INTRODUCTION

1.1 Wastewater treatment in Colombia and the Andean region

A supply of clean water is an essential requirement for the establishment and maintenance of diverse human activities. Water resources provide valuable food through aquatic life and irrigation for agricultural production. However, liquid and solid wastes produced by human settlements and industrial activities pollute most of the watercourses throughout the world. As pointed out by UN (2000), the life sustaining means offered by nature for our survival are being seriously degraded and disrupted by our own everyday activities. Fertilizer run-off and chemical pollution threaten both water quality and public health. More than 20 percent of freshwater fish stocks are vulnerable or endangered due to pollution or habitat modification. About half of the world's population lacks adequate sanitation and this has resulted in rivers downstream from large cities in developing countries being barely cleaner than open sewers. This situation causes an estimated 80 percent of all diseases in the developing world with an annual death quota of 5 million lives (UN, 2000). Hence, the provision of safe water and adequate sanitation to all will greatly contribute to the reduction of disease burden and life saving in developing countries (UN, 2000).

Domestic and industrial wastewaters contain a large number of potentially harmful microorganisms and chemical compounds (Horan, 1993). The discharge of raw wastewater into the aquatic environment may cause serious damage to many forms of life as a result of oxygen depletion in the receiving water bodies. Additionally, the discharge of raw domestic wastewater poses a potential risk for the transmission of a large number of water-related diseases. This situation has produced a growing worldwide awareness of the need for more effective sewage treatment methods.

Generally speaking, Governments in Latin America over the past decades have not considered wastewater treatment a priority. However, as social and economic development improve, an environmental consciousness has gradually arisen in the region. In this sense, the combined efforts of leading organisations such as PAHO and UN have endorsed strategic action plans to tackle wastewater management problems in Latin America. An example of ongoing actions in the region is the Global Programme of Action (GPA) endorsed by UNEP to address municipal wastewater disposal as a major land-based pollutant affecting coastal zones and marine ecosystems UNEP (2001, URL-1). The Montreal declaration agreed in November 2001 by the environment ministers of the Americas and by the Government of Canada stated the necessity of working on the alleviation of the widespread poverty in developing countries of the region since this factor contributes to water resources pollution due to the lack of adequate sanitation facilities (UNEP-GPA, 2001). The Montreal declaration also emphasised the need for development, improvement and transfer of sanitation technologies within the region in accordance with the recommendations of the United Nations General Assembly.

As reported by Feachem and Cairncross (1993) and Moscoso and Leon (1995), only 40 percent of the total population in Latin America and the Caribbean was served by sewerage systems towards the last decade of the 20th century. This figure represents a daily production of 40 million m^3 of sewage directly discharged into rivers, lakes and oceans. If sewerage coverage had reached 90 percent by the year 2000, there would have been a daily production of more than 100 million m^3 of raw wastewater. This huge amount of raw sewage would worsen the pollution of the water resources taking into consideration that only less than 10 percent of the existing sewerage systems undergo any kind of wastewater treatment. According to CEPIS (1995), less than 6 percent of the total population in Latin America possess some type of wastewater treatment plant (WWTP). As an example, in Colombia less than 4 percent of all municipalities were treating their wastewaters by the middle of the last decade (Peña, 1995). Most of those WWTP consisted mainly of primary treatment and some had secondary treatment stages to remove suspended and soluble organic matter respectively. It is therefore expected that neither organic matter nor microbiological indicators are effectively reduced and both of these constituents are polluting surface waters, groundwaters and soils.

Table 1.1 shows average data on the population served with public water supply and sanitation in the Andean region by 1995.

Table 1.1 Population served with public water supply and sanitation in the Andean region by 1995.

Country	**Population***		**Drinking water****		**Sanitation****	
	Urban	Rural	Urban	Rural	Urban	Rural
Bolivia	4.2	3.0	74	42	41	39
Colombia	26.4	10.3	86	32	65	27
Ecuador	6.5	4.7	79	10	61	26
Peru	16.8	6.6	63	31	59	23
Venezuela	19.8	1.7	73	79	62	60

* In millions of inhabitants ** In percentage of houses connected to the services

Source: Idelovitch and Ringskog (1997).

Figures in Table 1.1 confirm the difference in coverage between water supply and sanitation services in the Andean countries. Moreover, with the exception of Bolivia and Venezuela, the coverage of sanitation services in rural areas is less than half of the values in urban areas. Therefore, there is a clear necessity to improve the coverage and quality of sanitation services in small municipalities and rural areas of the Andean region and this requirement may well be extended to many other Latin American countries.

It is worth noting that urban centres (i.e. medium and large-sized cities) in Latin America have more economic resources and access to a wider technological market since most of the economic activity (i.e. industry and services) is concentrated around these cities. In contrast, most of the small municipalities and rural areas are disconnected from the main productivity poles and suffer consequently the burdens of low-income and poverty. Specific agro-industrial sectors such as coffee and sugar cane production provide a better standard of living to their farmers. These are however the exception and not the rule in most rural areas of the Andean region.

Another specific situation in the Andean region is related to the geographical location of rural communities that are usually settled on foothills and in highland areas. This factor poses restrictions to wastewater treatment technologies in terms of suitable land availability for WWTP. In this sense, Peña *et al.* (2002) found that land availability related to steep topography is the main constraint to the implementation of waste stabilisation ponds (WSP) technology in southwest Colombia. The geographic location of many rural settlements also enhances the pollution of surface water bodies in small basins located in the highlands. Thus, pollution drains down via natural drainage networks and spreads throughout entire regions with consequent negative impacts.

Recent figures from PAHO show that despite the achievements in water supply and sanitation coverage during the last decade, there are still 76.6 and 103.3 million people lacking access to adequate water supply and sanitation services in the Americas, respectively. The water and sanitation services limitations continue affecting greatly the inhabitants of small municipalities, rural areas and low-income settlements in large cities (PAHO, 2001). The *2000 Evaluation* carried out jointly by WHO, PAHO and UNICEF showed the situation of the water supply and sanitation sector in the region and made evident the constraints and inequalities in the provision of these services. Additionally, by the end of 1998 only 13.7 percent of all municipal wastewaters collected -corresponding to 48.6 percent of the population with sewerage servicereceived some degree of treatment before disposal (PAHO, 2001). Figure 1.1 shows the coverage of sanitation services by country at the end of 1998 in the Andean Region.

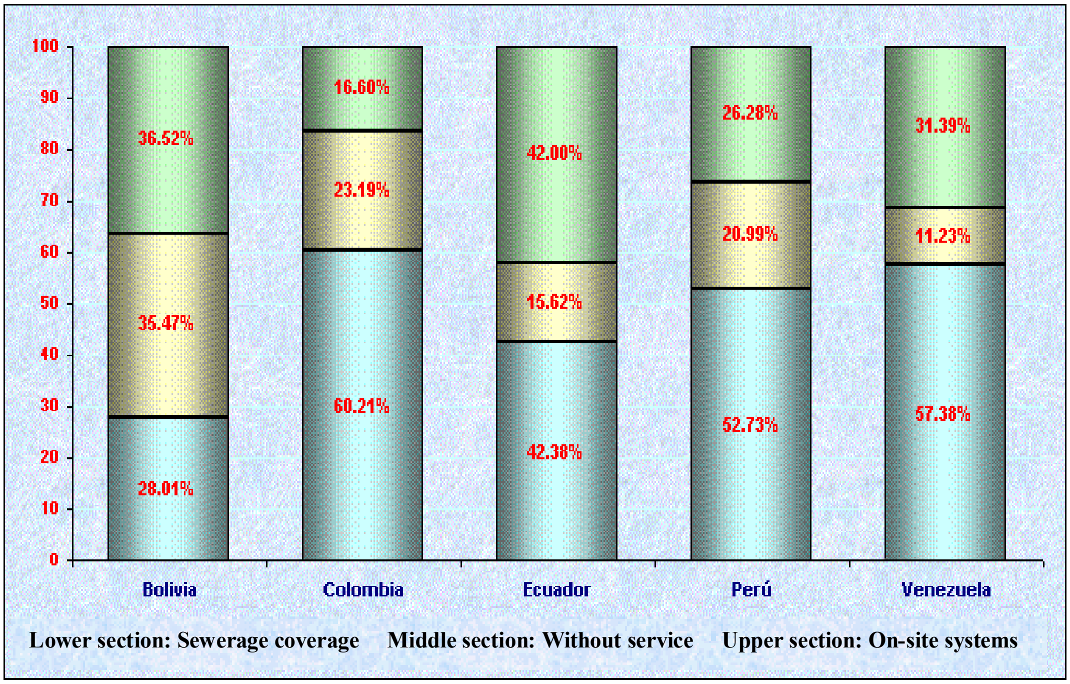


Figure 1.1 Coverage of sanitation services in the Andean Region by 1998.
Source: PAHO-CEPIS (2001, URL-2).

The percentages of population without access to adequate water supply and sanitation services in the rural areas are five times higher in comparison with the urban population. Furthermore, the inhabitants of small municipalities, rural areas and low-income settlements that are usually the poor people, expend proportionally more of their income on these services. Consequently, for similar levels of income, the urban populations have better access to water supply and sanitation services than the rural communities. Thus, inequalities in the provision of these services along with increasing poverty lead to a downward spiral of decline in services coverage and quality (DFID, 2000). Therefore, as pointed out by PAHO (2001), the development, improvement and adaptation of new management models and innovative technologies in the water supply and sanitation sector are still a challenge on the way to obtain more efficient and sustainable services in Latin America.

An additional problem to the physical shortage in the coverage of water supply and sanitation services is related to the high level of under-funding in the sector. Low tariffs and poor collection of service charges result in insufficient revenues to cover operating costs, let alone the costs of replacement or extension of existing systems.

Consequently, neither governments nor users generate enough money for maintenance, whilst budgets are allocated mainly to capital investment from which a significant proportion is frequently used to improve the levels of service to those groups with higher income (DFID, 2000). Again the challenge for the international community is considerable: how to manage increasingly scarce water resources to ensure that the global goal of poverty elimination can be achieved within safe and sustainable human environments (DFID, 2000).

In Colombia about 1200 tonnes of organic matter from domestic origin are daily discharged into water bodies. This causes the pollution of about 1300 rivers and minor water streams, 30 lakes, many natural ponds and marshes as well as various coastal areas. According to a recent study of the Colombian Ministry of Economic Development (MINDESAROLLO) only 131 municipalities (12 percent) out of a total of 1095 treat their wastewaters to some extent. However, about 87 percent of a 1000 municipalities with less than 100.000 inhabitants do not treat their wastewaters at all in Colombia (MINDESARROLLO, 1998). Towns with populations ranging from 2,500 to 10,000 inhabitants represent the highest proportion of the 1000 municipalities above mentioned and most of them are located below 1000 metres over sea level. These towns have land availability and mean temperatures between 20 and 30 °C throughout the year according to the Colombian Geography Institute-IGAC (2002, URL-3).

Based on the situation already presented, it becomes important to investigate and improve further the functioning and performance of wastewater treatment technologies currently in use in the Andean region. The present trend is to use conventional systems in large-sized cities, but for medium and small-sized towns non-conventional technologies are usually considered. The systems commonly implemented in the latter case are WSP and a variety of anaerobic reactors (i.e. septic and Imhoff tanks, anaerobic filters, UASBs and anaerobic digesters). Combinations of all these systems are also currently in use in various countries of the region in an effort to find cost-effective alternatives for pollution control. Nevertheless, it is necessary to carry out more research on these wastewater treatment technologies, so that they remove both organic matter and pathogens in the most efficient way possible but taking into consideration the critical factors that hinder their sustainability in developing countries. Such improved technological alternatives must be suitable to the diverse political, economical, technical and social contexts of the different countries in the region.

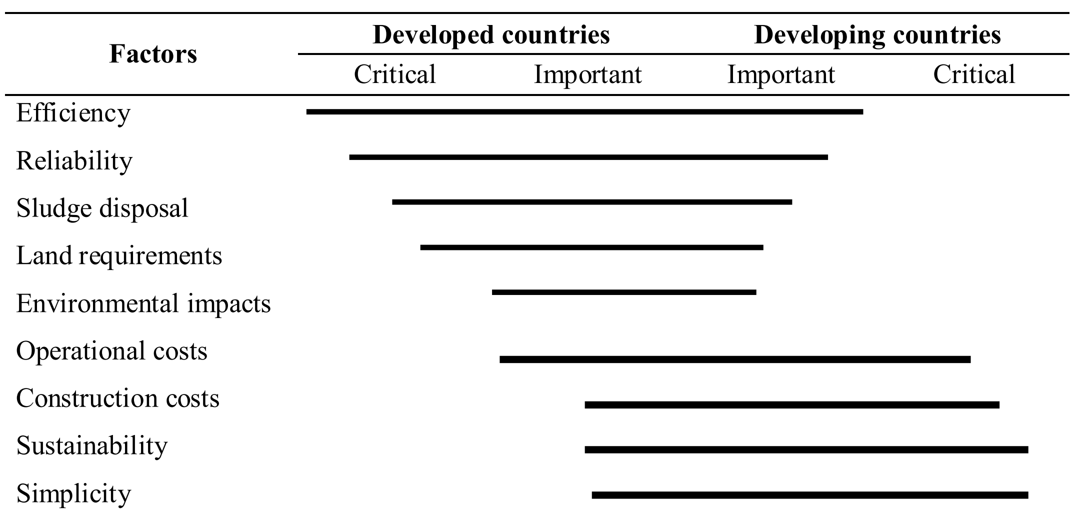
The following Section presents in more detail the technological options currently in use to treat domestic wastewaters in some countries of the region.

1.2 Sustainable technologies for domestic wastewater treatment

There is currently a wide variety of systems, which can be successfully applied for wastewater treatment. They should however be selected on the basis of the specific local context. Generally speaking, in industrialised countries the number of suitable alternatives may be more limited due to stricter regulations. In developing countries, however, the number of choices may be higher as a result of the more diverse discharge standards encountered. In this sense, effluent standards vary from the very conservative to the very relaxed. Likewise, the cost component and the operational requirements, while important in industrialised countries, play a much more decisive role in industrialising countries. Another important feature in the latter is the high contrast between urban and rural areas.

Von Sperling (1995) holds that all these issues become critical when preliminary selection of the more appropriate systems is undertaken. Table 1.2 presents a comparison of the most important aspects in the selection of wastewater treatment systems analysed in the context of both developed and developing countries. The comparison is rather general given the specific conditions of each scenario and the high contrasts observed in developing countries.

Table 1.2 Important factors in the selection of wastewater treatment systems in developed and developing countries.



Source: von Sperling (1995)

Table 1.2 shows that in developed countries critical items are: efficiency, reliability, sludge disposal and land requirements, whereas in developing countries the critical items are construction costs, sustainability, simplicity and operational costs.

These factors, although important in developed countries cannot be considered critical. Therefore, each situation must be analysed individually and local conditions must be incorporated from the very beginning of the project cycle.

As pointed out by von Sperling (1994), the consideration of multiple alternatives is the best way to reach an efficient, economical and adequate solution not only at the design stage, but also throughout the operational life of the WWTP.

Lettinga (1995) pointed out that anaerobic wastewater treatment should be regarded as the core method of a sustainable wastewater management strategy due to its benefits and enormous potentials. Although conventional aerobic treatment systems generally provide excellent treatment efficiency, they do not fully meet the criteria needed for a sustainable wastewater management strategy.

Recent developments in high-rate anaerobic reactor technology reveal that anaerobic wastewater treatment is also feasible for treating cold and even dilute wastewaters at loading rates exceeding 10 kg COD/m^3 at temperatures down to 10 °C and liquid detention times of a few hours. High treatment efficiencies can be achieved using the one-step reactor concept, but even better efficiencies are possible with staged anaerobic reactors (Lettinga, 1995). The enormous potentials of anaerobic sludge bed reactors systems are ignored in most wastewater treatment textbooks, yet anaerobic treatment represents a feasible treatment technology for a wide range of wastewaters. In order to extend the application of anaerobic treatment to difficult circumstances, it is necessary to understand the fundamentals of the technology, including the chemistry, microbiology, the kinetics and the effect of environmental factors (Lettinga, 1995).

Van Haandel and Lettinga (1994) proved the feasibility of domestic wastewater treatment by means of anaerobic digestion. Based on results obtained in comprehensive pilot plant investigations conducted in Cali, Colombia, full-scale conventional UASB reactors have been developed since 1989 in Colombia and India. More than 100 upflow sludge bed type facilities have been implemented in the state of Paraná, Brazil. A small UASB installation for domestic wastewater treatment was operated in Campina Grande, Brazil mainly for research and demonstration purposes.

On the other hand, WSP technology has also advanced greatly in terms of application and reliability for the treatment of domestic wastewater in developing countries. As pointed out by Pearson (1996), this has been the result of modern applied research. Pond technology can be designed to meet strict effluent standards and can treat domestic sewage as well as a wide range of industrial wastewaters. Ponds are a modern wastewater reclamation and resource recovery technology in tune with current environmental thinking (Pearson, 1996). Anaerobic ponds (AP) play an important role in the series since they are able to remove efficiently suspended solids and BOD_5. Mara *et al.* (1992) and Mara and Mills (1994) have shown that APs work extremely well in warm climates. An anaerobic pond properly designed can achieve around 60 percent BOD_5 removal at 20 °C and as much as 75 per cent at 25 °C. A domestic wastewater with BOD_5 contents of up to 300 mg/l can be treated in an AP with a retention time of only 1.0 day in order to achieve the efficiencies mentioned earlier.

Foresti (2001) summarises the potential and perspectives of anaerobic technology for the treatment of a variety of wastewaters including domestic sewage in the Latin American context. From the technical point of view, some countries in the region are prepared to use developing anaerobic technologies in order to solve their water pollution problems and improve their socio-economical conditions.

Borzacconi *et al.* (1995) showed that many research groups from Latin American countries have developed significantly the use of large-scale anaerobic reactors to treat both industrial and domestic effluents. By mid 1994 there were a total of 396 anaerobic reactors built in the region with a total volume of 394.421 m^3; about 57 percent of these were reactors treating domestic wastewaters. Foresti (2001) points out that by the end of 2000 there were more than 300 anaerobic reactors operating in the Paraná State alone in Brazil. Nowadays, many research centres in developing countries have recognized the advantages of anaerobic processes as the core of sustainable systems for natural resources conservation. However, there is plenty of room for improving, adapting and developing different process configurations.

Mexico is another Latin American country with an important number of WWTP currently in operation. According to Monroy *et al.* (2000), about 20 percent of the domestic wastewater produced in Mexico is treated. By the end of 2000 there were 946 municipal WWTP constructed, of which 40 percent are WSP, another 40 percent correspond to more conventional systems (i.e. activated sludge, oxidation ditches, aerated lagoons and trickling filters), 9 percent are anaerobic reactors and the remaining 11 percent comprise different sorts of systems (i.e. RBCs, Imhoff tanks, duckweed based ponds and others). A total of 755 municipal WWTP (79%) are currently in operation in Mexico. From these, only 312 WWTP (41%) have BOD_5 removal efficiencies higher than 75%, and 199 WWTP (26%) have average BOD_5 removal efficiencies below 50%.

Monroy *et al.* (2000) also point out that from the non-operating WWTP, 30 percent are conventional systems that failed due to lack of aerator maintenance.

Moreover, the sludge treatment expenses in these facilities added to the high investment and running costs make this type of WWTP a non-sustainable option in the long term despite Mexico having one of the most prosperous economies in Latin America.

On the other hand, Colombia and Venezuela are probably the countries with the best situation in terms of domestic wastewater collection and treatment in the Andean Region. Nonetheless, their situation is far from satisfactory in this regard.

Recent figures from the Colombian Ministry of the Environment show that there is a total of 180 municipal WWTP built and 140 WWTP more are at the design stage. Table 1.3 shows the technologies currently implemented in the country.

Table 1.3 Municipal wastewater treatment technologies implemented in Colombia by 1998.

Technology	Built (No / %)	Designed (No / %)
WSP	96 / 53	61 / 44
Activated sludge	43 / 24	5 / 3
Trickling filters	24 / 13	22 / 16
UASB	17 / 10	18 / 13
Without information		34 / 24
Total	180	140

Source: MINAMBIENTE (1998).

Data on the performance of the constructed WWTP in Colombia are very scattered due to design limitations, WWTP construction errors, inadequate and very low levels of plant monitoring, lack of adequate training of operational personnel and a general lack of experience on wastewater treatment projects. Nonetheless, some of the WSP systems located in southwest Colombia are adequately operated by the regional water company and meet the current discharge standards, that is, 80 percent removal of the influent BOD_5 and TSS loads. There are several factors hindering the development of sustainable wastewater management projects in the country. The most important factors are lack of political will at the central level, insufficient economic resources for investment, lack of technological options tested under local conditions, use of inadequate criteria for the selection of wastewater treatment technologies and inexperienced organizations responsible for O&M of the WWTP (MINAMBIENTE, 1998).

The situation and figures presented so far show that sustainable wastewater treatment management is a new field of work in Latin America and specially in the

Andean Region countries. Sustainable systems for wastewater treatment in the context of the region call for new developments and innovative solutions in different areas of expertise ranging from the pure technological aspects to the management of the service. This is particularly needed to control the pollution of water resources in small municipalities and rural settlements where poverty is a main constraint for building, operation, maintenance and administration of a given technological solution.

1.3 Research approach

As shown earlier, there are strong limitations in the Andean Region countries of Latin America related to technical, institutional and managerial aspects of wastewater treatment infrastructure. On the technical side, it is necessary to improve and strengthen the applied research under local conditions in order to enhance the performance of domestic wastewater treatment systems. It is also important to learn from the experience gained by different countries in the region. Based on these aspects and a review of the technical literature, it seems possible to improve the performance of wastewater treatment technologies widely used in the region such as WSP and anaerobic reactors.

There are some topics that deserve further investigation in order to develop more efficient yet simple and affordable technologies that can effectively contribute to the reduction of water pollution and public health hazards in small towns and rural areas of most Latin American countries.

This work focuses primarily on the study of the hydrodynamics and process performance of two well-established primary anaerobic treatment systems, the AP and the UASB reactor. The hydrodynamics and process performance of APs may be further improved by applying fundamental principles from reactor engineering and anaerobic treatment theory so that current reaction rates in these units are enhanced. This will clearly improve the applicability of this technology and WSP in general (via reduced land area requirements) provided that operation and maintenance remains simple.

On the other hand, UASB reactors have shown to be efficient at removing organic matter while having a more stable and predictable hydrodynamic behaviour. However, there are still some aspects of this technology that may be improved; for example, reduction of biomass losses during transient hydraulic loading rates. Additionally, UASBs seem to be a more care-demanding technology in terms of operation, maintenance and monitoring. This may well be a limitation for the proper functioning of the system in several small towns and rural communities where easiness of O&M is a crucial factor for sustainability. Thus, it is believed that an improved or high-rate AP configuration may be obtained by combining the best features of these two technologies. Hence, the following question guided the work carried out in this research: *is it possible to improve further the performance of current AP configurations to treat domestic wastewater in tropical regions?*

In order to answer this question the research approach comprised three main steps: first, studies of the hydrodynamic behaviour of two full-scale AP and a full-scale UASB reactor were carried out to find out their mixing patterns and related process performance. Second, computational fluid dynamics (CFD) simulations of one of the full-scale AP were developed so as to study the effects of sludge accumulation, baffling, inlet-outlet positioning and pond geometry on the overall hydrodynamic efficiency of the AP. Third, results from the full-scale studies were used to run hydrodynamic and process performance evaluations under steady state conditions on various modified pilot-scale AP configurations. It is worth noting that this research was primarily focused on the removal of organic matter from the liquid phase. Consequently, further detailed studies on biomass evolution as well as biogas production and composition are needed so as to complete the development of the high-rate AP concept. An experience at full-scale will provide the data to determine the economic feasibility of this technology.

1.4 Aim and objectives of the current work

The aim of this work is to establish the basis for continuous research on improvements of the technical design and performance of current anaerobic ponds. This may be a relevant topic for the development of more cost-effective wastewater treatment solutions in tropical regions. The specific objectives of this research are:

To assess the hydrodynamic behaviour and process performance of full-scale anaerobic ponds and UASB reactors treating domestic wastewater under tropical conditions;

To evaluate various modified configurations of anaerobic ponds at pilot-scale and their implications on mixing, contact patterns, biomass retention and process performance; and

To introduce the concept of high-rate anaerobic pond for the advanced primary treatment of domestic wastewater under tropical conditions on the basis of improved hydrodynamics and organic matter removal.