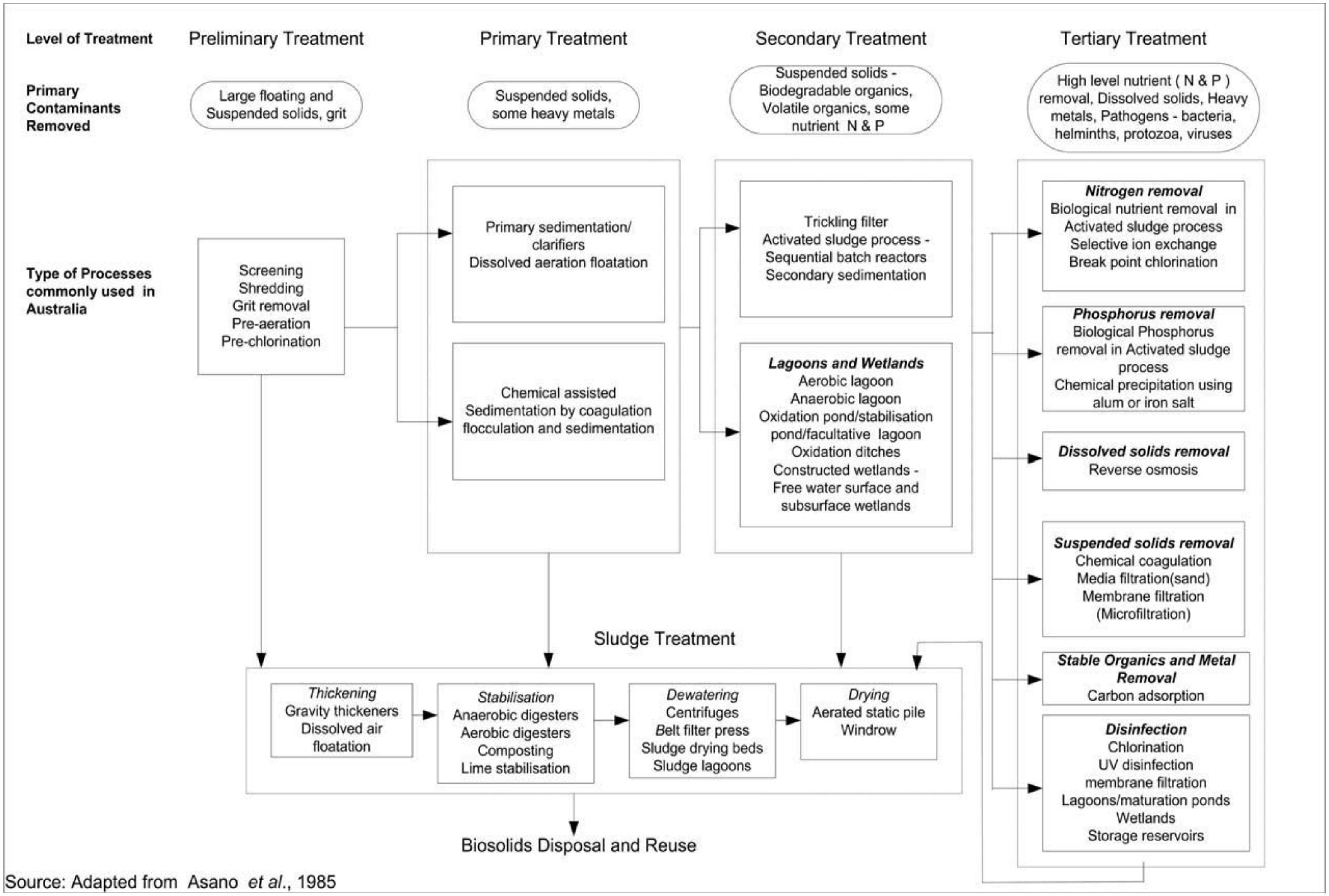

Figure 3.1 Flow sheet of commonly used wastewater reclamation processes.

Lagoons and wetlands

Lagoons and wetlands are often considered as an alternative to activated sludge or trickling filter processes as they can preserve open spaces and enhance wildlife habitat in addition to treating wastewater by oxidation, sedimentation and predation. These processes are regarded as an environmentally friendly alternative to energy intensive processes and are often preferred to conventional processes in most rural WWTPs as they can be low cost and simple to operate and maintain. However, these processes require relatively large land area compared to activated sludge or trickling filter processes, and have the potential for odour generation and risk of groundwater contamination and algal growth. Lagoons alone are not considered to be a reliable process for the removal of nutrients. Nevertheless, these drawbacks can sometimes be minimised by proper design and operational procedures.

The treatment in lagoons and wetlands is brought about by a range of microscopic and macroscopic flora and fauna. The oxygen produced by microscopic plants (phytoplanktons), through photosynthesis, is utilised for oxidation (thereby supplying the BOD). However, additional aeration may be provided mechanically as in aerated lagoons. The treatment of wastewater through a series of lagoons is common in many rural WWTPs and can achieve Class C irrigation quality water or higher depending on the operational conditions. The series of lagoons may consist of one or more types of lagoon including aerobic, anaerobic, facultative and oxidation ponds as listed in Figure 3.1. The detention time in each lagoon varies from 5 days to over 60 days depending on the type of lagoon, desired treatment objective, influent flow and loading conditions (Reed *et al* 1995).

Detention in a multiple lagoon system (after primary treatment) for 20 d to 25 d should provide Class C effluent (ie 1000 *Escherichia coli*/100 mL) (note that more than 60 days would be required in cooler climates) in addition to removing helminth eggs. Short-circuiting must be prevented in the lagoons to ensure a consistent quality of effluent. Usually SS in the lagoon effluent can rise to greater than 100 mg/L due to algal solids. Rock or coarse sand filters are often used at the lagoon outlet to improve the quality of reclaimed water and reduce clogging of irrigation equipment (DHS and EPA SA 1999).

Deep anaerobic lagoons have become an established technology for treating high strength biodegradable wastes produced by the food industry in rural environments. Good examples of these are provided in the bulk volume fermenter at Warnambool and the high rate anaerobic lagoons at Ballarat, Tatura, Mooroopna and Shepparton, all in Victoria. In addition, modified lagoon systems such as a Pond Enhanced TReatment and Operation (PETRO) and an Advanced Integrated Wastewater Pond System (AIWPS) have been developed to overcome algal problems in lagoon effluent and to increase nutrient removal. A good example of lagoon modification on a large scale is at the Western Treatment Plant owned by Melbourne Water.

Constructed wetlands are capable of removing pollutants such as SS, BOD, nutrients, pathogens, heavy metals and other toxic pollutants by physical (settling), chemical (oxidation) and biological (micro and macro fauna and flora) processes (Crites and Tchobanoglous 1998). Wetlands are becoming popular in Australia because of their advantages over other conventional processes in terms of lower operating cost and greater intangible benefits (Mitchell *et al* 1998). The two main types of wetlands include free water surface and subsurface wetlands. Free water surface wetlands are suitable for polishing secondary and tertiary effluent and for habitat development. Although subsurface wetlands, also known as rock reed filters or vegetated submerged beds, are appropriate for treating primary wastewater, they are more expensive to build and operate. Both these wetland types can be designed for either BOD removal alone or BOD and nutrient removal and the latter will, however, be much larger. Design details for Australian conditions can be found in Mitchell *et al* (1998).

Trickling filters

Trickling filters, also known as biological filters, trickle primary settled wastewater over layers of rocks or plastic media covered with microorganisms. Air is provided by simple natural countercurrent flow through the filter. The microbes use the organic matter present in the wastewater for their growth and reproduction. Microbes are peeled off from the media as they die and are then separated from wastewater in settling tanks. Trickling filters have been used in many wastewater reclamation plants to produce Class B quality water. In recent years activated sludge is being preferred to trickling filters in most reclamation and reuse plants, as activated sludge is capable of achieving lower levels of BOD and SS and can further reduce nutrient levels in the effluent.

Activated sludge

An activated sludge process is a continuous or semicontinuous (fill and draw) aerobic method of treatment where active biomass (referred to as activated sludge) is formed by aeration, followed by separation of treated wastewater from this activated sludge in settling tanks. Most of this activated sludge is recycled back into the system while the remaining is waste and treated by sludge treatment processes (see *Sludge treatment, disposal and reuse*). There are many types of activated sludge such as complete mix activated sludge, conventional extended aeration, intermittent decant extended aeration (IDEA), oxidation ditches, step feed activated sludge and sequencing batch processes as discussed by Metcalf and Eddy (2003, pp. 741–6). Many proprietary package plants are available from companies in Australia such as AMEC, Tenix (ESI) and Triwater (Aeroflo).

Activated sludge was primarily designed to remove BOD. However, they are increasingly being designed for nutrient removal (N and/or P) in addition to BOD and are known as biological nutrient removal processes (see *Tertiary processes*). In warmer climates in Australia, activated sludge inherently removes part of nitrogen and this uncontrolled nitrogen removal is often an operational issue. Phosphorus removal can also be achieved in activated sludge using either chemical precipitation or biological removal, which is often more cost effective for medium to large plants.

Typically, secondary effluent has a BOD of <20 mg/L and SS of <30 mg/L but 10 mg/L BOD and 10 mg/L SS can be achieved by good design and is suitable for Class B or lower class reuse applications. To enhance the effectiveness of SS and BOD removal, membranes are being combined with activated sludge (referred to as membrane bioreactors). The membranes, which may be internal or external to the activated sludge process, filter the effluent resulting in better quality effluent, eliminating the need for settling tanks.

Tertiary processes

Primary and secondary treatment (ie conventional treatment) are not capable of removing coliforms, parasites, dissolved solids, trace organics and heavy metals to levels suitable for sustainable Class A agricultural irrigation. Hence, additional treatment is applied to reduce the remaining contaminants by physical, chemical and biological methods to minimise health risks to consumers and workers and to reduce damage to soils and crops. There are several tertiary treatment processes available to remove specific contaminants (Table 3.4, and sections following). These processes, except for those which are activated sludge based, are similar to drinking water treatment processes as they consist of filtration, chemical coagulation, sedimentation and disinfection.

Table 3.4 Types of tertiary treatment processes.

Contaminant to be removed	Tertiary treatment process employed
Nitrogen	Nitrification/denitrification within activated sludge process; selective ion exchange; break point chlorination; air stripping
Phosphorus	Chemical precipitation; biological phosphorus removal within activated sludge process
Suspended solids	Chemical coagulation (alum, polymers); filtration (single media-activated carbon, sand, anthracite; dual media; membrane filtration)
Dissolved solids	Reverse osmosis; electrodialysis; distillation
Organics and metals	Carbon adsorption; ozonation
Coliforms/viruses[A]	Disinfection – ultraviolet radiation (UV), chlorination, ozonation; membrane filtration
Parasites (Helminth eggs)	Waste stabilisation ponds/ lagoons; wetlands; storage reservoirs, media filtration and microfiltration

Source: Rowe and Abdel-Magid (1995), Asano *et al* (1985).
[A] Electrodialysis, distillation, ozonation, ion exchange processes are not often used in Australia.

Nitrogen and phosphorus removal

Nutrient removal can be achieved either by biological or chemical means. Nitrogen removal is almost universally carried out using a modified activated sludge process such as sequential batch reactor or a continuous flow biological nutrient removal in many different configurations such as modified Ludzack Ettinger (MLE), Bardenpho, University of Cape Town (UCT) and Phoredox. Biological nutrient removal is a modified activated sludge process aimed at enhancing removal of nutrients in the wastewater. These systems can be designed to remove nitrogen and/or phosphorus by growing suitable microbes in anaerobic, anoxic and aerobic sections of the tanks.

The biological removal of nitrogen involves two steps: nitrification and denitrification. In the first step (nitrification), ammonia (NH_3) is converted to nitrite (NO_2^-) and this in turn to nitrate (NO_3^-) by microbes in an oxygen-rich environment. Once NO_3^- is formed it is then reduced (denitrified) to nitrogen (N_2) gas by a different group of microbes under anoxic (ie absence of dissolved oxygen and presence of nitrate) conditions (see Figure 5.3 for key processes in the nitrogen cycle).

Chemical methods for removal of nitrogen (eg air stripping and ion exchange) are not often used in

Australia as they are expensive to operate. Since 1985, biological nutrient removal has become the usual method for nutrient removal owing to their established performance and one-step treatment approach in many reclamation plants around Australia (Hartley 1995).

The biological removal of phosphorus can be brought about by uptake of different forms of phosphates under alternate anaerobic and aerobic conditions by facultative bacteria utilising readily biodegradable, soluble substrates. Although biological phosphorus removal processes are complex to operate they can be more cost effective than the chemical precipitation method for larger wastewater treatment plants. In smaller plants, precipitation of phosphorus using chemicals such as alum, lime or ferric chloride (which may require pH adjustment) is usually carried out at a lower cost than biological methods. However, this results in an increased sludge production, which has implications for the sludge treatment and handling requirements, and also increases the effluent salinity. Although biological phosphorus removal processes also result in increased sludge production (to a lesser extent than chemical), an added complication is that stabilisation processes must be carefully managed and designed so as not to allow the release of biologically encapsulated phosphorus.

Solids removal

Coagulation, flocculation and sedimentation using alum is commonly used as a pretreatment to enhance performance of media filtration processes. Media filters consisting of sand and/or anthracite coal are used to remove the remaining particulate matter in wastewater to significantly reduce turbidity. Sand filters, in conjunction with disinfection, are often used to treat secondary effluent to Class A irrigation quality water. Membrane filtration processes such as microfiltration, ultrafiltration and reverse osmosis are increasingly being used and are sometimes preferred to conventional sand filters in spite of their high capital and operating costs for Class A reuse schemes. This preference is because of a more effective removal of suspended solids (notably algae) and pathogens (including bacteria, protozoan cysts and helminths) with a small 'footprint'. Further, if reverse osmosis is used, removal of dissolved constituents, and natural organic and inorganic matter could also be achieved (Wilf 1998); Metcalf and Eddy 2003). Activated carbon can be used to remove stable organics such as pesticides and heavy metals. However, this is rarely used in reclamation plants in Australia.

Disinfection

Disinfection of wastewater is critical from a public health perspective in any reuse scheme and is usually the final step in wastewater treatment. In Australia, the most commonly used disinfection processes include lagoons, chlorination and UV. A qualitative comparison of these processes can be found in Hamilton (1996). The removal efficiency achieved in these processes is normally reported as log removal. For example, 1 log removal refers to 90% reduction; 2 log to 99%; 3 log to 99.9% removal and so on.

Many of the reclamation plants built in the 1960s to 1980s used maturation ponds or polishing lagoons and sometimes constructed wetlands to reduce pathogens by predation and UV through natural sunlight. Chlorination is also widely used and offers several advantages including low capital costs compared to UV systems. It is also highly robust and reliable and provides disinfectant residual, which is important for reuse schemes. Furthermore, the dosing control and monitoring of chlorine systems are well established. Although use of chlorine has been very popular, it is not favoured in recent times due to the potentially harmful effects of residual disinfection by-products where reclaimed water is discharged to waterbodies. However, dechlorination can be used to reduce impacts on receiving waters.

The UV systems have gained popularity in recent years as they can efficiently destroy bacteria, *Cryptosporidium* and *Giardia* and even viruses (at high UV dose) in less contact time than chlorine and have advantages (eg greater safety for operators and no harmful disinfection by-products). In some instances, post chlorination is used together with UV disinfection to provide residual chlorine to reduce the biological growth in storage and reticulation systems.

Chlorine dioxide and ozone have not been popular in Australia because of high operation and maintenance costs and the need for constant supervision. Membrane filtration is also gaining popularity in spite of its complexity and high operating and maintenance requirements as it not only removes solids but also provides disinfection. In addition to these processes, storage reservoirs can also lower numbers of bacteria and helminths in reclaimed water through sedimentation and predation.

Sludge treatment, disposal and reuse

Sludge or biosolids is the solid component produced during the wastewater treatment process. The sludge from primary, secondary and tertiary treatment processes requires treatment to reduce pathogens, odours, organic matter and water before its disposal or reuse. The cost of treating sludge is a major component of the overall cost of wastewater treatment. Hence, it is necessary to consider the sludge treatment as an integral part of any reclamation scheme.

Process trains for reclamation of wastewater

A process train is a number of individual treatment processes (as described in the previous section) combined together to achieve a given treatment objective. Typical process trains used to achieve Class A, B, C and D reclaimed water are shown in Figures 3.2 to 3.4. The dotted lines in these Figures indicate alternate process trains. Primary sedimentation is seldom included in any modern reclamation plant and UV disinfection or chlorination are optional to membrane filtration.

Generally secondary treatment, plus filtration or membranes, and disinfection, would be required to achieve Class A quality reclaimed water (Figures 3.2, 3.3 and 3.4). However, UV and reverse osmosis membranes can also produce Class A quality water without supplementary disinfection. Secondary treatment plus disinfection would suffice to achieve Class B or C quality water. Lagoons can achieve Class B, C and D quality and also offer the advantage of providing onsite storage. Several successfully applied process trains can be found in the following references (Rowe and Abdel-Magid 1995; Tchobanoglous 1996; Richard 1998, pp. 1344–54; WEF 1998; Metcalf and Eddy 2003).

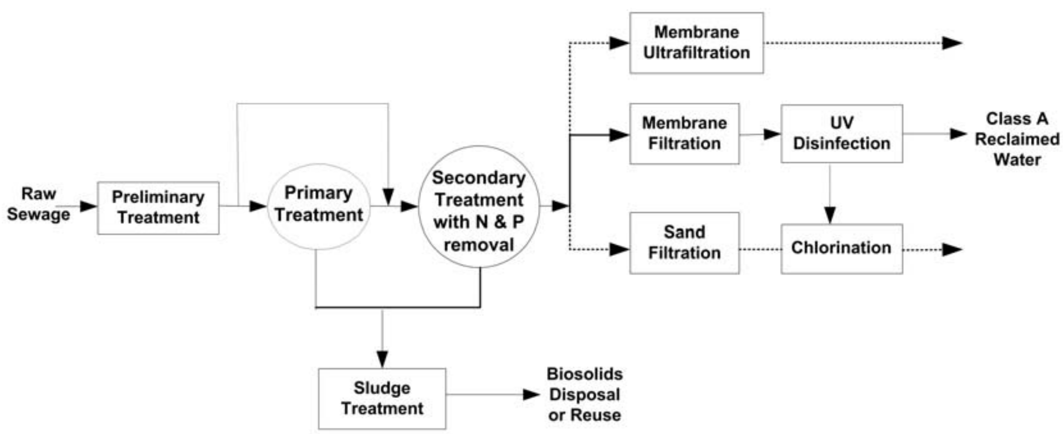

Figure 3.2 Typical process train for reclamation of wastewater for Class A irrigation.

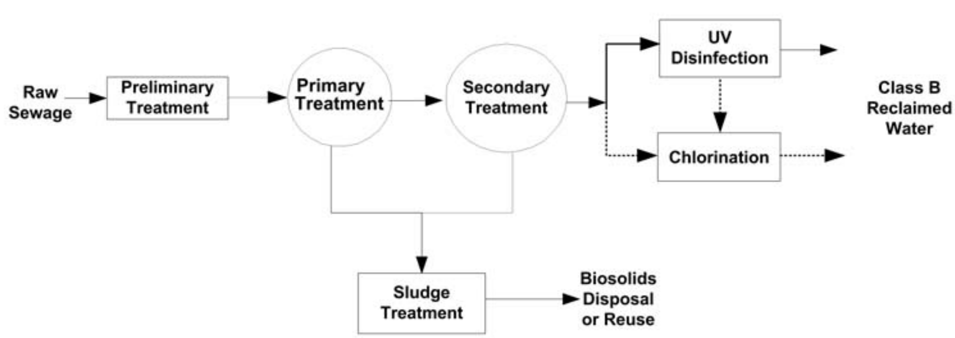

Figure 3.3 Typical process train for reclamation of wastewater for Class B irrigation.

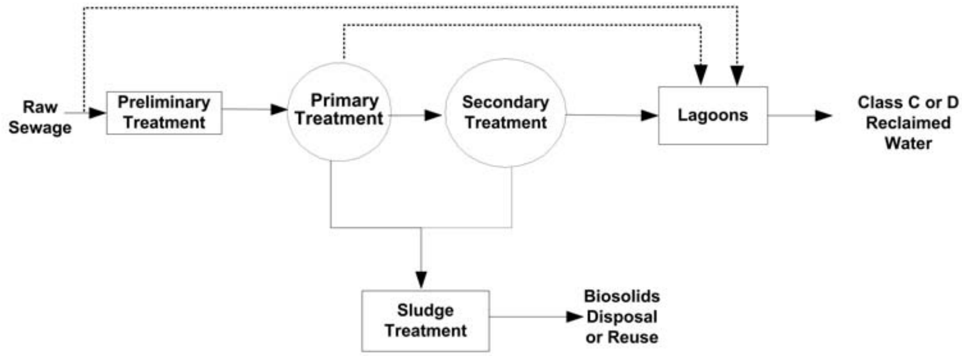

Figure 3.4 Typical process train for reclamation of wastewater for Class C and D irrigation.

Typical effluent quality achieved in process trains

Performance of individual treatment processes is usually reported in terms of minimum, average or maximum removal efficiencies while the process reliability is quoted in terms of 50 and 90 percentile removals (Williams 1982). Typical treated wastewater qualities achieved in commonly used process trains are shown in Table 3.5.

This table shows that performance can be variable and the values reported here should be used as a guide only, as the actual efficiency achieved in a treatment process depends on many parameters, including design, plant location, influent characteristics, environmental conditions, loading and condition of the plant (Tebbutt 1989).

Table 3.5 Typical treated wastewater quality reported for selected treatment trains.

	Typical final treated wastewater quality achieved							
Typical process trains	BOD (mg/L)	SS (mg/L)	TN (mg/L)	TP (mg/L)	Turbidity (NTU)	TDS (mg/L)	*E. coli* (No./100 mL)	Viruses (No./100 mL)
Primary	140–160	85–125	50–55[A]	15–18	—	—	—	700
Primary + sand filtration	50–100	20–40	20–30	6–10	20–30	—	7×10^5	
Primary + secondary	20–30	10–25	15–40	12–16	—	—	1.1×10^4	$0.05–10^4$
Primary + secondary (chemical P removal)	10–20	10–20	15–30	<2	5–10	—	6×10^5	—
Primary + secondary (biological P removal)	5–15	10–20	15–25	<2	5–10	—	—	—
Primary + secondary (N removal[B])	5–15	10–25	5–10	6–10	5–15	—	—	—
Primary + secondary + sand filtration	<5–10	4–6	15–35	4–10	<5	—	$10^3–10^5$	—
Primary + secondary (P removal) + BNR (N removal) + sand filtration	<5–10	<5–10	3–5	<1	0.3–2	—	—	—
Primary + BNR (N & P) + Cl_2	5–20	5–20	2–12	0.1–0.3	2–6	500–700	2.2–240	$10–10^4$
Primary + BNR (N&P) +UV[C]	5–20	5–20	2–12	0.1–0.3	2–6	500–700	—	—
Primary + BNR (N & P) + sand filtration + UV[C]	<5	1–4	<5	<2	<=2	500–700	2.2	$<10^{-4}$
Primary + BNR (N & P) + microfiltration + UV[C]	<1	<1	<1	<0.5	0.1–1	10–50	—	—
Series of lagoons	20–40	30–140	16–55	12–20[D]	—	—	40–300	—
Lagoons + sand filtration	20–35	25–50	15–50	8–14	—	—	30–280	—
Primary + wetlands[E]	<20	<20	<10	<5	—	—	—	—

Source: Martin and Martin (1991); Tchobanoglous (1996); Crites and Tchobanoglous (1998); Qasim (1998, pp. 52); Metcalf and Eddy (2003).
— indicates no data; [A] organic N; [B] nitrification and denitrification in separate stages; [C] postchlorination may be used to provide residual chlorination; [D] lower value is achievable with chemical addition; [E] both subsurface and free water surface wetlands can achieve this quality, however, subsurface wetlands require relatively less detention time.

Evaluation and selection of process trains

The selection of an appropriate process train forms an important step in the feasibility analysis of any water reclamation and reuse scheme (Tchobanoglous 1996). Traditionally, the evaluation and selection of process trains was based on economic considerations alone (Qasim 1999) but economics alone have often been over emphasised in the evaluation process (Martin and Martin 1991). However, in recent years, with an increased interest in the sustainability of treatment alternatives and environmental protection, several innovative processes have been developed and successfully incorporated in many wastewater reuse schemes. With the growing number of innovative and effective technologies, the decision process has become more complex and often diverse factors (Table 3.6) should be weighed to make a rational choice of alternatives.

Table 3.6 Criteria for selection of process trains for agricultural irrigation.

Name of the selection criteria	Remarks
Reuse criteria to be met	This dictates the physical, chemical and microbiological requirement of reclaimed water and depending on the Class of irrigation the processes can be selected as shown in Figures 3.2–3.4
Performance – effluent quality	The final effluent quality achievable by the overall treatment train decides the suitability of treatment trains (see text this section)
Influent wastewater characteristics	Carbon and nutrient loading to the plant is the key driver for process selection. For instance, if C levels are high relative to N and P in the influent, then a BNR process is adopted. Similarly, the presence of pesticides or heavy metals would indicate the necessity of activated carbon or similar process in the treatment train
Adaptability to upgrade, varying flow rate and change in influent quality	Due to diurnal and seasonal variation in the flow and concentration of the wastewater parameters, it is necessary to select a treatment train that is adaptable to varying flow rate and influent quality. Often the WWTP is upgraded to either match the flows and/or more stringent criteria
Method of irrigation employed, type of crop grown and compatibility with irrigation system	Drip, furrow and spray irrigation methods dictate the quality of reclaimed water required (see Table 12.4)
Ease of construction and operation and maintenance	Processes, which are easy to construct and operate, are often preferred in most reclamation schemes
Reliability	It is the most important factor that influences the acceptance of any reuse scheme. It is necessary to ensure that the effluent quality that meets the reuse criteria is achieved consistently
Power and chemical requirements	Most treatment processes are energy intensive and may require chemicals to enhance their performance
Odour generation potential and aesthetics	This factor influences the selection of lagoons and wetlands in urban areas
Local site specific conditions such as groundwater levels, land availability and requirement, climatic constraints such as temperature and rainfall	These factors mainly influence the selection of lagoons and wetlands and their design parameters (eg detention time (cooler the climate longer the detention time); and lining of lagoons to prevent groundwater contamination)
Quantity and quality of sludge generated	Selection of thickeners, digesters, dewatering equipment based on factors such as % solids in the sludge feed, sludge flow and land available
Total project, operation and maintenance costs	These are often the most critical factors to be considered during the selection of any treatment processes and may determine the success or otherwise of a project

Source: after Crites and Tchobanoglous (1998).

Case studies

The following case studies are presented to illustrate different process trains that have been successfully used in Australia to provide reclaimed water for agricultural irrigation.

Bolivar, South Australia

The Bolivar WWTP (north of Adelaide) is the largest of four plants serving the city of Adelaide in South Australia. It is also the largest reclamation plant for horticultural reuse in Australia. The annual average flow treated at this plant is approximately 57 000 ML (155 ML/d). In 1999, the Virginia Pipeline Scheme was commissioned to produce and distribute reclaimed water equivalent to Class A quality to irrigate horticultural crops in the Virginia region. The scheme provides about 14 500 ML/yr of high quality reclaimed water and is a valuable alternative to the overused groundwater resource in the area. During the peak irrigation months, the demand for reclaimed water rises to approximately 80 ML/d so that about 65% of available treated wastewater is reused. The process train used to provide water equivalent to Class A quality incorporates the following treatment processes (Figure 3.5):

- preliminary treatment (screening, grit removal, preaeration);
- primary treatment (primary sedimentation);
- secondary treatment (biological nutrient removal followed by lagoons);
- tertiary treatment (dissolved air flotation and granular multimedia filtration, DAFF, followed by chlorination); and
- sludge treatment and disposal consists of gravity thickeners, waste activated sludge thickeners, anaerobic digesters, and a combination of centrifuges, followed by air-agitated drying and lagoon stabilisation/air drying for biosolids, principally used for dryland agriculture.

The DAFF plant was designed to produce reclaimed water of a quality equivalent to Class A in recognition that while retention of polishing lagoons provided an additional pathogen barrier, algal production meant that physical parameters exceeded Class A. Performance testing was required to demonstrate that a quality fewer than 10 *E. coli*/100 mL (median) and less than 1/50 L for viruses, *Cryptosporidium* and *Giardia* could be achieved. The required performance has been met and continues to be demonstrated. Typical reclaimed water quality achieved in this plant is shown in Table 3.7.

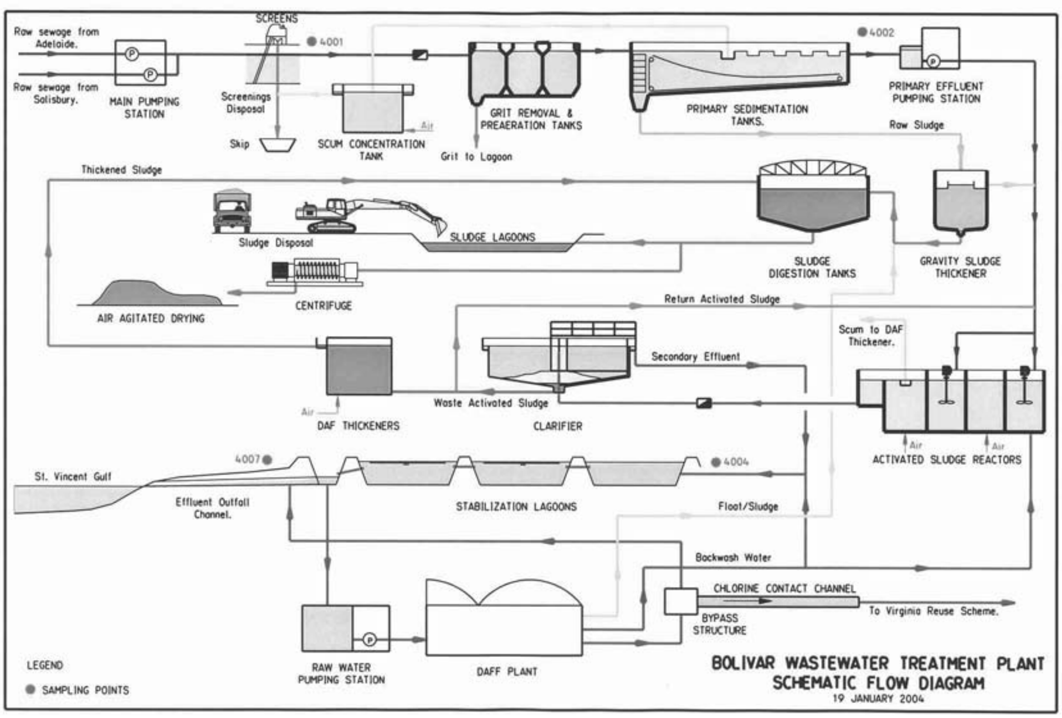

Figure 3.5 Process schematic for Bolivar wastewater reclamation plant in South Australia.

Table 3.7 Reclaimed water quality achieved in Virginia Pipeline Scheme (from Bolivar WWTP).

Parameter	Annual average values (2003/04 financial year) [A]
Soluble BOD (mg/L)	2.0
Turbidity (NTU)	1.2
TN (mg/L)	9.0
TP (mg/L)	3.1
Escherichia coli (No./100 mL)	0

Source: SA Water (2004).
[A] Refers to financial year, *E. coli* are a median value.

Hervey Bay, Queensland

In the early 1990s Hervey Bay City Council in Queensland initiated the use of reclaimed water for irrigation of native pasture, tea trees, golf courses, turf farms and over 300 ha of sugarcane farms to help protect the local marine environment. The reclaimed wastewater from two treatment plants, Eli Creek (4.9 ML/d) and Pulgul Creek (3.3 ML/d) (Figure 3.6a, 3.6b), is pumped to two storage dams with a total capacity of 1500 ML and is distributed to farms through 22.5 kilometres of reclaimed water distribution pipeline.

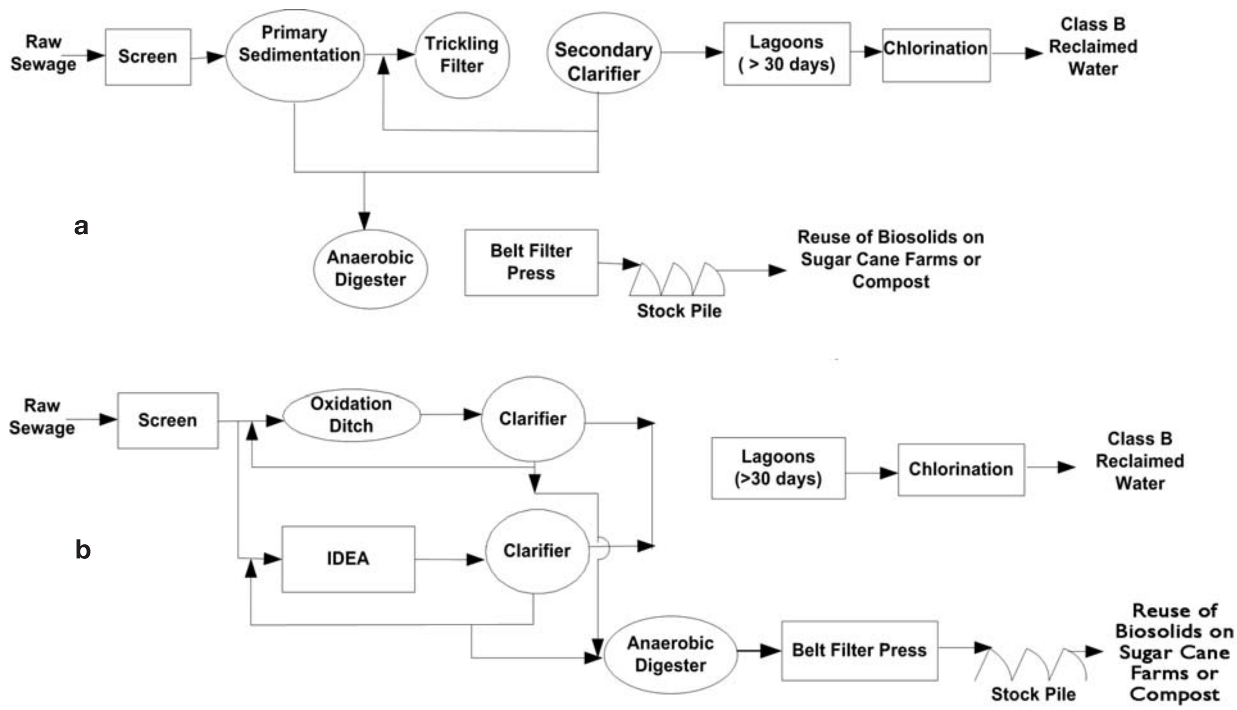

Figure 3.6 (a) Process schematic for Eli Creek and (b) Pulgul WWTP at Hervey Bay, Queensland.

Table 3.8 Reclaimed water quality achieved in Hervey Bay reuse scheme.

Name of the plant	Annual average values (2003/04[C])				
	BOD (mg/L)	SS (mg/L)	TN (mg/L)	TP (mg/L)	FC (No./100 mL)
Eli creek WWTP	9	13	33(5)[A]	8(4)	[B]
Pulgul WWTP	4	4	9(3)	5(2)	[B]

Source: McAuliffe (pers. comm. 2004).
[A] Total nitrogen (TN) and total phosphorus (TP) values after storage for both treatment plants are shown within brackets; [B] not detected in 90% of samples. [C] Financial year.

Table 3.9 Reclaimed water quality achieved in the Brighton reuse scheme.

Name of the plant	Annual average values				
	BOD (mg/L)	SS (mg/L)	TN (mg/L)	TP (mg/L)	FC (No./100 mL)
Brighton– Lagoon 4 (Jan. 2000–July 2002)	47.0	52.3	26.0	10.6	150
Brighton–Lagoon 5 (July 2002– Apr. 2003)	38.0	46.5	18.2	12.0	150
Green Point (Jan. 2000–Apr. 2003)	18.9	12.7	38.4	10.2	11

Source: W Lee (pers. comm. 2003).

These wastewater treatment plants are designed to achieve Class B quality reclaimed water (as per Queensland State guidelines, BOD <30 mg/L, SS <20 mg/L and faecal coliform <150 No./100 mL) (Table 3.8).

This scheme has won an Australian national award for World Heritage protection in 1997 and is the benchmark for future wastewater strategies in Queensland. Consideration is being given for expansion of the plant to accommodate stormwater runoff in accordance with the local Council commitment to preserving the marine environment.

Brighton, Tasmania

Brighton Council in Tasmania reclaims water (Brighton Reuse Scheme) from treatment plants at Brighton (0.3 ML/d) and Green Point (2 ML/d). These plants have been providing Class B reclaimed water (as per Tasmanian State guidelines) for growing mainly poppies, cereals, lupini beans, vegetable seed crops, pasture for stock feed, hemp and some minor viticulture and horticulture developments.

The Brighton lagoon system consists of an aerated primary lagoon, two aerobic lagoons and two storage lagoons. Lagoon 4 (first storage lagoon) has one week's storage while Lagoon 5 (second storage lagoon) has three month's storage. The Class B reclaimed water (as per Tasmanian State guidelines) has been used for irrigation since 1996. The Green Point WWTP has been reclaiming water for irrigation since 2000 and incorporates conventional treatment processes such as primary sedimentation, trickling filter and activated sludge with chlorination. The sludge is treated in anaerobic digesters and dewatered in belt filter presses. The annual average reclaimed water quality values achieved in both plants are shown in Table 3.9.

Mt Barker, South Australia

Mt Barker, South Australia, has a state-of-the-art wastewater reclamation plant which treats about 2.3 ML/d septic tank effluent from Mt Barker, Littlehampton and Nairne. Prior to 1996, septic tank effluent was treated in a series of oxidation ponds before discharging to the Mt Barker Creek. In 1997, due to increases in population and the impact on the creek, Mt Barker Council embarked on an environment improvement program (EIP) that outlined a strategy to provide treatment for a population of 15 000 (stage 1) to 25 000 (stage 2) to reduce SS, BOD and nutrients, particularly phosphorus. The upgraded treatment works consisted of desludging and conversion of the first oxidation pond to an aerated lagoon, and treating lagoon effluent with dissolved air flotation (DAF) and continuous microfiltration (CMF) (Figure 3.7) at an estimated cost of $2.2 million.

Wetlands (now known as Laratinga Wetlands) were constructed in late 1999, for storage and further polishing to reduce the discharge of nutrients to Mt Barker creek. This wetland site is located adjacent to the Creek for winter discharge and is also close to potential users of the reclaimed water during the irrigation season. The reclaimed water quality achieved in CMF and wetlands are presented in Table 3.10.

Table 3.10 Reclaimed water quality achieved in Mt Barker reuse scheme.

Name of the plant	Annual average values (2002/03)				
	BOD (mg/L)	SS (mg/L)	TN (mg/L)	TP (mg/L)	FC[A] (No./100 mL)
Continuous microfiltration	3.0	1.0	40	0.05	0
Wetlands	7.3	5.3	15.3	0.10	20

Source: A Berzins (pers. comm. 2003).
[A] Median values.

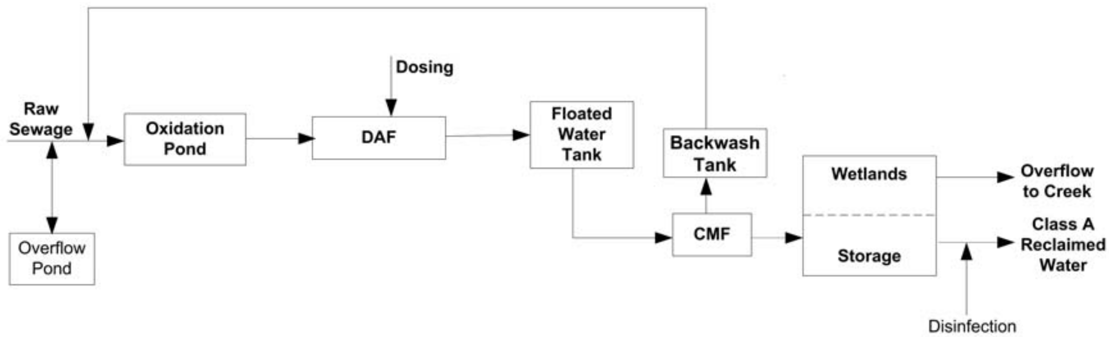

Figure 3.7 Process schematic for Mt Barker wastewater treatment plant, South Australia.

Reclaimed water quality monitoring

Monitoring associated with reclaimed water schemes is necessary to ensure that they do not cause adverse impacts to either public health or the receiving environment (ie soils, crops, surface water or groundwater). Consultation with local environmental and health authorities will be necessary prior to finalising any monitoring program for a scheme as their approval is likely to include specific monitoring requirements (see *Chapters 2 and 12*). This section deals with monitoring of reclaimed water quality only (see *Chapters 2, and 5 to 11* for monitoring needs for the receiving environment).

Monitoring of reclaimed water is carried out to maintain quality assurance of the treatment process and to demonstrate compliance with approval conditions. Factors affecting the level of monitoring required include the intended end use of the reclaimed water, characteristics of the source wastewater (ie the level and type of any trade waste inputs) and the type of treatment processes used. Monitoring requirements during commissioning will be the most intensive and will be designed to prove the effectiveness and reliability of the treatment processes. Routine monitoring will generally require less frequent measurements, although it may require an increase in monitoring intensity when certain events occur (ie if a significant *Cryptosporidium* increase is detected in the wastewater for Class A reuse scheme, based on results of routine monitoring). In this example such an event may trigger the commencement of some short-term intensive monitoring, on both the inlet and outlet of the process, to verify that effective removal is being achieved.

In general, the reclaimed water quality parameters to be measured together with the sampling frequency, sampling location and measurement method (eg grab sample, 24 hour composite sample and online measurement) will be specified by the regulatory agencies and may include microbiological, chemical and physical parameters.

Microbiological parameters

Testing for thermotolerant coliforms (or *E. coli*) will routinely be required in the reclaimed water. For Class A systems, frequent sampling will be required ranging from daily or every second day up to perhaps weekly. For Class B, C or D systems, weekly sampling may suffice.

Testing for pathogens such as protozoa, viruses and helminths will be required often in the reclaimed water for Class A systems and may also be required for Class B, C and D systems. The testing will generally be needed during commissioning, to determine the removal efficiencies achieved through the treatment process. However, the ongoing monitoring program may also include event-based monitoring for some of these pathogens, if specified by the health authority in the approval conditions for the scheme.

Disinfectant concentrations or UV dose will also need to be included in any routine monitoring program to demonstrate process performance. This can be achieved by periodic measurement or by the use of online instrumentation. For Class A systems, online measurement together with low level alarms and associated automatic shutdown of reclaimed water supply will generally be required by the health authority.

Physical parameters

Measurement of turbidity or suspended solids in the reclaimed water will be required in the routine monitoring program for any scheme. For Class A systems, online turbidity measurement with high level alarms and associated automatic shutdown of reclaimed water supply will generally be required by the health authority. For Class B, C and D systems periodic measurement (say weekly) of suspended solids will generally suffice.

Chemical parameters

Routine testing for BOD, salinity and pH in the reclaimed water will generally be required for any scheme. Measurement of nutrients will also usually be required to enable an assessment of any potential impacts to soils, groundwater and surface waters in the receiving area. In addition, during commissioning, and thereafter as required, the approval authority may also require routine testing of other chemical constituents such as metals, pesticides and other organic chemicals, depending on the type and level of likely trade waste inputs upstream of the WWTP and the sensitivities of the crops grown with reclaimed water.

Future trends in wastewater reclamation

The process of water reclamation has undergone many changes over the years. Although the basic principles of wastewater reclamation have remained, a shift in paradigm has occurred in the selection of treatment processes with the development of more efficient and novel technologies and the imposition of more stringent standards. For instance, in Australia, most treatment plants adopted lagoons and trickling filters for reclamation of wastewater up to late 1980s (Hartley 1995, 1998). However, since 1990, a wide range of efficient treatment processes including dissolved air flotation, microfiltration, activated carbon, Biological Nutrient Removal (BNR) and sequential batch reactors (SBRs) have been adopted for wastewater reclamation (Dillon 2000). The clear distinction between primary, secondary and tertiary processes is fast diminishing, and packaged proprietary units that combine one or more of the processes are becoming popular. These proprietary processes not only offer potential savings in construction, operation and maintenance costs (Metcalf and Eddy 2003, pp. 20), but also provide reliable performance within a small footprint.

The application of membrane technologies such as microfiltration and reverse osmosis for wastewater treatment has also increased significantly since the 1990s. This is mainly because of their effectiveness in removing pathogens, heavy metals, total dissolved solids and resistant organics within a small footprint. The membranes have been used not only in activated sludge processes (referred to as membrane bioreactors) but also postfiltration to produce very high quality reclaimed water. Membrane bioreactors have eliminated the need for secondary clarifiers in activated sludge and have also resulted in better effluent quality and lower sludge quantity. In the case of sludge treatment, mechanical dewatering equipment such as centrifuges and belt filter presses are being adopted in most plants and are being preferred over conventional sludge drying beds. Most reclamation plants are also adopting UV systems for disinfection over chlorination.

Since most WWTPs now have a more limited land area than in the past, processes which have a small footprint are being adopted. With decreasing buffer distances between the residents and the treatment plant due to growth of urban areas, it has also become necessary to adopt processes that can contain and treat odours. The 'good neighbour' aspect (aesthetics) is especially important when considering recent trends to sewer mining or neighbourhood WWTPs. Further, with the emphasis on aesthetics, plants closer to urban areas are either being constructed underground or aesthetically blended with the surroundings.

Conclusions

To overcome water demand, pollution and discharge issues wastewater reclamation for agricultural irrigation is becoming an integral part of many water resources management schemes in Australia. It is necessary to treat wastewater to remove contaminants to levels prescribed by the local regulations to overcome potential risks to public health, crops and the receiving environment. National and State reuse guidelines are in place in most States across Australia. Several treatment processes are available and many factors including the type of reuse and method of application decide the extent of treatment required. Often a combination of treatment processes is used to achieve the required wastewater quality suitable for agricultural reuse. Successful reclaimed water schemes for agricultural irrigation across Australia have demonstrated that high quality water can be produced consistently. The evaluation and selection of appropriate treatment processes, combined with regular sampling and assessment protocols, is critical to ensure reliability of wastewater reclamation schemes.

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4 Opportunities for reclaimed water use in Australian agriculture

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Being the world's driest inhabited continent and having a human population of around 20 million places significant strain on Australia's water resources. Environmental, economic and social drivers have increased the pressure on policy makers to manage this precious resource as efficiently as possible. Significant reform has occurred in Australia's water policy in recent years, with particular emphasis on the need to make better use of reclaimed water. There are several markets for reclaimed water, including agriculture, forestry, mining, manufacturing and power utilities.

This chapter provides an overview of how Australia exploits its water resources with a focus on reclaimed water. Arguments are progressed for the high-value horticultural sector being a competitive customer for reclaimed water. Factors to consider when assessing the suitability for reclaimed water use in horticulture either for substitution of existing water resources or expansion of production are also discussed.

Information for this chapter has largely been drawn from *Horticulture – productivity and sustainability* (HRDC and NLWRA 2001), *Water Account for Australia (2000–01)* (ABS 2004) and Radcliffe (2003, 2004).

Water consumption in Australia

Australian industry (including household and environment sectors) utilised 24 909 GL of water in 2000–01 (Table 4.1), with agriculture accounting for 67% (16 660 GL) of this total water usage (Table 4.1). Households were the next largest consumers, accounting for only 8.8% of total consumption.

Water use in Australian agriculture and horticulture

Of the water used by agriculture, 9132 GL (55%) was from self-extracted sources, 7105 GL (43%) was from mains and 423 GL (3%) was reclaimed water (ABS 2004). Mains water is that which is supplied to the user through non-natural infrastructure, such as pipes or open channels, and where an economic transaction has occurred for exchange of this water. Self-extracted water is that which is extracted directly from the environment for use *in situ*. This includes water from lakes, groundwater, farm dams, and direct sequestration of river water. For the purposes of ABS reporting, reclaimed water refers to wastewater that may have been treated to some extent and supplied to another user. It excludes water reused onsite at the wastewater treatment plant (WWTP).

The net water consumption by Australian agriculture is described in Table 4.2 and Figure 4.1. About one-third of the water consumed by agriculture is for 'livestock, pasture, grains and other agriculture'. The next largest consumers are cotton and dairy, which each account for about 17% of total usage. Other consumers are rice (12%), sugar (8%), and horticulture (vegetables, 3.3%; fruit, 4.8%; grapes, 4.4%). The livestock, pasture, grains and other agriculture category includes cut flowers, nurseries, turf growing and other commodities (ABS 2004).

Other major consumers of water include service and administration industries. Of particular interest to this chapter is the cultural, recreational and personal services

Table 4.1 Net water consumption in Australia by major sector and State/Territory 2000–01 (GL).

State or Territory	Agriculture	Mining	Manufacturing	Electricity and gas	Water supply, sewage and drainage	Household	Environment	Other	Total
NSW and ACT	7322.2	51.7	178.7	59.2	675.8	679.2	200.5	257.5	**9424.9**
Vic	3724.2	7.3	248.9	1536.2	745.3	472.3	253.2	152.1	7139.8
Qld	3453.9	108.6	181.4	70.9	216.4	500.9	4.5	174.1	4710.7
SA	1302.5	12.3	85.5	1.7	24.1	180.6	0.9	39.1	**1646.6**
WA	565.5	195.0	83.2	19.2	113.8	244.6	0.0	188.1	**1409.3**
Tas	221.6	21.3	79.1	0.0	9.5	59.3	0.4	26.0	**417.2**
NT	70.1	4.6	9.1	0.7	8.9	44.6	0.0	22.1	**160.1**
Total	**16 660.4**	**400.6**	**866.1**	**1687.8**	**1794.0**	**2181.5**	**459.4**	**859.0**	**24 908.7**

Source: ABS (2004). The sum of column and rows may differ from total figures due to rounding. Total values are correct.

industry which is a significant user of water. Water use in this industry includes that used on parks and gardens, golf courses and other sporting grounds.

Almost 90% of water consumed by agriculture is accounted for by three States: New South Wales-Australian Capital Territory, Victoria and Queensland (Table 4.3). The high consumption by NSW-ACT is mostly attributed to cotton; rice; and livestock, pasture, grains and other agriculture. In Queensland, cotton as well as livestock, pasture, grains and other agriculture account for much consumption, but sugar is the largest user in that State.Victorian water consumption can mainly be attributed to dairy, and livestock, pasture, grains and other agriculture.

Reclaimed water use in Australia

In the Water account for Australia (2000–01) reclaimed water (reuse water) is defined as 'wastewater that may have been treated to some extent, and then used again without first being discharged to the environment' (ABS 2004). The use of reclaimed water has increased dramatically from 134 GL in the 1996/97 financial year to 517 GL in 2000/01, making up 4% of total water supplied by water providers. This compares with a 1% contribution of reclaimed water in 1996/97 (ABS 2000). The agriculture industry was the largest user of reclaimed water in 2000–01, accounting for 423 GL or 82% of all reclaimed water in 2000/01 (ABS 2004).

Table 4.2 Net water consumption (GL) by Australian agricultural and horticultural sectors by source of water (self-extracted, mains water, reuse water).

Industry sector	Self-extracted	Mains water	Reuse water	Water consumption
Vegetables	422.0	117.0	16.7	**555.7**
Fruit	491.3	296.6	14.8	**802.6**
Grapes	345.4	364.2	19.6	**729.1**
Cotton	2502.0	404.1	2.1	**2908.2**
Rice	134.0	1692.7	124.5	**1951.2**
Livestock, pasture, grains and other agriculture	3471.1	1905.5	191.9	**5568.5**
Dairy farming	1210.7	1571.9	51.9	**2834.4**
Sugar	555.7	753.1	1.9	**1310.7**
Total for the agricultural industry	9132.1	7105.0	423.3	**16 660.4**
Cultural, recreational and personal services	131.3	231.2	32.5	**395.0**
Total	**9263.5**	**7336.2**	**455.9**	**17 055.4**

Source: ABS (2004). The sum of columns and rows may differ from total figures due to rounding. Total values are correct.

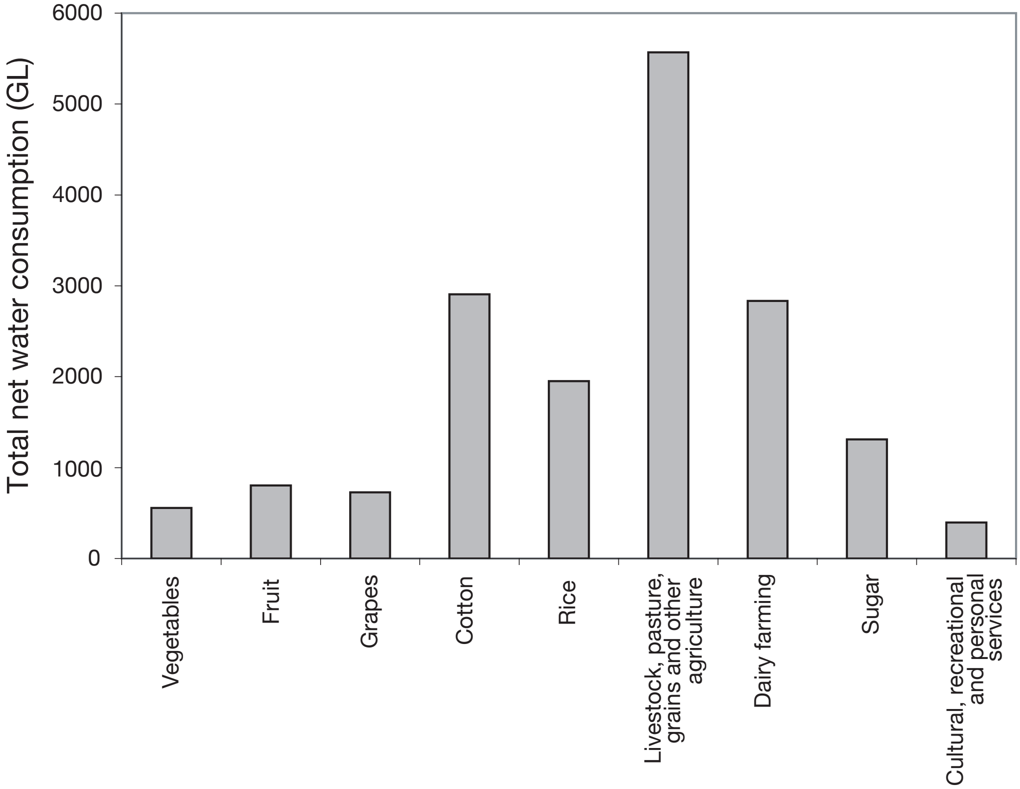

Figure 4.1 Total net water consumption (GL) by the Australian agricultural and horticultural sector (2000/01 financial year).

The terms reclaimed, recycled or reuse water can have a variety of meanings. This lack of consensus on definition is undoubtedly largely responsible for the disparity in estimates of reclaimed water use in Australia. For example, in estimating 2000/01 reclaimed water use, ABS (2004) presumably had a more liberal interpretation than Radcliffe (2003), with the ABS estimate being three times larger (517 GL) than Radcliffe's (167 GL).

Table 4.3 Net water consumption (GL) by Australian agricultural and horticultural sectors and by State.

Industry sector	NSW-ACT	Vic	Qld	SA	WA	Tas	NT	Australia
Vegetables	95.7	130.9	103.1	64.7	111.0	49.5	0.9	**555.7**
Fruit	214.1	209.4	107.4	160.7	64.9	10.3	35.9	**802.6**
Grapes	174.4	237.9	6.3	283.7	22.6	0.8	3.5	**729.1**
Cotton	1921.1	—	984.5	—	2.6	—	—	**2908.2**
Rice	1924.5	26.7	—	—	—	—	—	**1951.2**
Livestock, pasture, grains and other agriculture	2590.2	1434.7	778.9	473.6	176.2	85.1	0.7	**5568.5**
Dairy farming	401.2	1685.0	287.9	319.8	64.5	76.0	29.8	**2834.4**
Sugar	1.2	—	1185.8	—	123.7	—	—	**1310.7**
Total for the agricultural industry	7322.3	3724.6	3453.9	1302.5	565.5	221.6	70.1	**16 660.4**
Cultural, recreational and personal services	112.1	93.9	76.0	21.9	82.4	7.2	1.6	**395.0**
Total	**7434.4**	**3818.5**	**3529.9**	**1324.4**	**647.9**	**228.8**	**71.7**	**17 055.4**

Source: ABS (2004). The sum of columns and rows may differ from total figures due to rounding. Total values are correct.

Both Radcliffe (2003) and the ABS (2004) list New South Wales (or NSW-ACT) and Victoria as the largest users of reclaimed water (Table 4.4). The ABS (2004) also lists these two States as being the highest proportionate users (% reclaimed in Table 4.4) of effluent, whereas Radcliffe has South Australia as the highest proportionate user. Such disparities arise from substantial differences in the estimates of the volume of water reclaimed rather than the volumes of effluent (Table 4.4). In the case of Victoria, for example, the ABS (2004) deem the large volumes of water used for irrigation of pastures at the Western Treatment Plant (about 150 GL/yr) to be reclaimed, whereas Radcliffe (2003) considers such overland flow to be part of the treatment process and not recycling *per se*. The discrepancy with New South Wales is due to the inclusion of rice, and livestock, pasture, grains and other agriculture where the recycling of irrigation water (drainage industries) has been included in the ABS report.

The ABS estimate for 'effluent' represents all regulated discharge from the water supply, sewerage and drainage industries. Thus, some of this discharge would be non-sewage effluent. It does not include water supplied by other industries including mining, manufacturing and electricity and gas supply industries. Total amount of water reused when these other industries are included is 516.6 GL.

Reclaimed water use in Australian agriculture and horticulture

Agriculture is clearly the largest user of reclaimed water accounting for 423 GL and 82% of all reclaimed water used in Australia (ABS 2004). Most of the reclaimed water used by agriculture was for application to pastures (192 GL, 45%), followed by rice crops (125 GL, 29%) and dairy farming (52 GL, 12%) (Table 4.2, Figure 4.2). The next largest user of reclaimed water was other industries, with 36 GL used representing 7% of total reclaimed water use in Australia (ABS 2004). Most reclaimed water in this category is applied to golf courses and sporting grounds. Households used the smallest volume of reclaimed water in 2000/01 (0.2 GL), mainly for watering gardens.

The Water Account for Australia (2000–01) provides a summary of the main agricultural and horticultural users of reclaimed water in each State (Table 4.5) (ABS 2004). In NSW-ACT the predominant users are the rice industry (125 GL), and livestock, pasture, grains and other agriculture (89 GL). In Victoria the livestock, pasture, grains and other agriculture, and dairy industries are significant users (102 GL and 51 GL, respectively). The fruit and grape industry are moderate users in NSW-ACT (both 11 GL) and Victoria (3 GL and 7 GL, respectively). The vegetable industry is a moderate user in SA (10 GL). At a national level, horticultural crops use moderate quantities of reclaimed water (vegetables, 17 GL; fruit, 15 GL; grapes, 20 GL). The use of reclaimed water for golf courses and sporting grounds is also significant with a total Australian use of about 33 GL (Table 4.5).

The information provided in Table 4.5 represents an enormous number and diversity of reuse schemes across Australia. Radcliffe (2004) provides a comprehensive assessment of the reclaimed water schemes established in Australia. Table 4.6 attempts to summarise the information in his review with an assessment of the reclaimed water schemes, the user sector and the volume of water used (derived data from Appendix 1, Radcliffe 2004). As previously stated, the volume of reclaimed water in this assessment is significantly less than that

Table 4.4 Results from two State-based inventories of volume of sewage effluent (GL) produced and volume reclaimed (GL).

	ABS (00/01)			Reuse water		
	Effluent (GL)	Reclaimed (GL)	Reclaimed (%)	Effluent (GL)	Reclaimed (GL)	Reclaimed (%)
Qld	309.0	23.8	7.7	339	38	11.2
NSW	820.9	267.0	32.5	694	61.5	8.9
ACT				30	1.7	5.6
Vic	428.6	196.4	45.2	448	30.1	6.7
Tas	37.6	1.6	4.3	65	6.2	9.5
SA	84.0	17.6	18.7	101	15.2	15.1
WA	138.5	9.2	6.2	126	12.7	10.0
NT	18.6	1.2	6.5	21	1.1	5.2
Total	**1837.2**	**516.6**		**1824**	**166.5**	

Sources: Radcliffe (2003) and ABS (2004). ABS data for New South Wales and Australian Capital Territory are grouped.

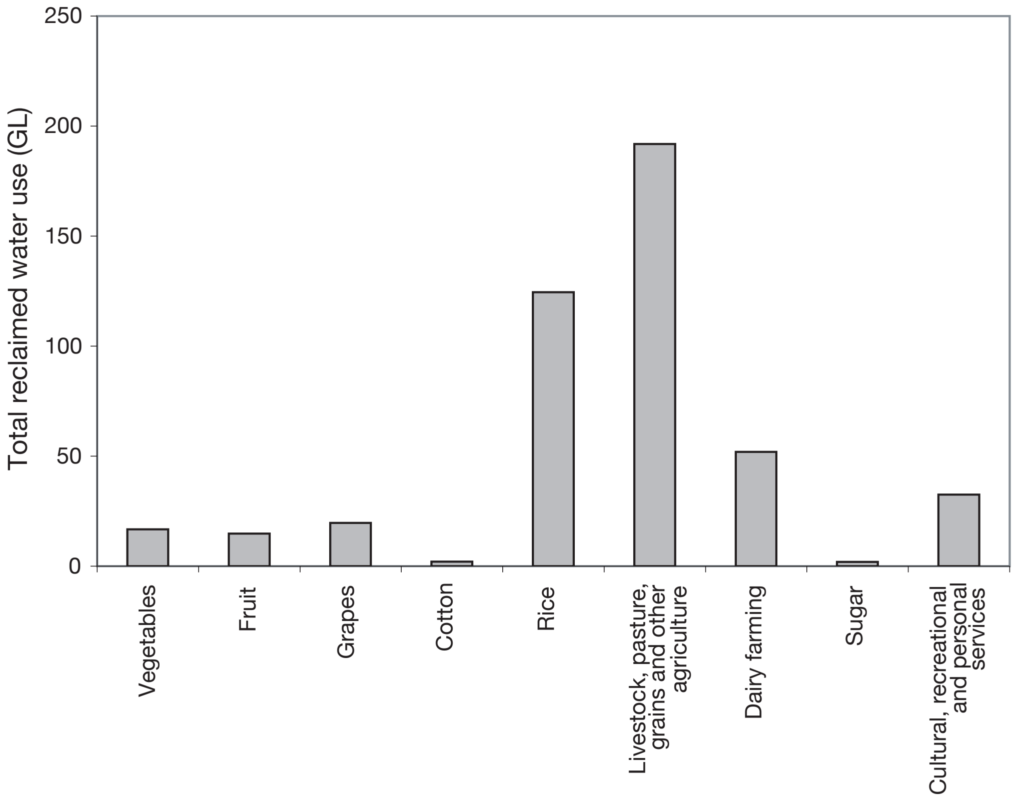

Figure 4.2 Total reclaimed water use (GL) by the Australian agricultural and horticultural sector (2000/01).

described by the *Water Account for Australia (2000–01)* (ABS 2004). The total reuse is estimated at 156 GL compared with 517 GL from ABS data. Radcliffe's data are qualified by the fact that data from some WWTPs could not be obtained (ie it is a summary including data from 2000/02), and certain assumptions were made in allocating water to specified uses. However, Radcliffe (2004) is the most comprehensive summary of reclaimed water use in Australia, and this gives an excellent picture of uses of reclaimed water across the country. The information aims to provide an analysis of the breadth and diversity of reclaimed water schemes across Australia.

The user sectors have been categorised into industrial, urban, agricultural and environmental. Popular urban uses for reclaimed water are golf courses and landscape/recreation space such as ovals and parkland (227 schemes, using a total of 33 GL) (Table 4.6). At the time of collation (2000–02), very few third pipe schemes were in operation in Australia (only two in NSW, using 1.0 GL) (Table 4.6). Similar to third pipe schemes, the intentional use of reclaimed water for environmental purposes is also small (6 schemes, using 3 GL) (Table 4.6).

Of greatest interest to this chapter are the urban (golf course and recreational) and agricultural schemes. New South Wales, Victoria and Queensland have the largest number of reclaimed water schemes of the Australian States (Table 4.6). There are a total of 227 urban (golf course and recreational) schemes, with most of these occurring in New South Wales (87) and Queensland (62). About 270 agricultural reclaimed water schemes exist across Australia. Most of these schemes involve irrigation of pastures/fodder (99) and trees/woodlots (58). However, a diversity of additional schemes is operating including cotton, flowers, orchards, nurseries, vegetables, viticulture, turf, cane and probably some cereal crops.

Relatively few schemes involve the irrigation of horticultural produce, although eight major horticultural reclaimed water schemes are in operation: two orchards, one flower grower, one vegetable production district (the Virginia Pipeline Scheme), and four unspecified horticultural schemes. South Australia's Virginia Pipeline Scheme is Australia's largest reclaimed water scheme for horticulture (Krackman *et al* 2001; Kelly *et al* 2003).

Table 4.5 Reclaimed water use (GL) by Australian agricultural and horticultural sectors by State.

Industry sector	NSW-ACT	Vic	Qld	SA	WA	Tas	NT	Australia
Vegetables	4.0	2.3	—	10.4	—	—	—	**16.7**
Fruit	10.5	3.2	1.1	—	—	—	—	**14.8**
Grapes	11.3	6.5	—	1.7	0.1	—	—	**19.6**
Cotton	0.9	—	1.2	—	—	—	—	**2.1**
Rice	124.5	—	—	—	—	—	—	**124.5**
Livestock, pasture, grains and other agriculture	88.5	101.9	0.8	—	—	0.7	—	**191.9**
Dairy farming	0.6	51.2	—	—	—	—	—	**51.9**
Sugar	—	—	1.8	—	0.1	—	—	**1.9**
Total for the agricultural industry	240.4	165.2	4.8	12.1	0.2	0.7	0.0	**423.3**
Cultural, recreational and personal services	7.4	8.0	9.5	1.4	5.3	0.1	0.8	**32.5**
Total	**247.8**	**173.2**	**14.3**	**13.5**	**5.5**	**0.8**	**0.8**	**455.8**

Source: ABS (2004). The sum of columns may differ from total figures due to rounding. Total values are correct.

There are many reclaimed water schemes under development. For example, the Werribee Irrigation District (Victoria), the South-Eastern Irrigation Scheme (Victoria) and the Pimpama-Coomera Scheme (Queensland) (Radcliffe 2004). See Radcliffe (2004) for a comprehensive analysis of existing and proposed Australian reclaimed water schemes.

Although there has been a significant increase in the use of reclaimed water between 1996/97 and 2000/01, there are several potential limitations to further increases in its use in Australia (Hamilton *et al* 2004; Stevens *et al*). These include public health concerns (see *Chapter 12*), social acceptance by all stakeholders (see *Chapter 13*), markets for produce and availability of expertise and cost of infrastructure. In addition, large volumes of wastewater are most often in low lying areas around cities (where sewers naturally drain to) and the pumping costs associated with delivering this water to elevated agricultural land in the catchment often mean that it is not economical (ABS 2004).

Agricultural and horticultural water use in the context of value of production

Given that the future development of reclaimed water schemes relies to a large extent on their economic viability it is appropriate to assess the economic performance of different industry sectors. The total gross value of irrigated agricultural production in 2000/01 was A$9 618 million (Table 4.7). In 2000/01 gross irrigated agricultural production represented 28% of the gross value of all agricultural production (ABS 2004). Vegetables were the largest contributor (A$1 817 million, 19%) followed by fruit (A$1 590 million, 17%).

While recognising the limitations of estimating the value of production from irrigated agriculture, the data provide a useful indicator for the higher value industries. Where water is scarce and becomes the most limiting factor to production, the economic value added will be a major driver for redistribution of water resources. Horticultural industries gain high returns per volume of water relative to other irrigation enterprises and, therefore, compete strongly with more traditional users (HAL 2003). Horticulture crops (vegetables, fruit and grapes) provide the highest return per unit of water (A$3.27 million/GL, A$1.98 million/GL and A$1.86 million/GL, respectively) (Table 4.8).

As the costs associated with the delivery of reclaimed water are likely to increase, and water is a relatively minor fraction of the total cost of horticultural production (vegetable, fruit and grapes), this industry is likely to have a continuing strong competitive position with respect to water access. However, water availability is only one factor to be considered and caution must be used (see *Assessing suitability for reclaimed water use in horticulture*).

Horticulture in Australia is both intensive and diverse, with more than 100 crop types grown with an approximate gross value of A$4 billion (1996/97). Annual and perennial crops hold about equal shares by value of production. The total area of the horticultural industry is about 2500 km^2. Horticultural production occurs across a wide range of environmental conditions and spans all agroecological regions of Australia. Distribution is restricted primarily by access to water,

Table 4.6 Reclaimed water schemes and volumes for Australia (2000–02).

	Ind	Urban			Agricultural																	Environ-mental			
Specific use of reclaimed water	Industrial	Third Pipe	Golf course	Recreational	Indirect use^A	General^A	Horticulture^A	Trees/wood-lots	Pasture/fodder	Pasture dairy	Lucerne	Cotton	Flowers	Orchard	Nursery	Vegetables	Viticulture	Hydroponics	Turf farm	Canefields	Cropping^A	Wetlands	Environmental^A	**Total no reuse schemes**	
State	Number of uses																								
NSW	38	2	52	33	2	3	1	17	29	4	4	3	–	2	–	–	–	1	–	–	–	1	–	**192**	
Vic	6	–	16	7	–	6	1	25	62	8	–	–	1	–	4	–	2	–	1	–	6	–	1	**146**	
Qld	28	–	40	22	1	9	1	5	3	3	3	–	–	–	1	–	–	–	4	8	–	–	1	**129**	
SA	1	–	3	4	–	3	–	2	2	–	1	–	–	–	–	1	4	–	–	–	–	1	1	**23**	
WA	5	–	8	29	–	–	1	7	2	–	–	–	–	–	–	–	–	–	–	–	–	–	1	**53**	
Tas	1	–	5	2	–	21	–	–	–	2	–	–	–	–	–	–	–	–	–	–	–	–	–	**31**	
ACT	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	**2**	
NT	–	–	1	4	–	–	–	2	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**8**	
Aust		2	126	101	3	42	4	58	99	17	8	3	1	2	5	1	7	1	5	8	6	2	4		
Total	**79**		**229**																		270		6	**584**	
																								Total	
	Volume of reclaimed water used (GL)																							**GL reuse**	**GL eff.**
NSW	18.4	1.0	5.8	3.8	1.4	0.7	0.1	4.1	6.2	2.5	1.0	1.4	–	0	–	–	–	0	–	–	–	1.0	–	**47.5**	**694**
Vic	7.5	–	2.3	1.4	–	4.4	0.1	11.8	12.6	1.3	–	–	0.6	–	3.3	–	0.4	–	0.6	–	3.2	–	0	**48.8**	**448**
Qld	6.6	–	4.9	2.9	1.1	0.6	0.1	0.4	1.0	0.3	0.6	–	–	–	0.2	–	–	–	0.6	2.3	–	–	0.8	**22.4**	**339**
SA	4.2	–	0.3	3.6	–	1.6	–	0.1	0.4	–	0	–	–	–	–	7.7	4.1	–	–	–	–	0.5	0.4	**18.7**	**101**
WA	1.5	–	1.7	3.7	–	–	0.1	1.6	0.9	–	–	–	–	–	–	–	–	–	–	–	–	–	0.2	**9.7**	**126**
Tas	0.2	–	0.5	0.3	–	4.3	–	–	–	4	–	–	–	–	–	–	–	–	–	–	–	–	–	**5.8**	**65**
ACT	–	–	0.9	–	–	–	–	–	–	–	–	–	–	–	–	–	0.9	–	–	–	–	–	–	**1.8**	**30**
NT	–	–	0.2	0.8	–	–	–	0.4	0.4	–	–	–	–	–	–	–	–	–	–	–	–	–	–	**1.5**	**21**
Aust		1.0	16.6	16.5	2.6	11.6	0.4	18.4	20.8	4.5	1.6	1.4	0.6	0	3.5	7.7	5.4	0	1.2	2.3	3.2	1.4	1.4		
Total	**34.6**		**34.2**		**85.1**																	**2.9**		**156.2**	**1824**

Total values may differ due to rounding. These data are taken from Radcliffe (2004). Some wastewater treatment plants (WWTPs) were not covered in the survey. In some cases the split of volumes related to use were not recorded, resulting in estimated values determined by the authors.
^A Specific uses not identified; – none recorded.

quality of soil and by topography (HRDC and NLWRA 2001). In broad terms, the greatest intensity for tropical crop production occurs on the east coast of northern Australia while temperate crop production is most intense in the Murray-Darling Basin of south-eastern Australia. For a comprehensive assessment of the geographical distribution of horticultural production, readers are referred to the Horticulture – productivity and sustainability report (HRDC and NLWRA 2001).

Assessing suitability for reclaimed water use in horticulture

The horticultural industries (vegetables, fruit and grapes) use 2087 GL/yr of water (of 16 660 GL used by all agricultural industries). In comparison, the recreational industry (golf courses and sporting grounds) uses about 395 GL. Horticultural industries use only 51 GL of reclaimed water (representing 2.4%) compared with 33 GL by the recreational industry (representing 8.2%).

Growth of the horticulture industry is expected to continue, but with reliable access to water identified as one of the major impediments to growth and continued sustainability (HAL 2003). Horticulture industries are also frequently located in low-lying areas near major

Table 4.7 Gross value of agricultural production (A$ million), 2000/01.

Industry sector	NSW-ACT	Vic	Qld	SA	WA	Tas	NT	Australia
Vegetables	228	465	545	248	186	143	2	1817
Fruit	223	370	584	235	102	45	31	1590
Grapes	225	328	15	685	82	9	12	1355
Cotton	84	—	373	—	1	—	—	1222
Rice	346	4	—	—	—	—	—	350
Livestock, pasture, grains and other	322	452	486	110	153	64	4	1501
Dairy farming	178	956	123	126	38	78	—	1499
Sugar	1	—	278	—	5	—	—	1499
Total	2371	2574	2402	1405	567	339	49	9618

Source: ABS (2004).

cities (and treatment plants). The opportunity to further exploit reclaimed water as a resource for horticulture is apparent. Much of this increased use of reclaimed water will be associated with substitution of a less secure water source. This has already occurred in schemes throughout Australia and in many cases is the preferred option. It is also expected that some expansion of horticulture (whether it is traditional or novel products) will occur. Reclaimed water may therefore provide opportunities for either substitution of existing water resources in established horticultural districts, or expansion of horticulture regions reliant upon additional water resources. Matching reclaimed water resources to potential horticultural production will be critical.

Given that it is not economically or environmentally viable to pump water over long distances, suitability for horticultural crops will need to be assessed within a defined radius of a WWTP (considering topography and elevation requirements). The production of horticultural crops that can be grown in Australia is extremely diverse (ie from annual vegetable crops to perennial ornamentals or grapevines), with some type of horticulture being possible in a wide range of climates and soil types. Due to this extreme diversity the assessment of opportunities for reclaimed water use in horticulture (either for substitution or expansion) should be conducted at a regional scale.

Table 4.8 Value of water consumed (A$ million/GL), 2000/01 (data pooled across States).

Industry sector	A$ million/GL
Vegetables	3.27
Fruit	1.98
Grapes	1.86
Cotton	0.42
Rice	0.18
Livestock, pasture, grains and other agriculture	0.27
Dairy farming	0.53
Sugar	0.22
Agriculture	0.58

Source: after ABS (2004) data.

To assess regional suitability, it will be necessary to consider:

- local topography;
- soil types;
- climatic conditions (climate types, average rainfall and evaporation);
- the feasible distance from a WWTP;
- local infrastructure;
- markets (domestic and export); and
- crop type and end use.

The only way to ensure success of any expanded horticultural production in relation to reclaimed water will be to conduct case-by-case assessments of economic, environmental and social sustainability (eg Bluml *et al* 2002). A framework has been developed to assist in the analysis of reclaimed water for horticultural schemes considering all stakeholders (Boland *et al* 2004). Any expansion must assess the impact on current markets and the opportunities to expand these markets domestically or via export.

Conclusion

This chapter provides an assessment of the opportunities for reclaimed water use in Australian agriculture. Agriculture consumes about 67% (16 660 GL) of Australia's water resources (including self-extracted, mains water and reuse water). Although not the largest water users, horticultural industries (vegetables, fruit and grapes) use significant volumes of water, about 12.5% (2087 GL) of the total for agriculture. This estimate does not include cut flowers, nurseries and turf growing which are included in an aggregation of other agricultural industries. Golf courses and sporting grounds consume an additional 395 GL.

Reclaimed water use has increased from 134 GL in 1996/97 to 517 GL in 2000/01, making up 4% of the total water supplied by water providers. The agricultural industry was the greatest user of reclaimed water, accounting for 423 GL in 2000/01. Horticulture industries (vegetables, fruit and grapes) were moderate users of reclaimed water, accounting for 51 GL, while golf courses and sporting grounds used about 33 GL of recycled water.

Current use of reclaimed water by the horticulture industry is relatively minor (2.4%) when compared with other agricultural industries and recreational uses (eg golf courses and sporting grounds, 8.2%). Limitations to further increases in the use of reclaimed water include such issues as perceived public health concerns, social acceptance, economic viability (delivery costs), and environmental costs associated with reclaimed water schemes.

Horticultural crops are high value users of water and are therefore well positioned to secure additional water resources. They are frequently located in low-lying areas near major cities where pumping distances and elevations are reduced, providing opportunities for economically and environmentally viable reuse schemes. The diversity of horticulture crops also means that production is suited to many different climatic regions with a wide range of suitability to soil types.

The relatively high proportionate use of reclaimed water in golf courses and sporting grounds has been observed. This is probably due to the early development of these schemes using reclaimed water of classes lower than Class A (ie much lower cost and easier to achieve), and a limited understanding of reclamation and reuse of wastewater decades ago. Increasing use of reclaimed water for these purposes is likely to continue, and as the community more readily accepts reclaimed water for recreational use, there may also be a shift in their perceptions (see *Chapter 13*) of using reclaimed water for horticultural production. Greater confidence in reclaimed water schemes that use Class A water and advances in treatment processes and technology that have minimised any associated risks should also facilitate increased use in the horticulture industry.

It is critical that the assessment of suitability of reclaimed water for horticultural production be conducted at a regional scale. There are many factors that must be considered in this assessment but of particular importance is the analysis of market trends (either domestic or export). Reclaimed water is a potential resource that can be exploited by the horticulture industry for significant gain.

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5 Crop nutrition considerations in reclaimed water irrigation systems

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Soils and the fertilisers applied to them provide the major source of the elements essential for plant growth (Table 5.1). The remainder (carbon, C; hydrogen, H; and oxygen, O) come from water or gases (carbon dioxide, CO_2; and oxygen, O_2). In plants, macronutrients (nitrogen, N; phosphorus, P; potassium, K; sulfur, S; magnesium, Mg; and calcium, Ca) are typically found in concentrations about 1000 times those of the micronutrients (boron, B; chloride, Cl; copper, Cu; iron, Fe; manganese, Mn; molybdenum, Mo; and zinc, Zn). In addition to these essential elements, plants also contain a range of beneficial elements (eg nickel, Ni; silicon, Si; and sodium, Na), and virtually all other inorganic elements that are to be found in soils, whether they are benign or toxic (see *Chapters 8 and 9*).

Table 5.1 Essential plant elements obtained by root uptake from the soil.

Element	Principal roles in plant metabolism and in metabolites plant components	Nominal concentration	Mobility from leaves
	Macronutrients	(% DM)	
Nitrogen (N)	Major component of amino and nucleic acids, and chlorophyll	2.5	Mobile
Phosphorus (P)	Important component of ATP, used for energy storage and transfer, component of nucleic acids, lipids and cell membranes	0.2	Mobile
Calcium (Ca)	Membrane and cell wall maintenance and function, osmotic adjustment, ionic balance, important role in cell division	0.2	Immobile
Magnesium (Mg)	Ionic balance, photosynthesis, pH regulation, protein synthesis, carbohydrate partitioning, chlorophyll component	0.2	Variable
Potassium (K)	Cation-anion balance, pH regulation, stomatal control, energy and water relations, osmotic adjustment	1.0	Mobile
Sulfur (S)	Component of amino acids and proteins, used in energy transfer reactions (ferrodoxins)	0.1	Variable
Sodium (Na)	Ionic balance, C4 photosynthesis, enzyme activation	500	Mobile
Chlorine (Cl)	Ionic balance, enzyme activation	100	Mobile
Iron (Fe)	Electron transport (redox reactions), component of ferrodoxins	100	Immobile
Boron (B)	Not well understood, cell wall component, nucleotide synthesis	12	Immobile
Manganese (Mn)	Redox reactions in electron transport, protection from the hydroperoxyl radical (HO_2) in photosynthesis via Mn superoxide dismutase	20	Immobile
Zinc (Zn)	Growth regulation (component of auxin), nucleic acid and protein synthesis, enzyme activation, carbohydrate transformation, membrane integrity	20	Variable
Copper (Cu)	Terminal oxidation reactions, carbohydrate and nitrogen metabolism, lignification of cell walls, pollen formation and seed viability	3	Variable
Nickel (Ni)	Essential for metabolism of urea via urease	0.1	Mobile
Molybdenum (Mo)	Required for nitrate reduction, and for dinitrogen fixation in legume nodules (rhizobia)	0.1	Variable

Source: collated from Marschner (1995), Reuter and Robinson (1997), and Atwell *et al* (1999).
For some particular plants, or groups of plants (eg legumes), other microelements may also have critical roles, see Jones (1998).

Untreated wastewaters are likely to contain all of these nutrients. In terms of macronutrients, untreated wastewaters contain some 20 mg/L to 85 mg/L of N, 10 mg/L to 30 mg/L of P and K (Pettygrove *et al* 1985), all of which originate principally from human and domestic wastes. A substantial portion of the P load comes from detergents. Since only about 50% of this N and 60% of P are removed from sewage during treatment (Bahri 1998, see *Chapter 3*), reclaimed water contains much higher concentrations of these two important plant nutrients than other irrigation water sources. In general, the higher the level of treatment the lower the concentrations of N and P in reclaimed water. Much N can also be lost during storage of reclaimed water due to denitrification (Schmidt *et al* 2003). Other irrigation waters may not be completely free of these nutrients. For example, in the audit of Australia's water resources (NLWRA 2001), it was found that 61% of the river basins examined exceeded nutrient quality standards for surface waters. In this chapter we discuss the critical crop nutrition issues as related to reclaimed water irrigation, and some information on nutrient concentrations recorded for some reclaimed waters used for irrigation in Australia are presented in Table 5.2.

The quantity of nutrients required for crop production is principally a function of crop growth or yield, and inherent differences in the uptake and nutrient efficiency of crop species. The fraction of fertiliser applied which is removed in harvested products is, largely, a function of the plant part harvested. For example, for root crops, in which most of the N (and K) resides in unharvested parts of the plant (leaves), total crop N uptake is 4.8 kg N/t of carrots and 6.6 kg N/t of potatoes. This contrasts with total plant N uptake per tonne of harvested product of celery (1.6 kg N/t) and lettuce (2 kg N/t) for which almost all of the aerial parts of the plants are harvested. Leaf crops thus tend to have a relatively high N demand, root crops a relatively high P demand, and fruit crops a relatively high K demand.

Nitrogen uptake in vegetable crops ranges from 40 kg/ha for capsicum to more than 500 kg/ha for a high yielding tomato crop (Table 5.3). Crop phosphorus uptake ranges from 4 kg/ha (capsicum) to >100 kg/ha (tomatoes) and potassium from 60 kg/ha (cabbage) to >800 kg/ha (tomatoes).

Water use and loadings

The amount of nutrients supplied in reclaimed water irrigation are a function of the amount of water applied and the concentration of the nutrients in the water. In irrigation scheduling the amount of water applied is usually calculated from the crop evaporative demand, or evapotranspiration (ET) (see Pruit and Snyder 1985 and Allen *et al* 1998) (see also *Chapter 6*), the capacity of the soil to store water (total and plant available), rainfall, and the hydraulic conductivity of the soil (leaching rate). A leaching fraction is required in all irrigation systems, regardless of water quality, to remove the salts that inevitably build up in the plant rooting zone (see *Chapters 6 and 7*).

In practice, the quantity of irrigation water applied to a crop is usually in the range 300 mm to 1000 mm (3–10 ML/ha). In Figure 5.1 we show the relationship between the amount of water applied and the elemental load as a function of the elemental concentration of the reclaimed water, and crop. Loadings per crop grown are typically >1 t/ha each for Na, Cl, bicarbonate (HCO_3^-) and sulfate (SO_4^{2-}), about 50 kg/ha to 400 kg/ha for N, K and Ca, <25 kg/ha for P, <5 kg/ha for iron (Fe) and B, and <0.5 kg/ha for heavy metals. When more than one crop is grown per year, annual loadings could be much higher.

If the data in Table 5.3 and Figure 5.1 are compared, it can be seen that crop uptake of N, P and K often approximates the amounts applied in reclaimed water irrigation and thus these nutrients are less likely to accumulate in soils than Na^+, SO_4^{2-}, Cl^- and HCO_3^- for which crop uptake is typically much less than that supplied

Table 5.2 Nutrient concentrations reported for reclaimed waters used for irrigation in Australia.

NH_4^+-N	NO_3^--N	Total N	Total P	SO_4^{2-}	K^+	Reference
		10.3	1.2		47	Kelly *et al* (2001)
		8	4.5^A	60	14^A	Kaddous *et al* (1986)
12	1	19				Smith *et al* (1996)
2.6	3.9	7.3	6		16	Falkiner and Smith (1997)
10	19		7			Sakadevan *et al* (2000)

^{A} Olsen P and 'available' K.
Ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), sulfate (SO_4^{2-}) and potassium (K^+); all values (mg/L), missing values were not reported.

through reclaimed water irrigation. Reclaimed water usually contains enough zinc (Zn) to correct soil deficiencies within one to three years (Westcot and Ayers 1984), depending on the degree that the water is treated and the availability of Zn in the soil. Those nutrients in the high loading group (Na^+, Cl^-, HCO_3^- and SO_4^{2-}) contribute substantially more to soil salinity and sodicity (see *Chapter 7*) than they do to plant nutrition, and for high water use crops such as citrus, management of these nutrients becomes a major focus of water and nutrient management (see *Chapter 9*). It is theoretically possible that the very high K loads in reclaimed water could contribute to soil sodicity (Biswas *et al* 1999; see *Chapter 11*), although this does not appear to have been reported to date.

The N and P in reclaimed water can be a benefit to crop nutrient management, but high nutrient loads can also cause offsite problems. Nitrogen may be a threat to groundwater bodies through NO_3^- leaching, and P contributes to eutrophication of surface waters if it is carried in runoff (see *Chapter 11*). The B load in reclaimed water can cause B toxicity in sensitive crops (see *Chapter 9*). The loads of heavy metals are not likely to cause immediate problems for plants, but they may accumulate in the soil with continued applications of reclaimed water and become harmful to animals (including humans) that consume the produce (see *Chapter 8*).

Nutrient management

The aim of nutrient management is to optimise crop yield and produce quality, while minimising the dollar costs and environmental problems associated with over use of nutrients or fertilisers (see *Chapter 11*). Good crop nutrition also improves plant health through greater disease resistance and suppression (Marschner 1995). The underlying principles of best management practice (BMP) are to combine information from scientific and practical knowledge to optimise crop yield and quality, while ensuring the protection of the environment. Crop production should not be limited by undersupply (deficiency) or oversupply (toxicity) of nutrients. Figure 5.2 shows the relationship between plant nutrient concentration and yield. Ideally, the management of plant nutrition should target the lower end of the adequate range which produces the maximum yield at the least cost, and with the least likelihood of environmental problems from oversupply of nutrients. In practice this can be difficult to achieve. The provision of an adequate and balanced nutritional program becomes increasingly challenging as the intensity of production increases (Grundon 1987), and the use of reclaimed water adds yet another level of complexity.

Table 5.3 Crop macronutrient content uptake.

Crop	Typical yield (t/ha)	Plant part	Nutrient content (kg/ha)				
			N	P	K	Ca	Mg
Cabbage	50	Total	147	24	147	36	13
Capsicum	20	Total	41	4	69	52	7
Carrot	44	Root	100	14	90	15	6
		Leaf	110	5	180	160	12
		Total	210	19	270	175	10
Cauliflower	50	Curd	119	23	134	55	10
		Leaf	62	5	91	72	8
		Total	181	28	225	127	18
Celery	190	Total	308	97	700	290	38
Cucumber	18	Fruit	28	5	45	4	2
		Leaf and stem	38	7	75	30	6
			66	12	120	34	8
Lettuce	50	Total	100	18	180	10	3
Potato	40	Tuber	132	15	180	10	3
		Leaf and stem	132	8	130	56	18
		Total	264	23	310	66	21
Tomato	57	Leaf and stem	32	13	45	68	14
		Fruit	79	33	147	6	8
		Total	111	46	192	74	22
	194	Leaf and stem					
		Fruit	211	49	241	315	58
		Total	361	84	615	33	29
			572	133	856	348	87

Source: Creswell and Huett (1998).

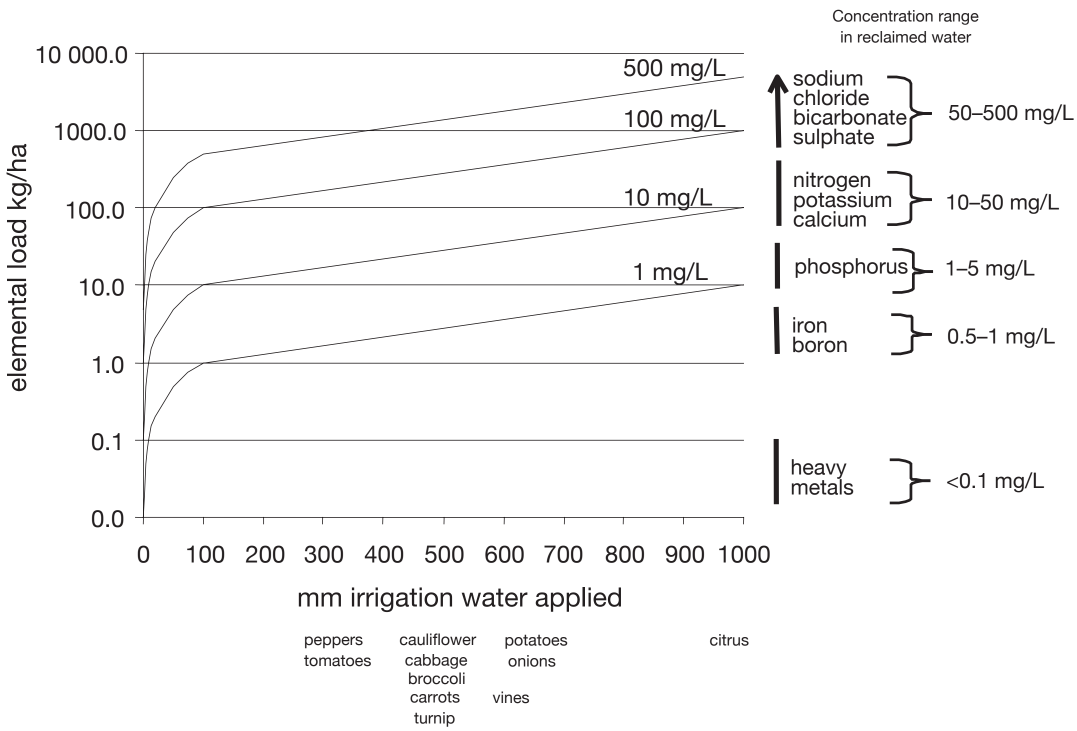


Figure 5.1 Relationship between irrigation water applied (mm), concentration of inorganic compounds (mg/L) and elemental load (kg/ha). The approximate range of concentrations for some reclaimed water constituents are indicated on the right, and approximate irrigation water needs of a range of crops underneath. This provides a guide to relative loadings of nutrients, heavy metals and salts for different crops. For example, for potatoes, which would typically receive some 600 mm to 700 mm irrigation, reclaimed water would add more than 1 t/ha of salt, <100 kg/ha of nitrogen and <10 kg/ha boron. Much larger loadings would be anticipated for a citrus crop and about half for tomatoes.

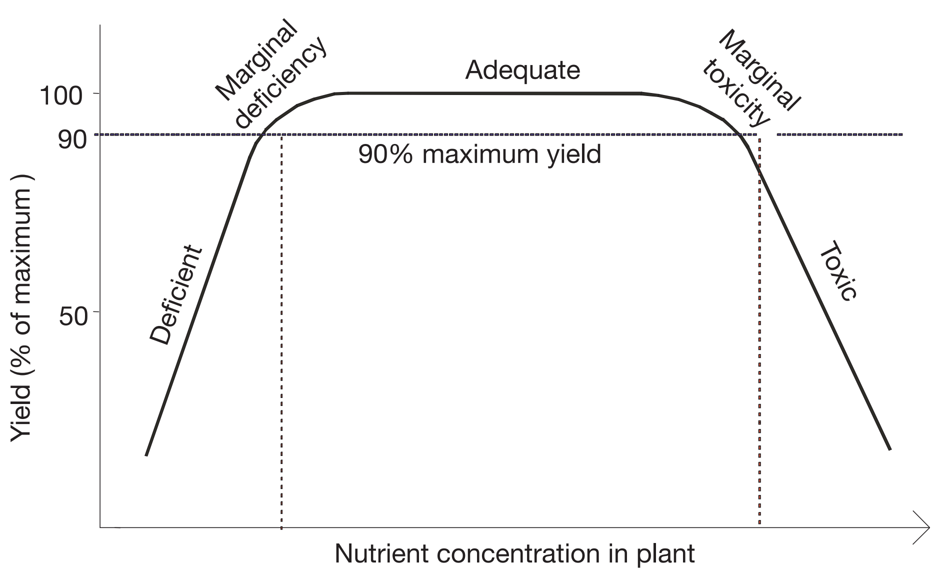


Figure 5.2 The relationship between plant nutrient concentration and crop yield.

The quantities of nutrients required by crops are calculated from estimates of crop demand, which requires realistic estimates of crop yield potentials, an understanding of the ability of the soil to provide available forms of nutrients, and knowledge of the fate of nutrients added in irrigation water and fertilisers. In the case of reclaimed water irrigation, nutrients are applied when water is used to meet crop water demands, not necessarily when plant nutrient demand is highest. If water and nutrient demands are not matched, overfertilisation may result, depending on the nutrient concentrations in the reclaimed water. Provided that growers develop nutrient budgets and have a soil or tissue testing program, underfertilisation should not be an issue as this can be readily corrected through fertiliser application. Critical nutrient values for crop tissue testing are discussed in Creswell and Huett (1998). Robinson *et al* (1997) provide detailed information for fruits, nuts and vines, and Huett *et al* (1997) for vegetable crops. See Peverill *et al* (1999) for interpretation of soil analyses.

The amount of nutrient applied in reclaimed water depends on the concentration of nutrients in the water, and the total depth of irrigation applied. The depth of irrigation will vary from season to season depending on evaporative demand. Table 5.4 is an example of the amounts of nutrient that would be added for a range of irrigation depths from a reclaimed water system on the North Adelaide Plains (Kelly *et al* 2001). The irrigation requirement for vegetables on the Northern Adelaide Plains, estimated using a model (LEACHM, Hutson *et al* 1997) and 24 years of historical rainfall data (1972–96), was predicted to vary from 340 mm in the wettest year, to 820 mm in the driest year. Clearly, the amount of nutrients added would then vary by more than two fold depending on seasonal irrigation requirements, making it necessary for growers to adjust fertiliser applications depending on seasonal conditions. In the case of many other water sources this would not be necessary since the amount of nutrients added in fertiliser could be maintained independently of the quantity of irrigation applied.

There are, however, other factors that need to be considered when constructing nutrient budgets for reclaimed water irrigation schemes. These include water use efficiency, uniformity of distribution (see *Chapter 6*), leaching rate and losses of nutrients from water and soil, particularly N (see *Nitrogen in soils and reclaimed waters*).

The fate of nutrients applied in reclaimed water must be understood to formulate reliable nutrient management programs and reduce losses from the site of application. There are benefits to growers in the supply of nutrients from reclaimed water (Table 5.4) which reduce the need for fertilisers, and the constant supply of nutrient in reclaimed water can promote more balanced and healthy plant growth (Hartling and Nellor 1998). Traditionally, a large proportion of the crop's fertiliser is applied prior to, or at planting, due to logistical problems associated with side dressing of crops later in the season (Creswell and Huett 1998), yet plants generally grow best when the nutrient concentration at the root surface is maintained close to the plant uptake rate. Since the amount of reclaimed water applied will mostly be a function of evapotranspiration, and this will increase with crop leaf area, increasing amounts of reclaimed water (and nutrient) application, are likely to be concomitant with crop nutrient demand. It could thus be expected that in many situations using reclaimed water irrigation may match nutrient supply with crop demand better than by using other water sources with fertilisers. For example, working in Victoria, Kaddous and Stubbs (1983) demonstrated that irrigation with reclaimed water provided a more even supply of nutrients than the use of conventional irrigation water plus bag fertiliser, and also provided some production benefits. Nevertheless, Pettygrove and Asano (1985) highlighted potential problems that can occur when nutrient loadings do not match plant requirements, particularly increased vegetative growth, which can reduce produce quantity and quality.

Table 5.4 Nutrients applied (kg/ha) from the Virginia Pipeline Scheme, South Australia, at different irrigation depths.

	Irrigation water applied (mm)							
Nutrient	300	400	500	600	700	800	900	1000
Nitrogen	25	33	41	49	58	66	74	82
Phosphorus	3.5	4.6	5.8	6.9	8.1	9.2	10.4	11.5
Potassium	141	187	234	281	328	375	422	468
Calcium	120	160	200	240	280	319	359	399
Magnesium	93	123	154	185	216	247	278	308
Chloride	1146	1528	1910	2292	2674	3056	3438	3820
Boron	1.1	1.5	1.8	2.2	2.5	2.9	3.3	3.6

Source: Kelly *et al* (2001).

Nutrient uptake, and crop yield and quality

Kelly and Stevens (2000) estimated the proportion of the nutrient requirement provided by reclaimed water in a reclaimed water scheme in South Australia for various crops (Table 5.5). For most of the crops investigated, <50% of the plant's N and P needs could have been met by the reclaimed water, while 150% to 1200% of the amount of K in the harvested produce was applied in the reclaimed irrigation water. However, not all of the nutrients applied as fertiliser or in reclaimed water will be available for plant uptake, since plants typically take up no more than 50% of applied N (Bacon 1994) or P (Ryden and Pratt 1980). In experiments in Victoria, Kaddous and Stubbs (1983) found that, on average, reclaimed water contributed 60% of the N, 33% of the P and 40% of the K requirements in a range of crops (*see Chapter 1*). They estimated that this represented a 35% saving in fertiliser costs at their irrigation rates.

Similarly, Smith (1982) found that across crops and seasons, irrigation with reclaimed water reduced fertiliser costs by up to 75%, and the use of groundwater reserves by 0.64 ML/ha to 5.6 ML/ha per crop. There was no significant accumulation of heavy metals in soils or crops. This author also reported increased crop yields under the reclaimed water system and attributed this to a more regular nutrient supply from the reclaimed irrigation water which better matched crop growth than that provided by irrigation with groundwater and applying bag fertiliser prior to sowing or as a side dressing. Where the conventional fertiliser regime was used together with reclaimed water, crops (lettuce, carrots, cabbage, celery, spinach and tomatoes) took longer to mature and had a higher percentage of non-marketable produce.

Table 5.5 Nutrients applied in reclaimed water as a percentage of nutrient removed in crop produce.

		Nutrient applied (% nutrient removed in crop)		
Crop	Yield (t/ha)	N	P	K
Cabbage	40	35	25	160
Capsicum	20	126	150	341
Carrots	44	25	32	87
Cauliflower	50	43	26	175
Celery	190	416	271	34
Cucumber	18	416	271	1180
Lettuce	50	62	40	157
Potato	40	55	56	183
Tomato	194	53	27	143

Source: Kelly and Stevens (2000).

In Australia, Premier *et al* (2000) found that the use of reclaimed water (effectively only secondarily treated) for irrigation of potatoes produced yields, potato size, disease levels, postharvest storage life, colour and cooking characteristics similar to crops irrigated with fresh water. Heavy metal concentrations were also similar in both sets of potatoes, and were well below risk levels. They concluded that potatoes grown with reclaimed water were of an equivalent quality to freshwater irrigated crops.

In Florida, USA, Zekri and Koo (1994) examined citrus fruit quality and production at 32 sites irrigated with either reclaimed or groundwater. They concluded that, over the six years, any differences in fruit yield and quality were due to differences in total water applied (reclaimed water sites had more water applied) and not due to the nutrient composition of the water. Although there were higher levels of some ions in the leaves of reclaimed water irrigated plants, the fruit quality remained well within acceptable standards. In other studies in the United States (Neilsen *et al* 1989a), yields of vines trickle irrigated with reclaimed water were higher than those irrigated with well water, despite the latter receiving more than 34 g N/vine per year. They concluded that the additional P and K applied in the reclaimed water contributed to the increased yield. Although this reflects poor crop nutrition rather than beneficial effects of the reclaimed water per se, it illustrates the economic value of the nutrients contained in reclaimed water. These authors found similar results from parallel studies on apples (Neilsen *et al* 1989b) and cherries (Neilsen *et al* 1989c). Other studies comparing reclaimed and non-reclaimed sources of irrigation water in lettuce, celery, sorghum, and maize have reported yield increases from using reclaimed water, especially in nutrient-deficient environments (Marecos do Momonte *et al* 1996; Sheikh *et al* 1998).

If nutrient concentrations in the reclaimed water are high, the ability of crops to use the nutrients applied with the water must be considered (Myers *et al* 1995; Vazquezmontiel *et al* 1996). Growers and managers may need to rotate crops to enable the removal of any excess nutrients applied through reclaimed water irrigation, or mix the reclaimed water with a low nutrient water source to avoid overfertilisation, and more importantly, offsite impacts (see *Chapter 11*).

The use of reclaimed water in irrigation not only affects the yield of the crop but can also affect quality. Very high concentrations of N, P and K, for example, can reduce fruit firmness, and high concentrations of K, relative to Ca, can increase fruit textural disorders (Sams 1999). Calcium was highlighted as being the element most critical to fruit quality as it contributes more to the maintenance of firmness than any other element, and may be more significant than storage conditions for some fruits such as apples. Thus, the relatively high cation content (particularly Ca^{2+}) of reclaimed water might contribute to improved firmness and textural quality of fruits. Produce quality and shelf life of crops grown with reclaimed water appear to be as good as, and in some cases superior to, produce grown with well water (Sheikh *et al* 1998).

In Chapter 9, evidence for interactions between salinity of reclaimed waters and crop nutrition is reviewed. The main effect of salinity is the reduced osmotic potential in the root zone and this cannot be alleviated by improved crop nutrition. However, where crop nutrition is suboptimal and salinity high, such as under reclaimed water irrigation, competitive nutrient exclusion and ionic imbalances are more likely to occur than under non-saline conditions. Thus, for reclaimed water irrigated crops, an optimal supply of plant nutrients can become a more critical element of crop management.

Turf culture nutrition

Turf grasses are well suited to the nutrients applied in reclaimed water. Grasses are effectively a leaf crop, and so they have a relatively high N requirement and are often tolerant of salt and flooding (George *et al* 1984). Moreover, mowing removes toxic ions as they accumulate in leaves. Furthermore, maximum production is not usually required, and so growth reduction due to salinity may not be a major drawback. Mujeriego *et al* (1996) described a reclaimed water system for irrigation of a golf course in Portugal. The study found that the nutrient content of the reclaimed water varied considerably, resulting in overfertilisation in summer and underfertilisation in winter. To circumvent this problem two storage ponds were used to produce different quality waters to manage nutrient inputs. When excessive N was applied in summer, the turf was observed to suffer from fungal infections (*Puccinia*, *Fusarium* and *Sclerotinia*) in the following autumn. Low Fe compared to N and P meant that some Fe deficiency was observed in the turf. Applications of iron chelate overcame this deficiency. Nevertheless, substantial savings in fertiliser use were achieved by the additions of nutrients in the reclaimed water. This study is an excellent example of how problems that arise from using reclaimed water for irrigation of amenity turf can be addressed by developing appropriate water management programs.

In the United States secondary treated effluent is used for turf production. Work by Hayes *et al* (1992a,b) and Mancino and Pepper (1992) highlights the care that is needed with N and Fe management to maintain turf quality relative to irrigation with potable water. However, with appropriate management significant savings in fertilisers can be obtained. The high levels of P in the reclaimed water eliminated the need for P fertiliser, but reduced Fe availability, which was corrected with a foliar spray of iron sulfate. Nitrogen fertiliser was required only when reclaimed water was used during times of low water application in autumn and winter. On heavy clay and high traffic soils additional applications of gypsum may be required to maintain an adequate leaching fraction, although this is soil and water dependent. Also in the United States Wu *et al* (1996) studied growth and nutrient (N, P and S) uptake by a mixture of five turf grass species irrigated with simulated wastewater with varying concentrations of ions (Cl^-, Mg^{2+}, Ca^{2+} and K^+) but with no nutrient (N, P and S) enrichment. The turf was fertilised every second month during the study. Growth rates of the five species were not influenced significantly by the ionic concentrations of the irrigation water (0.57–6.05 dS/m). The study showed that at low ion concentrations (2.3 dS/m), more than 60% of the added Cl^- was removed in grass herbage clippings. They concluded that turf grass could be very effectively irrigated with reclaimed water.

For the remainder of this chapter we will focus on the two macronutrients (N and P) that are generally considered the most significant nutrients provided in reclaimed water.

Nitrogen in soils and reclaimed waters

Nitrogen undergoes many transformations as it moves through the atmospheric, water, soil, plant and animal pools. Some of the most important flows and transformations are shown in Figure 5.3. The different forms of N have different physical and chemical properties that affect their fate (Brady and Weil 1999). For example, although N_2 gas makes up 78% of the atmosphere, under ambient conditions it is chemically inert, reducing its availability to most plants (Fernandes and Rossiello 1995). There are bacteria that can 'fix' atmospheric N_2, such as the free-living *Azotobacter*, and

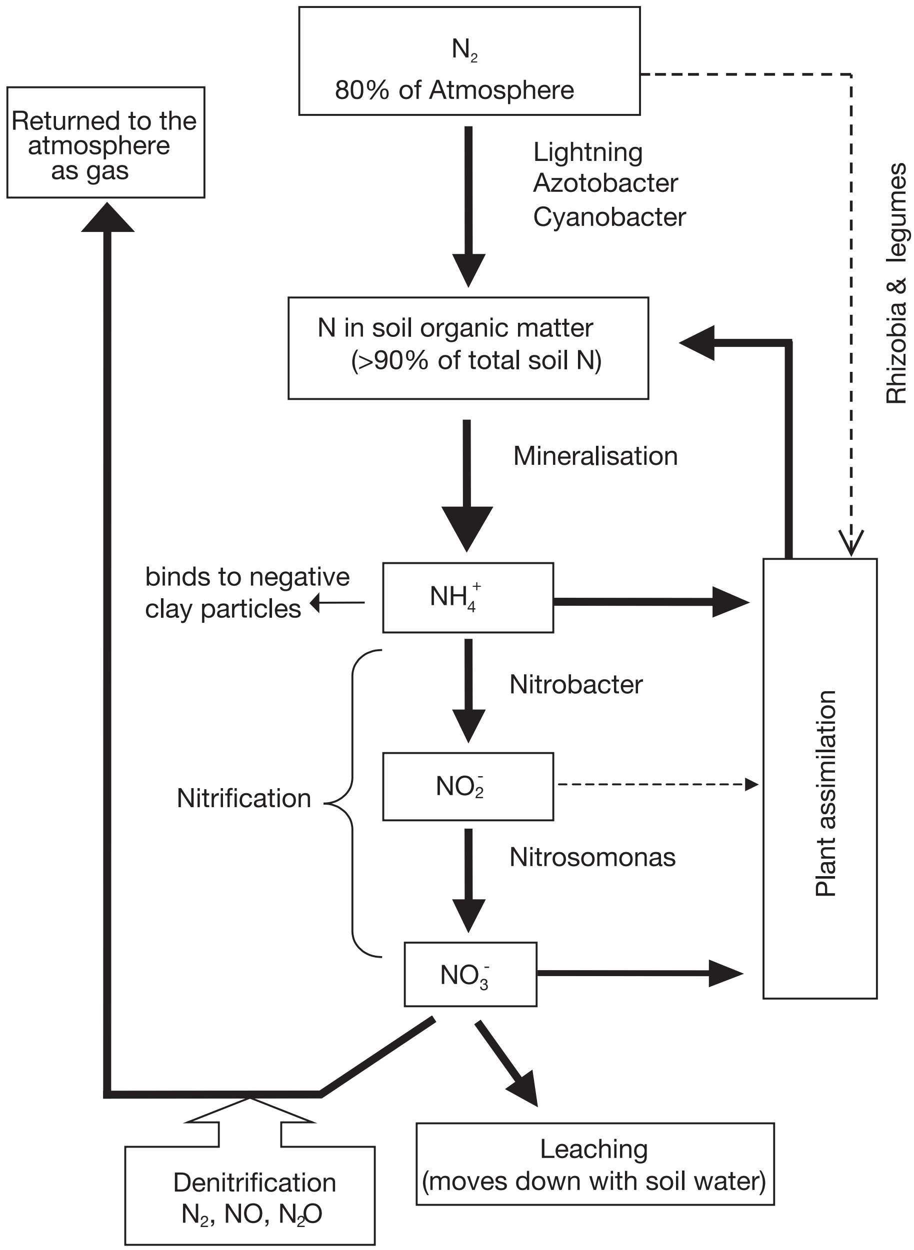


Figure 5.3 Key processes in the nitrogen cycle.

Rhizobia which fix N_2 in the soil and pass it on to legumes (peas and beans) via a special symbiosis (Sprent 1990). In the soil, N resides primarily in organic matter but this can be converted to plant-available NH_4^+ and NO_3^-. The conversion of NH_4^+ to NO_3^- is known as nitrification. A wide range of heterotrophic microorganisms release NH_4^+ from organic matter. This is then converted to NO_2^- by a very specific bacteria (*Nitrosomonas*), followed by the rapid conversion of NO_2^- to NO_3^- by another group of specialised bacteria (Nitrobacter). While plants are able to utilise $NH4^+$, NO_2^- and NO_3^-, in practice very little NO_2^- is taken up by plants because it is converted to NO_3^- by Nitrobacter immediately after it is formed from NH_4^+, and thus concentrations in the soil are usually extremely low. Exports of N from the plant-soil system occur from harvest of plant products, leaching of NO_3^- (if water moves down the soil profile beyond the root zone), denitrification (conversion of NO_3^- to gas under anaerobic conditions), NH_3 volatilisation under high NH_4^+ ion concentration and pH, and runoff or erosion. Gaseous losses could be considered useful management tools where there is a requirement to reduce N loads from reclaimed water onto soils, while NO_3^- leaching and runoff losses may pose considerable offsite problems (see *Chapter 11*).

Nitrogen occurs in three forms in reclaimed waters: organic-N, ammonium (NH_4^+-N) and nitrate (NO_3^--N) (see Table 5.6). The processes of mineralisation, nitrification, denitrification and volatilisation (as described above) occur in reclaimed waters as well as soils. During water treatment, cycles of aerobic and anaerobic conditions occur which promote nitrification and denitrification, and the loss of N to the atmosphere (see *Chapter 3*; Adin 1998). Loss of N may continue during storage of treated water causing the N content to decline between treatment and end use. Monnett *et al* (1995) found that denitrification in spray irrigated reclaimed water fluctuated with anoxia, caused by irrigation frequency. Gaseous losses averaged 5.3% and 26.2% of applied N for 12 mm and 25 mm irrigations per week, respectively. Since the objective of the system was to reduce N loads, the loss of N was considered to be a benefit. Under waterlogged (anaerobic) conditions denitrification may reduce NO_3^- concentrations in wastewater (Schmidt *et al* 2003) and groundwater (Wilson *et al* 1995). Kim and Burger (1997) found that when reclaimed water was applied at high rates of irrigation in forests, denitrification increased and contributed significantly to the bioremediation process by removing nitrate that otherwise would have been leached. Nevertheless, a net loss of N from leaching still occurred. Working in a forest plantation in south-eastern Australia, Smith and Bond (1999) found that losses of N under effluent irrigation were mostly due to leaching and not to denitrification.

Gaseous ammonia (NH_3) may also be lost from reclaimed water. The major factors which influence NH_3 volatilisation are wind speed, temperature, and pH (Freney *et al* 1983). Increases in all of these can increase volatilisation, but increasing pH>7 is the most critical. Reclaimed water pH is generally alkaline (Asano *et al* 1985) and so significant losses from volatilisation may be expected. Working in Victoria, Smith *et al* (1983) found that 38% to 82 % of the ammonia in reclaimed water was lost by volatilisation during water storage. Losses of NH_3 can also occur after irrigation. In a pasture irrigated with reclaimed water at Wagga Wagga, New South Wales, NH_3 flux density after irrigation was strongly related to evaporation. Under high evaporative demand, up to 24% of the NH_4^+-N in the reclaimed water was lost by volatilisation within two days of application (Smith *et al* 1996).

Although they are not easily measured at the field level gaseous N loss and NO_3^- leaching processes are important in determining both the availability of mineral N for crop growth, and the offsite impacts of reclaimed water irrigation systems.

Nitrate concentrations in reclaimed waters range from 0.2 mg NO_3^--N/L to 20 mg NO_3^--N/L (Westcot and Ayers 1984), and loads range from 1.0 kg NO_3^--N/ha to 200 kg NO_3^--N/ha for a 500 mm application of reclaimed water (Figure 5.1). However, reclaimed water is not usually the primary source of NO_3^- in the soil since NO_3^--N is produced from mineralisation of soil organic matter. It can also be produced by mineralisation and nitrification of organic N in reclaimed waters. In the studies of Polglase *et al* (1995) in a pine plantation irrigated with effluent, most of the N that was mineralised (<410 kg/ha) was converted to NO_3^-, with nitrification rates averaging about 80% of mineralisation rates. This illustrates that all N in reclaimed water potentially can be converted to NO_3^-. For this reason the Australian guidelines (ANZECC and ARMCANZ 2000; see *Chapter 2*) use total N as the indicator of the risk of NO_3^- pollution.

Nitrogen and crop management

Nitrogen is generally the nutrient that needs to be supplied to crops in the largest amounts (see Table 5.3). In crops irrigated with reclaimed water, matching water and N supply can be difficult since growers lose some control over the timing of fertiliser application (Baier and Fryer 1973). If periods of peak crop water demand do not match peak N demand, N supply may be in excess of crop requirements. This may reduce produce quality or cause a decline in yield, depending on the crop being grown, and cause offsite environmental problems. As N is probably the most variable component of reclaimed water (Westcot and Ayers 1984) these problems are complex and need to be addressed on a site-by-site basis. The importance of interactions between water and N in crop production has been well studied (eg Pier and Doerge 1995) and it is not necessary to discuss them here as they are not unique to reclaimed water irrigation.

Huett (1996) reviewed the influence of N nutrition on the vegetative to reproductive balance of horticultural crops. He concluded that tree crops were generally unaffected because much of the N demand for seasonal growth is met by utilisation of stored reserves, and N uptake often occurs during maturing and after fruit set. The exception was citrus where yield was depressed by high N. For vegetable crops, growth and yield were generally both depressed with excessive N, except for tomato, for which yield increased under high N fertility.

Baier and Fryer (1973) reviewed the principal concerns that relate to overfertilisation of horticultural crops with N. A precis of the major issues is as follows. If too much N is applied, yield can be reduced, particularly in perennial crops. The date of maturation of crops may also change (but not yield), or fruit size can decrease (eg peaches). Grape varieties respond differently to excess N: Malbec is very sensitive, and Pinot Noir one of the least sensitive. The principal problem for grapevines is caused by preflower bud shatter when tissue NO_3^--N reaches 1%. Problems may persist for more than one year if cane wood quality declines and impacts on next year's growth and yield. Grapes can also accumulate phytotoxic levels of NO_3^-. In potatoes and sugar beets too much N results in excessive vegetative growth and thus fewer and smaller tubers. Navel and Valencia oranges, when fertilised during the summer with excessive N (>17 g/m^2), produce grainy, pulpy oranges with less juice, and overfertilised Valencias can also regreen when ripe. Lemons are rarely affected by overfertilisation. Most stone fruit suffer a delay in maturation from overfertilisation rather than a direct decrease in quality, because high N levels keep the plants vegetative for longer, using up carbohydrates which are otherwise stored in the fruit. With melons and squash, excessive vegetative growth induced by high rates of N may keep moisture content high around the fruit and provide conditions conducive to development of rot.

In terms of plant toxicities, N is not usually a large problem, even though plants are able to take NO_3^- up very rapidly. Nitrate is not normally accumulated in high enough concentrations in food crops to be a problem for plant toxicity or human health (Broadbent and Reisenauer 1985). Leaf crops typically accumulate the highest levels of NO_3^- (Bergman 1992), if it is available in the soil. High NO_3^- concentrations in plants are much more likely to be a problem for grazing ruminants than humans (Harris and Rhodes 1969) since humans do not often eat sufficient amounts for problems to occur. The exception to this may be spinach which can accumulate as much as 3.8% of its dry weight as NO_3^- (Marschner 1995) if grown in high NO_3^- environments and large quantities are consumed.

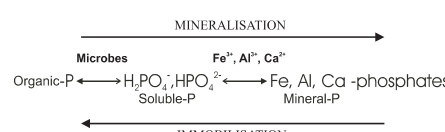
Where N applied in the irrigation water exceeds the demand of annual crops and NO_3^- builds up in the soil, annual or perennial fodder crops could be grown to reduce the potential for NO_3^- leaching as these often have a high capacity to scavenge N (Pettygrove *et al* 1985). The turf systems described previously are a good example.

Phosphorus in soils and reclaimed waters

Australia has some of the least P fertile soils in the world, resulting from extensive weathering of coarse-textured soils (Brady and Weil 1999; Moody and Bolland 1999). Most of the P found in soils is not phytoavailable, being strongly adsorbed to soil or precipitated in insoluble compounds. When soluble forms of P are added to soils they can quickly become fixed and unavailable to plants (Brady and Weil 1999). Phosphorus can be immobilised into both organic and inorganic forms, typically allowing only 10% to 40% of fertiliser P to be utilised by plants in the year of application (Wild 1988).

The several interacting P pools in soil are shown in Figure 5.4. The concentration of labile P in the soil solution is very low, ranging from 1μg/L to 1 mg/L in infertile and fertile soils respectively (Brady and Weil 1999). This is a small fraction of the total soil P; the largest fraction is held in non-labile organic forms (≥80%). Plants can only utilise phosphate ions from the small labile pool, which is not generally large enough to meet the needs of the plant without mineralisation from the non-labile pool.

The microbial decomposition of residues can both mobilise and immobilise P. Soluble P produced from microbial mineralisation is subject to fixation reactions in the presence of iron, aluminium and calcium (Eqn 5.1).



Equation 5.1 Mineralisation reactions of soil phosphorus showing the processes of mineralisation and immobilisation. After Brady and Weil (1999).

Soil pH has a large influence on P fixation since it controls the presence of active forms of iron, aluminium and calcium (Figure 5.5). Iron and aluminium phosphates form insoluble hydrous oxides at about

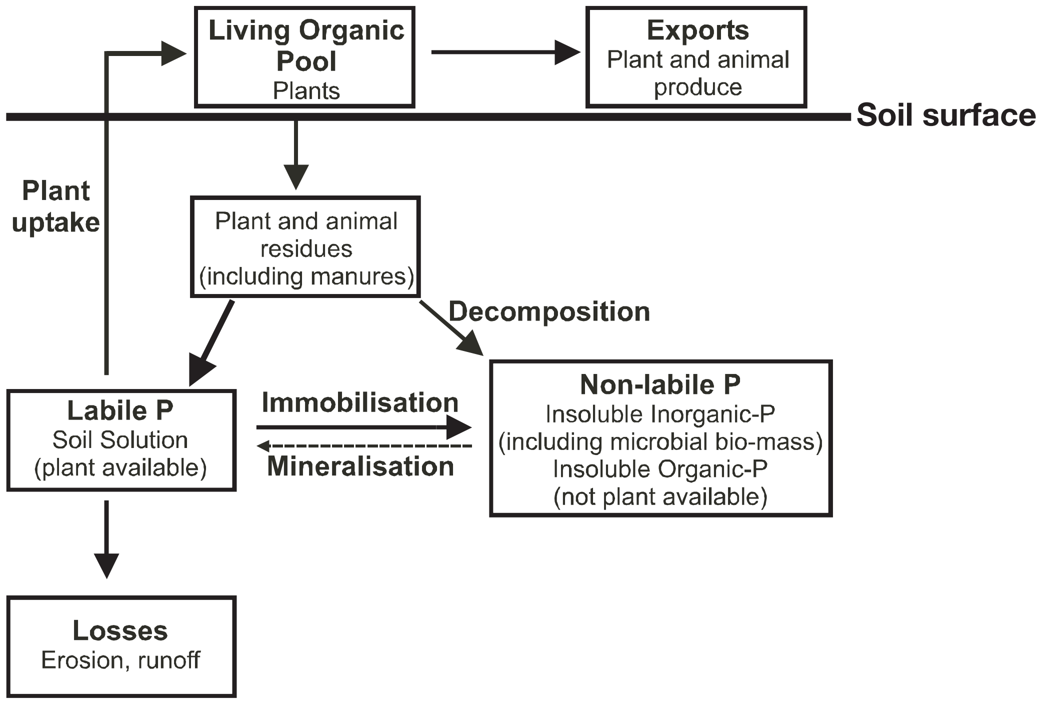


Figure 5.4 Some pathways for phosphorus transfer in the plant-soil system. After Brady and Weil (1999) and Moody and Bolland (1999).

pH<6, and in soils with a pH>7 calcium carbonate reacts to form insoluble calcium phosphates. A typical pH of reclaimed water is pH 7–8 (Asano 1998), which might provide no more than a moderately P fixing environment. A neutral to slightly acidic soil, about pH 6.5, should provide the greater P availability. This can be controlled to some degree through the application of soil amendments like lime which can increase soil pH.

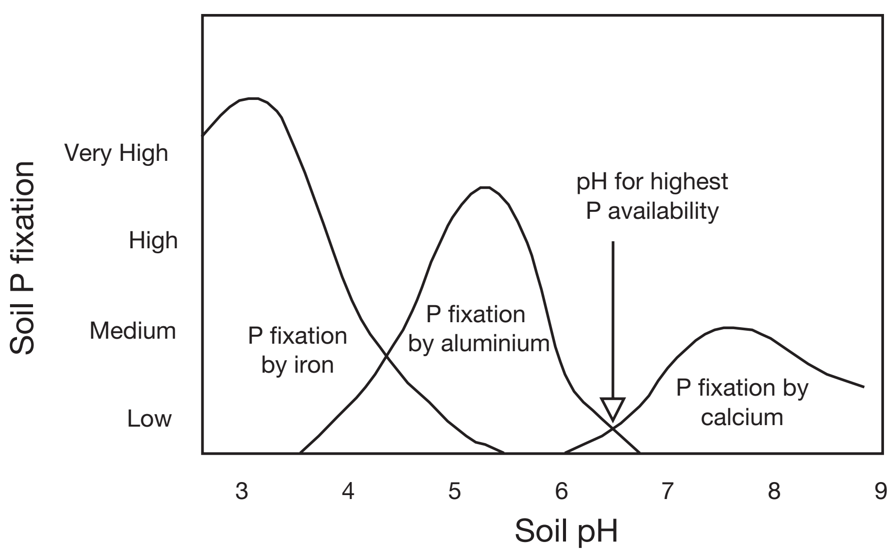


Figure 5.5 Relationship between soil pH and phosphorus fixation by iron, aluminium and calcium. After Glendinning (1999).

Phosphorus in reclaimed water may be organic or inorganic, both forms of which may be dissolved or particulate (Table 5.6). Dissolved P is generally readily bioavailable (approximately equal to phytoavailable), but the bioavailability of particulate P can vary from 10% to 90% (Tunney *et al* 1997). Particulate P usually requires microbial or chemical breakdown for release to a more readily phytoavailable form. Phosphorus concentrations in reclaimed water are typically <10 mg/L (Asano *et al* 1985) and usually very much less than N (Figure 5.1). Phosphorus in reclaimed water is stripped from the water as it moves through the soil since the P concentration in soil solution is lower than that of reclaimed water (Ryden and Pratt 1980). The slower the water moves through the soil, the more P is stripped out. In contrast to N, very little P is leached from agricultural soils. Compared to many other anions, phosphate has a relatively low mobility in the soil and is thus not prone to leaching. Nevertheless, when 34 kg P/ha (as single superphosphate) was applied to a pasture, 48% (16 kg P/ha) leached, compared to 26% (22 kg P/ha) of 86 kg P applied in reclaimed water irrigation (Sakadevan *et al* 2000). These results were obtained in sandy soil (>70% sand), which is prone to leaching. Presumably the more incremental application of phosphorus via reclaimed water contributed to the reduced leaching. When plant demand for P is less than the amount being applied, accumulation of P in the soil is more likely than leaching since much more of it is likely to be immobilised than say, for N (see *Chapter 11*).

Table 5.6 Nitrogen and phosphorus in reclaimed water used for irrigation on the Northern Adelaide Plains, South Australia.

Compound (mg/L)	Bolivar Channel reclaimed water, 1995	DAFF[A] treated reclaimed water, 1995	Bolivar Channel reclaimed water, 1998/9
Organic N	12.8	4.6	13
Ammonia	34.2	28	19
Nitrate	0.04	0.08	1.7
Total P	6.9	1.1	3.9
Soluble P	1.6	Not reported	0.62
pH	7.3	7.2	7.9

Source: Kelly and Stevens (2000).
[A]DAFF = Dissolved Air Flotation Filtration

Phosphorus and crop management

Based on the data of Table 5.5 the P supplied in reclaimed water would be insufficient for crop requirements in most cases. For example, total P concentrations in the reclaimed water would not meet more than 50% of plant P requirements, even if we assume that no P is immobilised from the reclaimed water. In general, the P added in reclaimed water is likely to be of great benefit to horticultural crops. The authors are unaware of any adverse effects on crop nutrition when using recycled water as a source of P. It is unlikely that overfertilisation with P will occur from reclaimed water irrigation, since most of the P will be immobilised in the soil and not be readily available to plants (Ryden and Pratt 1980). The exception to this is for some native plants. Phosphorus toxicity is a recognised problem for some sensitive native plants adapted to oligotrophic (nutrient poor) soils. Where plants are grown on these soils in gardens, additions of readily soluble P is likely to result in toxicity for sensitive species. Concentrations of P in reclaimed water are unlikely to be directly toxic in this context as most of the P is not in a soluble form, and the total P concentration would very rarely exceed 10 mg/L. However, if reclaimed water is used together with soluble P fertilisers the risk of P toxicity is greatly increased. Control measures would include reducing soluble and total P fertiliser inputs, selecting less P sensitive species for light soils, addition of iron chelates to relieve iron deficiency and P toxicity, and increasing soil pH for acid soils.

Summary

In general, reclaimed water provides an excellent nutrient source for crop production that can reduce grower fertiliser costs, provided that careful attention is paid to nutrient budgeting. Additional fertilisers may or may not be required depending on nutrient loadings (irrigation depth and nutrient concentration), the crop being grown, and background soil fertility. This must be assessed on a site, crop and year basis.

Gaseous and leaching losses of N are not easily measured at the field level but are important in determining plant available N in soils and reclaimed waters and the offsite impacts of reclaimed water irrigation systems.

There is little evidence to suggest that crops irrigated with reclaimed water, and managed appropriately, produce food of lower quality or shelf life than crops irrigated with other waters. In some cases, such as tomato, produce may have enhanced flavour when irrigated with reclaimed water.

Those nutrients in the high loading group (Na, Cl, HCO_3 and SO_4^{2-}) from application of reclaimed water contribute substantially more to soil salinity and sodicity (see *Chapter 7*) than they do to plant nutrition. Potassium could potentially contribute to sodicity at very high loadings.

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6 Design and management of reclaimed water irrigation systems

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As the world's population increases the need for good quality water to meet municipal, industrial and environmental demand will also increase. Agriculture is the largest user of water and will be, in many cases, the logical user of reclaimed water. However, it is anticipated that irrigated agriculture, which is now supplying 40% of the world's food supply on 20% of the farmed land, will be expected to increase production with a diminished water supply. Reclaimed water may be a significant source of water to meet the demands of irrigated agriculture (see *Chapter 4*). As such, it is a valuable resource that needs to be fully utilised to maintain crop production.

As with all water sources, reclaimed water needs to be assessed against a range of parameters for its suitability for irrigation. These parameters can affect crop growth and quality, soil chemical, biological and physical properties, and irrigation equipment. Consideration of these factors when designing and operating an irrigation system will help to increase the sustainability of the scheme, and reduce operating costs.

This chapter considers the design and management of irrigation systems using reclaimed water in terms of irrigation supply volume and quality, reductions in environmental degradation and maintenance of crop production. In particular we focus on the suitability of furrow, sprinkler and drip irrigation for production of horticultural crops using reclaimed water.

Irrigation water requirements

Irrigation requirements have been defined as being equal to the difference between the crop water requirement and the depth of rainfall at a location (Allen *et al* 1998). Rainfall can be measured easily using standard meteorological equipment, but the crop water requirement is more complex. More water has to be applied than required for the crop to grow, to leach salt down the soil profile and possibly to account for non-uniform distribution of irrigation water. The extra water used to displace salt is termed the leaching requirement (LR) and is a function of soil salinity, crop salt tolerance and growth stage, and the quantity of water applied. Distribution uniformity is a function of the irrigation system type, design and management. As uniformity decreases, additional water needs to be applied to ensure that all portions of a field receive the required depth of application. Inefficiency in the irrigation system can sometimes provide adequate deep percolation to meet the leaching requirement. In this situation, an additional depth of water is not included in the calculation of the irrigation requirement.

Crop water requirement

The crop water requirement is the water required to meet evapotranspiration losses from a cropped field (evaporation from soil and transpiration from the plant), or the minimum amount of water to be supplied, that will not result in crop water stress. Evaporation losses from free water surfaces are affected by air temperature, radiation, humidity and wind speed.

Soil evaporation losses are also affected by the amount of shading, water availability at the soil surface, soil water content, soil type (clay content) and the depth to shallow groundwater. For example, fine-textured soil has the capability of transmitting water by capillary rise from deep (up to 2 m) within the soil profile if the evaporative demand is low. As the soil surface dries, the potential loss drops significantly because hydraulic conductivity is reduced.

Crop transpiration is the vapourisation of liquid water contained in plant tissues and the removal to the atmosphere. Water is taken up by the roots and transported through the plant and to the leaf where the vapourisation occurs. Stomata control the vapour exchange between the leaf intercellular space and the atmosphere. Nearly all the water taken up by the plant is lost by transpiration. Transpiration is driven by the same factors as evaporation. This means that radiation, humidity, wind speed, temperature and vapour pressure gradient have to be included in the determination of transpiration. Other factors affecting transpiration include crop type, variety, developmental stage, canopy roughness, rooting characteristics, crop height, percentage ground cover, plant stand and resistance to transpiration. Waterlogging may reduce transpiration due to root damage and poor plant health from anaerobic conditions in the root zone.

Management and environment have a significant effect on evapotranspiration through plant health and water availability. Crop development and evapotranspiration may be limited by salinity, poor plant nutrition, pests and compacted or impenetrable soil layers. Windbreaks may reduce evapotranspiration in a field by limiting the wind across an area. Use of mulches will also contribute to reduction in evaporation. Early in the development of orchards significant water is lost to evaporation from the bare soil after surface irrigation or sprinkler irrigation. This is less of a problem after the trees are fully developed and the area is shaded. Limiting the wetted surface area through the use of drip irrigation can also reduce evaporation losses.

Determination of evapotranspiration

Evapotranspiration can be determined by several methods (Allen *et al* 1998), but owing to the problems with direct measurement in the field, is commonly computed from weather data. While there are many equations that have been developed for this purpose, the Penman-Monteith equation is the most widely used, and a robust procedure using this equation has been developed by an FAO committee (Allen *et al* 1998). This was developed to provide a consistent way to calculate evapotranspiration and water requirements throughout the world. The method consists of first calculating a value for reference evapotranspiration using the Penman-Monteith equation and then modifying this value to determine a value for a particular crop's evapotranspiration.

The Penman-Monteith equation incorporates both energy and mass balance terms. The original equation was derived to compute evaporation from an open water surface using standard climatological data of sunshine, temperature, wind speed and humidity. It was further developed for cropped surfaces by adding aerodynamic and surface resistance factors for plants (Allen *et al* 1998). To standardise the method, a hypothetical reference crop, with an assumed height of 0.12 m, a fixed surface resistance of 70 s/m, and an albedo of 0.23 was used, with locally gathered weather data, to calculate a reference evapotranspiration (ET_o). The reference evapotranspiration assumes a well-watered crop that is not growth limited.

The crop water requirement is then estimated by multiplying ET_o by a crop coefficient developed to account for the effect of crop development on water use. The equation (Eqn 6.1) is:

$$ET_c = ET_o \times K_c \quad \textit{(Eqn 6.1)}$$

where ET_c is the crop water use, and K_c is the crop coefficient.

Different crop coefficients have been developed by researchers throughout the world based on lysimeter and water balance studies of crop water use. The crop coefficient is defined as:

$$K_c = \frac{ET_c}{ET_o} \quad \textit{(Eqn 6.2)}$$

where the evapotranspiration of the crop has been measured by a lysimeter and the reference evapotranspiration has been calculated using the Penman-Monteith equation. These data were used to develop the coefficients found in Allen *et al* (1998).

The crop coefficient in the FAO 56 publication (Allen *et al* 1998) has been approximated as a linear function that characterises the following four growth stages: initial, crop development, mid season and late season. The first stage recognises a large soil evaporation component, the second characterises the ground cover development, the third reflects the crop canopy structure and the last relates to the harvest date. Tables detailing these growth stages are available for a wide range of crops in FAO 56 (Allen *et al* 1998) as are details for application of this method.

As most crops are not grown in 'ideal' conditions, methods are provided to account for non-standard conditions. Evapotranspiration is calculated by applying an additional coefficient to the standard equation to account for water stress. The resulting equation (Eqn 6.3) is:

$$ET_c = ET_o \times K_c \times K_s \quad \textit{(Eqn 6.3)}$$

where K_s is a coefficient for water stress due to under irrigation, salinity and/or waterlogging.

Adjustments can also be made to the crop coefficient to account for the percentage of area covered by the plants (leaf area index), percentage of wetted area, time between wetting events, and whether it is an annual or perennial crop. Procedures have also been developed to account for missing weather data.

The above procedure has been described as the single coefficient method. There is also a dual coefficient method that describes the basal transpiration and the evaporation component. This is more complicated and computationally intensive than the single coefficient method and more likely to be used in research applications. The use of the FAO method will give reasonable estimates of the crop water requirements when calculated with local weather and cropping data.

An alternative to computing evapotranspiration from weather data is to measure evaporation of water from a free water surface. This method is referred to as pan evaporation. It provides an index of the integrated effect of radiation, air temperature, air humidity and wind on evapotranspiration. There are significant differences between water loss from an open water surface and a crop surface but this technique does provide a useful index. However, it requires a coefficient that relates the measured water loss in the pan to reference evapotranspiration. The site of the evaporation pan is critical to obtaining consistent results. Class A evaporation pans are the standard used throughout the world (Howell *et al* 1983). These can be modified for automatic measurement and screened to prevent loss due to birds and animals (Phene *et al* 1992, 1996). The reference evapotranspiration then has to be modified to reflect the crop water use through the crop coefficient. The resulting equation (Eqn 6.4) is:

$$ET_c = ET_o \times K_p \times K_c \quad (\textit{Eqn 6.4})$$

where K_p is the pan coefficient, K_c is the crop coefficient and ET_o is the reference evapotranspiration.

Crop water requirements in irrigation planning

Doorenbos and Pruitt (1984) discuss the application of crop water requirement data in project planning in Section 2 of FAO–24 (Crop Water Requirement). The identified stages included:

1 production objectives;
2 project identification;
3 project design; and
4 project operation.

Crop water requirement data are needed in the final three phases of the process.

During the project identification, the physical resources are identified and characterised. These include soil types and the chemical and physical properties of soil, particularly those associated with water relations. Temperature, humidity, wind, radiation, evaporation, rainfall and other parameters that influence crop selection and crop water use are also evaluated. Particular consideration needs to be given to crop salt tolerance (see *Chapter 9*), ability to use nitrogen (see *Chapter 5*), year round evapotranspiration potential, susceptibility to waterlogging and possible phytoremediation capability when reclaimed water is the irrigation supply. The cropping intensity is determined by the water supply and the crop selection. The cropping pattern established will have to match peak irrigation requirements with available supply. This is not usually a problem in summer when evaporative demand is highest. During minimum demand periods the cropped area may need to expand to accommodate the reclaimed water supply if adequate storage is not available.

These tradeoffs can be determined by a three-step calculation procedure (Doorenbos and Pruitt 1984). First, the monthly water requirement is determined by calculating the crop water requirement based on the reference evapotranspiration and the crop coefficient. This computation is made for each crop included in the cropping pattern and the conditions that will exist during production. These values are then summed for each month. Second, the net irrigation requirement is calculated based on the monthly values. This accounts for the probable monthly rainfall, the estimated groundwater contribution to crop needs, and the stored soil water. Third, the irrigation requirement is determined using the leaching requirement for the crop, based on the water quality, crop tolerance and the irrigation efficiency depending on the irrigation method and delivery system. This provides a summary of the required irrigation supply on a monthly basis.

Water quality

The quality of reclaimed water needs to be considered in terms of plant and soil health (see *Chapters 7 and 9*), toxicities (see *Chapters 8 and 10*), offsite environmental problems (see *Chapter 11*), and protection of irrigation equipment from corrosion, fouling and clogging, due to salts, suspended solids, ions and trace elements.

Effects of contaminants on irrigation equipment

Corrosion

To limit corrosion of pipework, irrigation water pH should be in the range of 6 to 9. Corrosion can be caused by chemical, physical or microbiological agents that can corrode metal and concrete irrigation pipelines and equipment. Reclaimed water is generally of neutral pH (see *Chapter 2*) and as such is not likely to present a chemical corrosion risk.

Fouling

Poor water quality can result in clogging, encrustation, scaling and blocking of irrigation systems (Table 6.1). This affects the capacity of the system to apply water at the required rate, reduces the distribution uniformity of the system and increases pumping and maintenance costs. The risks associated with fouling are of particular concern for drip irrigation systems due to their low flow rates and small pipe/aperture sizes that make them prone to clogging.

Chemical precipitation results from excess of calcium, magnesium, carbonate, sulfate and iron. This precipitation is usually seen as scale buildup, commonly caused by the degassing of carbon dioxide from the water. The risk of precipitation of carbonate compounds can be assessed by the water hardness and the log of the chloride to carbonate ratio (ANZECC and ARMCANZ 2000). Iron and manganese precipitation is usually not a problem if pH is maintained between 5 and 9. However, this is also influenced by levels of carbon dioxide, sulfur, organic matter and microorganisms. Waters with elevated levels of iron should be treated as high risk and special analysis undertaken to assess the fouling potential (McLaughlan *et al* 1993).

Microorganisms such as bacteria, algae, slimes and fungi can cause biofouling in all types of irrigation systems. In reclaimed water systems the most common type of fouling is generally organic due to the high level of available nutrients. Other types of biofouling due to iron or other metals are more commonly associated with the use of groundwaters rather than reclaimed water.

Table 6.1 Principal causes of fouling in irrigation systems.

Parameter	Description
Physical	Accumulation of sand, silt, clay, and organic matter causing clogging
Chemical	Precipitation of chemical compounds causing scaling, blockage of emitters
Biological	Blockage of pipes, filters, and emitters due to growth of organisms (eg algae) within the system or organisms present in supply water

Source: modified from ANZECC and ARMCANZ (2000).

Algal growth in nutrient-rich reclaimed water supplies can lead to blockage of filters for drip irrigation systems. There are also risks associated with overhead sprinkler application of water with extremely high algal loads as this can result in a smothering of the crop. Certain types of algae can also potentially produce toxins which may affect produce quality (see *Chapter 12*).

Water quality for drip irrigation

As drip irrigation is particularly prone to blockage problems it is useful to give some specific guidelines (Table 6.2) on water quality criteria for drip systems.

Bicarbonate concentrations exceeding 2 meq/L and pH>7.5 can cause calcium carbonate precipitation, and bicarbonate concentrations >2.5 meq/L can cause precipitates when injecting phosphate fertilisers.

Drip emitters have apertures as small as 0.03 mm in diameter and all drip systems require some type of filtration process in order to prevent blockages. Generally, solids greater than one-tenth the size of the drip emitter should be removed to prevent bridging (eg 0.003 mm). For microsprinklers with simple orifices, removal of particles one-seventh of the orifice diameter is considered sufficient (Burt and Styles 1994). The filtration system itself is expensive and a requirement for high hydraulic pressure may make ongoing running costs expensive. Most filtration systems can manage water with up to about 100 mg/L of suspended solids. If the water has greater suspended solids than this, some pretreatment will be required, often in the form of a settling reservoir. However, algae, especially filamentous types, are a particular problem since they float and rapidly block filters. If there are high algal loads, then pretreatment in the reservoir will be required to kill the algae and make them sink.

Bacteria can form iron and manganese oxides that can also cause blockages. These problems can be overcome by injection of chlorine into the drip system to kill the microorganisms. Injection can be continuous at a low level (1–2 mg/L) or periodic dosing at high concentration (10 mg/L). Calcium and magnesium carbonate precipitation can be a serious problem, but can be overcome by injection of acid (sulfuric or phosphoric) or injection of sulfur dioxide. Carbonate precipitation is prevented by dropping water pH to 6.5. For detailed information on the filtration and management of drip and microsprinkler systems refer to Burt and Styles (1994) and Hanson *et al* (1997).

Table 6.2 Guidelines for potential problems with irrigation water for drip systems.

Type of problem	Potential for problems		
	Minor	Moderate	Severe
Physical			
Suspended solids (mg/L)	<50	50–100	>100
Chemical			
pH	<7	7–8	>8
Total dissolved solids (mg/L)	<500	500–2000	>2000
Bicarbonate (mg/L)	<100	100–350	>350
Manganese (mg/L)	<0.1	0.1–1.5	>1.5
Iron (mg/L)	<0.2	0.2–1.5	>1.5
Hydrogen sulfide (mg/L)	<0.2	0.2–2.0	>2.0
Biological			
Bacterial population (No./L)	10 000	10 000–50 000	>50 000

Source: Hanson *et al* (1997).

Effect of water quality on crops

Several chapters in this book detail the effects of substances commonly found in reclaimed water on the yield and quality of crops grown with reclaimed water (see *Chapters 5 to 10*). Irrigation methods can be used to limit or prevent these substances from causing detrimental effects. For example, many plants are sensitive to foliar application of chlorides, but not to their root systems (see *Chapter 9*) so irrigation methods that limit exposure of the leaf to the water sources are preferred.

Pathogens

Different levels of treatment produce different classes, or qualities, of water with respect to the pathogen levels in reclaimed waters (see *Chapters 2 and 3*). Often the pathogen level in reclaimed water is the limiting factor that governs the crop on which the reclaimed water can be used (see *Chapter 2*). However, the irrigation method and the consequent exposure of the edible portion of the crop to the reclaimed water can have a significant impact on which crops can be grown with a particular water quality. For example, in South Australia, crops with large surface areas grown on or near the ground and consumed raw (eg broccoli, cabbage, cauliflower, celery and lettuce) can be sprayed or flood irrigated if the water is Class A, drip or furrow irrigated if the water is Class B and subsurface irrigated if the water is Class C (DHS SA and EPA SA 1999; see *Chapter 12*, Table 12.4). A more detailed discussion on the microbiological quality of reclaimed water, irrigation methods and crop suitability can be found in Chapter 2.

Irrigation methods

In general terms, reclaimed water irrigation systems need to have high water use efficiency (WUE) to reduce costs and minimise negative environmental effects. In many situations the flexibility in timing and amount of water application may be controlled by the irrigation water supply. Potential for improving WUE depends on the degree of understanding of the crop and soil system, the flexibility in management offered by the irrigation system and water supply, and the sensitivity of yield-determining factors in providing an economic response to improvements in water management.

The choice of irrigation method has to take into consideration the site conditions, the irrigation water quality, crops grown, labour availability and cost. Crop characteristics are very important in terms of establishment and tolerance to waterlogged or saline conditions, particularly for annual crops. Many horticultural crops are small seeded (eg onions and tomatoes), making them difficult to establish under many environmental conditions. In other circumstances, establishment is a less critical concern, for instance where transplants are used or the crop is perennial (eg fruit crops). Lettuce crops, for example, are extremely sensitive to water stress. Many horticultural crops are susceptible to the root rot pathogen *Phytophthera* and hence waterlogging should be avoided (eg tomatoes). The method of irrigation also often affects crop quality in terms of marketability. Tomatoes are prone to low solids content when grown with drip irrigation compared to furrow irrigation. Onion crops are at risk of black mould, which can be exacerbated with sprinkler irrigation, as the foliage is frequently wetted. Irrigation methods can have direct affects on pathogen exposure to the crop or irrigator (see *Chapter 2*).

Surface, sprinkler or drip irrigation can be selected to manage reclaimed water irrigation schemes, providing an enormous number of possibilities to suit particular irrigation needs and crop/soil combinations. The advantages and disadvantages of each, relative to irrigation with reclaimed water, are discussed in the remainder of the chapter.

Surface irrigation

Background

There are many types of gravity flow systems where irrigation progresses from the higher end of the field to the lower (eg furrow, contour bay and border check). For irrigation of horticultural crops a high level of control is required to prevent waterlogging stress and offsite environmental effects (see *Chapter 11*). In practice, of the surface irrigation methods available, only furrow irrigation can provide the control required. For furrow irrigation the field is divided into small channels (furrows) with regular cross sections. Furrows have raised beds or hills in between, with the crop being planted on these beds, or hills. Water is supplied to the upstream end of the furrow and water advances down the furrow and infiltrates through the wetted perimeter, moving vertically and laterally thereafter. Once the water supplying the furrow is cut off, the water recedes down the furrow. Thus, efficient furrow irrigation will depend upon soil type, slope, layout and the crop to be grown. An important feature for furrow-irrigated soils is that the water is able to infiltrate the bed or hill and redistribute to the surface. This is essential for seed germination and crop establishment.

The advance and recession characteristics are the main factors which determine the uniformity of water application in furrow irrigation. Under ideal conditions, the advance and recession times should be managed to ensure that the infiltration opportunity time is uniform over the entire furrow length.

Distribution uniformity with surface irrigation

The main problems associated with surface irrigation are the non uniformity of water application and overirrigation (Smith *et al* 1983). Design and management of furrow irrigation systems are generally poor, causing inefficient irrigation and water wastage. These problems are exacerbated on light soils and reduced on heavy soils. Lighter soils, having more rapid infiltration, need to be on steeper slopes with shorter runs. Finkel (1979) listed the following parameters, which affect the uniformity of water application in furrow irrigation systems:

- inflow rate;
- cut-off time;
- furrow length and slope;
- furrow geometry;
- soil infiltration characteristics; and
- hydraulic resistance.

In order to design and manage efficient furrow irrigation systems, considerable understanding is required of the interaction between soil conditions, water supply and cropping. In general terms, it is more difficult to design and manage furrow irrigation compared to sprinkler or drip systems.

Furrow irrigation design and management

In order to aid design and management, computer models have been developed to solve the flow equations describing the water flow over the soil surface. Several models have also been incorporated into user-friendly PC-based programs; two of the more commonly used models are SIRMOD (Walker 1997) and SRFR (Strelkoff 1990).

The development of reliable design and management criteria using models can be achieved only if model simulations and predictions accurately represent field conditions. Due to the benefits of improved understanding and the ability to investigate parameter interaction, it is strongly suggested that a model such as SIRMOD (Walker 1997) or SRFR (Strelkoff 1990) is used in the design phase of reclaimed water irrigation, and then used to refine water management once the system is in place. This will provide an objective framework for the design process and allow assessment of management aspects for improvement.

Infiltration is one of the most important factors that affects surface irrigation performance. However, evaluation of infiltration parameters for a field is difficult due to spatial and temporal variations in soil physical properties, initial soil moisture content and differences in management practices (Bautista and Wallender 1993). Accuracy of surface irrigation simulation models depends on specific infiltration parameters being obtained accurately (McClymont and Smith 1996; Esfandiari 1997; Hornbuckle 1999).

Since the hydraulic characteristics of furrow irrigation are extremely complex, in the past, a reliance on empirical procedures has been largely employed in designing and managing furrow irrigation systems. However, with the advent of easily accessible computing power and numerical modelling advances, a move towards utilising computer simulation models should be encouraged due to the increased insight that can be gained.

Sprinkler irrigation

Background

Sprinkler irrigation is commonly used in horticulture. Field crop sprinkler systems are usually overhead systems that apply the water over the whole plant and ground area. For perennial horticultural tree crops, sprinklers can be overhead systems wetting the whole area also, but they are now more commonly found as under-tree microsprinkler systems that wet under the trees, but not the inter-row areas.

There is a large range of irrigation equipment that can be tailored to particular crops and soils. The application rate can be matched to the soil infiltration rate. This is advantageous as, unlike furrow irrigation, irrigation of sandy soils is possible with good management to minimise deep percolation. However, soils with very low intake rates (eg <3 mm/hour final intake rate) are prone to runoff and need special measures to increase intake or to provide uniform surface ponding to prevent runoff (Burt *et al* 1999). Sprinkler irrigation is also suitable for undulating and steep terrain, although surface runoff can still be a problem. Sprinkler irrigation has the advantage of providing a good germination and crop establishment since small amounts of water can be applied frequently, and with many systems this can be done with low labour requirements. It also has other agronomic advantages in the control of wind erosion by keeping the surface soil moist and incorporation/activation of herbicides.

Sprinkler irrigation has drawbacks in the high capital and operating cost, and foliar application of reclaimed water may cause concerns with specific ion injury to crops (see *Chapters 2 and 9*), human consumption (see *Chapter 12*), and increased risk of plant fungal disease. Design and management difficulties with sprinkler irrigation usually occur in two forms: Excessive ponding and runoff due to a mismatch in application rate and soil infiltration (most frequently a problem with travelling sprinkler systems), and excessive deep percolation (usually resulting from poor irrigation scheduling and poor distribution uniformity). These problems can be overcome by undertaking adequate soil investigations during the design phase, proper system maintenance and good irrigation scheduling techniques.

Types of sprinkler systems

Sprinkler systems for field crops include fixed (solid set), hand move (single lines of a solid set system that are moved across the field) and travelling irrigators. A solid set system is a system with a mainline and laterals that remain in place all of the growing season. It is well suited to irrigating crops that need light, frequent irrigations. These systems have high capital cost but require very little labour for irrigation. The fixed pipes and risers are obstacles to farming operations. The hand-move system generally consists of a portable main line that is in place for the growing season and one or two laterals. The laterals are moved across the field for each irrigation cycle. This system reduces the capital cost but dramatically increases labour costs. These systems are designed so the average application rate is less than the soil infiltration rate to avoid runoff.

Travelling irrigators are those such as travelling booms and guns, centre pivots and linear moves. Travelling booms and guns are high volume, high pressure systems where the application rate is determined by the sprinkler design, water pressure and advance speed. Due to large droplet size and high application rates these are best suited to light soils having high infiltration rates and crops that can sustain heavy wetting and have good ground cover. These systems generally have poor uniformity of application (Burt *et al* 1999).

Centre pivot and linear move systems carry a row of sprinklers either around in a circle (centre pivot) or across a rectangle of land (linear move). With centre pivot systems the outer end travels much faster than at the circle centre and so instantaneous water application rates are much higher at the end. With both these systems the application rate can be 60 mm/hour to 250 mm/hour (Heerman and Kohl 1981). This is much higher than the infiltration rate of most soils, so potential runoff is decreased by increasing the advance speed and having more frequent smaller irrigations. With both these systems there has been a trend to use nozzles and spray plates on drop tubes, so that the water is closer to the soil surface. These are alternative emission devices that run at lower pressure and have smaller droplet sizes (Burt *et al* 1999). This reduces the application rate and preserves soil structure. A disadvantage, however, is that these systems used on flat ground can pond water into furrows. Using these systems also minimises evaporation and negates the effect of the wind.

Distribution uniformity with sprinkler irrigation

With sprinkler systems the uniformity of water application depends upon the sprinkler type, its spacing in the row and spacing between rows. The depth of water applied is usually greater near the sprinkler and decreases with distance from the sprinkler. Uniformity of application is achieved by placement of sprinklers such that the wetting patterns overlap, usually about 60% to 80%. In design, the engineer will consider the nozzle pressure, discharge rate, wetted diameter and water distribution pattern to obtain acceptable uniformity. Poor distribution uniformity will occur around edges of fields or in odd-shaped fields where sprinkler overlap cannot be maintained. With under-tree sprinklers each line of sprinklers is an individual source and as such only the spacing along the line is critical and not the row-to-row spacing.

Other sources of non uniformity are pressure drop along the sprinkler line, incorrect system pressure and wind. System pressures higher than recommended will cause the water to break up into finer drops. This will cause more water to fall near the sprinkler, will increase susceptibility to wind drift and increase evaporative losses. System pressures lower than recommended will reduce the amount of overlap and also will result in larger water droplets and, hence, more water will be applied at the periphery of the wetting pattern.

Irrigation scheduling with sprinkler irrigation

With solid set systems irrigation scheduling is very simple as the whole area can be irrigated to any application depth, thus light or heavy irrigations can be used in accordance with crop requirements. Hand-move systems are less flexible and in order to reduce labour costs, irrigation frequency is reduced. Hence, the irrigation application is large, in the range of 50 mm to 150 mm. The soil moisture deficit threshold to start irrigation is set according to the minimum set time required for labour organisation. Centre pivots and linear moves have fixed application rates but variable advance speed (ie set time) so the application rate is varied by changing the machine speed. There is a minimum time to complete a cycle across the field, so scheduling needs to balance the time needed to complete the cycle with the desired depth of application. With these systems it is important not to fall behind in peak demand periods as it is impossible to rapidly apply a large volume of water. The lateral move system is particularly difficult as it traditionally finishes its cycle at the wet end of the field and has to traverse the full length of the field again prior to starting the next cycle. Stepped or triangular watering is often employed to overcome this drawback.

Drip irrigation

Background

Drip irrigation is likely to be the most suitable form of irrigation for use with reclaimed water for two important reasons. First, it limits contact of the reclaimed water with the plants and workers in the fields. Second, it provides the best control over the application of irrigation water. The high level of control is important as it leads to high yield of vegetable crops, for example 20 t/ML to 30 t/ML for processing tomatoes, compared to 10 t/ML to 20 t/ML for furrow irrigated crops (Hickey *et al* 2001). It also leads to reduced environmental impacts (ie no irrigation runoff and little rainfall runoff and little drainage past the root zone, if well managed).

Drip is a technologically advanced method of irrigation that can apply water evenly to plants across a paddock. To achieve this, water is pumped around the paddock in pipes to emission points that are at the plant root zone. The piping, pump and associated hardware are expensive, upwards of $3000/ha, making the system highly capital intensive. It is this combination of technology and high capital cost that makes drip irrigation a potentially risky investment. In order for a drip irrigation scheme to be successful it must be well designed, properly installed and well managed. For the enterprise to be financially successful the return from the crop must cover the high capital cost.

Drip irrigation requires high levels of management skill and financial investment and thus is a transition that can best be made when the crops to be grown with drip have already been successfully grown with furrow irrigation (ie high level agronomy, marketing and financial skills are already developed).
The following sections outline the key design and management factors that combine to create a successful drip irrigation enterprise. However, the topic area is extremely large and as such the reader is referred to three useful texts (Burt and Styles 1994; Burt *et al* 1995; Hanson *et al* 1997), which were used to develop this chapter.

The principles of drip irrigation

The overriding principle of drip irrigation, which sets it apart from all other irrigation systems, is that irrigation is closely matched to the crop water use on a daily (or sub-daily) basis. Below are the characteristics of drip systems that help achieve this.

- Water is applied frequently at low application rates. Drip irrigation can apply water only at low rates (eg 14 mm/d). This means that drip systems are operated frequently and are run for long sets. These features are a constraint to irrigation in that large soil water deficits cannot be replaced quickly. However, management of drip irrigation to prevent large soil water deficits from occurring creates a root environment where plant water uptake is near potential rates.

- Water is applied with high uniformity to all plants. The ability to apply practically the same amount of water to each plant in a paddock is a unique feature of drip irrigation.
- Water is applied directly to the plant root zone. This also makes drip irrigation unique from all other types of irrigation systems. With drip irrigation only the root zone of the plant should be wetted. Thus, in the horizontal plane for row crops, only the hill or bed is wetted (not the furrow area) and in the vertical plane the water is kept in the root zone, by not allowing drainage below the root zone. Thus, in most cases, up to 25% of the paddock area is kept dry.

When the above principles are considered it is not surprising that world record crops of tomatoes have been grown with drip irrigation and large yield increases are often found when drip irrigated crops are compared to furrow irrigated. However, in some cases, yields under drip irrigated crops are the same as, or even less than, comparable furrow irrigated crops. This can be due to poor system design or management. Drip irrigation is particularly difficult to manage and a few years of experience and experimentation may be required to optimise it.

Advantages and disadvantages of drip irrigation

As with any irrigation system, drip offers advantages and disadvantages. With a well designed and managed system the potential advantages are large and the disadvantages can be minimised. However, drip irrigation will not be suitable in all circumstances. It may not fit in with the current farming system or the potential advantages may not be great enough to cover the costs.

The advantages of drip irrigation include the following.

- Improved plant production. This may be in terms of total yield, quality or both. With a drip system irrigation takes place frequently (daily at peak evapotranspiration periods) allowing the root zone soil moisture content to be kept at an optimal level. The water and aeration stresses found with furrow irrigation cycles are avoided. Christen *et al* (1995) measured an 84% reduction in waterlogging from furrow to drip irrigation for tomatoes in the Murrumbidgee Irrigation Area. Drip irrigation allows an optimal soil water status to be maintained across whole paddocks due to the uniform delivery of water to the plants.
- Reduced weed growth, as only part of the paddock is wetted. With subsurface (buried) drip the entire soil surface should be dry, thereby minimising weed growth.
- Reduced disease. As drip irrigation maintains a dry soil surface, diseases of leaves and fruits are reduced. As the crop root zone is maintained at optimal soil moisture levels, root disease is also reduced.
- Irrigation of sloping ground and low water-holding capacity soils. Since runoff is minimised with drip, sloping ground can be used that would be unsuitable for furrow or sprinkler irrigation. Also undulating ground can be successfully irrigated where land forming costs for furrow irrigation would be prohibitive. As drip irrigation applies small amounts of water frequently, it allows successful irrigation of low water-holding capacity soils that would be economically and environmentally impossible with furrow.
- Increased irrigation efficiency, depending upon the management skills of the irrigator. While other irrigation systems can achieve comparable levels of irrigation efficiency to drip, they require a larger time commitment from the irrigation manager.

Drip irrigation allows for improved irrigation efficiency in the following ways.

- Evaporation is reduced from the soil surface, since only a small area of the paddock surface is wetted or not at all if the drip is buried.
- Irrigation runoff should be eliminated and rainfall runoff much reduced, as it can be stored in the dry soil between the drip lines.
- Reduced amounts of water pass below the root zone (deep percolation). Christen *et al* (1995) found that only 2% of rainfall drained from under drip irrigated tomatoes in the Murrumbidgee Irrigation Area, compared to about 26% of rainfall with furrow irrigation.
- Eliminates the need to overirrigate the top end of the paddock to apply sufficient water at the bottom end as occurs with furrow irrigation.
- Improved chemical application. With drip systems, fertilisers and other chemicals are applied with the water through the system resulting in several advantages over conventional fertiliser application methods: fertilisers are applied only to the plant root zone; fertilisers can be applied 'little and often' to more closely match crop nutritional needs; and since runoff and deep percolation are minimised, fertiliser loss is reduced. McPharlin *et al* (1995) demonstrated

Table 6.3 Comparisons of drip and furrow irrigation of tomatoes.

Irrigation method	Yield (t/ha)	Water applied (mm)
Drip	139	612
Furrow	102	1092

Source: Hermus (1986).

the advantage of drip over sprinkler irrigation by showing that the agronomic nitrogen use efficiency with drip was 25% higher. This was attributed to better placement and less leaching of the fertiliser.

The improved irrigation efficiency allows higher yield per ML of applied water (Table 6.3).

There are numerous examples, nationally and internationally, where yields with drip irrigation have exceeded other types of irrigation (Muirhead 1979; Hermus 1986; Warriner and Henderson 1989; McPharlin *et al* 1995) for a range of crops (eg tomatoes, lettuce, snap beans and rockmelons).

The disadvantages of drip irrigation are:

- **Restricted root zone.** As the drip system wets only a portion of the paddock soil the crop root zone is restricted to that wetted portion, unless significant rainfall occurs. The system manager must always remember that the soil water reserves are limited and the capacity for a drip system to 'catch up' are limited. Thus, missed irrigations or breakdowns during the peak demand period must be quickly repaired. This is a significant problem in soil with low water-holding capacity (ie a high content of sand).
- **High maintenance requirements.** Drip irrigation relies upon small diameter passageways in the emitters to control the amount of water being applied. This makes the emitters susceptible to blockage by particulates, roots and chemical deposits. A filtration system is required to keep particulates out of the system and chemical injection to prevent chemical deposits, growth of slimes and root growth in the emitters. Prevention of blockage is an ongoing task that requires planning and labour. The drip system is also highly susceptible to damage from machinery, labourers, insects and animals. Thus, the system needs to be constantly checked, which is difficult with buried systems.
- **Restricted tillage.** If a drip system is to be left in the paddock for several years then normal tillage operations have to be revised. If the drip tape is laid on the surface it may be retrieved to allow for tillage and then reinstalled. However, the labour costs in retrieval and installation and the large amount of damage that can occur to the tape make this an unattractive option. Surface laid drip tape also restricts tillage and other operations during the growing season. Buried drip tape can be left permanently in the ground for many years, but the depth of tillage is restricted to that of the depth of the drip tape.
- **Soil structural decline.** As the area around the buried drip tape remains very wet for long periods, there is a risk of soil structural decline. This has been experienced by growers and measured in a field trial in northern Victoria. In this trial Adem *et al* (1996) showed higher soil bulk densities and penetrometer resistance with buried drip irrigation on a duplex soil. The extent or severity of this phenomenon is unknown. However, on a grey self-mulching clay in the Murrumbidgee Irrigation Area there was a yield response to gypsum with and without soil loosening in drip irrigated tomatoes (Christen *et al* 1995). This was probably as a result of improved water movement with the gypsum treatments. Gypsum was also found to improve drip irrigated tomato yields in an alluvial soil in Western Australia (Muller 1993). This experiment found no benefit from deep ripping without gypsum. Design and management should consider the risk of structural decline. Possible remedies would be growing cereals to dry and loosen the soil, application of gypsum through the drip system and careful tillage.
- **Drip irrigation systems are costly.** Although, the cost per hectare is declining with better design. The financial aspects of costs and benefits must be carefully considered before a drip system is installed.
- **Difficult crop germination.** When buried drip tape is used for seed germination the soil needs to be wetted upwards from the tape. In many soils this is difficult to achieve and results in complete saturation of the soil. This keeps the soil cold, increases the risk of disease, causes soil structural deterioration and excessive deep percolation. A second irrigation system is often used for germination (ie sprinklers).
- **Salt accumulation near the root zone.** Drip systems move salt to the edge of the wetted zone where it accumulates. Leaching by rainfall is required, although leaching using surface drip systems is also possible.

Soil wetting patterns and deep percolation

The soil wetting pattern under a drip system is highly variable depending upon soil type, system design and management. For example, the pattern of soil water content on a clay soil with poor water distribution properties could have most of the wetting below the dripper tape and lateral wetting could be restricted, with little wetting above 150 mm depth (Hanson *et al* 1997). If 50% more water than required by crop evapotranspiration is applied, the wetting pattern may still have little moisture above 150 mm depth, although the lateral distribution would be somewhat greater. However, importantly, the very wet zone below the tape would be greatly expanded. Thus, it can be expected that most of the water applied in excess of evapotranspiration will drain past the root zone (Hanson *et al* 1997).

Deep percolation is a common issue with drip irrigation because of the uneven wetting pattern that can develop from poor maintenance. The very wet zone below the tape is likely to lead to deep percolation. This has been shown with sweet corn on beds in a loam over clay soil (de Vries 1997). In this trial the soil remained saturated for long periods below 500 mm and it was found that it took water 1 hour to 2 hours to reach 800 mm depth after the start of an irrigation, where it took more than 24 hours to travel 500 mm laterally at the tape depth (200 mm). Measurements of wetting patterns under a surface drip system in a vineyard revealed similar patterns (Cox 1995).

Clogging

Drip emitters have passages as small as 0.03 mm in diameter and as such are extremely vulnerable to blockage. The greatest source of non uniformity in a drip system after several years is due to emitter clogging. Reclaimed water is generally nutrient rich, which encourages algae growth in water storage facilities and at the dripper itself, which can lead to dripper clogging. The relative sensitivity of emitters to clogging depends upon many design features. Generally, large passages and high emitter flow rates are associated with lower clogging potential, a 1.3 mm hole will reduce the effects on economic returns should the system start to clog by 50% compared to a 0.8 mm hole (Burt and Styles 1994). System design, installation and management all contribute to clogging.

A good filtration system with sound system maintenance should minimise the risk of clogging in most situations. In situations of large sediment load (>100 mg/L suspended solids) the first and most effective filter will be a reservoir, which acts as a settling pond. If left too long, under the right conditions the reservoir can also have ideal conditions for creating an algal bloom. Reservoirs may also be required, with some drip systems, to buffer water availability from the reclaimed water supply system. This is especially the case if the reclaimed water is not supplied daily. In this case the reservoir should also be used as a sediment trap. Large debris need to be removed with a precleaner before the reclaimed water enters the pump.

The choice of filter system depends upon the reclaimed water quality. The best filters are media filters which are pressurised tanks filled with silica sand or crushed granite. The size and number of tanks depends upon the system flow rate and the cleanliness of the water. The filters are kept clean by backflushing. This operation can require large amounts of water compared to screen or disk filters, and a suitable disposal site for this water needs to be found as it will be high in nutrients. Media filters need to be chlorinated to control biological activity that may clog them, especially when not in use. Media filters are generally considered to be the best all-round filtration device but they are considerably more expensive than screen or disk filters and also take up much more space.

Soil and water properties

The drip tape should not be installed into sodic layers where the soil structure will deteriorate upon wetting (see *Chapter 9*). A dispersed or generally poor soil structure with low hydraulic conductivity around the tape will result in a restricted wetted soil volume. Similarly, installation of the tape into a heavy subsoil may create difficulties if the soil hydraulic conductivity properties are poor. If there is a soil textural change from lighter to heavier within the shallow root zone, then the best placement for the tape may be just above the boundary.

When using more saline reclaimed water the tape will need to be as shallow as possible to leach the soil. Buried tape cannot leach any soil above it, this has to be done by rainfall or other forms of irrigation.

Seed germination and rooting depth

For shallow rooted crops the tape placement may need to be nearer the surface, lower yields have been experienced with drippers 300 mm deep on onions compared with surface drip (Bucks *et al* 1981). For deeper rooted crops the depth of placement appears less critical (Davis *et al* 1985). When tape is buried the main trade off is between being able to achieve surface wetting for germination and adequate depth for tillage operations. There is a critical depth beyond which surface wetting of the soil is impossible to achieve with buried drip. This depth will vary between soils (sandy and clay soils shallower, loam soils deeper) and probably lies between 100 mm and 300 mm. If germination can be achieved using sprinkler irrigation, or avoided entirely by the use of transplants, then the tape may be installed at 300 mm to 350 mm. The desirability of keeping a dry soil surface to control weeds (which can be promoted by the nutrients in reclaimed water) and disease also needs to be considered. The loss of water below the root zone is likely to be greater if the tape is installed deeper. This is especially the case if frequent irrigations maintain the soil at high soil water content.

Chemigation

Chemical injection is a fundamental part of drip irrigation as fertiliser must be applied through the system in order to reach the roots. Even with reclaimed water supplies it is likely that fertiliser application will be required (see *Chapter 5*). Apart from fertilisers other chemicals need to be applied through the system to keep the laterals and emitters clean. There is also the possibility of applying herbicides, fungicides and nematicides through the system. Soil or water ameliorants can also be applied through a drip system.

Nutrient distribution under a drip system depends upon the wetting pattern, soil type and rate at which the reclaimed water and any fertiliser are applied. Nitrate is highly mobile and will distribute in proportion to the water movement. Thus, nitrate will be lost by deep leaching and will accumulate above the tape line where water is preferentially extracted by the crop. Ammonium tends to be strongly adsorbed onto the soil and thus does not move as readily as nitrate, and after some time the ammonium converts to nitrate. Phosphorus tends to be adsorbed by the soil and thus may not distribute evenly through the root zone. Potassium fertilisers are quite soluble but are easily adsorbed so they will have restricted movement. Higher concentrations will promote greater distribution. As nutrients are applied with the water, a uniform distribution is required.

Irrigation scheduling with drip irrigation

With drip irrigation the system has the potential to very closely match daily plant water use. This is very different from other irrigation methods (surface and sprinkler) where an assessment of soil moisture storage is made and at a maximum allowable depletion the crop is irrigated. With drip irrigation scheduling should be evapotranspiration based, simply the crop evapotranspiration from the previous day is estimated and replaced the following day. A soil moisture depletion approach is difficult since the estimate of the total soil moisture available relies on knowing the soil wetting pattern, which is difficult to accurately quantify under drip. The other drawback to the soil moisture depletion method is that the drip system is not designed to replace large soil moisture deficits quickly as can be done with furrow irrigation. The maximum allowable deficit under drip irrigation is a single day's evapotranspiration or less during the peak of the growing season. Phene (1995) shows that high frequency surface drip irrigation results in higher yields of tomatoes than low frequency surface irrigation but the best yields were obtained with high frequency buried drip. On corn, Caldwell *et al* (1994) found no correlation between yield and deficits between 13 mm and 51 mm, irrigated every 1 to 7 days. So a simple statement of irrigation scheduling with drip irrigation may be to maintain the main root zone at a high soil water content without creating aeration or disease problems, or creating excessive deep percolation.

Maintaining high soil water content requires frequent irrigation, which can be assisted by automation. The use of soil water sensors or evapotranspiration gauges directly linked to the system controller can switch on pumps. There is also a need to check that water is not lost from the root zone and thus a soil moisture sensor placed at the bottom of the root zone can be used to turn pumps off.

With drip irrigation, especially buried drip, soil evaporation is reduced compared to furrow irrigation, but crop transpiration is increased.

Above the drip line leaching must be achieved by rainfall or an alternate irrigation method. If this leaching occurs by rainfall, then the salts may be washed down into the main root zone. However, the root zone will be maintained at low soil water potentials (high water availability) during the main crop growth period and as such it is unlikely that there will be any effects of salt when using good quality irrigation water. The area below the drip tape is maintained at low soil water potentials and in normal circumstances water will be overapplied. Thus, there is a tendency for downward movement and leaching will occur.

Irrigation with drip needs to be frequent as the root zone is limited to the wetted area which, in turn, is much reduced compared to furrow irrigation. For shallow-rooted crops (onions and lettuce) irrigation should be once per day or twice per week. During peak season irrigation tends to be daily.

Soil moisture measurement is essential with drip irrigation to ensure that an adequate soil wetted volume is maintained. It is important to maintain the wetted volume as a buffer against peak demand. If the wetting pattern is allowed to contract early in the season, there may be no effect on the crop. However, when high crop water demand occurs, there may be insufficient soil storage if a wetting pattern contracts, since it is difficult to re-establish as the drying soil has a lower hydraulic conductivity to redistribute water away from the emitter.

If soil moisture content is gradually decreasing, irrigation should be increased; if it is increasing, irrigation should be reduced. The soil water content should be measured in the middle of the root zone, at the edge of the desired soil wetted pattern, and at the bottom of the root zone.

Irrigation management and scheduling

For most crops the water used shows a direct relationship with dry matter production. This relationship varies from crop to crop and also depends upon climate. The effect of any water limiting periods on crop yield will depend upon their timing and duration in relation to the crop growth stage.

Measuring soil water is useful in three areas of crop production:

1 assessing if the soil is too dry for optimum crop production in terms of yield and quality (when and how much to irrigate);
2 measuring the uniformity of soil water (due to soil variability and non-uniform irrigation); and
3 crop nutrition (nutrient availability for crop uptake depends upon the soil moisture status and keeping those nutrients in the root zone).

A few important factors that have restricted adoption of good irrigation scheduling and moisture monitoring are (Meyer 1993):

- water has been in plentiful, and cheap, supply in most irrigation areas, negating the need for careful management;
- historically water has been supplied in large irrigation schemes on a 'roster' system, every 10 days to 14 days, which has imposed an arbitrary irrigation schedule;
- traditional surface irrigation methods make precise water management difficult;
- one of the main irrigated crops has been pasture, which can tolerate indifferent water management and still be productive; and
- making soil moisture measurements tends to be labour intensive or expensive.

Many of these factors are changing. Importantly, water is more highly valued and is becoming more scarce. Most farmers, who are making soil moisture measurements, will be doing so for economic production reasons. The role of irrigation in producing quality crops is better understood and better appreciated by farmers striving to meet quality criteria for manufacturers and exporters. However, the most important overall factor that will continue to highlight the importance of good scheduling for reclaimed water irrigation is the environmental consequences of over-irrigation, such as pollution of groundwater with nutrients (see *Chapter 11*).

There are many methods for measuring soil water content for determining when to irrigate. These include techniques such as:

- tensiometers;
- gypsum blocks;
- capacitance probes;
- time domain reflectometry;
- neutron moderation; and
- heat dissipation.

There are also wetting front detectors that indicate when to stop irrigating. Soil water monitoring is a large and important topic that has been reviewed in detail by Charlesworth (2000).

Matching crops, soils, reclaimed water quality and irrigation methods

There can be no definitive answer as to which type of irrigation system is most suitable for use with reclaimed water as there are many site-specific variables. However, it is possible to rank the three main irrigation systems against the key criteria related to irrigation with reclaimed water. The main areas of assessment for irrigation systems are against water quality parameters, likelihood of minimising environmental problems and appropriateness for efficient and economic crop production.

Table 6.4 Water salinity and reclaimed water irrigation system suitability.

Salinity[A]	Total Dissolved Salts (TDS; mg/L)	Suitability[B] Drip	Sprinkler	Furrow
Low	<900	High	High	Medium
Moderate	900–2000	High	Medium[C]	Medium
High	2000–3500	Medium	Low	Low

[A] Estimates taken from Chapter 2, Table 2.5 assuming 1 dS/m = 640 TDS; [B] assuming soils have reasonable drainage, if drainage is very poor, then drip should be used;
[C] leaf burn becomes a problem.

Water quality – Salinity

The management of soil salinity will be the key to the sustainability of irrigation with reclaimed water. Irrigation systems with better water control (can apply water according to crop requirements and with high uniformity) are inherently better suited to managing salinity. Table 6.4 refers to the management of soil salinity; however, leaf burn with sprinkler irrigation may also be a problem when using saline waters.

Pathogens and aerosols

Proper risk management of pathogens is one of the key limitations to the use of reclaimed water. The risk of contamination varies according to the crop and irrigation system used and the class of water (see *Chapter 2*, Table 2.3 and *Chapter 12*, Table 12.4). Production and drift of aerosols is also an issue (Table 6.5).

If Class A reclaimed water, or the equivalent, is used, occupational risks are generally low for all irrigation methods. Generally, drip irrigation can be used with reclaimed water classes that are 1 to 2 levels lower than other irrigation methods (see *Chapter 12*, Table 12.4). If buried drip is used, then the risks are further reduced.

Clogging, precipitation and corrosion factors

There are varying risks of clogging, precipitation and corrosion affecting the operation and longevity of an irrigation system depending on the water source. Generally, furrow irrigation is least susceptible to these problems (Table 6.6).

Environmental management

All irrigation carries potential risks to the environment. These risks are exacerbated when using reclaimed waters due to potentially high levels of salts and nutrients. Apart from soil salinity, dealt with above, the other main factors are surface runoff and deep percolation.

Surface runoff in irrigated agriculture is caused by applying excess irrigation water (either total volume or rate of application) that can infiltrate into the soil, or is due to rainfall. Systems with good control of application rate and amount and high uniformity have lower likelihood of runoff. Systems that leave parts of the soil surface dry reduce the risk of runoff due to rainfall (Table 6.7).

Deep percolation

Deep percolation of irrigation water past the root zone is one of the major losses of irrigation water. This can be considerably higher with furrow irrigation than when using drip or sprinkler irrigation mainly due to higher non uniformity of application with these systems. The risk of deep percolation on sandy soils is high with all types of irrigation methods. Even with the best irrigation management, rainfall can cause considerable deep percolation (Table 6.8).

Table 6.5 Risk of occupational exposure to reclaimed water with reclaimed water irrigation system suitability.

Exposure	Risk level Drip	Sprinkler	Furrow
Ingestion risk	Low	Medium	Medium
Contact risk	Low	High	High
Aerosol risk	Low	High	Low

Table 6.6 Clogging, precipitation and corrosion risk and reclaimed water irrigation system suitability.

Water quality factor		Suitability Drip	Sprinkler	Furrow
High suspended solids	>100 mg/L	Low	High	High
High potential precipitates	>100 mg/L bicarbonate	Low	Medium	High
High biological activity	>10 000 bacteria/L	Low	Medium	High
pH	<6, >8	Low	Low	Medium

Table 6.7 Risk of surface runoff with reclaimed water irrigation system and soil type.

	Surface runoff risk		
Soil texture	Drip	Sprinkler	Furrow
Sand	Low	Low	Low
Loam	Low	Medium	Medium
Clay	Low	High	High

Agronomic factors

Soil water properties

For good crop production there needs to be an appropriate match between the irrigation system and the soil physical properties controlling water movement and retention. This affects the amount of water that can be stored in the soil at irrigation, the depth of wetting, wetting pattern and aeration status. These factors affect the ease of management and agronomic productivity of the land (Table 6.9).

Table 6.8 Deep percolation risk with reclaimed water irrigation system and soil type.

	Deep percolation risk		
Soil texture	Drip	Sprinkler	Furrow
Sand	Medium	High	Extreme[A]
Loam	Low	Low	High
Clay	Low	Low	Medium

[A] Furrow irrigation is generally unsuitable.

Crop establishment

Establishment of crops is a critical task in horticulture; the irrigation system must be able to do this with a high degree of success. Table 6.10 is suitable for this assessment except in the case of a buried drip system, in which case it is very difficult to achieve good seed germination in any soil type. Table 6.10 outlines irrigation system suitability for establishing various categories of plants.

Disease

Control of leaf and root diseases, especially fungal, is affected by the irrigation system, crop and soil type. In general, sprinkler systems increase risk of leaf fungal and bacterial infections, whereas furrow irrigation, because

Table 6.9 Soil type and reclaimed water irrigation system suitability for crop production.

	System suitability		
Soil texture	Drip	Sprinkler	Furrow
Sand	Low	High	—[A]
Loam	High	Medium	High
Clay	Medium	Low	Medium

[A] Furrow irrigation is generally unsuitable.

Table 6.10 Reclaimed water irrigation system suitability for crop establishment.

	Ease of establishment		
Type of crop	Drip	Sprinkler	Furrow
Small seeded crops	Low	High	Medium
Large seeded crops	Low	High	High
Transplants or cuttings	High	Medium	Medium

of waterlogging, increases the risks of root rot. A broad assessment of irrigation systems and potentials for disease are given below (Table 6.11).

Summary

The above section has described, in general terms, the suitability and risks associated with different reclaimed water irrigation systems. Site-specific characteristics and a more detailed assessment of the appropriate irrigation system for specific reclaimed water schemes should be undertaken before their development.

Table 6.11 Reclaimed water irrigation system and disease risk.

	Disease risk		
Crop type	Drip	Sprinkler	Furrow
Large surface area crops	Low	High	Medium
Root crops	Low	Medium	Medium
Cucurbits and tomatoes	Low	High	Medium
Trees, vines and cane fruit	Low	Medium	Medium

Conclusions

An appropriately designed and operated irrigation scheme is crucial to maximise the benefits of reclaimed water in irrigated agriculture. Horticultural crops and other high value crops will be the best crops to utilise reclaimed water since they should be economically viable and they will benefit from the use of irrigation systems that have good water application control and uniformity.

Although the method of water application depends on many site and economic considerations, the most efficient system, with least human and environmental risk, is generally considered to be drip irrigation. However, this may not be suitable for a particular agricultural system due to soil physical properties, establishment difficulties, cost considerations and other factors outlined in this chapter. Furrow irrigation is most often the cheapest option, but has low levels of control and uniformity. Where furrow irrigation is to be used, good design using modern techniques can make a large difference in the performance of the system.

Irrigation management is crucial when using reclaimed water. Good irrigation scheduling and management methods are important to maximise production while minimising environmental effects. Good drainage is also required to suit the soil, water and environmental conditions of the reclaimed water irrigation scheme. All these factors are crucial for the success and sustainability of any reclaimed water scheme.

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7 Soil salinity and sodicity

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Two of the major soil related problems from irrigation with recycled water are salinity and sodicity. This chapter provides a fundamental understanding of salinity and sodicity in the Australian landscape and discusses their affects on soil productivity from a reclaimed water quality perspective. Chapter 9 provides a more detailed discussion on phytotoxic responses from some components of salinity and Chapter 11 presents a synopsis of the environmental impacts of salinity and sodicity.

Soil salinity

Salt accumulation in the landscape

Over many thousands of years, salt has been accumulating in the landscape from the minute quantities of salt blown in from the oceans by wind and rain. In addition, weathering of rocks during soil formation has also generated salts. In recent years, rising watertables have contributed to the accumulation of salts in the soil upper layers. Salinity levels and composition of many saline groundwater samples in Australia are similar to seawater composition. However, stable isotopic studies (Herczeg *et al* 2001) indicate that the source of salinity is mainly through rainfall, not by seawater intrusion. Groundwater chemistry has evolved by a combination of atmospheric input of marine and continentally derived salts, and removal of water by evapotranspiration over tens of thousands of years of relative aridity (Herczeg *et al* 2001). During salt flow through soil layers, chemical reactions such as cation (positive ions) and anion (negative ions) exchange, complexation, precipitation and dissolution involving different ionic species have resulted in groundwater composition being similar to seawater. Further studies have indicated that contribution to the present day salinity in the Australian landscape is <0.5% by rock weathering, <2% by aeolian deposits and >95% through rainfall input.

Before agriculture was introduced in Australia, the salts were leached down the profile by rain and accumulated below the root zones of native vegetation. Under semiarid conditions, the rainfall was not sufficient to leach the salts to the groundwater. An early observation by Holmes (1960) identified a 'salt bulge' at depths below 4 m from the surface of a site in a semiarid part of South Australia containing a virgin, mallee-heath community. The clay layers in deep subsoils hindered the movement of water and salt. As a result, a huge 'bulge' of salt accumulated in the soil layers from 4 m to 10 m depths from the surface. The groundwater table was generally >30 m depth from the surface, and the quality of groundwater was good as measured by electrical conductivity (EC <3 dS/m).

While investigating a large area (10^4 km^2) of fresh groundwater that occurs in the unconfined aquifer in the south-western part of the Murray Basin, Leaney and Herczeg (1999) also reported salt concentrations ranging from 4000 mg/L to 16 000 mg/L in the unsaturated zones (5–30 m depth) with fresh groundwater tables at 35 m to 60 m below. Furthermore, the pilot study using an airborne electromagnetics system by Lawrie *et al* (2000) in central-west New South Wales confirmed the occurrence of salt bulges in deeper soils.

Salinity in the landscape has developed under different environmental conditions over many geological periods. Recent agricultural activities in Australia have led to many soil processes that have resulted in various types of salinity. Three processes lead to saline lands all over the world (ie groundwater associated salinity, non-groundwater associated salinity and irrigation associated salinity) (Figure 7.1). First, we have to distinguish 'irrigation salinity' (reclaimed water or any irrigation water source) from 'dryland salinity'. The salt content of the irrigation water induces irrigation salinity, without appropriate leaching of the excess salts accumulated in the soil horizons caused by evapotranspiration and limited drainage. In contrast, dryland salinity is caused by the salt input through natural processes of precipitation or the movement of saline groundwater. However, in both cases, the same principles govern the salt storage in soil layers and the consequent effects on soil properties and crop productivity. Strategies to combat salinity to increase productivity of food crops will vary according to the type of salinity encountered in the field. Hence, it is crucial to diagnose what type of salinity affects the farm so that appropriate management methods are undertaken.

Salinity induced by a shallow watertable (seepage salinity)

Different types of salinity in dryland regions of Australia are given in Figure 7.2. In foot slopes of the landscape, the watertable is shallower and closer to the surface. Leaching of salts from the soil due to natural processes led to the accumulation of salts in the groundwater. The salinity of the groundwater in dryland regions is often very high, ranging from EC 15 dS/m to 150 dS/m, although low saline (<5 dS/m) groundwater can be found in some irrigation areas. As long as the watertable was below 4 m, saline groundwater did not affect native vegetation.

With the introduction of agriculture and clearance of perennial native vegetation, watertable equilibria changed. In low lying regions, where watertables were shallower, more water with salt has leaked from the upper soil layers and raised the levels of groundwater. Introduction of pastures and annual crops led to the lower utilisation of captured water from rainfall and leakage of water down the profile. As the saline groundwater approaches the surface, soil layers (top 1 m) are salinised and waterlogged. In most irrigated lands, excessive watering accelerates the rise of groundwater to the surface if the natural drainage of the landscape is exceeded. Given that reclaimed water is generally more saline than many traditional sources of water, and higher leaching fractions are required to maintain soil salinity levels in acceptable ranges, it is crucial to ensure the natural drainage of the reuse scheme is appropriate without excessive drainage that would lead to a rise in the watertable.

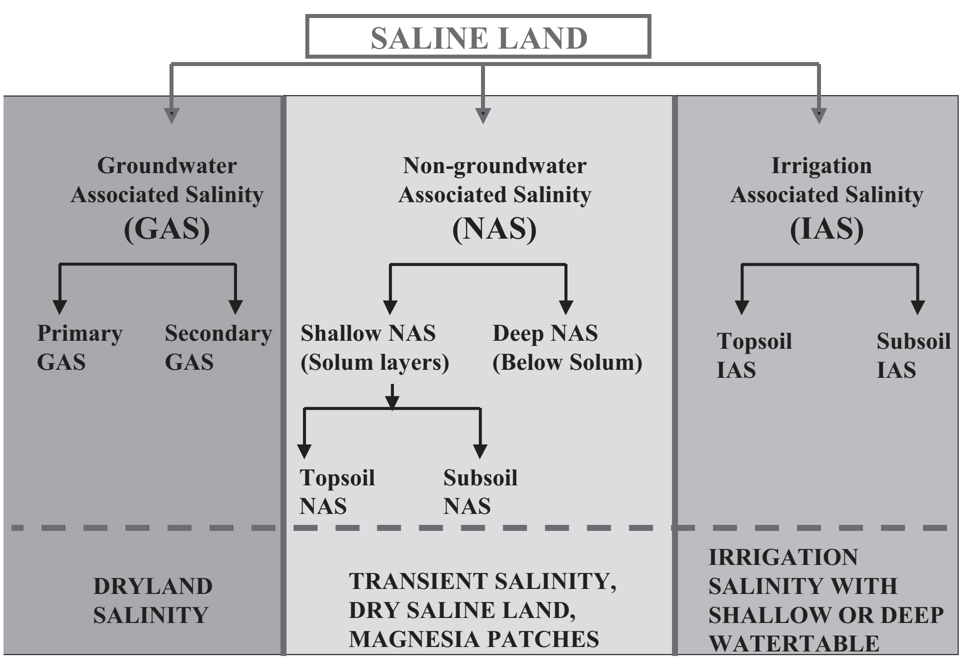

Figure 7.1 Formation of saline land by three different processes.

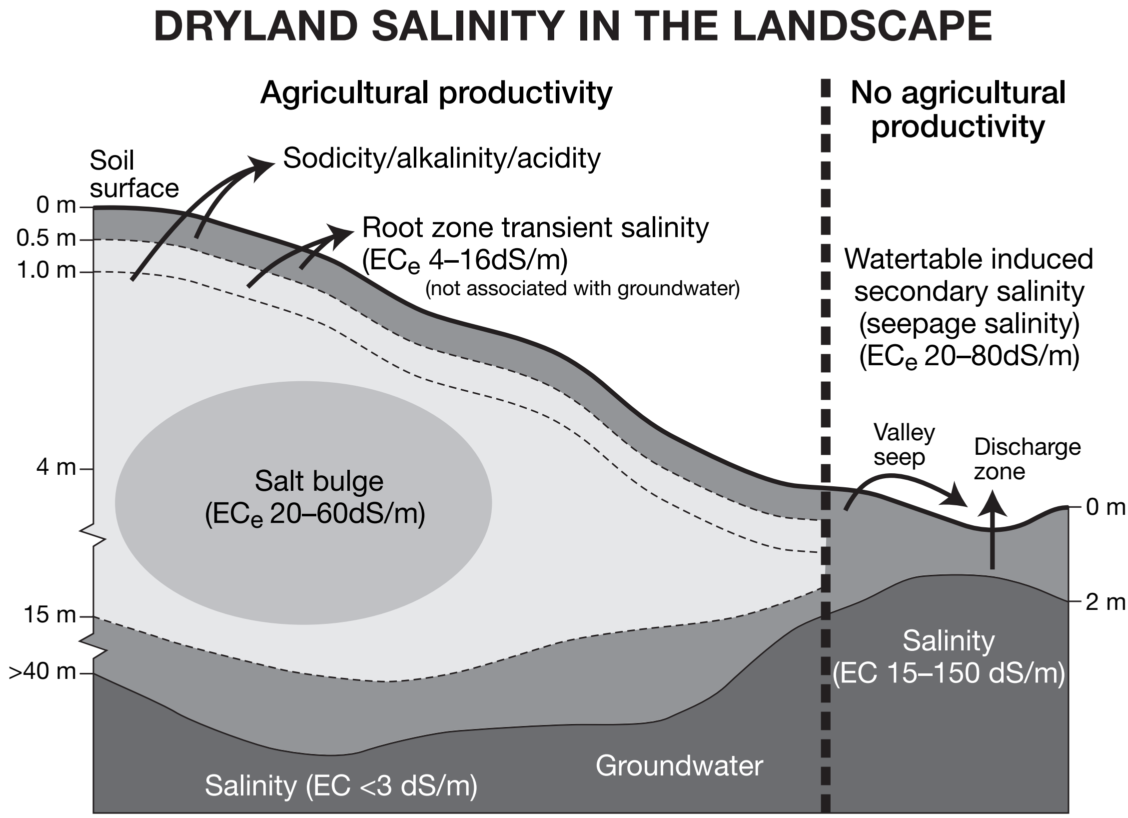

Figure 7.2 Different types of dryland salinity found in the Australian landscape (Rengasamy 2002a).

Generally, watertables around 2 m depth can cause salinity in the surface soils by capillary rise of saline water. On the valley sides of the landscape, saline groundwater can also seep through to the soil surface. This type of salinity is usually called 'seepage salinity'. The National Land and Water Resources Audit (2001) estimated that about 5.7 million hectares of Australia's agricultural and pastoral zone have a high potential for developing this type of salinity due to shallow watertables. The report warns that unless effective solutions are implemented, the area under this type of salinity could increase to 17 million hectares by 2050.

Transient salinity in sodic subsoils

Water infiltration is very slow if the subsoils are sodic and water does not move down below that layer. This causes temporary waterlogging in the subsoil and a 'perched watertable'. Salts can accumulate in the perched watertable. After the wet season, when the water evaporates quickly, salts are left in the subsoil layers of these sodic soils. The amount of salts accumulating is not huge, but may be sufficient to be detrimental to crop growth. This 'transient salinity' fluctuates with depth and also changes with seasonal rainfall. A schematic diagram explaining the processes causing salt accumulation in sodic subsoils is given in Figure 7.3.

Transient salinity in sodic subsoils occurs both in irrigation and dryland regions. Accumulation of salts in irrigated soils is well known all over the world and there is abundant scientific literature on the subject. However, the occurrence of subsoil salinity in dryland regions has received inadequate attention. The extent of subsoil salinity (transient salinity) occurring in dryland regions, not associated with saline groundwater, is large in many landscapes dominated by subsoil sodicity. Shaw *et al* (1998) established a good logarithmic relationship between rainfall, subsoil exchangeable sodium percentage (ESP, the percentage of the cation exchange capacity occupied by sodium) and EC_e (electrical conductivity of saturation paste extract) for north-eastern Australian soils. Subsoil salinity not affected by a shallow watertable results from the reduced leaching caused by sodic clays, low rainfall, transpiration by vegetation and high evaporation during summer.

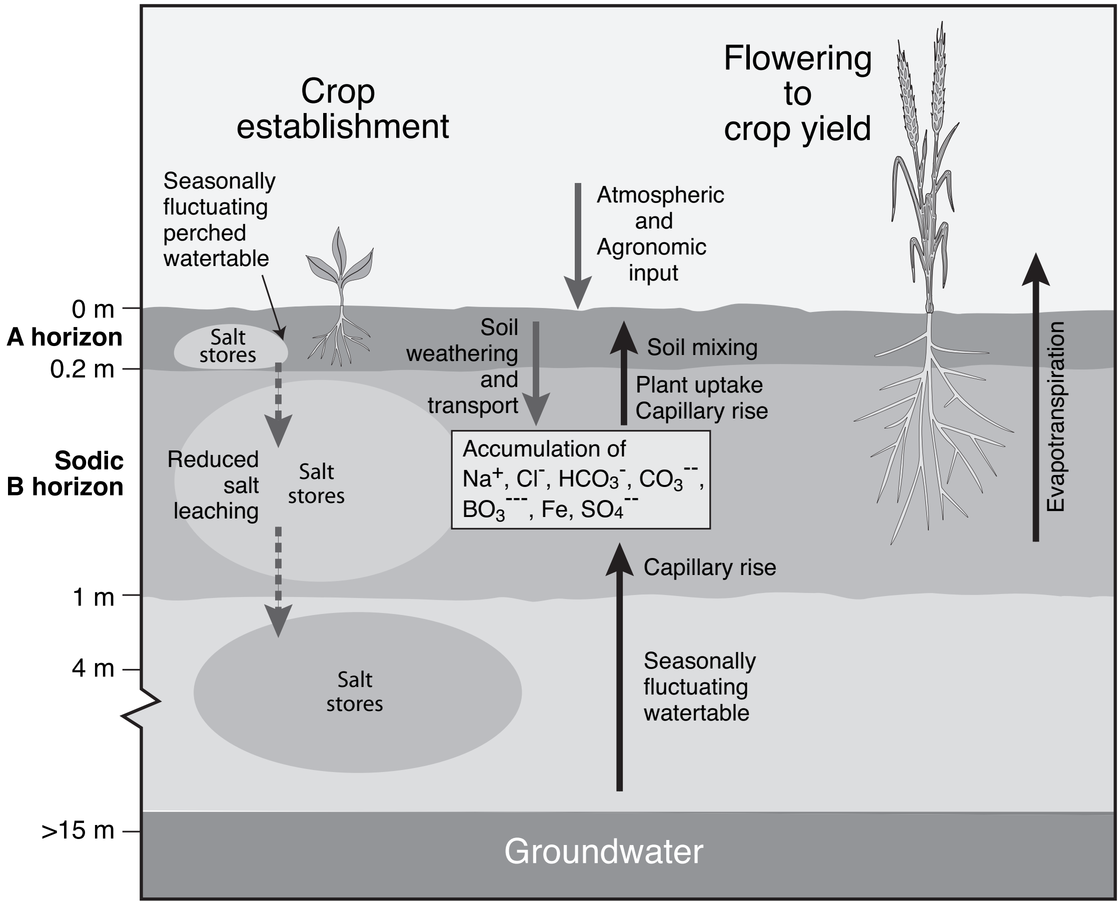

Figure 7.3 Soil processes and accumulation of salt in sodic subsoil layers (Rengasamy 2002a).

By analysing 660 soils in north-eastern Australia within a mean annual rainfall range of 400 mm to 1000 mm, Shaw *et al* (1998) found about 78% of soils with clay contents between 35% and 55% accumulated salt above EC_e 7.7 dS/m in layers between 0 m and 0.9 m from the surface. Soil survey reports indicate that around 4 million ha of dryland soils in South Australia, Victoria and Western Australia have subsoil (0.2–1.0 m) salinity above an EC_e 4.0 dS/m (Rengasamy 2000). In dryland regions with annual rainfall between 250 mm and 600 mm, sodic subsoils have an EC_e between 2 dS/m and 16 dS/m that can dramatically affect crop production through osmotic effects during dry periods. Laboratory measured EC_e will increase several fold under field conditions as the soil layers dry in between rainy days. Poor water storage and osmotic stress combine to enhance crop water stress in dryland environments.

Osmotic effect on subsoil water availability

Osmotic potential added to matric potential renders subsoil water unavailable to crops. Figure 7.4 illustrates the water profile in an alfisol with sandy loam topsoil and clay subsoil. While matric potential indicates water availability to plants, total potential, adding osmotic potential (average root zone salinity of 4 dS/m) reveals that plants are struggling to take up water, as is observed by drought symptoms. Since topsoil water is most often not enough for the plant's needs, subsoil water is essential for its survival and production. However, multiple problems can arise when the salts accumulated in the subsoil water contain boron and carbonates in toxic amounts, as found in many parts of Australia (Rengasamy *et al* 1992). In the case of irrigation with reclaimed water, good irrigation practice should overcome the need for subsoil water.

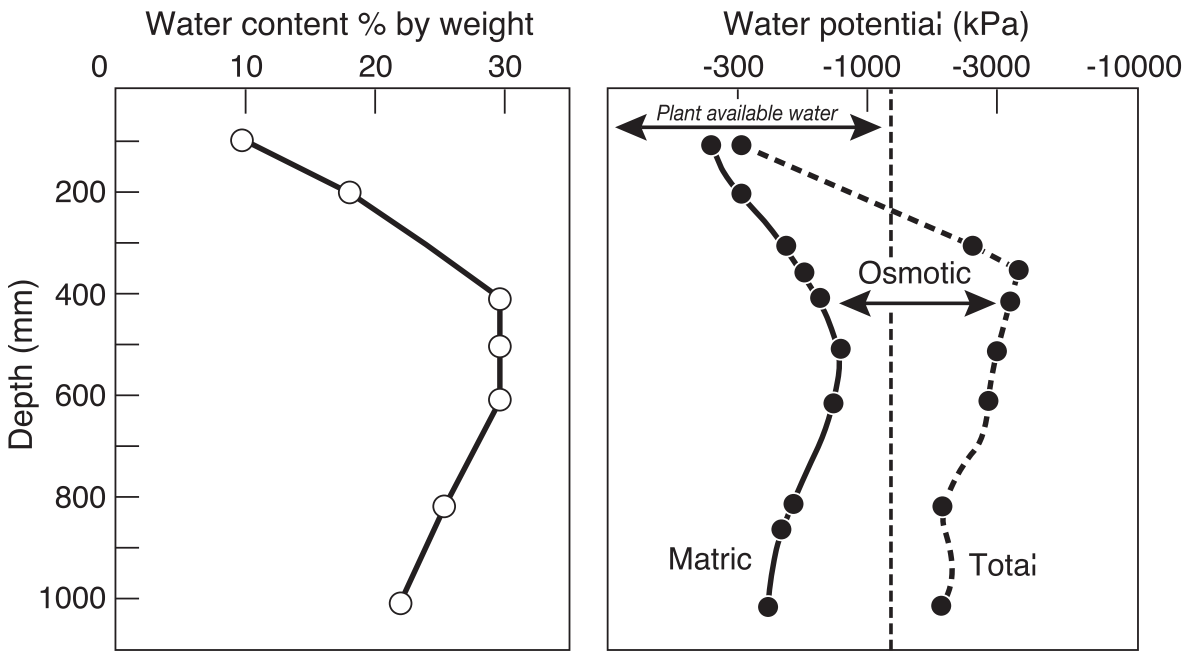

Figure 7.4 Gravimetric water content and soil water potential (matric and total) of an alfisol profile (after Rengasamy 2002a).

Yield decline in saline soils

Most of the plant salt-tolerance data found in the literature uses the EC_e as measure for assessing soil salinity in relation to plant growth. However, methods of saturation paste extracts used to determine the EC_e are laborious. The 1:5 ratio of soil to water extract is commonly used in some countries (Rengasamy *et al* 1984) and can be converted to EC_e. If the clay content of the soil is known, the following equation (Eqn 7.1) gives approximate conversion from $EC_{1:5}$ to EC_e:

$$EC_e = (14.0 - 0.13 \times \text{clay\%}) \times EC_{1:5} \quad (Eqn\ 7.1)$$

This relationship was obtained by using 40 soil samples collected in the author's laboratory from different soil types with clay content ranging from 6% to 60%.

Shaw (1999) gives a good approximation of $EC_{1:5}$ values for different soil textures (clay content) equivalent to EC_e values that correspond to 10% yield reduction of plant species grouped on the basis of their sensitivity to salt (Table 7.1). Plant sensitivity to salinity also varies with the growth stage of the plant. Once established, some species are more tolerant to salinity than they are at emergence. Maas (1986) compared some species (Table 7.2) which highlights that a 50% decrease in emergence (a young growth stage) from salinity can vary considerably from a mature plant where a 50% yield decrease is measured. For example, at emergence, cowpea has a 50% reduction in yield when the EC_e is 16, but a 50% decrease in yield if the EC_e is 9.1 (Table 7.2).

Soil sodicity

Land managers with paddocks that are prone to waterlogging, poor crop or pasture emergence, gully erosion or tunnel erosion may be experiencing the effects of sodicity. Sodic soils are formed as a result of the adsorption of sodium ions (Na^+) by the negatively charged sites on soil particles (particularly soil clays) from soil solutions containing free sodium salts such as sodium chloride (NaCl), sodium carbonate (Na_2CO_3), sodium bicarbonate ($NaHCO_3$) and sodium sulfate (Na_2SO_4). The soils are considered to be sodic when these free salts are leached from the soil layers and only exchangeable sodium remains adsorbed on soil particles. If the free salts are also present, the soils become saline–sodic. Sodic soils are generally found in arid and semiarid regions. High evapotranspiration and low rainfall associated with low leaching is responsible for salt accumulation (Figure 7.3). Reclaimed waters often have a high concentration of sodium ions (Na^+) relative to other cations and, therefore, have a potential to change soils chemically, favouring the formation of sodic or saline–sodic soils.

Table 7.1 Soil salinity criteria as EC_e, corresponding to a 10% yield reduction for the plant salt tolerance groupings of Maas and Hoffman (1977) and the equivalent $EC_{1:5}$ for four ranges of soil clay content.

Plant salt tolerance	Salinity	EC_e[A] range (dS/m)	Corresponding $EC_{1:5}$[B] based on soil to clay content (dS/m)			
			0%–10% clay	20%–40% clay	40%–60% clay	60%–80% clay
Sensitive crops	Very low	<0.95	<0.07	<0.09	<0.12	<0.15
Moderately sensitive crops	Low	0.95–1.90	0.07–0.15	0.09–0.19	0.12–0.24	0.15–0.30
Moderately tolerant crops	Medium	1.90–4.50	0.15–0.34	0.19–0.45	0.24–0.56	0.30–0.70
Tolerant crops	High	4.50–7.70	0.34–0.63	0.45–0.76	0.56–0.96	0.70–1.18
Very tolerant crops	Very high	7.70–12.2	0.63–0.93	0.76–1.21	0.96–1.53	1.18–1.87
Too saline for crops	Extreme	>12.2	>0.93	>1.21	>1.53	>1.87

Source: Shaw (1999).
[A] EC_e, Electrical conductivity of a saturation paste extract; [B] $EC_{1:5}$, electrical conductivity of a 1:5 ratio soil to water extract.

Table 7.2 Salt tolerance of plants at emergence compared with mature plants yield.

Common name	Scientific name	50% emergence[A] EC_e (dS/m)[B]	50% yield EC_e (dS/m)[B]
Grain crops			
Barley	*Hordeum vulgare*	16–24	18
Corn	*Zea mays*	21–24	5.9
Cotton	*Gossypium*	15	17
Rice	*Oryza sativa*	18	3.6
Safflower	*Carthamus tinctorius*	12	14
Sorghum	*Sorghum bicolor*	13	15
Wheat	*Triticum aestivum*	14–16	13
Heavy vegetables			
Beet, red	*Beta vulgaris*	13.8	9.6
Onion	*Allium cepa*	5.6	4.3
Sugarbeet	*Beta vulgaris*	7.5	15
Pasture species			
Cowpea	*Vigna unguiculata*	16	9.1
Lucerne	*Medicago sativa*	8–13	8.9
Vegetables			
Bean	*Phaseolus vulgaris*	8	3.6
Cabbage	*Brassica oleracea capitata*	13	7.0
Lettuce	*Lactuca sativa*	11	5
Tomato	*Lycopersicon lycopersicum*	7.6	7.6

Source: Maas (1986).
[A] Emergence percentage of saline treatments was determined when non-saline control treatments attained maximum emergence; [B] EC_e, electrical conductivity of a saturation paste extract.

The negative charge, which depends on the type and amount of clay materials, is vital in the adsorption of Na^+ ions. Negative charges in soils increase with the content of clay minerals in the order smectites > illites > kaolinites. Soils dominated by positively charged sites such as oxisols, which contain oxides of aluminium (Al) and iron (Fe), and low pH soils generally have negligible amounts of exchangeable sodium. Soils with pH-dependant charge minerals increase their negative charge with increasing pH. The greater the negative charge, the greater the adsorption of Na^+ in soils. Although soil sodicity is a result of a chemical reaction (cation exchange) with the salts, it mainly affects soil physical properties and, thus, plant growth and productivity. The release of high amounts of Na^+ in soil solutions can be toxic (see *Chapter 9*), a condition that is encountered in saline–sodic soils. Sodic soils have an extremely poor physical condition, leading to an inadequate balance between water and air regimes within the soil. The imbalance stems from restricted water acceptance and transmission properties, which result in the soil being too wet or dry for much of the time, leading to poor root development and crop growth. In addition, sodic soils are difficult to cultivate and have poor load-bearing characteristics. The lack of structural stability in these soils promotes soil hardening throughout soil profile and seal and crust formation at the soil surface, resulting in soil erosion and pollution of waterbodies (see Quirk 1978; Shainberg and Letey 1984; Rengasamy and Sumner 1998). Poor drainage in sodic soils also causes secondary salinity in subsoil layers (Shaw *et al* 1998).

Soil processes

Swelling and dispersion of clay particles on wetting are the major processes responsible for the deterioration of physical behaviour of sodic soils. In saline–sodic soils with high electrolyte concentration, swelling is minimal and clay dispersion is absent. Both swelling and dispersion behaviour are governed by the balance between attractive and repulsive forces, arising from intermolecular and electrostatic interactions between the solution and the solid phases in the soil. The distinction between saline and sodic soils arises because these forces vary depending on whether the soil solution is concentrated (saline) or dilute with a high proportion of Na^+ to divalent ions in the solid exchange phase to cause swelling and dispersion (sodic).

Soil scientists have used models based on pure clay minerals that involve Lifshitz-van der Waals, ion correlation, hydration and electrical diffuse double-layer forces generated between colloidal particles suspended in water to explain sodic soil behaviour (see Quirk 1994). However, soil clay systems that are complex heterogeneous intergrowths of different clay structures intimately associated with organic components and biopolymers do not behave in the same way as their pure clay mineral counterparts. Thus, classical theories of colloidal behaviour such as Derjaguin-Landau-Verwey-Overbeek (DLVO) theory (van Olphen 1977) may not satisfactorily explain the behaviour of sodic soils.

The processes that occur during the initial wetting of dry sodic soil aggregates, resulting in swelling to the final stage of aggregate disintegration and leading to dispersion of soil clays when completely wet, are important in understanding sodic soil behaviour. The polar nature of water molecules and solvation reactions with the solid phase are primary factors in causing swelling and dispersion. Clay particles in dry sodic soil aggregates are bound together by inorganic and organic compounds involving several types of bonding which produce strong attractive pressures of the magnitude of megapascals (Rengasamy and Olsson 1991). The water stability of a soil aggregate depends on the strength and persistence of these linkages in the presence of water molecules, which, in turn, are functions of the type of bonding. The bond strength in the presence of water generally decreases in the following order: covalent, hydrophobic, Lifshitz-van der Waals, coordination complexing, hydrogen, and finally, ionic bonds. In contrast to covalent bonds, ionic bonds are readily solvated by water molecules. Similar to pure sodium compounds, the Na^+- clay linkage is easily solvated and the ionic bond broken. Calcium and magnesium ions are linked to clay particles by polar covalent (combination of covalent and ionic) bonds, and thus have decreased ionicity compared to the Na^+ linkage.

The degree of covalency in a bond involving metal cations depends on ionisation and ionic potentials (Rengasamy and Sumner 1998). For example, the tendency to form covalent bonding increases in the order: $Na^+<K^+<Mg^{2+}<Ca^{2+}<Fe^{3+}<Al^{3+}$. Thus, both the type of cation and the nature of the clay ligand determine the ionicity of the clay–cation–clay bonds. Highly ionic bonding in sodic clays leads to extensive hydration and swelling with increasing water content. Finally with separation of linkages on water saturation, clay particles disperse spontaneously in water. However, in calcium-saturated or magnesium-saturated clays with polar covalent bonding, limited hydration leads to limited swelling without any separation (or dispersion) of clay particles. Only on mechanical agitation do these clays disperse. Flocculation of dispersed clay particles is brought about by the addition of electrolyte, which, as result of its osmotic effect, causes dehydration of the clay–water system, thereby bringing clay particles together. Therefore, saline–sodic soils do not have the severe deterioration of physical properties of sodic soils. The order of flocculating power is $Ca^{2+} > Mg^{2+} > K^+ > Na^+$. Thus, gypsum, a calcium compound, is very effective in reclaiming sodic soils. In addition to its flocculating effect, gypsum also promotes removal of sodium from clays by way of cation (calcium) exchange.

Classification of salt-affected soils

There is a need for a uniform system of classification of salt-affected soils which distinguishes between saline and sodic conditions, and is also useful for soil management.

The international nomenclature (Szabolcs 1989) includes the terms sodic, alkali, solonchak, solonetz and solodised solonetz, and the complex interrelationship between them makes comparison between sodic soils difficult. The classification of saline and sodic soils as devised by the United States Department of Agriculture is widely followed in many countries (Table 7.3).

Table 7.3 Classification of saline and sodic soils.

Soil classification	Parameters
Saline, non-sodic soils	Exchangeable sodium percentage (ESP) <15, electrical conductivity in saturation paste extract (EC_e) >4 dS/m
Sodic, non-saline	ESP >15 and EC_e <4 dS/m
Saline, sodic	ESP >15 and EC_e >4 dS/m
Non-saline, non-sodic	ESP <15 and EC_e <4 dS/m

Source: US Salinity Laboratory Staff (1954).

In Australia, a soil is considered sodic if the ESP is above 6. Australian scientists have observed, however, that many Australian soils develop undesirable physical properties (eg clay dispersion and reduced hydraulic conductivity) even when the soil ESP is as low as 6.

The effects of exchangeable sodium on soil physical behaviour varies from soil to soil and are influenced by several factors such as electrolyte concentration, pH, mineralogy, organic matter, biopolymers and aggregate stability in water. Therefore, the definitions used on the basis of ESP vary according to practical experience. Rengasamy *et al* (1984) proposed the following classes on the basis of physical behaviour of sodic soils.

Class 1 *Dispersive soils*: Soils that disperse spontaneously without shaking will have severe problems associated with crusting, reduced porosity, etc., even when subjected to minimum mechanical stress (eg under zero tillage).

Class 2 *Potentially dispersive soils*: Soils that require inputs of mechanical energy (eg raindrop impact and tillage) to bring about dispersion will experience soil physical problems when mechanically disturbed.

Class 3 *Flocculated soils*: Soils that contain more than the minimum electrolyte concentration required for flocculation of clays (or prevention of dispersion of clays) will present few physical problems, but salts could be excessive and limit productivity.

Measurements of clay dispersion along with ESP or sodium adsorption ratio (SAR), EC and pH will be necessary for managing saline and sodic soils. Sumner *et al* (1998) have proposed a detailed, but not yet tested, classification based on these principles.

Dispersive potential

Most of the investigations on clay dispersion have concentrated on soils with high exchangeable sodium, the other complementary cation in the exchange complex being calcium. However, a few studies have indicated that magnesium and potassium ions in the exchange complex can enhance the effects of exchangeable sodium on clay dispersion (see *Chapter 11*). As mentioned earlier, dispersion of soil clays is influenced by several factors. The definition of sodic soils on the basis of ESP varies according to practical experience.

The properties of sodic soils and their management centre on clay dispersion. In order to derive a single parameter that will combine the effects of several factors causing clay dispersion, Rengasamy *et al* (1991) proposed the use of 'dispersive potential', which is derived from the electrolyte concentration and composition at which the tendency of soil aggregates to disperse spontaneously (or mechanically) is prevented. This potential, P_{dis}, is defined as the difference in osmotic pressure between the concentration required to flocculate (or prevent dispersion from aggregates), P_{tec}, and the ambient solution concentration, P_{sol} (Eqn 7.2), so that:

$$P_{dis} = P_{tec} - P_{sol}, \text{ for } P_{sol} < P_{tec} \quad (Eqn\ 7.2)$$

In the original proposal, P_{tec} and P_{sol} are estimated using the valence factor of the Schulze-Hardy rule for divalent ions and from the osmotic pressure as a result of individual ions using Equation 7.3:

$$P_{osm} = (\Sigma C_i Z_i)\ RT \quad (Eqn\ 7.3)$$

where C_i is the concentration, Z_i is the valence of ion 'i' and R is the gas constant. Due to uncertainties about the degree of dissociation of solute molecules, Equation 7.3 does not provide an accurate means for determining the osmotic pressure of a soil solution (Marshall *et al* 1996). Therefore, we use the relationship established by the US Salinity Laboratory Staff (1954) between the osmotic pressure and the electrical conductivity of soil solutions (Eqn 7.4). This is:

$$P_{osm}\ (\text{Pa}) = 3.6 \times 105\ \gamma \quad (Eqn\ 7.4)$$

where γ is the electrical conductivity (EC) in S/m. Making use of the relationship between EC and ionic concentration (mol_c) (1 dS/m = 10 mol_c/m^3, where mol_c/m^3 = meq/L), Equation 7.5 is derived:

$$P_{osm} = 3.6 \text{ kPa per } mol_c/m^3 \quad (Eqn\ 7.5).$$

The flocculating effects of individual ions within a valence group differ and hence the Schulze-Hardy factor is inappropriate. Rengasamy and Sumner (1998) derived the following relationship to calculate the flocculating power of the cations (Eqn 7.6):

$$\text{Flocculating power} = 100(I_Z/I_{Z+1})^2 \times Z^3 \quad (Eqn\ 7.6)$$

where Z is the valence of the cation whose ionisation potential is I_Z and I_{Z+1} is the ionisation potential when the valence of the cation changes to Z + 1. On the basis of this equation and experimental values on soil clays, they concluded that compared to Na = 1, the flocculating power of the other common cations would be K = 1.8, Mg = 27 and Ca = 45. They also suggested using these values instead of the Shulze-Hardy factor in the calculation of dispersive potential. Thus, P_{tec} or P_{sol} can be determined by using Equation 7.7:

$$P_{tec} \text{ or } P_{sol} \text{ (kPa)} = 3.6\ [(45\ C_{Ca}) + (27\ C_{Mg}) + (1.8\ C_K) + (C_{Na}) \quad (Eqn\ 7.7)$$

where C is the concentration of Ca^{2+}, Mg^{2+}, K^+ and Na^+ (mol_c/m^3) in equilibrium solution which contains threshold electrolyte concentration (TEC) or the original soil solution in which clay dispersion is observed. This dispersive potential is a new concept that has not been widely tested. The methodology is given in detail in Rengasamy (2002b).

Interpretation of dispersive potential

Dispersive potential indicates the energy associated with the dispersive reactions in a soil-water system. Due to dispersive potential, P_{dis}, being determined using a given soil, it eliminates the differences due to soil factors such as mineralogy, organic matter and other cementing agents. Further, the different effects of cations are also taken into account in the calculation.

An application of P_{dis} is in the calculation of amount of amendments such as gypsum required to flocculate clays or to prevent clay dispersion. Thus, for a P_{dis} value of 1000 kPa, 6.2 mol_c/m^3 of Ca, or 0.53 g/L of gypsum, is required. Comparing this with other cations, 10.3 mol_c/m^3 of Mg, 154.3 mol_c/m^3 of K and 277.8 mol_c/m^3 of Na are required to prevent clay dispersion. More data need to be collected for developing guidelines for reliable field application.

If spontaneous P_{dis} is >0, the soil is in Class 1, dispersive soil. Similarly, when mechanical P_{dis} is >0, the soil is in Class 2, potentially dispersive soil, and when P_{dis} is zero, the soil can be classified as flocculated (Class 3, Rengasamy *et al* 1984).

Yield decline in sodic soils

Sodic soils are prone to waterlogging, resulting in poor crop emergence and establishment, gully erosion and, in some instances, tunnel erosion. Due to the heterogeneity in the accumulation of sodium by soil particles, these symptoms may be observed only in parts of a paddock. Generally, patchy growth and barren patches are visible in several spots in a paddock while the remainder may look normal. However, the effects of sodicity are fully realised in the harvested yield. The actual yield obtained in sodic soils is often less than half of the potential yield expected on the basis of climate, particularly rainfall and evapotranspiration (French and Schultz 1984; Rengasamy 1997). Table 7.4 (Rengasamy 2000) illustrates the influence of multiple subsoil problems in reducing the yield potential of wheat in different rainfed soils in South Australia. The potential yield is calculated on the basis of 100% efficiency of rainfall and other climatic factors. In spite of proper management of topsoils, subsoil limitations such as salinity, sodicity, alkalinity and toxic concentrations of boron have led to lower yields than expected.

The relationship between the relative yield of cereals grown in 25 sodic soil sites in South Australia, Victoria and New South Wales and the average root zone ESP (average of soil layers between 0 cm and 100 cm depth) is given in Figure 7.5.

Sodic soils are subject to severe structural degradation and exhibit poor soil-water and soil-air relations. Swelling and dispersion of sodic aggregates destroy soil structure, reduce the porosity and permeability of soils, and increase the soil strength even at low suction (ie high water content). These adverse conditions restrict water storage and transport. Soils are, therefore, either too wet immediately after rain or too dry

Table 7.4 Potential yield and actual yield of wheat in different soil types in South Australia.

Soil type	Rainfall (mm/yr)	Potential yield (t/ha)	Actual yield (t/ha)	Subsoil (20–60 cm) limitations
Alfisol	450	4.2	1.7	ESP>18, pH>9
Ultisol	380	3	1.2	B>50 ppm, EC_e >4 dS/m
Vertisol	450	4.2	2.8	ESP>10, EC_e >6 dS/m

Source: after Rengasamy (2000).
Exchangeable sodium percentage (ESP); electrical conductivity of a saturation paste extract (EC_e).

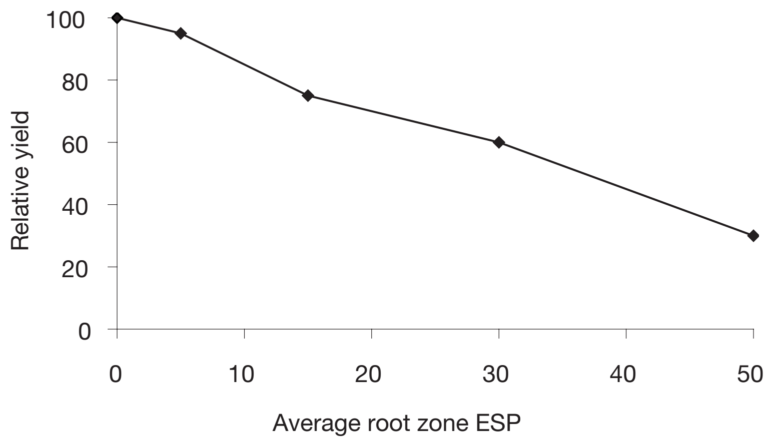

Figure 7.5 Relative yields of cereals grown in Australian sodic soils in relation to average exchangeable sodium percentage (ESP) in the root zone.

within a few days for optimal plant growth. Thus, the range of soil water content that does not limit plant growth and function (ie the non-limiting water range) is very small (Letey 1991; see also Table 7.5).

The inherent sodicity of subsoils in Australian dryland regions is the major factor determining their high strength and lack of porosity. About 86% of sodic soils in Australia have dense clay subsoils with a high ESP (ESP>15) and an alkaline pH (>8.5) trend. Dense, slowly permeable sodic subsoils reduce the supplies of water, oxygen and nutrients needed for obtaining maximum potential yield. During the rainy season, even with prolonged ponding of water on the surface, only a small increase in water content occurs in the subsoil. The low porosity leads to slow internal drainage and water redistribution within the profile (Oster and Jayawardane 1998). This reduction in water storage causes water stress in crops during prolonged dry periods. The subsoil as a source of water and nutrients becomes more important in dryland cropping regions than in irrigated soils.

In layers where calcium carbonate has accumulated during pedogenesis, sodium accumulation generates sodium bicarbonate and carbonate increases the soil pH above 9. In addition to the toxicity of carbonate and bicarbonate species, high pH also leads to iron (Fe), manganese (Mn), copper (Cu), zinc (Zn) and phosphorus (P) deficiency (Naidu and Rengasamy 1993). Ma *et al* (2003) have shown possible phytotoxicity of aluminate ions [$Al(OH)_4^-$] in soils with a pH above 9.

Table 7.5 Example of properties of sodic subsoils compared to an ideal soil that is highly productive.

Properties	Sodic subsoil	Ideal soil
$pH_{1:5}$ (water)	9.2	6.0–8.0
$EC_{1:5}$ (dS/m)[A]	0.2	<0.4
Organic carbon (%)	0.3	>1.0
$SAR_{1:5}$[B]	9.9	<3.0
Spontaneously dispersed clay (%)	8.7	0
Hydraulic conductivity at saturation (mm/d)	4	>80.0
Penetrometer resistance (MPa) at 100 kPa suction	3.8	<2.0
Aeration porosity (%)	5.6	>15
Bulk density (Mg/m^3)	2.2	<1.5
Non-limiting water range (mm^3/mm^3)	0.38–0.42	0.1–0.5

Source: after Rengasamy (1997).
[A] Electrical conductivity measured in a 1:5 soil to water extract;
[B] sodium adsorption ratio measured in a 1:5 soil to water extract.

Effect of irrigation water quality on soil sodicity

The ratio of sodium to calcium and magnesium in irrigation water or soil solution, the sodium adsorption ratio (SAR, see Equation 2.4, *Chapter 2*), is important in relation to the structural stability of the soil. The SAR of water or soil solution/extract is an important measure for assessing the quality of water and its potential effects on sodification of soils. Generally, a relationship between ESP and SAR can be found to give a good indication of the ESP from SAR (simple to measure). Measurement of ESP is more complicated and expensive. Equation 7.8 (US Salinity Laboratory Staff 1954) can be used to convert the SAR of a saturation paste extract (SAR_e) to the ESP of soils:

$$SAR_e = 0.6906 ESP^{1.128} \quad (\textit{Eqn 7.8})$$

Similarly, the following relationship (Eqn 7.9) was established by Rengasamy *et al* (1984) between ESP and the SAR of a 1:5 soil to water extract ($SAR_{1:5}$) using 138 red-brown earths in Australia:

$$ESP = 1.95\, SAR_{1:5} + 1.8 \quad (\textit{Eqn 7.9})$$

Stevens *et al* (2003) found a similar relationship to Rengasamy *et al* (1984) where reclaimed water and bore water had been used for irrigation on the Northern Adelaide Plains.

A sodium balance equation (Rengasamy and Olsson 1993) (Eqn 7.10) that describes the soil sodicity of a given soil layer may be obtained by summing the various inputs and outputs of ionic species to the soil solution and the proportion of sodium to divalent ions, as follows:

$$SCM_{i+r} + SCM_{s+m} + SCM_{a+f}\, SCM_{gw} - SCM_{dw} - SCM_{p+c} - SCM_{cu} = SCM_{ss} \quad (\textit{Eqn 7.10})$$

where S, C and M denote the concentrations of sodium, calcium and magnesium ions, respectively, and the subscripts i, r, s, m, a, f, gw, dw, p, c, cu and ss denote the sources of these ions: irrigation water (i), rainwater (r), solids (s), minerals (m), amendments (a), fertilisers (f), groundwater (gw), drainage water (dw), precipitation (p), complexation (c), crop uptake (cu) and soil solution (ss).

Saline irrigation in Australian soil risks the accelerated sodification of soil layers unless soluble calcium and magnesium minerals are present in the soil profiles to minimise the SAR of the soil solution. Average root zone SAR of a saturated extract (SAR_e) is highly influenced by the leaching fraction of the soil layers and the SAR of the irrigation water (Figure 7.6). The leaching fraction (LF) (Eqn 7.11) can be expressed as follows:

$$LF = \frac{EC_i}{EC_o} = \frac{D_o}{D_i} \quad (\textit{Eqn 7.11})$$

where D is the quantity of water expressed as mm depth, EC is the electrical conductivity and the subscripts i and o refer to input water (i) and output drainage water (o).

Irrigating with reclaimed water

Irrigation with reclaimed wastewater is widely practiced in Australia. It has a number of advantages, as well as disadvantages. The principal factors that need to be considered before deciding to irrigate with reclaimed water are described schematically in Figure 7.7. The composition of the water and the quantity applied will determine how the soil properties and crop productivity will be affected. Analysis of soil solutions before and after irrigation will help in developing appropriate strategies such as drainage facilities and addition of amendments (eg gypsum and fertilisers). Environmental considerations such as impacts on groundwater or disposal of drainage water are also necessary (see *Chapter 11*).

The risk of soil sodicity is high when using reclaimed water for irrigation because often these waters contain high amounts of sodium salts. Sodicity develops over a period of years, particularly in soils with a low leaching fraction (see *Chapter 6*). Soil texture is an important factor in controlling leaching fraction, with clayey soils with low hydraulic conductivity being difficult to leach.

As sodicity increases, the leaching fraction is further reduced. When the leaching fraction is less than the leaching requirement, salt accumulates in the soil layers (Figure 7.3). The fraction of total water applied in irrigation that must pass through the root zone in order to maintain the required salinity level is called the leaching requirement.

Several experiments on the effects of saline–sodic irrigation water on soil properties and plant productivity have led to the following conclusions (Rengasamy and Olsson 1993):

1 when irrigation water salinity exceeds 0.2 dS/m and the leaching fraction is below 0.5, salt accumulation in the soil layers is inevitable;
2 if the SAR of the irrigation water is >3 and the leaching fraction is <0.5, sodium accumulates in soil layers as exchangeable sodium;

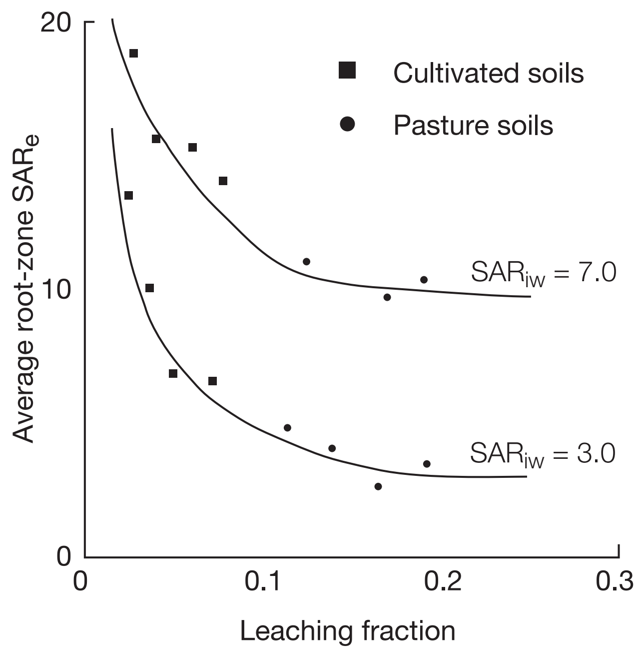

Figure 7.6 Average root zone SAR of a saturated extract (SAR_e) as influenced by leaching fraction and SAR_{iw} (after Rengasamy and Olsson 1993). The subscripts e and iw denote saturation extract and irrigation water, respectively.

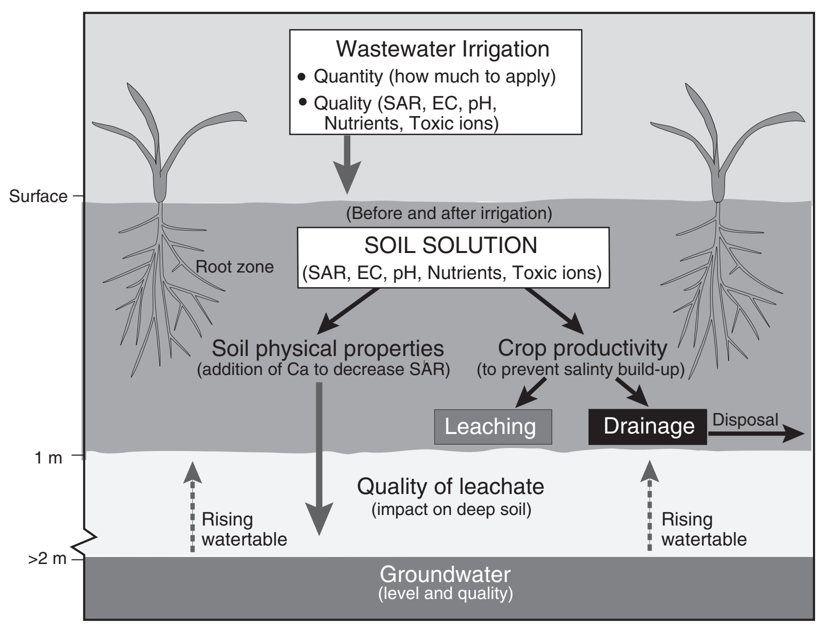

Figure 7.7 Factors and processes to be considered when irrigating with reclaimed water.

3 average EC and SAR of the root zone soil solution increase with increasing EC_{iw} and decreasing leaching fraction; and
4 the increase in both EC and SAR of the root zone soil solution above tolerance threshold levels (Maas and Hoffman 1977; ANZECC and ARMCANZ 2000) leads to the decrease in yields of crops.

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8 Managing risks to soil and plant health from key metals and metalloids in irrigation waters

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State guidelines for heavy metals and metalloids in reclaimed water are generally derived from the *Australian and New Zealand guidelines for fresh and marine water quality 2000* (National Water Quality Management Strategy No. 4; ANZECC and ARMCANZ 2000) and other international guidelines (see *Chapter 2*). The ANZECC and ARMCANZ (2000) guidelines specify limits for the following heavy metals and metalloids: aluminium (Al), arsenic (As), beryllium (Be), boron (B – see *Chapter 9*), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), fluoride (F), iron (Fe), lead (Pb), lithium (Li), manganese (Mn), mercury (Hg), molybdenum (Mo), nickel (Ni), selenium (Se), uranium (U), vanadium (V) and zinc (Zn). We have adopted the definitions for heavy metals and metalloids of ANZECC and ARMCANZ (2000) to maintain a consistent Australian perspective, yet acknowledge there are inconsistencies in the literature for how these terms are used and defined (Duffus 2001). The term 'contaminants' does not refer directly to an unwanted component, as often implied. Contaminant refers to a substance that makes the material of reference (eg reclaimed water) impure. In this sense, contaminants can be beneficial (needed) when present in required concentrations and detrimental (not wanted) when present in concentrations toxic to plants. For example, zinc is a heavy metal referred to as a contaminant in reclaimed water. However, it is a micronutrient required for plant growth at low concentrations (ie needed as a fertiliser) but potentially phytotoxic at high concentrations (unwanted).

Simple loading calculations (volume applied multiplied by element concentration) allow the calculation of potential for increases in contaminant concentration in soils, which may lead to toxicity in the short-term or long-term. More detailed modelling should consider crop removal and possible leaching of the element through the soil profile – this is particularly important for boron (see *Chapter 9*).

The ANZECC and ARMCANZ (2000) guidelines provide an extensive Australian resource on inorganic elements with respect to plant toxicity, and hence protection of crop production systems. However, to date, the guidelines have not considered the possible toxicity to all endpoints in soil (eg to some soil invertebrates or microorganisms), and further work is underway to improve and extend the range of ecological receptors considered. Other future improvements could also include measures of bioavailability (microbial or plant) in place of total soil concentrations. This improvement would allow for more site-specific conditions to be considered and bring the theoretical consideration closer to the practical implementation of these guidelines.

In this Chapter we consider the basic methodology for developing guidelines for heavy metals and metalloid contaminants in irrigation water in an Australian context (translation of this to reclaimed water specific guidelines is discussed in Chapter 2), outline some of the key contaminants, discuss how they react in the soil, and discuss the implications for food safety and quality. We have intentionally not discussed Australian State guidelines for reclaimed water, as they are discussed in Chapter 2, but focussed on the logic behind developing guidelines for heavy metals and metalloids, or in more general terms inorganic elements, and how they relate to food quality.

Development of guidelines for inorganic elements in reclaimed water

The Australian and New Zealand guidelines for fresh and marine water (ANZECC and ARMCANZ 2000) use the following assumptions to calculate loading rates of contaminants from irrigation of soil:

- annual application of irrigation water is 1000 mm;
- inorganic contaminants are retained in the top 150 mm of the soil profile;
- irrigation will continue on an annual basis for a maximum of 100 years; and
- soil bulk density is 1300 kg/m^3.

Trigger levels and cumulative contaminant loading in soil were determined with the aim of preventing potential adverse affects of inorganic contaminants on plants and organisms. This was undertaken by assessing the two main pathways by which metals and metalloids could have a negative impact on crops (ANZECC and ARMCANZ 2000):

1 contaminants may be directly phytotoxic to crops during irrigation, through foliar uptake; and
2 prolonged irrigation will lead to the build-up of heavy metals and metalloids in the soil surface layer and the potential for contaminants to reach concentrations in soil that are toxic to crops or cause a reduction in crop quality, through plant root uptake.

The guidelines also assessed the following for each contaminant:

- existing Australian, New Zealand and international soil quality criteria and guidelines;
- minimisation of contaminant uptake into food crops (food quality);
- impact on farm infrastructure (eg bio-clogging of irrigation lines due to iron or manganese);
- offsite impacts; and
- impact on soil biota (ecotoxicity).

The assessment and assumptions listed above led to the development of three types of guideline value, where sufficient data were available, for each contaminant:

1 **short-term trigger value (STV)** – the STV is the maximum concentration (mg/L) of contaminant in the irrigation water which can be tolerated for a relatively short time (20 yrs), assuming the annual irrigation water loading to soil detailed above;
2 **long-term trigger value (LTV)** – the LTV is the maximum concentration (mg/L) of contaminant in the irrigation water which can be tolerated assuming 100 yrs of irrigation, based on the annual irrigation water loading to soil detailed above; and
3 **cumulative contaminant loading limit (CCL)** – the CCL is the maximum contaminant loading in soil defined in gravimetric units per unit area (kg/ha) and indicates the cumulative amount of contaminant added, above which site-specific risk assessment is recommended if irrigation and contaminant addition is continued.

The CCL (Table 8.2) is calculated based on background concentrations of contaminants in Australian agricultural soils. It allows the calculation of the additional contaminants that can be applied to the soil before testing may be required to determine if contaminant loadings applied through irrigation are of concern (ANZECC and ARMCANZ 2000). In many cases, there was insufficient background soil information to calculate the CCL for many contaminants (Table 8.2), highlighting the lack of data for many heavy metals and metalloids in Australian soils.

These CCL guideline values are based on total contaminant concentrations in soil, yet in many cases a measure of the bioavailable, or potentially bioavailable, element would describe risk more appropriately. However, suitable bioavailability thresholds for inorganic contaminants in agricultural soils have not yet been derived in Australia (McLaughlin *et al* 2000; see *Contaminant mobility and bioavailability*).

Contaminant concentrations in reclaimed water

The concentration of heavy metals and metalloids in reclaimed water can vary considerably as a result of the diversity of wastewater streams flowing into a wastewater treatment plant (WWTP) and the range of treatment processes available (see *Chapter 3*). These factors should be considered when developing reuse schemes to ensure the appropriate quality of water is used for the intended application (Tables 8.1 and 8.2; see also *Chapter 2*). Contaminant element concentrations in reclaimed water are generally low (Table 8.1). In treatment of sewage, metals, which are generally cationic, sorb strongly to negatively charged organic matter and clay minerals in the sewage stream, and thus these metals partition strongly to the solid waste (biosolids) and out of the liquid effluent stream (Pettygrove *et al* 1985; Bunel *et al* 1995). An exception to this is B, which exists as an uncharged boric acid ion at normal sewage pH values, so this element is not retained in the biosolids, and reclaimed water contains most of the B load (Page and Chang 1985). Nutritional and phytotoxic symptoms from increases in soil B concentrations are discussed in *Chapter 9*.

Arsenic, Mo and Se, which exist as oxyanions in solution, will generally partition to the biosolids due to binding to iron or aluminium oxides in the solid waste stream, particularly for As. Fluoride, a halogen and therefore strongly negatively charged in the sewage stream, also partitions strongly to the biosolids due to precipitation reactions (with Ca) and strong sorption to oxides through ligand exchange. Thus, many contaminants in the sewage stream can usually be removed easily by treatment. Targets for reclaimed water, such as the CCLs and the long-term or short-term trigger values, can be easily met in most situations (Table 8.1 and 8.2; Smith *et al* 1996; ANZECC and ARMCANZ 2000; Stevens *et al* 2000).

As many contaminants in sewage partition to the biosolids during treatment, and as biosolids are often used as a soil conditioner and fertiliser (Epstein 2002; Stevens *et al* 2002; Weggler *et al* 2003), the major concerns related to contaminants in sewage are therefore with biosolids use on land rather than reclaimed water irrigation of crops. Most States in Australia have detailed guidelines related to biosolid use in agriculture, with a range of maximum biosolid and soil concentrations specified (DENR SA 1997; NSW EPA 1997; DPIWE 1999; Davies 2002; EPA Victoria 2004). These are reviewed in McLaughlin *et al* (2000) and will not be discussed further. The only elements where some caution is needed in reclaimed water irrigation are B, Mo and possibly Se, as these are more likely to pass through the treatment process and remain in the effluent stream.

Even though heavy metals are generally not found in high enough concentrations in reclaimed waters to be a direct threat to human health, they do have potentially harmful cumulative effects and should be monitored to ensure they are below guideline values (Chang *et al* 1996; Bahri 1998). Similarly, effects from long-term accumulation of heavy metals in soils on plant growth should not be ignored as this could affect the long-term sustainability of a reclaimed water irrigation scheme (Smith *et al* 1996; Stevens *et al* 2003).

The use of three different threshold values – CCL, LTV and STV – highlights the importance of the pathways of exposure to toxicity (as discussed), and the requirement not only to consider concentrations of heavy metals in the reclaimed water, but also the concentrations that might accumulate in the soil from long-term irrigation. Guidelines also vary considerably depending on the endpoint they are designed to protect (Table 8.2). Several examples are discussed below.

From a soils perspective, the National Environmental Protection Council in 1999 released the National Environmental Protection Measure, which included suggested health-based investigation levels (HILs) for contaminants in soils (Table 8.2). These were developed principally for urban or residential areas and are not appropriate for application to agricultural areas (unless these are being developed for residential use). A second series of investigation levels, interim urban environmental investigation levels (EILs), were developed based on environmental thresholds, with plant phytotoxicity being used as the critical risk pathway. There are several shortcomings in using these EILs to assess contaminant risks in agricultural soils (McLaughlin *et al* 2000), including lack of consideration of soil microbial risk pathways (ie risk of contaminants to soil health), poor inclusion of soil background concentrations and the drawbacks associated with using total contaminant concentrations to assess risk (ie a lack of appreciation of contaminant bioavailability).

Compared with the guidelines for drinking water (Table 8.2), guidelines for irrigation water (LTV; ie reclaimed water used for irrigation) are generally higher. This difference is logical from a human health perspective, as drinking water is directly ingested while contaminants in irrigation water have two possible barriers (soil adsorption and plant root membrane) before ingestion of the plant material by humans. The notable exceptions to this are Cu, Mn and Mo (Table 8.2). In these cases, factors other than human health dominate the setting of the guideline. Copper and Mn are phytotoxic at relatively low concentrations, when compared to concentrations which may affect human health from ingestion of drinking water. Low levels of Mo in soil solution can lead to high accumulation in plant tissue which may be harmful to livestock consuming contaminated feed (molybdenosis) (ANZECC and ARMCANZ 2000).

If the trigger values and CCLs specified in Table 8.2 are used as a guide to monitor contaminant loading rates,

Table 8.1 Metal and metalloid concentration in reclaimed water from two Australian reuse schemes compared with guideline trigger values.

				Virginia Pipeline Scheme (SA) reclaimed water (mg/L) 2002/03		Werribee (Vic) reclaimed water (mg/L)
Heavy metal and metalloid	Symbol	STV (mg/L)[A]	LTV (mg/L)[A]	Median	(90th percentile)	(90th percentile)
Aluminium	Al	20	5	0.141	0.252	0.336
Arsenic (total)	As	2	0.1	0.002	0.003	0.0044
Barium	Ba	—[E]	—	0.004	0.005	—
Bervllium	Be	0.5	0.1	0.0005	0.0005[D]	—
Boron	B	<0.5–15[B]	0.5	0.366	0.407	0.734
Cadmium	Cd	0.05	0.01	0.0005[D]	0.0005[D]	0.0001
Chromium (III)		—	—	—	—	—
Chromium (VI)		1	0.1	0.01[D]	0.01[D]	—
Cobalt	Co	0.1	0.05	0.0009	0.0011	0.002
Copper	Cu	5	0.2	0.0045	0.021	0.008
Fluoride	F	2[E]	1	1.0	1.3	—
Iron	Fe	10	0.2	0.03[D]	0.041[D]	0.568
Lead	Pb	5	2	0.002	0.0033	0.0026
Lithium	Li	2.5[C]	2.5[C]	0.009	0.010	0.25
Manganese	Mn	10	0.2	0.07	0.117	0.12
Mercury	Hg	0.002	0.002	0.001[D]	0.001[D]	0.00005
Molybdenum	Mo	0.05	0.01	0.012	0.016	0.0036
Nickel	Ni	2	0.2	0.012	0.018	0.016
Selenium	Se	0.05	0.02	0.003[D]	0.003[D]	0.0008
Uranium	U	0.1	0.01	—	—	—
Vanadium	V	0.5	0.1	0.0055	0.013	0.002
Zinc	Zn	5	2	0.027	0.054	0.0178

Sources: Reclaimed water data (SA Water, pers. comm. Cliff Liston 2004) (Virginia Pipeline Scheme, South Australia) and RMCG, URS (2004). [A] STV and LTV, short-term and long-term trigger values (ANZECC and ARMCANZ 2000); [B] see Table 9.8 for detailed descriptions for plant tolerances; [C] 0.075 mg/L for citrus crops; [D] several samples were less than the detection limit and in this case the detection limit has been used to calculate statistical parameters; [E] incorrect in ANZECC and ARMCANZ (2000), Table 9.2.17; — data not available.

their concentrations in soils should be easily managed. Prevention of soil contamination is much easier than remediation. Even though there are several hyper-accumulator plants and chemical methods for removing contaminants from soils (Brown *et al* 1995), remediation is generally inefficient and much more costly than prevention.

Contaminant mobility and bioavailability

Contaminant mobility and bioavailability in soil varies significantly with soil properties for similar total soil concentrations. Some inorganic contaminants pose little hazard of food chain contamination due to their strong phytotoxic effects (ie increasing metal concentrations cause plant mortality before transfer to the next trophic level has an opportunity to occur). This has been termed the 'soil-plant barrier' (Chaney 1983) and metals can fall into four groups based on their retention in soil and translocation within the plant (Table 8.3). Other contaminants can be micronutrients or macronutrients (see *Chapter 5*) at lower concentrations. However, as concentrations increase, they can become toxic either directly in the reclaimed water, or indirectly as they accumulate in soil over time.

Arsenic, Cd, Hg and Pb are the main inorganic contaminants likely to be scrutinised in relation to food quality as maximum levels in foods have been defined by Food Standards Australia New Zealand (FSANZ) (Table 8.4).

Cadmium

Cadmium is loosely bound to soils (relative to other heavy metals) and is toxic to plants at relatively low concentrations (about 200–1000 nM in solution, CSIRO, pers comm. Mike McLaughlin; Will and Suter 1994). However, human and animal health concerns are found

Table 8.2 Guideline values for contaminant concentrations for heavy metal and metalloids in soil, biosolids, drinking water and irrigation water (mg/kg).

		Soil						Water				
		Health-based investigation[A] Levels (HILs)						RSCL and biosolids	ADWG[F]			
Heavy metal or metalloid	Symbol	A (mg/kg)	D (mg/kg)	E (mg/kg)	F (mg/kg)	EIL[B] Interim urban	Back-ground ranges	Upper limit[C]	Health (mg/L)	LTV[D] (mg/L)	STV[D] (mg/L)	CCL[D] (kg/ha)
Aluminium	Al	—	—	—	—	—	—	—	0.2	5	20	—
Arsenic (total)	As	100	400	200	500	20	1–50	20	0.007	0.1	2.0	20
Barium	Ba					300	100–300	—	0.7	—	—	—
Bervllium	Be	20	80	40	100	—	—	—		0.1	0.5	—
Boron	B	3000	12 000	6000	15 000	—	—	—	0.3	0.5	0.5–15	—
Cadmiium	Cd	20	80	40	100	3	1	1	0.002	0.01	0.05	2
Chromium (III)		12%	48%	24%	60%	400	—	400	—	—	—	—
Chromium (VI)		100	400	200	500	1	—	—	0.05	0.1	1	—
Chromium (total)[E]	Cr	—	—	—	—	—	5–1000		—	—	—	—
Cobalt	Co	100	400	200	500		1–40		—	0.05	0.1	—
Copper	Cu	1000	4000	2000	5000	100	2–100	100	2	0.2	5	140
Fluoride	F	—	—	—	—	—	—	—	1.5	1	2	—
Iron	Fe	—	—	—	—	—	—	—	—	0.2	10	—
Lead	Pb	300	1200	600	1500	600	2–200	300	0.01	2	5	260
Lithium	Li	—	—	—	—	—	—	—	—	2.5	2.5	—
Manganese	Mn	1500	6000	3000	7500	500	850	—	0.5	0.2	10	—
Methyl mercury		10	40	20	50	—	—	—	—	—	—	—
Mercury (inorganic)	Hg	15	60	30	75	1	0.03	1	0.001	0.002	0.002	2
Nickel	Ni	600	2400	600	3000	60	5–500	60	0.02	0.2	2	85
Selenium	Se	—	—	—	—	—	—	3	0.01	0.02	0.05	10
Uranium	U	—	—	—	—	—	—	—	—	0.01	0.1	—
Vanadium	V					50	20–500	—	—	0.1	0.5	—
Zinc	Zn	7000	28 000	14 000	35 000	200	10–300	200	—	2	5	300

Source: NHMRC and ARMCANZ (1996); NEPC (1999a, 1999b); ANZECC and ARMCANZ (2000); EPA Victoria (2004).

—, No data available.

[A] Human exposure settings based on land use have been established for health-based investigation levels (HILs) (see NEPC 1999a). These categories are as follows. *A*, 'standard' residential with garden/accessible soil (home-grown produce contributing less than 10% of vegetable and fruit intake; no poultry): this category includes children's day-care centres, kindergartens, preschools and primary schools. *D*, residential with minimal opportunities for soil access: includes dwellings with fully and permanently paved yard space such as high-rise apartments and flats. *E*, Parks, recreational open space and playing fields: includes secondary schools. *F*, Commercial/industrial: includes premises such as shops and offices as well as factories and industrial sites. For details on derivation of HIL for human exposure settings based on land use, see Schedule B (7A).

[B] EIL, Ecological investigation levels. Interim EIL for the urban setting are based on considerations of phytotoxicity, ANZECC B levels, and soil survey data from urban residential properties in four Australian capital cities (NEPC 1999b).

[C] RSCL, Receiving soil contaminant limit (EPA Victoria 2004).

[D] STV, Short-term trigger value. LTV, long-term trigger value; CCL, cumulative contaminant loading limit (see text for a full description) (ANZECC and ARMCANZ 2000).

[E] Valence state not distinguished – expected as Cr (III).

[F] ADWG, Australian Drinking Water Guidelines (NHMRC and ARMCANZ 1996).

Table 8.3 Contaminant bioavailability grouping.

Group	Heavy metal or metalloid	Soil adsorption	Phytotoxicity	Food chain risk
1	Ag, Cr, Sn, Ti and Zn	Low solubility and strong retention in soil	Low	Little risk because they are not taken up to any extent by plants
2	As, Hg and Pb	Strongly sorbed by soil colloids	Plant roots may adsorb them but not translate to shoots or are generally not phytotoxic except at very high concentrations	Pose minimal risks to the human food chain
3	B, Cu, Mn, Mo, Ni and Zn	Less strongly sorbed by soil than groups 1 and 2	Readily taken up by plants, and are phytotoxic at concentrations that pose little risk to human health	Conceptually, the 'soil–plant barrier' protects the food chain for these elements
4	Cd, Co, Mo and Se	Least of all metals	Pose human or animal health risks at plant tissue concentrations which are not generally phytotoxic	Bioaccumulation through the soil–plant–animal food chain

Source: Chaney (1980).

at subphytotoxic levels (ANZECC and ARMCANZ 2000) and therefore Cd poses potentially the highest human health risk of all heavy metals in reclaimed water.

Cadmium has been found at concentrations in harvestable portions of crops that could be potentially harmful to humans, but showed no toxic signs to the plant. Thus, there are many national and international food quality assurance schemes, as well as national food Cd standards (Food Standards Australia New Zealand, see www.foodstandards.gov.au) that require crop Cd concentrations to be monitored (Table 8.4). As a result of this food-chain risk, Australia has established a national Cd minimisation strategy in agriculture (Australian Cadmium Minimisation Strategy, see www.cadmium-management.org.au). Maximum levels for Cd in traded food commodities are also being developed by the Codex Alimentarius Commission of the World Health Organization and the Food and Agriculture Organization of the United Nations (McLaughlin 2004). Thus, Cd is a contaminant of concern that requires careful monitoring from a food quality perspective. On a more positive note, improvements in the quality of trade wastes entering sewage systems has led to a gradual decline in Cd concentration in Australian sewage over the last decades (Oliver *et al* 2004), minimising the likelihood of direct Cd contamination when irrigating with reclaimed water.

Indirect effects of reclaimed water on plant Cd concentrations should also be considered. Even though the concentration of Cd in reclaimed water could be negligible, and insignificant amounts of Cd would be added to the soil through irrigation with reclaimed water, other water quality parameters could affect food quality by mobilising soil Cd. Changes in soil salinity and chloride concentrations (see *Chapters 7 and 9*) due to use of reclaimed water has the potential to increase plant availability of Cd which is already in the soil (Table 8.5) (McLaughlin *et al* 1994; ANZECC and ARMCANZ 2000).

Other metals

Lead is rarely an issue in terms of crop uptake, as it is strongly sorbed by soil, and if taken up by roots is rarely translocated to edible plant parts. Where Pb contamination has been identified, it is usually due to aerial contamination of the produce, either through dust contamination, or uptake of atmospheric Pb derived from automobile or industrial sources. Similarly, Hg is strongly retained by soil and is generally not regarded as a high risk for food chain contamination via plant uptake.

While As is strongly retained by soils, transfer of As through the food chain can cause potential health risks, as recently found in south-east Asia.

It is unlikely that either Cr or Ni in effluents pose great risks as these elements are often at trace concentrations in effluents, and are strongly adsorbed or precipitated in soils. For Cr, elemental speciation is critical in assessing risks, as the Cr (III) form is relatively non toxic and immobile in soil, while Cr (VI) is highly toxic and mobile.

Conclusion

In summary, heavy metals and metalloids in reclaimed water are generally insignificant from a food quality and crop yield perspective. However, they are potentially an issue if guideline values are exceeded and this needs to be monitored. Loading rates of heavy metals and metalloids in irrigation water can be easily calculated and potential issues identified with readily available guidelines and ongoing monitoring.

Table 8.4 Maximum level of metal contaminants permitted in food in Australia and New Zealand.

Contaminant and food	Contaminant mg/kg as consumed
Arsenic (total)	
Cereals	1
Arsenic (inorganic)	
Crustacea	2
Fish	2
Molluscs	1
Seaweed (edible kelp)	1
Cadmium	
Chocolate and cocoa products	0.5
Kidney of cattle, sheep and pig	2.5
Leafy vegetables (as specified in Schedule 4 – Standard 1.4.2)	0.1
Liver of cattle, sheep and pig	1.25
Meat of cattle, sheep and pig (excluding offal)	0.05
Molluscs (excluding dredge/bluff oysters and queen scallops)	2
Peanuts	0.1
Rice	0.1
Root and tuber vegetables (as specified in Schedule 4 – Standard 1.4.2)	0.1
Wheat	0.1
Lead	
Brassicas	0.3
Cereals, pulses and legumes	0.2
Edible offal of cattle, sheep, pig and poultry	0.5
Fish	0.5
Fruit	0.1
Infant formulas	0.02
Meat of cattle, sheep, pig and poultry (excluding offal)	0.1
Molluscs	2
Vegetables (except brassicas)	0.1
Mercury	
Crustacea, mean level of	0.5[A]
Fish (as specified in Schedule 4 – Standard 1.4.2) and fish products, excluding gemfish, billfish (including marlin), southern bluefin tuna, barramundi, ling, orange roughy, rays and all species of shark	0.5[A]
Gemfish, billfish (including marlin), southern bluefin tuna, barramundi, ling, orange roughy, rays and all species of shark	1[A]
Fish for which insufficient samples	1
Molluscs	0.5[A]
Tin	
All canned foods	250

Source: FSANZ (2005).
[A] Mean level.

Table 8.5 Trigger values for assessing chloride levels in irrigation water and the risk of increased levels of Cd in crops.

Irrigation water chloride concentrations (mg/L)	Risk of increasing crop cadmium concentrations
0–350	Low
350–750	Medium
>750	High

Source: ANZECC and ARMCANZ (2000).

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9 Managing risks to plant health from salinity, sodium, chloride and boron in reclaimed waters

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Although reclaimed water contains elements that have beneficial effects on plant and crop production, some elements are potentially harmful to crops and soils. Among a range of potential contaminants (see *Chapters 8, 10 and 11*), reclaimed water can also contain significant (potentially toxic) concentrations of sodium ions (Na^+), chloride ions (Cl^-) and boron (B).

In terms of suitability for irrigation of crops, salinity is probably the factor of greatest concern. The effect of salinity on plants may be osmotic, which impacts on energy expenditure and water uptake, or relate to specific ion toxicities, such as Na^+ or Cl^- which concentrate in the leaves where they are left behind from the transpiration stream, or result in ionic imbalances due to competitive effects from these ions. Excessive salts may also cause soil structural decline (see *Chapter 7*). In plants it is often hard to differentiate between symptoms of Na^+ and Cl^- toxicity because toxicity symptoms for both ions are very similar. Although Na^+ is more toxic than Cl^-, chloride toxicity is far more common as Na^+ is more readily excluded by plant roots (Weir and Cresswell 1993).

Although B deficiency is a widespread problem for crop production across much of the world (Shorrocks 1997), B toxicity may be manifest in crops irrigated with reclaimed water as these typically have a much higher B concentration than most other water sources.

Other irrigation water sources (ie surface and groundwaters) are not always free of contaminants. For example, while reclaimed water salinity tends to fall in the 1.5 dS/m to 3 dS/m range, Walker *et al* (2002) report salinity levels in groundwater used for irrigation in South and Western Australia to be 0.6 dS/m to 3.0 dS/m, and in South Australia, the EPA (EPA SA 2002) reported that over ten years salinity in the Murray River averaged from 3.4 dS/m to 6.0 dS/m as one moved downstream. In the Victorian study of Kaddous *et al* (1986), total dissolved solids, Na^+, Cl^- and the sodium adsorption ratio (SAR) were all higher in groundwater than in reclaimed irrigation water. While there is great variability in the quality of 'fresh', surface and ground irrigation waters, there is nevertheless a strong tendency for reclaimed water to have higher salinity and higher concentrations of Na^+ and B concentration than other waters generally sourced for irrigation (Asano *et al* 1985). Given the relatively higher concentrations of salinity, Na^+, Cl^- and B in reclaimed water, this Chapter discusses the phytotoxic effects of these elements, so as to facilitate a better understanding of their management.

The manifold effects of salinity

Under saline soil conditions the concentrations of Na and Cl (two micronutrients) typically exceed those of important macronutrients such as potassium (K), nitrate (NO_3^-) and phosphate (PO_4^{3-}) by one or two orders of magnitude (Grattan and Grieve 1999a), and even more so for other macronutrients (eg calcium, Ca, and magnesium, Mg). High concentrations of ions in the soil cause an osmotic effect which makes it more difficult for plants to absorb water from the soil. The high concentrations of salts (principally Na and Cl) which move into plants under saline conditions also pose problems for osmotic adjustment within plant organs, toxicity in leaves, and they can also compete with other more useful ions (eg K^+ and Ca^{2+}) in biochemical reactions.

Osmotic effects

High concentrations of salts in the soil lower the water potential of the soil, slowing the movement of water into roots. The resultant reduced water uptake can stimulate the production of a hormone (abscisic acid) in the roots (Hartung and Davies 1994), or in leaves if they wilt, which causes stomata to close, reducing transpiration (water loss) and carbon dioxide (CO_2) assimilation (photosynthesis) and slowing plant growth. For spinach grown under saline conditions, Delfine *et al* (1998) found that as salt accumulated in leaves, photosynthesis was reduced because less CO_2 reached the photosynthetic machinery (chloroplasts), a consequence of both stomatal closure and changes in leaf structure which decreased CO_2 diffusion rates. Similar observations have been made in olives (Bongi and Loretto 1989). These effects of high concentrations of salt in the soil may thus be similar to those which occur under drought. While water uptake may thus be reduced it will nevertheless continue, and bring with it ions from the soil solution.

For ions such as Na^+ and Cl^-, which are taken up by plants in greater quantity under saline conditions, high concentrations can accumulate where they are left behind when water is transpired from leaves (hence, toxic symptoms often first appear in tips or margins of older leaves). At the point of accumulation, high concentrations of Na^+ and Cl^- are usually quarantined in vacuoles. In such circumstances many plants synthesise specific organic compounds, called 'compatible solutes' or 'osmolytes' (eg proline and glycinebetaine), which are then kept in the cell cytoplasm to balance leaf turgor (Robinson and Jones 1986). However, some plants are unable to synthesise some of these osmolytes. For example, tomato is unable to synthesise glycinebetaine, although it is able to respond favourably to exogenous supplies (Makela *et al* 1998a). When glycinebetaine was applied to leaves of tomato in pot trials under saline conditions, stomatal conductance was increased; however, leaf abscisic acid and water relations were not (Makela *et al* 1998b). Leaf Na^+ and K^+ concentrations were also unchanged. This study did not follow effects through to fruit yield, although positive tomato yield responses to gylcinebetaine application were observed in the work of Makela *et al* (1998a). An alternative approach to providing salt-adaptation through exposure to osmoticants is found in the work of Balibrea *et al* (1999). They found that tomato seedlings pre-exposed to polyethyleneglycol (PEG) for 12 hours grew 50% more than untreated plants after six weeks when grown in 100 mM NaCl. The PEG-treated plants also accumulated 1.2 to 2 times more Na^+ and Cl^- and 25 mM more K^+, and twice as much proline, as untreated plants. The study was not followed through to fruit yield. Clearly, more work is required to ascertain whether exogenous supplies of osmolytes might provide practical adjuncts to other salinity management strategies in horticulture.

Sodium toxicity

Sodium is widely distributed in nature, and tends to accumulate as salt in arid and semiarid environments following evaporation of incident rainfall and irrigation waters (see *Chapter 7*). Sodium is not an essential element for the growth of all plants but Marschner (1995) classifies sodium as a 'beneficial' element because it stimulates growth for some plant species under certain conditions (Brownell 1979). Halophytic plants, which live in saline environments, have a high Na^+ requirement for osmoregulation to maintain cell turgor (Marschner 1995). Sodium ions may enter the plant through the root, or directly through the leaf from rainfall or overhead irrigation. Woody plants (trees and vines) are the most susceptible to Na^+ toxicity (Maas 1985; Weir and Cresswell 1993). Direct plant toxicity due to high soil Na^+ concentrations is partially managed by plants which have some control over Na^+ uptake at the root surface. However, these root exclusion mechanisms are not at all effective if salt is applied directly to foliage through sprinkler irrigation (Table 9.1). Symptoms of sodium toxicity are leaf burn, scorch and dead tissue along the margins of leaves. The symptoms occur first in the oldest leaves. As the severity increases, the symptoms move inwards between the leaf veins toward the centre of the leaf. The degree of injury is affected by site-specific environmental and agricultural conditions.

Cation imbalances

High concentrations of sodium in the soil can also interfere with plant uptake of potassium (K^+) and calcium (Ca^{2+}) ions. The displacement of Ca^{2+} by Na^+, or other cations, can cause Ca^{2+} deficiency which may be manifest as cupping of the youngest leaves, leaf tip burn of vegetables or bent over apices and inflorescences. In tomatoes Na^+ induced Ca^{2+} deficiency causes blossom end rot of fruit (Cuartero and Fernandez-Munoz 1999). Antagonism between the uptake of Na^+ and K^+ has also been observed in wheat (Hu and Schmidhalter 1997), and in cucumbers where Martinez and Cerday (1998) found that increasing substrate salinity increased leaf Na^+ but decreased K^+. Pardossi *et al* (1999) found that in celery Na^+ may replace K^+ in the maintenance of cell turgor.

Table 9.1 Approximate sodium concentration that can cause foliar injury in plants from saline sprinkling water.

Sensitive <115 mg/L	Moderately sensitive 115–230 mg/L	Moderately tolerant 230–460 mg/L	Tolerant >460 mg/L
Almond	Pepper	Barley	Cauliflower
Apricot	Potato	Maize	Cotton
Citrus	Tomato	Cucumber	Sugar beet
Plum		Lucerne	Sunflower
Grape		Safflower	
		Sesame	
		Sorghum	

Source: ANZECC and ARMCANZ (2000).

Although Ca may have general non-specific functions within most plants (see *Chapter 5*), it is probably important with pectates in cell walls for maintaining firmness in many fruit crops (eg see Taylor *et al* 1995), which may have higher Ca requirements than some other plants. In experiments with wheat, Kinraide *et al* (1999) concluded that while Na^+ can displace Ca^{2+} it is most often of minor importance, K^+ displacement by Na^+ did not occur to any significant extent, and that, apart from osmotic effects, high concentrations of Na^+ in the rooting medium and in plant tissues were not toxic unless Ca^{2+} was also deficient. Reid and Smith (2000) reviewed the evidence for competitive interactions between these cations and concluded that displacement of Ca^{2+} by Na^+, and Ca^{2+} deficiency at low Ca^{2+} supply, increased Na uptake which reduces K channel selectivity and K influx to roots. This problem can be overcome by maintaining Ca^{2+} sufficiency. Like Kinraide *et al* (1999) they concluded that osmotic effects would remain the principal problem under salinity but that this would not be overcome by increasing Ca^{2+} supply above nutritional demands. Clearly, improved cation nutrition does not alleviate osmotic constraints under saline conditions. For this, compatible osmotic solutes are likely to be more effective.

Nevertheless, sodium toxicity is sometimes expressed relative to the availability of other cations (SAR, Table 9.2; see *Chapter 7*). Interestingly, the deciduous fruit crops appear to be the most sensitive to high amounts of sodium relative to other cations.

Chloride toxicity

Chlorine exists in soil principally as the anion (Cl^-), the salts of which are readily soluble. Chloride is not readily adsorbed to soil minerals and is therefore mobile in the soil and easily leached (Flowers 1988). It is readily taken up by plant roots, and has high mobility in the plant, occurring mainly as the free chloride ion or loosely bound to exchange sites (Marschner 1995; Jones 1998). Crops grown in high Cl^- environments can suffer from chloride toxicity and associated nutrient imbalances. In addition to irrigation waters, sources of Cl^- include soil

Table 9.2 Effect of sodium, expressed as sodium adsorption ratio (SAR) on crop growth and quality under non-saline conditions.

SAR tolerance and range	Crop	Growth response under field conditions
Extremely sensitive SAR = 2–8	Avocado, deciduous fruits, nuts, citrus	Leaf tip burn, leaf scorch
Sensitive SAR = 8–18	Beans	Stunted growth
Medium SAR = 18–46	Clover, oats, tall fescue, rice, dallis grass (*Paspalum dilatatum*)	Stunted growth, possible sodium toxicity, possible Ca or Mg deficiency
High SAR = 46–102	Wheat, cotton, lucerne, barley, beets, Rhodes grass (*Chloris gayana*)	Stunted growth, soil structural problems

Source: ANZECC and ARMCANZ (2000).
SAR, sodium adsorption ratio; Ca, calcium; Mg, magnesium. Sodium absorption ratio measured in a 1:5 soil to water extract.

reserves, fertilisers, rain, chemicals and air pollution (Marschner 1995). The incidence of Cl^- toxicity is more widespread in arid and semiarid environments (Marschner 1995), perhaps due to greater evaporative concentration.

Chloride is critical in photosynthesis and respiration, enzyme formation and catalysis, and osmotic regulation in saline environments (Marschner 1995; Fageria *et al* 1997). Although a micronutrient, and only required in small quantities (eg 200–400 µg/g dry matter), concentrations of 0.2% to 2% are common in plant tissues (Mengel and Kirkby 1978; Marschner 1995; Jones 1998). Flowers (1988) found a direct, plant-specific, relationship between external Cl^- concentration and plant Cl^- concentrations (dry tissue weight). Once taken up by the plant root, chloride has been shown to accumulate in the leaves but not significantly in the roots, grain or stems (Flowers 1988; Jones 1998), probably because the bulk of the transpiration stream is through leaves. Chloride can also be taken up directly through leaves when spray irrigation is used (Maas 1985; Weir and Cresswell 1993). Leaves of deciduous trees readily absorb Cl^- while some trees (eg citrus) absorb Cl^- more slowly, though usually still fast enough to cause problems (Maas 1985). As plant leaves are the major sink for Cl^- this is the site where toxic symptoms are first expressed. Chloride accumulates in older leaves, with reduced Cl^- concentrations in younger shoots (Flowers 1988). Chloride toxicity is manifest as premature senescence (seasonal wilting of leaves), leaf burn, bronzing and defoliation (Hu and Schmidhalter 1997; Jones 1998; Storey and Walker 1999), resulting in reductions in photosynthesis and hence production (Hu and Schmidhalter 1997).

For citrus, which are probably the most sensitive group, the major pathway to alleviate Cl^- toxicity is through the use of rootstocks that are able to reduce the uptake of Cl^-. An example of the importance of rootstock in determining uptake and accumulation of ions under saline conditions is illustrated in Table 9.3. From this it can be seen that salt 'tolerance' in citrus comes mostly from salt exclusion at the root rather than through tolerance to high ion concentration in leaves. The relative tolerance of a range of fruit crops and rootstocks to soil Cl^- are listed in Table 9.4.

Anionic imbalances

Chloride not only reduces production through direct phytotoxicity, but also possibly by its interaction with other mineral nutrients. Chloride can compete with anions like NO_3^-, phosphates (HPO_4^{2-}, $H_2PO_4^-$), and sulfate (SO_4^{2-}) for plant uptake (Mengel and Kirkby 1978; Jones 1998). This can cause nutrient imbalances that, in turn, may decrease crop quality or production. Although there is some evidence that under saline conditions Cl^- may reduce NO_3^- uptake (Hu and Schmidhalter 1997; Martinez and Cerda' 1998; Pardossi *et al* 1999), this probably does not cause reduced growth or crop yield where crops are grown under sufficient nitrogen conditions (Munns and Termaat 1986; Grattan and Grieve 1994). When NO_3^- was added to the substrate, plant Cl^- uptake was decreased, while NH_4^+ additions enhanced Cl uptake (Feigin *et al* 1987; Martinez and Cerda' 1998). In glasshouse sand cultures of strawberry fruit, yield responses to foliar applied calcium nitrate ($Ca(NO_3)_2$) (Kaya *et al* 2002) or potassium dihydrophosphate (KH_2PO_4) (Kaya *et al* 2001) were seen in plants grown in both saline and non-saline conditions. Although the increase was greater under saline conditions, yield remained substantially less than that under non-saline conditions. Although competitive uptake at the root surface was thus eliminated, the mechanisms for the responses were not elucidated. Interpreting the literature with respect to interactions between Cl^- and P uptake in soils is somewhat more complex due to variation in the availability of different P forms in different soils and culture conditions. In a review of the published data, Grattan and Grieve (1999b) concluded that, under field conditions of lower P availability, uptake of P by crops is

Table 9.3 Leaf and root tissue water ion concentration (mM) from citrus grown on root stocks differing in ion exclusion.

Rootstock salt tolerance	Potassium (K^+)		Sodium (Na^+)		Chloride (Cl^-)	
	Leaves	Roots	Leaves	Roots	Leaves	Roots
High	192	107	60	96	50	89
Low	320	138	25	109	140	106

Source: after Atwell *et al* (1999).

Table 9.4 Tolerance of some fruit crop cultivars and rootstocks to chloride.

Crop	Rootstock or cultivar	Maximum chloride (Cl^-) in soil water without leaf injury (mg/L)
Avocado	West Indian	535
	Guatemalan	425
	Mexican	355
Citrus	Sunki mandarin, grapefruit,	1775
	Cleopatra mandarin, Rangapur lemon	1065
	Sampson tangelo, rough lemon, sour orange, Ponkan mandarin	710
	Citrumelo 4475, trifoliate orange, Cuban shaddock, Calamondin, sweet orange, Savage citrange, Rusk citrange, Troyer citrange	
Grape	Salt Creek, 1613-3	2840
	Dog ridge	2130
Stone fruit	Marianna	1775
	Lovell, Shalil	710
	Yunnan	355
Berries	Cultivar	
	Boysenberry	710
	Olallie blackberry	710
	Indian Summer raspberry	355
Grape	Thompson seedless, Perlette	1420
	Cardinal, Black rose	710
Strawberry	Lassen	535
	Shasta	355

Source: after Maas (1986).

often reduced, but under glasshouse conditions in sand or solution culture, where P availability is relatively high, several groups of crop plants (corn, sesame, soybean, lupin) appear to suffer from supraoptimal P uptake under saline conditions. While good nutrition is clearly pivotal to achieving maximal crop yields, it may be more critical under saline conditions.

Salinity tolerance of horticultural crops

There is voluminous literature on the effects of salinity on crops, as it is a widespread problem relating to many irrigation waters (ie not just reclaimed water) and to dryland agriculture (see Maas and Hoffman 1977; Shannon and Grieve 1999). 'Salinity tolerance' is a general term which must include a wide range of adaptations which might help plants to withstand or adjust to saline environments. Although the ability of plants to withstand the varied osmotic and toxicity effects of saline waters and soils depends on both plant and soil factors, crops can nevertheless be ranked in general terms to their sensitivity to saline irrigation waters and soils (Table 9.5). In general:

1 vegetable crops are more sensitive to salinity than other crops;
2 although many woody fruit crops are very sensitive to salinity, saline-tolerant rootstocks are available and are often used for increasing the salinity tolerance of crops;
3 sensitivity to salinity increases with soil clay content; and
4 for some species, sensitivity increases with leaf exposure to sprinkler irrigation with saline water.

Shallow-rooted crops may be more susceptible to salinity effects as there is a tendency for salt to accumulate in the surface layers where most plant water uptake and evaporation from soil occurs. The effects of this can be managed to a large extent by irrigation technology, particularly drippers for which a wet zone equal to the salinity of the irrigation water can be maintained (Elder *et al* 2000, and see *Chapter 6*). In cases where irrigation with saline water decreases vegetative growth, fruit yield may be improved as photosynthate is diverted to reproductive parts (Pasternak and De Malach 1994). The effects of salinity on horticultural crops were well reviewed in 1999 for vegetable (Shannon and Grieve 1999), citrus (Storey and Walker 1999) and tomato (Cuartero and

Fernandez-Munoz 1999) crops, as was the interaction between salinity and mineral nutrition (Grattan and Grieve 1999b). For citrus, which are probably the most sensitive group, Cl^- toxicity in leaves is the principal problem. The major pathway to alleviate this is through the use of rootstocks that are able to greatly reduce the uptake of Cl^-. In the case of Na^+ there are less marked differences between plants in their ability to exclude salt at the root. An example of the importance of rootstock in determining uptake and accumulation of ions under saline conditions is illustrated for grapevines in Table 9.6. From this it can be seen that salt 'tolerance' comes mostly from salt exclusion at the root rather than through tolerance to high ion concentrations in the leaves.

Cass *et al* (1995) highlighted that most grapevines in Australia would be suffering substantial yield penalties due to salinity of normal irrigation waters and soils if not grafted onto salt-tolerant rootstocks. Sprinkler irrigated vines may be more sensitive to Na^+ and Cl^- since the salts are readily absorbed by the leaves without the benefit of the salt-excluding rootstocks. In this case, Francois and Clark (1979) found that the presence of counter ions (Ca^{2+} or SO_4^{2-}) did not reduce Na^+ or Cl^- absorption. High ion levels of Na^+, Cl^- and K^+ have been shown to both reduce (McCarthy and Downton 1981) and increase (Walker *et al* 2002) wine quality. Since the European Economic Community requires wines to have <1 g/L NaCl, the concentration of these ions in grapes and wines needs to be kept down (Lee 1990) to maintain wine quality and export markets.

Cuartero and Fernandez-Munoz (1999) summarised research on salinity and tomatoes. The key points were:

1. germination and early growth is sensitive to salinity, but this can be minimised by 'priming' the seeds or seedlings with low–moderate concentrations of saline water prior to planting out;
2. salinity tends not to affect the dry matter distribution between fruit, shoot and root;
3. fruit weight, but not fruit dry matter, declines with increasing salinity, thus the effect of saline irrigation water is probably osmotic rather than a specific ion toxicity – irrigation with 5 dS/m – 6 dS/m water results in a 10% yield reduction (fruit size), and with 8 dS/m a 30% reduction in fruit size/yield;
4. since fruit size is reduced by salinity it might be prudent to use smaller fruited varieties and cherry tomatoes under saline conditions;
5. fruit development and maturation is faster under saline conditions;
6. blossom end rot, caused by a local Ca^{2+} deficiency at the distal placental fruit tissue, can increase under saline conditions due to reduced Ca^{2+} uptake, but can be managed to some extent with varietal selection, particularly for smaller fruited varieties;
7. salinity enhances tomato fruit taste by increasing both sugars and acids, but tends to produce more acid fruit as salinity increases from 2 dS/m to 9 dS/m;
8. shelf-life of fruit is not reduced for long shelf-life varieties, although fruit produced from saline irrigated crops is more susceptible to handling damage due to higher CO_2 and ethylene production on injury; and
9. crop nutrition needs to be optimised to minimise effects of salinity wherever possible, since crops may be more sensitive to high or low P, or N availability due to interactive effects.

Similarly, attention should be paid to maintaining high Ca^{2+} nutrition that can help reduce Na^+ uptake and increase both Ca^{2+} and K^+ uptake, which are generally depressed under saline conditions. Overall, tomatoes provide an attractive option for irrigation with reclaimed water, for although they are considered moderately sensitive to salinity, fruit size (and thus yield) does not decrease until irrigation water salinities rise above 2.5 dS/m to 3.0 dS/m, and saline waters enhance the flavour.

Boron

Boron (B) is a micronutrient that is only required by plants in small amounts (<500 g/ha). However, B deficiency is a widespread problem across much of the world (Shorrocks 1997). Although B concentrations are not often reported, reclaimed water may have higher levels of B than other irrigation waters (Table 9.7). The discharge of sodium perborate into the environment during production and end use of detergents has resulted in the accumulation of B in waste effluent and consequently in groundwater and natural aquatic systems (Vengosh *et al* 1994). Boron in reclaimed waters also originates from water softeners (Westcot and Ayers 1984). The composition of B in wastewater is determined by the composition of incoming domestic water supply plus mineral pickup of 0.1 mg/L to 0.4 mg/L, resulting from domestic water use (Asano *et al* 1985). Bouwer and Chaney (1974) reported a range of B concentrations in primary and secondary effluent of <0.01 mg/L to 2.5 mg/L (median 1.0 mg/L) and <0.1 mg/L to 2.5 mg/L (median 0.7 mg/L), respectively. Calculations by the German Government Environment Agency attribute 50% of the B in wastewater to the use of detergent products (Butterwick *et al* 1989). Some soils also have naturally elevated levels of B, particularly in the subsoil (Ryan *et al*

Table 9.5 Average root zone salinity tolerance of vegetable and fruit crops, threshold irrigation water salinities before yield loss as a function of soil type, and percentage yield loss after a threshold is reached.

Common name	Scientific name	Mean root salinity tolerance (EC_e[A] dS/m)	Max. irrigation water salinity before yield loss (dS/m)			% Yield loss/ dS EC_e[A]
			Sandy soil	Loamy soil	Clay soil	
Avocado	*Persea americana*	1.3	2.3	1.3	0.8	
Almond	*Prunus dulcis*	1.5	2.7	1.5	0.9	19.0
Apple	*Malus sylvestris*	1.0	2.0	1.2	0.7	
Asparagus	*Asparagus officinalis*	4.1	5.2	3.0	1.7	2.0
Avocado	*Persea americana*	1.3	2.3	1.3	0.8	
Bean	*Phaseolus vulgaris*	1.0	1.9	1.1	0.6	19.0
Beet sugar	*Beta vulgaris*	7.0	11.0	6.3	3.7	9.0
Beet, garden	*Beta vulgaris*	4.0	6.5	3.7	2.1	
Broad bean	*Vicia faba*	1.6	3.3	1.9	1.1	
Broccoli	*Brassica oleracee*	2.8	3.3	2.8	1.6	9.2
Cabbage	*Brassica oleracea*	1.8	3.5	2.0	1.2	9.7
Carrot	*Daucus carota*	1.0	3.3	1.2	0.7	14.0
Cauliflower	*Vrassica oleracea*	2.5	3.3	1.8	1.1	
Celery	*Apium graveolens*	1.8	3.3	2.5	1.4	6.2
Cucumber	*Cucumis sativus*	2.5	3.3	2.4	1.4	13.0
Eggplant	*Solanum melongena*	1.1	3.2	1.8	1.1	6.9
Grape	*Visis* spp.	1.5	3.3	1.9	1.1	9.6
Grapefruit	*Citrus paradise*	1.8	3.3	1.7	1.0	13.5
Kale	*Brassica campestris*	6.5	3.3	4.7	2.7	
Lemon	*Citrus limon*	1.0	1.3	0.7	0.4	12.8
Lettuce	*Lactuca sativa*	1.3	3.3	1.5	0.9	13.0
Olive	*Olea europaea*	4.0	5.1	2.9	1.7	
Onion	*Allium cepa*	1.2	3.3	1.3	0.8	16.0
Orange	*Citrus sinensis*	1.7	3.3	1.7	1.0	13.1
Pea	*Pisum sativum* L.	2.5	3.3	1.8	1.1	10.6
Peach	*Prunus persica*	3.2	4.7	2.7	1.6	21.0
Pear	*Pyrus* spp.	1.0	1.3	0.7	0.4	
Pepper	*Capsicum annum*	1.5	3.3	1.6	0.9	14.0
Plum	*Prunus domestica*	1.5	2.5	1.4	0.8	31.0
Potato	*Solanum tuberosum*	1.7	3.2	1.8	1.1	12.0
Pumpkin	*Cucurbita pepo pepo*	1.7				
Radish	*Raphanus sativus*	1.2	1.5	0.9	0.5	13.0
Rockmelon	*Cucumis melo*	2.2	4.6	2.6	1.5	8.4
Rosemary	*Rosmarinus lockwoodii*	4.5	5.7	3.3	1.9	
Spinach	*Spinacia oleracea*	2.0	4.2	2.4	1.4	7.6
Squash	*Cucurbita maxima*	2.5	3.2	1.8	1.1	
Squash, scallop	*Cucurbita pepo melopepo*	3.2	4.8	2.7	1.6	16.0
Strawberry	*Fragaria* supp.	1.0	1.6	0.9	0.5	33.0
Sweet corn	*Zea mays*	1.7	3.3	1.8	1.1	12.0
Sweet potato	*Ipomoea batatas*	1.5	3.0	1.7	1.0	
Tomato	*Lycopersicon esculentum*	2.3	3.5	2.0	1.2	9.9
Turnip	*Brassica rapus*	0.9	2.5	1.4	0.8	
Zucchini	*Cucurbita pepo melopepo*	4.7	7.3	4.2	2.4	9.4

Source: collated from Maas (1987), ANZECC and ARMCANZ (2000), Kelly *et al* (2001).
[A]EC_e, Electrical conductivity of saturation paste extract.

Table 9.6 Chloride, sodium and potassium content (% dry matter) of grapevine petioles and laminae of scions of grapes on 'own roots' or grafted onto salt-tolerant rootstocks.

Common name	Chloride (Cl^-)		Sodium (Na^+)		Potassium (K^+)	
	Petioles	Laminae	Petioles	Laminae	Petiole	Laminae
Own roots	1.64	0.248	0.57	0.113	0.74	0.69
Rootstock 1	0.29	0.039	0.07	0.038	3.08	0.72
Rootstock 2	0.15	0.028	0.09	0.036	3.83	0.76

Source: after Atwell *et al* (1999).

1998; Nuttall *et al* 2003), and relatively low concentrations of B added to these soils can lead to a toxic response presenting in sensitive crops in reclaimed water irrigation systems. Boron in soils is often associated with marine deposits and paleosalinity (Kabata-Pendias and Pendias 2001) and, consequently, problems of salinity and B toxicity often co-occur and are exacerbated by reclaimed water irrigation.

Special care is needed in the management of B because there is only a small concentration range between plant deficiency and toxicity. Excess B can accumulate in the root zone if it is not leached down through the soil, leading to toxicity problems. Higher plant uptake rates are often seen in sandy soils than clayey soils, and plant uptake tends to be lower at soil pH of 7.5–9.0 when boron hydroxide $B(OH)_3$ predominates and is more strongly adsorbed to soil particles than the boron hydroxide ion $B(OH)_4^-$ which predominates at pH >9 (Dudley 1994). Boron toxicity typically appears first in older leaves and includes a yellowing and brown speckling pattern found between the veins and near the edge of the leaf, followed by the edges becoming necrotic, often at the margins and tips of older leaves (Eaton 1944; Bennett 1994). Other symptoms include yellowing (chlorosis), tip burn, cupping of the leaves, reduced size, premature leaf drop and the development of a red, pink, purple or bluish band (anthocyanins) on the edge of chlorotic leaves. Substantial variation exists among species and among cultivars of the same species in tolerance to high B (Maas 1987).

Boron can be leached from soil by rainfall or irrigation leaching fractions (see *Chapter 6*). However, leaching can be difficult because B is often adsorbed onto soil particles, requiring about three times more water to leach than more soluble species such as Cl^- and Na^+ (Dudley 1994). In many cases, leaching is unlikely to provide a permanent solution because more B will be resupplied through breakdown of naturally occurring boron-containing minerals in the soil (Keren and Bingham 1985), and from further irrigation water additions. Stevens *et al* (2003) studied B in irrigation waters and soil in a reclaimed water system in South Australia. Reclaimed water from the scheme had a higher concentration of B (average of 0.36 mg/L) than local groundwater (0.15–0.17 mg/L). A comparison of the B concentration in soil irrigated with groundwater, reclaimed water or unirrigated (virgin) soils indicated that at the soil surface, reclaimed water irrigated soils had higher average B concentrations than virgin or groundwater irrigated soils (Figure 9.1). Even though the average surface soil B concentration increased with the use of reclaimed water, it remained below the toxic threshold value. In the subsoil, irrigation with reclaimed water led to decreases in boron concentration compared with virgin soil while irrigation with local groundwater reduced the concentration of boron all the way through

Table 9.7 Boron concentration (mg/L) in reclaimed and other irrigation waters.

Country, State	Reclaimed water	Ground (G), well (W), river (R) or potable (P) water	Reference
Australia	0.36	0.16 G	Kelly *et al* (2001)
Australia	0.2	0.0	Kaddous *et al* (1986)
Canada	2.6	Not measured	Neilsen *et al* (1989(
Chile	Not measured	7.5–17.2 R	Ferreyra *et al* (1997)
Italy	1.91	0.64	Meli *et al* (2002)
Spain	1.0	0.16 G	Reboll *et al* (2000)
USA, Arizona	0.03–0.52	0.02–0.40 P	Pepper and Mancino (1994)
USA, California	0.6–1.3	Not measured	Asano *et al* (1985)
USA, Florida	0.14	0.02 W	Zekri and Koo (1994)

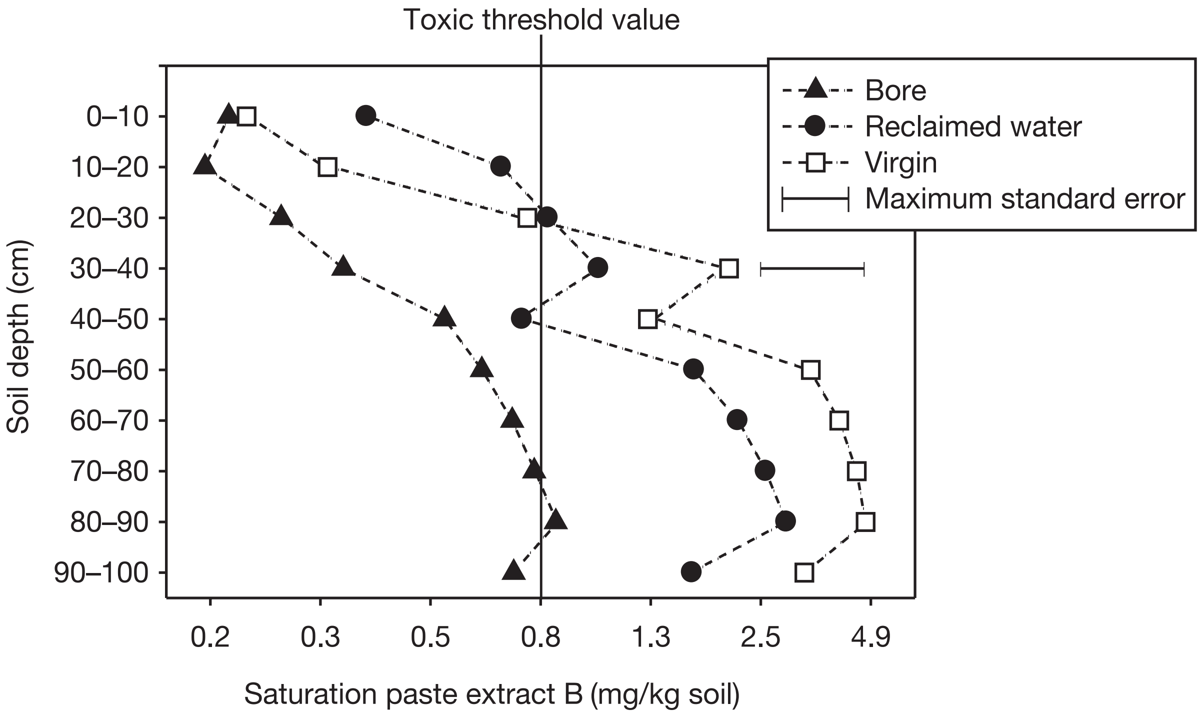

Figure 9.1 Change in soil boron (B) concentration for soils on the Northern Adelaide Plains irrigated with bore or reclaimed water, or unirrigated and uncropped (virgin). Soil B concentration is a log scale. The vertical line indicates toxic yield threshold above which yield reduction begin to occur. Source: Stevens *et al* (2003).

the soil profile (Figure 9.1). These decreases were probably a result of B leaching. One implication of the increased need for leaching as the B concentration of the irrigation water increases is that soil-physical properties must be maintained, and in some cases improved, so that the additional water required for leaching will infiltrate and move through the soil.

One method of management is to grow more tolerant crop species or varieties. Table 9.8 lists the concentrations of B in irrigation and soil water tolerated by various crops without reduction in yield or vegetative growth. Researchers studying the response of several crops to excess B found that onion was relatively tolerant to B, with yield not declining until B reached 9 mg/L in the culture solution (Francois 1984; Francois 1988; Francois 1991; Francois 1992). In contrast, garlic bulb size and yield was reduced from 4 mg/L B. For celery receiving >10 mg/L B, produce was bitter tasting and not of marketable quality, whereas for lettuce leaf, damage was only on the outer wrapper leaves which could easily be removed. Fruit size, and thus yield, of tomato was reduced at B concentrations > 6 mg/L. For zucchini and squash fruit number and not fruit size were reduced at B concentrations > 1 mg/L. The tolerance of *Prunus* rootstocks to boron and salinity were studied by El-Motaium *et al* (1994). They found that there was large variation in B tolerance of different rootstocks, that the B toxicity was manifest in *Prunus* stems and not leaves, and that increasing salinity reduced B uptake. They recommended that for scions on *Prunus* rootstocks B toxicity be assessed on stems and not leaves.

These values provide a guide only, as the rate of uptake of B by plants depends on other factors. More work needs be done to better define some of these trigger values since there is some confusion in the literature with respect to the tolerance of different crops to B in irrigation waters (eg see Westcot and Ayers 1984; Keren and Bingham 1985; ANZECC and ARMCANZ 2000). Differences between values may be a result of culture conditions, interactions with other ions, and between environment and cultivar. The relationship between these four factors (salt, B, cultivar and climate) illustrates the complexity of the issues for both researchers and growers.

There is a narrow window between plant B deficiency and toxicity, and although soils in many regions of the world suffer from B deficiency, B toxicity may be a problem in reclaimed water irrigation systems. In a very

Table 9.8 Maximum boron (B) concentrations in irrigation or soil water tolerated by a variety of crops, without reduction in yields.

Tolerance	Concentration of B in irrigation or soil water (mg/L)	Crop
Very sensitive	<0.5	Blackberry, lemon, avocado, grapefruit
Sensitive	0.5–1.0	Peach, cherry, plum, grape, onion, garlic, sweet potato, wheat, sunflower, mung bean, sesame, lupin, strawberry, Jerusalem artichoke, kidney bean, lima bean, snap bean, peanut
Moderately sensitive	1.0–2.0	Broccoli, capsicum, pea, carrot, radish, potato, cucumber, lettuce, olive, pumpkin, radish
Moderately tolerant	2.0–4.0	Cabbage, turnip, bluegrass, oat, corn, artichoke, tobacco, mustard, sweet clover, squash, musk melon, barley, cowpea, cauliflower
Tolerant	4.0–6.0	Tomato, alfalfa, purple vetch, parsley, red beet, sugarbeet
Very tolerant	6.0–15.0	Asparagus, celery, sorghum, cotton

Source: Keren and Bingham (1985), ANZECC and ARMCANZ (2000).

few regions of the world, such as low rainfall south-eastern Australia, soils may have naturally toxic concentrations of B, providing a greater challenge for reclaimed water systems. Crop and varietal selection affords the greatest opportunity for managing yield loss and crop quality, but more work is needed to clarify the relative tolerance of crops and cultivars to B, and the interactions with salinity and climate.

Summary

Sodium, chloride and boron in reclaimed water need to be carefully managed in irrigation systems if crop yields are to be maintained. Although Na^+ is far more toxic than Cl^-, chloride toxicity is more common because sodium is selectively excluded by plant roots to a greater extent. Citrus and some other woody fruit crops are the most sensitive to Cl^- toxicity. Overhead sprinkler irrigation should be avoided for such sensitive crops since it renders the protection afforded through the use of 'salt excluding' rootstock ineffective. Attention to good crop husbandry, particularly nutrition, should provide some protection against competitive uptake of Na^+ over K^+ and Ca^{2+}, and Cl^- over NO_3^-, PO_4^- and SO_4^-, but will not overcome the principal problem, which is osmotic.

Where irrigation water and soil boron are high, careful selection of crop varieties provides opportunity for reducing problems of B toxicity and crop yield decline. Where possible, an appropriate leaching fraction will minimise the accumulation of boron in the soil profile explored by the plant root and minimise the risk of long-term toxic responses from accumulation of boron in the soil profile.

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10 Organic compounds in reclaimed water and their potential risks to the environment and human health

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Water from wastewater treatment plants (WWTPs) is increasingly being reclaimed, recycled and reused for various purposes in many countries (Asano and Levine 1996). In some parts of the world, especially in arid areas, reclaimed water has been recognised as a valuable resource for irrigating crops. However, application of wastewater and biosolids from WWTPs in agriculture may pose risks to the environment and public health because they contain toxic inorganic and organic chemicals, and pathogens (Abdulraheem 1989; Gallegos *et al* 1999).

Several guidelines have been developed in regard to reclaimed water use for irrigation (US EPA 1992; Chang *et al* 1996; Marecos do Monte *et al* 1996; DHS and EPA SA 1999; ANZECC and ARMCANZ 2000; Jackson 2003; Hogan 2004). Most of the irrigation water quality criteria focus on pathogens, nutrients and inorganic compounds (Chang *et al* 1996; Jackson 2003; Hogan 2004), with few guidelines defining parameters for organic contaminants such as pesticides and disinfection by-products (DBPs) (DHS and EPA SA 1999; ANZECC and ARMCANZ 2000). This may not adequately address the possible risks to the environment and human health posed by the thousands of potential trace organic pollutants in reclaimed water (eg Richardson and Bowron 1985; Simpson and Hayes 1998; Liteplo *et al* 2002; Singer *et al* 2002; Ying *et al* 2002a,b). Many studies have been undertaken on inorganic compounds and pathogens in wastewater and their possible effects on soil and plants as well as human health. However, little research has been done on organic compounds until the 1980s. This chapter will introduce the major classes of organics in reclaimed water and discuss their potential impact on the environment and human health.

Organics in reclaimed water

There are three main groups of organic chemicals in reclaimed water:

1 natural organic matter, mainly fulvic and humic acids already present in the drinking water or formed during the water reclamation process due to decomposition of organic compounds;
2 disinfection by-products formed by chlorination during treatment; and
3 synthetic organic compounds added to sewage by households, hospitals and industries, and not removed during the water reclamation process (Drewes and Jekel 1998).

The third group includes many different classes of organic compounds such as pesticides, organohalogens, aromatic compounds, phthalates, surfactants, hormones (naturally excreted by animals and humans, or synthesised as drugs), pharmaceuticals and personal care products. There are also other chemicals of concern in wastewater such as N-nitrosodimethylamine (NDMA), geosmin and 2-methylisoborneol (MIB). These organic chemicals are very different, containing molecules of various weights, ranging from simple compounds to very complex polymers.

Natural organic matter

Natural organic matter (NOM) in reclaimed water can range from low molecular weight compounds such as simple organic acids and sterols, to macromolecules such as fulvic and humic acids. This NOM exists as dissolved organic carbon (DOC) in reclaimed water; or is associated with particulates. The concentrations of NOM in reclaimed water range from several to tens of milligrams per litre, depending on the wastewater load and treatment plant efficiency (Percherancier *et al* 1996; Drewes and Jekel 1998; Dignac *et al* 2000; Skjemstad *et al* 2002; Ziegler *et al* 2002; see *Chapter 3*).

Natural organic matter in reclaimed water is relatively refractory or poorly degradable because readily degradable organics have largely been eliminated during the treatment processes. Those readily biodegradable organics mainly consist of small molecules of volatile fatty acids, carbohydrates, alcohols, peptones and amino acids (Henze 1992). The concentration of easily biodegradable organics is a function of reclamation (treatment) technology and thus can vary significantly. However, in some cases, biodegradable organic matter still accounts for about 50% to 70% of DOC in reclaimed water based on a simple biodegradability test on treated wastewater (Percherancier *et al* 1996). According to Dignac *et al* (2000), 41% of the soluble organic matter in wastewater and 22% in reclaimed water could be characterised. Proteins and lipids accounted for most of the loss of characterised organic matter, with total organic carbon (TOC) of the reclaimed water comprising 13% of proteins (20% in the wastewater), 10% of sugars (11% in wastewater) and less than 1% of lipids (8% in the wastewater). The uncharacterised fraction in wastewater and reclaimed water is mainly humic substances (Dignac *et al* 2000). There exists a comparable biodegradation pattern of NOM between natural ecosystem and wastewater treatment systems, especially under aerobic conditions (Dignac *et al* 2000). Therefore, NOM is not believed to be a major concern for reclaimed water applied directly onto agricultural land. However, it may become a water quality issue for aquifer storage and recovery in anaerobic environments.

Disinfection by-products

Disinfection is an effective water treatment process to control microbial pathogens that cause waterborne diseases and improve human health. Chlorine has traditionally been the preferred disinfection agent because of its proven effectiveness and low cost. However, research undertaken in the 1970s indicated the presence of disinfection by-products (DBPs) in drinking water (Rook 1974). The two most significant groups of DBPs formed during chlorination are trihalomethanes (THMs) and haloacetic acids (HAAs) (Table 10.1). In addition to THMs and HAAs, many other DBP compounds have been found in treated drinking water and wastewater. They are haloacetonitriles (HANs), haloketones (HKs), haloaldehyde, halopicrin, cyanogens chloride, halophenol and chloral hydrate (Palacios *et al* 2000; Lee *et al* 2001).

Disinfection by-products are formed via reaction of chlorine with NOM (Garcia-Villanova *et al* 1997; Singer 1999). When chlorine is added to raw drinking water, it reacts with the NOM in the water to produce chloroform, mono-, di-, and trichloroacetic acid, and other by-products. If the water contains appreciable amounts of bromide, chlorine will oxidise the bromide to hypobromous acid which in turn will react with NOM to produce brominated DBPs such as bromoform and brominated acetic acids. Overall, the addition of chlorine to raw drinking water or wastewater containing NOM and bromide leads to the formation of chlorinated, brominated and mixed bromochloro DBPs. The formation of the DBPs depends on many factors such as chlorine, bromide and organic matter concentrations, pH value and temperature (Garcia-Villanova *et al* 1997) as well as ammonia (Nicholson *et al* 2002). Research has indicated humic substances as the main precursors in the organohalogenated DBP compounds formation (Singer 1999).

Disinfection by-products have been suspected to have toxic, mutagenic, carcinogenic or teratogenic effects (Horth 1989; Cantor 1997; Simpson and Hayes 1998). Taking into account the risks on humans, maximum recommended levels for drinking water have been established in many countries (WHO 1993; Simpson and Hayes 1998). For example, the US EPA initially set out the regulated THMs at a maximum limit of 100 μg/L, but this has subsequently been reduced to 80 μg/L in Stage I, and 40 μg/L in Stage II (US EPA 1993). A level of 60 μg/L has also been introduced for HAAs, and 10 μg/L for bromate in the USA. In Germany, the guideline value for total THMs is only 10 μg/L, while in Australia it is 250 μg/L (Simpson and Hayes 1998).

The DBPs in treated drinking water occur at concentrations in the microgram per litre (μg/L) levels (Lee *et al* 2001; Pavelic *et al* 2002). A survey of DBPs in drinking waters around Australia found 25 μg/L to 191 μg/L of THMs, and 18 μg/L to 252 μg/L of HAAs (Simpson and Hayes 1998). The HANs (0.2–36 μg/L) accounted for 5% of the total halogenated DBPs

Table 10.1 Compounds in each of the four main disinfection by-product groups.

Group	Compounds
Trihalomethanes (THMs)	Chloroform (CF), dichlorobromomethane (DCBM), chlorodibromomethane (CDBM), bromoform (BF)
Haloacetic acids (HAAs)	Monochloroacetic acid (MCAA), dichloroacetic acid (DCAA), trichloroacetic acid (TCAA), dibromoacetic acid (DBAA)
Haloacetonitriles (HANs)	Dichloroacetonitrile (DCAN), trichloroacetonitrile (TCAN), Dibromoacetonitrile (DBAN), bromochloroacetonitrile (BCAN)
Haloketones (HKs)	1,1-Dichloropropanone (1,1-DCP), 1,1,1-trichloropropanone (1,1,1-TCP)

analysed. Chloroketones (0.2–24 μg/L) and chloral hydrate (0.2–19 μg/L) each made up 3% while cyanogens chloride only 1%.

Microbial degradation is important in determining the fate of DBPs, in particular THMs and HAAs (Nicholson *et al* 2002). The HAAs are readily degraded under both aerobic and anaerobic conditions because they contain a positive carboxylic acid (–COOH) group. But highly reducing conditions are required for effective degradation of all THMs with half-lives ranging from 35 days for bromoform to 330 days for chloroform under methanogenic conditions. Under denitrifying conditions all THMs except chloroform were biotransformed with half-lives ranging from 300 days for bromoform to 1700 days for dichlorobromomethane (DCBM) (Nicholson *et al* 2002). Under aerobic conditions, THMs are not degraded. The persistence of these THMs is due to the multiple halogen atoms in their molecular structure.

N-Nitrosodimethylamine

N-Nitrosodimethylamine (NDMA) is the simplest dialkylnitrosamine with a molecular formula of $C_2H_6N_2O$. NDMA is volatile and fully water soluble, and has a low log K_{ow} (octanol–water partition coefficient) value of 0.57 (Liteplo *et al* 2002). NDMA has been classified as a probable human carcinogen by the US Environmental Protection Agency (US EPA 1997). Based on laboratory animal studies in which tumours have been induced in all species examined at relatively low doses, NDMA is clearly carcinogenic, mutagenic and clastogenic (Liteplo *et al* 2002). Hepatic, pulmonary and renal carcinogenicity was observed in mice administered NDMA via drinking water or through inhalation. Increases in tumour incidence were observed at concentrations of NDMA in drinking water ranging from 0.01 mg/L to 5 mg/L (Liteplo *et al* 2002).

NDMA is produced by industry only in small amounts for research but is unintentionally formed during various manufacturing processes, and in air, water and soil from chemical or microbial reactions involving other chemicals like alkylamines and nitrite (Alexander 1999; Choi and Valentine 2002; Mitch and Sedlak 2002). Other pathways may exist for the formation of NDMA during chlorination of secondary treated wastewater and drinking water such as via the reaction between dimethylamine and monochloramine (Choi and Valentine 2002). Chloramination, cationic polymers and detention times have been identified as the factors that may increase the levels of NDMA (California Department of Health Services 2002). Chloramination provides nitrogen species that may trigger the formation of NDMA, and some cationic polymers may be releasing precursors of NDMA into water.

Different physical–chemical techniques such as granular activated carbon adsorption have been tried to remove NDMA from waters (Fleming *et al* 1996). It is also found in some seafood products, bacon, cheese and pickled foods, some consumer products such as cosmetics and personal care products, products containing rubber and tobacco, as well as some pesticide formulations (Liteplo *et al* 2002).

The US EPA recommends that NDMA levels in lakes and streams should be limited to 0.7 ng/L to prevent possible health effects from drinking or eating fish contaminated with NDMA (US EPA 1997). Although there is no state or federal regulation on its maximum concentration in drinking water, the California Department of Health Services has established an action level for NDMA of 10 ng/L. Two drinking water production wells under the influence of recharge water from the advanced wastewater treatment system of the Orange County Water District's Water Factory 21 recently suspended operations due to their inability to meet this action level (Mitch and Sedlak 2002).

NDMA has been detected in drinking water with concentrations ranging from <1 ng/L to 63.7 ng/L in California and higher concentrations of NDMA were found in treated wastewater (eg up to 220 ng/L in

Ontario) (California Department of Health Services 2002; Liteplo *et al* 2002). NDMA was also found in activated sludge ranging from 5 mg/kg to 10 mg/kg in southern Ontario (Liteplo *et al* 2002) and 0.6 mg/kg to 45 mg/kg in the USA (Mumma *et al* 1984). NDMA was found to be a new DBP (Choi and Valentine 2002; Mitch and Sedlak 2002).

Fugacity modelling predicts that when NDMA is continuously released into a medium, most of it will be present in that medium at steady state (Liteplo *et al* 2002). NDMA is susceptible to photodecomposition due to its absorption of UV light. So photolysis is an important pathway for the removal of NDMA from the environment, especially in air with a half-life of 5 hours (Liteplo *et al* 2002). However, in surface and groundwater and soil, biodegradation is the major process to remove NDMA (Mallik and Tesfai 1981; Kaplan and Kaplan 1985; Gunnison *et al* 2000; Liteplo *et al* 2002). Predicted half-lives for NDMA were 42 d to 206 d in surface water (Howard *et al* 1991), 229 d in sediment and 71 d in soil (Liteplo *et al* 2002). The N-nitroso functional group in its structure may retard microbial degradation. In an unamended sandy loam, 17% of added NDMA was lost in 10 d of incubation; thereafter, no further loss was noted during the next 30 d incubation period (Mallik and Tesfai 1981). Kaplan and Kaplan (1985) found the rate of mineralisation of NDMA in soil depends on its initial concentration. Rate constants and the total percentage mineralised increased with decreasing initial concentrations of NDMA.

Gunnison *et al* (2000) investigated the attenuation of NDMA in a contaminated aquifer in Rocky Mountain Arsenal, USA, and found that sorptive capacity of the site soil was insignificant and the adsorption was almost completely reversible. The measured soil sorption coefficient (K_d) values ranged from 0.40 L/kg to 1.14 L/kg with corresponding organic carbon sorption coefficient (K_{oc}) values of 157 to 422. Laboratory biodegradation studies found half-lives for NDMA at a spiked concentration of 50 μg/L of slurry ranged from 12 to 35 d under aerobic conditions and 26 to 39 d under anaerobic conditions (Gunnison *et al* 2000). This indicates that the native microorganisms have the capacity to mineralise the NDMA under both aerobic and anaerobic conditions.

Synthetic organic compounds

Wastewater treatment systems receive synthetic organics from food and house-related compounds, preservatives and antioxidants, odorants and perfumes, pesticides and herbicides, plasticisers and flame-retardants, solvents, hydrocarbons, washing and cleaning related compounds as well as many other types of industrial compounds (Paxeus 1996). After treatment, trace amounts of these organic compounds may still remain in reclaimed water. Unfortunately, limited monitoring data are available and their existence in reclaimed water is a concern due to potential impacts on the environment and human health.

Pesticides

In addition to agricultural use, pesticides are also widely used in urban environments to control, for example, insects and weeds. As a group, the toxicity and environmental fate of pesticides have been well studied (eg Kidd and James 1991; Wauchope *et al* 1992; Augustijn-Beckers *et al* 1994). Atrazine is one of the most widely detected pesticides in the environment, and it can be degraded in aquifer materials under both aerobic and anaerobic conditions (Shapir *et al* 1998; Larsen *et al* 2000). However, field studies give mixed results, ranging from no or little degradation to rapid degradation with a half-life of 14 days (Agertved *et al* 1992; Widmer and Spalding 1995; Patterson *et al* 2000). Dealkylation and ring cleavage are the major degradation pathways for atrazine by microorganisms (Ma and Selim 1996). Atrazine is mobile in soil with a K_{oc} value of 100 (Wauchope *et al* 1992).

Organohalogens

Organohalogens, like dioxins, furans and polychlorinated biphenyls (PCBs), are listed by the World Health Organization as priority pollutants because of their persistence and toxicity. These chemicals may have half-lives of up to 10 yrs in soil and are strongly sorbed to solids (Pal *et al* 1980; Arthur and Frea 1989). They can be degraded in the environment but at a very low rate via reductive dechlorination (Kastanek *et al* 1999; Kao *et al* 2001). Laboratory and field studies indicate that PCBs with fewer chlorine atoms are amenable to complete aerobic mineralisation (Kastanek *et al* 1999) but PCBs with higher chlorination levels are generally resistant to aerobic degradation. However, these highly chlorinated PCBs and dioxins may be partially degraded through reductive dechlorination under anaerobic conditions.

Phthalates

Phthalates (phthalic acid esters) are another class of organic chemicals widely detected in the environment (Staples *et al* 1997). They enter the environment through wastewater from plastic production, and leaching and volatilisation from plastic products during their usage and after disposal (Staples *et al* 1997). The chemical properties vary, with their K_{oc} values ranging from 200 for dimethyl phthalate (DMP) to 5.1 × 104 for diethylhexyl phthalate (DEHP) (Staples *et al* 1997). Some phthalate esters have weak oestrogenic activities (Jobling *et al* 1995; Harris *et al* 1997). They can be degraded under both aerobic and anaerobic conditions (Staples *et al* 1997; Wang *et al* 2000). Research suggests that the metabolic pathway for the microbial degradation of phthalates under both aerobic and anaerobic conditions begins by ester hydrolysis to form a monoester and corresponding alcohol. Wang *et al* (2000) reported half-lives for three phthalates of 24 hours (dimethyl), 32 hours (di-n-butyl) and 513 hours (di-n-octyl phthalate) under anaerobic digestion of sludge. Persistence increases with the molecular weight of the phthalate (Shelton *et al* 1984; Wang *et al* 2000). The primary degradation half-lives for phthalates under aerobic conditions ranged from <1 d to about 15 d in waters and from less than one week to several months in soils (Staples *et al* 1997).

Aromatic hydrocarbons

Aromatic hydrocarbons are ubiquitous compounds and are commonly found in treated wastewater (Paxeus 1996; Byrns 2001). Many polycyclic aromatic hydrocarbons (PAHs) exhibit toxic, carcinogenic and mutagenic properties and have been identified as priority pollutants by the US EPA (Yuan *et al* 2000). Some PAHs like benzo(a)pyrene are listed as endocrine disrupting chemicals (EDCs) (Ying and Kookana 2002). PAHs generally become more lipophilic, less soluble and less volatile with increasing molecular weight (Howard *et al* 1991). Degradation by bacteria occurs primarily under aerobic conditions involving oxygenase-mediated ring oxidation and subsequent catabolite formation, ring fission and metabolism (Yuan *et al* 2000). PAHs can also be degraded under anaerobic conditions (Chang *et al* 2002). The anaerobic biodegradation rates from high to low order were found to be sulfate-reducing > methanogenic > nitrate-reducing conditions (Chang *et al* 2002). The half-lives have been reported to range from 1 d to 20 d for naphthalene, 16 d to 400 d for phenanthrene and 21 d to 2800 d for pyrene (Howard *et al* 1991). Persistence of PAHs increases with increasing ring numbers in the structure (Alexander 1999).

Surfactants

Surfactants are a diverse group of chemicals that are designed to have cleaning or solubilisation properties. Surfactants are mainly of three types: anionic, non-ionic and cationic. Commonly used commercial surfactants are linear alkylbenzene sulfonates (LAS), alkylethoxy sulfates (AES), alkyl sulfates (AS), alkylphenol ethoxylates (APE), alkyl ethoxylates (AE) and quaternary ammonium compounds (QAC). They are widely used in household cleaning detergents, personal care products, textiles, paints, polymers, pesticide formulations, pharmaceuticals, mining, oil recovery and pulp and paper industries. Linear alkylbenzene sulfonates, APE and QAC are the most extensively studied surfactants.

After use, residual surfactants and their degradation products are discharged to wastewater treatment plants. Surfactants and their degradation products have been detected at various concentrations in wastewater and sludges (Matthijs *et al* 1999; Ying *et al* 2002b). Concern has increased recently due to their widespread use and high consumption. For example, some European countries banned the use of APE because of their relatively stable biodegradation products, nonylphenol (NP) and octylphenol (OP). NP and OP have been demonstrated to be toxic to both marine and freshwater species (McLease *et al* 1981; Comber *et al* 1993), and to induce oestrogenic responses in fish (Jobling and Sumpter 1993; Purdom *et al* 1994).

Figge and Schöberl (1989) conducted an extensive study of LAS effects on plant species using a plant metabolism box. They estimated the 'no observed effect concentrations' (NOEC) to be 16 mg/kg for bush beans, grass and radish and 27 mg/kg for potatoes. From the terrestrial toxicity data available in the literature, LAS can be considered as not being highly toxic to terrestrial organisms (Litz *et al* 1987; Figg and Schöberl 1989; Mieure *et al* 1990; Jensen 1999).

Hormones

Humans can excrete hormone steroids that end up in sewage treatment plants. These steroids have been detected in treated waste, and in surface water (Ying *et al* 2002a). In the aquatic environment they may interfere with the normal functioning of endocrine systems in wildlife, affecting both their reproduction and development (Jobling *et al* 1998). The steroids of concern for the aquatic environment due to their endocrine disruption potential are mainly oestrogens and contraceptives, which include 17β-oestradiol (E2), oestrone (E1), oestriol (E3), 17α-ethynyloestradiol (EE2) and mestranol (MeEE2).

Vitellogenesis (plasma vitellogenin induction) and feminisation in male fish have been observed in British rivers and are attributed to the presence of these oestrogenic compounds (Desbrow *et al* 1998; Jobling *et al* 1998). Concentrations as low as 1 ng/L of 17β-oestradiol led to induction of vitellogenin in male trout (Purdom *et al* 1994; Hansen *et al* 1998). Hormone steroids in the environment may affect plants as well as wildlife (Shore *et al* 1995; Lim *et al* 2000). Alfalfa irrigated with treated wastewater, which contained hormone steroids, was observed to have elevated levels of phytoestrogens (Shore *et al* 1995).

Pharmaceuticals and personal care products

An enormous quantity of pharmaceutical drugs are prescribed to treat various diseases and/or are used in personal care products. After use, high percentages of the used drugs end up in WWTPs and many of these drugs have been detected in reclaimed water (eg Richardson and Bowron 1985; Singer *et al* 2002). In 1992, the drug metabolite clofibric acid was at first found in groundwater samples collected beneath former sewage irrigation fields near Berlin (Stan and Linkerhagner 1992; Heberer 2002). Unfortunately, little is known about the fate of many drugs in the environment and the possible long-term effect on humans and ecosystems.

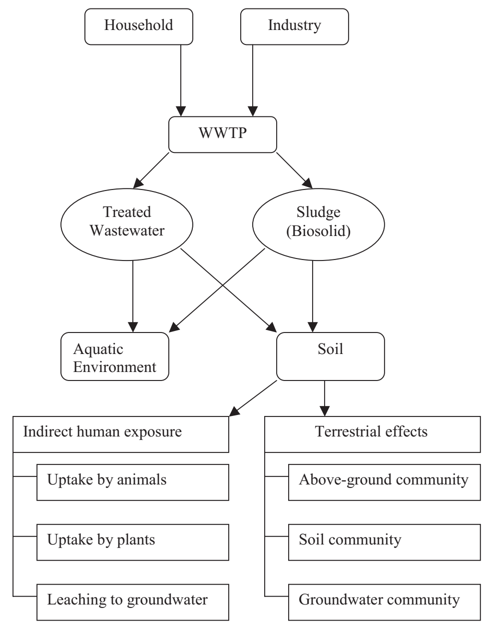

Figure 10.1 Possible exposure paths for organic contaminants in the environment. WWTP = wastewater treatment plant.

Potential risks to the environment and human health

Application of reclaimed wastewater on agricultural land may lead to accumulation of persistent organic chemicals in soils, leaching of mobile organics to groundwater, contamination of crop products with toxic organics, and exposure of humans and animals to toxins (Figure 10.1). Although the limited research performed to date has not revealed clear evidence that organic compounds in reclaimed waters cause serious effects on the environment or human health, there is a need for serious consideration of the potential risks.

Persistence and mobility

Following application of reclaimed water on agricultural land, the organics that remain in the reclaimed water will undergo many different processes which determine their fate, behaviour and possible effects on soil, groundwater, plants, animals and humans. The processes include: sorption to soil and plant; movement in soil to groundwater (or surface water); volatilisation; chemical degradation (eg hydrolysis); and biodegradation by microbes and plants (Duarte-Davidson and Jones 1996; Harms 1996; Wilson *et al* 1996).

The mobility of an organic compound in soil is based on a combination of its physico-chemical properties and the soil type (Wilson *et al* 1996). Laskowski *et al* (1982) evaluated the comparable mobility of organics in soils by ranking them according to leaching potential (L_p) (Eqn 10.1), defined as:

$$L_p\ S/(V_p \times K_{oc}) \quad (\textit{Eqn 10.1})$$

where S is water solubility (mg/L), V_p is vapour pressure (Pa), and K_{oc} is the organic carbon sorption coefficient. In general, compounds with higher K_{oc} values tend to adsorb more strongly onto soil organic carbon than those with lower K_{oc} values, which are more readily leached. Therefore, K_{oc} values provide a good indication of leachability of organic compounds through soil (Table 10.2). DBP THMs and HAAs as well as NDMA are highly mobile in soil due to their low sorption on soil. However, those DBPs in treated wastewater are volatile, so they can be lost through volatilisation following application of wastewater onto land. However, there are many non-volatile, mobile organic compounds in wastewater (eg atrazine and polar drugs). Irrigation using reclaimed wastewater containing mobile and persistent organics may also lead to contamination of groundwater.

Table 10.2 Partition, sorption and degradation values for some organic compounds of environmental concern.

Chemical name	log K_{ow}[A], [reference]	log K_{oc}, [reference]	Half-life (d) in aquifer or soil, [reference]
Chloroform (CF)	1.97, [11]	1.77, [11]	<1–550, [11]
Dichlorobromomethane (DCBM)	1.88, [11]	1.68, [11]	<1– >130, [11]
Dibromochloromethane (DBCM)	2.08, [11]	1.89, [11]	5–>130, [11]
Bromoform (BF)	2.38, [11]	2.18, [11]	5–210, [11]
Dichloroacetic acid (DCAA)	0.92, [11]	0.72, [11]	<1–13, [11]
Trichloroacetic acid (TCAA)	1.70, [11]	1.51, [11]	<1–13, [11]
N-Nitroso dimethylamine (NDMA)	0.57, [10]	2.20–2.63, [9]	12–35 (aerobic); 26–39 (anaerobic), [9]
Atrazine	2.52, [4]	2.00, [3]	60, [3]
DDT [ED1]	5.94, [4]	6.30, [5]	2000, [5]
Dimethyl phthalate ester (DMP)	1.61, [7]	2.30, [8]	1, [7]
Di (2-ethylhexyl) phthalate ester (DEHP)	7.50, [7]	5.71, [7]	8–72, [7]
Naphthalene	3.34, [6]	3.11, [1]	1–20, [2]
Phenanthrene	4.53, [6]	4.36, [1]	16–400, [2]
Benzo*a*pyrene	6.23, [6]	6.65, [1]	530, [2]
Bisphenol A (BPA)	3.32, [12]	2.89, [12]	>100, [12]
17β-oestradiol (E2)	3.94, [12]	3.64, [12]	2 (aerobic); 70 (anaerobic), [12]
17α-ethinylestradiol (EE2)	4.15, [12]	3.68, [12]	81 (aerobic), [12]
4-*tert*-octylphenol (4-t-OP)	4.12, [12]	4.26, [12]	>100, [12]
4-n-nonylphenol (4-n-NP)	4.48, [12]	4.59, [12]	7 (aerobic), [12]

[A] Octanol-water partition coefficient of an organic compound.
References: [1] Sims and Overcash (1983); [2] Howard *et al* (1991); [3] Wauchope *et al* (1992); [4] Sicbaldi and Del Re (1993); [5] Augustijn-Beckers *et al* (1994); [6] Meador *et al* (1995); [7] Staples *et al* (1997); [8] Thomsen *et al* (1999); [9] Gunnison *et al* (2000); [10] Liteplo *et al* (2002); [11] Pavelic *et al* (2002); [12] Ying *et al* (2003).

Persistence of organic compounds in soil depends on many factors, particularly chemical structure and environmental conditions. Although there is no simple rule, the presence of some functional groups such as hydroxide (OH^-) and carboxylic acid ($COOH^-$) enhance biodegradation, whereas other groups such as quaternary carbon and halogens appear to retard biodegradation. Persistent organic compounds could accumulate in soils receiving reclaimed water irrigation.

Uptake by plants

The uptake of organic compounds by plants is complex. There are four main pathways by which organic compounds in soil can enter plants (Topp *et al* 1986; Polder *et al* 1995):

1 root uptake followed by translocation in the plant's transpiration stream (ie liquid phase transfer);
2 absorption of volatilised organics from the surrounding air by roots or shoots (ie vapour phase transfer);
3 uptake by external contamination of the above-ground parts of plants by wastewater, soil and dust, followed by retention in the cuticle or penetration through it; and
4 uptake and transport in oil channels which are found in some oil-containing plants such as carrots.

Uptake of organic compounds by plants is found to be influenced by physico-chemical features of the compounds, environmental conditions and plant characteristics (Duarte-Davidson and Jones 1996; Harms 1996). An empirical relationship exists between plant uptake and the octanol-water partition coefficient (K_{ow} value) (Tables 10.3 and 10.4) (Polder *et al* 1995; Duarte-Davidson and Jones 1996). Adsorption of organic compounds onto plant root surfaces increases with increasing K_{ow} values. However, uptake by the root system and subsequent translocation within the plant is more efficient for organic compounds with log K_{ow} values in the range of 1 to 2.5.

One of the best examples of uptake by plants are provided by phthalate compounds. Different effects of di-*n*-butyl phthalate (DnBP) and di-2-ethylhexyl phthalate (DEHP) on the quality of capsicum fruit in contaminated soil have been reported by Yin *et al* (2003).

Table 10.3 Potential for organic compounds to adsorb onto the root surface of plants and to leach to groundwater.

Classification	K_{ow}[A]	Potential for root retention	Mobility in soil
Class 1	Log Kow >4.0	High	Low
Class 2	2.5 < log Kow <4.0	Medium	Medium
Class 3	Log Kow <2.5	Low	High

[A] K_{ow}, Octanol-water partition coefficient of an organic compound.

The results showed that DnBP concentration in fruit, shoot and root increased with the increase of soil-applied DnBP/DEHP concentration, but DEHP was not detected in all samples. Vitamin C and capsaicin contents in fruit were found to be negatively correlated to DnBP concentration in capsicum fruit, which suggest that DnBP uptake by plants may be responsible for a decrease in fruit quality. This can be explained by their physico-chemical properties. DnBP and DEHP have water solubilities of 11.2 and 0.003 mg/L, and log K_{ow} values of 4.45 and 7.50, respectively. DEHP is strongly adsorbed by soil and thus not easily accessed by plants. Both compounds are teratogenic, mutagenic and carcinogenic as well as possessing oestrogenic properties (Jobling *et al* 1995; Harris *et al* 1997; Moore 2000), and have been classified as priority pollutants by the US EPA.

Despite low concentrations of organics in reclaimed wastewater, some of them can be bioconcentrated by plants irrigated with the treated wastewater, then passed into the food chain to humans. Some of these chemicals can also be metabolised.

Endocrine disruption

Many organic compounds identified or suspected of being endocrine disrupting have often been found in reclaimed water (Ying and Kookana 2002). Endocrine disrupting chemicals (EDCs) can interfere with the normal functioning of hormone systems in humans and wildlife. Examples of EDCs found in reclaimed water or sludges include pesticides (eg DDT, atrazine, pentachlorophenol), organohalogens (eg dioxins and furans, PCBs, 2,4-dichlorophenol), alkylphenols (eg nonylphenol and octylphenol), phthalates (eg diethylhexyl phthalate), hormone drugs (eg oestradiol and ethinylestradiol), phenols (eg bisphenol A) and aromatic compounds [eg benzo(*a*)pyrene]. The effects observed included feminisation of fish, developmental abnormalities of birds and frogs, as well as increasing human testicular and breast cancer rates (Ying and Kookana 2002). However, no direct cause/effect relationships have been found so far between the exposures to EDCs and human health. In addition, the concentrations of these EDCs in reclaimed water are very low (eg Ying *et al* 2002a,b) and therefore indirect human exposure to these chemicals is expected to be very low. The possible effects on human health due to long term exposure to EDCs in wastewater and its reuse is still to be determined.

Effects of organic compound in reclaimed water on human health

The extent of human exposure to toxic organic compounds in reclaimed water is dependent on factors such as their concentration and behaviour, and the environmental conditions. The principal human exposure pathways include:

Table 10.4 Potential for plant root uptake and translocation.

Classification	K_{ow}[A]	Potential for uptake and translocation
Class 1	1.0 <log K_{ow} <2.5	High
Class 2	2.5 <log K_{ow} <3.0 or 0.5 <log K_{ow} <1.0	Medium
Class 3	log K_{ow} <1.0 or log K_{ow} >3.0	Low

Source: after Duarte-Davidson and Jones (1996).
[A] K_{ow}, Octanol-water partition coefficient of an organic compound.

1 via edible plants, ie
   - uptake by plant roots, direct application onto plants, sorption of chemical vapours by plant foliage, and
   - plants exposed to chemicals used as feed by livestock;
2 ingestion of contaminated soil by livestock;
3 direct intake of airborne dust;
4 ingestion of soil by grazing animals and transfer to animal food products;
5 surface runoff to rivers used as drinking water sources;
6 leaching of organics to groundwater aquifers used as drinking water sources; and
7 direct intake of vapours containing volatile organics in wastewater.

Organic compounds in reclaimed water have different toxicities and modes of action on organisms. Due to low levels of toxic organic compounds in reclaimed water and diverse human exposure routes, it makes human health risk assessment difficult to undertake. However, caution should be exercised to reduce possible human exposure to toxic organics (eg by washing raw food).

Summary

Reclaimed water can potentially contain a cocktail of organic chemicals belonging to different structural classes and having various adverse effects on organisms. Although the concentrations of these organic compounds in reclaimed water may be relatively low, use of some sources of reclaimed water to irrigate crops may still pose unknown risks to the environment, food quality and human health. Endocrine disruption and antibiotic bacterial resistance are two new emerging human health issues. An ongoing watching brief is required for the monitoring and screening of organics in reclaimed water used for irrigation to minimise the potential risks to the environment and human health. One of the best ways to reduce the potential risk is improving wastewater treatment technology to remove potentially toxic organic compounds. However, this may increase the treatment cost and restrict the economic viability of reuse schemes.

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11 Environmental implications of reclaimed water use for irrigated agriculture

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Reclaimed water is generally rich in the nutrients nitrogen (N) and phosphorus (P), contains soluble salts not removed in the treatment process, and often has a high concentration of sodium (Na^+) or potassium (K^+) relative to other cations. It may also contain traces of heavy metals, toxic organic compounds or other substances that are highly soluble in water and are therefore not removed in the treatment process. This chapter discusses the potential onsite and offsite impacts that may result from these constituents if irrigation with reclaimed water is not carefully managed. When irrigation with reclaimed water results in application of more nutrients than can be used by the crop, the excess either accumulates in the soil or is leached from it. Phosphorus is strongly sorbed and, therefore, tends to accumulate near the surface in most soils, posing a risk of being washed into surface waters. Excess nitrogen accumulates in soluble form (nitrate) and may be subject to leaching beyond the crop root zone and, eventually, to groundwater. Other potential impacts include the development of salinity, and the accumulation of sodium, which adversely affects soil structure and permeability (see *Chapter 7*). High concentrations of potassium can have a similar effect to sodium. Heavy metals (see *Chapter 8*) and toxic organic chemicals (see *Chapter 10*) are usually not present in sufficient concentrations to be of immediate concern, but their potentially serious impact needs to be recognised.

Introduction

There has been increasing pressure to avoid the direct discharge of wastes into rivers, oceans and other waterbodies. This pressure stems from recognising the need to protect the environment. In many parts of Australia and the world, discharge of nutrient-rich wastes has exacerbated the eutrophication of river systems and contributed to toxic blue-green algae blooms (Gutteridge Haskins and Davey 1991). When discharged into the ocean, the disturbance of the nutrient balance affects marine life, and if the waste has received minimal treatment, it may cause both aesthetic and human health problems on beaches (Brodie 1995; Zann 1996). In some countries there are also cultural reasons for land application rather than disposal to a waterbody (Cameron *et al* 1997).

The use of reclaimed water for irrigating productive agricultural, horticultural or forest crops has become a widespread alternative to discharge into rivers and oceans. The extra costs of treatment or diversion can be offset by the value of the product. Waste streams contain a significant amount of water (estimated to be 1600 GL/yr in Australia; Dillon 2000) and reclaimed water is potentially a valuable resource for irrigation in the dry Australian environment. Most reclaimed water contains plant nutrients (eg N, P and sometimes K) that need to be added as fertilisers to achieve satisfactory plant yields. Thus, reclaimed water contains the ingredients most limiting to crop production in Australia. However, the nutrients may not be in the correct ratios required for optimum plant growth and therefore require special management to prevent nutrient imbalances in the crop (see *Chapter 5*).

Although irrigation with reclaimed water enables diversion of nutrients from waterbodies, it may have other environmental impacts if not carefully managed (Bond 1998). The National Water Quality Management Strategy (1997) publication 'Australian guidelines for sewerage systems – effluent management' sets the basic environmental principles for land application of reclaimed water as:

1 the build up of any substance in the soil should not preclude sustainable use of the land in the long term;
2 the reclaimed water is not detrimental to the vegetative cover;
3 any change to the soil structure should not preclude the use of the land in the long term;
4 any runoff to surface waters or percolation to groundwater should not compromise the agreed environmental values; and
5 no gaseous emissions are to cause nuisance odour.

The focus of this chapter excludes the second of these – earlier chapters have provided advice on ensuring that reclaimed water will not be directly harmful to the crop (see *Chapters 5 to 10*). The others can be grouped as onsite impacts (1 and 3) and offsite impacts (4 and 5). Reclaimed water schemes must be designed to capture the benefits from the water and nutrients, while minimising both the onsite and offsite impacts of the scheme.

Some of the possible constituents of reclaimed water are listed together with a brief indication of their potential onsite and offsite impacts (Table 11.1). The onsite impacts may affect the growing of plants with reclaimed water or they may have long-term effects that restrict the use of the land for other purposes. In many cases, the same constituents of reclaimed water that can be beneficial for plant use have the potential to be detrimental if they accumulate in the soil (K) or move offsite to rivers and groundwater (N and P). Other constituents of reclaimed water not removed by the treatment process that may have both onsite and offsite impacts include sodium, heavy metals, organic chemicals and microorganisms. In this chapter we discuss some of the more important and more common of the potential impacts identified in Table 11.1.

Irrigation management

Sound irrigation management is fundamental to the minimisation of onsite and offsite risks associated with the use of reclaimed water. All irrigation requires careful matching of irrigation to crop water requirements.

Table 11.1 Constituents in reclaimed water with the potential for onsite and offsite impacts.

Constituent	Potential onsite impacts	Potential offsite impacts
Water	Waterlogging	Watertable rise and displacement of salt into streams or low lying land
Inorganic constituents		
Total soluble salts	Salinisation	Salinisation of groundwater
Nitrogen	Inorganic nitrogen accumulation in the soil leading to over-stimulation of plant growth and decreased yield	Nitrate leaching to groundwater
Phosphorus	Accumulation in the soil	Phosphorus leaching to groundwater or runoff to streams, with potentially unacceptable ecological impacts (eutrophication)
Sodium	Soil structure degradation, reduction of permeability, waterlogging	
Potassium	Soil structure degradation, reduction of permeability, waterlogging	
Boron	Plant toxicity	
Heavy metals (As, Cd, Cr, Co, Cu, Fe, Hg, Pb, Mn, Ni, Zn)	Plant toxicity; plant uptake; human ingestion risk	Leaching to groundwater or runoff to streams, with potentially unacceptable ecological impacts
Organic constituents		
Organic matter	Clogging of pores and reduction of permeability	Odours
Organic chemicals	Effect on plant growth; human ingestion risk	Leaching to groundwater or runoff to streams, with potentially unacceptable ecological impacts
Microbial pathogens		
Viruses, bacteria, protozoa, helminths	Human health risk from food ingestion or occupational exposure	Groundwater contamination with subsequent human health risk

Excess irrigation results in increased costs, more rapid use of a potentially scarce resource (in dry years), and the risk of waterlogging, groundwater accessions and watertable rises. Irrigators determine their management strategy by balancing these risks against the risk of poor crop performance if too little water is applied (see *Chapter 6*). With reclaimed water, the risks associated with applying water in excess of crop requirements increases. The more water applied, the more the potential contaminants (Table 11.1). Thus, if any of the constituents in the reclaimed water have potential onsite or offsite impacts, the magnitude of these impacts increases with increasing irrigation rate.

For many sources of reclaimed water, irrigation to match crop water requirements will result in the application of more nutrients than the crop is able to take up and use. In this case, leaching of nitrate to the groundwater is almost certain and using the reclaimed water at a reduced rate to match the crop's nutrient requirement must be considered. This will result in an alternative source of water being required to provide the difference between the amount of reclaimed water applied and the crop water requirement. This is discussed in more detail later in this Chapter.

Salinity

Typically, the concentration of total dissolved solids (TDS) in reclaimed water ranges from 200 mg/L to 3000 mg/L for sewage effluent (Feigin *et al* 1991), and may be higher in water reclaimed from intensive rural industries and industrial processing. Irrigation with such water results in the addition of large amounts of salt to the soil. As an example, annual application of 500 mm (50 ML/ha) of water with a salinity of 1000 mg/L TDS would add 5 t/ha per year of salt. As with all irrigated agriculture, careful management is required when such large amounts of salt are applied. Managing salinity is probably one of the biggest threats to the development of an environmentally sustainable reclaimed water scheme (Stevens *et al* 2003). Problems arise when salt accumulates to a concentration that is harmful to plants through removal of water by evapotranspiration. Even small reductions in growth as a result of salt accumulation may be problematic. Usually, the water balance of a reclaimed water scheme is designed assuming optimum plant growth and water use; if the latter declines, then the operational water balance may not meet the design criteria and problems may escalate.

Therefore, it is essential that irrigation with reclaimed water be designed to allow adequate leaching to remove salt from the root zone. Salt can be allowed to accumulate in the soil until the soil salinity reaches a level that will adversely impact on the crop's growth and performance. When such a threshold salinity level has been reached, irrigation management must be such that the mass of salt being applied is equal to the mass removed from the plant root zone. Otherwise, soil salinity will continue to increase causing a reduction in plant growth, and water and nutrient use. The effects of climatic variations from year to year are important and must be taken into account. In years with average (or better) rainfall, sufficient leaching may take place as a result of rainfall. However, this is unlikely in years with less than average rainfall. Furthermore, in such years the reclaimed water may become more saline as a result of changed water use habits by contributors to the waste stream, and greater concentration in storage ponds as a result of less dilution by rainfall and greater water loss by evaporation. In order to ensure adequate leaching, the soil must be sufficiently permeable, and this is an essential selection criterion for a successful reclaimed water irrigation site (see *Chapters 6 and 7*). The effects of seasonal and yearly variations in rainfall on salt storage in the soil profile and on leaching were demonstrated by Smith *et al* (1996b).

If irrigation with reclaimed water is managed so that salt does not accumulate in the root zone, then what is the ultimate fate of the added salt? This will depend in a large part on the underlying stratigraphy and groundwater conditions. If the underlying material is sufficiently porous, it may be possible to store some salt between the root zone and the watertable. For typical conditions this is likely to be limited and not a long-term solution. Once this storage is filled, salt will reach the watertable, lateral movement is probable and the salt will move offsite. The potential impact of salt on groundwater is discussed later in this Chapter.

Nitrate

The main environmental risk associated with nitrogen when irrigating with reclaimed water is nitrate leaching. If more nitrogen is applied than the crop uses, nitrate accumulates in the soil during the irrigation season. When the total water application exceeds the crop water requirement (usually in the season with the highest rainfall), nitrate leaches from the soil profile. The significance of nitrate leaching to the groundwater depends on local circumstances (see *Groundwater*). However, in general, nitrate poses a threat to animal and human health in drinking water, and is active in eutrophication of surface waters.

Therefore, as a first approximation, the amount of nitrogen added in the reclaimed water should be commensurate with the expected plant uptake of nitrogen. In many guidelines (eg ANZECC and ARMCANZ 2000) this is the basis for determining the nitrogen loading rate (ie the annual application of nitrogen per unit of land area). For reclaimed water with a high nitrogen concentration, this requirement may conflict with the water requirement of the plants; the amount of water that needs to be applied to grow a successful crop may result in a nitrogen loading in excess of that needed to meet the crop's demand.

The reclaimed water loading rate that can be applied without causing nitrogen accumulation and leaching is calculated as follows (Eqn 11.1):

$$V = \frac{R_n}{C_p} \quad (Eqn\ 11.1)$$

where V is the annual reclaimed water loading rate (ML/ha per year), R_n is the amount of nitrogen removed in the harvested crop (kg N/ha per year), and C_p is the concentration of nitrogen in the reclaimed water (mg N/L). The nitrogen removal by the crop is the product of the harvested biomass (dry matter; kg DM/ha per year) and the nitrogen concentration of the biomass (kg N/kg DM). Concentrations of nitrogen in the harvestable biomass for a wide variety of crops may be found in ANZECC and ARMCANZ (2000, Table 9.2.20).

The relationship between these quantities is shown in Figure 11.1, for three example values of nitrogen removal in the crop. For low concentrations of nitrogen in the reclaimed water, and high nitrogen uptake and removal by the crop, the amount of reclaimed water required to meet the nitrogen requirement may exceed the irrigation requirement of the crop and supplementary fertiliser may be required. However, for high concentrations of nitrogen in the reclaimed water, the nitrogen requirement of the crop will be reached with only small reclaimed water-loading rates even for crops with a large demand for nitrogen. In these cases, the water requirement of the crop may exceed the loading rate to satisfy the nitrogen requirement (see *Chapter 5*). Irrigation at the water requirement will therefore result in application of excess nitrogen, which will accumulate and leach. In such cases, consideration needs to be given to mixing the reclaimed water with an alternative water source to reduce the nitrogen concentration, or irrigating for part of the season with reclaimed water and part with an alternative water source. This will require a source of 'fresh water' and a larger area to be irrigated to use a given volume of reclaimed water.

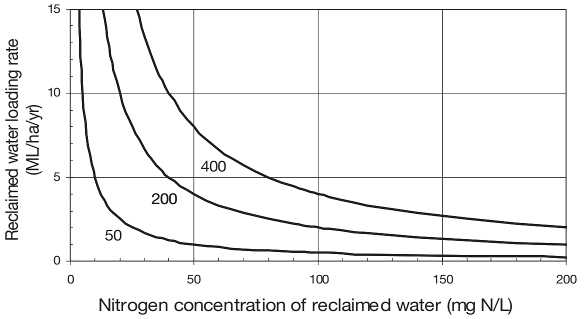

Figure 11.1 Relationship between the loading rate and the nitrogen concentration of the reclaimed water to satisfy different nitrogen requirements of the crop per year (50, 200 and 400 kg N/ha). These figures assume no gaseous losses of nitrogen or mineralisation of existing soil organic matter.

The calculation above (Eqn 11.1) makes no allowance for other mechanisms that affect soil nitrogen. Volatilisation and denitrification have the potential to convert the applied nitrogen to gaseous forms, which are released to the atmosphere. In some cases, an allowance for the amount of nitrogen lost by the mechanisms of volatilisation and denitrification is also considered when determining acceptable loading rates (ANZECC and ARMCANZ 2000). Unfortunately, realistic estimates of these are very difficult to obtain without direct measurement. Smith *et al* (1996a) found that volatilisation losses of nitrogen from reclaimed water irrigated pasture were highly variable, and under some conditions may account for only a few per cent of the applied nitrogen. In permeable, freely draining soils, which are preferred for irrigating with reclaimed water, Smith and Bond (1999) found that denitrification losses were also small. However, inorganic nitrogen may be generated by the breakdown of soil organic matter, a process called mineralisation. Furthermore, the rate of mineralisation may be enhanced by irrigation, releasing often quite large amounts of nitrate into solution (Polglase *et al* 1995). While mineralisation is expected to decrease with time, in some cases it may result in more nitrogen being released than is required by the plants. Under such circumstances, all nitrogen added in the reclaimed water may be surplus to crop requirements.

Despite these uncertainties, Equation 11.1 and Figure 11.1 provide a good starting point. Nevertheless, an effective monitoring strategy and adaptive management are required to prevent the accumulation of excessive amounts of nitrate-N in the soil profile and its subsequent leaching to ground or surface waters increasing the risk of algal blooms (*Chapter 12*).

Phosphorus

The main environmental risks associated with phosphorus are runoff to surface waters (increasing the risk of algal blooms) and leaching to groundwater. Provided that reasonable precautions are taken to prevent or contain runoff, the risk of contaminating surface waters can be controlled. The likelihood of leaching to groundwater depends strongly on soil type and, in particular, the ability of the soil to retain phosphorus, with sandy soils having the greatest risk of phosphorus leaching.

Phosphorus is an essential plant nutrient and is therefore a valuable constituent in reclaimed water (see *Chapter 5*), which often contains high phosphorus concentrations, especially when derived from rural industries. Phosphorus concentrations also depend on the wastewater treatment process (see *Chapter 3*). In contrast to nitrogen, there are no gaseous loss mechanisms and the main sinks of phosphorus are in plant biomass, the soil and organic matter. Like nitrogen, phosphorus is held in organic forms in the soil and may be released by mineralisation in response to irrigation, increasing the effective loading of inorganic phosphorus to the soil. The application of reclaimed water results in an immediate increase in the level of soluble phosphorus in the soil solution. Some of this phosphorus will be taken up by the crop, but most will react with the soil by adsorption and precipitation (Feigin *et al* 1991; Falkiner and Polglase 1999). There is also some evidence that continuous small application of phosphorus in reclaimed water improves the plant phosphorus efficiency (applied phosphorus to phyto-available phosphorus), compared with one-off higher fertiliser applications (Sakadevan *et al* 2000). The amount of phosphorus that is sorbed in the soil varies with the concentration of phosphorus in the reclaimed water, soil texture and the type of clay. Relatively sandy soils have low phosphorus retention capacity, compared with soils that have a high clay content. Generally, the phosphorus retention capacity is high for Australian soils.

Rapid sorption results in the clay fraction of the surface soil being high in phosphorus, and this generates the risk of phosphorus contamination of surface waters by runoff from the site in suspended colloidal material. Engineering works, careful site selection and irrigation management, and buffer strips, can effectively control the risk of phosphorus-enriched soils entering dams and rivers.

Over time, the capacity of the surface soil to retain phosphorus will be exceeded and phosphorus will move deeper into the soil. Falkiner and Polglase (1999) found that after five years of irrigation with municipal effluent there was an increase in total phosphorus in the soil to a depth of 0.8 m, although an increase in phosphorus in solution (leachable phosphorus) was confined to the top 0.4 m. In this study the reclaimed water had a concentration of total phosphorus of 5.4 mg/L, and was irrigated onto Red Chromosols and Red Kandosols which had sandy loam surface horizons (0–0.4 m) and clay textured subsoils. It is estimated that it would take many decades of irrigation with reclaimed water at this site before soluble phosphorus would pass beyond 1 m, and many hundreds of years before it reached the watertable (several metres deep). In a sandy soil with little clay and a much lower phosphorus retention capacity, the movement of soluble phosphorus to depth will occur much quicker and may pose a significant offsite risk.

In summary, the management of phosphorus requires that the soil be used as a sink for phosphorus. By doing this, the soil will be progressively loaded with phosphorus and it will accumulate to concentrations that greatly exceed those found naturally in most soils. The rate of accumulation will depend on the phosphorus concentration of reclaimed water, the irrigation rate, the soil properties and phosphorus fertiliser management. The phosphorus accumulation is largely irreversible and therefore constitutes a long-term change in the soil properties, which may affect the growth of phosphorus-sensitive plant species (eg Wajon *et al* 1999).

Sodium and potassium

High concentrations of sodium and potassium in irrigation water relative to other cations are of concern because they are known to adversely affect soil structure and permeability (see *Chapter 7*), causing restricted water entry, root growth and soil aeration, and increased erosion potential. Reclaimed water commonly has high concentrations of sodium (Na^+) relative to other cations. In some cases, the relative concentration of potassium (K^+) may also be high, for example, in intensive piggery waste (Biswas *et al* 1999), or from woolscour effluent, winery waste or dairy whey.

The effect of high sodium concentrations on soils has been extensively documented (see *Chapter 7*). While potassium has received less study, it has a similar effect on soil structure, although higher relative concentrations are required to have the same effect as sodium (Chen *et al* 1983; Biswas *et al* 1999; see *Chapter 7*).

The concentration of sodium relative to other (divalent) cations in irrigation water is quantified by the sodium adsorption ratio (SAR, see *Chapter 7*, Effect of irrigation water quality on soil sodicity for definition). Treated sewage effluents typically have SAR in the range of 4.5 to 7.9 (Feigin *et al* 1991). The combination of relatively high salinity and SAR is expected to cause the exchangeable sodium percentage (ESP, the percentage of the cation exchange capacity occupied by sodium) in the soil to increase. With increased ESP comes the risk of deterioration of soil physical properties, specifically dispersion of clay with subsequent breakdown of soil structure, blocking of pores and decreasing in soil permeability. This in turn may lead to waterlogging, impaired plant performance, decreased leaching and salinisation.

The consequences for soil physical condition of high ESP depend on many factors. The most important factor is the concentration of the soil solution: for a given ESP, breakdown of soil structure is less likely for a high soil solution concentration. For a given combination of soil ESP and soil solution concentration, the likelihood of soil structural breakdown increases (Sumner 1993) with:

1 increasing
   - soil pH
   - clay content
   - proportion of smectitic and illitic clays
   - mechanical disturbance; and
2 decreasing
   - organic matter
   - proportion of kaolinitic clays
   - proportion of sesquioxides.

The relationship between soil ESP, solution concentration and soil structure is complex and not easily predicted.

Some qualitative observations on the likely effect of sodicity on soil properties can be made. The interaction between soil sodicity (ESP) and soil solution concentration means that while irrigation with reclaimed water continues, there is unlikely to be deterioration in soil structure because the expected high salinity of the reclaimed water will counterbalance the high SAR and resulting ESP (see *Chapter 7* for more detail). Exceptional combinations of salinity, SAR and soil type may lead to immediate dispersion, particularly if the soil is cultivated. If tillage is not an integral part of crop management, changed land use after irrigation with reclaimed water that results in cultivation may lead to structural deterioration. Similarly, ceasing irrigation with reclaimed water and returning to rain-fed agriculture may result in a decrease in salinity, or ionic strength of the soil solution, and consequent breakdown in soil structure.

Increased soil sodicity resulting from irrigation with reclaimed water is an insidious, latent problem which may render the land unsuitable for other uses. Addition of a calcium source such as gypsum with the reclaimed water may counterbalance the effects of the sodium but the application of gypsum required could be several times the normal agricultural application, depending on the SAR and salinity of the reclaimed water. Furthermore, although an applied calcium source may prevent problems in the root zone, the sodium will be pushed deeper into the soil and may affect subsoil permeability.

Contamination by trace constituents

Heavy metals and metalloids

Accumulation of heavy metals and metalloids in the soil as a result of irrigation with reclaimed water from most sources is unlikely to present a serious risk as their concentrations are generally very low (see *Chapter 8*). However, the potential effect of heavy metals on the environment is a concern to regulatory agencies and must be considered (Page and Chang 1985; Feigin *et al* 1991; Tiller 1992). Metals applied in irrigation water are usually retained in the topsoil and have varying degrees of plant availability. Some heavy metals are phytotoxic and concentrations in the soil must be kept low to prevent a detrimental effect on plant growth (eg arsenic and zinc). Others are accumulated by plants and lead to animal and human health concerns at levels lower than would cause a decline in crop yield (eg cadmium, lead, molybdenum and selenium).

The *Australian and New Zealand guidelines for fresh and marine water quality* (ANZECC and ARMCANZ 2000, table 4.2.10) identify 'trigger' concentrations of individual heavy metals and metalloids that should not be exceeded without carrying out a specific risk assessment (see *Chapter 2*, Table 2.8). This table also specifies a trigger value for the concentration of metals in soil, called the cumulative loading limit. For many sources of reclaimed water, the concentrations of heavy metals are unlikely to exceed these trigger values. For example, the range of heavy metal concentrations usually found in secondary treated municipal effluent are below the trigger values (Feigin *et al* 1991). Reclaimed water with significant industrial sources, however, may contain concentrations of heavy metals that exceed the trigger values and will require further investigation.

Organic toxins

Depending on the source, reclaimed water may contain a range of toxic organic chemicals such as organochlorines, PCBs and trichloroethylene. If present, they are most likely to accumulate in the soil and be available for plant uptake. ANZECC and ARMCANZ (2000, table 4.2.12) identify residue limits in irrigation water for a range of herbicides. However, this is generally an area with few guidelines (see *Chapters 2 and 10*). If contamination of the reclaimed water by organic chemicals is suspected, then a specific investigation should be undertaken to determine the risk of soil contamination and crop uptake.

Groundwater

In the earlier discussion of salinity and nitrate leaching, conflicting requirements of irrigation with reclaimed water were identified: that leaching is essential to prevent salinisation of the root zone and yet, because there may be excess nitrate in the root zone, leaching will result in the movement of nitrate to the groundwater. As increased recharge to groundwater is usually regarded as an inevitable consequence of irrigation, and maintaining a low salinity in the root zone is an overriding short-term consideration, it is inevitable that under irrigation with reclaimed water there will be salt-laden and nitrate-laden water moving from the root zone towards the groundwater.

While leaching of salt and nitrate has the potential to affect the quality of groundwater, the effects are mitigated by a range of factors. The depth to the watertable will affect the length of time before effects are seen at the watertable. This may also give the opportunity, in the case of nitrate, for further denitrification to occur if the soil is wet enough and there is a suitable carbon source. The quality of groundwater prior to irrigation will determine whether or not the salt and/or nitrate reaching the groundwater will have a detrimental impact. For example, if the groundwater is already saline, the extra salt from irrigation with reclaimed water is unlikely to be of concern. Similarly, if the groundwater is not potable, an increase in its nitrate concentration may not be considered a problem, provided it does not discharge to surface water.

On reaching the groundwater, salt and nitrate will be subject to dilution. The extent of dilution will depend on the rate of recharge and the rate of flow of groundwater beneath the irrigation site, which in turn depends on aquifer permeability and hydraulic gradient. The amount of dilution will also depend on the size of the irrigation area. For example, a large reclaimed water irrigation area will have a greater effect on down-gradient groundwater quality than a small reclaimed water irrigation area, given similar circumstances, because there will be less dilution by the receiving groundwater of the salt and nitrate coming from the larger area.

Proximity of the irrigation site to discharge zones and to water supply wells also determines the likelihood of contaminated water finding its way into rivers, drinking water supplies or groundwater. Thus, although leaching of salt and nitrate from sites irrigated with reclaimed water is almost certain, a resulting adverse impact is not inevitable, particularly in the short term. Nevertheless, considerable care must be taken that irrigation with reclaimed water does not result in the creation of a groundwater problem that takes many years to express itself, and will take as long or longer to remediate, as has been the case with dryland salinity resulting from tree clearing. Monitoring of groundwater is an essential indicator of environmental performance for irrigation with reclaimed water.

Environmental flows

In a dry climate such as Australia's, water is a valuable resource. As urban population centres grow, it is becoming increasingly difficult and costly to meet the demand for water. By replacing fresh water with reclaimed water for some uses, such as watering of both public and domestic gardens, which many water supply and sewage treatment authorities are now exploring, the total community demand for fresh water is decreased and water is used more efficiently. In contrast, the use of reclaimed water to irrigate crops, which could otherwise be grown under rainfed conditions, could be considered as inappropriate use of the water. However, substitution of reclaimed water for other sources of water in existing irrigation areas is an efficient use of scarce water resources.

When a treated waste stream is returned to the river, water is recycled. For example, the water (and wastes) discharged to the river in Canberra, near the headwaters of the Murray River, contributes to the water supply for the people in South Australia more than 1000 km away. Off-river disposal of all potentially reclaimable water in inland Australia would affect river flows and river ecology and reduce water resources for communities downstream. The magnitude of this effect will be greater for small rivers and during times of low flow (either seasonally or climatically induced). These considerations suggest that in inland areas it may be valuable to treat wastewater to a quality sufficient for discharge to rivers rather than using it for irrigation. For coastal areas, where the treated waste streams flow directly to the sea, this argument does not apply.

Summary

Reclaimed water generally provides a valuable source of plant nutrients (particularly nitrogen and phosphorus) that can promote crop production. Environmentally sound use of reclaimed water requires that it does not result in changes to the soil that may preclude future uses and that it does not result in any surface water or groundwater accessions that compromise the quality of the receiving waterbodies. Nutrient concentrations in reclaimed water are usually not in the right proportions relative to the crop irrigation requirements, which could mean excess applications may occur when irrigating to meet crop water requirements. These can have potentially adverse environmental implications such as runoff of phosphorus-rich topsoils into surface waters or leaching of nitrate to groundwater if not carefully managed. Reclaimed water may contain other soluble constituents with the potential for environmental impact. Soluble salts may cause both onsite and offsite salinisation. Sodium and potassium may cause a deterioration of soil structure resulting in decreased permeability and waterlogging. In some cases, heavy metals and toxic organics may accumulate to unacceptable levels in the soil, although this is unlikely for most sources of reclaimed water. With due diligence, the establishment and management of irrigation schemes using reclaimed water can be environmentally sustainable. However, it is a delicate balancing act where many interactions must be considered and appropriate guidelines followed.

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12 Managing health risks to consumers

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Consumer risks

Irrigation of agricultural produce by reclaimed water poses potential risks to consumers when the following three conditions are present:

1. Hazardous microorganisms or chemicals are present;
2. Concentrations of the hazardous agents are high enough to cause illness; and
3. There is a route of exposure leading to contact between consumers and the hazard in a manner that would cause illness.

This risk characterisation applies equally to any other water used for irrigation and any other material such as fertiliser used in the production of food crops.

Therefore, to ensure agriculture products are safe, control measures need to be applied to:

1. Prevent hazards from being present – one example would be to apply strict trade waste control programs to prevent hazardous chemicals being released into sewers and transported to wastewater treatment plants (WWTP). However, this approach cannot be applied to microbial hazards.
2. Reduce the concentrations of hazards below the level that would cause illness – reducing concentrations of pathogenic microorganisms is the principal function of WWTPs. The higher the level of treatment, the lower the concentrations of pathogenic microorganisms.
3. Prevent or minimise the exposure of consumers to the hazards. This can be achieved by:
   - restricting the types of crops that are irrigated (eg fruit trees, crops that are processed or cooked before consumption)
   - controlling methods of application (eg drip irrigation rather than spray irrigation); the impact of this measure will depend on the nature of the crop (eg root vegetables, salad vegetables with ground contact or crops borne on vines or trees)
   - setting withholding periods between application of water and harvesting, and sale of crops.

The various mechanisms for reducing risks, including prevention, removal and onsite control are important components of reclaimed water guidelines, which allow a balanced approach to the management of health risks. In schemes where high levels of treatment are applied, to minimise concentrations of hazards, lower levels of onsite control are required to reduce exposure to hazards. Conversely, if lower levels of treatment are applied, then methods to control exposure need to be increased.

Pathogens

The types and concentrations of enteric pathogens present in raw sewage reflect illness in the community. For instance, in Australia the occurrence of large numbers of the highly pathogenic cholera organism, *Vibrio cholerae*, is very unlikely. In some cases, illness and occurrence of pathogens may be seasonal. For instance, infections with *Cryptosporidium* are typically more common in late summer and autumn in countries such as Australia and the United States while in other countries infections occur more commonly in spring and autumn.

Table 12.1 provides a list of the typical pathogens that can be found in raw sewage while Table 12.2 provides an indication of concentrations of organisms detected in raw sewage.

Table 12.1 Typical pathogens found in raw sewage.

Pathogen type	Examples	Illness	Infectious dose
Bacteria	Atypical mycobacteria	Skin, respiratory infections	Unknown
	Campylobacter	Gastroenteritis, Guillain-Barre syndrome	10^3
	Helicobacter pylori (?)	Peptic ulcers	Unknown
	Pathogenic *E. coli*	Gastroenteritis, haemolytic uremic syndrome	10^1–10^8
	Pseudomonas aeruginosa	Skin, eye, ear infections	>10^5
	Salmonella	Gastroenteritis	10^4–10^7
	Shigella	Dysentery	10^1–10^2
	Staphylococcus aureus	Skin, eye, ear infections, septicaemia	Unknown
	Vibrio cholerae	Cholera	10^3
	Yersinia	Gastroenteritis, septicaemia	>10^3
Viruses	Enterovirus	Gastroenteritis, respiratory illness, nervous disorders, myocarditis	1–10 pfu[A]
	Adenovirus	Gastroenteritis, respiratory illness, eye infections	1–10 pfu
	Rotavirus	Gastroenteritis	1–10 pfu
	Hepatitis A	Infectious hepatitis	1–10 pfu
	Calicivirus	Gastroenteritis	1–10 pfu
	Astrovirus	Gastroenteritis	1–10 pfu
	Coronavirus	Gastroenteritis	1–10 pfu
Protozoa	*Cryptosporidium*	Gastroenteritis	1–2000 oocysts
	Giardia	Gastroenteritis	1–10 cysts
	Naegleria fowleri	Amoebic meningitis	Unknown
	Entamoeba histolytica	Amoebic dysentery	1–10 cysts
Helminths	*Taenia* *T.saginata*	Tapeworm Beef measles	1–10 eggs
	Ascaris	Roundworm	1–10 eggs
	Trichuris	Whipworm	1–10 eggs

Source: after Feacham *et al* (1983), Geldreich (1990), Bitton (1994), National Research Council (1996).
[A] pfu = plaque forming unit.

Results from two Australian wastewater treatment plants indicate that the raw sewage contained 2000 *Cryptosporidium*, 8000 adenovirus and 7000 *Campylobacter* per litre (as a 95th percentile) (NRMMC and EPHC 2005).

Hazard reduction

Wastewater treatment processes

The primary purpose of wastewater treatment is protection of public health through reduction of enteric pathogens present in raw sewage. Typical reductions achieved by traditional treatment processes (see *Chapter 3*) are shown in Table 12.3.

A WWTP that incorporates primary screening, secondary treatment, coagulation, filtration and disinfection should be able to produce a high-quality reclaimed water containing <1 *E. coli*/100 mL and low numbers of enteric viruses, *Cryptosporidium* oocysts, *Giardia* cysts and helminth ova (Asano *et al* 1992; Yanko 1993; Rose *et al* 1996; National Research Council 1996; Cunliffe and Stevens 2003).

Onsite controls

Onsite controls and restrictions on the use of reclaimed water can also be deployed to reduce the potential for hazard transmission and human exposure. Lower qualities of reclaimed water can be used to irrigate crops, providing post-treatment controls are applied to reduce human exposure to potential hazards in the water. Log reductions in exposures can be ascribed to onsite preventive measures. These log reductions can range from 0.5 log/d for withholding periods to 5–6 logs for crop processing (NRMMC and EPHC 2005).

Table 12.2 Numbers of microorganisms detected in raw sewage.

Organism	Numbers in sewage (per L)
Adenoviruses	10^1–10^4
Cryptosporidium	0–10^4
Enteroviruses	10^2–10^6
Escherichia coli	10^5–10^{10}
Giardia	10^2–10^5
Helminth ova	0–10^4
Rotaviruses	10^2–10^5
Salmonella	10^3–10^5
Shigella	10^1–10^4

Source: after Feacham *et al* (1983), Bitton (1994), National Research Council (1996).

Health-based targets

Health-based targets are the benchmarks that have to be achieved to ensure safety for consumers of irrigated produce. The normal benchmarks are guideline values for chemical hazards and performance targets for microbial hazards. The inputs into the calculation of health based targets are a definition of tolerable risk and the elements associated with risk assessment:

- concentrations of hazards in raw sewage;
- dose response data for these hazards; and
- exposures associated with the use.

Tolerable risk

There are several definitions of tolerable risk including an acceptable upper limit of 1 infection per 10 000 people per year (Regli *et al* 1991) for microbial hazards. This limit has been cited as a basis for establishing microbiological limits for drinking water guidelines (Macler and Regli 1993). Other definitions exist for chemical hazards (NHMRC and NRMMC 2004).

However, the 'Draft national guidelines for water recycling' (NRMMC and EPHC 2005) have adopted disability adjusted life years (DALYs) as the best metric for describing health impacts and risks. DALYs have also been adopted in water guidelines developed by the World Health Organization (WHO 2004). A DALY is the sum of years lost through being in less than good health and premature death associated with exposures to either microbiological or chemical hazards. Determining DALYs includes considering both acute impacts (eg diarrhoeal disease) and chronic impacts (eg cancer or reactive arthritis associated with a low proportion of Campylobacter and Salmonella infections).

Both the 'Draft national guidelines on water recycling' (NRMMC and EPHC 2005) and the latest edition of the WHO's 'Guidelines for drinking-water quality' (WHO 2004) have adopted 10^{-6} DALYs per person per year as a tolerable level of risk. This is equivalent to an annual risk of illness of 10^{-3} (ie 1 illness per 1000 people) for a diarrhoea-causing pathogen such as *Cryptosporidium*. This is well below the Australian reported rate of 0.8–0.92 cases of diarrhoeal illness per person per year (OzFoodNet Working Group 2003).

Microbial risk assessment

Sewage can contain a wide range of pathogenic microorganisms and it is not practical to undertake a risk assessment for all of these organisms. A standard approach is to select reference pathogens representing the major groups of pathogens (NRMMC and EPHC 2005). Reference pathogens need to have several properties including high occurrence and pathogenicity, and for risk assessment purposes there needs to be data on occurrence and dose response. *Cryptosporidium* is a standard choice as a reference pathogen for enteric protozoa, rotavirus can be used as a reference for viruses, and *Campylobacter* for enteric bacteria. Dose response data are available for each of these pathogens (Haas *et al* 1999; Messner *et al* 2001) and Australian data are available for occurrences of *Cryptosporidium* and *Campylobacter*. Data for adenoviruses can be used as an indicator for rotavirus concentrations (NRMMC and EPHC 2005).

Table 12.3 Log reduction of microorganisms achieved by treatment processes.

	Level of treatment[A]			
	Primary	Secondary	Lagoons	Tertiary (filtration & disinfection)
Organism	Log reduction			
Bacteria	0–2	0–2	1–6	4–6
Cryptosporidium	0–1	0–1	1–3	2–3
Enteric viruses	0–1	0–2	0–2	3–4
Giardia	0–1	0–2	3–5	2–4
Helminth ova	0–2	0–2	1–3	2–3

Source: after Feacham *et al* (1983), Bitton (1994), National Research Council (1996).
[A] See Chapter 3.

There is a limited range of exposure data associated with agricultural application of reclaimed water. Unrestricted spray irrigation of salad crops represents the highest potential exposure associated with agricultural irrigation. Shuval *et al* (1997) determined that 10.8 mL of water could adhere to 100 g of lettuce whereas 0.4 mL could adhere to cucumbers. These types of data can be used together with figures on consumption of salad vegetables by Australians (ABS 1995) to determine typical or average exposures to components of irrigation water.

Calculated log reductions (performance targets)

Using the information discussed above, log reductions of pathogens in raw sewage can be calculated to ensure that health risks do not exceed the tolerable health risk of 10^{-6} DALYs when salad crops are irrigated with reclaimed water (NRMMC and EPHC 2005). The calculated reductions are 4.8 logs for *Cryptosporidium*, 5.9 logs for adenoviruses / rotaviruses and 4.9 logs for *Campylobacter*. These reductions equate to concentrations in reclaimed water of about 3 *Cryptosporidium*, 1 rotavirus and 10 *Campylobacter* per 100 L. These concentrations are provided as an indication of a final target. However, testing for these pathogens would not be a part of routine monitoring programs.

The required log reduction could be achieved by treatment alone or by a combination of treatments and onsite controls. For example, for commercial food crops it can typically take 36–48 hours to move from final irrigation through to harvest, transport to retail outlets and purchase. This time period would lead to about a 1 log reduction in virus numbers, hence the log reduction target for treatment would be reduced to about 5 logs.

The use of onsite controls to reduce potential exposure and, hence, to reduce required log reductions can be extended as shown in Table 12.4. This enables lower quality reclaimed water to be used as shown in Table 12.5. For example, drip irrigation of crops with no ground contact (eg tomatoes, peas, citrus and orchard fruit) reduces exposure by 4 logs while decay of organisms between final watering, harvesting and consumption reduces exposure even further. Log reductions required through treatment for this type of reclaimed water use would be less than 1 log for protozoa, viruses and bacteria. These reductions can be achieved by secondary treatment and disinfection. Processing of food crops such as cereals, wine grapes and potatoes reduces exposure by 5–6 logs, meaning that only limited treatment is required such as secondary treatment or primary treatment with lagoons.

Table 12.4 Log reductions provided by onsite controls.

Control measure	Log reduction in exposure to pathogens
Cooking or processing of crops (eg potatoes, wine grapes)	5–6
Removal of skins from produce before consumption	2
Drip irrigation	2
Drip irrigation of crops with no ground contact	4
Subsurface irrigation of above-ground crops	4
Withholding periods	0.5 per day (viruses and bacteria)

These calculations err on the side of caution. The calculated log reductions assume that all organisms detected are infectious for humans through ingestion but this is unlikely to be the case. For example, it is doubtful that all of the *Cryptosporidium* and *Giardia* detected in treated effluent are infectious. Most analyses of these organisms base assessments of viability on dye exclusion (US EPA 1999b), but the relationship of this to infectivity is uncertain (eg see Clancy *et al* 1998). Analysis of adenovirus excreted by humans has shown that only a small proportion belongs to the serotypes generally associated with enteric illness (for a review of serotypes see Hierholzer 1991). Human behaviour such as washing of produce before use and consumption has also not been considered.

This caution and conservatism is probably necessary to achieve acceptance by consumers and wholesalers (see *Chapter 13*).

There are at least two examples where unrestricted irrigation of food crops with reclaimed water has been practised. The first is the Monterey Scheme (California, USA) which has been operating for almost 20 years and the second is the Virginia Pipeline Scheme (South Australia) which has operated since 1999. Microbiological and chemical testing of crops grown in these schemes has not detected any differences between produce irrigated with bore water and reclaimed water (Sheikh *et al* 1990, Kelly and Stevens 2002).

Cyanobacteria

Cyanobacteria or blue-green algae are common in surface waters including farm dams used for agricultural irrigation in Australia. Some species produce toxins. The possibility that cyanobacterial blooms may affect crop quality has been raised as a research need but there has

Table 12.5 Reclaimed water quality requirements for specific food crops.

Type of crop	Application method	Treatment log reductions	Onsite control reductions
Large surface area grown on or near the ground and consumed raw (eg broccoli, cabbage, cauliflower, celery, lettuce)	Spray	Secondary, filtration disinfection 4–5 log protozoa 6 log viruses > 6 log bacteria	1.0 log virus and bacteria due to decay prior to sale
Crops without ground contact (eg tomatoes, peas, beans, capsicums, non-citrus orchard fruit, non-wine grapes)	Drip	Secondary and disinfection 0.5–1 log protozoa 1–3 log viruses >6 log bacteria	4 log (drip) 1.0 log virus and bacteria due to decay prior to sale
Crops without ground contact and skin that is removed before consumption (eg citrus and nuts)	Spray Drip	Secondary and disinfection 0.5–1 log protozoa 1–3 log viruses >6 log bacteria	3 log (spray) 5 log (drip) 1.0 log virus and bacteria due to decay prior to sale
Crops processed before consumption (eg potatoes, brussel sprouts, cereals, grapes for wine making)	Spray, drip	Secondary treatment 0.5–1 log protozoa 0–2 log viruses 1–3 log bacteria	5–6 log cooking/processing
Crops not for human consumption Silviculture, turf growing	Any	Secondary treatment 0.5–1 log protozoa 0–2 log viruses 1–3 log bacteria	>6 log

been very limited work undertaken. The potential for public health impacts would require the presence of significant numbers of toxic cyanobacteria, uptake or irreversible attachment of toxins to crops and limited environmental degradation. Uptake of cyanobacterial toxins into cellular material is problematic, and, although it is known that environmental microorganisms can degrade toxins, the rate at which this would occur for the range of identified cyanobacterial toxins is unknown (see Chorus and Bartram 1999). Codd *et al* (1999) demonstrated physical carriage of *Microcystis aeruginosa* and the associated toxin microcystin on lettuce leaves due to spray irrigation, but the initial concentrations of the organism in the irrigation water was not reported. There was no attempt to assess the potential risks to human health from consuming these leaves.

Studies of open storages associated with the Virginia Pipeline Scheme demonstrated that most of the species of cyanobacteria detected were non-toxic (Kelly and Stevens 2002). Although possible impacts of cyanobacterial blooms on crop quality have not been established, such blooms can cause problems with blocking of irrigation systems and decaying blooms can cause odour problems. One mechanism for reducing cyanobacterial blooms is to maintain rapid turnover of water. Cyanobacteria prefer still and stable conditions. Dams with long retention times are more likely to support the growth of blooms.

Chemical quality

Heavy metals

The concentrations of individual chemicals in domestic wastewaters, especially heavy metals, are generally below guideline values recommended for crop irrigation (ANZECC and ARMCANZ 2000) and also below those specified for safe drinking water (NHMRC and NRMMC 2004). The principal cause for concern is the discharge of industrial wastes into sewerage systems. Most jurisdictions have policies against this practice. However, ongoing policing needs to be maintained to protect the quality of reclaimed water used for irrigation and, for that matter, the alternative of discharge to fresh or marine waters.

An assessment should be undertaken of industrial activities within the areas served by sewerage systems to assist the monitoring of trade waste restrictions and to provide a better understanding of worst case scenarios for reclaimed water schemes. As previously discussed, testing of crops grown at Monterey and Virginia has detected no exceedances of chemical requirements for food quality associated with the use of reclaimed water (Sheikh *et al* 1990; Kelly *pers comm* 2004).

Pesticides and other organic chemicals

In well-managed systems with sound trade waste monitoring there should be few, if any, detections of pesticides or significant concentrations of organic chemicals. Long-term monitoring of the four metropolitan WWTPs in South Australia has not detected the presence of pesticides and the concentrations of organic chemicals have all been very low (see *Chapter 10*).

Endocrine disruptors (xenoestrogens)

Although there has been little evidence of human health effects from environmental exposure, there has been a lot of discussion in both the scientific and popular press about the issue of potential endocrine disrupting chemicals (Safe 2000; see *Chapter 10*). Reviews have been published by the World Health Organization (WHO 2002) and the CRC for Water Quality and Treatment (CRCWQT 2003). Even the term used to define these chemicals has been a subject of debate and various labels have been used including xenoestrogens and hormonally active agents. For simplicity, the term 'endocrine disruptor' will be used here to refer to the group of chemicals with the potential to interfere with the normal function of the endocrine system.

Hundreds and thousands of possible endocrine disruptors have been identified including pesticides, non-pesticide organics, inorganic chemicals (eg lead and cadmium), plasticisers and pharmaceuticals (eg female contraceptive hormones). The US EPA has estimated that 87 000 chemicals could be considered as potential endocrine disruptors (US EPA 1999a).

There are several issues that need to be borne in mind when considering the possible impact of endocrine disruptors:

- at this stage, there is no compelling evidence of impacts on human health from exposure to these chemicals from environmental sources (Safe 2000);
- the ever increasing list of potential endocrine disruptors is almost ubiquitous (eg phthalates, which have been identified as a cause of concern, are a normal component of plastics commonly used to wrap foods after production) (Jobling *et al* 1995);
- human exposure to natural compounds, with the potential to be endocrine disruptors, far outweighs the small amounts of manufactured compounds that may or may not be present in water (eg some plants such as soybeans contain very high concentrations of phytoestrogens) (Mazur and Adlercreutz 1998; Safe 2000); phytoestrogens have been shown to cause infertility and developmental toxicology in some animals including sheep clover infertility reported in Western Australia (Adams 1998).

There have been several reports that discharge of treated wastewater into streams can affect aquatic species including fish (Safe 2000). However, extrapolating these data to humans is very difficult for several reasons including important differences in the pharmokinetics and metabolism of fish compared to humans and consideration of the mechanisms of exposure. Fish exposure entails continuous full body immersion while human exposure is indirect through ingestion of irrigated produce.

The question that must be asked in regard to the use of reclaimed water to irrigate food crops is, does this source of irrigation water significantly increase exposure to potential endocrine disruptors? For this to occur the compound would need to be present in significant concentrations and taken up into irrigated plants and retained during growth. At this stage, for reclaimed water that is sourced predominantly from domestic wastewater, there is no evidence that these conditions are fulfilled.

Pharmaceutical chemicals

Issues raised for pharmaceuticals have been similar to those for endocrine disruptors. Low concentrations of pharmaceutical compounds have been detected in waters that receive discharges of sewage effluent (Kolpin *et al* 2002). However, the relatively low human exposures to reclaimed water through agricultural use mean that the likelihood of health impacts is minimal. In addition, there is uncertainty concerning plant uptake and retention of these chemicals.

Conclusions

There are advantages for using reclaimed water to irrigate food crops. Where highly treated reclaimed water is used for purposes such as spray irrigation of salad crops, the quality is measured continuously, and, at least microbiologically and physically, reclaimed water is generally superior in quality to surface waters used across Australia for unrestricted irrigation of food crops. Reclaimed water quality is also routinely tested for compliance with established Australian guidelines for agricultural uses. Other sources of water used for the same purpose are tested far less frequently, if at all. Some emerging issues such as endocrine disruptors, pharmaceutical chemicals and cyanobacteria have been identified (see *Chapter 10*). Although the likelihood of health impacts through irrigation of agricultural produce seems minimal, further research is required on concentrations of these hazards in recycled water and their survival, fate and transport in irrigated produce. Finally, Australian guidelines applied to the use of reclaimed water in agriculture are conservative and are designed to be protective of human health.

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13 Social psychological considerations in the acceptance of reclaimed water for horticultural irrigation

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Social acceptability in the short-term and medium-term is likely to be a major determinant of the uptake of the use of reclaimed water for horticultural irrigation. While this issue has been discussed, there has been no comprehensive investigation to underpin planning in this area. Unless this occurs, the potential for reclaimed water to contribute to the overall water conservation effort may be diminished, either through outright rejection or slower than necessary uptake. There is now substantial literature describing the potential benefits of using reclaimed water for a variety of purposes from garden and park irrigation, through horticultural irrigation to potable reuse (eg Anderson 1996). The literature in regard to the health risks posed by the use of such water also points to the feasibility of using this source for a variety of purposes including horticulture (Sheikh *et al* 1999), but, as many would attest, the potential for adoption of this water source will be dependent on community acceptability. In this discussion, we concentrate on community perceptions of the use of this water for horticultural crops, but many of the issues raised will be common to other uses which result in human consumption (eg potable supply). The acceptability of the use of reclaimed water for a variety of uses is shown in Table 13.1. These data were taken from a stratified random sample of 720 Perth residents at personal interview but it is reasonable to assume that similar results would be obtained from other cities, given a similar list of possibilities.

From this study (Table 13.1), there was widespread support for the use of reclaimed water for activities that do not involve personal skin contact or the possibility of ingestion. But as the proximity to body contact or ingestion occurs, acceptance dwindled. People were told that wastewater was the treated water arising from secondary treated wastewater plants that was currently disposed of to the sea. A review of other surveys in Australia using slightly different techniques have come to similar conclusions (Syme and Nancarrow 1999). Finally, a recent survey (McKay and Hurlimann 2003) has found the same relationship between bodily contact and acceptability at Mawson Lakes in South Australia.

Other Australian information in regard to acceptance of reclaimed water is less specific. For example, Sydney Water (1999) found a very high proportion (94%) of their sample of 771 respondents favoured using reclaimed water for 'agriculture'. Figures quoted in the Bruvold (1988) review of attitudes towards irrigation of crops also showed high support, with only about 15% opposing irrigation of vegetables, vineyards or orchards. In these studies the degree of acceptance may depend on where people considered that the reclaimed water was coming from but, nevertheless, most of the above results appear to have arisen in the context of treated wastewater.

This has led some to conclude, that given that there is a concern that may be based on risk considerations, it may be better not to specially label produce irrigated with reclaimed water to prevent unnecessary 'risk amplification' or fear in the community (Kasperson *et al* 1988; Sheikh *et al* 1998; Michels Warren 1999). Nevertheless, lack of labelling in these circumstances may seem to also be a 'risky' strategy in the context of the increasing demands for detailed labelling on foodstuffs.

In the long term, it would be prudent to more fully understand the community or consumer psychology issues in regard to reclaimed water and its uses, particularly in regard to those that involve personal contact or ingestion. Without ready consumer acceptance, the basic motivation of profitability, which will stimulate farmer adoption, is likely to provide a major problem for the development of this source. This is especially the case if individual farmers are required to make significant capital investments.

In this discussion, we review the literature pertaining to four key areas of potential significance to horticultural use of reclaimed water. On the basis of this literature, we make some suggestions as to the data needs for assessing the potential of this water resource in the long term. Specifically, we explore the significance of the risk perception literature, the role of trust and knowledge, and the more emotively based idea of disgust as they pertain to acceptability of food. We also outline an attitudinal model, which shows some promise in the area of predicting food preferences. While each of the four areas is presented separately, there is no reason why they cannot be creatively combined to assist our understanding of reactions towards irrigating with reclaimed water for horticulture. Finally, we briefly introduce the elements of a social research program, which could be undertaken on the basis of the earlier discussion.

Table 13.1 Community acceptability of a series of technological approaches to reuse water.

Technological approach	Acceptable (%)
Reuse stormwater that has been treated to approved health standards on golf courses and ovals	98
Reuse stormwater that has been treated to approved health standards for fire fighting	97
Reuse stormwater that has been treated to approved health standards on your home garden	96
Reuse wastewater that had been treated to approved health standards for fire fighting	95
Reuse wastewater that has been treated to approved health standards on golf courses and ovals	95
Reuse stormwater that has been treated to approved health standards for toilet flushing	95
Reuse wastewater that has been treated to approved health standards for toilet flushing	92
Install a small, enclosed and quiet wastewater treatment plant in your neighbourhood to allow for reuse of wastewater in local parks and gardens	89
Reuse wastewater that has been treated to approved health standards on your home garden	88
Store stormwater that has been treated to approved health standards in wetlands for reuse at a later time	81
Install and regularly maintain a domestic wastewater treatment unit underground at your property to allow for reuse of the wastewater in your garden	72
Install, but have maintained by approved authorities, a domestic wastewater treatment unit underground at your property to allow for reuse of the wastewater in your garden	71
Store wastewater that has been treated to approved health standards in wetlands for reuse at a later time	70
Reuse stormwater that has been treated to approved health standards in the laundry for washing clothes etc.	68
Reuse wastewater that has been treated to approved health standards in the laundry for washing clothes etc.	51
Reuse stormwater that has been treated to approved health standards in the bathroom for personal washing etc.	50
Install a composting toilet where approved authorities maintain it and dispose of the compost	35
Install a composting toilet and use the compost on your property	33
Reuse wastewater that has been treated to approved health standards in the bathroom for personal washing etc.	31
Reuse stormwater that has been treated to approved health standards for drinking	29
Reuse wastewater that has been treated to approved health standards for drinking	16
Install a domestic urinal	13
Implement rostered water use, where you would be provided with specific times for such activities as washing or garden watering	12
Buy bottled drinking water which would allow lesser quality water to be provided through the water supply system	11

Risk attitudes and food acceptability

There is surprisingly little literature on risk perception and food preferences (Knox 2000). Despite the confidence many consumers have in their supermarket foods (eg Senauer 1992), the recent appearance in the media of 'mad cow disease' and genetically modified foodstuffs have engendered growing risk perception literature. For example, in the Australasian context, Worsley and Scott (2000) have examined the structure of people's perceived risk in relation to food intake and health. Their study showed similar results for both Australia and New Zealand. There were a series of factors used by respondents in assessing food risk, the two most relevant for this discussion being 'safety quality' (including harmful bacteria in food) and 'additive-safety' of prepared food (eg safety of drinking water, uncertainty about what is in foods). Both of these may be the basis of some concern over irrigation of crops with reclaimed water.

While the emphasis on differing aspects of risk tends to vary from food to food (Miles and Frewer 2001), there seem to be three underlying psychological dimensions that will govern factors such as the perception of 'safety quality' (Breakwell 2000). These are 'controllability', 'novelty' and 'naturalness'. That is, for those foods for which the preparation is seen to be under one's individual control, those that are familiar and are seen to be produced by natural means are regarded as less risky than others.

In the absence of specific research, it would seem that in Australia at least, such vegetables irrigated by reclaimed water would be seen as novel, but we know little about the other two factors. For example, the feeling of control over the hygienic quality of vegetables may be enhanced by the thought that any pollutants from reclaimed water can be personally washed off. However, there may be the feeling that residuals of wastewater may be inevitable from inadequate treatment of the water by suppliers. To some, it may seem to be 'unnatural' that reclaimed water is used for irrigation of food; for others such recycling may seem to be a healthy advance in the utilisation of nature's resources. Some may have ambivalent attitudes in this case as health and environmental beliefs collide. This may have significant consequences for the long-term acceptability of such food (Shepherd 1999).

The role of trust and knowledge

While risk seems the logical place to start an analysis of why reclaimed water may or may not be accepted, there are other considerations. Key variables when it comes to water and food quality include: trust in authorities; knowledge of issues pertaining to reclaimed water; and belief in the adequacy of scientists' knowledge. Perceptions of drinking water quality (and it is easy to imagine food derived from irrigation) seem to be consistently dependent on one's trust in the authorities that provide it (eg Syme and Williams 1993, Siegrist 2000).

It is tempting for the proponent of reclaimed horticultural irrigation to presume that trust in the water source will emerge when the community's knowledge about it grows. For example, if research shows that the health risks are minimal, knowledge of this will encourage adoption. From this point of view, it is pertinent to note that in many situations, knowledge of food risk and hygiene issues is moderate to poor among significant groups in the population (eg Angelillo *et al* 2001). Increased education may, therefore, enhance trust derived from knowledge.

Unfortunately, despite the positive relationship between knowledge and trust being plausible, research shows that knowledge in itself does not necessarily lead to trust and acceptance (Healy 2001). Trust, in itself, is a multifaceted concept. Frewer *et al* (1996), for example, have shown that there are multiple sources of trust. These include perceived vested interest of the supplier, track record of the supplier, and hearsay or rumour. Siegrist (2000) suggests that trust is also filtered through perceived benefits and risks of a new food-related technology to govern acceptance. That is, if the perceived benefits of consuming food irrigated by reclaimed water are not greater than those for normal irrigation, but are thought to raise the probability of health risk, acceptance will be less likely (Nelson 2001).

Finally, the issue of choice may be significant. In many circumstances, benefits can be very easily demonstrated when the choice is between produce irrigated with reclaimed water or little or no production due to the unavailability of other sources of water. Also, if the choice involves significant price differentials between produce irrigated with reclaimed and other sources of water, rational acceptance may be encouraged.

Is using reclaimed water for irrigation disgusting to Australians?

The above discussion of risk largely concentrates on thinking, or cognitively determined precursors of acceptance. The fact that rejection of reclaimed water increases the closer that it comes to personal contact leads to the thought that the concept of disgust, or food-related emotion, may be relevant (Rozin 1999). Rozin and Fallon (1987) describe disgust as 'revulsion at the prospect of (oral) incorporation of an offensive object'. The offensive objects are contaminants. That is, even if they briefly contact an acceptable food, they tend to render that food unacceptable.

Although the array of disgust objects varies across cultures, they almost always include body waste products (Angyal 1941). Theoretically at least, the association between body waste disgust and consumption of food associated with reclaimed water could be strong enough to evoke rejection. For example, Sydney Water's (1996) survey on community attitudes showed that 54% of people would find drinking reclaimed water to be 'disgusting' when answering spontaneously. This rose to 58% if people had time to reflect.

The notion of the significance of disgust in this area is given some credence by research on the topic. There are some who presume that disgust may be classically conditioned (Schienle *et al* 2001) and that there are 'sympathetic magic' effects associated with disgust objects. That is, once an object has been touched by something disgusting, it somehow 'magically' becomes disgusting in itself.

While research shows several forms of this phenomenon, the one particularly relevant to this discussion is that of the threat of contagion or personal contamination, despite a miniscule or purely symbolic contact with the object of disgust. A vivid example is a laboratory demonstration of a vehement rejection of a glass of orange juice once a cockroach, which was known to be sterilised, had been immersed and removed from it, as compared with one which had an innocuous object submerged for the same period (Rozin *et al* 1986).

Further, individual differences in the tendency to make 'magical' associations can be reliably measured. It is feasible that those more prone to make these associations may be less accepting of reclaimed water as a source of irrigation (Haidt *et al* 1994). This, of course, is an empirical question, which is open to future investigation.

Perhaps one way to begin the investigation would be to use the concept of the latitude of acceptance and rejection in the measurement of attitudes. Sherif and colleagues (eg Sherif *et al* 1965) introduced this concept, some time ago, pointing out that people have breadth as well as strength to their attitudes. Although there is a range of outcomes on particular topics that may be acceptable (latitude of acceptance) there were thresholds that could be reached over which rejection would occur (the latitude of rejection). This theory has been successfully used to establish the community's latitudes of acceptance and rejection for water restrictions policy (Nancarrow *et al* 2002) and may be applied to establish a first cut of those uses of reclaimed water that lie outside the realms of current acceptance. These can then be investigated using the 'disgust' framework.

The potential for formal attitudinal modelling

The three areas above have been developed with specific theoretical aims in mind. The food attitude literature tends to try to derive generic food-based attitudinal dimensions. The trust literature is heavily intertwined with the risk perception paradigm and is intended to explain the nature and function of trust. Finally, the disgust theory has tended to grow within a cross-cultural, developmental, psychological framework to define and understand it as a phenomenon. Attitudinal theory provides the concepts and tools to bring these perspectives together to assist in understanding the acceptance, or otherwise, of reclaimed water use for horticulture.

Shepherd (1999), among others, has suggested and demonstrated that food choice could be profitably explained by recourse to the attitudinal theory of planned behaviour. This theory has enjoyed a wide application. The rudiments of this model are outlined in Figure 13.1.

This model proposes that a person's intention to perform a behaviour (ie purchase or consumption of food irrigated with reclaimed water) is a prime predictor of actually doing so. The intention is determined by attitudes toward the consumption or purchase, social norms, and perceived behavioural control in being able to do so. The measurement of attitudes refers to the respondent's positive or negative evaluations of performing the behaviour of consuming horticulture irrigated by reclaimed water (and the beliefs that lead to

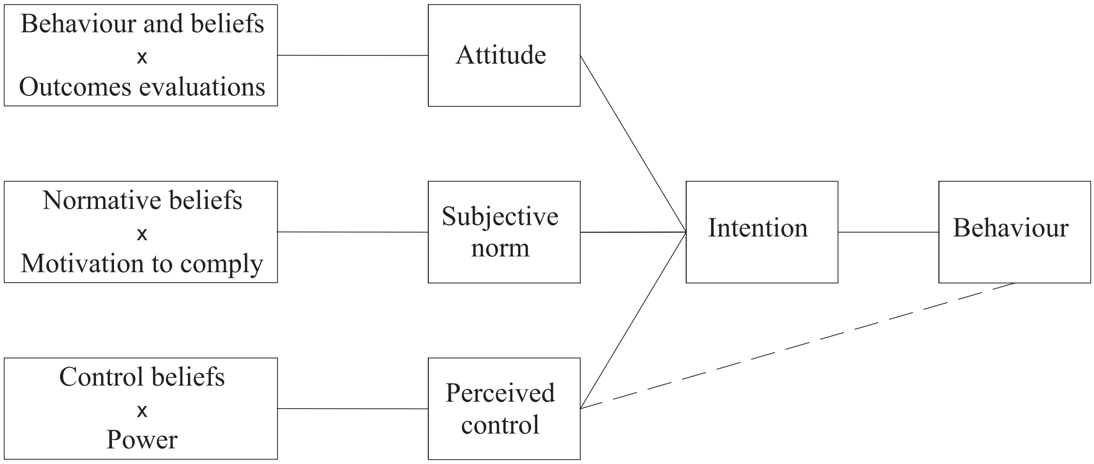

Figure 13.1 Schematic representation of the components of the theory of planned behaviour of Ajzen (1985).

that overall attitude). Social norms refer to the effect of others on one's overall intention (eg the perceived attitudes of family members to eating fruit or vegetables irrigated by reclaimed water and one's motivation to comply with these attitudes). Perceived behavioural control relates to the feeling that one can personally achieve a particular behaviour (eg the feeling that one can control the quality of the produce by washing). This model has proven to be very useful in a variety of circumstances in understanding attitude behaviour relationships including food preference and consumption (Ajzen 1985; Shepherd 1999).

The advantage of attempting to apply this model to irrigation with reclaimed water is that it systematically identifies individual beliefs, which form attitudes. It can also examine the impact of the social influence and assess the degree of confidence people have in their own intentions. This enables a quantitative and purpose-built model to be developed for this issue, which can provide a useful estimate of uptake from the marketers' perspective. Further, the model can be augmented in a modular manner to establish whether there are other determinants of acceptance or uptake that can add explanation to the standard planned behaviour model. For example, one could test whether wider social norms added to the explanatory value of the basic models, or whether a measure of feelings of disgust actually dominate over more 'rational' beliefs. One possibility is anticipated regret (ie noting that negative effects of consumption may not appear until some time after the act of consumption has been completed) (Richard *et al* 1996). These authors tested the theory of planned behaviour to assess whether this variable could add to the explanation of a variety of behaviours, including eating junk food and drinking alcohol. They found that anticipated regret significantly added to the prediction of behaviour. It is conceivable that this would also be the case for produce irrigated with reclaimed water.

The theory of planned behaviour tends to focus on cognitive (or thinking) rather than emotional bases of attitudes. For irrigation with reclaimed water, both attitudinal dimensions are likely to be significant and they may conflict (Eagly and Chaiken 1993). Logically, people may consider that the advantages of water conservation are to be supported, but emotionally 'draw the line' at eating produce from reclaimed water irrigation. Thus, their attitude is ambivalent. In such cases, some authors have found that the emotive component to the attitude is more 'accessible' and, therefore, more likely to dominate and motivate behaviour (eg Lavine *et al* 1998). However, the presence of ambivalent attitudes has been shown to lead to more detailed information processing by the individual about an object or an issue, thus perhaps leading to more likely acceptance of a logically justifiable proposition such as irrigating with reclaimed water (Maio *et al* 1996).

From the above discussion, many feasible alternative predictions can be made about attitudes and their propensity for change in terms of the use of reclaimed water for irrigation (and other uses which require personal contact). Simple opinion polls which will describe the degree of general support cannot tell one how or why this support exists and, therefore, what is appropriate planning in the long term. Formal attitudinal modelling of this nature, done well, can greatly aid forecasting of demand and the planning of marketing or persuasive programs.

Where to from here?

The use of reclaimed water in general has a great deal of support from the public, but there may be significant public resistance to its adoption for irrigation of horticulture. This chapter has summarised some of the reasons why this may occur. The discussion would apply as equally well, or even better, to potable reuse issues.

What the discussion shows is that it is unlikely that the 'say nothing' technique will be socially acceptable in the long term and it is important to move on from the simplistic nature of opinion polls. It is important, therefore, to systematically use these and other theoretically based insights to contribute to the long-term planning in this area so that responses to public perceptions can be adequately informed. As Healy (2001) states, we are well past the stage that the community can simply be fed 'the facts'. The benefit:cost ratio of systematic social research is therefore likely to be high.

What would a useful, proactive research program for reclaimed water acceptance look like? The key lies in understanding the psychology of the use of reclaimed water for horticultural irrigation in comparison with other water sources. First, there is a need to provide a basic background on what people think and feel about irrigating with reclaimed water for different purposes. A simple ranking or rating approach could be supplemented by qualitative techniques. These could provide a perceptual or psychological map of the elements of people's rejection or acceptance of horticultural uses as compared with other key uses (eg park irrigation and potable reuse).

There are several methods for organising data of this kind, such as laddering (Miles and Frewer 2001), creating mental models (Jungermann *et al* 1988) and constructing repertory grids (Rowe 1996). While it is beyond the scope of this chapter to describe these models, all provide a detailed picture of people's overall views of reclaimed water and can include both cognitive and emotive factors. These pictures can be used to provide hypotheses for areas that require more detailed analyses. Single factors such as risk, trust or disgust may become the focus for analysis, or quantitative attitudinal models predicting planned behaviour may be more useful. An investigation may need to incorporate all of the above approaches in one model. At this point, as with many other food-related issues, cultural factors will be important. These will need to be scoped in the initial study.

On this basis, it can be ascertained whether the greatest progress for horticultural use can be made by concentrating on more fully analysing risk issues, trust and knowledge and/or one of the attitudinal approaches outlined. It is also likely to be evident whether it should be 'marketed' as a single 'policy' for horticulture or in conjunction with other potential water uses. In the case of marketing horticulture individually, if trust issues are important, it will be necessary to include consideration of people's trust in the water managers themselves, as well as the perceptions of what is in the water supply. If the personal ingestion side is important, there are likely to be differences in perceptions for different foods. For example, is there any difference in perceptions between processed and unprocessed foods (eg table grapes versus wine) or cooked and raw produce (eg lettuce in a salad versus boiled potatoes)?

The issue of persuasion in changing of attitudes and behaviour has not been specifically canvassed. This may not be a simple issue where fundamental concerns such as those associated with food occur (Wood 2000). However, communications which acknowledge and are responsive to a consumer's psychological response to the product are more likely to succeed in progressing the issue, and there are many examples of successful information campaigns based on such analyses (eg Cialdini 1993) .

Addendum

Since writing this chapter, the theory development that was initiated here has been used as a basis for an international literature review (Po and Nancarrow 2004). This then underpinned a systematic social research program that has been identifying and investigating the variables that might be influential in communities' intentions to purchase horticultural products irrigated with recycled wastewater. As a basis, Ajzen's theory of planned behaviour (1985) was further developed to include several of the variables discussed above.

A social experiment was then conducted where almost 100 community residents in Perth, Western Australia, were invited to consume samples of what they were told were recycled stormwater, grey water and wastewater and four different products grown with these waters. The products represented differing degrees of contact with the recycled waters. Participants answered pre-experiment and post-experiment questionnaires as well as one during the experiment. In addition, they answered questions associated with each sample. All questions were designed to develop measurements of the hypothesised model variables and test their influence on the participants' actual behaviours. Participants were debriefed after the experiment to explain that the samples had not been associated with any recycled waters.

Following this experiment, a survey questionnaire was developed. The model was then tested on a city-wide survey in Melbourne, Victoria. Participants were questioned about their intention to buy horticultural products that had been grown locally at Werribee in a recently completed recycled wastewater irrigation scheme.

The results showed that attitudes, subjective norm, trust and the disgust emotion were the major predictors of intended behaviour. Perceived control, risk perceptions and feelings of obligation for the environment also contributed to the model. Of greatest interest, however, was that knowledge of the recycling scheme did not emerge at all in the model.

This was further tested on another water reuse case study with similar results. The research program is ongoing to allow refinement of the variable measures. The report of the program to date can be found in Po *et al* 2005.

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Abbreviations

ABS	Australian Bureau of Statistics
ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agricultural and Resource Management Council of Australia and New Zealand
ASR	Aquifer storage and recovery
A$	Australian dollars
BMP	Best management practice
BNR	Biological nutrient removal
BOD	Biochemical oxygen demand
CCL	Cumulative contaminant loading limit
CCR	Cation exchange capacity/clay ratio
cfu	Colony forming units
CMF	Continuous microfiltration
d	day
DAFF	Dissolved air flotation and (granular multi-media) filtration
DAIS	Department of Administration and Information Services
DHS	Department of Human Services
DOE	Department of Environment (in Western Australia)
DPIWE	Department of Primary Industry, Water and Environment (in Tasmania)
DU	Distribution uniformity
DWR	Department for Water Resources, a consortium
EC	Electrical conductivity
EC_e	Electrical conductivity of a saturation paste extract
EC_{iw}	Electrical conductivity of irrigation water
EILs	Interim urban environmental investigation levels
EIP	Environmental improvement plans
EP	Equivalent persons
EMA	Environment Management Protection Authority
EPA	Environmental Protection Authority (or Agency)
EPP	Environment protection policy
ERA	Environmentally relevant activity
ESP	Exchangeable sodium percentage (the percentage of the cation exchange capacity occupied by sodium)
ET	Evapotranspiration
ET_c	Crop water use (crop evapotranspiration)
ET_o	Reference evapotranspiration
FC	Faecal coliform
GL	Gigalitres
HACCP	Hazard Analysis and Critical Control Point
hour	hr
HILs	Health-based investigation levels
IMP	Irrigation management plan
Kc	Crop coefficient
kL	Kilolitres
K_s	Coefficient for water stress
K_{sat}	Saturated hydraulic conductivity
KWRP	Kwinana Water Recycling Project
L	Litre
LF	Leaching fraction
Lpcd	Litres per capita per day
LR	Leaching requirement
LTV	Long-term trigger value
meq	milliequivalents
mg	Milligram
ML	Megalitres (106 litres)
mL	Millilitre
ML/yr	Megalitres per year
MMBW	Melbourne and Metropolitan Board of Works
mol_c	mole concentration or meq/L
MPN	Most probable number
NH_3-N	Ammonia nitrogen
NHMRC/ ARMCANZ	National Health & Medical Research Council and Agriculture & Resource Management Council of Australia and New Zealand – now replaced by a Natural Resource Management Council
NPDES	National pollutant discharge elimination system
NSW	New South Wales
NTU	Nephelometric turbidity unit
NWQMS	National Water Quality Management Strategy
PDZ	Prime development zones
POEO	*Protection of the Environment Operations Act* (1997)
RWCC	NSW Recycled Water Coordination Committee
SAR	Sodium adsorption ratio
SAR_e	Sodium adsorption ratio of a saturation paste extract
SAR_{iw}	Sodium adsorption ratio of irrigation water
SBR	Sequential batch reactor
S/m	Siemens per metre
SPCC	State Pollution Control Commission
SPWQM	State Policy on Water Quality Management
SRWSC	State Rivers and Water Supply Committee
SS	Suspended solids
STEDS	Septic tank effluent disposal scheme
STV	Short-term trigger value
t	tonne
TDS	Total dissolved solids
TEC	Threshold electrolyte concentration
TF	Trickling filter
TN	Total nitrogen
TP	Total phosphorus
US EPA	United States Environmental Protection Agency
UV	Ultraviolet radiation
WHO	World Health Organization
WUE	Water use efficiency
WWTP	Wastewater treatment plant, also commonly refered to as Sewage treatment plant (STP)

Organic materials and constants relating to their use

μg/L	Micrograms/litre
AE	Alkyl ethoxylates
AES	Alkylethoxy sulfates
APE	alkylphenol ethoxylates
AS	alkyl sulfates
DBPs	Disinfection byproducts
DCBM	Dichlorobromomethane
DEHP	Di-2-ethylhexyl phthalate
DEHP	Diethylhexyl phthalate
DMP	Dimethyl phthalate
DnBP	di-n-butyl phthalate
DOC	Dissolved organic carbon
E1	estrone
E2	17β-estradiol
E3	estriol
EDCs	endocrine disrupting chemicals
EE2	17α-ethynylestradiol
HAAs	haloacetic acids
HANs	haloacetonitriles
HKs	haloketones
K_d	Soil sorption coefficient
K_{oc}	Organic carbon sorption coefficient
K_{ow}	Octanol-water partition coefficient
LAS	Linear alkylbenzene sulfonates
MeEE2	mestranol
MIB	2-methylisoborneol
NDMA	*N*-Nitrosodimethylamine
NOEC	No observed effect concentrations
NOM	Natural organic matter
NP	Nonylphenol
OP	Octylphenol
PAHs	Polycyclic aromatic hydrocarbons
PCBs	polychlorinated biphenyls
PEG	polyethylene glycol
Phthalates	Phthalic acid esters
QAC	Quaternary ammonium compounds
THMs	Trihalomethanes
TE	Toxic equivalent
DM	Dry matter

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