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A FEASIBILITY STUDY ON SUSTAINABLE WASTEWATER TREATMENT USING CONSTRUCTED WETLANDS

- AN EXAMPLE FROM COCHABAMBA, BOLIVIA

FUNDACIÓN
AGUATUYA

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ABSTRACT

Cochabamba in Bolivia is an example of a city that faces increasing environmental problems and health risks due to insufficient sewage system coverage and municipal wastewater treatment. The situation is especially severe in peri-urban fast growing settlements. A decentralized alternative to conventional wastewater treatment plants is constructed wetlands with horizontal subsurface flow (HSF). This treatment method exists in many parts of the world and a few wetlands have been constructed in Cochabamba. The present study includes an evaluation of the treatment efficiency of one of these systems, a pilot plant built by the foundation AGUATUYA treating wastewater coming from a kindergarten, and an investigation of the applicability of the method in Cochabamba. Field work was performed in Cochabamba during November and December 2008.

The treatment plant shows 80-97 % reduction in biochemical oxygen demand (BOD_5), 80-90 % reduction in chemical oxygen demand (COD) and 50-80 % in turbidity. The pH and temperature conditions are favourable for degradation by microorganisms. Nutrients were not observed to be removed from the wastewater. The wetland is largely anaerobic which is likely to be the reason why no nitrogen removal was observed. The microbiological analyses were few but the results indicate that faecal coliform bacteria are reduced by 90 %. The effluent concentration of coliforms does not meet treatment requirements for unrestricted re-use of the water.

The wetland has two sections containing different media: gravel and plastic pieces. The plastic medium has significantly higher surface area per bed volume but the analyses showed little or no difference in treatment efficiency between the sections. To better understand the difference in treatment capacity between the sections and to be sure that they work properly, the outlet of the wetland has to be redesigned. Tracer experiments were performed and showed a large variation in transport time for the gravel section. The transport time of the plastic section could not be determined from the experiments. The nominal retention time was calculated to 6.2 and 8 days for the gravel and the plastic section respectively.

Cochabamba has a long dry season, creating a great need for water re-use and especially for irrigation of agricultural and recreational areas. Treated water from constructed wetlands can be used for this purpose in the vicinity of the wetlands, reducing the consumption of potable water, shortening water transports, reducing the risk of eutrophication in adjacent waterbodies and lowering energy requirements. Climate and terrain conditions in Cochabamba are suitable for constructed wetlands. HSF constructed wetlands require little energy, construction material and maintenance. They are a good alternative in sparsely populated, poor areas like peri-urban Cochabamba. Use of constructed wetlands could lead to more green areas with lawns and trees, and this in turn decreases soil erosion.

Key words: Cochabamba; Bolivia; constructed wetlands; horizontal subsurface flow; wastewater; sewage water; water treatment; reuse of wastewater; minor field study

RESUMEN

Cochabamba en Bolivia es un ejemplo de una ciudad que enfrenta problemas crecientes ambientales y riesgos de salud por causa de la baja cobertura de alcantarillado y tratamiento de aguas residuales. La situación es especialmente grave en comunidades periurbanas que están creciendo rápido. Una alternativa a las plantas de tratamiento convencionales son los humedales artificiales de flujo subsuperficial. El método existe en varios sitios del mundo y algunos humedales han sido construidos en Cochabamba. El presente trabajo incluye una evaluación de la eficiencia de uno de estos sistemas, una planta piloto, construida por la fundación AGUATUYA, que está tratando aguas residuales de un colegio, y además una investigación sobre la factibilidad de uso de esta tecnología en Cochabamba. El trabajo en el terreno fue realizado durante Noviembre y Diciembre 2008.

La planta de tratamiento muestra eficiencias de remoción de 80-97 % de demanda bioquímica de oxígeno (DBO_5), 80-90 % de demanda química de oxígeno (DQO) y 50-80 % de turbiedad. Las condiciones de pH y temperatura son favorables para la descomposición de microorganismos. Según los análisis realizados los nutrientes no son eliminados del agua. El hecho que el pantano está funcionando en condiciones anaerobias es la razón probable para que no se observe ninguna remoción de nitrógeno. Los análisis microbiológicos fueron pocos pero los resultados indican que 90 % de las bacterias coliformes fecales son removidas. La concentración de coliformes fecales en el efluente no cumple los límites permisibles para reuso indiscrecional del agua.

El humedal tiene dos secciones conteniendo medios porosos diferentes; piedras pequeñas y piezas plásticas especiales. El material plástico tiene una área mucho más grande por volumen de estrato pero los análisis demostraron ninguna o pequeña diferencia de eficiencia entre las secciones. Para entender mejor las diferencias de capacidad entre las secciones, y para estar seguro de que funcionan correctamente, hay que rediseñar la salida del humedal. Los experimentos de trazador realizados presentaron una variación grande de tiempo de transporte concerniente a la sección de piedra. El tiempo de transporte en la sección de plástico no se podía determinar. Según los cálculos, los tiempos de retención teoréticos son 6.2 días para la sección de piedra y 8 días para la sección de plástico.

La época de sequía de Cochabamba es larga, lo cual crea necesidades grandes de reciclar el agua, sobre todo para riego de zonas agrícolas y recreacionales. El agua tratada en humedales artificiales puede ser utilizada para este fin en los alrededores de los humedales, lo que reduce el consumo de agua potable, disminuye los transportes de agua, reduce el riesgo de eutrofización en cuerpos de agua cercanos y baja la demanda de energía. Los humedales subsuperficiales no requieren mucha energía, material para construcción o mantenimiento. Concluimos que la tecnología empleada por AGUATUYA es una buena opción en zonas periurbanas de bajos ingresos de Cochabamba. El clima y el terreno en Cochabamba son convenientes para humedales artificiales. La implementación puede contribuir a la creación de parques verdes con pastos y árboles, lo que a la vez reduce la erosión.

Palabras clave: Cochabamba; Bolivia; huemdales artificiales; humedales construidos; flujo subsuperficial; pantanos; aguas residuales; tratamiento de agua; reuso de aguas residuales

SAMMANFATTNING

Cochabamba i Bolivia är ett exempel på en stad som står inför växande miljöproblem och hälsorisker på grund av otillräckliga avloppssystem och bristande kommunal avloppsrening. Situationen är särskilt allvarlig i peri-urbana snabbväxande stadsdelar. Ett decentraliserat alternativ till konventionella avloppsreningsverk är konstruerade våtmarker med horisontellt flöde under den fasta våtmarksytan. Reningsmetoden existerar i många delar av världen och några sådana våtmarker har redan konstruerats i Cochabamba. I denna studie utvärderas effektiviteten i ett av dessa system; en pilotanläggning som behandlar avloppsvatten från en förskola, byggd av stiftelsen AGUATUYA. En utredning görs också av metodens tillämpbarhet i större skala, i Cochabamba. Fältarbete gjordes under november och december 2008.

Våtmarken visar stor reduktion av biokemisk syreförbrukning, BOD_5 (80-97 %), kemisk syreförbrukning, COD (80-90 %) och turbiditet (50-80 %). pH- och temperaturförhållandena är fördelaktiga för mikrobiell nedbrytning. Näringsämnen avlägsnas inte nämnvärt från avloppsvattnet. Våtmarken är syrefattig vilket troligtvis är anledningen till att kväve inte avlägsnas. De mikrobiologiska analyserna var få men resultaten visar att tarmbakteriehalten reduceras med upp emot 90 %. Koncentrationen av bakterier i utloppet är för hög för att vattnet skall uppfylla de krav som ställs på oreglerad återanvändning.

Våtmarken har två sektioner som innehåller små stenar respektive plaströrsbitar. Plastbitarna har signifikant större ytarea per volym, men analyserna visade liten eller ingen skillnad i effektivitet mellan sektionerna. För att bättre förstå skillnaden i reningskapacitet mellan sektionerna, och för att vara säker på att de fungerar som planerat, måste våtmarkens utlopp designas om. Spårämnesförsök gjordes och visade på stor variation i vattnets transporttid i stensektionen. Transporttiden i plastsektionen kunde inte bestämmas utifrån försöken. Den nominella uppehållstiden beräknades till 6,2 och 8 dagar för sten- respektive plastsektionen.

Cochabamba har en lång torrperiod vilket skapar stora behov av återanvändning av vatten, särskilt för bevattning av jordbruks- och rekreationsområden. Behandlat vatten från konstruerade våtmarker kan användas för detta ändamål i närheten av våtmarkerna vilket reducerar konsumtionen av dricksvatten, minskar vattentransporter, reducerar risken för övergödning av närliggande vattendrag och sänker energibehovet. Konstruerade våtmarker kräver mycket lite energi, konstruktionsmaterial och underhåll, och de är bra alternativ i glest befolkade, fattiga områden som t.ex. peri-urbana Cochabamba. Klimat- och terrängförhållandena i Cochabamba är lämpliga för konstruerade våtmarker och anläggande av sådana kan leda till fler gröna områden med gräsmattor och träd, vilket minskar jorderosion.

Nyckelord: Cochabamba; Bolivia; konstruerade våtmarker; våtmarksfilter; avloppsvatten; vattenrening; återanvändning av avloppsvatten

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GLOSSARY

Aerobic – presence of oxygen

Anaerobic – absence of oxygen

Biofilm – thin layers composed of microalgae, bacteria and carbohydrate mucus, which is found on surfaces of living and dead plant tissue, sediment surfaces and stones in aquatic environments.

Emergents - rooted aquatic plants with leaves and photosynthesis above the water surface

Macrophytes - aquatic plants

Peri-urban area – a city area on the border between urban and rural areas. The expression is derived from the word 'peripheral'.

Rhizom – in plants elongated underground stem often containing nutrient reserves. Survival organ during winter or dry period.

Rhizosphere – root zone. Part of the ground directly affected by the roots of the plant growing there.

Abbreviations

BOD – biochemical oxygen demand
C.A.S.A. – Centro de Aguas y Saneamiento Ambiental
COD – chemical oxygen demand
CFU – colony forming units
CSTR – continuously stirred tank reactor
DS – dissolved solids
HSF – horizontal subsurface flow
MPN – most probable number
PFR – plug flow reactor
PTAR1 – planta de tratamiento de aguas residuales 1. The wetland in San Antonio de Buena Vista, built by AGUATUYA.
SS – suspended solids
TS – total solids
USEPA – United States Environmental Protection Agency
WSP – Water and Sanitation Program

1. INTRODUCTION

Solving problems regarding water and sanitation throughout the world is a big challenge. Forty two percent of the world's population lack access to basic sanitation (WHO/UNICEF, 2005). Last year, by UN General Assembly assigned to be the International Year of Sanitation 2008, focus was placed on the issue. The goal was to, together with partner organisations, raise awareness and to accelerate progress towards the Millennium Development Goal to reduce by half the proportion of the 2.6 billion people without access to basic sanitation by 2015 (UN 2007). This will help save lives and encourage economic and social development. Lack of clean water is an integral part of the sanitation problem, and each year many people die from water borne diseases. In even more cases the untreated infiltration and outflow of wastewater into the groundwater, rivers, lakes and the sea creates massive environmental problems besides being a nuisance and a health risk.

1.1 Background

Conventional sanitation and water treatment approaches, largely developed in richer, developed countries, have some requirements difficult for many developing countries and poor areas to meet. Some of these are high capital costs to install pipe networks and treatment plants, high operating and maintenance costs for both plants and networks and finally indoor functional water and sewer connections. A large part of all wastewater in the world is released without being treated. (Ujang and Henze 2006)

Poor people in peri-urban areas mainly rely on alternative or informal service providers of water and sanitation, but these are often invisible to policymakers and remain outside support strategies (Butterworth and Warner 2007). In many developing countries, conventional treatment systems are adopted without considering difficulties in funding, development of alternative techniques and environmental awareness of the public that is crucial to make any new treatment system work as intended. One could ask if developing countries really should follow the same track as the developed countries; risking making the same mistakes and not benefiting from the technology development in the sanitation and water treatment field.

In this report the city of Cochabamba in Bolivia, with a rapidly growing population, will serve as an example of a developing country city that faces increasing environmental problems and health risks due to insufficient sewage system coverage and municipal wastewater treatment. The situation is similar in large parts of Bolivia, and is especially severe in peri-urban fast growing settlements and in rural areas with small populations. There are however people who work hard to improve the situation and develop new solutions to these problems. The need is great for solutions that are affordable, reliable and sustainable. Ujang and Henze (2006) also define the later as systems which are technically manageable, socio-politically appropriate and that utilise small amounts of energy and resources, recovering as much usable matters as possible. Three major parts of such a system is source separation of pollutants, decentralisation and reuse of products, in this case e.g. treated water.

Cochabamba has many inhabitants that come from surrounding regions to make a better living. There is little control over housing development in the poorer parts. This situation is not unique, and in many developing countries dense squatter communities are very common in larger cities. These areas are usually not included in sanitation, sewer or drinking water plans of the city. Since the largely poor population have little means to buy any such systems themselves, local solutions are necessary even though they are not controlled or supervised to check for health and environmental risks. If the country has problems with water scarcity, the situation is often worse (Ujang and Henze 2006). The peri-urban areas of Cochabamba are not very densely populated, which means that these types of problems are not acute yet. However, there is rapid population growth, little control of wastewater disposal and insufficient water supply.

Many questions arise when looking at the water and sanitation situation in the world in general, and Bolivia and Cochabamba in particular. How is the situation in Cochabamba today? Is there a will to continue developing reliable systems which do not have consequences on the environment? What happens to the consumers who cannot afford large centralized systems and what alternatives are there? Could a separated, local system, where wastewater is treated in a wetland, be an alternative in some areas? The people at the foundation AGUATUYA, presented below, are some of the first in Cochabamba to seriously look into these issues and to present an alternative.

1.2 AGUATUYA

The foundation AGUATUYA ("Your Water") in Cochabamba works with design, construction and financing of systems of potable water and basic sanitation, but it is also a forum which supports the already constructed systems and promotes interchange of information and experiences between different actors in the field. AGUATUYA implements models which generate local solutions aimed to be appropriate, dignifying and sustainable. The working models include participation of the users, for example quarters of the town, villages, municipalities or water cooperatives. Mostly the projects concern drinking water, like water distribution to villages with less than 10 000 inhabitants and the project *Agua para Todos* ("Water for all"). In the latter project the organisation cooperates with the municipality of Cochabamba, the municipal company for water and sanitation called *Servicio Municipal de Agua Potable y Alcantarillado de Cochabamba* (SEMAPA) and United Nation Development Programme (UNDP) to facilitate loans for water and sanitation services to people with low incomes in the peri-urban areas. The result of AGUATUYA's effort is that more than 85 000 inhabitants now have water 24 hours a day, at an acceptable cost. (Heredia 2008)

In their work with water distribution AGUATUYA has noticed the demand of low-cost sanitation solutions in peri-urban areas and AGUATUYA has several pilot projects promoting "Ecological Sanitation". People in the pilot areas that are interested in participating can get dry toilets with urine separation installed near the house at a low cost. They only need is to supply maintenance of the system. In addition they can get a faucet for hand washing, and treatment of the washwater,. The idea is that active participation and a price, although low, make people more interested in maintaining the systems carefully. So far AGUATUYA has existed during 10 years without any external financial support. AGUATUYA proposes a change in the way international cooperation works towards higher local counterpart of the total costs, for a more sustainable approach. The coming three years AGUATUYA will receive funds from SIDA that will be invested in local capacity development, hence not creating a long term financial dependency.

In the field of sanitation, the foundation has also constructed a wastewater treatment plant, called PTAR1, as a pilot project to treat wastewater coming from a school in the Buena Vista area, Cochabamba. Treatment in constructed wetlands is a relatively new solution in Bolivia and is currently tried out at different locations in peri-urban regions (Bomblat 2008, Heredia 2008). This type of treatment solution is very low cost and needs little maintenance, making it suitable for the poorer southern areas in Cochabamba where sanitation so far has been non-existent in many cases (Bomblat 2008). AGUATUYA has run the plant for less than one year and started to monitor the chemical characteristics of the water in June 2008. Further evaluation and testing are still needed. The future goal is to construct large wetlands, treating wastewater from up to 300 households in peri-urban residential areas. The wastewater treatment plant is designed as a horizontal subsurface flow wetland, made especially accessible for evaluation and sampling with several observation pipes. It is also designed to compare two carrier materials: stones and cut pieces of plastic pipes. More understanding of this type of wetland is needed and this project will hopefully answer some of the questions about improved performance and design.

Centro de Aguas y Saneamiento Ambiental

Centro de Aguas y Saneamiento Ambiental (C.A.S.A.) is a division at the Faculty of Science and Engineering at the public university Universidad Mayor de San Simón in Cochabamba. The centre works with education at the university and research concerning contamination of water, soils and sediments and treatment of potable water and wastewater. C.A.S.A. also offers physicochemical and microbiological analyses, studies about contamination of waterbodies, ecotoxicological studies and guidance regarding construction of water treatment plants. The centre cooperates with various national and international organizations. They have an interest in alternative wastewater treatment techniques and have performed analyses on samples taken from the AGUATUYA wetland. The cooperation will continue as AGUATUYA develops the system.

1.3 Purpose

The aim with this project is to evaluate the treatment efficiency of the constructed wetland built in San Antonio de Buena Vista, and to investigate whether this local solution is applicable in more places, on a larger scale in Cochabamba. AGUATUYA will be provided with assistance in the form of technical evaluation and suggestions on development of the treatment plant and a plan for further monitoring.

One goal is to assess the wastewater treatment plant and monitor several parameters regarding hydraulics and chemistry in order to investigate if the plant is functioning and the water properly treated. Suggestions on improved design will be presented. This includes suggestions about which measures need to be taken to safely re-use the water efficiently. A comparison between the different carrier materials will be done to see if any of the two are better suited for future treatment plants.

Taking the results of an improved design as a starting point, it will be evaluated whether it is worth investing in more constructions of the same type. Cost and time of construction and maintenance will be taken into account. Through interviews the current treatment facilities will be described, other examples of constructed wetlands in Cochabamba will be examined and finally a comparison will be made between the current system and the improved design suggestion.

1.4 Disposition

Chapter 1 draws the background of this project and the world scene in which it is set. It also describes the local Bolivian foundation AGUATUYA and finally the purpose of this project.

Chapter 2 gives an introduction to the country of Bolivia and the city of Cochabamba, where the field work for this project was carried out, and its water and sanitation situation.

Chapter 3 encompasses the relevant parts of the theory behind wastewater characteristics and treatment, focusing at the end on the mechanisms in subsurface flow wetlands. Bolivian and international treatment requirements are presented.

Chapter 4 describes the wetland and the school Sagrado Corazón de Jesús in San Antonio de Buena Vista, together with the surrounding area. The other visited wetlands are also presented.

Chapter 5 lists the methods used to evaluate the wetland and all results are presented in chapter 6.

Chapter 7 discusses the results, the water situation and future possibilities for sanitation solutions in Cochabamba. Conclusions, thoughts and recommendations to AGUATUYA in their future work, are presented.

2. BOLIVIA – COUNTRY OF OPPOSITES

2.1 Introduction to Bolivia

Bolivia, a country of opposites, is situated in the middle of South America, bordering to Argentina, Brazil, Chile, Peru and Paraguay. Around 10 million inhabitants are living in the country, mostly in the Altiplano region, and the surface area of Bolivia is 2.4 times larger than the surface area of Sweden. It is a mountainous country with the Andes covering more than a third of its surface to the south and west, including mountains reaching over 6000 meters. The constitutional capital is Sucre but the government and parliament are located in La Paz which is also the commercial, industrial and cultural centre. La Paz is situated in the Altiplano region at the impressive altitude of 3660 meters above the sea. This is a harsh land to those unaccustomed, with a dry, cold climate and a relentless sun. It has an impressive history of large empires and advanced cultures, the Tiahuanaco and later the Inca are two well known examples, long before the Spanish colonized the area in the 16th century. The east and north of Bolivia, the *Oriente* region, has a character completely different. Here in the dense jungles of the Amazon basin, the only things higher than the mountains in the west are the humidity and intensity of its tropical downpours. (Armstrong 2007, NE 2009)

Figure 1. *Top right:* Map of where Bolivia is situated in South America. *Main picture*: A more detailed overview of Bolivia. Cochabamba is located almost in the centre of the country. (Pictures from NE 2009 and Microsoft World Atlas 2009)

In 1825 Bolivia was declared independent, joining the recently proclaimed states Venezuela, Colombia, Ecuador and Peru, after almost fifteen years of growing independence movements, battles and guerrilla warfare. A history of corrupted regimes and political instability, with over 70 presidents since the independence, has not benefited the economy of the country. Even though rich in natural resources, Bolivia is still considered very poor. Sixty three percent of the population lives below the poverty line and a quarter are considered extremely poor. (Armstrong 2007, UNDP 2007)

Mean life expectancy is 65.5 years (INE 2008a) but there are major differences in living standards, access to healthcare, education, safe sanitation and clean water between the poorest and the richest people, between different regions and between different sections of the population. Economic and social inequalities are linked to ethnic and social discrimination. (SIDA 2008)

The indigenous languages Aymará and Quechua are today official languages together with Spanish since the era of the colonization, but the country still has obvious social differences and problems related to ethnic issues. There are 36 recognized indigenous population groups (Armstrong 2007). Distribution of incomes from the extraction of natural gas, land distribution and autonomy for some regions are frequently debated issues that have recently threatened to divide the nation. President, former cocalero (coca grower) and first indigenous person on the post, Evo Morales is however fighting to keep this large and impressive country together. He is a controversial person, intensely loved or disliked by different parts of the population. On February 7th, 2009, Evo Morales proclaimed a new Bolivian constitution, after a referendum held the 25th of January where 61.4 % of the votes supported the new text orientated towards indigenous integration and nationalized economy (El País 2009).

Figure 2. Map of the Bolivian regions where Cochabamba is situated in the middle. The map also shows the provinces of Cochabamba and the position of the city of Cochabamba. (Picture from CGIAB)

2.1.1 Water and Sanitation

Absence of water and sanitation services is affecting the everyday life of many Bolivians and leads to contamination of the environment. When looking at the Bolivian population in total, 15 % of the population do not have potable water and 54 % do not have access to sanitation (Butterworth and Warner 2007). The coverage is higher in urban areas than in rural areas where the coverage of sewage systems is almost zero. Only 20 % of the wastewater collected in sewage systems is treated (VSB 2009). In the countryside and in poor, peri-urban areas it is more common with seepage pits or to deposit the wastewater on the street or ground outside the house, resulting in foul smell, health hazards and unwanted animals like rats (Heredia 2008).

There is a plan for the development of the basic sanitation in Bolivia called *Plan Nacional de Saneamiento Básico 2001-2010* (PNSB). It attempts to improve the coverage of water and sanitation but also to guarantee sustainability of services and to control negative environmental impacts. PNSB is now reformulated by the Vice Ministry of Basic Services to also concern the coming years until 2015 (VSB 2008). An analysis of the sector showed that while the coverage of potable water had reached 90% in urban areas the sustainability was still very fragile. Only 48% were guaranteed continuous and reliable service (Ministerio de vivienda y servicios básicos 2001). The problems are insufficient water production, interruption of service during part of the day, loss of water before it reaches the consumer and insufficient water quality (VSB 2009).

In Bolivia locally-managed water supply systems are common but the policy presented in PNSB is to develop large centrally-managed water and sanitation utilities at least in urban and peri-urban areas. This would be possible with high levels of external investments and cost recovery from the consumers. There have however been critical voices discussing the issue. According to Bustamante et al. (2004) there is a gap between the policy document PNSB and the reality where locally-managed organisations are very important as service providers, developing, operating and maintaining water and sanitation systems. Reliable water and sanitation systems do not automatically imply large costs for the consumers.

Lack of water for irrigation is one of the main limiting factors for the development of agriculture in many regions in Bolivia (Juanico et al. 2000). The yearly average accumulated rainfall is only 200-300 mm at the tableland of Altiplano, compared to 1800 mm in the Amazon basin (CGIAB 2009). During the dry months there is no rain in many regions. At higher altitudes where precipitation is lower and evaporation and radiation is significantly higher, the water shortage makes large scale farming of irrigation intensive crops impossible. Many times there is a lack of money to construct larger collection tanks for rainwater or melt water from glaciers.

In 2006 the president Evo Morales created a new ministry, the Ministry of Water, with the objective to have a state structure specialized in guaranteeing access to water and to preserve its public character. Earlier, the responsibility for water resources was divided between the ministry of farming, the ministry of sanitation and public works and the ministry of environment. The aggregation can be seen as a response to the two civil revolts against privatization of water in Bolivia, in Cochabamba in April 2000 and in El Alto, La Paz in January 2005. The mission of the Ministry of Water is to improve equal access to water for necessities, water services and the quality of the water resources. In order to facilitate a dialogue and coordination between actors involved in water issues, from the state and from the civil society, the ministry includes an inter-institutional council (CONIAG) and a technical council (CTS). There are also a superintending authority (SISAB) and three vice ministries: the Vice Ministry of Basic Services, the Vice Ministry of Catchment Areas and Water Resources, and the Vice Ministry of Irrigation. (Ministerio del Agua 2008)

2.2 Cochabamba

The city of Cochabamba is situated at the edge of the Andes (2550 m.a.s.l.) within the upper part of the Amazon basin, in a natural bowl with impressive mountains surrounding it. The region in which the city is situated is also called Cochabamba and consists of 16 provinces and 45 municipalities. The city was founded in the 16th century, by the Spanish, even though the area has been populated for much longer. In the central province *Cercado*, where the city of Cochabamba is situated, live 595 000 people but including the villages surrounding the city the population is about 1.1 million. Cochabamba is the third largest city in the country and it is growing fast. There is a rural-urban migration process but there is also migration from the city centre to the peri-urban areas. (Faysse et al. 2007, INE 2008a, NE 2008)

The population in the Cochabamba region is young; half of the population is younger than 22 years. Cochabamba has a many-sided industry sector, and compared to the rest of the country Cochabamba is economically active and expanding. Much of the population is poor but there are also wealthier areas and people who make a good living. The boom in recent years has among other things increased the number of cars in the streets, which has contributed to air pollution and traffic congestion. In urban areas in the Cochabamba region 92 % of the population has access to electricity in their homes, while the number is only 36 % in rural areas (INE 2008a). In 2001 14.5 % of the population in the Cochabamba region was illiterates (INE 2008a) but in December 2008 Bolivia declared itself free from illiteracy according to the measure from UNESCO that a country is free from illiteracy when more than 96 % of the population has been taught to read and write (El País 2008).

Figure 3. Cochabamba seen from the east.

Cochabamba is called the city of eternal spring, and has an even and much appreciated climate. The valley is fertile and the area has a long history of agriculture. It has been called the "breadbasket of Bolivia", many times supplying other areas with maize and wheat. The weather is mild and relatively dry. During November and December, when the field work for this project was done, the average temperature is 20 °C (around 25-30 °C in the day, 10-15 °C in the night). The rain period usually starts in November and lasts until April but in 2008 the rains were scarce also during the last two months of the year. During the years 1998 to 2007 is has been raining between 69 and 101 days per year in Cochabamba with a mean of 81 days. For an overview of temperature and rainfall averages, see Appendix 1, Figure 46 and Figure 47.

2.2.1 Waterbodies

The city's largest river, Río Rocha, runs through the city from east to west. It is the recipient of much waste and wastewater, e.g. from industries, homes, detergents and oil production, hospitals and car washing, thus becoming an environmental problem for the city of Cochabamba. The upstream part of the river has no serious problems and the water is used for irrigation and human consumption. The downstream part though, contains water with high amounts of organic and inorganic pollutants. Still this water is used for irrigation of crops, washing of clothes, cars and even personal hygiene, which has a large influence on human health. (Romero et al. 1998)

Most part of the year, when rain is scarce, there is almost no water in the river. In 1939 a tunnel was built to lead water from Río Rocha to the Laguna Alalay, a constructed lake, in order to regulate the rising of Río Rocha and the flooding in the city. Laguna Alalay is situated in the southeast of the city, at the lowest point, which means that it receives runoff water of varying quality.

Figure 4. View over the south parts of Cochabamba city and Laguna Alalay.

Laguna Alalay is shallow but the depth and the surface area vary during the year with lower values during the dry season and higher values during the rainy season. The lake has developed into a complete ecosystem with macrophytes, plankton communities, fish and high diversity of birds and has become an interesting landscape component. It is used for recreation and irrigation. However, due to various factors, the quality of the water of the lake has deteriorated during the last decades. Some of the reasons are large fluctuations in water level because of non-equal flow, droughts and rainfalls, intensive deforestation, increased erosion, more people settled in the surrounding area and release of untreated domestic and industrial solid waste and wastewater. The water coming from Río Rocha and the dam La Angostura also brings pollutants. Studies have shown an advancing eutrophication and contamination of Laguna Alalay. Strategies for recuperation of the Laguna Alalay have been proposed. They include removal of sediment, improvement of the quality of the water entering the lake, management of the macrophyte community and biomanipulation of the fish fauna. (Cadima Fuentes 1998, Van Damme et al. 1998)

2.2.2 Water and Sanitation – Post Water War Situation

The people in Cochabamba went through and won the Water War in the year 2000. They fought against the transnational consortium *Aguas del Tunari* ("Tunari Water"), in which the US-based company Bechtel held the major interest, for the right to water resources and water, irrigation and sewage systems. To get extended loans from the World Bank, Bolivia launched an ambitious privatization program in 1999. This included the water and sanitation services in Cochabamba. There was much controversy over the fact that not only the municipal but also private, self made and communal water systems could be included in the rights of the new owners. This was just one of many far reaching consequences of the new law, viewed by many as too broad and general, regulating the water systems. A popular example is the loss of right to collect the rainwater from your own roof. To jump start a much needed expansion and renovation program for the water distribution system, tariffs were raised 35 % which fuelled protests from poor farmers all the way to wealthier middle-class people and large industry owners. After strikes, road blocks and protest marches rapidly increasing in size, the president ordered a state of emergency, fearing a spread of the protests. Finally they grew too big though, and after violent clashes with police ending in deaths, the corporate representatives fled to Santa Cruz. The contract with Aguas del Tunari/Bechtel was declared revoked and the new legislation was later changed. (Olivera and Lewis 2004, SEMAPA 2009, Wikipedia 2009)

The urbanisation process in Cochabamba has led to an explosion in demand for water and sanitation services which the State and the Municipalities have not been able to meet. To fill the gap, alternative service methods have developed, including community-managed water systems (Faysse et al. 2007). People and communities around Cochabamba have an integrated approach to the use of water. Irrigation water is commonly used for domestic needs and domestic water supplies are often utilised for small-scale productive activities. Community-based water supply committees provide the domestic water, and irrigation committees, associations and authorities develop and manage irrigation water. It is argued that as the city expands, the productive water use, such as irrigation of gardens, will increase demands on new domestic water supply systems. These uses are likely to have an important impact on the overall availability of water resources (Bustamante et al., undated). The largest part of the potable water consumption in the Cochabamba region is used for domestic purposes; see Appendix 2, Figure 48. The major part of the households gets water distributed by pipe systems. The second most common form is rivers, water channels and springs. Other sources are public tanks, delivering trucks, wells and dams (INE 2008a). The majority of the households has an extra drinking water tank to reduce problems with intermittent water distribution. Unfortunately these systems are often inappropriately sized, either too small or too large (Bomblat 2008).

In 2001 only 67 % of the households did have access to sanitation service in the Cochabamba region but the number had increased since 1992 when it was 45 % (INE 2008a). In Cochabamba the sewage pipe system covers 76 % of the city but it includes separate systems where a septic tank is emptied and the wastewater carried by truck to the municipal wastewater treatment plant (Lizarazo 2008 and SEMAPA 2009). In some peri-urban areas where people have more money, sewage systems are installed in the houses and there are combined systems of grey- and blackwater going to septic tanks. Septic tanks are expensive though, and many people living in peri-urban areas cannot afford them. Instead they use a *pozo ciego* (a hole in the ground) as a latrine, and throw out the greywater used e.g. for washing and cooking onto the ground outside the house. Even if the *pozo ciego* may have a stone lining there can still be seepage contaminating the groundwater and the water in freshwater wells (Bomblat 2008, Heredia 2008). In 2003, only in Cochabamba, 20 000 people suffered from diarrhoea (Bomblat 2008). The proportion between the different ways in which households handle wastewater in the Cochabamba region was analyzed by the Bolivian National Statistical Institute (INE) in 2001. 33 % of the households were connected to sewage pipe systems, 25 % used *pozos ciegos* and other recipients like streets and rivers and 8 % used septic tanks (INE 2008a). In many cases the effluent water from septic tanks is not treated any further but discharged from the tank directly into a river (Lizarazo 2008).

Cochabamba has only one large wastewater treatment plant, *Alba Rancho,* operated by SEMAPA, the water company of Cochabamba. The treatment plant is a waste stabilization pond system consisting of four modules, each including two primary facultative ponds in parallel followed by a maturation pond (Juanico et al. 2000). The annual mean flow is 550 l/s (Lizarazo 2008) but the treatment plant is designed for a flow of 400 l/s (Bomblat 2008). The treated wastewater is used for irrigation of large areas with corn, alfalfa and pasture for animal consumption (Lizarazo 2008). There are high costs for electricity and there are sometimes problems with odour (Bomblat 2008). According to SEMAPA (2009) the capacity is satisfying but the fast growing population and the uncontrolled increase in new contributions is generating an overload that soon will be uncontrollable.

Figure 5. Wastewater pumping (left) and stabilization ponds (right) at Alba Rancho.

There is a large reduction in BOD-level, from 400 mg/l to 75-85 mg/l, when comparing the affluent and the effluent of Alba Rancho. The concentration of faecal coliforms is around 10^4 in the outlet and does not satisfy the limit of the Bolivian law (see 3.3.1). There are plans to install a UASB reactor at Alba Rancho where the produced biogas could be used as energy source at the treatment plant, lowering the consumption of electricity. Further proposed improvements are another maturation pond and additional disinfection but there is currently not enough money. (Lizarazo 2008)

3. THEORY AND LITERATURE STUDIES

3.1 Wastewater

Water is abundant on this planet but not in forms that are always useful to humans. Of all water, 98 % is salt water, 1.6 % is ice, 0.4 % is ground water and 0.004 % is surface water. Only the later two are important and possible as water sources for human needs, and it is clear that the resource of water is scarce. When contaminating water we also risk spreading disease and increasing environmental problems through uncontrolled release and lack of treatment. (Kemira 2003)

Wastewater generally includes a large variety of contaminants. It can be very complex in composition, originating from households, industries and stormwater collection. In this project no industrial wastewater will be considered, only domestic. Typical components of wastewater are microorganisms, biodegradable and other organic material, nutrients, metals and other inorganic material. There are also physical effects like odour and heating of the recipient environment. (Henze et al. 1995)

Domestic wastewater can be categorized by its origin. Blackwater is water from the WC, containing faeces and urine. Greywater is water from the kitchen, bathroom and laundry (Ujang and Henze 2006). The water treated in the constructed wetland is supposed to be greywater. This literature study focuses on the parameters that were tested in the project. Chemical, physical and biological characteristics are presented below.

3.1.1 Chemical Characteristics

Organic material

Wastewater contains a vast number of organic materials of different kinds. In the case of domestic wastewater, these originate from sources like kitchens and bathrooms, and are comprised of carbohydrates, fat, proteins, higher fatty acids and soluble organic acids, among others (Kemira 2003). It is hard to determine all organic materials in detail but they share common characteristics that can be tested in more collective analyses. The average composition of the organic material is $C_{18}H_{19}O_9N$, which is oxidized into CO_2, ammonium and water, when degraded (Henze et al. 1995). The parameters included in the analyses of this study, except for organic nitrogen, are listed below.

Biochemical oxygen demand, $BOD_{5(7)}$

BOD indicates the amount of biodegradable substances in wastewater, and is widely used and recognised as an important parameter in wastewater treatment processes. It is a measure of the oxygen demand of microorganisms, when degrading organic matter in wastewater, at 20°C. In Sweden the standard is to measure BOD over seven days (BOD_7), but internationally a five day period is more common (BOD_5). The later will be used in this project. "BOD" in the report text refers to BOD_5. (Henze et al. 1995, Kemira 2003)

BOD is measured by aerating a sample of wastewater well and sealing it in a container. The sample is left in a dark place for five (seven) days, at a constant temperature. Microorganisms in the wastewater consume oxygen during the degradation process. At the end of the period the residual oxygen is measured, and the amount needed for degradation calculated. No air should be allowed to come into contact with the liquid since it is the decrease in oxygen concentration in the liquid that is of interest. It is thus important to ensure that the oxygen in the sample is sufficient for the whole incubation period. (Henze et al. 1995)

Chemical oxygen demand, COD

COD describes the total content of organic matter in a sample, and is given by the amount of organic material that can be oxidized by a strong chemical oxidant at high temperature, in a strongly acidic solution. Potassium dichromate or potassium permanganate can be used, one being a stronger oxidant than the other. The consumed amount of these chemicals is converted to an equivalent amount of oxygen needed for the same level of oxidation. This is the COD value. (Henze et al. 1995, Kemira 2003)

Inorganic material

Inorganic material in wastewater is mainly dissolved salts. What amounts and which kinds depend largely on the character of the incoming water and its sources. The following parameters are studied to better understand the treatment process.

pH

The pH is a logarithmic index of the concentration of hydrogen ions (H^+) in water solution. A pH value of 7 indicates neutral conditions. Above 7 is basic and below is acid. When measuring pH the voltage between a glass and a reference electrode is measured. The pH is regulated by the proportions of concentrations of CO_2, HCO_3^- and CO_3^-, photosynthesis, respiration as well as oxidation of dissolved inorganic material, which produces H^+, and reduction of organic material, which consume H^+ (Limnology compendium, undated). The pH is a useful and important parameter in measuring the conditions in and quality of wastewater during the whole treatment process. Especially metabolic reactions in biological processes are highly pH dependant and sensitive to low pH levels or changes in pH. The pH may be low in influent wastewater and it might drop e.g. in connection with the nitrification process. (Björnsson and Murto 2007, Henze et al. 1995) Optimal pH ranges are described further in the sections concerned, in this chapter.

Conductivity

Water containing dissolved ions has the ability to conduct electric currents. This ability is called specific conductivity and is a direct function of the amount of ions present in the water (salinity). More ions give a higher conductivity, and this is measured using a conductivity meter. In this instrument the resistance of a liquid to conduct an electric current between two 1 cm^2 electrodes at a distance of 1 cm, is measured. The conductivity is reversely proportional to the resistance. (Enell and Larsson 1985)

The conductivity is temperature dependent and increases with about 2 % for every °C. Therefore it is standardized to 25 °C, and if the instrument used does not compensate for the temperature difference this has to be done manually. It is, however, better the closer the sample is to the standard temperature when measuring, because then the values will be more reliable. If the sample has a high concentration of hydrogen ions (low pH) this will strongly influence the result since these ions have a high conductivity. pH should thus be controlled before measuring and the results corrected if the pH is below 5.9. (Enell and Larsson 1985, Leonardson 2007)

Oxygen

The natural inputs of oxygen to waterbodies are through diffusion from the atmosphere and photosynthesis. The losses of oxygen are through

1) diffusion to the atmosphere
2) respiration by organisms and oxidation of organic material
3) oxidation of inorganic substances, e.g. nitrification
4) photooxidation of dissolved organic matter by solar radiation

The solubility of oxygen (O_2) in water is dependent on the temperature, the salinity and the pressure. Increase in temperature leads to decrease in solubility of O_2, i.e. at a higher temperature less oxygen can be dissolved in water (see Figure 6). Also higher salinity gives a lower solubility. The solubility increases with increase of atmospheric pressure.

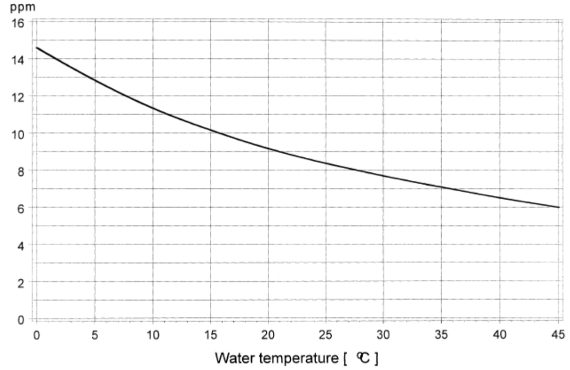

Figure 6. Saturation of dissolved oxygen as a function of water temperature at sea level (Juanico et al., 2000).

The atmospheric pressure decreases with altitude and thereby the oxygen saturation. In Figure 7 correction factors for calculation of oxygen saturation at different altitudes are presented. The city of Cochabamba is situated at an altitude of 2550 m.a.s.l. and according to Figure 7 the correction factor is 0.75 for that altitude.

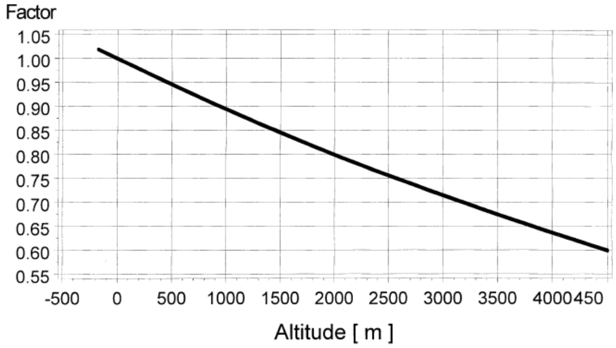

Figure 7. Correction factor to determine dissolved oxygen saturation in water at different altitudes and fixed temperature, as a function of atmospheric pressure. At sea level the correction factor is 1. (Juanico et al., 2000)

In Cochabamba the climate and the altitude give relatively high temperatures and low pressure, which both lead to low solubility of oxygen in water. These parameters, for three different parts of Bolivia, are presented in Table 1. Cochabamba is situated in the area *Valles*. The water temperatures are measured in wastewater stabilization pond systems.

Table 1. Altitude and water temperature and their effect on dissolved oxygen saturation in three different parts of Bolivia (the water temperatures are measured in wastewater stabilization pond systems). Modified from Juanico et al. (2000)

Parameter	**Units**	**Altiplano**	**Valles**	**Llanos**
Altitude	m.a.s.l.	4000	2500	400
Mean water temp.	ºC	9	20	24
Diss. oxygen saturation	mg/l	7.3	7.0	8.4

The altitude and mean water temperature vary between different areas of Bolivia. However, the total effects of altitude and temperature give a quite similar saturation of dissolved oxygen in water in the different areas. The oxygen saturation was calculated to 7.0 mg/l in Valles which is 0.3 mg/l and 1.4 mg/l lower than in Altiplano and Llanos respectively (Juanico et al. 2000).

3.1.2 Physical Characteristics

Suspended solids and total solids

Pollutants in wastewater can be categorized in different ways. One important distinction, concerning particle size, is that between suspended solids (SS) and dissolved solids (DS) in the water. This is because many wastewater treatment techniques are only designed to be effective against one of these (Henze et al. 1995). There are also other fractions of solids: colloidal and settleable solids (Kemira 2003). They will, however, not be regarded in this case.

When filtering a sample, the suspended solids are the pollutants retained in the filter, whereas the pollutants passing through the filter are the dissolved solids. In most countries the filter pore size for testing SS is standardized and set to 1 or 0.45 µm (Henze et al. 1995). The sum of SS retained in a filter is also called total suspended solids (TSS). TSS is measured by weighing the filtered sample after two hours of drying at 105 °C. Total solids (TS) can be measured using the same technique as for TSS. The difference is that the sample is not filtered before drying.

Temperature
Temperature affects chemical and biological processes in a profound way. It influences several parameters, e.g. specific conductivity, biological activity, biologically mediated cycling of nutrients and organic material and solubility of gases (Limnology compendium, undated). The rate of chemical reactions and biological activity increases with increased temperature. Metabolism and growth of microorganisms are affected by this but only up to a certain level, after which the rate becomes lower and eventually lethal temperatures stop the growth altogether. Different microorganisms tolerate different temperature intervals. In the case of wastewater treatment and disease prevention it is mesophilic bacteria that are interesting. Their optimal growth temperature is around 37 °C; hence they are favoured by the human body temperature. (Björnsson and Murto 2007)

Turbidity
In the case of water, turbidity is a measure of clarity. It is a measure of the physical, optical property that scatters light and absorbs it in particles and molecules in the water column. Turbidity is caused by suspended matter, e.g. soil particles of clay or silt, small organic and inorganic particles, plankton and protozoa. Besides being an esthetical parameter, turbidity is an important characteristic since it is often correlated with pathogen and parasite occurrence in water. In particulate matter, microbes can find food and shelter from disinfectants. Examples of removal in decentralized small scale systems are sedimentation or filtration through cloth, fibre, sand or simple membranes. (USEPA 1999, WHO 2008)

Turbidity is often measured using a nephelometer, which determines the amount of light scattered at a 90° angle from the original direction of the light beam. This angle is considered the least sensitive to variations in particle size in the sample. The unit for turbidity measured with this instrument is nephelometric turbidity units (NTU). It is directly comparable with another common unit, formazin turbidity units (FTU), given by a different testing procedure. (Kemira 2003, USEPA 1999)

3.1.3 Biological Characteristics

Microorganisms
A microorganism is an organism too small to be seen by the human eye. Microorganisms can be divided into prokaryotes and eukaryotes. The distinction is made because of significant differences in structure. Prokaryotes lack, for example, membranes around several important parts of the cell, including the nucleus. There are also differences in cell wall and cell membrane construction. Larger organisms can be very important to the populations of the groups mentioned below. Some are called metazoa and are multicellular higher animals, 0.1-0.5 mm in size. Examples of these are the nematodes and rotifers. Together with protozoa they feed on bacteria and other smaller organisms. (Björnsson and Murto 2007)

Prokaryotes
The prokaryotes are divided into two groups: bacteria and archaea. Bacteria are unicellular and can have a number of different shapes and sizes (0.1-40 μm). The two most common shapes are the spherical cocci and the rod shaped bacilli. The cocci can live separately or clumped together in clusters, and the bacilli can be twisted into different shapes. All these different ways of existing have been given separate names. They can exist freely in water or attached to a surface, and they are important in performing transformation and degradation of dissolved organic compounds in wastewater. Archaea have generally the same size and shape as bacteria, but are very different in e.g. genetic composition, cell wall structure, membrane lipid structure and metabolism. These organisms are often very tolerant against extreme environmental conditions. (Björnsson and Murto 2007, Henze et al. 1995)

Eukaryotes
The eukaryotes can be divided into three groups, fungi, algae and protozoa. Fungi can be both unicellular, reproducing through growing new cells from the old ones and detaching them, and grow in filamentous hyphae that grow as a network of filaments called mycelium. Reproduction through spores can also be the case. Fungi often degrade organic material through excreting enzymes and then absorbing the resulting simpler compounds. They thrive under moist conditions and in lower pH. The algae are found in water, both freshwater and salt water. They are a number of different unicellular and multicellular organisms. Since they have chlorophyll they can produce oxygen through photosynthesis, but they have simple vascular and

reproductive systems. The algae require light to grow so they are often found on the surface of water. Protozoa are unicellular, motile organisms that are only related by common trait of not being multicellular. Examples of protozoa are amoebas, ciliates, flagellates and sporozoa. These can be free swimming, crawling or attached to a surface. They eat bacteria, fungi, algae and suspended organic matter. (Björnsson and Murto 2007, Henze et al. 1995)

Nutrition and growth

There are also distinctions to be made between different organisms based on how they obtain carbon and energy. Autotrophs use CO_2 as carbon source, while heterotrophs use reduced organic compounds. Phototrophs use light energy from photosynthesis, and chemotrophs oxidise organic and inorganic molecules for energy. Which microorganisms that occur in a specific environment, is governed by different selection parameters and adaptation possibilities of the organisms. In an environment where the constituents of the water do not change much over time, a specialized fauna can develop for efficient removal of for example particles, nutrients and pathogens. (Björnsson and Murto 2007)

Pathogens

Pathogens are disease causing organisms. Certain bacteria, protozoa and viruses are examples of these, and are measured as number/100 ml of fluid (Kemira 2003). Some of these are indicator organisms for the total amount of pathogens in wastewater. Outside the host protozoa and viruses are not able to multiply and decrease therefore naturally. Bacteria on the other hand, may continue to multiply under favourable conditions (EcoSanRes 2008). One subgroup of coliform bacteria is called thermotolerant (faecal) coliforms. These are found predominantly in the intestine and faeces of humans and warm-blooded animals. *Escherichia coli (E.coli)* is one member of the thermotolerant coliform group and is the most specific indicator organism of faecal contamination in water. (Cooperative Research Centre for Water Quality and Treatment 2006)

3.2 Nutrients

Nitrogen and phosphorus are plant and animal nutrients that are utilized in many biological processes, and exist in different forms in wastewater. Nutrient removal is often the focus of water treatment since nitrogen and phosphorus are major sources of eutrophication in rivers, lakes and the sea. Hence they deserve a separate chapter.

3.2.1 Nitrogen

Nitrogen occurs in different forms in nature. As nitrogen gas (N_2) it makes up 78 % of the atmosphere. From that form it is fixated by specialized microorganisms and converted into organic material. This is a very energy demanding conversion, and is only done when the access to ammonium or nitrate is low. Nitrogen is a building block in many complex molecules like amino acids, proteins and nucleic acids in DNA. When organisms die, organic matter is decomposed and nitrogen re-enters the nitrogen cycle of nature. (Kemira 2003)

Ammonification

When organic matter is decomposed by bacteria the organically bound nitrogen is transformed via dissolved organic nitrogen and mineralized to ammonium (NH_4^+).This process is called ammonification and takes place in soil, sediment and water, both in presence and absence of oxygen. Ammonium may also be released by living organisms. It can be utilised in a number of ways, for example be assimilated by bacteria or plants to build up biomass, be adsorbed to the surface of soil particles, humic material or dead plant tissues. Ammonium is an easily accessible nutrient for aquatic and land-based plants, but a large part will still be released into the surroundings. Ammonium exists in a chemical equilibrium with ammonia (NH_3). The relative distribution between the compounds is governed by pH and temperature. At neutral pH levels almost all reduced nitrogen is in the form NH_4^+ but if pH or temperature is elevated the ratio changes towards a larger NH_3-part. (Kemira 2003, Leonardson 2003)

Nitrification

Nitrification includes two consecutive processes where ammonium is oxidized by autotrophic bacteria to nitrite (NO_2^-) which, after it is formed, immediately is oxidized to nitrate (NO_3^-). Nitrite occurs therefore invery low concentrations while nitrate may occur in high concentrations.

The first step:
$NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O$ Group of bacteria: *Nitrosomonas*

The second step:
$NO_2^- + 0.5O_2 \rightarrow NO_3^-$ Group of bacteria: *Nitrobacter*

Nitrification can occur in soil, at the surface of sediments of lakes, ponds and marine areas, in the water column and in biofilms. The process is aerobic, i.e. oxygen is required. If an oxygen deficit develops, the activity of the nitrifying bacteria stops. (Leonardson 2003)

The nitrification process produces acid that reacts with carbonate in the water. If the alkalinity of the water is low (low carbonate content) then the pH may drop sharply during nitrification. It will inhibit the nitrifying bacteria which work best at pH 8-9. If the pH drops below 5.5 the nitrification stops, but the oxidation of nitrite is favoured by a low pH so the pH must not be too high either in the nitrification process. (Kemira 2003)

Temperature has a major effect on the rate of nitrification. The rate of all aerobic biological processes increases exponentially with increased temperature in the range 0-32 ºC. At temperatures of 30-35 ºC the growth rate of nitrifying bacteria is constant and between 35-40 ºC it starts to decline towards zero. The nitrifying bacteria are sensitive to sudden variations in temperature. (Henze et al. 1995)

Denitrification

During denitrification, nitrate is reduced to nitrogen gas (N_2) by microorganisms. This is an obligate anaerobic process, i.e. it only takes place in environment without oxygen. The end product N_2 dissolves in the water and slowly diffuses to the atmosphere. Nitrate dissolves in water and is not absorbed to surfaces, hence it can be transported with rain water, ground water or drainage water from soil to streams, lakes and all the way to the sea if it is not taken up by organisms or denitrified on the way. (Leonardson 2003)

Denitrification can occur everywhere where easily decomposed organic material is accumulated, nitrate is present and there is no oxygen, e.g. bottom of lakes, wet soils and root zones of plants. In microzones where there is a lot of easily decomposed organic material, aerobic decomposing bacteria will be very active. Oxygen deficiency develops when oxygen is consumed faster than it is introduced into the system. (Leonardson 1994)

In *heterotrophic denitrification,* decomposing bacteria gain energy by oxidizing organic material to among other things carbon dioxide and water. In *autotrophic denitrification* the bacteria oxidize inorganic compounds, e.g. reduced iron, manganese or sulphur. Usually when discussing denitrification in connection to wetlands it is the heterotrophic denitrification which is considered. In both heterotrophic and autotrophic denitrification, nitrate is used as electron acceptor in the oxidation. If oxygen is present facultative anaerobes (bacteria that can use both oxygen and nitrate for the oxidation) will use this as electron acceptor instead and no denitrification will take place. The bacteria prefer oxygen since it gives a slightly higher energy yield. (Leonardson 2003)

The denitrification process occurs stepwise:

$NO_3^- \rightarrow NO_2^- \rightarrow N_2O \rightarrow N_2$

The total process can be written (unbalanced formula):

Org./inorg. material + $NO_3^- + H^+ \rightarrow N_2 + CO_2 + HCO_3^- + NH_4^+ + H_2O$

All of the intermediate products are toxic or undesirable (Henze et al. 1995). At low pH (4-5) and low temperature, there is a risk of the process being inhibited and the end products being N_2O or NO_2^- instead (Leonardson 2003). The optimum pH for denitrification processes is 7-9. The process leads to an increase in alkalinity. Half of the alkalinity lost in the nitrification process is recovered. The denitrification rate is dependent on temperature but not as much as the nitrification rate. (Kemira 2003)

3.2.2 Phosphorus

Phosphorus (P) is also an important nutrient for organisms. It has no gaseous phase which makes it the limiting nutrient in many cases, together with the fact that phosphorus compounds are very reactive and form complexes with other substances. Therefore the availability of phosphorus is usually very low in natural systems, and phosphorus is the limiting nutrient for primary production in many lakes. A consequence of this is the risk for eutrophication if large amounts of phosphorus are released into receiving waters. In domestic wastewater phosphorus exists in the form of particulate and dissolved organic phosphorus, and dissolved poly- and orthophosphate (PO_4^{3-}). Phosphorus from detergents makes up one third of the P load, and comes in the form of polyphosphates. These are, however, quickly hydrolysed into orthophosphate. In pre-treatment up to 30 % of the P can be removed since this is more or less the fraction bound in organic, suspended compounds. (Kemira 2003, Leonardson 2003b)

In wetlands, lakes, ponds and rivers particulate phosphate may be deposited by sedimentation, trapped by macrophytes stems or sorbed to biofilms. Soluble phosphate may be sorbed to plant biofilms or to the sediments. There is an exchange of soluble phosphate between the pore water in the sediments and the overlaying water column. In the sediment pore water the phosphates may be precipitated as ferric, calcium or aluminium phosphates, or adsorbed onto clay particles, organic peat or ferric and aluminium oxides and hydroxides. Release of phosphate from the metal complexes depends on the redox potential of the sediment. For example anaerobic conditions may lead to leakage of sediment bound phosphate, while an increase in oxygen levels leads to adsorption of more phosphate. pH also influence the release of phosphate. (Leonardson 1994, USEPA 2000)

3.3 Treatment Requirements

3.3.1 Legislation

Activities influencing the environment are regulated in the Bolivian Environmental Law, *Ley No. 1333 de Medio Ambiente*[1]. The law is followed by five ordinances. One of the ordinances concerns contamination of water, *Reglamento en materia de contaminación hídrica* (RMCH), and it is applicable to anybody whose activities could cause contamination of water resources. In Annex A of this ordinance there are tables with maximum admissible values for different compounds in receiving waters. There is a classification A-D of water resources after quality, and there is a list of what purposes the classes can be used for. (RMCH 1995)

The maximum values in the classification must not be exceeded on any occasion by discharge of treated or untreated wastewater (article 35). All discharges of wastewater to lakes, rivers and aquifers coming from domestic use, industry, agriculture or any other activity that can contaminate the water, should be treated before discharge to satisfy the limits of water quality established for the recipient (article 46, 47, 64). (RMCH 1995)

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[1] In Sweden small, decentralized wastewater treatment systems (for less than 200 persons) are regulated by the Swedish Environmental Law, *Miljöbalken*. Before constructing a treatment system, permission from the municipality is needed. In some cases it can be enough to send in a notification. The house-owner has a large responsibility to acquire sufficient knowledge about the risks and to hinder damage of the environment and people's health. The house-owner is responsible for the system working properly in accordance with the permission. It is prohibited to discharge water from a septic tank without further treatment. An assessment should be done in each case and it is the municipality that sets the requirements. (Avloppsguiden 2009)

Small, decentralized wastewater treatment systems in Sweden are expected to reach a minimum BOD_7 reduction of 90 %, or an effluent concentration of 30 mg/l. The reduction of total P should be at least 70 % or reduced to 3 mg/l. Techniques limiting the water consumption, and detergents free from phosphates should be used. The system should make reuse of nutrients from wastewater fractions possible. Discharge of the treated water should not significantly increase the risk of infections or odour, where people may be exposed. There is a higher protection level, with stricter recommendations, if for example the recipient is extra sensitive, there is a lot of discharges in the area or if the system is situated close to groundwater or surface water used as potable water source. (Naturvårdsverket 2006)

The reuse of wastewater will be authorized by the regional government when the interested party can show that the water reaches the quality established in Table 1 in Annex A, RMCH. According to the table, water used for irrigation of vegetables consumed raw, and fruits with thin skin that are ingested raw, must have at least the quality of "class B". Water used for recreation with primary contact, e.g. swimming, must have the quality of "class C". The values in the classification apply for a mix of discharged water and receiving water calculated from an equation given in RMCH. Some parameters from the classifications are presented in Appendix 3.

There are also limits for liquid discharge in the mentioned ordinance which are absolute values and do not depend on the water quality of the receiving water. For example, the permitted effluent level for faecal coliforms is 1000 MPN/100 ml and the maximum values for BOD_5 and COD are 80 and 250 mg/l respectively (Table 2). The ordinance for the industrial sector in Bolivia, *Reglamento ambiental para el sector industrial manufacturero* (RASIM) has almost identical permitted values for waterbodies and liquid discharge as RMCH (Cámara nacional de industrias 2008).

Table 2. Highest values allowed in liquid discharge according to the Bolivian ordinances RMCH and RASIM (MPN = most probable number).

Parameters	Daily limit	Monthly limit
pH	6-9	6-9
Temperature	+/- 5 ºC	+/- 5 ºC
Suspended Solids (mg/l)	60	
Faecal Coliforms (MPN/100 ml)	1000	
BOD_5 (mg/l)	80	
COD (mg/l)	250	
NH_4-N	4.0	2.0

3.3.2 Guidelines

There are also requirements recommended in the literature. Some of the recommendations regarding reuse of treated wastewater for irrigation purposes and decentralized wastewater treatment systems will be presented here. To reuse water for activities and areas with public access, for example parks and irrigation of crops that will be eaten raw or that are not commercially processed, USEPA (2004) recommends that there should be no detectable faecal coliforms/100 ml of water, and BOD values of less than 10 mg O_2/l. This is called unrestricted irrigation. For restricted irrigation, when irrigating areas with limited or no public access and cereal crops, industrial crops, fodder crops, pasture and trees, the recommendations from USEPA (2004) are faecal coliform concentrations of less than 200 faecal coliforms/100 ml and BOD and SS levels of less than 30 mg/l. In the guidelines from WHO (1989) on safe wastewater reuse, the recommended limit was 1000 faecal coliforms/ml for unrestricted irrigation, the same value as in the Bolivian regulation, and no standard for restricted irrigation was given.

The guidelines of USEPA regarding permitted levels of faecal coliforms and required water treatment methods, have been criticized to be unnecessarily strict and to result in high costs that cannot be justified in developing countries where enteric diseases are more often transmitted through poor sanitation and hygiene than through wastewater reuse (Blumenthal et al. 2000). When revising the guidelines of WHO from 1989, Blumenthal et al. (2000) recommended a limit of $1 \cdot 10^5$ faecal coliforms/100 ml for water used for restricted irrigation. Also WSP (2006) recommends that an effluent with up to $1 \cdot 10^5$ faecal coliforms/100 ml can be used for irrigation of industrial crops, energy plantations, fruit trees and plants where the product is cooked before consumption. In the new guidelines from 2006, WHO validated their earlier general recommendation of 1000 *E.coli*/100 ml for unrestricted wastewater use in agriculture, but other values were also given, e.g. 10^5 *E.coli*/100 ml for drop irrigation of higher crops (WHO 2006a).

Plants can only tolerate a certain amount of salinity without being negatively influenced, and it is thus important not to have too high conductivity in the wetland influent water or anywhere in the wetland. This concerns both wetland plants and grass, fruit trees etc. irrigated with the effluent water. High salt concentrations reduce water uptake in plants by lowering the osmotic potential of the soil (Haering et al. 2008). Different crops have different abilities to tolerate salinity in irrigation water, see Table 3. Some crops and fruit plants can stand salinity levels (specific conductivity) up to 5 300 µS/cm. The most sensitive plants only tolerate a conductivity of 700 µS/cm. The tolerance is mainly influenced by climate, drainage characteristics and soil type within the root zone. These factors are important for accumulation and leachate of salts. The levels in Table 3 refer to moderate to slow draining soils and inland climate of New South Wales, Australia. Other important factors are irrigation method and stage of plant growth. Generally grass species tolerate higher salinity levels. (New South Wales Department of Primary Industries 2006)

Table 3. Maximum levels of salinity, measured as specific conductivity, where crops do not suffer from reduced growth (N.B. these levels may vary due to different factors in the environment).

Crop	Specific conductivity (µS/cm) Limit for no growth reduction
Zucchini	3 100
Tomato	1 700
Spinach	1 300
Potato	1 100
Lettuce	900
Maize	1 100
Onion	800
Carrot	700
Olive	2 600
Orange	1 100
Peach	1 100
Lemon	700
Apple	700
Different grass species	1 000-10 000

Modified from New South Wales Department of Primary Industries 2006.

Monitoring water quality and wetland effectiveness

To control the effectiveness and the quality of the effluent, a constructed wetland needs to be monitored regularly. There are different types of monitoring. *Validation* is performed to test that a system is capable of meeting specified targets when a new system is developed or new processes are added. *Operational monitoring* relies on simple measurements on a regular basis to investigate whether the processes are working as expected. *Verification* will show if the end product meets treatment targets and can indicate trends over time. (WHO 2006a)

When it comes to the frequency of the chemical and physical analyses there are different opinions. In Nicaragua it is necessary to take samples three times per year from the affluent and the effluent of the constructed wetland, and the samples should be an average from at least 12 hours (Water Sanitation Program 2006). The recommendations from USEPA indirectly concern constructed wetlands since they concern reuse of treated wastewater. USEPA (2004) recommends that water used for irrigation of areas without public contact and crops not eaten raw should be monitored as follows: pH and BOD should be controlled weekly while faecal coliforms and suspended solids should be monitored daily. In the Bolivian water contamination ordinance, it says that monitoring of receiving waters and discharge of wastewaters will be done by a representative of the regional government, with personnel from authorized laboratories, every six months. Composite samples should be taken during the hours of maximal production. (RMCH 1995)

According to the recommendations from the Swedish Environmental Protection Agency, concerning small wastewater treatment systems in Sweden, the municipality should demand control of the system at least every ten years. If the system is sensitive to disturbances, control every year is recommended. The superintending authority may, if it is suspected that the system does not fulfil the requirements, demand monitoring of the effluent. (Naturvårdsverket 2006)

3.4 Constructed Wetlands

A constructed wetland means a wastewater treatment system consisting of one or more shallow basins, where natural processes help to increase the quality of the water. There are three base types of wetlands: free water surface, horizontal subsurface flow and vertical subsurface flow wetlands. They all have macrophyte coverage of varying degree and the flow is usually driven by gravity. In constructed wetlands pollutants are removed through a combination of physical, chemical and biological processes, including sedimentation, precipitation, adsorption to soil particles, assimilation by plant tissue and microbial transformations. Constructed wetlands imitate natural wetlands through removal mechanisms, but in constructed wetlands the size, composition of substrate, type of vegetation and flow pattern can be designed to fit the environmental conditions and wastewater composition. The degree of control is larger than in a natural wetland where species composition and performance may change over time. (Brix 1993, Kadlec 2009)

The treatment method was developed in Europe in the 1950's (Bomblat 2008). It has been tested in large scale, and is an accepted method to purify residual water from small communities and single houses in sparsely populated areas (Tonderski et al. 2002). A relatively large amount of treatment plants are currently in use in Europe and North America. Most of them are small, but for example in Denmark, where the total amount is about 100 plants, there are more than 30 plants constructed for 5 000-6 000 person equivalents (Leonardson 1994). In Central America there exist at least 8 systems of constructed wetlands with subsurface flow (WSP 2006). Also in Africa, Asia, South America and Australia these types of wetlands have been constructed.

3.4.1 Horizontal Subsurface Flow Constructed Wetlands

In a constructed wetland with horizontal subsurface flow (HSF) the water flows horizontally through a bed of a relatively homogenous medium, like gravel, sand or stones of different sizes. The typical water depth is 50 cm and the water fraction 40 % (Kadlec 2009). Other names used in literature are vegetated submerged bed, biofilter, artificial wetland and root-zone wetland.

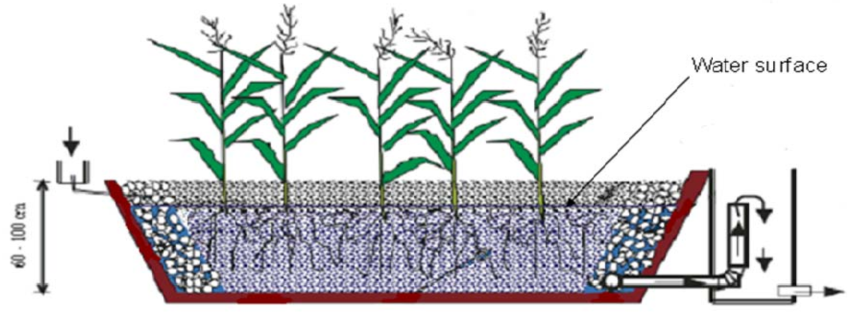

Figure 8. Cross section of an HSF constructed wetland. (Picture from WSP 2006)

The medium in the wetland is underlain with an impermeable layer, made of plastic or soil with very low permeability, to prevent seepage of wastewater down to the groundwater. During the passage through the wetland, the decomposable parts of the wastewater are transformed by microorganisms which are attached as biofilm to plant roots and the filter medium (Thiel-Nielsen 2005). The vegetation in the wetland consists of emergent macrophytes (rooted aquatic plants with leaves above the water surface). To achieve a good stand and coverage of plants during the first growing season, a distance of 0.9-1.2 m between the plants is given as general recommendation (Surrency 1993) but macrophyte planting density can be as close as 0.3 m. A constructed wetland will take at least two full growing seasons to approach equilibrium and optimal performance, if planted with 1 m distance. It is recommended to let clean water enter the wetland during the planting phase. Plant growth may be inhibited by the high oxygen demand in wastewater coming from a septic tank effluent. The wastewater can be introduced after a few weeks of plant growth. When planting an HSF wetland it is typical practice to flood the chamber to the surface of the media until growth has occurred and then lower the level to the operating level (USPEPA 2000).

Compared to a wetland with free water surface, the need of surface area is decreased when using an HSF wetland (Tonderski et al. 2002). Gravel, sand, rhizome, roots and dead plant material together create very large surfaces for microorganisms to grow on. Biofilm formation on the medium is favoured by the constant addition of nutrients and carbon sources from the wastewater. It also depends on the surface characteristics of the medium. Coarser, more porous media have a larger surface for the microorganisms to grow on. Unlike the free surface wetland, water should never reach the surface of the HSF wetland. This would mean short circuiting of the treatment, as the water is no longer in contact with the biofilm or the root zone. Hence before entering an HSF wetland, wastewater needs to be pre-treated in a septic tank or similar, to remove solids. If allowed to enter the wetland, these could effectively clog the medium and prevent water passage and subsequent treatment.

3.4.2 General Advantages and Disadvantages

There are advantages with HSF constructed wetlands compared to conventional treatment systems, and some of them will be presented here. Treatment of wastewater in HSF constructed wetlands is considered a robust process which gives a stable effluent quality because of the relatively long retention time (Thiel-Nielsen 2005). The systems are usually more flexible and less susceptible to variations in loading rates (Brix 1993). They can stand low loading for an extended period of time, e.g. during a vacation, and also handle extra large loads during a short period, and still keep a good effluent quality (Thiel-Nielsen 2005). Untreated water is not exposed to the atmosphere, hence there are less odour problems than in basin or lagoon treatment plants, and there are fewer problems with mosquitoes since the water surface is inaccessible (WSP 2006).

There is no need for chemical products or pumps, but pumps might be needed to distribute the effluent for e.g. irrigation. The energy requirements are low and so is the cost for construction and maintenance. The costs can be reduced even more if the people involved in the project help out. The treatment plant can be run by relatively untrained personnel, for example a person with interests in the area (Bomblat 2008). The treated water might be acceptable as irrigation water, if certain treatment levels are reached (see chapter 3.3). The wetland can be integrated and enhance the esthetical value of an area with its vegetation. (Brix 1993)

Some disadvantages with HSF wetlands are risk of shortcuts on the surface between inflow and outflow and possibility of clogging if pre-treatment is insufficient (Brix 1993). Due to limited oxygen transfer the systems may turn anaerobic, thus requiring a long retention time to achieve desired water quality (Chan et al. 2005). Compared to conventional systems constructed wetlands require larger land area but compared to free water surface constructed wetlands HSF wetlands require less land area. In temperate regions the performance might be decreased during winter. Constructed wetlands are regarded as an attractive alternative for small to medium-sized communities in sparsely populated areas and in developing countries. (Brix 1993)

3.5 Hydraulics in Constructed Wetlands

3.5.1 Retention Time

Nominal retention time, also called hydraulic residence time or theoretical retention time, is a measure of how long time it takes for the whole water volume of a lake, dam or wetland to be replaced. It is defined as $RT = V/Q$, where V is the total water volume and Q is the flow through the wetland. The assumptions are steady-state conditions, i.e. the inflow is equal to the outflow ($Q = Q_{in} = Q_{out}$), and no mixing of the water column.

The whole volume of the wetland is not occupied by water but also by the medium, e.g. gravel. The water volume is therefore limited to the total void space between the grains. The nominal retention time for a constructed wetland is given by the following expression (USEPA 1993):

$$RT = \frac{A \cdot y \cdot n}{Q} \qquad (1)$$

A = surface area of the wetland (m^2)
y = depth of water-filled part of the wetland (m)
n = porosity, % expressed as decimal
Q = average flow through the bed (m^3/day)

Equation 1 takes into consideration the porosity of the medium but not plant roots, biofilm nor non-degradable residues. Over longer time, the accumulation of non-degradable residues in the pore spaces and the spreading of plant roots will also add resistance to the flow. Eventually this could lead to clogging of the medium and unwanted surfacing of the wastewater.

The required energy to overcome the resistance of the medium, plant roots and residues, is provided by the difference in hydraulic head between the inlet and the outlet of the wetland. The time it takes for the water to pass from the inlet to the outlet of the wetland may be less than the nominal retention time since the velocity of the water may be higher in certain channels of the bed and shortcuts can be formed. According to USEPA (2000) the actual retention time has frequently been reported to be 40-80 % less than the theoretical retention time. The explanations have been loss of pore volume, preferential flow and dead volume, i.e. stagnation points in the bed where the flow is zero.

3.5.2 Porosity and Permeability

Porosity is defined as Void volume divided by Total volume in a mineral soil and is expressed in percent (Svensson 1996, USEPA 2000). The porosity is larger for clays (45-50 %) than for stones because of the shape of the grains. If the stones are round and even, the porosity is 26-48 %. If they have an uneven shape, the porosity is only 20 %. The porosity discussed so far is the *total porosity*. There are not necessarily ways for the water to pass between these void spaces though. The *effective porosity* is the uninterrupted void volume needed for water to percolate through a material. Clay has a very low effective porosity while sand, gravel and stone have an effective porosity close to the total porosity. (Svensson 1996)

Permeability is the measure of a soil's or a rock's ability to transmit water and it is largest for coarse well-sorted soils, e.g. coarse gravel with grains of the same size. In a less sorted sample, the small grains fill the voids between the large grains and lower the permeability. The permeability can be expressed with a coefficient, called *hydraulic conductivity.* (Svensson 1996)

3.5.3 Flow Model

Ideal models are often used when describing and simulating both natural and industrial systems of flowing water and reactions. Two such models will be presented here. Transport processes affecting the system, and a method to investigate the hydraulic characteristics, will also be explained.

Continuously Stirred Tank Reactor

The ideal continuously stirred tank reactor (CSTR) is a completely mixed reactor (Figure 9). The concentration of all compounds and the tank temperature are identical in the whole reactor. Consequently, the reaction rates are identical in the whole tank volume. (Warfvinge 2007)

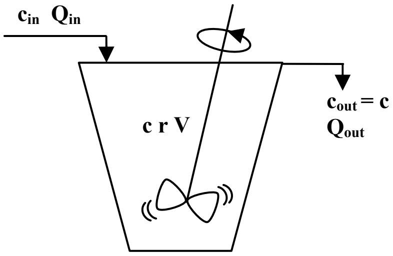

Figure 9. Continuously stirred tank reactor.

The general material balance can be described as follows:

$$\textit{In} + \textit{Produced} = \textit{Out} + \textit{Accumulated}$$

$$Q_{in} \cdot c_{in} + rV = Q_{out} \cdot c + \frac{d}{dt} cV$$

where Q = flow, c = concentration, r = reaction rate, V = volume and t = time. The reaction rate can symbolize for example a first order decay of a pollutant c and be written $r = -k \cdot c$. If there is no accumulation and steady-state conditions ($Q_{in} = Q_{out} = Q$), the concentration of the pollutant in the tank, and in the outlet, is

$$c = c_{in} \cdot \frac{1}{1 + k(RT)} \text{ where } RT = \frac{V}{Q}$$

If the model concerns a concentration of an inert tracer, there is neither production nor degradation. Depending on the initial conditions and c_{in} there could be accumulation. If $c_{in}=0$ at $t=0$ the solution is:

$$c = c_{in} \left(1 - e^{-\frac{t}{RT}} \right)$$

Plug Flow Reactor

The ideal plug flow reactor (PFR) can be represented by a flow passing through a tube while reacting (Figure 10). The fluid concentration is not mixed in the direction of the flow. Instead the flow moves forward through the reactor as "thin discs" with the volume *dV*, within which the conditions are identical. (Warfvinge 2007)

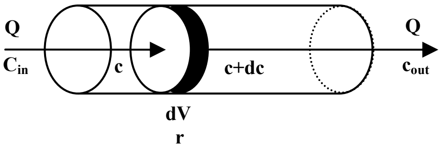

Figure 10. Plug flow reactor.

The material balance for the small, moving volume element *dV* is:

$$In + Produced = Out$$
$$Qc + rdV = Q(c+dc)$$

$$\frac{dc}{dV} = \frac{r}{Q} \qquad \begin{cases} V = 0, c = c_0 \\ V = V, c = c \end{cases}$$

and the solution for the whole reactor, with a first order reaction, is:

$$c = c_0 \cdot e^{-k\frac{V}{Q}} = c_0 \cdot e^{-kRT}$$

Tracer Studies

Non-ideal mixing conditions are a result of shortcutting by channel formation in the tank, stagnant zones, recycling, spreading and retardation processes. A system including such conditions is hard to describe well with an ideal reactor model like CSTR or PFR. To calibrate and verify models, and to investigate the hydraulic characteristics and flow paths of a system, tracer experiments are often done.

When a tracer is added to the inlet of a system, it is transported with small volumes of water. The tracer should be a compound that is not consumed or produced in the system, for example anions (Cl^- or Br^-) or stable or radioactive isotopes. A tracer added to an ideal CSTR will be rinsed out from the reactor with an exponential lapse. A tracer added to an ideal plug flow reactor exits the reactor as a Dirac function. In natural systems, spreading and retardation processes have an effect on the tracer and sometimes experimental data fit best to models built from a combination of the two reactor types. The retention time distribution for a series of tank reactors becomes more similar to that of a plug flow reactor, as more tanks are added in series. (Warfvinge 2007)

Transport Processes

The transport of water into, and through, a reactor or constructed wetland because of water pressure, is called *convective transport*. Forced convection can be driven by a pump and natural convection by only gravity or lift forces caused by density differences. (Warfvinge 2007) Diffusion and advection are the two main processes transporting solutes in porous media. Particles and compounds dissolved in water are transported from areas with higher concentration to areas with lower concentration by *diffusion*. Scattering is caused by random molecular motion (molecular diffusion) and by turbulent motion determined by flow properties (turbulent diffusion). The process where the compounds are carried by the water is known as *advection*. The solutes are travelling at the *average linear velocity,* which is the mean flow rate of water through the pores in the medium.

There is a spreading mechanism during transport of water in porous media called *mechanical dispersion*. The reasons for this are that some parts of a contaminated fluid will be transported longer pathways than other parts of the fluid and flow paths can branch out to the sides after they have split. Besides, the velocity of the water varies depending on the pore size and the friction of the pathway. Altogether, mechanical dispersion results in a distribution of the retention time, where some elements of the water travel through the system faster than the average velocity, and other slower. In flowing groundwater, as well as in wastewater flowing through a constructed wetland, diffusion and mechanical dispersion cannot be separated. Instead they are both included in the concept *hydrodynamic dispersion*. Hydrodynamic dispersion causes the added tracer to spread out behind and ahead of the mass centre. The pattern follows a Gaussian distribution, where the variance grows with time and distance from the injection. (Fetter 2001)

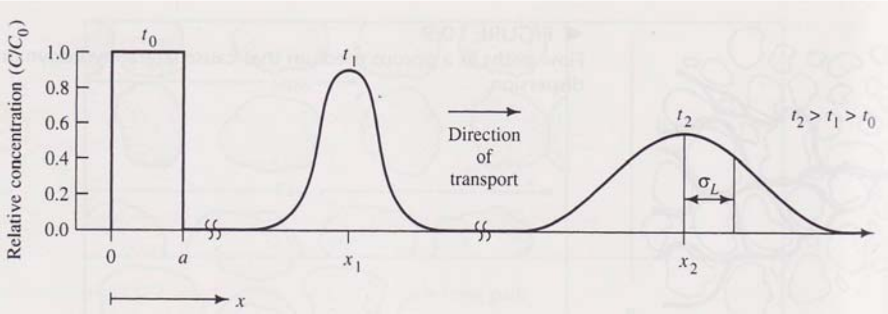

Figure 11. Transport and spreading of a tracer due to advection and dispersion. The tracer is injected at x=0+a, at time t_0. The water flow is left to right. (Picture from Fetter 2001)

The general transport equation (2) below describes transport of a compound, e.g. a tracer, by advection and hydrodynamic dispersion. Here, it is presented in one dimension, e.g. a pipe, channel or small river, but can also include more dimensions.

$$\frac{\partial c}{\partial t} + U\frac{\partial c}{\partial x} = E\frac{\partial^2 c}{\partial x^2} \qquad (2)$$

$\frac{\partial c}{\partial t}$ is the change in concentration with time

$U\frac{\partial c}{\partial x}$ is the change due to advection where U = average longitudinal fluid velocity

$E\frac{\partial^2 c}{\partial x^2}$ is the change due to dispersion where E = dispersion coefficient

If the transported compound is a pollutant which is degraded during the transport, a reaction term should be added to the equation. If adsorption is considered, a retardation factor can also be included in the equation. The dispersion coefficient E can be hard to determine since it is caused by non-uniformities in the porous medium. (Larsson 2008, Warfvinge 2007)

Modelling HSF Constructed Wetlands

HSF constructed wetland design has in many cases been based on the simplification that internal processes can be represented by ideal plug flow and first order decay of contaminants. The assumption is used even if researchers have found that plug flow does not describe the flow of water through HSF wetlands accurately (García et al. 2004). In reality, HSF wetlands are influenced by flow variations, internal flow paths, mixing and dispersion (Ascuntar Ríos et al. 2009). Attempts have been made to model the flow with plug flow *and* dispersion or continuously stirred tank reactors in series. Also multi-parameter modelling has been tried. In modelling studies, the models have been calibrated with data from tracer studies. One problem is that the knowledge of hydraulic properties of HSF wetland obtained from tracer experiments is scarce, and therefore the kinetic rates have been obtained from an assumed plug flow model. This causes underestimation of the kinetic rates and over-dimensioning of constructed wetlands. (García et al. 2004)

The degree of mixing can be quantified with the dimensionless dispersion number δ.

$$\delta = \frac{E}{UL}$$

where E = dispersion coefficient (m^2/s), U= average longitudinal fluid velocity (m/s) and L= length of the system (m).

Low dispersion numbers (less than 0.025) indicate near plug flow conditions, while dispersion numbers above 0.2 indicate high degree of dispersion (USEPA 2000). In HSF wetlands there is normally a moderate to high degree of dispersion. There is a wide range in dispersion numbers in different studies because of different conditions in hydraulic loading rate, size of medium, type of macrophytes, dimensions of the plant, etc. (García et al. 2004).

Several studies have combined PFR and CSTR to represent interactions between channel transport and storage zones within the bed. An approximation of two-dimensional dispersed flow has also been used (Ascuntar Ríos et al. 2009). King et al. (1997) developed a multi-parameter model with one initial plug flow reactor and three following parallel plug flow reactors with variable volume, flow and dispersion characteristics to simulate channelling. This provides better approximation of experimental data than a plug flow with dispersion model. According to García et al. (2004), their model of continuously stirred tanks in series with delay represent tracer data better than a model of plug flow with dispersion, because the former better fit the asymmetry of the tracer response. They found that if the aspect ratio (length:width ratio) was increased, the delay time and the dispersion also increased. A wetland in Colombia, studied during 5 months of biological growth, showed hydrodynamic behaviour close to CSTR (in series). It was concluded that the hydraulic pattern changed towards a higher degree of mixing and dispersion during the test period, and the reason was believed to be the influence of growing plant and roots. Thus it is expected that mixing in the active parts of an HSF wetland increases with the age of the system. (Ascuntar Ríos et al. 1999)

3.6 Treatment Mechanisms in Constructed Wetlands

According to Kadlec (2009) wetlands are effective in treating BOD, TSS, N and P, and also in reducing metals, organics and pathogens. In a subsurface flow wetland TSS and BOD are generally removed effectively while the removal of P and N is variable and depends on loading rate, type of substrate, oxygen supply and composition of wastewater (Brix 1993). Removal of larger particles is mainly done in a sedimentation tank before the inlet to the wetland.

3.6.1 Removal of SS and BOD

The physical removal mechanisms for SS and particulate BOD are in general sedimentation, adsorption to surfaces, straining and filtration. Because of the low water velocity, these mechanisms are favoured and large quantities of matter are removed from the influent, especially in the first part of the wetland bed. There is also removal through flocculation of colloidal particulates and subsequent sedimentation. If the bed medium is not coarse enough, there is high risk of clogging in the first section. To minimize this, pre-treatment in e.g. a septic tank also has to be sufficient. Any slowly degradable organic matter and other solids can accumulate and cause clogging in the bed. Dead plant material decomposing in the bed also adds to BOD levels, making a complete removal difficult. The BOD addition this would cause in a smaller bed is, however, likely to be of low significance. (Seabloom and Hanson 2005, USEPA 2000)

For soluble organic compounds there is significant sorption to biofilm on medium and root surfaces in the wetland, where degradation through bacterial conversions occurs. HSF wetlands can be seen as fixed film bioreactors in this aspect. The degradation is likely to be anaerobic due to the frequent lack of oxygen in the beds. This means hydrolysis of the compounds, followed by acidogenesis, acetogenesis and methanogenesis, ending in the production of methane and CO_2. These processes are temperature sensitive and a warm climate with relatively constant temperatures would favour the degradation process. (Björnsson and Murto 2007) The very large internal surface of the wetland bed ensures an effective biofilm for efficient degradation. The efficiency is generally considered good for HSF wetlands. (Brix 1993, Leonardson 1994, USEPA 2000)

3.6.2 Nitrogen Removal

Nitrogen (N) enters the wetland as organic N (proteonaceous matter and urea dominantly), and undergoes ammonification in the wetland bed. The ammonium is available for plant uptake, depending on the location of the roots. Flow below the roots will just transport ammonium downstream. Both according to Brix (1993) and Leonardson (1994), nitrification followed by denitrification is the major removal process for N in constructed wetlands. USEPA mentions N fixation as important in natural wetlands, but doubts the importance for wastewater where N is plentiful (USEPA 2000). Some reduction also occurs through sedimentation and filtration of larger particles containing N (Brix 1993). For biological removal to occur, the right conditions need to be present in the wetland. This means both aerobic and anaerobic conditions simultaneously in different parts.

According to *the microzone model* nitrification and denitrification can take place simultaneously, in the same sediment, biofilm or rootzone, but in microzones with different bacterial activity. Nitrate can be produced through nitrification in aerobic microzones and then diffuse to adjacent anaerobic microzones where the nitrate concentration is low. Here the nitrate may be denitrified to N_2. This is called *coupled nitrification-denitrification*. (Leonardson 2006)

For horizontal flow wetlands, almost constantly filled with water, aerobic zones with oxygen levels sufficient for nitrification are unlikely. The N leaving the wetland is thus probably in the form of ammonium or ammonia. Oxygen is required by other microorganisms than the nitrifying bacteria, and it is consumed rapidly during decomposition of biodegradable substances, especially in the first part of the wetland (USEPA 1993, Thiel-Nielsen 2005). For example, in a study on constructed wetlands in Morocco it was concluded that the limited nitrogen removal probably was caused by the low oxygen availability in the system (El Hamouri 2006). Since oxygen levels are often negligible, nitrification is only possible in the very low loaded systems. If there is any nitrification, it will occur close to the plant rhizomes or near the bed surface where there might be some oxygen transfer from the air. It is also more likely to occur downstream, where oxygen demand is lower. (Seabloom and Hanson 2005, USEPA 2004)

If any nitrification occurred prior to entry, the largely anaerobic subsurface flow wetland could be well suited for denitrification. This would, however, require a sufficient source of readily available carbon. Decomposing plant material or carbon present in the wastewater could constitute such a source. If denitrification is dependent on plant material for carbon, the system is influenced by seasonal changes in plant growth and temperatures. (Seabloom and Hanson 2005, USEPA 2004)

Nitrification and denitrification is also affected by the flow patterns in the wetland. Water should be well distributed and no dead zones or shortcut channels allowed to form, since this obstructs inflow of oxygen and carbon to the whole wetland. Obstructed flow hinders diffusion and spreading of converted N fractions to other zones. It also affects temperature, which in turn influences conversion rates. (Leonardson 1994)

3.6.3 Phosphorus Removal

Phosphorus in wastewater occurs mostly in the form of phosphates. Organic phosphates come from faecal matter and food residues, and the largest source of the inorganic fraction is detergents. Since P has no gaseous phase in the biogeochemical cycle, retention mainly takes place through adsorption or chemical binding to inorganic or organic complexes in the wetland. Some sedimentation also occurs. Where there are low levels of minerals, P adsorption is very limited. (Leonardson 1994)

Soil with high amounts of clay has a large capacity to bind P, but the permeability is low. Hence there have been hydraulic problems in constructed wetlands where this soil type was used. Most HSF wetlands constructed today consist of gravel or coarse sand to avoid problems with low permeability (Thiel-Nielsen 2005). A disadvantage, though, is the difficulty to remove P in gravel or sand beds, because of the low levels of metals and clay particles.

P is also taken up by plants in the wetland, but phosphate loading to HSF wetlands is large compared to plant uptake, and harvesting would not provide significant removal (Seabloom and Hanson 2005, USEPA 2000). Some minerals, when introduced like a cross sectional filter in an HSF wetland, can provide temporary removal by precipitation, exchange and sorption mechanisms. However, these effects would be short term (less than one year) and depend on the material in the filter. (USEPA 2000)

The P removal can be improved using a filter medium that has a large capacity to bind P, like gravel with high amounts of calcium or iron, but it is not possible to reach an effective removal with only gravel. Neither do other tested calcareous materials remove P in domestic wastewater sufficiently, during a longer period of time. An alternative to P removal in constructed wetlands is to use chemical precipitation in the sedimentation tank. (Thiel-Nielsen 2005)

3.6.4 Macrophytes

Function in wetland

The plants, with their roots and rhizomes, in a constructed wetland provide surfaces and a suitable environment for microorganisms to be active. The growth of roots and rhizomes also stabilize the hydraulic conductivity and prevent clogging of the filter medium. The evaporation from the plants reduces the amount of effluent water, and the macrophytes are also involved in oxygen transport, nutrient uptake and pollutant removal. (Thiel-Nielsen 2005)

Oxygen transport

In emergents, the photosynthesis takes place above the water surface and oxygen is transported down to the roots where part of the oxygen may leak into the surrounding rhizosphere. This can create aerobic zones and stimulate aerobic decomposition of organic matter and growth of nitrifying bacteria. The microorganisms are supplied with oxygen, but also low molecular organic acids and nutrients that may leak or may be exudated from the plants (Tyler 2007). The amount of oxygen that can be transferred by the roots into the wastewater depends on the dissolved oxygen concentration in the water, the root depth, air and leaf temperatures and the growth intensity of the plants (USEPA 2000).

The quantitative importance of oxygen transport in plants has been questioned. Many scientists say that even though oxygen leaks out from the roots, the amounts are too small to be of any importance for decomposition and nitrification in wetlands that receive high amounts of ammonium and organic material (Tonderski et al. 2002). USEPA (2000) points out that the theory that plant oxygen transport is a major oxygen source for microorganisms, has not been confirmed in side-by-side comparisons of planted and unplanted systems. A review showed that oxygen transport by macrophytes ranges from 0 to 3 g O_2/m^2/day. If the roots only penetrate a part of the water depth in the bed, there will be a significant flow beneath the root zone that is not affected by the oxygen transport. Planted systems are, however, more desirable aesthetically and plants do not appear to hinder performance of constructed wetland systems (USEPA 2000). El Hamouri et al. (2007) have in their experiments with both unplanted and planted HSF wetlands in Morocco compared the constant $K_{20°C}$ in the beds. This constant determines the decomposition rate when degradation is assumed to follow a first order reaction. It was concluded that $K_{20°C}$ was 42-54 % higher in the beds with plants, compared with the unplanted control bed. This fact suggests an advantage of planted beds. In another study, where the results also favoured planted beds, all 4 planted wetlands improved removal of pollutants compared with the unplanted control wetland (Camacho et al. 2007).

Nutrient uptake
Besides supplying surface for biofilm, macrophytes remove nutrients by direct uptake through the roots, but the importance of this removal is debated. Maltais-Landry et al. (2007) found that presence of macrophytes improved nitrogen and phosphorus removal in HSF wetlands and suggested that the role of plants goes beyond the addition of oxygen to the root zone. The uptake of P may be significant when the loading rate is low. On the other hand, the expected maximum removal rate of nutrients by plants is small in relation to the total content introduced with the wastewater (Thiel-Nielsen 2005, USEPA 2004) and plant uptake of N is generally of less importance than denitrification, if the latter occurs (Brix 1993).

Most of the nutrient uptake occurs during the period of rapid plant growth, and if the plants are not harvested before senescence, a large part of the nutrients are released back into the water. The plants make the nutrient levels in the treatment plant more variable. According to Seabloom and Hanson (2005) and USEPA (2000), it is unlikely that the amount of nutrients or metals removed by harvesting is worth the time required to harvest and reuse or dispose the biomass. Harvesting of plants is not a reliable alternative to microorganism degradation. It might, however, be a good supplement and necessary to keep the wetland aesthetically appealing if there is uncontrolled large plant growth.

3.6.5 Pathogen Removal

Pathogens enter the wetland as a part of solids or free-floating in suspension. If incorporated in the solids fraction, pathogens can be removed through the mechanisms listed above in 3.6.1. Regardless of location, pathogens are removed through natural die-off, predation and competition with other organisms and species in the wetland. Plants can excrete antibiotics from their roots, killing pathogens. The environment in a wetland can, however, also be favourable to pathogens, and growth can occur. Removal efficiency can be disrupted by peak flows, e.g. after heavy rain. (Brix 1993, USEPA 2000)

Since only indicator species are used when testing pathogen levels, actual die-off rate is not certain. Many species are more sensitive than the indicators, but some are the opposite. Solids removal and hydraulic retention time are important parameters for the removal efficiency (WSP 2006, USEPA 2000). HSF wetlands are in general capable of reducing faceal coliforms one to four logarithmical units where the median value is about two logs (Kadlec 2009). However, the effluent levels of faecal coliforms are not likely to meet effluent standards of maybe less than 200 coliforms/100 ml (USEPA 1993). To reduce the concentration of faecal coliforms in these kinds of treatment processes, by filtration, die-off and decomposition, a longer retention time of about 14 days can be necessary (Persson 2009).

4. SITE DESCRIPTION

4.1 The Area

The school where the wetland is built is situated in the hilly landscape of San Antonio de Buena Vista in Pukara, a peri urban area in the south part of Cochabamba. The surroundings are dry, strewn with rocks and stones. Small bushes and a bit of grass grows where it can on the slopes, but are kept small by hungry goats and cattle. There are some eucalyptus trees, but not much. In the plane part between the hills there are cultivated fields.

Figure 12. View of the Pukara area from the south, and the street outside the school garden wall.

Sometimes there is a lot of space between the houses. Outside the school for example, is a large open area with a tree and a soccer field, but they are not irrigated and therefore not green. The soil is rich in clay, so in the rain period the dirt fields which are normally dry and easy to cross in a car or on foot, are turned into mud fields without any vegetation. Sediments are easily transported with the rainwater downhill, and since Cochabamba is a hilly area, sediments, pollutants and garbage are often carried all the way to the river Río Rocha.

Figure 13. The large open field west of the school wall.

A small channel, with origin in the dam La Angostura, runs through uphill Pukara. This is one of the two major water sources when there is no rain, and in this sediment heavy water many residents wash clothes and children swim. It is also used for irrigation along the way. Water is only let on a few days at a time, then another channel is filled for a few days. The other major water source is tank trucks delivering water to large tanks spread around the area. The water arrives from SEMAPA, pumped in wells in other parts of Cochabamba. A water meter keeps track of how much water each house has used and should pay for. (Heredia 2008)

Figure 14. The water channel providing the area with irrigation water and a place to wash people and clothes. Animals also drink from the water.

4.2 The School

Centro Infantil Sagrado Corazón de Jesús is a catholic kindergarten, founded by *Padre* Santiago and run by nuns. The kindergarten consists of six houses, a school yard with a lawn and a vegetable garden in which the constructed wetland is placed. The whole area is surrounded by a 2 meter brick wall, like most of the gardens in Cochabamba. Around 100 children in the ages of 6 months to 6 years are in the kindergarten each weekday. The kindergarten employs four teachers, four assistant teachers, one cook, one assistant in the kitchen and one cleaning lady. Two gardeners work in the garden. Besides the staff that comes every day, a family of five lives in a house at the school taking care of it. During 2008 the director was the nun Macarena Muñoz and in January 2009 the ordinary director Marianela García returned.

Figure 15. The school entrance and the irrigated lawn around the school playground.

Breakfast comes ready made to the school. Lunch, however, is prepared in the kitchen and served at noon in the dining hall. It is both the 100 school children and about 50 children coming from the neighbourhood that eat lunch every day. (Gonzales Villaroel 2008, Medina Flores 2008)

The water used in the school comes from two sources. The potable water comes from the local water net with a tank uphill the school. This water is used in the kitchen, when washing clothes and in the shower. In the garden fruits and vegetables, e.g. carrots, maize, onion and lettuce, are cultivated for consumption in the kindergarten. In Nov-May 2008 a new well and a basin of 10 000 litres was built in the garden and is now used for irrigation of the vegetables. This is the other water source and the water extracted is used for other purposes, e.g. for flushing toilets. (Gonzales Villaroel 2008, Medina Flores 2008)

4.3 The Wetland

The construction of the wetland PTAR1 started in November 2007 and the plant has been operating since April 2008. The estimated effective construction time was one month (Müsch 2008). The water entering the constructed wetland comes from the kitchen, toilets, hand washing, showers etc. The distance from the source to the treatment plant is only about 20 m, the piping is newly installed and rainfall in the region is comparatively low (see Appendix 1), so any influence of stormwater, either through leaking pipes or rainfall, is disregarded. Before the plant was constructed, the greywater was let out on the ground and the blackwater ended up in a septic tank from where it probably was left to infiltrate into the ground (Müsch 2008). Information about previous systems and the location and nature of any septic tank is neither written down nor known to the staff currently responsible for the kindergarten.

PTAR1 is a gravity driven HSF constructed wetland. Design parameters can be seen in Table 4. Construction costs were originally planned to 2675 USD, but because of some technical mistakes and the need of additional equipment, the final cost for materials and construction of the whole treatment system was 3130 USD. This includes a grease trap tank, a septic tank, the wetland, an effluent tank with a flotation device and an effluent pump, pipes, wetland medium and lining with high density polyethylene (HDPE). The latter was the single most expensive part of the system.

The water entering the plant is pre-treated in a grease trap and a septic tank. Grease, hair, faecal residues etc. caught in the grease trap, are removed manually by the gardener Oscar Medina Flores when the level gets too high. All residues used to be collected together with the garbage, but the garbage collectors do not want to handle it any more. No solution for this has been found yet. The septic tank is relatively new and has not been emptied yet, but there is a plan to remove sludge regularly (Heredia 2008).


Figure 16. The HSF constructed wetland PTAR1. The black part is the plastic medium and the white tubes are observation pipes.

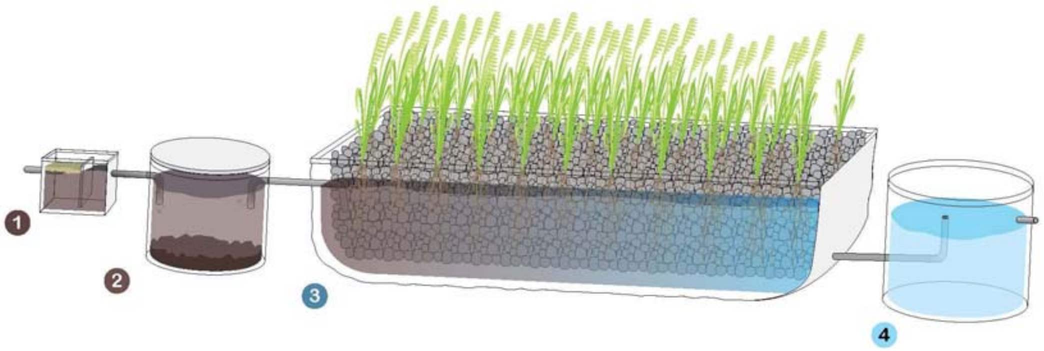

Figure 17. Cross section of the treatment system. Grease trap (1), septic tank (2), PTAR1 (3) and effluent tank (4). The figure is not drawn to scale. (Picture by AGUATUYA)

A plastic membrane made of HDPE prevents seepage from the treatment plant to the soil and ground water. The wetland has an inclination of 2 %. The plant is designed for a water depth of 0.8 m and a water level 0.2 m below the surface of the bed. According to observations, the water level normally stays at that height. The inflow is situated 0.1-0.15 m below the surface, and the outflow 0.2 m below the surface. PTAR1 is divided into two parts along the flow direction; one part contains plastic medium and the other part small stones.

Figure 18. Plastic (left) and stone medium (right).

The two sections are in turn divided into 5 chambers, each 1 m long and 1.25 m wide. In the entrance and the exit of the plant there are 1 m long compartments with large stones, approximately 9 cm in diameter. In the 14 chambers there is an observation pipe close to the outlet of each chamber, reaching from the bottom to about 20 cm above the medium surface. The series of 7 chambers is connected through pipes situated at different positions, with variation both horizontally and vertically (see Figure 19 and Figure 20).

Table 4. Design parameters of PTAR1, the grease trap, septic and effluent tanks.

Wetland	
Depth	1 m
Chamber length	1 m
Chamber width	1.25 m
Total length	7 m
Total area	17.5 m^2
Total volume	17.5 m^3

Grease trap	
Volume	0.216 m^3
Septic tank	
Height	1.58 m
Diameter	1.4 m
Volume	2.43 m^3
Effluent tank	
Volume	1.2 m^3

The stone medium is relatively well sorted with a mean stone diameter, calculated in Appendix 7 for theoretically spherical stones, of approximately 30 mm. This puts the stone medium in the geological category *coarse gravel*. For well sorted gravel, hydraulic conductivity is normally 10^{-2} – 1 cm/s (Fetter 2001). The plastic medium is very well sorted originating from plastic tubes with the outer diameter 32 mm. During the construction of the wetland the tubes were deformed, in order to increase the surface area per bed volume, and cut into ca 30 mm long pieces.

The effluent water enters a regulation tank before it is used for irrigation in the afternoons. There is a pump with a water meter for this purpose. If the water level in the regulation tank rises above a certain level, a volume of water is pumped out onto the ground outside the garden wall. The treated water is normally used for irrigation of the lawns in the school yard and for the trees in the garden, since the beginning of August.

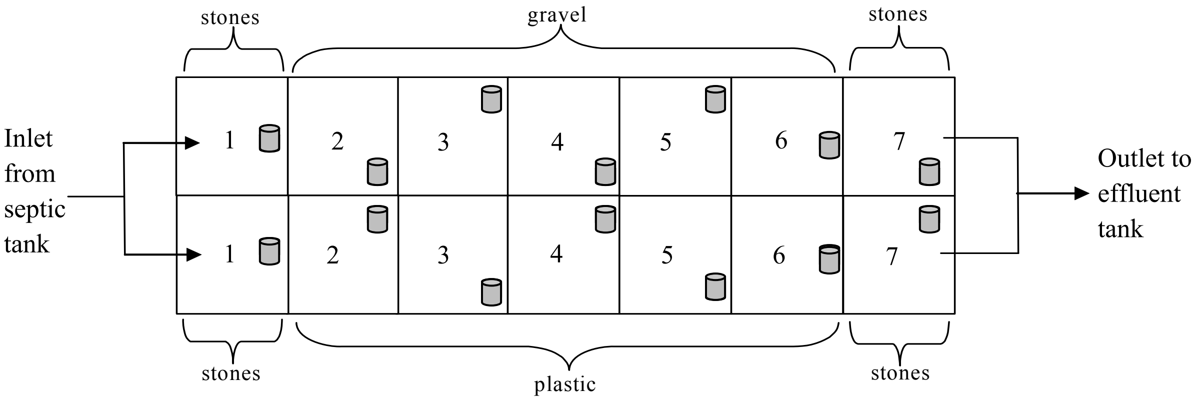

Figure 19. Planar view of the constructed wetland PTAR1 with the different media and numbers of chambers shown. The grey cylinders represent the observation pipes. (Figure is not drawn to scale.)

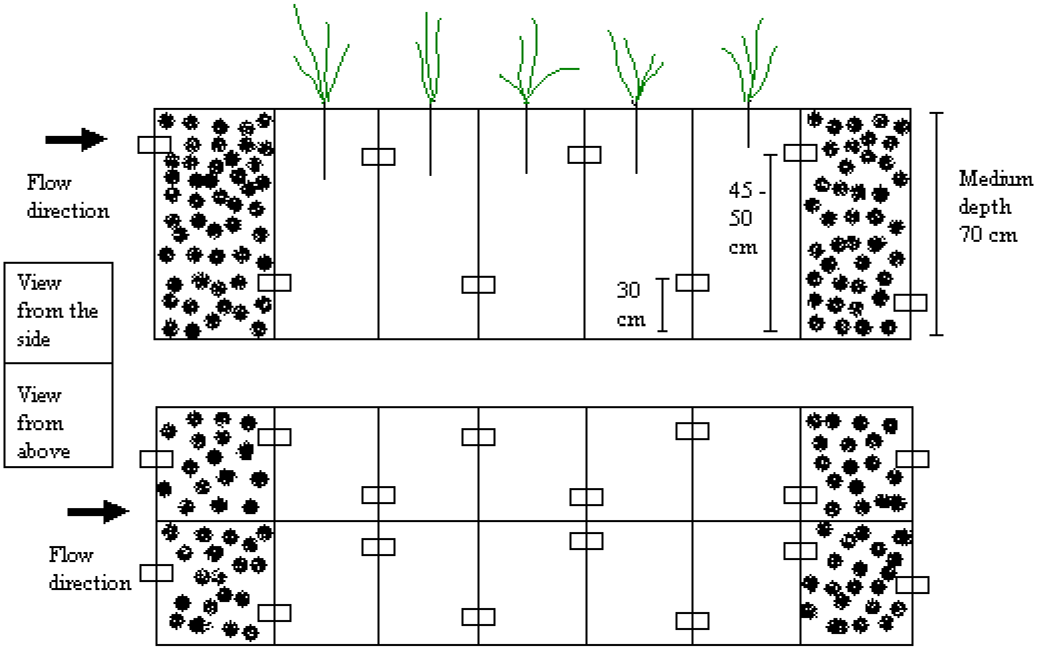

Figure 20. Connection pipe location in PTAR1. Cross sectional view and planar view respectively. (Figure is not drawn to scale.)

The wetland is planted with a macrophyte species that has not been well determined. It is probably a rush (*Juncus sp.*) or a bulrush (*Typha sp.*) The plants are grown 25-80 cm apart, with a mean distance of 40-50 cm. The plants are normally several meters high but they were pruned when planted in April 2008 to the current height of about half a meter (Müsch 2008). Since then they have not grown well, and out of the 68 plants first introduced, only 18 have survived. In December 2008 these had, however, only grown a few green leaves, 0.5-1 m long, mostly in the downstream part of the wetland.

4.4 Other Wetland Examples in Cochabamba

Visits have been made to five other HSF constructed wetlands in Cochabamba. Two of them are treating blackwater and greywater from families, and are located in the gardens next to each of the two houses. One round of tests was made on the water from the Müsch wetland.

Müsch residence

The environmental engineer at AGUATUYA that constructed the wetland in San Antonio, Martha Müsch, has constructed a wetland in her own house together with her father Raphael Müsch. This wetland was also sampled and analysed for comparison and for evaluation of the design, which is different from the one at San Antonio. Interviews were done with Martha Müsch and her father on the history and current status of the wastewater treatment system.

The Müsch family residence houses twelve people and is located in the northeast part of Cochabamba. On the premises are houses, large gardens and green houses. The family grows flowers and plants for commercial purposes and many of these are grown in the garden. In the lower part of the garden the family constructed a wetland in October 2007, for treating their wastewater and reusing it for irrigation of the plants and the garden. Before reusing wastewater, irrigation water came from a well. Now the electrical bills are lower as there is no need for pumping to the same extent. The treatment plant is designed for a flow of 2 m^3/day. The installation cost was 1000 USD.

Figure 21. *Calla Ethiopia*, to the right with white flowers, grown in the Müsch wetland.

The treatment system starts with a septic tank located close to the house. The water is then led to a collection tank just before entering the wetland. The wetland is U-shaped and 34 meters long. Depth and width are both 1 meter. The medium in the wetland is small stones, and in these are grown *Calla Ethiopia*. The water level is fairly constant at 0.8 meters. From the beginning another plant was grown in the bend, half way through the wetland, but this was never successful. Now *Calla Ethiopia* is grown in the whole wetland with good results, except for the first six meters of the wetland where no plants tested have ever been able to grow. The flowers are large, white and can be harvested and sold. After the wetland the water enters an effluent tank, dripping from a pipe half a meter above the water surface. The tank is open to the atmosphere but covered with iron gratings keeping anyone from falling in. The water is then pumped up to one of the greenhouses where it is stored in three consecutive open tanks to aerate it for three days, according to Raphael Müsch, before it is used for irrigation.

Bomblat residence

Christian Bomblat is environmental scientist and the director of the Simón I. Patiño Centre of Applied Ecology in Santa Cruz. At the centre there are two model farms for research and technology transfer to small farms. Christian Bomblat has worked several years with environmental science and engineering in Cochabamba and has experience from HSF constructed wetlands. He was the supervisor for two Swedish students from Uppsala University who were in Cochabamba in 2007, also doing an MFS project on three constructed wetlands in the area. The constructed wetland at Christian Bomblat's house was one of these and the wetland was visited to see how it was doing compared to last year. The project report from Johan

Söderblom and Johanna Spångberg (2007) was read for background information and an interview was conducted with Christian Bomblat at his house on the 4th of December. The questions concerned both his wetland and its design, the general water situation in Cochabamba and Bolivia, and the problems and possibilities with this type of solution for wastewater treatment compared to conventional and existing techniques.

His wetland was built in 2003 and was designed for a household of 10 people. There are currently three people living in the house. The treatment system consists of a 4 200 l septic tank beside the house, and all water used in the house flows into this tank. After the tank, the water flows by gravity down into the 11 m^3 wetland, which is divided into three compartments. Between each compartment, and underneath the whole wetland, is impermeable geomembrane made of HDPE. The walls separating the three sections have holes at the top, and these are placed diagonally across the compartment so the water is forced to flow a longer way. The wetland medium is a 0.7 m deep gravel bed with a porosity of about 37 %. There have been problems with clogging of the bed leading to surface flow, so the wetland had to be emptied once and the stones washed. Since then there has been no surfacing. In the bed, plants of different species are planted. They are all aquatic plants but are otherwise only chosen to look nice in the garden. The wetland cost 1000- 1500 USD to build.

The whole system is designed for an average inflow of 1.7 m^3/day and a retention time of about 14 days. There is recirculation in the system which means that the treated water, with help from a pump, can enter the wetland once more. The water is not always recirculated though; after treatment, the water enters a pond where fish, turtles and frogs live. No chemical analyses are ever done on the effluent water, but the animals are used as indicators for water quality. The water that is not used for irrigation of the garden is led in a pipe onto the hillside opposite the house, on the other side of the road. Only trees and bushes grow there, and there are no other houses nearby that could be affected. In general the family is pleased with the system and it works well, albeit occasional light odour problems.

Aldea Infantil SOS in Tiquipaya

In Tiquipaya, one part of Cochabamba, there is a school with education in agricultural techniques and ecology for students coming from rural areas. An interview was done with the director of the agro-ecology program at Aldea Infantil SOS, Alberto Melgar. Students of the program live at the school, and the wastewater from the toilets, kitchen and showers is treated in an HSF wetland. There are in fact two wetlands; one is 50 m^2 and designed for 30 people while the other is 6 m^2 and designed for 10 people.

The use of the smaller wetland is combined with urine diverting dry toilets, why this plant is treating only greywater and urine. The wetland was recently reconstructed during a course in maintenance of water resources and the vegetation was still small when observed at the 17th of December. There is only one chamber and the influent water is distributed horizontally along one side, with a perforated tube. The outlet is constructed in the same way. The medium in the bed consists of layers of stones of three different sizes. The smallest are placed on top and the largest in the bottom.

The large wetland is preceded by a 10 m^3 septic tank. A daily average of 2 700 m^3 (Spångberg and Söderblom 2008) is then led in plastic tubes to the treatment plant that was constructed in 2003, with a surface of 5x10 m and a depth of 70 cm. Like in the small wetland, the medium in the bed consists of stones of three different sizes. The wetland is planted with several species, e.g. *Shoenoplectus* sp*.*, *Juncus* sp., bulrush (*Typha latifolia* L.) and paper reed (*Cyperus papyrus* L.). The plants are growing very well and they are harvested twice a year. One problem has been that the paper reed is very competitive and tends to invade the whole wetland. Therefore everything has been replanted. The treated water is clear and without unpleasant odours. It is collected in a 150 l tank. The water is reused for irrigation of corn and alfalfa at the large school area. The whole system, with all tanks, is designed for a retention time of 15-20 days (Spångberg and Söderblom 2008).

The school San Nicolas in Pukara

The HSF wetland at the San Nicholas school was constructed in August 2007 and studied by Johan Söderblom and Johanna Spångberg some months later. Water comes in trucks and is stored in two 5 000 l tanks, buried uphill from the school buildings. They are filled once every week. Around 100 children attend the school, and the wastewater comes from toilets and showers used by the pupils. Wastewater is first collected in two septic tanks of 3 000 l each. After primary treatment, the water is led in pipes to the wetland, were it is spread evenly along the side.

Figure 22. The wetland (left) and potable water tanks (right) at San Nicholas in Pukara.

The wetland surface is 10x3 m and the depth is 1.2 m (Spångberg and Söderblom 2008). Gravity driven with an inclination of 2 %, the wetland is designed for a flow of 10 m^3/week and 7 days retention time (Bomblat 2008). A small stone medium with a porosity of 45 % is used. There are no plants in the wetland because they will be eaten by goats grazing in the area. The bottom is isolated with clay and plastic to prevent infiltration. Effluent water is collected in a tank of 1200 l, and used for gravity irrigation of trees. Maintenance of the system is done by personnel at the school and AGUATUYA.

Centro de Aguas y Saneamiento Ambiental (C.A.S.A.)

At the university Universidad Mayor de San Simón (UMSS) in Cochabamba there is a wastewater treatment system located close to the building of the Division of Water and Sanitation (C.A.S.A). The system treats all wastewater coming from the building, including toilets and laboratories. The water is pre-treated in different aerobic and anaerobic tanks before entering an HSF constructed wetland. The water coming from the laboratories is specifically pre-treated in a reactor, to handle the chemical waste content. The medium in the wetland is coarse gravel and the species planted is Totora (*Schoenoplectus sp.*) which grows well. This species was chosen because of the ability to remove phosphorus and nitrogen. The plants are harvested when they start to bend and fall down on the ground. Wastewater enters the wetland through several inlet slots spread along one side, and then passes through the two large compartments of the wetland. The effluent looks transparent and analyses have shown good water quality. Since the treated water is used for irrigation of lawns, trees and bushes in the university area closest to treatment plant, quality needs to be high. (Ledezma 2008)

Figure 23. The C.A.S.A. wetland (left) and daily irrigation of the university area (right).

5. METHODS AND FIELD WORK

All field work was performed in Cochabamba, including measurements, water sampling, visits, interviews and laboratory experiments and analyses. Some delimitations were made in this study. When determining wetland retention times, evaporation and precipitation were not taken into consideration due to time limitations. Plant roots and other organic material in the wetland were not included in the porosity calculations because of the difficulty in digging into the wetland. Extensive digging would also have disturbed the wetland functions. In the laboratory analyses of the water, 14 of the most important parameters were investigated while some macroconstituents and heavy metals were excluded for financial reasons. Focus was instead on e.g. nutrients, organic material, bacteria and solids.

5.1 Porosity

The porosity of the different media was measured to establish a nominal retention time for the wetland. The measurements were done on carriers taken from the dry surface of the wetland. Plastic and stone carriers were measured, and also the coarser stones in the first and last compartments.

In a bucket 4 litres of water was added. The surface level was marked on the bucket wall and the water poured out. Then carriers were added up to the mark, and the bucket was shaken to make sure the carriers were packed as much as possible. Then water was added up to the mark, and the volume was registered as the water was being poured. The porosity was calculated by dividing the volume of water *with* the carriers, by the volume without them (4 litres).

Figure 24. Porosity measurement of the plastic medium.

5.2 Pipe Exchange

The observation pipes installed when constructing the wetland were 4 inches in diameter, PVC pipes reaching from 20 cm above the wetland surface down to the bottom. No holes were made to facilitate water exchange in the pipes, so before any sampling or conductivity measurements could be done the pipes had to be exchanged. This was deemed the easiest way of addressing the problem.

New PVC pipes were bought, this time with a 3 inch diameter to fit into the old pipes. This was done to avoid having to excavate the wetland in order to install the new pipes. They were cut in 1.2 meter sections. On the lower 0.8 meters, holes of about one cm in diameter were drilled, evenly distributed. In the wetland the pipes were introduced into the old pipes, and the old ones extracted. The result was good, and the old glass jar used for sampling barely fit into the new pipes as well. The pipe exchange was done one day before any sampling to make sure that the water in the pipes was exchanged.

Figure 25. New observation pipe with drilled holes, ready to be installed in the wetland.

5.3 pH Field Measurements

pH was measured in the field with Litmus paper in the first, fourth and seventh compartment of the wetland in both stone and plastic media and in the outlet from the wetland. The glass jar was first filled once with water from the observation pipe. This water was used to rinse the jar and was then poured out downstream onto the wetland surface. The second sample was taken from the bottom of the observation pipe (the glass jar was quickly pushed down) during the measurements the 10th of November, since the observations pipes were still not perforated then. In this second sample, pH was measured.

5.4 Flow Measurements and Calculations

5.4.1 Long Time Average Flow

When the water flows out from the wetland, it enters an effluent tank. Some water is used for irrigation and the rest flows out onto the ground when the water in the tank reaches a certain level. The amount of water pumped out from the tank is measured by a water meter, and the effluent volumes have been registered regularly by AGUATUYA during July to December. The mean flow between each reading and an overall mean value was calculated.

5.4.2 Measured flow

On the outflow of water from the wetland into the effluent tank, flow measurements were performed. The time it takes to fill a bucket of 1 litre with effluent water was measured with a stop watch every half hour on the 10 Nov (10.00-15.00). Duplicate measurements were made. Then the flow (l/s) was calculated, see Appendix 4 for calculations and assumptions. This calculated flow is also called *short time average flow* in the following text. The flow was measured in the same way on the 14th, 24th and 27th of November.

5.5 Nominal Retention Time

The parameters used to calculate the nominal (theoretical) retention time for different parts of the wetland are presented in Table 5, except for the flow Q. The nominal retention time was calculated with both long time average flow and short time average flow, using equation (1), chapter 3.5.1. The total flow is divided by 2, since half of the flow is assumed to pass into each part (stone and plastic respectively).

Table 5. Design parameters and measured porosity for different parts of the constructed wetland (units in meters).

Plastic medium		**Stone medium**		**Entrance or exit sections with large stones**	
Width	1.25	Width	1.25	Width	1.25
Length	5	Length	5	Length	1
Area A	6.25	Area A	6.25	Area A	1.25
Porosity n	0.6	Porosity n	0.43	Porosity n	0.43
Depth y	0.8	Depth y	0.8	Depth y	0.8

5.6 Tracer Experiments

To better understand the flow pattern in the wetland, and to determine the transport time of the water, a tracer experiment with salt was conducted. Addition of salt to the septic tank should give an increase in conductivity that can be measured to determine flow rate and dispersion patterns.

Part 1 – Salt/ Specific Conductivity Relationship 10 Nov

At the process laboratory at C.A.S.A., a series of conductivity measurements were performed on the 10 Nov. The aim was to see if there is a linear relationship between the mass of salt (NaCl) added to the water, and the measured conductivity. The salt concentration that corresponds to the doubled conductivity or higher, should also be found, so a sufficient amount of salt could be added to the septic tank in the later experiment. The conductivity increase must be clearly visible, but not harmful to the wetland organisms.

One litre of sample water was taken from the five litres of wetland effluent brought to the laboratory. The conductivity in both was measured using a HACH Conductivity/TDS meter (model 44 600), distilled water for cleaning and a 10 % HCl solution for calibration of the instrument (Table 13).

1 g of salt was added to the sample, and the water was stirred to dissolve and distribute the salt evenly. A dilution of 1:10 was made (10 ml of sample water and 90 ml of distilled water) and the conductivity was measured in the dilution. Between each measurement, the electrode was carefully rinsed. This procedure was repeated several times with an addition of 1 or 2 g of salt each time. 10 ml of water was extracted each time, but no new sample water was added. This lead to a decrease in volume from 1 to 0.910 litres during the series of measurements. The effect of this is, however, not believed to influence linearity in a significant way.

Part 2 - Adding Salt 11 Nov

Each of the two entrance chambers in the wetland has a volume of 1 m^3. If it is assumed that the salt will be diluted in the water of the whole chamber, 1 kg of salt/chamber corresponds to the concentration of 1 g/l. Then 2 kg of salt should be added to reach the desired increase in conductivity. The volume of the septic tank is 2.4 m^3, and according to observations, the water level does not change much over time. 2 kg of salt/2.4 m^3 water gives the concentration 0.83 g salt/l water. According to equation (3) chapter 6.4.3., this corresponds to a conductivity of 2 431 µS/cm, which is supposed to give a detectable change in the wetland water. Two kg of salt, of the same type as used in the laboratory measurements (NaCl with iodine and fluorine), was dissolved in 15 litres of water. The solution was poured into the second chamber of the septic tank at 11.20-11.30 on the 11 Nov. The second chamber was assumed to be close enough to the outlet for the solution not to spread out in the septic tank but go directly through the outlet. This was done to create as narrow salt concentration peak as possible.

Figure 26. Adding the salt solution to the septic tank.

Part 3 – Specific Conductivity Measurements 13-14 Nov

The conductivity was first measured two days after the salt water was added to the septic tank. On 13 Nov, 10.00-10.30, the conductivity in all observation pipes was measured using the same equipment that had been used at C.A.S.A. Our supervisor, engineer Marcelo Ledezma, accompanied us on this first occasion.

Measurements were done starting downstream, where lower conductivity was presumed, moving upstream so that samples with lower conductivity would not be contaminated. The glass jar was first filled with water from the top of the pipe. This water was used to rinse the jar and was then discarded downstream onto the wetland surface. The second sample was taken halfway between the bottom and the water surface, and this was used for measurements. Between each measurement the electrode was thoroughly rinsed with distilled water. The sampling and measuring procedures were the same on 14 Nov. Measurements were done 9.00-9.30 and 11.30-12.00. At both these occasions, the temperature of all samples was also registered.

Figure 27. Sofia and our supervisor Marcelo Ledezma, measuring conductivity.

Part 4 – A new round 3-8 Dec

The results from the first round of conductivity measurements were inconclusive for the plastic part of the wetland (see Figure 36). A second round of adding salt and measuring conductivity was therefore decided on, to conclude if the transport time for the plastic part was longer or shorter than that of the stone part. On 3 Dec, another 2 kg of salt were added to the septic tank after being diluted in 15 litres of effluent water from the wetland. This time, the conductivity was measured after only one day, then again after two and five days. Conductivity and temperature measurements were done like in the first round, described above.

5.7 Chemical and Physical Analyses - Field Work

Water samples for chemical and physical analyses were taken from the observation pipes in the wetland PTAR1 and analysed at C.A.S.A. Three rounds of sampling were done during two weeks in November. For each round, three days passed between the sampling in the upstream part and sampling in the downstream part of the wetland. There were also three days between each start of a new round. Sampling days were 18th, 21st, 24th and 27th of November 2008. The explanations for the sample coding can be seen in table 7. See also Figure 19.

Table 6. Explanations of the sample point coding.

Sample point code	Chamber	Medium
A	Septic tank outlet	
B	2nd	Gravel
C	2nd	Plastic
D	7th	Plastic
E	7th	Gravel
F	Effluent tank	
G	5th	Gravel
H	5th	Plastic

The order of the sampling points was: starting in the outlet, moving upstream and ending in the septic tank. This way, contamination of samples with dirtier water that could influence results, was avoided. Sampling was done with a glass jar attached to a thin rope. The jar was pushed down in the observation pipe, and was first filled and rinsed twice with top water from the pipe. The samples were then taken from 0.4 m below the surface (at half the water depth) and poured into different containers brought from C.A.S.A.. On these, there were instructions printed on how to handle the sample, and these instructions were followed. Samples were always returned to C.A.S.A. within two hours of the last sampling time. All samples were stored in a dark, insulated box until the return to the laboratory.

Figure 28. *Left*: Analyses equipment ready to be used in the field. *Middle:* Filled containers were placed in an insulated, dark box. *Right:* Helena is inspecting and marking the containers at the laboratory.

One set of duplicate samples were taken on the last day of sampling, to get an idea of the consistency of the results from C.A.S.A.. The water temperature was measured with a field thermometer at the same time as the samples were taken at each sampling point. The tested parameters are listed in table 8 below.

Table 7. Parameters tested in PTAR 1.

Parameters	Unit
Conductivity	mS/cm
Turbidity	NTU
Total solids (TS)	mg/l
Dissolved solids (DS)	mg/l
Suspended solids (SS)	mg/l
BOD_5	mg O_2/l
COD	mg O_2/l
Dissolved oxygen	mg O_2/l
NO_3-N	mg NO_3-N /l
NH_3-N	mg NH_3-N /l
Tot-N	mg N/l
PO_4-P	mg PO_4-P /l
Tot-P	mg P/l
E.coli / thermotolerant coliforms	CFU/100 ml
pH	-

The sample for COD, pH, turbidity, NH_3-N, tot-N, PO_4^{3-} was preserved with sulphuric acid (H_2SO_4) added to the container, at C.A.S.A.. With this method the sample is acidified to pH 1-2. This prevents precipitation of metals, but may cause changes in the state of the ions in the solution (Golterman 1969). The sample for nitrate analysis was conserved with 2 ml of chloroform, added with a pipette into the container just before the sample was poured in.

The Winkler bottle for dissolved oxygen (DO) was filled twice and rinsed before the sample was added. It was filled almost to the top of the bottle in order to prevent air bubbles. As a first step of the Winkler titration method, 2 ml of $MnSO_4$ was added followed by 2 ml of Iodine Azid. The bottle was closed tightly with a lid equipped with a conical inner "roof" and it was shaken until a precipitation was clearly visible. The sample for DO was the last one taken in order to get representative water from the chamber regarding oxygen levels. If these samples would have been taken first, it was supposed that the oxygen diffusion through the free water surface in the observation pipe would have resulted in unrepresentative oxygen levels.

Sampling procedure was always the same and followed the instructions given by C.A.S.A.. Some exceptions occurred though, and the following possible sources of error when collecting samples should be taken into account when viewing the results. On 18th of November a little less quantity of Iodine Azid was added to the oxygen sample from the second chamber with plastic media, due to problems with leaking bottles. This sample may also have been contaminated. The amount of chloroform was insufficient during the sampling the 18th of November; hence three of the samples were stored without preservative until the return to C.A.S.A. one hour later. The original idea was to do two sample rounds on that day; one at high flow and one at low flow. The time interval estimation was based on the flow curves done previously. Due to problems with the containers, sampling began later than planned and it appeared that the flow on both sampling occasions were roughly the same. Therefore the second sample can instead be seen as a control sample for the first one. The results in Appendix 6, Figure 49 to Figure 59, for samples taken in the septic tank and the second chamber during the third round, are mean values for these two sample sets. The medium for growing bacteria had run out at C.A.S.A. on 24th of November, so no samples for testing *E.coli* were taken that day. Instead an extra analysis of *E.coli* in the septic tank was done on the last testing day. Water transport time in the wetland was not taken into consideration for that sampling round.

Sampling in private home wetland 26 Nov

On the 26 Nov, sampling of the Müsch family wetland was conducted at 10.00-11.00. The same parameters were measured as in PTAR1, and the samples were conserved and stored in the same way as described above. The outside temperature was 25 °C. Samples were taken from three points, in the inlet tank to the wetland, at the outlet pipe and in the last of the three, open post treatment tanks. From the inlet tank the samples were not taken from the same depth as in the other wetland, but instead from about 10 cm under the surface. In the post treatment tank the samples were taken halfway between surface and bottom.

Sampling of drinking water 27 Nov

At 11.20 on 27 Nov, tap water from the school kitchen was collected to test some of the parameters analysed in the wastewater samples. Parameters tested were pH, conductivity, TS and content of *E.coli*. From the tap, the water was poured into a water bottle that was first rinsed twice, and then into the different containers from C.A.S.A.

5.8 Chemical and Physical Analyses - C.A.S.A

The laboratory analyses were performed in the laboratories, and by the personnel, at C.A.S.A.

Nitrogen and phosphorus fractions

Concentrations of nitrate, total nitrogen, phosphate and total phosphorus were determined by spectrophotometry. The fractions were let to react with other compounds to form coloured complexes that could be detected through measuring the absorbance with a spectrophotometer. The absorbance was compared to calibration curves.

Orthophosphate (PO_4^{3-}) forms a yellow solution with molybdate ions in acid solution. The molybdate complex can be reduced to a highly coloured blue complex. The phosphate is measured as "molybdate reactive phosphorus" (MRP). Ammonium molybdate, ammonium metavanadium (H_4NO_3V), and hydrochloric acid (HCl) were used. The absorbance was measured at 415 nm.
Total phosphorus was also measured as MRP but after digestion with nitric and sulphuric acid, in 180-200ºC during 2 h. This was done to transform all phosphorus fractions to orthophosphate. Then the amount of phosphate was determined as described above.

Nitrate (NO_3-) was reduced to nitrite (NO_2^-) with cupperized cadmium granules, and measured as nitrite. The concentration of ammonium nitrogen (NH_4^+-N) and ammonia nitrogen (NH_3-N) was determined with an ion selective electrode and presented as NH_3-N. The "total nitrogen" determined by C.A.S.A. was later explained to be "total *organic* nitrogen compounds", which is also called Kjeldahl-nitrogen and includes ammonium and organic nitrogen. It was analyzed with the micro-Kjeldahl method. The total nitrogen compounds can be calculated as the Kjeldahl-N + NO_2-N + NO_3-N.

Figure 29. Equipment for reducing nitrate with cupperized cadmium granules.

Solids

Total solids (TS) are measured by gravimetry. A sample of known volume is poured into a small dish that has been weighed first, empty. The sample is dried in an oven at 105ºC for two hours until all water has evaporated. The sample is cooled and stored in a desiccator to ensure that no moisture is present in the sample when weighing it. TS is calculated from the difference in sample weight before and after drying.

Dissolved solids (DS) are calculated in a similar manner. The sample used is, however, obtained from filtering the original sample. It is a known volume of the filtrate that is dried in an oven and weighed after cooling. This way it is only the weight of the dissolved fraction in the water that is determined.

Dissolved oxygen

The amount of dissolved oxygen was determined by Winkler titration. The reagents added to the sample in the field caused first a white and then a brown precipitation. In the laboratory sulphuric acid (95-97 % H_2SO_4) is added and the precipitation dissolves. If the sample contains any oxygen, the liquid turns yellow. Starch is added, which reacts with I_2 and forms a blue complex. The solution is titrated with tio-sulphate ($S_2O_3^-$) until the sample turns transparent. The amount of tio-sulphate used determines the oxygen concentration in the sample.

BOD_5

The nutrients ferric chloride, manganese sulphate, calcium chloride and phosphate buffer were added to 10 litres of water, 1 ml of each of the nutrients/litre of water. The water was then aerated for at least 15 minutes. 1 ml, 3 ml and 0.5 ml of the sample was poured into three different Winkler glass bottles. The bottles were inoculated with microorganisms, 0.5 ml in each, and filled to the top with the nutrient rich, aerated water. The oxygen concentration in each bottle was registered with a dissolved oxygen-meter (YSI model 58) and the bottles were left to incubate for 5 days in 5.4 ºC. After 5 days the concentration of dissolved oxygen was measured again.

Figure 30. Bottles with nutrients for the microorganisms in the BOD_5 test and equipment for measuring oxygen content.

COD

COD was determined by oxidation with dichromate. 25 ml of potassium dichromate (c=0.25 M) was added to 50 ml of the sample. Mercuric sulphate was added and a precipitation formed. Sulphuric acid and silver sulphate was added, and the solution was left for digestion for 2 hours in 150 ºC. After cooling down, it was titrated with ferrous ammonium sulphate.

Figure 31. Staff at C.A.S.A. adding sulfuric acid as a part of the COD analysis.

Accuracy

The accuracy of the measurement methods is not known. The laboratory personal renamed the samples during analysis, hence they did not recognize where in the wetland the sample was taken and what levels to expect which should imply more objective analysis results. During the third round of analyses duplicate samples were taken from the 7th stone chamber and a couple of parameters analysed to get an indication of the precision potential of the analyses. The duplicate samples contained water taken at the same time as the ordinary set of samples in that sample point. The staff at the laboratories could not tell from the protocol that duplicates were made or where the duplicate samples were taken.

5.9 Visual Examination of Water in Observation Pipes

On the 4 Dec, water samples were taken from the middle of each pipe in PTAR 1. The water in the jar was visually examined and compared to the other samples. Photos were taken in the same order as the samples, one from the side of the jar and one from above. The glass jar used contains approximately 4 dl of water when filled.

Water depth in observation pipes 9 Dec

On 9 Dec the water level in the pipes was controlled, using a tape measure and the glass jar attached to a rope. This was done to learn if the water depth was appropriate and to calculate the head loss in the wetland.

5.10 Biofilm Evaluation

Surface area

Measurements and calculations of mean surface area of the carriers were done on both stones and plastic pieces. The mean stone is assumed to be spherical and completely smooth. Mean radius, mean surface area per stone and surface area per m^3 of bed were determined according to calculations in Appendix 7. The plastic carriers are pieces cut from a plastic tube. They are cylindrical, with an outer diameter of 32 mm before deformation. The carriers are deformed in order to increase the surface area per volume unit of the bed. The inner surface of the carriers is not smooth but ridged, which increases the total surface area further. After examining the cross section of the plastic carriers the maximum inner circumference was assumed to consist of 63 small half circles. The thickness of the plastic tube was measured with a slide calliper and the minimum inner circumference was assumed to be an imaginary even circle. Calculations of maximum and minimum surface areas of the plastic carriers are presented in Appendix 7.

Amount of biofilm

The biofilm mass on carriers from chambers two and six, in both sections, was evaluated. On 27 Nov, holes were dug in the plastic and gravel beds to reach down below the water level. Carriers from just below the surface were photographed and described. On 17 Dec, new holes were dug and carriers extracted in the same way. This time four containers of 600 ml were filled with carriers from each of the four sampling points. These were taken to C.A.S.A. the same afternoon. Each container was emptied into a plastic bowl, and distilled water added for washing. Each carrier was vigorously scrubbed with a toothbrush, and the water was kept in the bowl. When carriers from one container were ready, the water was poured back into the container. The same was done with all four samples.

Figure 32. Left: Washing stones to do biofilm evaluation. Right: Filtering wash water using a vacuum pump.

The wash water was filtered through a Wattman filter, using a vacuum pump. Several filter papers were used for each sample. After filtration, the filter papers were dried in 110 °C in an oven for a few hours, to evaporate all water. Once dry, they were burned in another oven at 550 °C for two hours, to determine the content of organic matter (carbon) that was removed from each sample. Each sample was weighed before and after burning. The filter papers have low ash content, so the residues from these are not expected to influence the results significantly.

5.11 Oxygen Consumption

A sample of several litres was taken from the second chamber of the wetland, with stone medium, and brought to C.A.S.A. In the laboratory it was aerated during 31 minutes with an air flow of 5 600 cm^3/min. The air entered through two tubes placed on the bottom of the bucket. After the aeration stopped, a part of the sample was poured into a Winkler bottle with 2 ml of manganese sulphate ($MnSO_4$), and directly afterwards 2 ml of Iodine Azid was added. The bottle was filled to the top, closed with a lid and shaken. The rest of the sample was set to wait without lid or aeration for 16 minutes. Then the same procedure was performed on a new part of the sample. Two more tests were made, after 21 and 32 minutes. After a few minutes, sufficient for the first reaction to be complete, sulphuric acid (95-97 % H_2SO_4) was added to all of the bottles to see if there was any change of colour to indicate oxygen in the sample. If oxygen was detected, Winkler titration (see 5.11) would be performed.

5.12 Interviews

Interviews were made with Gustavo Heredia, Martha Müsch, Christian Bomblat and Alberto Melgar, concerning their experiences with constructed wetlands and the sanitation and wastewater situation in Cochabamba in general. Abel Lizarazo is the responsible engineer at the wastewater treatment plant Alba Rancho. During a tour of the plant and later of the wetland PTAR1 in Pukara, an interview was conducted on current treatment capacity of Alba Rancho, wastewater problems facing the city and his thoughts on decentralized solutions like constructed wetlands. Macarena Muñoz and Silvia Gonzales Villaroel both work at the school in Pukara and they were interviewed on the history of the facilities, water consumption, water usage, staff feelings towards the new solution and the overall impression of, and future for, the wetland. Oscar Medina Flores was interviewed about the work in the garden, irrigation routines, water consumption and his impression of the wetland, with which he comes into contact daily.

All interviews were semi-structured. A set of questions was prepared for each one, but new topics and discussions that arose from the answers were included. Besides the more formal interviews with Heredia and Müsch, there were several occasions for further discussion about the wetland, the school, the garden and the general water situation in the area and the whole of Cochabamba, during the eight week field work period.

6. RESULTS

6.1 Temperature

The temperatures measured in all sampling points (observation pipes) in PTAR1, on four different days, are displayed in four graphs (Figure 33). If two sets of measurements were done on the same day, they were marked “I” and “II”. The temperature varied between 20.6 ºC and 28.3 ºC. At all occasions the temperature was highest in the septic tank and a decreasing trend downstream could be seen in the results from all days except for the 4th of December. When comparing the temperatures in the plastic and the stone chambers, at the same distance from the inlet and at the same time, they are similar. The maximum difference is 1.1 ºC. The temperatures in the Müsch wetland can be seen below in table 9.

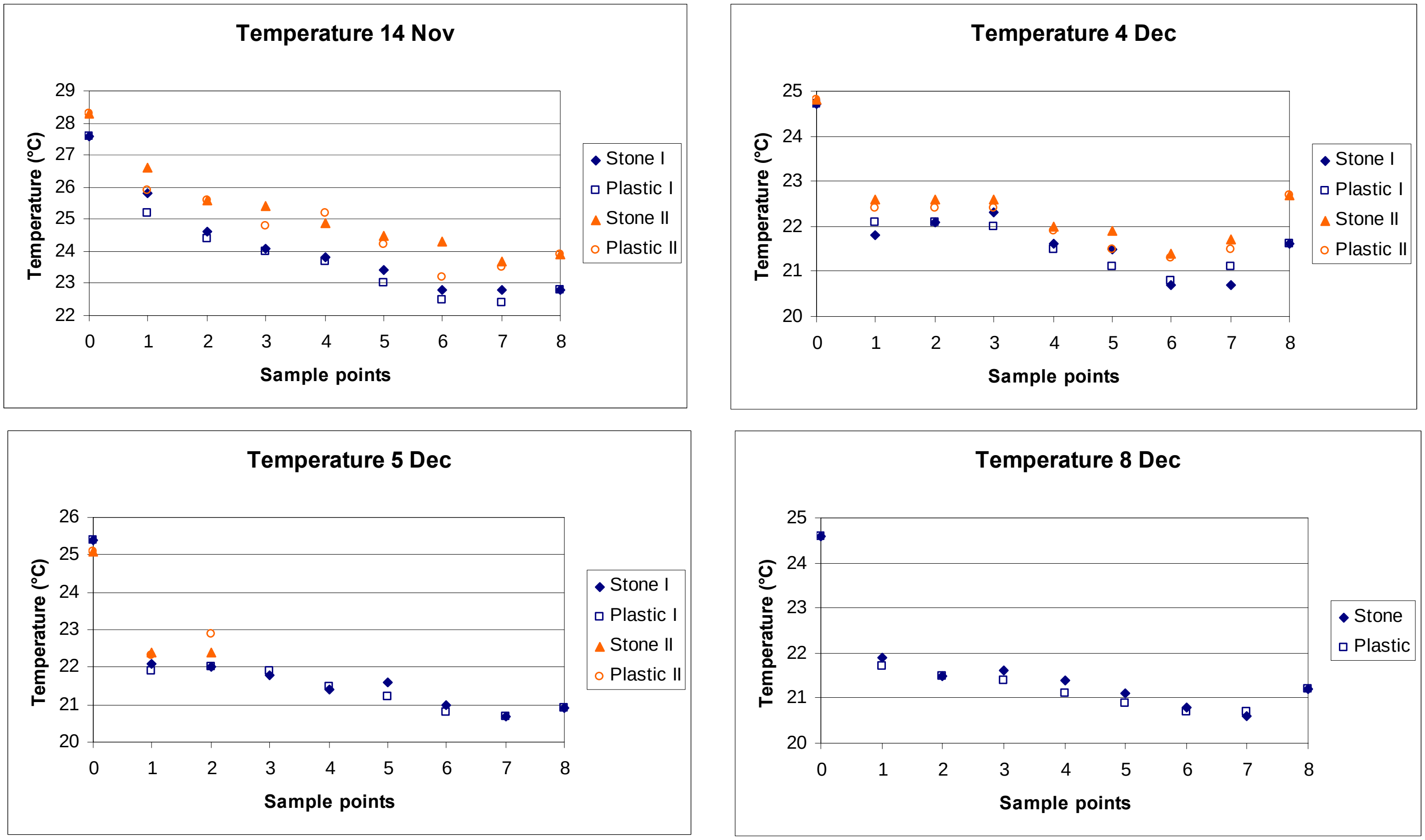

Figure 33. Temperature measured the 14th November (I = 9.00, II =11.30), the 4th (I = 9.40, II =12.00), the 5th (I = 9.00, II =10.45) and the 8th (9.00) December. Sample point 0 refers to the septic tank and point 8 to the outlet, these are the same for both media.

Table 8. Temperatures in the Müsch wetland on the day of sampling.

	Time	Temperature (°C)
Entrance	10.50	22
Outlet	10.35	20
Open tank	10.20	18.5
Air	10.10	25

6.2 Porosity

The porosity was determined to 60 % for the plastic medium and 43 % for the stone media (see Table 9).

Table 9. Porosity calculations for the different media. The volume of water without carriers is 4 litre in all three cases.

Carrier type:	Volume of water *with* carriers (l):	Porosity (%):
Plastic	2.40	60
Stone (small)	1.70	42.5
Stone (large)	1.73	43.25

6.3 Flow

6.3.1 Long Time Average Flow

The readings of accumulated outflow from the regulation tank downstream the PTAR1 wetland and flow calculations are presented in Table 10. The minimum flow calculated is 0.539 m^3/day and the maximum flow is 1.494 m^3/day. An average value of approximately 1 m^3/day (0.01 l/s) was calculated.

Table 10. Measured accumulated volume of outflow from the regulation tank and calculated outflow.

Date	**Accumulated outflow (m^3)**	**Days between readings**	**Flow (m^3/day)**
28-jul	66.74		
12-aug	74.82	15	0.539
27-aug	89.07	15	0.950
10-sep	106.95	14	1.277
23-sep	116.05	13	0.700
07-okt	136.97	14	1.494
05-nov	166.74	29	1.027
05-dec	190.59	30	0.795
			Mean: 0.969

6.3.2 Measured Flow

The flow patterns during the 10th, 14th, 24th and 27th November are shown in Figure 34. The maximum flow measured was 31 ml/s and the minimum flow 5.6 ml/s.

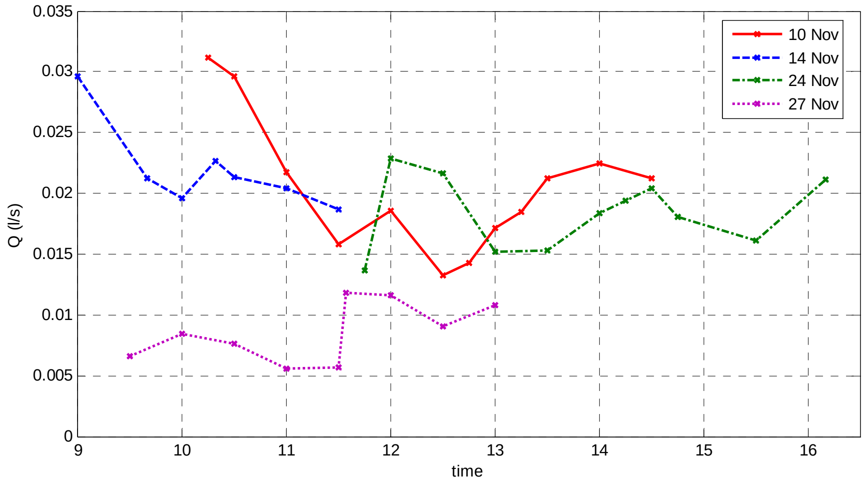

Figure 34. Flow pattern in the outflow from the constructed wetland into the regulation tank during Monday the 10th November, Friday the 14th November, Monday the 24th November and Thursday the 27th November. The time scale is from 9.00 until 16.30.

The 10th and 14th November the flow was highest in the morning and decreased towards lunch time. It can be explained by the use of bathrooms and washing of dishes from the breakfast. Around twelve o clock the children have a break and eat lunch why the bathrooms are probably frequently visited. In all of the measured time series a peak can be seen around 12.00. The measurements done in the afternoon show an increase from 12.30 to 14.00 and from 13.00 to 14.30, respectively. At this time the dishes from the lunch are washed. The 27th November the flow was considerably lower than the other days but according to the personnel in the kitchen there were not less children attending the kindergarten than usual. It was noted, however, that the water level in the septic tank was elevated at 13.30 why a higher flow was expected during the afternoon.

From the measurements during the 10th November the average flow was calculated to be 0.724 m^3/day.

6.4 Retention Time

6.4.1 Nominal Retention Time from Long Time Average Flow

Nominal retention time was calculated using long time average flows (mean, maximum and minimum flow). The results are presented in Table 11.

Table 11. Nominal retention time for different parts of the constructed wetland (PTAR1) using long time average flows.

		RT (days)		
	Q (m3/d)	Plastic medium	Small stone medium	Large stones
Mean flow	0.484	6.19	4.44	0.89
Min flow	0.270	11.13	7.98	1.60
Max flow	0.747	4.02	2.88	0.58

The calculated nominal retention times are 6.2 days for the plastic medium (chamber 2-6), 4.4 days for the small stone medium and 0.89 days for one chamber of large stones. The total mean retention time for the whole wetland is 8.0 days for the plastic medium and 6.2 days for the stone medium.

6.4.2 Nominal Retention Time from Measured Flow

The nominal retention time using measured flow (short time average) was calculated to 8.3 days for the plastic medium, 5.9 days for the small stone medium and 1.2 days for one chamber of large stones (Table 12). In total, the nominal retention time for all 7 chambers is calculated to 10.7 and 8.3 days for plastic and stone media respectively.

Table 12. Nominal retention time for different parts of the constructed wetland (PTAR1) using short time average flow.

	RT (days)		
Q (m^3/d)	Plastic medium	Small stone medium	Large stones
0.362	8.29	5.94	1.19

6.4.3 Tracer experiments

The results of the specific conductivity measurements, performed during a dependency investigation in the laboratory, are presented in Figure 35 and in Appendix 5, Table 17. The results show a linear relationship between the conductivity and the salt concentration.

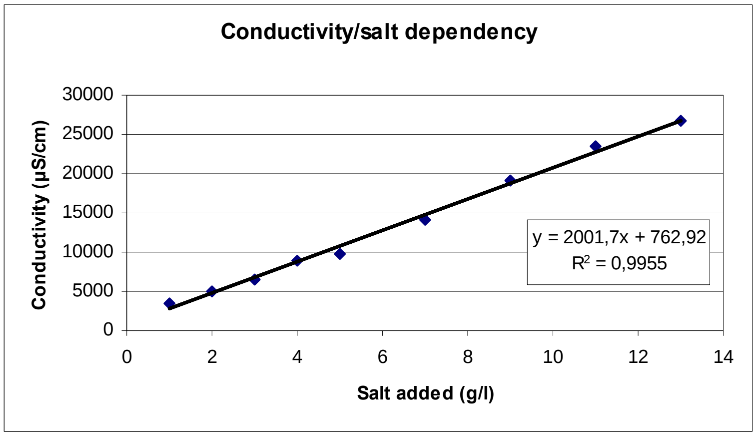

Figure 35. Measured conductivity (µS/cm) as a function of salt concentration (g/l).

The R^2-value is close to 1. The equation of the linear regression is

$$y = 2001.7x + 762.92 \qquad (3)$$

Table 13. Conductivity of non-diluted sample.

Non-diluted sample	1.265 mS/cm	1 liter of sample
0 g added salt/l	1.314 mS/cm	whole sample

According to equation (3) 1 g of salt added in 1 litre of water corresponds to a conductivity of 2 765 µS/cm. This value is slightly higher than two times the conductivity measured in the natural sample, 2·1.265 mS/cm = 2530 µS/cm (Table 13). The conclusion drawn from this dependency investigation was that a concentration of 1 g salt/litre sample water should be chosen for the tracer experiments in field.

In Figure 36 and Figure 37 results from tracer experiments are presented. The experiments were performed in the wetland PTAR1 at two separate occasions. The average background concentration of specific conductivity was 1376 µS/cm according to the laboratory analyses.

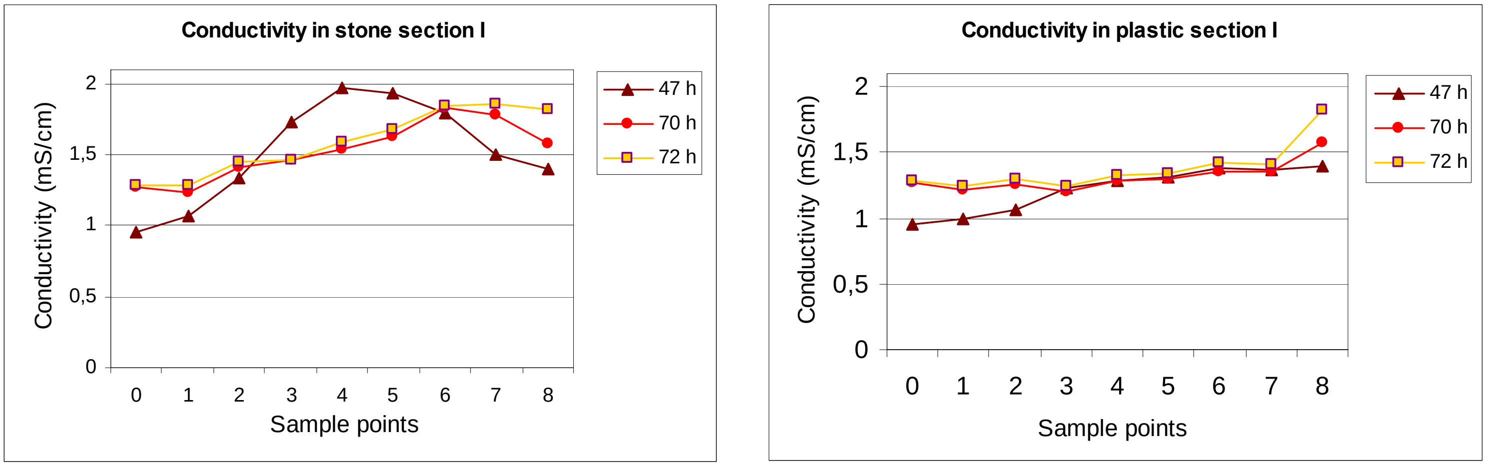

Figure 36 a and b. Specific conductivity, measured during tracer experiment I, in 8 sample points in the stone (a) and the plastic section (b) of the wetland. The curves represent the conductivity 47, 70 and 72 hours after the salt was added. Sample point 0 refers to the septic tank and point 8 to the effluent.

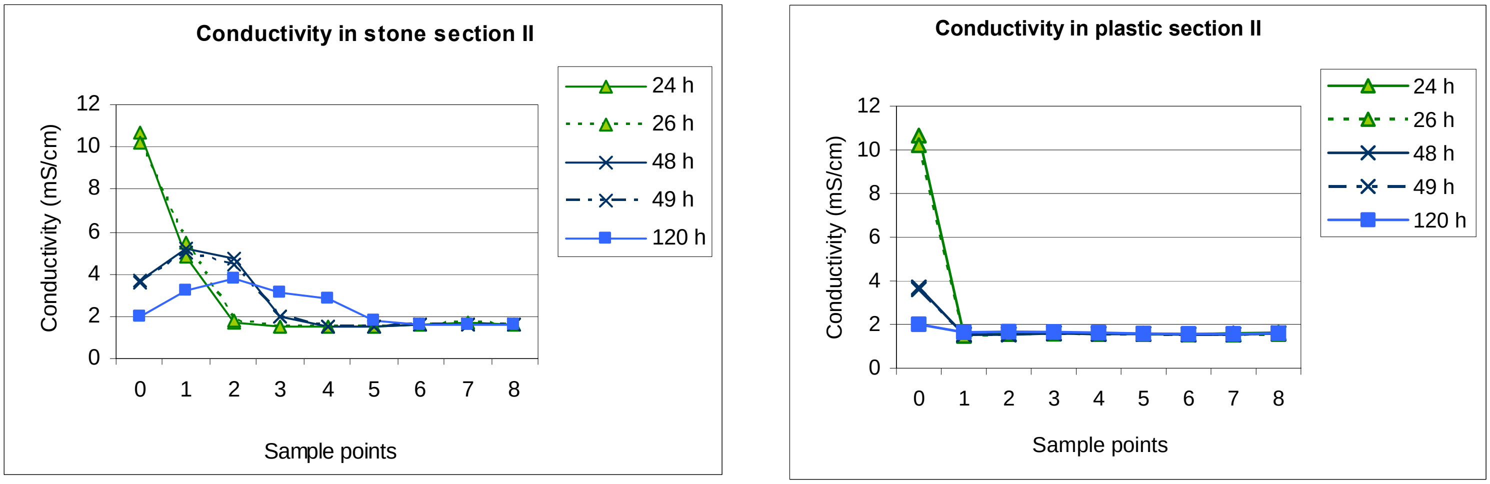

Figure 37 a and b. Specific conductivity, measured during tracer experiment II, in 8 samples points in the stone (a) and the plastic section (b) of the wetland. The curves represent the conductivity 24, 26, 48, 49 and 120 hours after the salt was added. Sample point 0 refers to the septic tank and point 8 to the effluent.

In the results from the stone medium, the specific conductivity is increased and a "salt peak" moving downstream with time, is visible. The salt is spread out on both sides of the mass centre, the height of the peak decreases and the variance increases with time and distance from the source. According to the measurements the median transport time seems to vary a lot. The results from the first round of measurements show a median transport time of three days for the stone section. After three days the peak exits the wetland (Figure 36a). From the second round the median transport time is estimated to be around 20 days. It took three days for the peak to move one chamber (Figure 37a) and this result was extrapolated to cover all seven chambers. No salt peak could be seen in any of the results from the investigations of the plastic medium (Figure 36b and Figure 37b). The conductivity was even throughout the wetland and lower than in the stone section. Since no peak was visible the median transport time could not be determined.

6.5 Laboratory Analyses

Analyses were made to compare influent and effluent water quality, as well as the difference between the stone and plastic sections. Reduction results for the whole wetland are presented in Figure 38 and Figure 39 below. Here, the difference between stone and plastic is not visible. Results from each section and sample point can be seen in Figure 49- Figure 60 in Appendix 6.

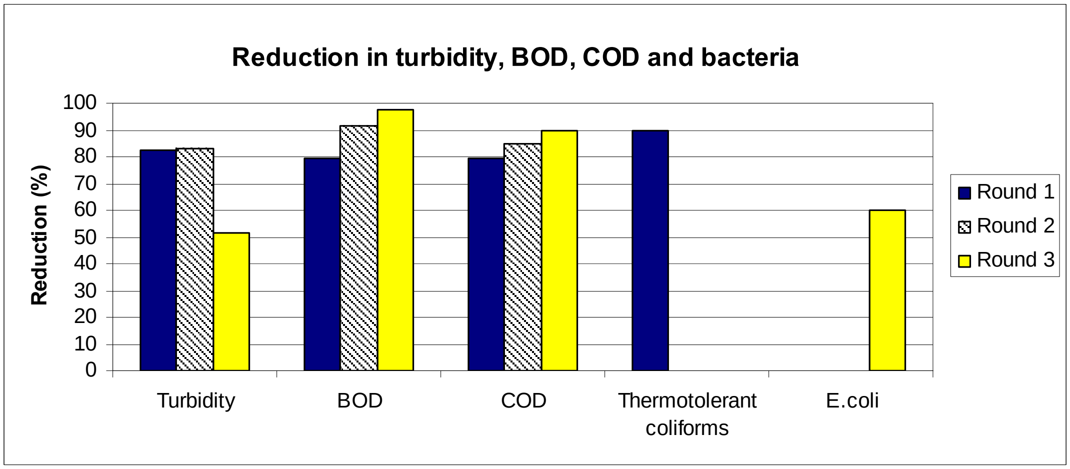

Figure 38. Reduction (%) of turbidity, BOD_5, COD and bacteria in PTAR1.

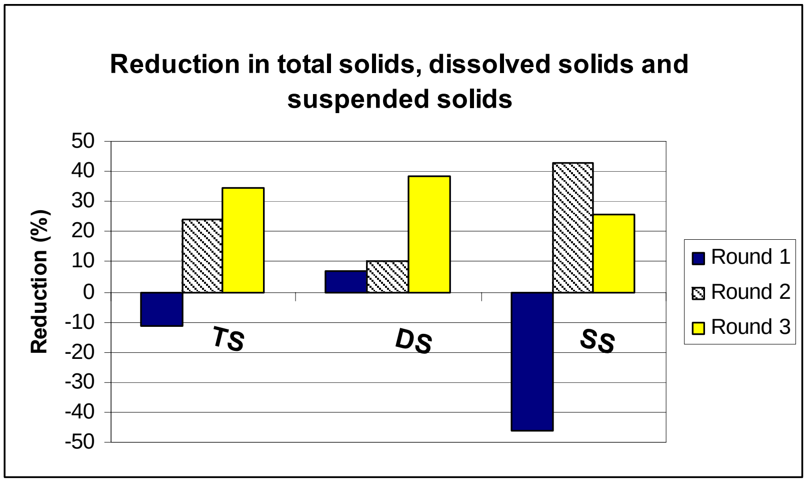

Figure 39. Reduction (%) of TS, DS and SS in PTAR1.

The laboratory analyses showed that pH was steady between 7 and 8, in all samples. These results confirmed the field measurements where the levels were approximated to be the same. The reduction in turbidity is approximately 50-80 %. Conductivity in both media is even through the whole plant and relatively high, just above 1 300 μS/cm. In the water going out from PTAR1 the average specific conductivity is 1 352 μS/cm.

Reduction of TS, DS and SS varies, and possibly improves slightly through the test series. The limit for effluent SS is, however, 60 mg/l, and neither of the media is that effective in reducing SS. The level in PTAR1 is a few hundred mg/l in the effluent. The results were roughly the same for both stones and plastic. In the 7th chamber in the plastic section of the wetland the concentration of SS is 16 times higher than the average of the other sample points, in the first and the second round. It reaches 6 000-8 000 mg/l, which is very high. The concentration of TS in the same chamber is 7 times higher than the average, on the same sampling occasion.

PTAR1 shows a large reduction of BOD_5 and COD. The reduction of BOD_5 is 80-97 % and the reduction of COD is 80-90 %, when comparing the septic tank and the outlet. The effluent level of BOD_5, for both stone and plastic, is mostly below the limit of 80 mg/l stated in Bolivian law. In Sweden the recommended limit for effluent BOD_7-concentration, from small decentralized wastewater systems, is 30 mg O_2/l (Naturvårdsverket 2006) which corresponds to a BOD_5 level of 26 mg O_2/l [2]. The effluent limit for large treatment plants is, as a yearly average of BOD_7, 15 mg O_2/l (Naturvårdsverket 1994) which corresponds to a BOD_5 level of 13 mg O_2/l [2]. Only in the last round was the level in the effluent tank of PTAR1 below these values. The COD levels, in the 7th chamber for both media and in the effluent, were all far below the Bolivian limit of 250 mg O_2/l.

Total N and ammonia nitrogen (NH_3-N) are not significantly reduced in PTAR1. Instead, the levels increase slightly in the first and second round. In the last round the levels are more even, especially in the stone part. In general, levels are higher in the plastic part. This result is clearer for the NH_3-N. The outlet limits for ammonium nitrogen (NH_4^+-N) is 4 mg/l (in liquid discharge) according to the Bolivian law, and the levels of NH3-N in the outlet are between 8.5 and 10.2 mg/l. Even if presented as NH3-N in the results, the major part of the reduced nitrogen exists in the form of NH_4^+ in the wetland. This is because of the pH-depending chemical equilibrium between ammonium and ammonia. The values in the effluent and the law are directly comparable. The concentration of nitrate is low in the whole wetland. The maximum value measured is 2.38 mg/l but in most samples the concentration was below 0.10 mg/l. Since nitrite concentrations are also

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[2] $BOD_5=BOD_7/1.15$ according to Ahlqvist (2005)

assumed to be very low, levels of total nitrogen are estimated not to differ much from that of total organic nitrogen calculated by C.A.S.A.

The concentrations of P are varying and some are very high. Only in the second round there seems to be a reduction, both in total P levels and in phosphate levels. In the other two rounds, there is no reduction and even an increase. Levels are in general slightly lower in the stone part.

The total reduction of thermotolerant coliform bacteria is 90 %. The level to which the concentration has decreased in the 7th chamber is equal in the plastic and the stone media. The concentration of thermotolerant coliform bacteria was $8.0 \cdot 10^5$ CFU/100ml in the effluent, which is higher than the limit of 10^3 CFU/100ml for liquid discharge stated in the Bolivian law. The result for *E.coli* shows an effluent concentration of $2.0 \cdot 10^5$ CFU/100ml. It is higher than the recommended limits for unrestricted irrigation (WHO 2006a) but in the same magnitude as the recommended limit for restricted irrigation, $1 \cdot 10^5$ CFU/100ml (Blumenthal et al. 2000). The concentration of *E.coli* was reduced by 60 %.

Müsch wetland

Reduction results from the Müsch wetland can be seen in Figure 40 and Figure 41 below, and results from the analyses in Figure 61-Figure 63 in Appendix 6.

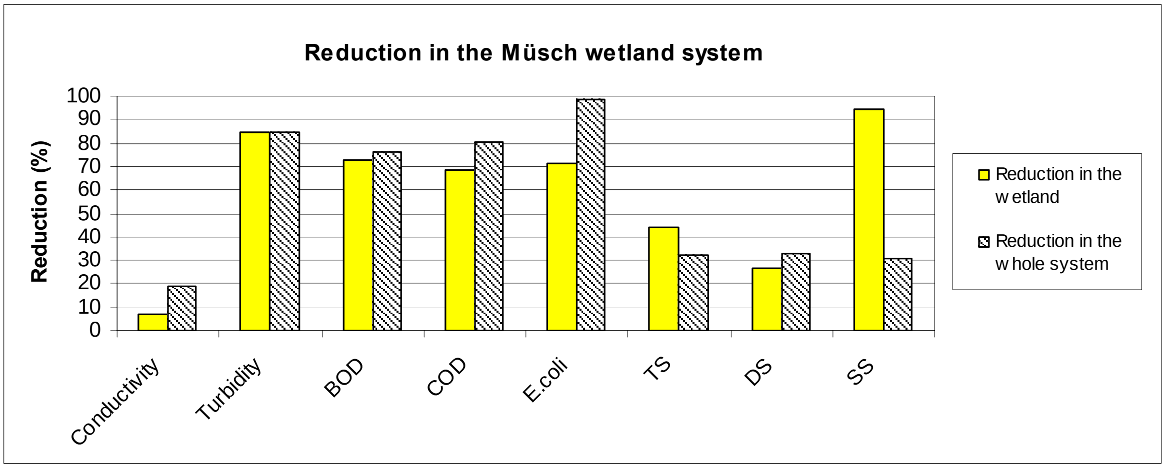

Figure 40. Reduction (%) of conductivity, turbidity, BOD_5, COD, E. coli, TS, DS and SS in the Müsch wetland.

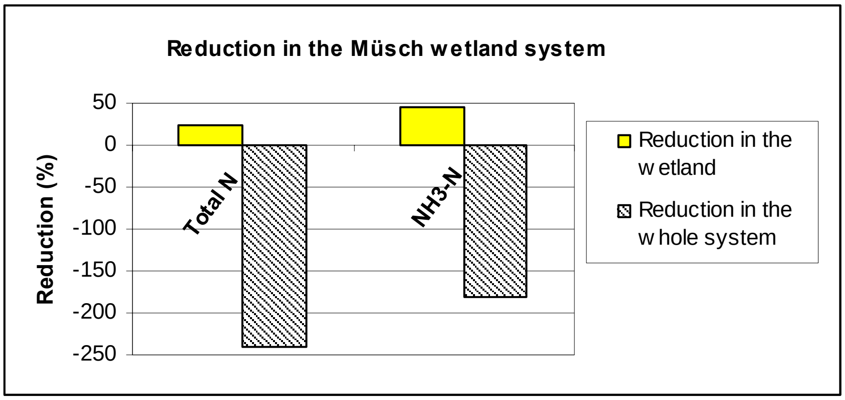

Figure 41. Reduction (%) of total N and NH_3-N in the Müsch wetland.

pH in the samples were between 7.3 and 8, increasing through the system. Oxygen was below detection limit in the first and second sampling points. In the open tank, however, it was 1.73 mg O_2/L. Nitrate was below detection limit in all sample points. Both total N and ammonia N were very high in the aeration tank, well over 300 mg/L, but in the wetland the levels are not higher than 110 mg/L in the entrance chamber. Both nitrogen levels also decrease in the wetland. Results for phosphate and total P can be seen in Figure 62; there was little change in any of them in the wetland, and a slight increase in the open tank.

Potable water in the school at San Antonio

Potable water quality was tested and the results can be seen in Table 14.

Table 14. Results for the parameters analysed in water taken from the tap in the school kitchen 08-11-27.

	Value	Unit
pH	7.9	
Conductivity	210	µS/cm
TS	188	mg/L
DS	145	mg/L
SS	43	mg/L
E. coli	2	UFC/100 mL

6.6 Visual Examination of Water in Observation Pipes

Descriptions from the examination are presented starting from the effluent tank and then in upstream order, ending in the grease trap.

1. Effluent pipe

Turbid, black water but no larger particles or white foam. Slight odour (not offensive). (See figure 43)

X. Effluent tank

Surface water more transparent than nr 1. No smaller particles (visible), but dark (black) water. Slight odour (not offensive).

Figure 42. *Left*: effluent pipe. *Right*: water from effluent pipe.

Plastic	Stone
2. Clear, transparent. Some smaller, single particles suspended. 9 mosquito larvae, 6 small, very motile shrimp like larvae (from now on called species 1 and 2).	3. Slightly turbid. Some smaller suspended particles. No visible animal life. Resembles X.
4. Relatively clear. Some plastic pieces floating around and smaller suspended particles. Species 1 and 2 present (6 animals in total).	5. Darker than 4. More of smaller suspended particles. Species 1 and 2 present (4 animals in total). Some larger settled particles.
6. Transparent, a few plastic pieces and smaller suspended particles, 4 dead animals (species 1).	7. More turbid than 6. Some smaller suspended and larger settled particles. 2 living and 2 dead animals (species 1 and 2).
So far all samples were lighter than the water from the effluent pipe. Resembled the water in the effluent tank. From here on, the stone samples were more turbid than in the effluent.	

8. Transparent, some smaller suspended particles, no animal life.	9. Turbid with many small suspended particles, not transparent. White foam on the surface. Possibly some animal life (hard to tell). (See figure 44.)
10. Transparent, white foam on the surface, some smaller suspended particles, no animal life.	11. Turbid and black with many small suspended particles, not transparent. Some smaller animals of new species (larvae like, 2-3 mm).
From here on, the samples resembled more the water in the septic tank. There was a distinct odour, and the samples from both stone and plastic resembled each other more than in the downstream chambers.	
12. Relatively transparent, grey, hazy, some smaller suspended particles (unclear if organic or plastic), no animal life. Slightly offensive odour.	13. Slightly darker, less transparent and more grey than 12. Smaller suspended particles, no animal life, white foam on the surface, offensive odour.
14. Not transparent, grey and hazy. Many particles both suspended and settled, of many sizes and both black and grey. Some of them foam like. Slightly oily surface, no animal life, offensive odour. (See figure 44)	15. Same as in 14.

16. Septic tank
Not transparent. Grey and hazy but very light. No larger particles. Oily, grey surface with some foam. Offensive smell. (See figure 44)

Y. Grease trap
In this smaller tank only the matter floating on the surface was observed.
Thick, grey and brown sludge. Very offensive smell. Visible faecal matter, hair and paper residues.

Figure 43. *Left*: septic tank. *Middle*: 4th stone chamber. *Right*: 7th plastic chamber.

Water depth
In general, the water depth is below the medium surface. No surfacing has been reported by the staff in the garden. On the measuring occasion, water depth was never less than 20 cm from the surface in any observation pipe.

From the water level measurements and the 2 % slope in the construction, the hydraulic gradient was calculated to be 0.9 % in the plastic section and 0.7 % in stone section.

6.7 Biofilm Evaluation

Surface area
The mean stone in chambers 2-5, PTAR1, has a surface area of 2 930 mm^2/stone. The surface area per plastic carrier was calculated to be 6480-8040 mm^2/plastic carrier, where the interval corresponds to the range from minimum to maximum inner circumference.

When taking into consideration the measured porosity, 43 % for stone medium and 60 % for plastic medium, the surface areas per bed volume was calculated to be 110 m^2/m^3 and 420-530 m^2/m^3 for stones and plastic pieces respectively.

Amount of biofilm
There was no clear difference between the two types of carriers regarding the amount of biofilm, when just looking at them. Biofilm was clearly visible in both cases but it was not possible to tell if other organic matter was stuck to the carriers as well. This was especially the case for the stone medium.

Figure 44. Biofilm and residue from the wastewater can be seen on stones (left) and plastic (right), excavated from just below the water surface.

From the investigation of weight of biofilm on the different media, it was found that there was more organic material on the stones than on the plastic pieces. The results showed 27 times more organic matter on the stones compared to the plastic carriers in the upstream part of the wetland (chamber 2). In the downstream part (chamber 6) there was 13 times more organic material on the stones. For both media, the weight of organic material was larger in the upstream than in the downstream part.

6.8 Oxygen Consumption

During the oxygen consumption experiment in the laboratory the oxygen in all aerated samples was consumed immediately and completely. Aeration for 30 minutes was not enough to produce a detectable level of oxygen. The results from the experiment can be seen in Table 15.

Table 15. Levels of oxygen at a certain time after aeration of the sample stopped.

Time after aeration (min)	0	16	21	32
Oxygen conc. (mg/l)	0	0	0	0

7. DISCUSSION AND CONCLUSIONS

7.1 Flow and Retention Time

Tracer studies with addition of salt and conductivity measurements gave clear results regarding the part of the wetland containing stone medium while the part with plastic medium showed results harder to interpret. For the stone medium the median transport time was estimated from the two experiments, to be both considerably lower and higher respectively, than the nominal retention time of 6.2 days. The time it takes for the water to pass from inlet to outlet is expected to be less than the nominal retention time since the velocity of the water may be higher in certain channels of the bed and shortcuts can be formed. Clogging in some parts of the wetland may also change the flow path and is likely to get worse with time if the degradation of organic material is insufficient and the size of the media is too small.

In PTAR1 there is no real plant growth that could generate organic matter to degrade. However, many of the existing plants are dead and their entire root system is left for degradation, though not in a magnitude that would significantly alter flow paths. Aging of the wetland could also have a positive influence on the flow pattern, e.g. more developed plants increase mixing and dispersion. To have these positive effects the plants must grow better than the present plants in PTAR1. The volume of plant roots and other organic material existing in the wetland were not included in the porosity calculations. Thus they were not considered in the nominal retention time calculations, and neither were effective porosity nor clogging. The nominal retention time is a measure of the residence time in a simplified model. It is not intended to regard all complex processes occurring within a wetland.

The large variation in median transport time in the stone section is likely to be related to differences in flow rate. During the second study the flow was considerably lower than during the first one, performed one month earlier. Possible water shortcuts and retardation processes are not supposed to change much during one month and are not likely the main reason for the large variation. Most HSF constructed wetlands referred to in the literature consist of one large chamber. For the design, idealised models like PFR and CSTR are used. Recent studies (Ascuntar Ríos et al. 2009, García et al. 2004) have shown that models with a series of tank reactors can fit experimental data from HSF wetlands without separate chambers, well. The wetland PTAR1 in San Antonio can be simplified to a series of tank reactors where each chamber is a CSTR. The results from the tracer studies (Figure 36 and Figure 37) in the stone section are more similar to a retention time distribution curve for CSTR in series than for a PFR-model. In the results from the tracer experiment, spreading of the salt with time can be noticed. The height of the peak decreases and the variance increases with time and distance from the source, probably due to dispersion and diffusion.

All connections between the chambers in the wetland PTAR1 are placed to force the water to enter the chambers at different heights. Even if there were no complete mixing in the chambers, this design ensures a longer path for the water through the wetland than if the connections were placed at the same height. Hence, the worst case scenario, with no spreading at all in the chambers, still gives a longer retention time than a single wetland bed without internal divisions. The flow pattern in the chambers is unknown but dead zones could be expected in the two other corners of each chamber compared to where the connection pipes are located. Depending on the location of the connection pipes the flow pattern will look different. In the chambers where the water enters near the bottom and exists near the top the flow moves against the gravity, resulting in lower water velocity and better treatment, compared to the chambers where the connection pipes have the reverse position (Suliman et al. 2007). The Müsch wetland consists of one single chamber and has a higher length/width ratio than PTAR1, making it more similar to a PFR. The question of whether a higher ratio gives better treatment has been discussed in other studies but this is not clearly seen in the results of this study. BOD_5 and COD reduction is about 5-25 percent units higher in PTAR1, but reduction of different solids is half or less. A comparison is also hard to make since the plants treat different magnitudes of pollutants and have shown very different plant growth rates.

The median transport time in the plastic part of the wetland could not be determined through the tracer studies. The most probable explanation for the lack of detectable differences in conductivity is that there is no, or just a little amount of water entering the plastic section from the septic tank. One reason could be that the inlet tube is clogged. Since the tubes are connected, both in the inlet and in the outlet like T-junctions, the flow can also be obstructed if the inlet or outlet pipes to the plastic chamber are located a little higher or lower than the stone chamber pipes. The even water level in all stone and plastic media chambers does not mean that water is passing the two inlets/outlets. Water can enter through the plastic chamber outlet pipe, into the plastic medium. However, when digging into the first chambers on both sides, a large amount of non-decomposed particulate matter was observed in both chambers, which could signal that wastewater is entering the “right” way.

Another reason could be that the hydraulic conductivity is lower in the plastic medium, which means a higher resistance for the water to pass. As a result, the water would flow mainly through the stone section. If the total flow entering the wetland goes through only the stone part, the nominal retention time is calculated to 3.1 days. The density difference between salt water and fresh water is yet another possible explanation; salt water is denser and may sink below the fresh water in the chambers. All samples were taken from half of the total chamber depth, possibly resulting in conductivity levels being lower in the samples than at the bottom of the bed. If this was the case it should have influenced the stone section as well and is therefore not the most probable reason.

An assumption made in the calculations of the nominal retention time is that half of the flow is going to each part, stone and plastic media, of the wetland. This is probably not the case in reality since the two media could have different hydraulic conductivity and more water may be flowing through one of the parts. The short time average flow was calculated from measurements performed during only one day and with the assumption that there is no flow during the night. These calculations are based only on a few measurements and we have seen that the flow vary between different days. Thus, when comparing the nominal retention time with the median transport time, the nominal retention time calculated from long time average flow should be used. To make more useful short time average flow calculations, extensive flow measurements and tracer experiments would have to be done at the same time.

When determining the nominal retention time in the wetland, evaporation and precipitation was not taken into consideration. Rain was scarce during the period of field studies, and only fell for a few hours on 7 days during two months. Earlier measurements of average flow were also done during the dry period. Evapotranspiration from the wetland plants is assumed to be insignificant compared to the inflow because of the low plant growth rate. The evaporation from the wetland is supposed to be significant though, due to the high temperature of the air, wastewater and carrier material. If a water balance or a mass balance of compounds for an HSF constructed wetland is calculated, precipitation and evaporation must not be ignored. The evaporation could be determined by extended flow measurements of the effluent and affluent, and precipitation measurements.

During the summer vacation, from December to February, there is almost no activity at the kindergarten, and the flow into the wetland is assumed to be low. This period coincides with the rain period in Cochabamba, and the wetland receives water from precipitation. The decrease in wastewater load during this period will not seriously influence the flow of water in the wetland, but instead the concentration of compounds in the water. Water flow also varies during the day, the rest of the year, but there is no need for an equalizing tank. HSF constructed wetlands can stand low loading for an extended period of time and also handle high loading rates during a short time.

The nominal retention time was calculated to 6.2 and 8 days, for stone and plastic media respectively, which correspond well to the retention time of 7 days the plant was designed for. It is not surprisingly since they are all based on the same type of theoretical calculations. The median transport time for the stones is likely to vary with the flow. The transport time for the plastic medium is not known. Probably, the transport time is shorter than the nominal retention time of 8 days. To investigate the transport time in the plastic medium, the outlets of the two parts should be separated to prevent uncertainties about backwards flow. It is also necessary to control both inlet pipes and remove any obstructions. If the current construction is not altered, a water level could be used to make sure that the two inlet pipes and the two outlet pipes respectively, are level. After these changes, new salt tests can be done to determine a more accurate transport time. Improving the testing method is also possible; salt can be added like in this experiment, and conductivity can then be measured at even intervals, only in the outlet point. In this way, the result is closer to the true water retention time in the two sections.

7.2 Laboratory Analyses

The laboratory analyses were performed by the personnel at C.A.S.A.. The centre is in the final phase of accreditation, where the goal is to become a certified laboratory according to the standard ISO EC 17025:2005. The policy is to keep a high quality of services, do accredited analyses and use the necessary economical, technical and human resources. We visited the laboratory several days while the analyses were performed, and were given explanations about the methods. The laboratory work seemed to be well-organized and analyses performed thoroughly and carefully. In the protocols, the accuracy of the analyses results were not presented. To test the precision of the lab results, a duplicate test of some parameters was done. The difference in pH was 0.21 and in turbidity 8.0 NTU. DS only varied with 24 mg/l while the differences in TS and SS were 265 and 289 mg/l respectively. The nitrogen compounds differed with 2.3-8.3 mg/l. This could imply small differences in laboratory work, but also differences in water quality. Even though the samples were taken back to back, there is no guarantee that they had similar quality; the mixing within one chamber is not likely perfect at all time, like in an ideal CSTR. The problem is not unique for this set of samples and these analyses; it is a general problem when sampling water. To overcome this, many test rounds have to be made to achieve statistical certainty. Only three rounds were done in this study and the accuracy in the results is not certain. The results are in general not statistically proven and should thus not be used if exact values are needed. They can, however, be a good indication of the status in PTAR1 and the general levels of the different parameters tested. Low number of analysis rounds is believed to cause larger deviation from true pollutant values than variations in the sampling routine and the laboratory work. Increasing this number is the single most important factor in securing reliable results.

Heavy metals are an important factor when discussing water quality since water containing high levels of these is toxic for plants, animals and humans. Heavy metals, e.g. cadmium, zinc, lead and mercury can be accumulated in organisms, the phenomenon is called biomagnification. However the risk of receiving wastewater contaminated by heavy metals is larger when the water has been used for industrial purposes, compared to domestic purposes. With regard to the uses of the water in the school, the risk that heavy metals are included in the wastewater was considered small. Heavy metals were therefore not tested in this set of analyses.

BOD_5 and COD

BOD_5 and COD levels decrease in the water on the way through the wetland, according to all chemical analyses performed. This is in line with results found in the literature studies. The ability to reduce BOD and COD shows that the microorganisms in PTAR1 have developed well and the wetland has a design that gives sufficient time and internal surface for degradation of organic matter to occur. The levels are, however, similar for both plastic and stone media. Without knowing anymore about the flow within the plastic section, it is hard to say anything about if the treatment capacity in the plastic section is higher in reality than shown in the results.

Temperature, pH and turbidity

The temperature is between 21 and 28 degrees in the wetland, pH is steady on a neutral level and there seem to be no sudden changes. This should be a good environment for nitrifying bacteria but nitrification is limited by the oxygen deficiency. Temperature and pH conditions also favour other microbiological degradation processes. The pH is found to be steadily in the permitted range for receiving waters and discharges given in the Bolivian ordinance of water contamination. There is no noteworthy difference in pH or temperature between the different media. The higher temperature in the septic tank and the upstream part of the wetland is most likely caused by discharge of hot water in the kitchen. The decrease in turbidity, from the upstream part to the downstream part of PTAR1, is probably due to sedimentation and filtration of larger particles in the media bed. This is a natural effect in functioning constructed wetlands. Turbidity is often correlated with pathogen and parasite occurrence in the water, why a decrease indicates a possible reduction of pathogens and parasites.

Conductivity

Specific conductivity levels are rather stable in the different sample points. Reactions and ion exchange that occur in the wetland are not shown in the conductivity results since the conductivity is a total measure of all ions. Sources of high conductivity are probably the incoming water and additions in the kitchen. Levels are not expected to decrease in the plant since no change in water usage is likely. They could even increase slightly because of water evaporation that makes the water more concentrated. Irrigation using the treated water might affect some of the fruit trees, e.g. apple and lemon, since these plants could be more sensitive to the relatively high conductivity levels. Grass is not likely to be affected since grass species generally tolerate higher salinity levels. When comparing with the recommended salinity limits presented in chapter 3.3.2, one should keep in mind the variation in tolerance because of local soil and climate conditions. The values in Table 3 refer to crops grown in moderate to slow draining soils, in inland climate of Australia, which could be comparable to the conditions in Cochabamba. Still the salinity tolerance of the plants in the garden at San Antonio could be higher or lower. The conductivity level of alternative irrigation sources, e.g. a well situated in the area, is not known, so a comparison cannot be made. When interviewing the gardeners, no negative effects from the treated water, on trees or grass, is reported. Because of the dry climate, ground water is not replenished often and possibly has a high salinity as well, making any salinity difference small and insignificant when choosing between water sources. The potable water in the tank comes from a local well, and can thus be expected to have similar salinity levels.

In the third test round, the levels of DS and conductivity were elevated in the septic tank compared to the rest of the sample points and rounds, where the levels were relatively even. The difference is several hundreds of mg/l and µS/cm respectively. Elevated levels could be caused by water from the kitchen carrying larger amounts of Na^+ and Cl^- ions than usual, originating from salt in cooking water. These high levels are not detected in the other chambers, probably because the actual time it takes for the water to be transported from the inlet to the outlet of the wetland varies from the three day transport time that the sampling plan was based on. This means that the same water elements are not followed all the way through the wetland. The compounds causing the high salinity are also subject to spreading and retardation processes. The high initial salinity level gives a misleading high reduction level for this round; effluent levels were about the same in all three rounds.

TS, DS and SS

The reduction of DS and SS varied in the different sample rounds. In the two last rounds there was 10-43% reduction of both. The first round showed an increase in SS. A comparison between the inlet and the last chamber of the stone section shows a slight decrease though. In the last chamber in the plastic section the concentration of SS was 16 times higher than the average of the other sample points, in the first and the second round. The concentration of TS in the same chamber and rounds, was 7 times higher than average. SS is calculated by subtracting DS from TS, hence the high SS concentration. Small plastic particles originating from the plastic carriers are expected to increase the SS concentration, but not only in the 7th chamber and not to these very high levels (6.2-8.6 kg/l). This is likely due to an error made either in the laboratory, when calculating the level, or in the field work.

Oxygen and nutrients

Oxygen should be transported down to the roots to keep plants alive, but there are disagreements in the literature on how much excess oxygen that is available for biological activity in the root zone of a constructed wetland. It is likely to be available only in small microzones around the roots and not diffusing to the whole bed profile. The results from the analyses for PTAR1 during November 2008 show that there is no dissolved oxygen in the water throughout the bed profile. The possible oxygen excreted by the plants, or diffusing through the medium or the observation pipes, is supposed to be in low concentrations and consumed quickly in decomposition of organic material. The supplementary laboratory experiment on oxygen consumption rate showed that oxygen in an aerated water sample from PTAR1 was consumed very fast. This was not a surprise since the BOD-levels are high in the wastewater. The result explains the fact that there is no detectable oxygen in the wetland. Anaerobic conditions are not a unique feature for PTAR1; in the samples from the inlet and outlet of the Müsch wetland there was no detectable oxygen either. Low solubility of oxygen, due to the high altitude in Cochabamba, is of minor importance compared to the oxygen deficiency caused by degradation of organic material.

There is no easy way of improving oxygen levels without redesigning the treatment system. One suggestion is to construct a vertical flow wetland before the existing tank. Here, a pipe in the bottom of the bed ensures some oxygen supply. The water is distributed on top of the bed, percolated and collected in the bottom pipe. This method would increase nitrification. A subsequent anaerobic horizontal flow unit, like PTAR 1, can reduce nitrogen levels through denitrification. The re-aeration and nitrification are higher in beds with vertical flow than in beds with horizontal flow. However, this solution might not be desirable since these systems need pumping to get good spreading of water and tend to be more expensive and technically more complicated. There would also be an open water surface which could lead to more mosquitoes and odour problems. A less expensive option is to intermittently lower the water level in the wetland, to allow air to reach the bottom of the bed. However, this requires a space to store the untreated wastewater while the bed is being emptied, or alternation between two parallel beds; one in use and one being aerated.

The BOD and COD levels decrease in the water on the way through the wetland according to all chemical analyses performed, but the concentration of nitrate does not increase in the downstream part of the wetland. In fact, the nitrate levels are low in all test results. The reason is probably the oxygen deficiency. Oxygen is needed for nitrification and the anaerobic environment in PTAR1 cannot be used by denitrifiers unless combined with an aerobic step. This leads to poor reduction in total nitrogen and ammonium nitrogen. Another reason for low nitrate levels is that if nitrate is produced in some part of the wetlands it can be consumed by denitrifying bacteria in other parts without being detected in the analyses. The total amount of nitrogen compounds can be calculated as Kjeldahl-N + NO_2-N + NO_3-N. Nitrate concentrations were very low and the nitrite concentration is assumed to be low, so the total nitrogen concentration is estimated not to differ much from that of total organic nitrogen.

Levels of total P are high and it is difficult to say if there is any real reduction. In the second round there seems to be a reduction, but this can be caused by the high influent values in this round, possibly following laundry in the house on the school premises with subsequent release of detergents in the water. This could also explain the high readings in the first round, in the septic tank and second chamber of both media. Phosphate is the form that is readily available to living organisms and can be taken up by the plants and microorganisms in the wetland and by plants irrigated with the treated water. Phosphate can also be adsorbed to clay particles, minerals and metal complexes, and in that way be removed from the water. This kind of removal process is far more probable in a natural sediment or soil than in a wetland consisting of stones and plastic pieces. The P concentrations were, however, expected to be a little lower in the stone section because the stone bed contains soil residues which could improve P removal. The levels are, for some test rounds, lower in the stone section than in the plastic section, but conclusions are hard to draw. The anaerobic conditions also decrease the possible adsorption of phosphate. No better medium for P removal can be proposed without increasing the risk of clogging and surface flow due to low permeability in the wetland.

The slight increase in N and P levels that was observed in some of the rounds could be explained in different ways. Firstly the transport time of three days used to set the sampling interval, can be incorrect. If the same "water package" was not sampled both times, differences in influent concentrations could have been significant and made the results incomparable. There could also be an addition from dead plant tissue decomposing in the bed, and finally the accuracy in the laboratory methods is not known.

A decision has to be made on how much treatment is worth. Costs cannot be too high if people in the area are to afford and accept the solution. Any form of forced aeration is too costly to be a viable solution. The reuse pattern is vital in making a good decision; if the recipient is a waterbody, the levels of nutrients like N and P are important to control in order to prevent eutrophication. In the case of PTAR 1, there is no stream or lake near the wetland. Alternative to irrigation is only infiltration into the ground. Since the garden is located on a hill slope, with no wells dug within a few hundred meters downhill, infiltration could work. This would, however, be a waste of a valuable resource. Irrigation is the best way to reuse water in this semi-arid region, and in this case the nutrient content is only beneficial to the plants and not a problem. Spending money on aeration devices or new design is thus not advised.

Bacteria

The concentration of thermotolerant coliform bacteria is reduced by 90 % in the plant. Although it is a significant reduction the levels of the effluent exceed the limits for liquid discharge, and for reuse of water with public contact, in the Bolivian ordinance for water contamination. The reduction is one logarithmic unit which is lower than the median value for HSF wetlands, two logarithmical units, according to Kadlec (2009). There are few microbiological results in the water analysis; only one round of thermotolerant coliforms and one round of *E.coli* tests were done. Water transport time in the wetland was not taken into consideration for the *E.coli* sampling round. The reduction of *E.coli* was 60%, which was not as high as the 73% reduction determined from the analysis done 5 weeks earlier by AGUATUYA and C.A.S.A. but certainly in the same order of magnitude. The effluent concentration of *E.coli* was also lower, $3 \cdot 10^4$ CFU/100ml, in that analysis.

According to the analysis performed in November, the *E.coli* concentration in the outlet of PTAR1 is in the same magnitude, 10^5, as in a study made at an HSF constructed wetland in Masaya, Nicaragua, which had a similar retention time (WSP 2006). 10^5 is also the limit for unrestricted reuse of wastewater for agriculture recommended by Blumenthal et al. (2006). In a study on how vegetables and fruits are affected by irrigation with water treated in a constructed wetland (Masaya, Nicaragua), carrot, yuca and onion, vegetables growing under the surface of the ground, showed low concentrations of faecal coliforms while the fruits grown above the ground showed no faecal contamination. The water used had *E.coli* concentrations of between $1.5 \cdot 10^4$ and $1.3 \cdot 10^5$ MPN/100 ml. (WSP 2006) The concentration of faecal coliform bacteria in PTAR1 is higher than the recommended limits for both restricted and unrestricted irrigation. Still we think the treated water can be reused in the same way as now, for irrigation of lawns and trees in a limited area, at hours when the children do not have access to the lawns. It is important not to risk exposing children and staff to sources of possibly disease causing bacteria. If new treatment plants of this type are constructed, they should be designed to reduce the effluent bacteria level far below the requirements in Bolivian ordinance and the WHO guidelines. In that way there are less health risks even if the water quality fluctuates.

Drinking water

Drinking water was tested to see if any pollutants were introduced into the wetland this way. Solids and levels of bacteria were, however, low, pH was rather normal and the water looked clear. Conductivity was slightly high, and this could help to explain the high levels in the wetland. Since ground water is not abundant in the Cochabamba area, this result is not surprising.

Müsch wetland

The Müsch wetland shows relatively high reduction of BOD_5, COD, turbidity and *E.coli*. If the aeration tanks are taken into account, the reduction is even better albeit not reaching the discharge levels in the law for all parameters. Both BOD_5 and COD are below discharge limits. The wetland seems to have developed well and the good status is also indicated by the abundant plant growth. Reduction of SS is higher here than in PTAR1, which is likely because of the length of the Müsch wetland, giving solids more time to settle and get caught in the medium. Nutrients are, however, not reduced in any significant way in the wetland. P levels are almost constant and there is a slight reduction in N. In the last open water tank, both levels have instead increased. Low nutrient reduction in HSF wetlands is not unexpected but instead rather probable due to oxygen and soil particle absence. In general, this wetland seems to function better than PTAR1. The open tanks contribute to increased quality, but it might not be a good idea on a larger scale because of the mosquito risk.

General water quality

All constructed wetlands need time to fully develop and reach their full treatment capacity. This is true for many techniques relying on biological processes. PTAR1 is not one year old, and probably has not reached a steady state yet. With changes made to inlet and outlet pipes, to determine correct flow patterns, new testing could show more reliable results and the actual development of the wetland. Comparing the current effluent quality to the previous untreated wastewater infiltrated into the soil, the current situation is a real improvement. Even though effluent standards are not always met, the general quality is improved, reducing health risks and environmental problems. The current use is also beneficial to garden crops, school lawns and ultimately to the children. The Müsch wetland serves the large garden with irrigation water, and this is good both for the environment and for the family business.

Theoretically, if the sampling interval and the water transport time through the wetland was the same it should be possible to analyse samples from the upstream and downstream part of the wetland having the same initial concentrations. According to the tracer experiments, however, the median transport time for water in the stone section is likely to vary with the flow. Some of the water is also transported faster and some slower than the median, regardless of flow. This means that the water can be transported slower or faster than the three days used as sampling interval. As discussed in the sections *Conductivity* and *Oxygen and nutrients* above, water samples in the same sampling series might not originate from water with the same inlet concentrations which can influence the comparison between analyses results.

Because of the uncertainties about the blackwater content of the influent water to PTAR1, it is possible that the wetland was under-dimensioned when built. With a lesser hydraulic flow treatment results would improve. Since this is unlikely to occur though, adding a sandfilter after the wetland is an alternative. To treat blackwater from a school of this size, it has to be at least 1 meter deep. Sandfilters give good tertiary wastewater treatment and effectively polishes treated water, further reducing solids, BOD and bacteria. They are also low cost alternatives, and when the water already has a low SS content the filter should last longer since there is reduced risk of clogging[3].

The biggest remaining problem with a large scale application in arid peri-urban areas is the high content of bacteria in the treated water. This effectively reduces options for water reuse, and needs to be addressed before planning an expansion of the HSF constructed wetland as a viable treatment solution in Cochabamba. There is some pollution reduction in both PTAR1 and the Müsch wetland, but effluent levels are still too high. Any system constructed near shallow drinking water wells need improved capacity, monitoring of the effluent and knowledge of groundwater flow, to make sure there is no contamination.

If any wetland systems are planned near the Laguna Alalay or the Río Rocha, the problem of minimal nutrient reduction also has to be solved, not to risk deteriorating water quality even further and increasing eutrophication. A sand filter, placed after the wetland, could be a good complement in order to decrease the concentration of solids, ammonium, BOD_5 and bacteria further. It would also result in water with higher transparency which may increase the acceptance for reuse. Since the reduction of solids is large already in the wetland, a sand filter would last for a longer time before a change due to clogging is necessary.

7.3 Future Monitoring

A specialized fauna for removal of particles, nutrients and pathogens can develop in an environment where the constituents of the water do not change much over time. A constructed wetland with a relatively evenly distributed load of domestic wastewater can create such an environment. The wetland in San Antonio has only been in operation since the spring of 2008. The time required for the biological processes to reach steady state, the microorganism fauna to evolve and for the ecosystem to develop fully, is long. PTAR1 has probably not reached its final capacity yet, and further tests are needed to monitor the development of the plant. Treatment capacity could change while microorganisms and plants establish properly. The wetland is built as a pilot plant, and to investigate the development of the wetland more thorough analyses are needed. Monitoring during this year could be done in May and November. In May the first rain period in the history of PTAR1 has passed and a six month interval between samplings is maintained. During these analyses, more sample points than just the inlet and outlet should be chosen to check internal levels.

Basic parameters to test could be pH, turbidity, conductivity, BOD_5, SS and thermotolerant coliforms in the septic tank and the outlet of the wetland. These parameters give an adequate picture of water quality, in view of the current use of treated water and the financial possibilities of AGUATUYA. Suggestions have been made about how many samples should be taken on each testing occasion. One suggestion is to take multiple samples over a longer period and then to mix them. Analyses are done on the mix and give an average value for the time period chosen. More samples are taken and this makes the method statistically better. However, if the mean value of all samples is used the result, outlying, high values can raise the mean value and give a misleading increase in results. Another option is to take two or three samples each test period, with a few days in between. More than one sample is necessary to assure against local abnormalities, sampling errors and other mistakes. This method is more expensive and the fewer samples taken, the lesser statistical certainty. It, however, allows AGUATUYA to see the exact values. If any value is remarkably high, a single sample or the laboratory calculations can be redone without affecting a whole set of samples. Which method is used depends on what AGUATUYA can afford and how much time they have to take samples over a longer period.

Since the test results have shown that there is very little oxygen in the water, analyses of different nitrogen compounds are of minor interest. In addition, nitrogen and phosphorus are taken up by plants when the treated water is used for irrigation and the need of input of extra nutrients to the soil decrease. Specific

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[3] For design suggestions, see for example http://www.epa.gov/owm/mtb/sandfltr.pdf or http://www.unh.edu/civil-engineering/research/erg/cstev/fact_sheets/sand_filter_fact_sheet_08.pdf

conductivity is a measure of all ions in the treated water and could be compared to recommendations regarding different agricultural plants. If wetland design changes or if problems like clogging and surface flow occur, more tests should be done. Contacts with the school Sagrado Corazón de Jesús should be maintained to notice if the water use in the school changes, for example more use of washing machines or a large change in the number of children could influence the water quality. These recommendations presuppose that the treated water is used in the same way as the present use; irrigation of lawns and fruit trees. If the water usage changes more analyses might be necessary. If other treatment plants are planned where the water will be discharged into rivers or other waterbodies, N and P contents have to be taken into consideration.

Parameters that have not been taken into consideration during the tests in November 2008 are sodium, boron, potassium, chlorides, peroxides and chlorine, originating from e.g. detergents. Some of the compounds are useful for plants in low concentration but toxic if too high (WHO 2006b). If the irrigated plants seem to be damaged by the water, these parameters could be monitored. Presently, no plants show signs of damage. Plant growth rate could not be monitored in this project, but the gardeners did not see any problems with plants being too small.

7.4 Comparison between Stone and Plastic Media

The character of the stone and plastic media respectively, differ significantly from each other. The porosity of the plastic medium is higher than the porosity of the stone medium. Besides, the density is low for the plastic material; hence the plastic pieces tend to float, creating more space at the bottom of the bed. The surface area per bed volume of the plastic medium is considerably larger than that of the stone medium according to the calculations, between 3.8 and 4.7 times larger. The outside of the plastic carriers is smoother than the surface of the stones, why it could be harder for microorganisms to grow on. Still, the major part of the surface area of the plastic pieces is inside the carriers. This inner surface is rough, promoting biofilm growth in a sheltered environment. The total surface area of *one* plastic piece, when assuming no ridges inside, is only twice the surface area of one stone. Most interesting when discussing treatment capacity though, is the surface area per bed volume. Thanks to the deformed shape of the plastic pieces the surface area per bed volume is ca 4 times the stone surface area. At Anox Kaldnes, a company in Lund producing biofilm carriers, the surface area of the different carrier types varies from 230 $m^2/m^3$to 1400 m^2/m^3 (Anox Kaldnes 2009). The surface area result for the plastic carriers in PTAR1, 420-530 m^2/m^3, is within this range and can be considered realistic.

The water colour was generally darker in the stone part than in the plastic part of the wetland. On the other hand there were small plastic particles in the water from the plastic medium, but these did not seem to exit through the outlet from the wetland. The risk for release of toxic substances from the plastic material is considered low. The same type of pipes is used for distribution of drinking water in other systems and they are expected to last for a long time. Water colour generally influences how willing people are to reuse wastewater. Transparent water with no colour is more acceptable for irrigation. It also requires odour free water, and in this case both parts reduce smell effectively. Neither the water in the last two compartments nor the water in the effluent tank do smell much. At the school in San Antonio de Buena Vista the staff is not disturbed by any odour (Muñoz 2008, Gonzales Villaroel 2008). A more transparent water colour of the effluent may lead to an even more positive attitude to the treatment method. Before taking any further measures in redesigning the size of the wetland, the outlets from the stone and plastic sections should be separated. After investigation of whether the separated sections are working properly, a new evaluation about water colour could be done.

The results show more organic material on the stones compared to the plastic carriers. It is hard to tell if this is the real difference in biofilm weight or just a result of the sources of errors; there were several in this biofilm amount experiment. Only carriers from just below the water surface in the bed, were used in the experiment. It was difficult to dig deeper into the bed only using hands and feet. In the top layer the water level fluctuates, so the biofilm here might not be representative for the whole bed. The stones, especially upstream, were covered in thicker layers of black sludge. This is not all biofilm, but large parts were still included in the results. When scrubbing the carriers probably not all biofilm was removed, especially from the stones which have a coarse surface that is hard to clean completely. The inside of the plastic carriers was also hard to reach in some cases because of the folding. Some biofilm could have stuck to the toothbrushes and the plastic bowl. When filtering the water, only one size of filter paper was available. The filtered water was still turbid, which means that some of the organic material passed the filter. The fraction should however be the same for all four samples, and the results are only used to compare the different sections, not as absolute values. All of the above could have influenced the results and makes them difficult to interpret correctly. Thus, the results regarding biofilm amount on the different media are not reliable.

Theoretically the plastic carriers have more capacity, with a larger surface area than the stones. This leads to more possible sites for microorganism activity and to a more extensive wastewater treatment. However, the analyses results do not show neither more nor less removal of BOD_5, COD, solids or bacteria in the part with plastic media. One explanation could be the possibly obstructed flow in the plastic section, changing retention time and influencing treatment mechanisms. Separated outlets from the wetland are recommended to further investigate which media is working best in this type of treatment plant.

7.5 Plants

The plants have not grown well in PTAR1, but they are not likely to be limited by P or N levels since the water is rich in these nutrients. The distance between the plants, 0.25-0.8 m, is less than the recommended 0.9-1.2 m (Surrency 1993) but this fact is not regarded as a problem for plant growth. Higher macrophyte density should increase the development rate of the wetland rather than be a problem. Perhaps the pruning of the plants, at the same time as they were planted in a new environment made them extra vulnerable. Any impact from low growth rate on treatment capacity is, however, assumed to be low but not negligible.

In the Müsch wetland the plants did not grow well in the first meters of the wetland, which could be partly caused by low oxygen levels due to a high load of organic matter. In PTAR1 the organic load is higher, which could explain the poor growth in the first part. In the plant at SOS Aldea Infantil and at the Bomblat residence the plants now grow well, and the growth rate at the former is rather too high, demanding harvesting twice each year. These plants did not grow that well when examined in 2007 by Spångberg and Söderblom, but after some time they are now well established.

Plants in constructed wetlands are believed to facilitate oxygen transport into the bed, but it has been shown in different studies that this rate is low in comparison to what is needed to decompose organic compounds. In PTAR 1 the oxygen levels are very low. This environment might have proved to be too adverse for the plants, together with the early harvesting. However, this is not believed to be a large problem for the overall treatment capacity, only for aesthetics. The major part of the treatment probably comes from biofilm activity, sedimentation and filtration, non biological P-removal and other sources not related to plant growth. Still the decomposition rate is higher in planted than in unplanted wetlands. Increased growth of plants creates more surface and suitable environment for biofilm, and can also increase water mixing. Roots and rhizomes can prevent clogging by creating channels in the medium, but dead plant tissue could also add to clogging problems. (El Hamouri et al. 2007, Maltais-Landry et al. 2007)

During the rain period in the beginning of 2009 the surviving plants grow well in PTAR1 according to AGUATUYA. We recommend AGUATUYA to plant new macrophytes in the part of the wetland where the plants are dead. The same type can be chosen or other species that are known to grow well in the local climate. The macrophytes should not be too sensitive to low oxygen levels in the water and able to create roots that can penetrate deep into the bed. *Calla Ethiopia*, *Schoenoplectus sp.* and *Typha latifolia* have been observed to grow well in the other visited wetlands in Cochabamba. After planting, plants should be left to establish properly, without harvesting. Wastewater from the septic tank effluent may be diluted with clean water from the irrigation basin during the first weeks after planting in accordance with recommendations from USEPA (2000).

Harvesting should only be done if the mass of vegetation roots threatens to clog the wetland bed, or if the leaves and stems grow abundantly and hinders access to e.g. observation pipes. Like at C.A.S.A., dead stems or stems that break and fall down could be removed to make room for new ones. Brix (1993) and USEPA (2004) mentioned the importance of harvesting at the right time, before plant senescence, but since Cochabamba has an even, warm climate, there is no particular period of low growth. Each plant type must be monitored to find any such periods.

7.6 Excess Water

Today, large amounts of treated water, not used for irrigation, are pumped outside the garden wall and into the street (see Figure 45). This is not a good solution since children walk right past on their way to school and back home for lunch break.

Figure 45. School children passing close by effluent water from the wetland.

The effluent water contains high amounts of bacteria and should not be discharged without protecting humans and animals that might come into contact with it. For PTAR1 we recommend that the water is used in the garden or infiltrated into the ground in the garden. The first option is better since the water is reused and not wasted. If it is not used for irrigation of crops, more trees could be planted in the garden and the excess water used for irrigation. When there are no children in the kindergarten and water flow through the wetland is low, the rain period makes sure that the trees do not die. The personnel at the school are positive to a change where the water is used in some way instead of being lost (Muñoz 2008, Gonzales Villaroel 2008). If the effluent tank is exchanged to a larger one, all water can be saved for irrigation. In possible future treatment plants where treated water will be reused, a larger effluent tank (compared to the flow through the wetland) or other storage solution is needed. This would make it easier to save all effluent water for reuse.

7.7 Grease Disposal

Currently there is no sustainable solution for disposing of grease, hair, faecal residues etc. removed in the grease trap. A possible solution could be composting on site, in the garden, or at another location. The residues would have to be mixed with e.g. dry plant material from the garden, like weeds and dead branches, or saw dust to assure a sufficiently high dry content. Also other organic waste can be added to guarantee a good mix of substances, benefiting the decomposing organisms in the compost. This way, waste from the kitchen can also be treated locally, and the resulting compost matter used for soil improvement in the garden.

The compost needs to be aerated and turned for several months, and it requires sufficient space. This might be the limiting factor here, since the garden for the most part is used for cultivation. Not much space is free. The compost also needs to be monitored to assure that it reaches the right temperature during enough time, so any harmful bacteria is killed. If the compost soil is used to grow vegetables that are eaten directly (unlike e.g. fruit trees), this is especially important. To just bury the grease or burn it in an uncontrolled environment is not recommended.

7.8 Constructed Wetlands and Reuse of Treated Wastewater in Cochabamba

Reuse of treated wastewater leads to an increase in total quantity of available water. The need of producing new potable water is reduced if treated water is used instead in industrial, housing and recreational projects. Less freshwater from lakes, rivers, wetlands and groundwater can be extracted, which could influence the base flow in rivers and the groundwater level, already low in Cochabamba today. The water quality in the former receiving waterbodies increases if the treated water is used for irrigation and nutrients are taken up by plants and not discharged into the recipient. Less energy is needed if the pump is used only for irrigating a garden or a field instead of extracting groundwater for the same purpose.

If there are no aquifers or waterbodies close to a site requiring irrigation, reuse of wastewater from the vicinity is an energy saving alternative compared to transporting water by truck from a completely different place. Water could be reused for different purposes like fire protection, toilet flushing, landscape and aesthetic purposes, street cleaning, cooling water or agricultural irrigation. Cochabamba is situated at high altitude and fires do not start easily, but the air temperature does not vary much and the mean temperature is high, leaving the city very dry for the major part of the year and making the need for reuse of water large, especially for irrigation of agricultural and recreational areas. Climate conditions are well suited for a treatment method where decomposing microorganisms are involved. Wetlands have been tried and work in many different climate regions of the world. When the altitude is higher and the temperature cooler, compared to for example the tropics of Bolivia, there is just a need for longer retention time (Bomblat 2008). There seems to be sufficient space for this type of decentralized treatment plant in the area and slopes, needed for gravity force acting on the water, exist everywhere in Cochabamba. Implementation could lead to more green areas with lawns and trees, and less erosion. According to Christian Bomblat it is a question of convincing politicians and talking to people living around park areas without irrigation, abandoned during the dry season.

24 % of the city of Cochabamba is not connected to the central sewage system or the municipal treatment plant Alba Rancho (SEMAPA 2009). This is also the case in San Antonio, located about 10 kilometres outside of the city centre. Alternatives for poor people living in peri-urban areas are often to just let wastewater run into the street or a nearby stream, if not directly infiltrated into the soil. Septic tanks are also common, but rarely emptied or inspected. Maintenance is low, and the effluent is often just infiltrated into the surrounding soil. Existing requirements regarding water quality are not met, and there are no sanctions, e.g. fines, for contamination. There is a need for political discussions about the municipalities in the area sharing general goals. The total impact on the environment is not satisfactorily reduced by the treatment at Alba Rancho as long as there are discharges of untreated wastewater upstream and downstream in the same river. (Heredia 2008, Lizarazo 2008)

The cost for expanding the sewerage network is very high. Already today there is not enough money to increase the treatment capacity of the central wastewater treatment plant to the required level, even without adding any more households to the system. The plant is not big enough for the rapidly growing city and no solution is visible in the near future. In this situation, decentralized solutions, focusing on local recovery of resources like water, are the only economically viable alternative. This is true both for poor peri-urban and sparsely populated areas (Ujang and Henze 2006). People in this region are very poor and do not have the means to finance any major piping system on their own. They can, however, afford a low maintenance alternative that requires little energy, machinery or construction material. Constructed wetlands are an example of this. Even if the results vary and do not always meet the requirements of the Bolivian law, there are few alternatives that give that much pollutant reduction at this low cost.

According to Cooperation Research Centre on Water Quality and Treatment, Australia (2007), recycling for irrigation of parks and gardens and industrial uses is the most acceptable option for increasing water supplies, and it carries the lowest risk for public health. Furthermore this type of reuse decreases the environmental impact of wastewater on receiving waters. In this case, there are no waterbodies nearby and water deficiency is significant, so extended use in gardens and fields could probably be accepted in large scale. New technology, however, requires time to get used to, and there is some suspicion about the constructed wetlands as a good option to central systems or the old traditions. Some think it is too “simple”. Visits to well functioning systems are a way to reduce public worries about inconveniences that any new kinds of treatment plants may cause.

The results from PTAR1 and the attitudes from school and garden staff show that with information, education and “see-for-yourself”, people with no previous experience can come to accept and appreciate this solution. There is not one solution for everybody. A household with a combined sewage system installed in the house and a water-flushed toilet may, together with neighbouring households, share a constructed wetland. In areas where EcoSan-toilets (urine diverting dry toilets) are installed, smaller constructed wetlands can be used when taking care of the greywater coming from washing, cooking, showers etc. Urine can be used directly as fertilizer, and faecal matter can be stored in a dry environment for a longer time period before being used as fertilizer, or be fermented to produce biogas. Pathogens are thus destroyed, and in the later case organic household waste can be included. This decreases costs for garbage disposal; a service that does not function very well today and could use sustainable alternatives.

Education on how to maintain a wetland system is needed, and often it requires that some of the residents take an extra interest in the system. There is a growing interest for environmental issues in Bolivia today (Bomblat 2008). With more successful examples, people are more interested in this kind of solution. It would, however, probably require time, patience and a larger campaign about improved waste and wastewater management in general, and the effectiveness and simplicity of constructed wetlands in particular, to truly win people's hearts.

7.9 Conclusion Summary

The general quality of the effluent water from PTAR1 is improved but it is still unfit for many uses. The relatively low effluent quality highly limits the application possibilities. Only three test rounds were made and this reduced the reliability of the results. The analyses results can, however, be a good indication of the treatment capacity of PTAR1 and the general levels of the different parameters tested. The water is fairly clear and the reduction in BOD_5, COD and turbidity is acceptable. Reduction of bacteria is mediocre. The wetland is largely anaerobic which is likely to be the reason why no nitrogen removal was observed. A low reduction in nutrients is mostly a problem if the water it let out into a lake or river. Here they fertilize the crops and grass that are irrigated with the water. Re-use of the treated water is beneficial since the area is very dry. In the school and garden, it can be put to good use. Today there is a problem with excess water that is let out onto the street, and since it still contains much bacteria, the children who walk passed it every day could be at risk. The water could be used in the garden instead.

To better see which material is superior, stones or plastic, we suggest that the outlet of the wetland is separated into two outlets and that new measurements are made. More plants are needed since most of the old ones are dead. One option is to install a sandfilter after the wetland, to further reduce solids, BOD and bacteria.

Cochabamba has a long dry season, creating a great need for water re-use and especially for irrigation of agricultural and recreational areas. Treated water from constructed wetlands can be used for this purpose in the vicinity of the wetlands, reducing consumption of potable water, shortening water transports, reducing the risk of eutrophication in adjacent waterbodies and lowering energy requirements. Climate and terrain conditions in Cochabamba are suitable for constructed wetlands. HSF constructed wetlands require little energy, construction material and maintenance. They are a good alternative in sparsely populated, poor areas like peri-urban Cochabamba, where there are few other alternatives. Use of constructed wetlands could lead to more green areas with lawns and trees, and this in turn decreases soil erosion.

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Photos

All photographs were taken by the authors except for Figure 14 (right) which was taken by Martha Müsch.

Appendix 1. Temperature and Rainfall in Cochabamba

The annual mean temperature in Cochabamba between 1998 and 2007 was 18.0 ºC, the annual maximum mean temperature was 27.0 ºC and the annual minimum mean temperature 9.0 ºC (INE, 2008b). Figure 46 and Figure 47 show monthly mean temperature and monthly mean precipitation during the years 1961-1990.

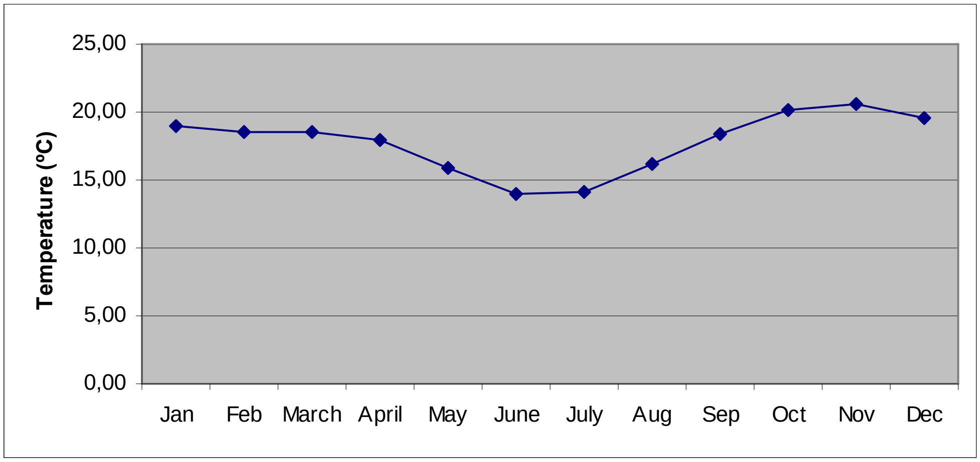

Figure 46. Monthly mean temperature from the years 1961 to 1990 in Cochabamba according to the World Organization of Meteorology. Modified from INE (2008a).

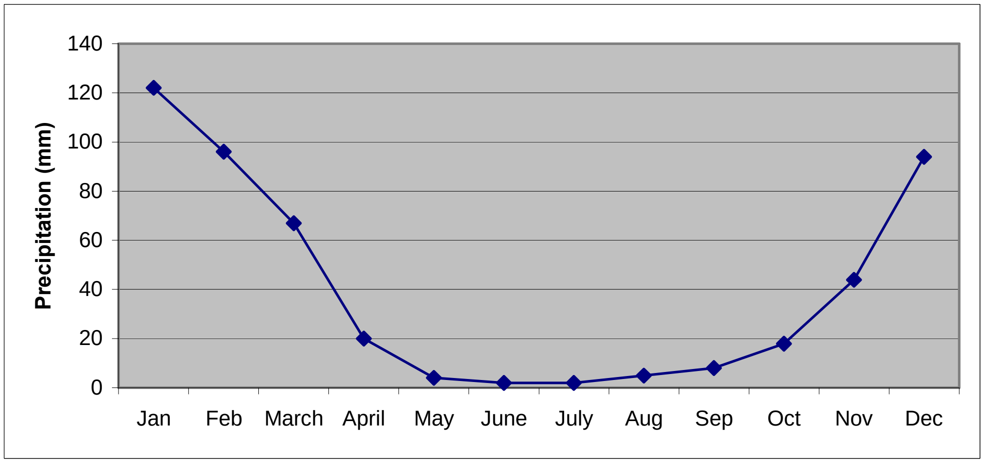

Figure 47. Monthly mean precipitation from the years 1961 to 1990 in Cochabamba according to the World Organization of Meteorology. Modified from INE (2008a).

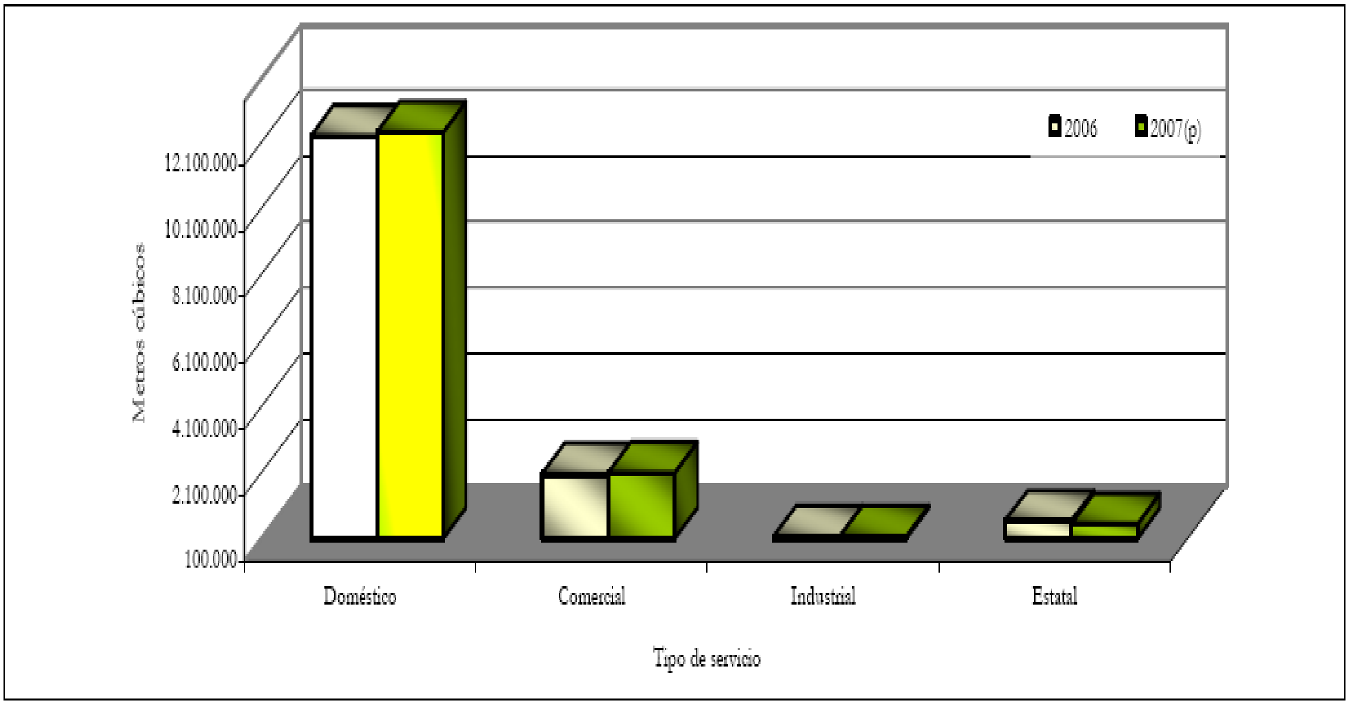

Figure 48. Consumption of potable water in the Cochabamba region during the years 2006 and 2007. The consumption is divided into domestic, commercial and industrial uses and consumption by the state. The y-axis shows the consumption in cubic meters. Source: INE (2008a).

Table 16. Some of the water quality limits for the classes "B" and "C" of receiving waters according to Table A-1 in the Bolivian ordinance RMCH (1995).

Parameters	**Units**	**Class "B"**	**Class "C"**
pH		6.0-9.0	6.0-9.0
Temperature	°C	+/- 3°C compared to recipient	+/- 3°C compared to recipient
Total dissolved solids	mg/l	1000	1500
Oil and grease	mg/l	Absent	0,3
BOD	mg/l	<5	<20
COD	mg/l	<10	<40
Faecal coliforms	No./100ml	<1000 and <200 in 80% of the samples	<5000 and <1000 in 80% of the samples
Parasites	N/l	<1	<1
Colour	mg Pt/l	<50	<100
Dissolved oxygen	mg/l	>70% sat.	>60% sat.
Turbidity	NTU	<50	<100-<2000
Phosphate	mg/l	0.5	1.0
Ammonia NH_3	mg/l	1.0	2
Nitrate NO_3	mg/l	50.0	50.0
Nitrite N	mg/l	1.0	1.0
Total nitrogen N	mg/l	12	12

According to RMCH (1995) water resources classified as class "B" (Table 16) can be used for recreational purposes, industrial use and unrestricted irrigation, e.g. irrigation of vegetables and fruits that will be eaten raw. These water resources need complete physicochemical treatment before it can be use as potable water. Class "C" can be used for the same purposes as class "B" except for irrigation of vegetables and fruits that will be eaten raw. There are two more classes, class "D" can only be used for industrial purposes while class "A" can be used for anything. Water classified as "A" only needs disinfection to be used as potable water. For a complete overview of the limits and classes, see RMCH (1995).

Appendix 4. Calculation of Short Time Average Flow

According to Oscar Medina Flores, one of the gardeners at the school, the outflow from the wetland usually stops at 16-16.30. The following assumptions were made when calculating the short time average flow from the measurements the 10 Nov: There is water flowing through the wetland from 8.00 until 18.00 (10 hours) while the flow is zero from 18.00 until 8.00. This is based on the information that only the family is active on school premises before eight in the morning and after four in the afternoon. In the evening the family might cook etc. but the simplification is that all this occurs before six o'clock in the evening.

The mean value of the flow from the measurements the 10th of November was 0.0201 l/s = 72.40 l/h. The flow was assumed to be constant over a period of ten hours, why the volume of water entering and leaving the wetland was calculated to 72.40 l/h * 10 h = 724 l = 0.724 m^3.

During the remaining 14 hours of the day, Q was assumed to be 0, why the flow was calculated to be 0.724 m^3/day.

Table 17. Results from conductivity measurements, performed in laboratory, of sample water with different salt concentrations.

Concentration of added salt	conductivity dilution	conductivity	
(g/l)	(mS/cm)	mS/cm	µS/cm
1	0.339	3.39	3 390
2	0.509	5.09	5 090
3	0.651	6.51	6 510
4	0.886	8.86	8 860
5	0.982	9.82	9 820
7	1.404	14.04	14 040
9	1.915	19.15	19 150
11	2.34	23.4	23 400
13	2.67	26.7	26 700

Appendix 6. Results from C.A.S.A. Analyses

Results from chemical and physical analyses on sample water from the wetland PTAR1 are presented in Figure 49- Figure 60. Results for the Müsch wetland are presented in Figure 61-Figure 63. Duplicate sample results are presented in Table 18.

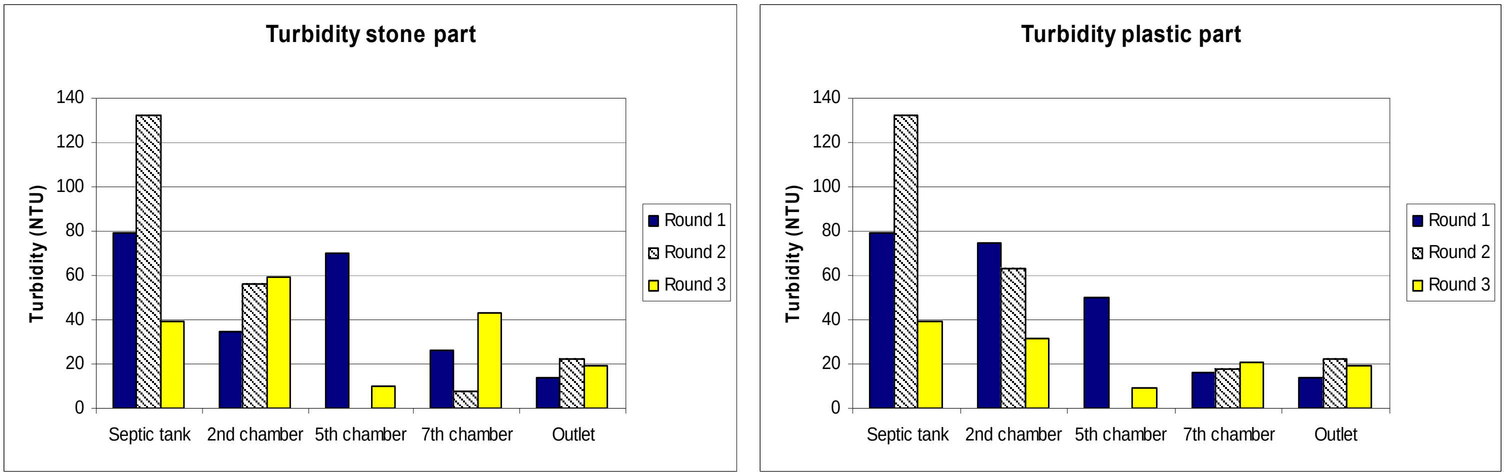

Figure 49. Turbidity results for the stone (left) and the plastic (right) media of the wetland. The sample points "septic tank" and "outlet" are the same in the two diagrams. During the second round no analysis was made on the water of the 5th chamber.

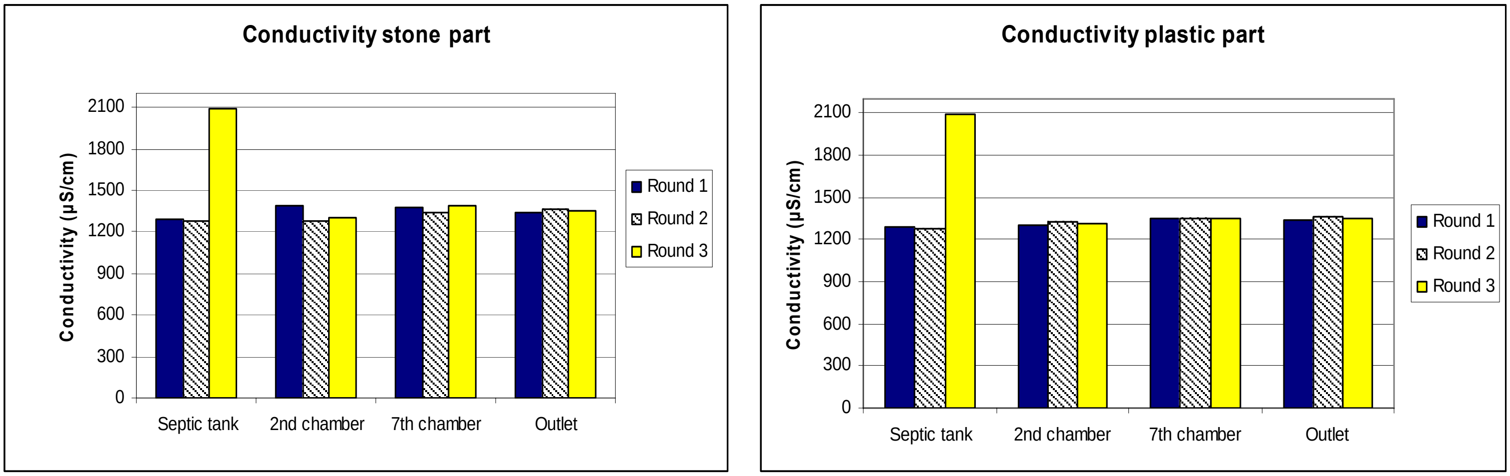

Figure 50. Conductivity results for the stone (left) and the plastic (right) media of the wetland. The sample points "septic tank" and "outlet" are the same in the two diagrams.

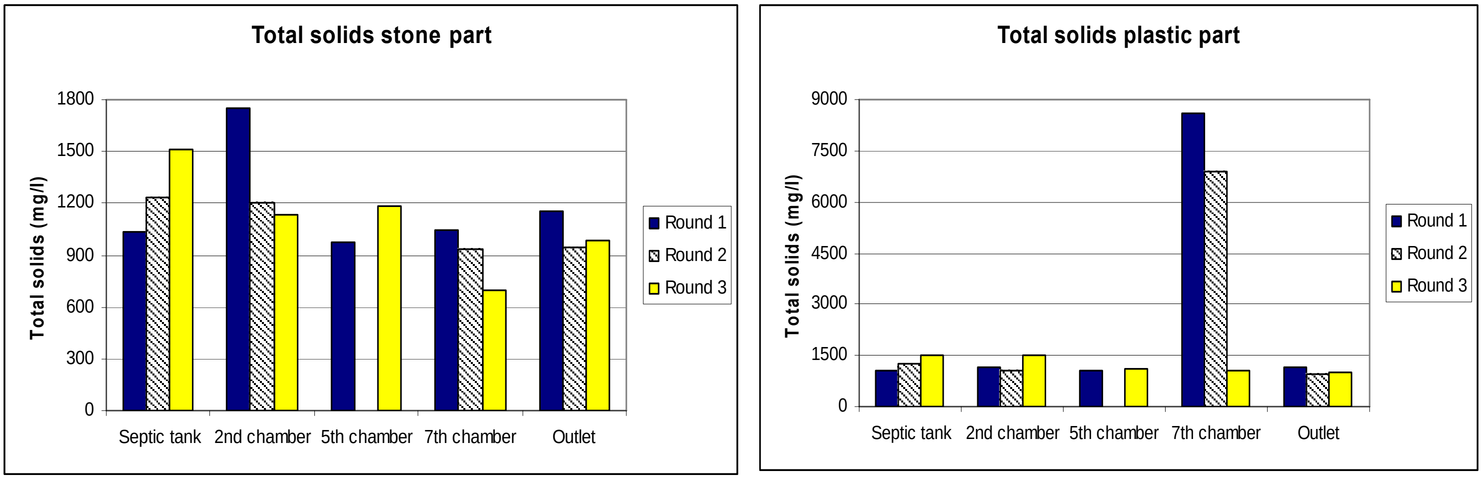

Figure 51. Results of total solids analyses for the stone (left) and the plastic (right) media of the wetland. The sample points "septic tank" and "outlet" are the same in the two diagrams. During the second round no analysis was made on water from the 5th chamber.

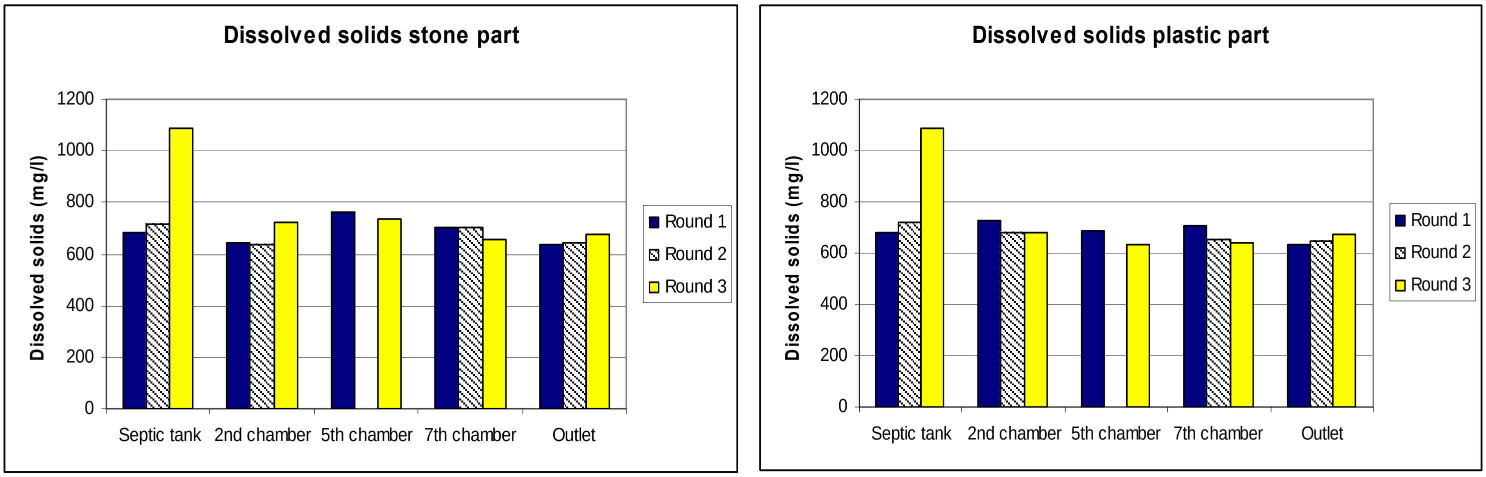

Figure 52. Results of dissolved solids analyses for the stone (left) and the plastic (right) media of the wetland. The sample points "septic tank" and "outlet" are the same in the two diagrams. During the second round no analysis was made on water from the 5th chamber.

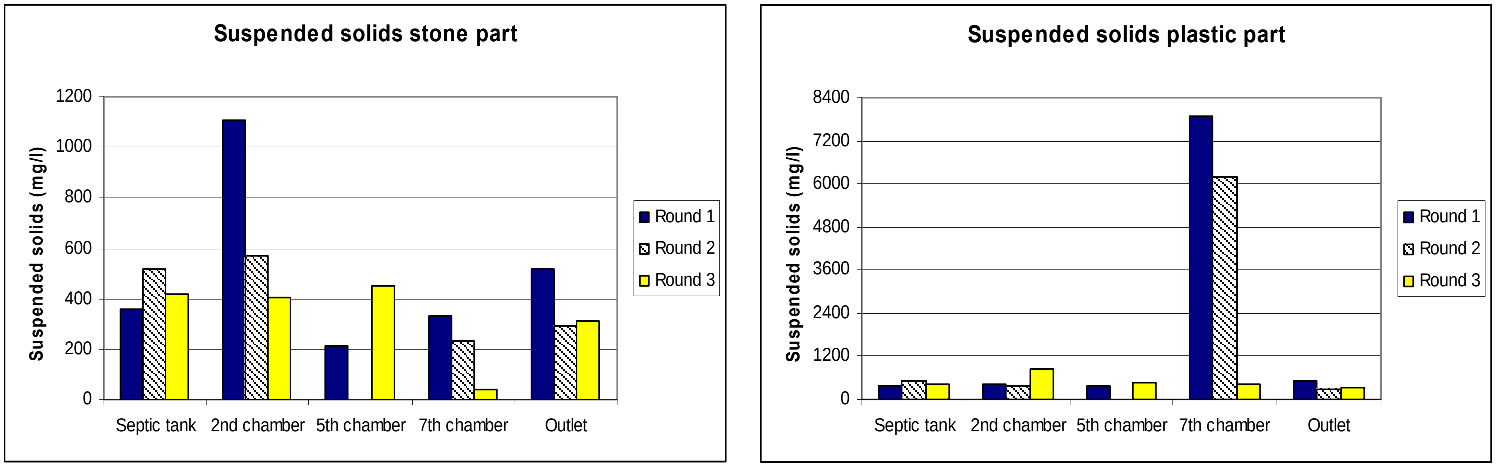

Figure 53. Results of suspended solids analyses for the stone (left) and the plastic (right) media of the wetland. The sample points "septic tank" and "outlet" are the same in the two diagrams. During the second round no analysis was made on water from the 5th chamber.

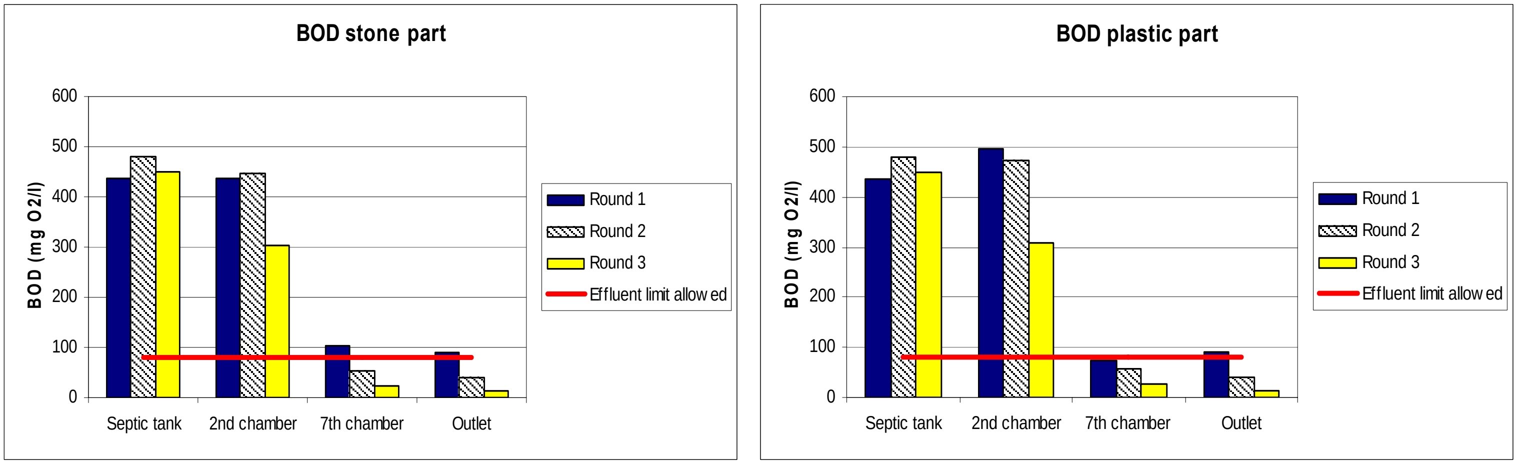

Figure 54. Results of analyses of biological oxygen demand (BOD) for the stone (left) and the plastic (right) media of the wetland. The sample points "septic tank" and "outlet" are the same in the two diagrams.

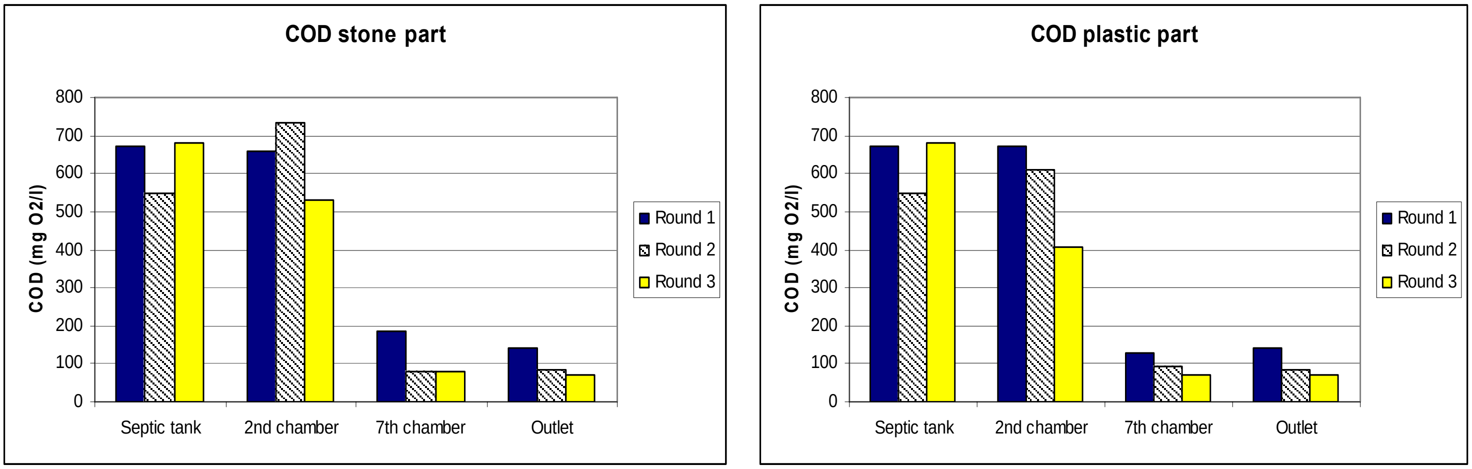

Figure 55. Results of analyses of chemical oxygen demand (COD) for the stone (left) and the plastic (right) media of the wetland. The sample points "septic tank" and "outlet" are the same in the two diagrams.

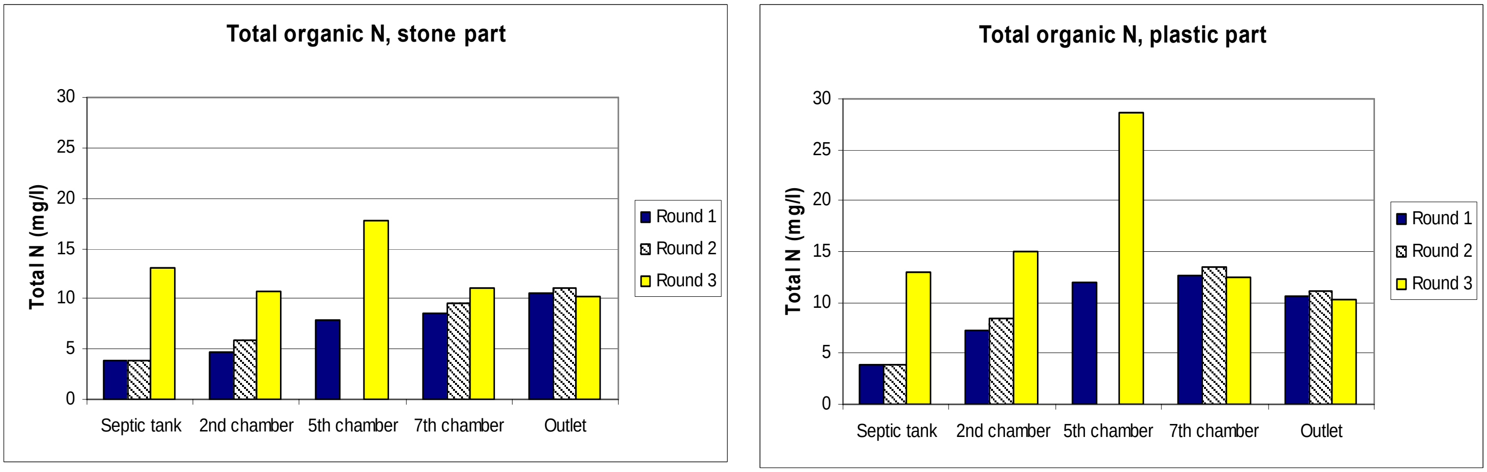

Figure 56. Results of analyses of total organic N for the stone (left) and the plastic (right) media of the wetland. The sample points "septic tank" and "outlet" are the same in the two diagrams. During the second round no analysis was made on water from the 5th chamber.

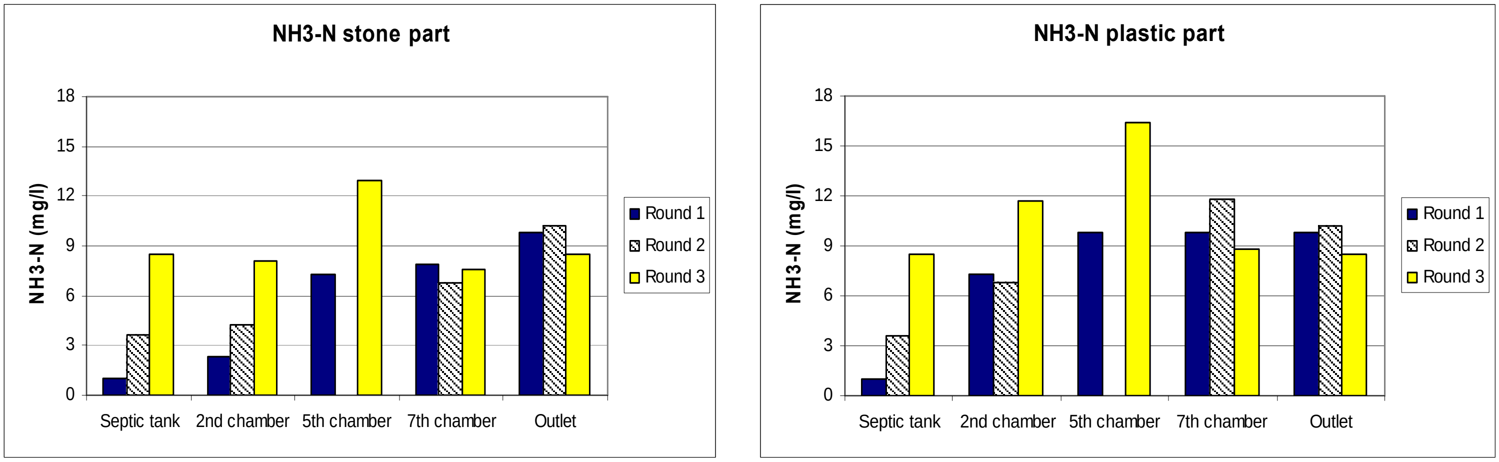

Figure 57. Results of analyses of NH_3-N for the stone (left) and the plastic (right) media of the wetland. The sample points "septic tank" and "outlet" are the same in the two diagrams. During the second round no analysis was made on water from the 5th chamber.

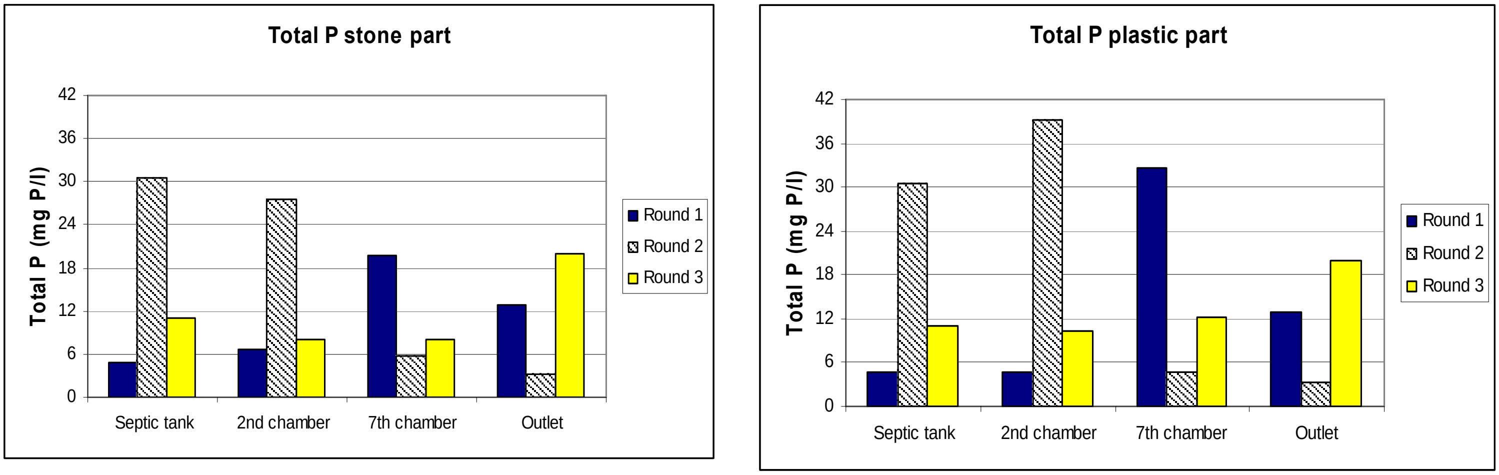

Figure 58. Results of analyses of total P for the stone (left) and the plastic (right) media of the wetland. The sample points "septic tank" and "outlet" are the same in the two diagrams.

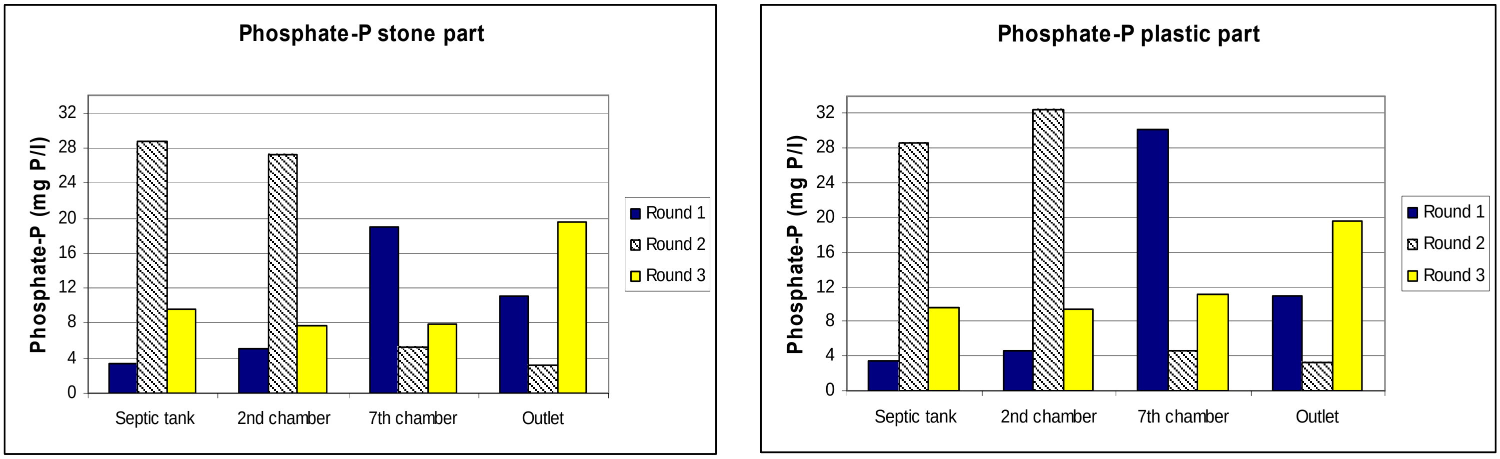

Figure 59. Results of analyses of PO_4-P for the stone (left) and the plastic (right) media of the wetland. The sample points "septic tank" and "outlet" are the same in the two diagrams.

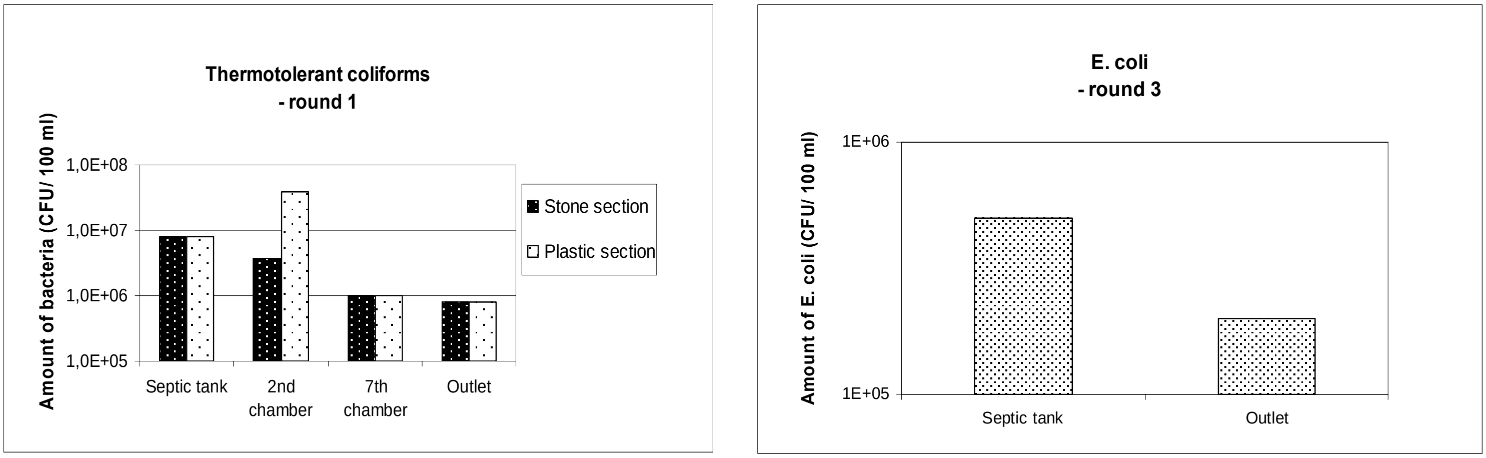

Figure 60. Concentrations of thermotolerant coliforms (to the left) and concentrations of *E.coli* (to the right). N.B. log-scale on y-axis.

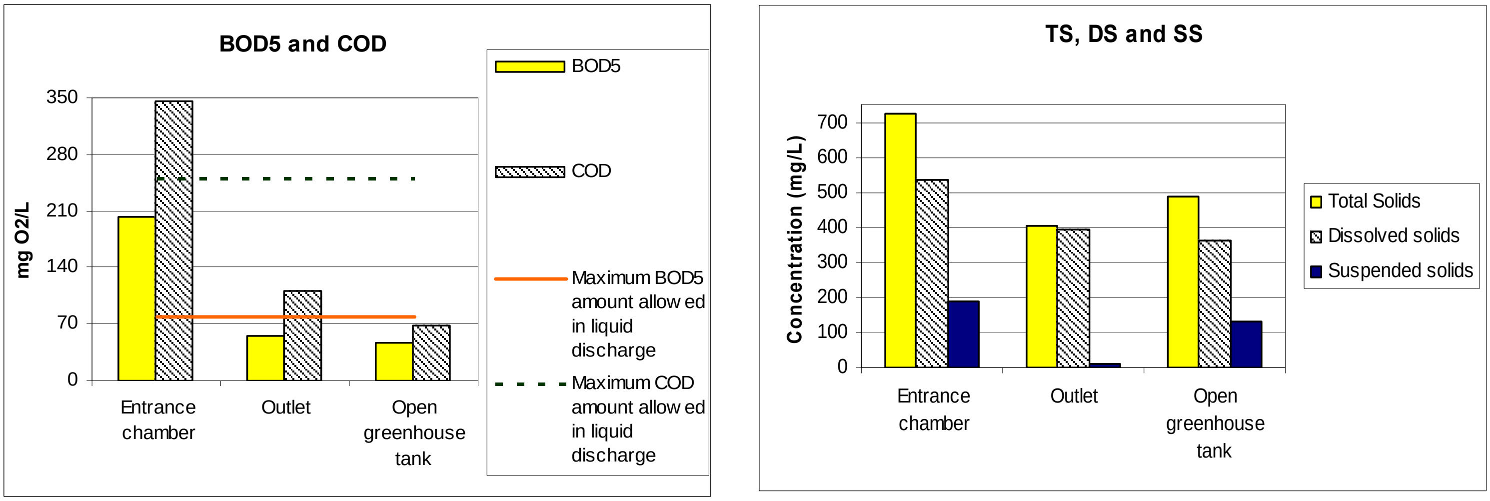

Figure 61. Concentrations of BOD_5, COD, total solids, dissolved solids and suspended solids in the Müsch wetland.

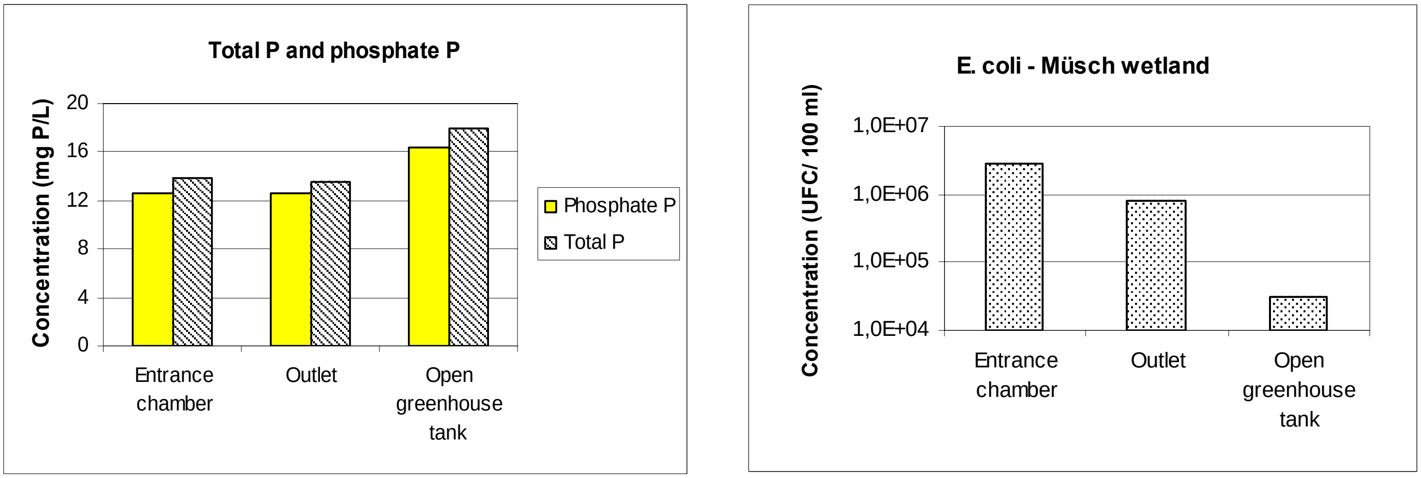

Figure 62. Concentrations of total P, phosphate-P and *E.coli* in the Müsch wetland.

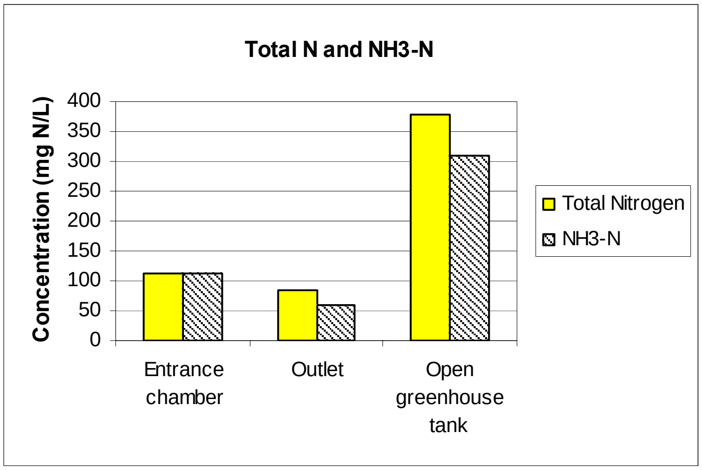

Figure 63. Concentrations of total N and NH_3-N in the Müsch wetland.

Table 18. Duplicate sample from PTAR1, taken 2008-11-27, to test the precision of the laboratory results.

	Value from round 3	**Duplicate value**	**Unit**
pH	7.31	7.52	
Turbidity	43	51	NTU
TS	695	960	mg/L
DS	658	634	mg/L
SS	37	326	mg/L
Total N	11.0	19.3	mgN/L
NH3-N	7.6	13.0	mgN-NH3/L

Stones
The volume of 67 stones was determined to 1 litre, using a bucket and water, during an investigation at the wetland in Buena Vista on the 17th of December.

Volume per stone: $V_{stone} = 1/67 = 0.014925\ \text{dm}^3 = 1.4925 \cdot 10^{-5}\ \text{m}^3$

Assumption: The stones are spherical.

$$\Rightarrow V = \frac{4\pi \cdot r^3}{3} \text{ and } A = 4\pi \cdot r^2$$

$$r = \sqrt[3]{\frac{3V}{4\pi}} = \sqrt[3]{\frac{3 \cdot 0.014925}{4\pi}} = 0.1527\ \text{dm} = 15.27\ \text{mm}$$

$$\text{A} = 4\pi \cdot r^2 = 4\pi \cdot 15.27^2 = 2930\ \text{mm}^2 = 2.93 \cdot 10^{-3}\ \text{m}^2$$

where r is the mean radius and A the surface area per stone.

The porosity in the bed of stones was determined on the 5th of November, to 43%. This result gives a proportion of stones in the bed of 57 %. Looking at 1m^3 of bed ($V_{st,tot}$ = total volume of stones and n = number of stones):

$$V_{bed} = 1\ \text{m}^3$$

$$V_{st,tot} = 0.57\ \text{m}^3$$

$$n = \frac{V_{st,tot}}{V_{stone}}$$

$$A_{tot} = n \cdot A = \frac{V_{st,tot}}{V_{stone}} A = \frac{0.57}{1.4925 \cdot 10^{-5}} \cdot 2.93 \cdot 10^{-3} = 111.90\ \text{m}^2$$

The surface area per bed volume is approximately 110 m^2/m^3 for the stone medium.

Plastic pieces
The plastic carriers had a cylindrical shape with an outer diameter of 32 mm, before deformation. The thickness is 2.0 mm. Thereby the inner diameter is 28 mm, when the ridged surface is not considered. The cross sections of the plastic carriers show that the maximum inner circumference can be assumed to consist of 63 small half circles, considering the ridges. The minimum inner circumference is an imaginary smooth circle with the diameter 28 mm.

$d_{inner} = 28$ mm

The minimum inside circumference A is
$A = 2\pi r_1 = \pi\, d_{inner} = 87.96$ mm

The number n of ridges at the inside of one plastic piece or cylinder is
$n = 64$

The diameter a of each small half circle is
$a = A/n = 87.96/64$ mm $= 1.374$ mm

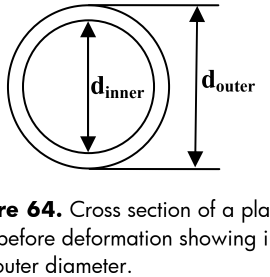

Figure 64. Cross section of a plastic tube before deformation showing inner and outer diameter.

b is the curve arc length of each half circle

$b = \pi a/2 = \pi 1.374/2$ mm = 2.159 mm

The maximum inside circumference is
$B = (n-1)b = (64-1)2.159$ mm = 136.02 mm

$d_{outer} = 32$ mm

The circumference of the outside is
$C = 2\pi r_2 = \pi d_{outer} = 100.53$ mm

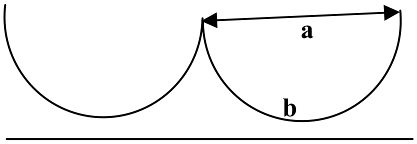

Figure 65. When calculating the maximum inner circumference the inside of the plastic carriers are assumed to be shaped as half circles with the diameter *a* and the curve arc length *b*.

The area of one carrier end (where the pipe was cut) is

$$A_{end} = (\pi r_2^2 - \pi r_1^2) = \pi\left(\left(\frac{d_{outer}}{2}\right)^2 - \left(\frac{d_{inner}}{2}\right)^2\right) = \pi\left(\left(\frac{32}{2}\right)^2 - \left(\frac{28}{2}\right)^2\right) = 188.495\,\text{mm}^2$$

The mean length of the plastic pieces L was calculated to 32.4 mm with a standard deviation of 7.5 (N = 11).

The maximum surface area per carrier is
$A_{max} = L(C+B)+2\cdot A_{end} = 32.4\cdot(100.53+136.02) +2\cdot 188.495$ mm^2 =
8041.21 mm^2 = $8.04121\cdot 10^{-3}$ m^2

and the minimum surface area per carrier is
$A_{min} = L(C+A) +2\cdot A_{end} = 32.4\cdot(100.53+87.96) +2\cdot 188.495$ mm^2 =
6484.07 mm^2 = $6.48407\cdot 10^{-3}$ m^2

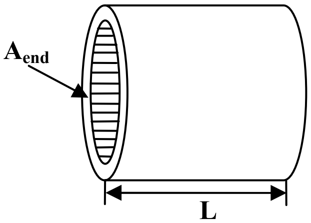

Figure 66. A plastic carrier before deformation with ridges inside. *L* is the length and A_{end} the cross sectional area.

The volume of the plastic material of one carrier is calculated, assuming the volume of the ridges inside is negligible:
$V_{carrier} = L\cdot A_{end} = 32.4\cdot 188.495$ = 6107.24 mm^3 = $6.10724\cdot 10^{-6}$ m^3

The porosity in the bed of plastic pieces was determined the 5th of November to 60 % why 40 % of the bed consists of plastic carriers.

Looking at 1 m^3 of bed:

$$V_{bed} = 1\,\text{m}^3$$

$$V_{pl,tot} = 0.40\,\text{m}^3$$

$$N = \frac{V_{pl,tot}}{V_{carrier}}$$

$V_{pl,tot}$ = total volume of plastic carrier material and N = number of plastic carriers

According to the calculations of A_{max} and A_{min} the surface area is in the range 6484-8041 mm^2 per carrier. The minimum and maximum surface areas per cubic meter of bed are calculated as

$$A_{tot,\min} = N\cdot A_{\min} = \frac{V_{pl,tot}}{V_{carrier}} A_{\min} = \frac{0.40}{6.10724\cdot 10^{-6}}\cdot 6.48407\cdot 10^{-3} = 424.7\,\text{m}^2$$

$$A_{tot,\max} = N\cdot A_{\max} = \frac{V_{pl,tot}}{V_{carrier}} A_{\max} = \frac{0.40}{6.10724\cdot 10^{-6}}\cdot 8.04121\cdot 10^{-3} = 526.7\,\text{m}^2$$

The surface area per bed volume is ca 420-530 m^2/m^3 for the plastic medium.