Chapter 1 ~ Introduction

1.1 Introduction and Background

Samuel Taylor Coleridge who probably knew little, if anything, about nitrogen in wastewater and the importance of its removal, wrote the following famous lines in The Rime of the Ancient Mariner:

> ***"Water, water, everywhere,***
> ***And all the boards did shrink;***
> ***Water, water, everywhere,***
> ***Nor any drop to drink."***

The above is just a small excerpt from what is a long and involved story told in poetic verse. It is a beautiful poem, which is about the copious supply of dirty and stagnant water which could not be used, in what could be called the greatest pond of all: the sea. However it could well apply to the lack of clean, clear, and accessible water on land, a diminishing commodity today. The effect of this lack of water is graphically described in the poem. So then to develop my thesis:

Good public health requires that a population's wastewater should be collected and treated for the removal of physical, chemical, and microbiological contaminants in order to prevent endemic and communicable disease, and to preserve a good quality of environmental health. The field of wastewater engineering is vast and expansive, incorporating a huge variety of different physiochemical and microbiological treatment options, unit designs and reactor configurations, operating either to harness natural resources and forces, or employing electromechanical input to initiate the process. Wastewater treatment is typically divided into two categories: conventional and unconventional. Municipal wastewater treatment systems which are the conventional systems originated in, and are commonly used in, the Western world. They use large amounts of electrical energy to power pumps and mechanical equipment, and typically comprise primary and secondary settlement tanks, activated sludge units and often a tertiary polishing process.

The predominant unconventional municipal wastewater treatment system in use is the wastewater stabilization pond (WSP). Waste stabilization ponds are widely recognised as consistently reliable systems, producing high quality effluents, often well within the parameters and discharge consents stipulated by environmental regulators and legislation. Wastewaters are treated within a series of simply engineered units, which require only a fraction of the initial capital expenditure required for conventional wastewater treatment systems. They are an ancient technology, which have been employed for the treatment of wastewater for over 3,000 years (Middlebrooks *et al.*, 1999).

Typically, WSP systems consist of a calculated number of lagoon-like ponds, each with its own specific design, dimensions and geometry. WSP are shallow in depth (usually of no more than 5 m and usually 1−3 m) and operate in series to comprise the total treatment unit. For larger scale systems, ponds of the same type and function are often run in parallel, or as a number of series, to facilitate a much higher volume of wastewater treatment. Examples of this are to be found in the Werribee WSP in Melbourne, Australia, and the Dandora WSP in Nairobi, Kenya. Wastewater is collected and delivered to a pond system by a chosen method of sewerage, where constituent wastes within the water undergo a number of different treatment processes, brought about by natural mechanisms, which are encouraged by environmental variables. These processes exist without any man-made intervention, occurring typically through gravitational settlement, insolation, temperature, wind mixing and aeration, the diffusion of oxygen into the wastewater, and others. As with all forms of wastewater treatment, the microbiological community plays an intrinsically valuable role. These processes are widely harnessed in many different countries. WSP systems are found commonly in warmer climates, where their extensive use has been pioneered primarily within the field of tropical public health engineering. The climatic conditions often associated with these regions, such as high levels of diurnal insolation and warm temperatures with little seasonal variation, enable the wide array of the crucial microbiological fauna associated with WSP to function fully. The prime merits of these systems are their very low construction costs, low running costs, their ease of operation, their simple maintenance requirements, their high performance, and their proven longevity. If so designed, wastewater can be fed to WSP by gravitational flow alone, which enables systems to operate in the absence of power-fed pumping stations.

WSP contribute fundamentally to healthy societies – particularly in developing countries − by providing high quality holistic wastewater treatment, where the effluents of the system, if deemed microbiologically safe, can be used for agriculture and/or aquaculture. Good levels of public health are achieved as faecal and household wastes are drawn away from the home by simplified sewerage or other means, thus helping to decrease mortality and morbidity. Environmental health is unquestionably improved by such sanitary interventions. WSP systems are continually being adopted throughout the developed world too, in cooler, more temperate climates, as their conceptual simplicity and merits are increasingly being acknowledged. In cold weather climates where there can be four or more months of ice cover (such as in the northern parts of the USA and in Canada), WSP operate under slightly different operating principles and hydraulic regimes of intermittent discharge, but can still produce satisfactory treated effluents although the stabilization of wastes in significantly longer (Oleszkiewicz and Sparling, 1987; Rockne and Brezonik, 2006).

There is a very real and pressing need for wastewater treatment companies to adhere to more stringent legislation on discharge consent limits, especially within the European Union (EU). Empirical data repeatedly demonstrate that a well designed WSP system can provide the same, and in most cases a higher, biochemical oxygen demand (BOD) reduction, as other forms of wastewater treatment. In addition to total ammonium reductions, non-algal suspended solids (SS), and a significantly higher removal of faecal coliforms and excreted pathogens, the WSP system, under study, works exceptionally well, again far better than conventional forms of wastewater treatment.

Some of the other merits (amongst many) of the systems include:

- the ability of the design to tolerate hydraulic and organic shock loads and intermittent flows (which makes them ideal for tourist and holiday towns and/or villages where the annual distribution of flow alters hugely in the holiday season);

- relatively low capital start-up and operational costs;
- self-contained sludge production, storage, and partial treatment;
- a very high degree of wastewater purification is easily achieved;
- they can be operated and maintained by a moderately unskilled work-force;
- typically, much higher removal rates of pathogenic microorganisms are achieved in contrast to conventional wastewater treatment plants;
- maturation and other tertiary polishing ponds can be used to support aquaculture and large fish stocks, where algae and other micro-organisms provide a good food source for the fish;
- land is easily reclaimable so that, should it be needed again, the ponds can simply be emptied and in-filled;
- a range of industrial and agricultural wastes can also be successfully treated; and
- the inlet and outlet levels of a pond can over time be altered, thus increasing or decreasing its volume and therefore changing the degree of treatment. (Mara, 1976).

One possible disadvantage of constructing a WSP system within the United Kingdom, is that the area of land needed is greater than that required for conventional systems. (The availability of land in developing countries is seldom a problem, as more space means more places to develop the WSP because these countries have such a large land mass, and the cost of land is usually considerably cheaper.) The efficient size of a WSP is invariably a constraint and a limiting factor where land is at a premium, as found within the United Kingdom and some other developed Western countries.

It is usual practice for an anaerobic pond to be the primary unit within a WSP system. This receives raw and unscreened wastewater, unless the wastewater stream has undergone screening, and then a primary facultative pond can be used. These ponds then usually feed facultative ponds, which in turn feed maturation ponds or rock filters. The first two pond types are predominantly responsible for, and are designed to achieve, a large proportion of the wastewater BOD, SS and total nitrogen (total-N) removals. The maturation or polishing ponds are designed for faecal pathogen removal and also for some removal of the remaining BOD, SS and macronutrients (Mara, 2004). Other types of WSP also exist, namely macrophyte ponds, high-rate algal ponds, polishing and fish ponds (Curtis, 1990; Mara, 2004), but these are not discussed herein, as they are used less frequently than their more customary and better known predecessors, nor have they been used for purposes of this research.

1.2 Nitrogen in wastewater and the importance of its removal

Wastewater effluents contain high concentrations of varying nitrogenous species, the most dominant of which come from inorganic sources such as ammonia (NH_3), its ionised form − ammonium (NH_4^+), and to a much lesser extent those of nitrite (NO_2^-) and nitrate (NO_3^-) which are oxidised products of ammonia. Organic sources of nitrogen occur within wastewater from faecal material and from urea contained in urine, which originate from the human and mammalian metabolic breakdown of proteins. Other sources of organic nitrogen in wastewater exist in more complex compounds such as amino acids, amino sugars, proteins and peptides, to name but a few (Metcalf and Eddy, 2003). The complexity of nitrogen chemistry, the interaction of various species of nitrogen within wastewater, and their removal from the wastewater stream is comprehensively presented in Chapter Two of this thesis.

The removal of nitrogen compounds from any wastewater, and within the United Kingdom in particular, is an essential component of its treatment, for several important reasons. These are, amongst others:

- Free NH_3 in quantities above 0.2 mg/l is extremely toxic and often lethal to several species of fish and other aquatic species (Sawyer *et al.*, 1994; Hiet Wong *et al.*, 2003).
- The autotrophic oxidation of NH_3 to NO_2^- and NO_3^- can exert a sizeable oxygen demand on a water body.
- Eutrophication can occur as a result of nitrogen-rich water entering a receiving water body if the nitrogen content of the additional influent water is too high. Nitrogen is one of the fundamental building blocks for the synthesis of proteins, and thus of life, and is an essential biostimulant

for microbiological growth which can result is unprecedented algal blooming (Cohen and Fong, 2004), and then the colonisation of other higher-level aquatic plants (Metcalf and Eddy, Inc., 2003). The adverse effects of eutrophication on other aquatic organisms within the habitat are caused by shifts in water pH due to photosynthesis, the physical crowding of a water body by elevated levels of plant biomass, and night-time respiration by photosynthetic plants which utilise oxygen, thus depriving fish of their essential oxygen intake.

- Drinking waters containing high levels of nitrate often cause methemoglobinemia (also referred to as infantile cyanosis or blue-baby syndrome) (Horan, 1990; Sawyer *et al.*, 1994). This occurs in infants below the age of 6 months, when their haemoglobin is reduced to methaemoglobin by the conversion of nitrates to nitrites in the intestinal tracts; this leaves the methaemoglobin with an inability to bind with other oxygen sources, and therefore the infant is starved of oxygen and subsequently dies (Horan, 1990).

1.3 Nitrogen removal with respect to EU Directives

Two key pieces of European legislation have come into force in the last few years, which have stipulated tighter limits for pollutants entering a receiving water body. All wastewater treatment companies within the United Kingdom, and indeed Europe, are subject to the new directives. The first directive to be passed was the European Union's Urban Waste Water Treatment Directive (UWWTD – Directive 91/271/EEC, Council of the European Communities, 1991, amended on the 27th February 1998 and also on the 29th September 2003) which detailed the need for the provision of collecting systems for urban wastewater. Under Article 3 of this directive, member states should have ensured that by 31st December 2005, all "agglomerations" with population equivalents of between 2,000 and 15,000 had been provided with a system suitable to collect and treat urban wastewater – both domestic and industrial, as well as rain run-off. The directive defines an agglomeration as "an area where the population and/or economic activities are sufficiently concentrated for urban wastewater to be collected and conducted to an urban wastewater treatment plant or to a final discharge point" (UWWTD 91/271/EEC, Article 2, point 4). This has represented a challenge for wastewater treatment companies, when, previously, the wastewater produced within smaller settlements, in many areas, was treated by other means, such as septic tank systems, and no single larger scale treatment facility existed. The directive concerning the precise parameters applicable to the maximum permissible limits of flow allowed to leave a works in the final effluent, was supplemented by the Freshwater Fisheries Directive and the Water Framework Directive (Council of the European Communities, 1978; European Parliament and Council, 2000).

The UWWT Directive's broad requirements for discharges from urban wastewater treatment plants are summarised in Table 1.1; however, within England and Wales the Environment Agency generally set higher standards whereby each wastewater treatment works is often subject to lower maximum permissible limits, especially that for ammonia.

Table 1.1 A summary of Urban Waste Water Treatment Directive maximum limits of requirements for discharges from urban wastewater treatment plants with reference to the main parameters only.

List of Parameters	Maximum Permissible Limit – Concentration
BOD_5	25 mg/l*
COD	125 mg/l
SS*	35 mg/l*
Total Nitrogen (which comprises Total Kjeldahl Nitrogen (i.e., NH_3 and NH_4^+ and organic nitrogen), plus NO_2^- and NO_3^-.	15 mg/l for plants of over 100 000 population equivalent; 10 mg/l-N for smaller plants of between 10 000 and 100 000 population equivalent
Total Phosphorus	2 mg/l for plants of over 100 000 population equivalent, 1 mg/l for smaller plants of between 10 000 and 100 000 population equivalent.

*Where WSP (described as "lagooning" in the Directive) are concerned, the analysis of the above parameters must be carried out on filtered samples, although for the total suspended solids (TSS) parameter analysis must be carried out on unfiltered final treated effluent and the concentration must not exceed 150 mg/l (Section D, Table 1, UWWTD, 91/271/EEC).

Directive 2006/44/EC of the European Parliament and of the Council (passed on the 6th September 2006) was the second directive on the quality of fresh waters needing protection, or improvement, in order to support fish life (European Parliament and Council, 2006). The previous directive 78/659/EEC was repealed, as it had been significantly amended on several occasions and needed codifying.

(European Parliament and Council, 2006). The main aim of this second directive is to safeguard and improve running or standing fresh waters capable of supporting fish. Waters which currently support, or are capable of supporting salmon, trout, grayling and whitefish, are classified as salmonid. Waters which currently support, or are capable of supporting cyprinids, pike, perch and eel amongst others, are classified as cyprinid. Maximum permissible limits for discharge of pollutants into these waters are even more stringent than those stipulated in the Urban Waste Water Treatment Directive. A summary of the requirements for the main parameters where wastewater treatment works are concerned is presented below in Table 1.2.

Table 1.2: A summary of Directive 2006/44/EC outlining the maximum limits of pollutants entering either still or running fresh waters within EU Member States. Not all parameters are listed here, only the main ones regularly tested for by wastewater treatment companies.

List of Parameters	**Maximum Permissible Limit − Concentration**			
	Salmonid waters		Cyprinid waters	
	G*	I*	G	I
BOD_5	≤ 3 mg/l		≤ 6 mg/l	
SS	≤ 25 mg/l		≤ 25 mg/l	
Nitrites	≤ 0.01 mg/l		≤ 0.03 mg/l	
Ammonia	≤ 0.005 mg/l	≤ 0.025 mg/l	≤ 0.005 mg/l	≤ 0.025 mg/l
Total Ammonium	≤ 0.04 mg/l	≤ 1mg/l**	≤ 0.2 mg/l	≤ 1 mg/l**

*Where G = values stated as a guide, and I = mandatory implementation.
** Where in particular geographical or climatic conditions and particularly in cases of low water temperature, and of reduced nitrification or where the competent authority can prove that there are no harmful consequences for the balanced development of the fish population, Member States may fix values higher than 1 mg/l (European Parliament and Council, 2006).

Within conventional wastewater treatment, nitrogen removal can be controlled by a number of different factors − for example, by those principles used to run biological nutrient removal (BNR) and sequential batch reactors (SBR).

1.4 Research Objectives

It is the fundamental purpose and aim of this research to explore, and investigate further, within a United Kingdom setting, some of the known complex interactions which occur within the various mechanisms and pathways of nitrogen removal in facultative WSP. The majority of the practical work undertaken has been conducted at pilot-scale experimental ponds constructed at the Yorkshire

Water Esholt wastewater treatment works in Bradford, West Yorkshire, England, with subsequent analysis of the various samples carried out in the School of Civil Engineering, University of Leeds.

WSP repeatedly demonstrate their adequate capability of removing nitrogen fractions from their received wastewater stream. To date, much work has been undertaken to investigate the way nitrogen is removed from WSP; however, these methods have not been undertaken, or adequately researched, in the United Kingdom. In order to evaluate and investigate exactly how these interlinking processes occur, a number of research objectives have been formulated. The end product of the research is to contribute to the development of a conceptual model which in theory, and better still in practice, is able to define total nitrogen removal from within facultative WSP.

The overall research aim of this work is specifically to:

Further the understanding of nitrogen removal mechanisms and pathways occurring and operating within facultative waste stabilization ponds in the United Kingdom.

In definition of the terms used within this research, a removal mechanism refers to the operation of physical and chemical processes under which nitrogen can undergo transformation from one form to another, and ultimately be removed from the system altogether. A nitrogen removal pathway refers to a sequence of biochemical reactions which take place in a living organism, where nitrogen is removed by an organism through assimilation into cell material or another process.

In order to achieve the aim of the thesis, the following objectives will be met:

1. To evaluate the importance of ammonia volatilization with respect to total nitrogen removal in primary facultative ponds.
2. To determine the physical hydraulic characteristics of the pilot-scale primary facultative ponds using dye tracer studies.

3. To assess the degree of hydraulic short-circuiting of ammonium within primary facultative ponds, and whether the passage of ammonium leaving the pond mimics the hydraulic tracer studies.
4. To use stable isotope tracking studies to identify mechanisms of nitrogen mass transfer within the system.
5. To use the molecular microbiological analytical tools of PCR and DGGE to determine the presence or absence of nitrifiers and denitrifiers, and other nitrogen-utilising microorganisms, within the system.
6. To determine the effect, if any, that summer and winter seasonality has on nitrogen removal from the system.

1.5 Thesis Presentation

This thesis comprises a comprehensive literature review which spans Chapter 2, and details the current understanding of the process in which nitrogen can be removed from wastewater. In addition, it will present well established empirical models which have been formulated to describe this removal, and various other occurrences, such as hydraulic mixing, within WSP.

Chapter 3 is a short chapter which describes the nitrogen work already undertaken at Esholt, and presents the findings submitted in this research.

The core of the thesis is devoted to the experimental work conducted at Esholt (all procedures of which are described in full in Chapter 4), and the results obtained from this (presented in Chapter 5), culminating with the discussion (Chapter 6) and conclusions (Chapter 7) verified from these results.

Included in Chapter 7 are recommendations for a further study of questions and observations which have arisen during the maturation of this research. These highlight the necessity for further investigation into the known nitrogen removal mechanisms and pathways within facultative WSP.