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Nutrient removal of domestic waste water in constructed wetlands in Cochabamba, Bolivia

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PREFACE

The study is funded by a Sida (Swedish International Development Co-operation Agency) programme called Minor Field Studies (MFS) and thereby follows the framework of this scholarship.

The aim of this programme is to offer Swedish students an opportunity to conduct field work during about two month in a Third World country in order to give them an opportunity to get to know and understand more about developing countries and also to establish contacts in these countries to promote internationalisation in higher education.

The result of the study is presented in a report at the Master Degree level. The subject of the Minor Field Studies should be of importance from a development perspective and also within the area of the faculty from where the scholarship is administered.

This Minor Field Study is administered by the Working group for Tropical Ecology in Uppsala which offers scholarships in the area of natural resource management and ecology.

ABSTRACT

In the city of Cochabamba, Bolivia, around 170,000 people out of a population of 800,000 are connected to the municipal waste water treatment system. The rest of the waste water produced in the city is mainly just treated with precipitation in a septic tank, in most cases without any treatment at all, before being disposed into rivers and lakes around the city. This is one of the big causes of the lake Alalay, in the south of the city, and the river Rocha, that runs through the city, to today suffer from eutrophication and pollution. The bad water treatment is also one of the reasons for the many water related diseases, like diarrhoea, that are frequent in the city.

Constructed wetlands are a possible solution to improve the water treatment in the city and its surroundings. Since these are based on a spontaneous biological cleaning of the water, they are considered to be a cheap method with little impacts on the environment and also in need of little attendance. The environmental engineer Christian Bomblat and his colleagues have constructed a couple of wetlands in the area of Cochabamba. One of their projects is in Mr Bomblat's compound and another one is connected to a school in Pukara in the outskirts of Cochabamba. These two constructed wetlands together with a third one, connected to an SOS children village, have been studied in this project.

The purpose of the study is to evaluate the efficiency of these wetlands, mainly to provide data and evaluations to the creators of the constructed wetlands for their continued work. Another purpose is to look at the efficiency of wetlands of different age and with small differences in construction and to see how they performed in this kind of climate. We analysed total nitrogen, ammonium, orthophosphate, thermotolerant coliforms, DOC, TSS, conductivity, dissolved oxygen, pH and temperature.

The results of the study show that a reduction of nutrients and pathogens is taking place in most of the cases. Still the levels of nitrogen, phosphorus and pathogens exceed both the Bolivian and the EU norms for disposal in waters which are subject to eutrophication. In spite of the high levels of nitrogen and phosphorus the water is still safe to use for irrigation, although it should not be let out in water recipients as it could lead to eutrophication. Since the water in these cases mainly is used for irrigation, the sanitary conditions are here of great importance. A too high level of pathogens makes the water unsafe to use for irrigation of crops being in direct contact with the irrigation water. For this reason it would be recommended to further improve the treatment. Exactly what part of the system that should be improved is hard to say since the number of analyses in this study was limited. Possible improvements indicated from the study would be to cut down and remove the vegetation more often, at least twice a year. It could also be taken in consideration to complement the system. This could for example be done by putting a sand filter after the outlet of the wetland, as this is an efficient way of reducing pathogens, or by a filter with phosphorus absorbing characteristics. The true retention time could also be measured in further studies to see if the water stays in the system long enough for the treatment to be efficient.

Key words

Bolivia; Cochabamba; Wastewater management; Wastewater treatment; Constructed wetlands; Treatment efficiency

RESUMEN

De los 800.000 habitantes que viven en la ciudad de Cochabamba son alrededor de 170.000 los que están conectados a la red pública de aguas residuales. El resto de las aguas residuales solo se limpian con tanques sépticos o se botan directamente a recipientes sin tratamiento alguno. Esta es una de las razones por la cual el agua en la ciudad está gravemente contaminado y sufriendo de eutrofización, tanto en el río Rocha que pasa por el centro de Cochabamba como la laguna Alalay al sur de la ciudad. Este tratamiento insuficiente de las aguas es una causa importante de enfermedades como por ejemplo la diarrea, algo muy común en los sectores urbanos.

Pantanos artificiales es una solución posible para mejorar el tratamiento del agua residual que se produce en la ciudad. Estos sistemas funcionan con procesos biológicos espontáneos y se considera que es un método barato con pocos efectos negativos para el medio ambiente y que no necesita mucha supervisión ni mantenimiento. El ingeniero ambiental Christian Bomblat junto con sus colegas, han construido varios pantanos artificiales en el departamento de Cochabamba. En el siguiente estudio se ha evaluado el funcionamiento de dos de estos pantanos, ubicados uno en la casa del ingeniero Bomblat, otro en una escuela situada al oeste de Cochabamba, en Pukara, y también un tercero en el hogar de niños SOS-Aldea Infantil que han construido su mismo.

El objetivo de nuestro estudio fue evaluar la eficacia en los tres pantanos artificiales. El motivo principal fue reunir datos de los creadores de estos sistemas para ayudarlos en su futuro trabajo con los pantanos. Otro objetivo fue el de evaluar tres distintos pantanos artificiales en tres diferentes edades y con pequeñas diferencias en su construcción, para ver como funcionan este tipo de sistemas en este ambiente y como se pueden mejorar. Los parámetros que fueron analizados eran el nitrógeno total, nitrógeno amoniacal, fósforo, coliformes termotolerantes, carbón orgánico disuelto, sólidos suspendidos totales, oxígeno disuelto, conductividad, pH y temperatura.

El resultado del estudio muestra que hay tratamiento de limpieza de nutrientes y patógenos en estos tres pantanos. Los niveles de nitrógeno, fósforo y patógeno fueron más altos que las normas para aguas residuales en Bolivia y UE. Los niveles de nitrógeno y fósforo no son dañinos en el caso que el agua se use para el riego, pero es mejor que no lo desvía a el recipiente porque lo puede causar eutrofización. Agua con niveles altos de patógenos no se debe usar para regar cultivos de alimentos que tiene contacto directo con la agua. Es recomendable de mejorar las sistemas. Con pocas muestras que fue tomado, hay ciertas dificultades de decir exactamente donde en las sistemas que se puede hacer mejoramientos. Posibles mejorías indicadas en este estudio, serían por ejemplo el cortar la vegetación frondosa, por lo menos dos veces al año. También se puede considerar el complementar a estos sistemas otro tratamiento, por ejemplo añadir un filtro que contenga cuarzo para capturar fósforo antes o después que pase el agua por los pantanos. Para reducir los niveles de patógenos, se podría construir un filtro de arena fina al final del pantano. Calculando también el tiempo real de retención en los sistemas se podría saber si el agua se mantiene el tiempo suficiente en los pantanos para que obtenga un tratamiento efectivo.

Palabras claves:
Bolivia; Cochabamba; Manejo de aguas residuales; Tratamiento de aguas residuales; Pantanos artificiales; Eficencia de tratamiento

SAMMANFATTNING

Av de ca 800.000 invånare som bor i Cochabamba stad så är ungefär 170.000 kopplade till det kommunala avloppsnätet. Det resterande avloppsvattnet som produceras i staden blir huvudsakligen endast behandlat via sedimentationstank, om behandling över huvud taget sker, innan det släpps ut i recipienter i omgivningen. Detta är en av orsakerna till att vatten som sjön Alalay i södra delen av staden och floden Rocha som går genom staden idag är starkt förorenade och lider av övergödning. Den dåliga vattenreningen är också en bidragande orsak till den stora andel vattenrelaterade sjukdomar, till exempel diarré, som är vanliga i staden.

Konstruerade våtmarker är en möjlig lösning för att förbättra reningen av stadens producerade avloppsvatten. Då dessa bygger på spontana biologiska processer så anses det vara en billig metod med liten negativ inverkan på miljön och som kräver relativt lite tillsyn och underhåll. Miljöingenjören Christian Bomblat har tillsammans med kollegor inom samma område konstruerat ett antal våtmarker i Cochabamba och dess omgivningar. Ett av deras projekt är en våtmark på Christians egen gård och en annan vid en skola i Pukara, ett område i utkanten av Cochabambas västra delar. Dessa två våtmarker, plus en tredje kopplad till en SOS barnby i staden, har studerats i detta projekt.

Syftet med studien är att utvärdera effektiviteten hos dessa konstruerade våtmarker i huvudsak för att samla in relevanta data till skaparna av våtmarkerna till hjälp för deras fortsatta arbete med våtmarker. Ett annat syfte är också att utvärdera tre olika våtmarker, i olika åldrar och vissa skillnader i konstruktionen, för att se hur bra våtmarker fungerar just här och hur de eventuellt skulle kunna förbättras. Parametrar som analyserades var total-kväve, ammonium, ortofosfat, termotoleranta koliforma bakterier, DOC, TSS, löst syre, konduktivitet, pH och temperatur.

Resultatet av studien visar att reningen av närsalter och patogener pågår i de flesta av de studerade fallen. Nivåerna av kväve, fosfor och patogener överskrider dock de normer som Bolivia och EU har satt upp för vad som är säkert att leda ut i sjöar och vattendrag. I de fall där utgående vattnet används till bevattning är de höga halterna av kväve och fosfor ej skadliga; här är smittskyddsaspekten den viktiga. Vatten med för höga halter av patogener bör ej användas till bevattning av grödor som är i direktkontakt med vattnet. Ytterligare förbättring av reningen rekommenderas. Då få tester gjordes i denna studie så är det svårt att peka ut exakt vad i systemen som borde förbättras. Möjliga förbättringar som dock indikerats utifrån studien är till exempel att klippa ner och avlägsna växtligheten på våtmarken oftare, åtminstone två gånger per år. Man borde också överväga att komplettera systemen med eventuellt ytterligare reningssteg. Man skulle kunna sätta till en filterbädd som innehåller till exempel kvarts för att fånga upp fosfor före eller efter våtmarken. För att minska halten patogener, som är särskilt relevant i dessa fall, skulle ett finkornigare sandfilter kunna konstrueras i slutet av våtmarken då detta är ett effektivt sätt att reducera denna parameter. Den verkliga retentionstiden skulle också kunna beräknas för att se att vattnet verkligen uppehåller sig tillräckligt länge i våtmarken för att dess behandling ska vara effektiv.

Nyckelord

Bolivia; Cochabamba; Behandling avloppsvatten; Skötsel avloppsvatten; Konstruerade våtmarker; Reningseffektivitet

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ABBREVIATIONS

CASA – Centro de Aguas y Saneamiento Ambiental

DOC – Dissolved Organic Carbon

MFS – Minor Field Study

SEMAPA – Servicio Municipal de Agua Potable de Cochabamba

SF – Surface-Flow

SSF – Sub Surface-Flow

TSS – Total Suspended Solids

1 INTRODUCTION

Organisms, including human beings, can not exist without water. For this reason, we have to be careful with the accessible fresh water reserves. Special attention has to be paid to water as it is a carrier of pollutants and also of a lot of waterborne diseases. Infectious diarrhea is the largest water-related contributor to global diseases and about 1,800,000 people die from diarrhea diseases in the world each year (World Health Organization). Already the Romans realized that sewage water could cause damage to people and thereby led it away from the most crowded areas. Still today in a big part of the world sewage water is left untreated. In developing countries, generally 90 per cent of the used water is left untreated (Año International del Agua Dulce). Untreated water not only has negative effects on human beings, it can also cause environmental damage by overload of toxic substances for organisms or by eutrophication caused by an overload of nutrients.

1.1 BOLIVIA

Bolivia, with its close to nine million inhabitants, is situated in the west part of central South America. The country was founded in 1825, though due to conflicts with neighbouring countries Bolivia has decreased in size several times. In the War of the Pacific (1879 – 1884) Bolivia lost access to the Pacific Ocean to Chile, and the country has been landlocked since then. Even if rich in natural resources such as minerals and natural gas, Bolivia is considered the poorest country in South America (Central Intelligence Agency).

Since the altitude changes greatly between different parts of the country, the variation in vegetation is considerable and the climate goes from humid and tropical to cold and semiarid (Central Intelligence Agency). Farming is the most common occupation and about one third of the population lives in rural areas, though, as in most countries in South America, urbanisation is steadily increasing. High population density together with industries and a growing number of vehicles are factors that have contributed to severe environmental problems in parts of the country. The environmental law, Ley 1333, is strict and cover most important areas, but the funds and knowledge needed to be able to follow them are still missing (Huáscar Medrano Hervás, pers. comm.).

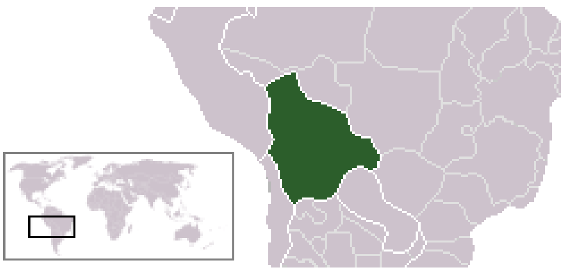

Figure 1 Bolivia’s position in the world and in South America.

Figure 2 Map of Bolivia.

1.2 COCHABAMBA

Cochabamba is the third largest city in Bolivia with a population of over 800,000. The city was founded in the 16th century but the valley of Cochabamba had been populated for a long time before this, mostly because of its favourable conditions for cultivation. The city is situated in the heart of Bolivia between the Andes in the west and the Amazon in the east. With Bolivian standards, Cochabamba is an economically active city and its population is growing fast.

Cochabamba is located at 17°5′S, 66°1′W and is thus not so far from the equator and does not have that big difference between the seasons. This gives the area of Cochabamba a mild climate and the city is sometimes referred to as the "City of Eternal Spring". The largest variations in temperature occur between day and night. During the months of August to October, when this survey was being conducted, the temperature fluctuate between about 25°C in daytime and 10°C in night time with an average of 17°C. The climate is generally dry and during the months August to October there is normally little or no rain at all. The rain period starts in late November and continues to February. The average precipitation is between 1000 and 1800 millimetres per year (Gran Atlas de Bolivia, 2007).

Figure 3 Map of Cochabamba with sample points and important water sources pointed out.

1.2.1 Water situation

The city of Cochabamba suffers from several environmental problems, such as air pollution, inadequate garbage recycling and lacking water reserves. One of the most serious problems is the lack of waste water treatment, leading to contamination of rivers and lakes. The treatment plant for waste water, maintained by the company SEMAPA (Servicio Municipal de Agua Potable de Cochabamba), is located in the southern parts of the city. SEMAPA manages waste water from about 170,000 out of the 800,000 inhabitants, though due to overcharge the quality of the effluent does not meet the national standards concerning pathogens and salinity (Luis Camargo, pers. comm.). Bedside SEMAPA there are some local initiatives of treatment, but the majority of the population dispose their waste water directly after going through a septic tank or in many cases with no treatment at all (Jennifer Rojas, pers. comm.). These septic tanks are usually constructed by a dug pit lined with boulders, from where the waste water easily infiltrates into the porous ground and contaminates the groundwater and neighbouring wells (Christian Bomblat, pers. comm.).

There is still lacking studies in Cochabamba that can confirm the link between the poor water quality and diseases related to this, but according to doctor Gonzalo Melean (pers. comm.) of the Viedma hospital "there is of course an obvious correlation". Gran Atlas de Bolivia states that more than 20,000 cases of diseases with diarrhoea were reported during the year 2003 only in Cochabamba (Gran Atlas de Bolivia, 2007).

The only lake in the central part of Cochabamba city is the lake Alalay, which is located in the lower parts and therefore is a recipient of water that goes through the city. Rio Rocha is the only river in central town, though being almost dry most parts of the year.

1.2.2 Laguna Alalay

The lake Alalay is a constructed lake situated in the south eastern part of central Cochabamba. It was constructed in the 1930's to balance the flow in the part of Rio Rocha that goes through the city centre. South of the Alalay is an area where there is no sewage system, and the waste water of those living there, approximately 300,000 persons, goes directly to the lake Alalay. There are also industries located in the vicinity that occasionally dump their waste water, containing heavy metals such as chromium and cadmium, in the lake Alalay. These factors have contributed to making the lake useless for any human use. In the 90s it became a subject for eutrophication which led to actions. 1997 the local authorities implemented a sedimentation removal and introduction of the fish *Odontesthes bonariensis*. Between the years of 2004 and 2006 also a manual mass removal of floating macrophytes took place. (Ayala, 2007) Today the lake is not suffering from acute eutrophication but the quality of the water is still even too bad to use for irrigation due to high levels of pathogens and heavy metals. (Huáscar Medrano Hervás, pers. comm.)

1.2.3 Rio Rocha

The river Rocha can be divided into three different zones. The first part goes through a sparsely populated area where the inhabitants use the water both for agriculture and domestic use. The second part goes through the central Cochabamba, where the river mostly is used as a recipient of pollutants from households and for washing clothes and vehicles. The third part is where the river passes Quillacollo, where it once again is used for irrigation and to some extent domestic use. (Maldonado et al., 1998)

The river Rocha passes the town of Cochabamba from east to west. Due to that a big part of the river is being diverted to the lake Alalay, and the part of river Rocha that goes through central Cochabamba is almost completely dry most time of the year. The garbage collection service in Cochabamba is inadequate and that is likely a contributing reason why the river Rocha occasionally serves as an alternative refuse dump (Huáscar Medrano Hervás, pers. comm.).

1.3 BACKGROUND TO THE PROJECT

Since the municipal water treatment in Cochabamba is poor, the environmental situation of the waters surrounding the city is severe. Cochabamba is a growing city and there are needs for more and better systems of water treatment. One complementary way of doing this, besides the traditional type of treatment plants, is installation of constructed wetlands. Constructed wetlands use the same biological processes that occur in natural wetlands, and are thereby a cheap method that needs little attendance for cleaning of domestic waste water. It is considered as a possible solution for many of the problems with waste water treatment in developing countries (Haberl, 1999).

Central Cochabamba has a high population density, and constructed wetlands are unlikely to be a general solution since relatively much space would be required. In the surrounding areas and suburbs of Cochabamba, however, the population density is lower and the inhabitants are mainly farmers. A few constructed wetlands exist in Cochabamba today, which are spread out in the town and surrounding areas and with different initiators. One of these is Christian Bomblat, who has been involved in different projects of establishing constructed wetlands in the Cochabamba valley. Information about the efficiencies of these systems is lacking and this study was suggested as a way of contributing to an evaluation of the systems.

1.4 PURPOSE OF THIS STUDY

The purpose of this study is to investigate the possibilities of constructed wetlands, as a method that is low in cost and maintenance, to contribute to the treatment of waste water in a developing country. This is done by evaluating and describing three different systems, that are constructed by the same principle but with small differences in the structure of the system and different ages of operation.

2 THEORY

2.1 GENERAL ABOUT WETLANDS

Today all over the world there are problems with eutrophication from high nutritioned water being directly, or with little treatment, sent out into the surrounding nature. An alternative to the conventional water treatment systems is then to construct or use already existing natural wetlands. A wetland is a land area that is partly or all of the year filled with water. Abundant water is a very good environment for biological activity which also means that in this environment nutrients have a fast transformation time. The elements are quickly transformed into useful components for the wetland's biological world, mainly by the help of bacteria. For that reason wetlands can be used as a way of treating waters high in nutrients, metals and pathogens, like sewage water.

When wetlands are being constructed they can either be built as an SF (Surface-Flow) constructed wetland or an SSF (Sub Surface-Flow) constructed wetland. In the case of an SF constructed wetland the system has a free water surface where the water is lead through an open water body with different conditions that helps transforming the nutrients to components ready to be absorbed by plants and animals. In an SSF constructed wetland the water is lead under the surface through gravel which acts as a filter for the water. In both cases the most common thing is to first let the water go into a septic tank before it goes into the wetland, mainly to lower the amount of solid particles by sedimentation.

2.2 PARAMETERS

2.2.1 Nitrogen

Nitrogen is a very important nutrient as it is the building block of many complex molecules formed by plants and animals; some examples are amino acids, proteins, and nucleic acids used in DNA. When organic material is broken down by bacteria, nitrogen compounds are formed and mineralized to ammonia. This process also occurs when plants and bacteria excrete and when urea or uric acid is hydrolysed. The process is called ammonification and takes place both in an anaerobic and an aerobic environment. In the form of ammonia nitrogen can now be taken up by plants and other micro organisms. Some of this ammonia is immediately taken up by the bacteria while a big part of it is released to the surroundings.

The ammonia can now be taken up by plants and other micro organisms or make complexes with clay or organic materials. It can also undergo another process called nitrification. This is a process that is depending on presence of oxygen and is performed by the bacterium groups Nitrosomonas and Nitrobacter. These bacteria gain energy from transforming ammonia to nitrate. The process is reducing the pH and the bacteria work best in a surrounding of around pH 7.

Nitrate can then continue to be transformed to nitrogen gas. This process is called denitrification and is performed by denitrifying bacteria. These bacteria are heterotrophs so in an anaerobic environment they can use organic compounds as energy source. The nitrogen gas, which is a natural, dominating gas in the atmosphere, can then be released.

2.2.2 Phosphorus

Phosphorus is another important nutrient for organisms and plants. Phosphorus compounds are in general very reactive and easily form complexes with organic and inorganic materials in the soil, water and sediment. In the phosphorus cycle there is no gas form. These two aspects make phosphorus often to be the limiting nutrient element.

The main natural sources of phosphorus to enter waters are surface inflow and atmospheric deposition (both wet- and dryfall). The compound then undergoes a number of alteration and transformation steps. The main input form of phosphorus is orthophosphate (PO_4^{3-}) which is an immediately available form for organisms since it is in dissolved form. There is a high competition for the nutrient, but a lot of it will be bound to complexes or adsorbed to mineral complexes and organic substances in the water or at the surface of the sediment. Sorption to the soil in the sediment is the only form which provides a net long-term storage of the phosphorus in lakes and wetlands. Therefore the composition of the soil is a very important factor for the phosphorus removal in wetlands. But there is also a risk here that the sediment will be saturated and with a change in the input of phosphorus the phosphorus sink can become a phosphorus source.

2.2.3 Total Suspended Solids and Dissolved Organic Carbon

Total Suspended Solids (TSS), is a measure of the content of suspended solids in the free water. Since this fraction is an important carrier of many pollutants, it is an important factor to study for the transfer of suspended solids to the wetland sediment. TSS is determined by filtering the water and then drying the sample until all water is removed. This dried substance is then weighed. The parameter is also a good indicator of the turbidity of the water since particles have less tendency to suspend in a water of low velocity.

Carbon is an important component in many wetland processes. The growth of plants depends on CO_2. Carbon dioxide is produced by all animals, plants, fungi and microorganisms during respiration and decomposition. When water gets in touch with high organic soils, some of these components can be drained into rivers and lakes high in organic carbon. Dissolved Organic Carbon (DOC), is a way to measure the level of organic carbon in the water. Therefore DOC is an indicator of the organic loading in the recipient and to what extent the organisms have an adequate energy source. Also, organic carbon is a complex former with metals which lowers their bioavailability.

2.2.4 Pathogens

Pathogens are biological agents, such as certain types of bacteria, viruses or fungi, that cause disease to its host. Human pathogens are often present in untreated domestic wastewaters, where the population of the pathogens depend on the health state of the people. A normal level of bacteria in human faeces is about 10^{11} organisms per gram (Kadlec & Knight, 1996). Most of these organisms, however, live in symbiosis with their host while some are pathogens occurring at higher levels in infected individuals. For many years the most conventional treatment for this unwanted component in water has been chlorination. This has today showed to have negative effects as it harms aquatic organisms. A wetland can reduce the levels of pathogens if the retention time is long enough, greater than about 10 days (Kadlec & Knight, 1996).

As the amount of most pathogens is very low, it is difficult to detect them. For this reason indicator organisms are used to measure pathogens in wastewater. Indicator groups often used are total coliforms and fecal streptococcus. *Escherichia coli* is one of the indicators for total coliforms that show a high correlation with the level of pathogens.

Water containing high amounts of pathogens should not be used for irrigation as this could lead to human intake of the pathogen and thereby cause disease. In some cases, where the plant does not touch the ground or where the edible part is not in contact with the water being distributed it would be alright to use pathogen containing water for irrigation. This would for example be corn and fruit trees. The pathogens are very sensitive for UV-radiation and die fast in direct sun, in just a couple of hours, while they can survive for much longer time in a water recipient (Lars Hylander, pers. comm.).

2.2.5 Heavy metals

Some metals are essential for most organisms, but at very small levels. At certain concentrations they become toxic to the organisms, either acutely or by biomagnification, which means that they are being accumulated until they reach a toxic level in the organism. Since metals have very few gaseous routes they are more likely to bind to soils, sediments and other particles or to precipitate as insoluble salts. They can also be taken up by plants, including algae, and bacteria. But since they cannot transform to any permanent non-toxic component they will, if the load is too big, accumulate in the sediment and organisms until they reach toxic thresholds for sensitive organisms and the biota will be severely damaged. Therefore, one must be very careful with wetlands and the input of metals. If the concentrations are too big some kind of pretreatment should be considered. Toxic metals as mercury, lead and cadmium should not at all be added.

2.2.6 Other parameters; oxygen, temperature, pH and conductivity

Even though there is a high percentage of oxygen in the atmosphere, the dissolved oxygen (DO) in water is usually relatively low, and the level of oxygen is one of the most important factors that determine the activity of bacteria (Carlsson & Hallin, 2003). The level of oxygen depends on a variety of factors, such as temperature, salinity and biological activity, and the level normally varies within the wetland. The consumption of oxygen in the wetland can be divided into four different groups; sediment oxygen demand, respiration in plants and animals, biological oxygen demand and nitrogenous oxygen demand (Kadlec & Knight, 1996). Nitrification is an important process in wetlands since it leads to a reduction of nitrogen in the effluent, and for nitrification to occur it is important with plenty of oxygen in the system. Oxygen is also important for the reduction of phosphorus, since oxygen is necessary to keep the phosphorus complex in the sediment. If the oxygen levels are low, the complex might dissolve and the phosphorus is released into the water again (Tonderski et al., 2002).

The temperature is important for wetlands since it affects both the chemical and the biological processes. The temperature varies during the season, with a magnitude that is depending on the climate. On average, the mean temperature in a subsurface-flow wetland is close to the daily average temperature in the air (Kadlec & Knight, 1996). To a certain level, increased temperature leads to an increased biological activity. High temperature will for example lead to a high denitrification (Tonderski et al., 2002).

The concentration of hydrogen ions, pH, is an important indicator of the state of the wetland system. Most of the bacteria that are important for the treatment only exist between pH 4.5 and 9.5. For example, bacteria that transform nitrogen between its different phases work best if pH is between 6.5 and 7.5. Many chemical processes also depend on the pH, for example the precipitation of aluminium and iron. The biofilm that is present in gravel filters in subsurface-flow wetlands generally buffers the variations in pH (Kadlec & Knight, 1996). Irrespective of the amount of oxygen, a high pH will dissolve the complexes with phosphorus and release the phosphorus to the surrounding water (Tonderski et al., 2002).

Electrical conductivity is a function of the total quantity of ionized materials in the water being analyzed. The specific conductivity is measured at 25°C and is reported in microsiemens per centimetre (µS/cm). Most natural inland surface waters have levels between 10 and 300 µS/cm and in really salty lakes it can reach levels over 60,000 µS/cm. As conductivity is proportional to the salt level of the water this is a good way of measuring the salinity which is an important factor of the water quality. If the water is going to be used for irrigation the salinity should not be too high due to possible salt stress for the plants.

2.3 HYDROLOGY

The hydrology of a wetland is one of the most important characteristics for the efficiency of the system. It is very important that the water entering the wetland has time enough to go through the different cleaning processes and interact with the aquatic biota. The time most looked at here is the retention time which tells how long the water stays in the system, only the wetland or the whole system. This variable can be controlled by regulating the inflow and outflow together with the depth and storage. The retention time is generally calculated by dividing the volume of water in the system with the flow rate. In sub surface-flow wetlands the volume of water depends on the porosity and the absence of vegetation in the pore space. To make this calculation easier it is usual to use the clean pore space in the calculations. Therefore it has been showed that the real retention time is normally 40 to 80 per cent less than the theoretical, mainly due to preferential flow and the difference in the calculated and the real pore space (EPA, 2000). The maximal flow is normally used as it gives the lowest retention time.

It is considered important that the water level does not reach the surface in sub surface-flow wetlands (EPA, 2000). This is mainly because it leads to increased evapotranspiration which will concentrate the pollutants, and the water passing the wetland above the filter will not undergo any treatment.

Another important aspect is the velocity with which the water passes the system. If the velocity of the water is too high there will be less chance for the particles to sediment, to make complexes with other particles or to attach to the biofilm of the plants. Controlling the water depth and the flow through the system is of great importance also for the establishing of the vegetation in the wetland. One has to take rainfall and evapotranspiration in consideration to calculate the true hydraulic loading. The way the water takes through the wetland also has a great impact on the cleaning efficiency. If the water is not spread out well enough, the retention time is lowered and also it can lead to saturated parts where no more processes can occur and the water basically goes through untreated while other parts of the system are not used at all in the cleaning process.

2.4 PLANTS

Numerous studies on wetland treatment show that wetlands with plants perform a much better treatment than wetlands without plants (Kadlec & Knight, 1996). The plants are very important for the wetland efficiency, both because they work as direct uptakers of the nutrients and because they form important habitats for most of the organisms that mediate in the processes of cleaning the water. Plants can also act as filters for bigger particles in the water, they create calm zones where sedimentation can occur, and where there is a risk for erosion the root system can be a helper of stabilizing the shore material. Also they are an important source of carbon for the denitrification process and by the photosynthesis the submerged plants release oxygen to the surroundings. Some of the wetland plants also provide shading of the water surface and thereby hinder algal growth. Except for these physical and chemical aspects there is an esthetical aspect of having a green and flowering wetland.

3 SITE DISCRIPTION

When first coming to Cochabamba, we were shown a few constructed wetland systems. We wanted to look at as many constructed wetlands as possible and also with as different ages as possible. Of those showed, we decided to analyze three in our study. The chosen objects were a constructed wetland connected to an elementary school, San Nicolas in Pukara, one constructed wetland connected to a family house in the district Alto Mirador in the city of Cochabamba and one constructed wetland connected to an SOS children village in the district Tiquipaya in the city of Cochabamba.

3.1 SAN NICOLAS ELEMENTARY SCHOOL

The school of San Nicolas is situated in the zone of Pukara in the ninth district of Cochabamba prefecture, approximately 15 kilometres south of the Cochabamba city centre. In this area there is no collective system for potable water or sewage. The wetland system at San Nicolas was first put in use two months before this study was conducted. 116 pupils are attending the school using the toilets and showers that are connected to the constructed wetland system.

The school has an agreement with the government to have their two water tanks, in total 10,000 litres, filled up once every week. So far this has not worked so well, sometimes they do not come at all or most of the water is bought by people further down in the valley. The water in the tanks is led down to the toilets and showers. From here the used water then goes into two septic tanks holding 3,000 litres each. From the septic tanks the water is lead through plastic tubes to the wetland where it is equally spread over the short side of the wetland. The constructed wetland has a 20-25 centimetre bottom layer of compacted clay to protect the water from contaminating the groundwater. The clay layer is covered with a plastic foil to further prevent leakages. Over the plastic linen a layer of stones and gravel is put. This layer is 1.20 metres thick and the water is supposed to reach maximum one metre above the bottom to prevent it from exceed the gravel layer. From the constructed wetland the treated water is then collected into a tank holding 1,200 litres. The treated water is then distributed through a plastic tube system to 150 planted trees. The whole system is driven by gravity force only.

Figure 4 Constructed wetland at San Nicolas elementary school.

Figure 5 Water tanks at San Nicolas elementary school.

Figure 6 Septic tank at San Nicolas elementary school.

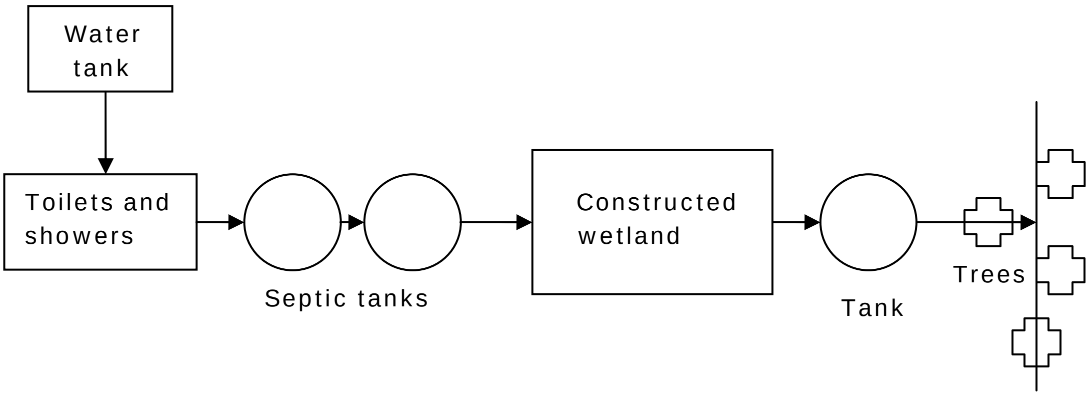

Figure 7 The San Nicolas elementary school constructed wetland system.

Table 1 Technical data of the San Nicolas system.

Parameter	Value
Starting	August 2007
GPS-coordinates	x: 802269.91 y: 8071404.10
Volume septic tank	2 × 3000 L
Volume wetland	37.2 m^3
In flow	1.2 m^3/day
Length	10 m
Width	3.1 m
Depth	1.2 m
Surface	31 m^2
Inclination	2 %
Porosity	45 %
Designed retention time	7 days

3.2 SOS – ALDEA INFANTIL

The Aldea Infantil SOS is located in the centre of Cochabamba and is connected to the municipal water system. One branch of the organization is the agriculture school Centro de formacion – tecnica en agriecologia. A constructed wetland is connected to the buildings of this school. Water comes to this wetland from their kitchen, showers and toilets. Approximately 30 persons work at the school daily.

The waste water that leaves the kitchen, toilets and showers is first collected in a septic tank. This water is then led to a constructed wetland consisting of gravel material which the water is led through. Finally the water is collected in another tank containing 150 litres. On the gravel of the wetland a mixture of paper reed, *Cyperus papyrus* L., and bulrush, *Typha latifolia* L., has been planted and grows in great amount. Last time it was cut down was about two years ago. After the wetland the water ends up in another tank from which the water is used as irrigation water on one of the fields in the school area.

Figure 8 Constructed wetland at SOS.

Figure 9 Observation pipe.

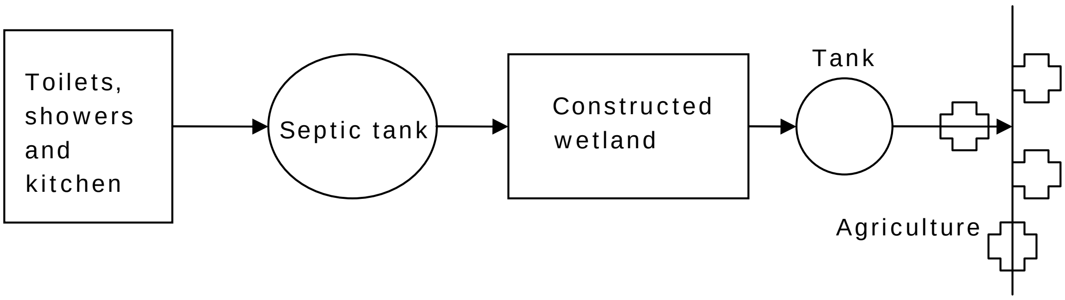

Figure 10 The SOS constructed wetland system.

Table 2 Technical data of the SOS system.

Parameter	Value
Starting	November 2004
GPS-coordinates	x: 798245.0 y: 8079293.0
Volume septic tank	Approx. 10 m^3
Volume wetland	50.4 m^3
In flow	2700 m^3/day
Length	10.9 m
Width	7.7 m
Depth	0.6 m
Surface	83.9 m^2
Inclination	None
Porosity	35 %
Designed retention time (total system)	15-20 days

3.3 PRIVATE HOME

The third studied system is connected to a private house in the outskirts of the central Cochabamba. Their potable water is connected to the municipal net. Most days there are 3-4 people in the house using water.

Waste water from the kitchen, toilets and showers are first collected into a system of two septic tanks. When the water leaves the second tank it is led into the constructed wetland. This is built from gravel placed on plastic linen where plants have been planted on top. The vegetation is in abundance with tall plants, mainly paper reed, *Cyperus papyrus* L., and bulrush, *Typha latifolia* L. These plants were last cut down one year ago. The wetland is also divided into three departments so it flows in a zigzag way down. After the wetland the water flows out into a pond where fishes, frogs and turtles live. The water in the pond is then partly used for irrigation of the garden, and the rest of it is disposed into the surroundings.

Figure 11 Constructed wetland at a private home.

Figure 12 Plants in the gravel filter.

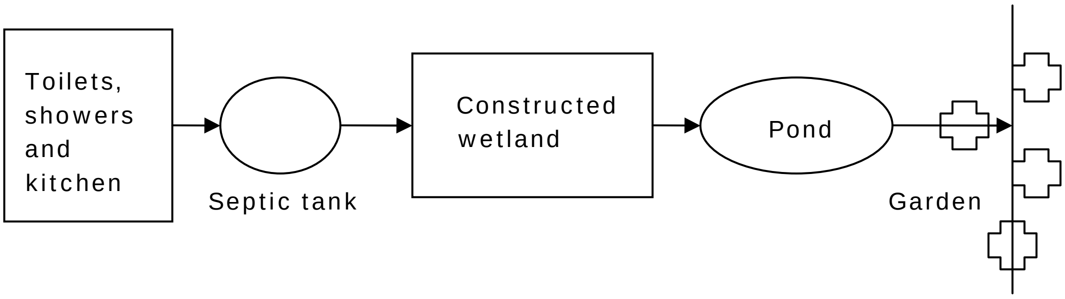

Figure 13 The Private home constructed wetland.

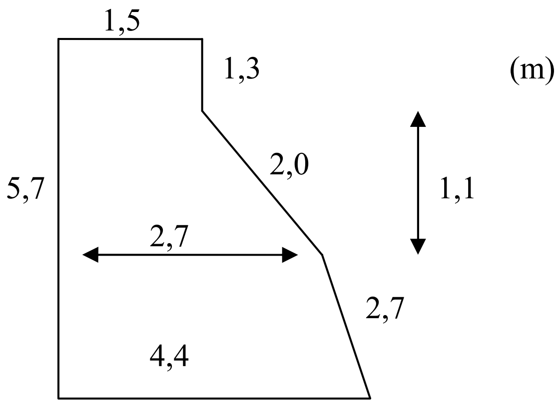

Figure 14 Drawing of the filter part of the wetland system at the private home, seen from above.

Table 3 Technical data of the Private home system.

Parameter	Value
Starting	2003
GPS-coordinates	x: 803648.13 y: 8076482.50
Volume septic tank	4200 L
Volume wetland	11 m^3
In flow	1.7 m3/day
Length	(see drawing)
Width	(see drawing)
Depth	0.7 m
Surface	16 m^2
Inclination	About 10 %
Porosity	37 %
Designed retention time (of total system)	14 days

4 METHODS

4.1 FIELD WORK

4.1.1 Collection of samples

The samples were handed in at the laboratory CASA (Centro de Aguas y Saneamiento Ambiental) in Cochabamba. From here we were provided with containers for the samples. On the containers from the CASA there were instructions on how to take the samples. These instructions were followed and the containers were left as instructed to the laboratory, always on the same day as the sample had been collected. Sample dates were the 13th of September, the 3rd of October and the 24th of October 2007. For the DOC analysis, that was going to be done in Sweden, plastic containers had been brought. Using a water injector (see figure 4) connected to a filter with a pore size of 1.2 µm, the samples were filtered and collected in a 25 ml container. These were filled in advance with small amounts of acid as conservatives at the CASA laboratory. A duplicate sample was taken for each parameter.

Figure 15 Injector for filtration of DOC-samples.

4.1.2 Field measurements

Some of the parameters of interest were measured directly in the field. Oxygen was measured with a WTW Oxi 191 and conductivity with a WTW LF 191. The measurements were performed with the instruments directly in a container with a representative sample of the water. The oxygen level was measured immediately to make sure that the oxygen level had not changed.

Figure 16 Measurement with conductivity meter.

Flow was measured, when possible, by using a container with known volume and a stopwatch. This was done at the time when the flow was assumed to be at its maximum and repeated several times to get an average value. pH was measured with litmus paper and the temperature with a field thermometer.

Figure 17 Collection of water sample.

To measure the porosity of the gravel filters, a representative sample of the gravel was placed in a container of 10 litres, and water was filled and measured so that the pore space could be calculated.

To get the retention time a tracer test was conducted using a natural colouring substance that was injected in the inlet of the wetland. Since the amount of colouring substance was large, it was assumed to spread out enough so that only one observation was needed at the outlet each day.

4.2 LABORATORY

4.2.1 Analyses at Universidad Mayor de San Simon

The majority of the analyses were performed at CASA, a laboratory in the final phase of being accredited to ISO IEC 17025:2005. The laboratory is situated at the biggest university in the city of Cochabamba, University Mayor de San Simon, with which it also collaborates. The parameters analyzed there were nitrogen (total and ammonia), phosphorus (orthophosphate), fecal coliforms and the amount of suspended materials (total suspended solids).

The analyses were performed by personnel at CASA. We were allowed to participate when the samples were analyzed, and we were given a presentation of the personnel and the equipment.

When analysing the samples for fecal coliforms, the 9222-D-method was used with multi-tube membrane filters. Different dilutations of the samples were sucked through filters where the bacteria got caught. The filters were placed in a oven with a constant temperature of 44.5 °C and after 24 hours the number of bacteria on each filter were calculated manually.

Figure 18 Laboratory equipment for measurement of pathogens.

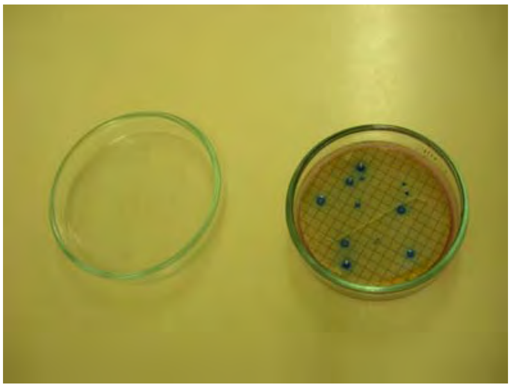

Figure 19 Filter with fecal coliforms.

For total suspended solid, an APHA gravimetric method was used with the temperature 105 °C. The total nitrogen was determined by the standard micro-Kjeldahl method and the ammonium nitrogen by using an ammonium ion selective electrode. Phosphorus was analyzed by the vanado-molybdate colorimetric method.

Figure 20 Analysis of nitrogen.

Figure 21 Analysis of nitrogen.

Figure 22 Preparation of samples for analysis of nitrogen.

4.2.2 Analyses at Uppsala University

At the Department of limnology at Uppsala University, an analysis of DOC (Dissolved Organic Carbon) was performed. The samples were analyzed with a Shimadzu TOC-5000, using a ASI-5000[a] sample exchanger. The samples were burnt at 680 °C, in the presence of a catalyst, with clean air (free from carbon dioxide) as a carrying gas. The gas was cooled and dried, and afterwards it passed through a halogen scrubber. Finally the levels of carbon dioxide were detected in an infrared detector. The results were given as a peak which was proportional to the content of dissolved organic carbon.

4.3 INTERVIEWS

A number of interviews were performed. Apart from the spontaneous questions that arose and were discussed during the project work, the interviews were planned as semi-structured interviews. Predefined forms of questions were used, which were answered and gave inspiration to further questions that were handled in the same interview.

5 RESULTS

The majority of the analyses were performed at the CASA laboratory. To test the reliability of the laboratory an extra duplicate of samples was handed in for analysis of ammonium nitrogen from a sample point that was already analyzed. The personnel at CASA did not know that it was the same sample. The results from the first two samples were 7.24 and 9.94 mg/l, and the second two were 8.26 and 11.06 mg/l.

Retention time

The tracer tests, that were conducted in two of the systems to measure the retention times, did not succeed. The injected tracer was never observed at the outlet or in any of the observation pipes.

A theoretical retention time was calculated in all three systems, using equation (1) where R is retention time, P is porosity, V is volume and Q is flow.

$$R = \frac{V_{WATER}}{Q_{MAX}} = \frac{V_{TOTAL} \cdot P}{Q_{MAX}} \qquad (1)$$

Porosity, flow and volumes were measured manually and presented in chapter 4. This gives the following retention time for San Nicolas elementary school

.

$$R_{SanNicolas} = \frac{V_{WETLAND}}{Q_{MAX}} = \frac{V_{TOTAL} \cdot P}{Q_{MAX}} = \frac{37.2m^3 \cdot 0.45}{1.2m^3 / day} = 14 days.$$

At SOS – Aldea infantil, the theoretical retention time is

$$R_{SOS} = \frac{V_{WETLAND}}{Q_{MAX}} = \frac{V_{TOTAL} \cdot P}{Q_{MAX}} = \frac{50.4m^3 \cdot 0.35}{10.8m^3 / day} = 1.6 days,$$

and at the private home the theoretical retention time is

$$R_{RrivateHome} = \frac{V_{WETLAND}}{Q_{MAX}} = \frac{V_{TOTAL} \cdot P}{Q_{MAX}} = \frac{11m^3 \cdot 0.37}{1.7m^3 / day} = 2.4 days.$$

Temperature

In all three systems, temperature was measured in both inlet and outlet. This was done at three different occasions, with two weeks in between. In San Nicolas elementary school the temperatures fluctuated between 21 °C at the lowest and 23 °C at the highest. In SOS – Aldea infantil the temperatures fluctuated between 17 °C at the lowest and 23 °C at the highest, and in the constructed wetland at the private home the temperature fluctuated between 15 °C at the lowest and 19 °C at the highest.

pH
pH was measured at both sample points at three different occasions, with two weeks in between. In San Nicolas elementary school the lowest measured value was 7 and the highest was 8. In SOS – Aldea infantil the lowest measured value was 6 and the highest was 7, and in the constructed wetland at the private home the pH was 6 at both inlet and outlet at each measurement.

Oxygen
Oxygen levels were measured at both inlet and outlet, at three different occasions with two weeks in between. In San Nicolas elementary school the values ranged between 1.3 mg/l and 2.8 mg/l. In SOS – Aldea infantil the values ranged between 0.9 mg/l and 2.7 mg/l and in the system at the private home the values ranged between 1.0 mg/l and 2.7 mg/l.

Conductivity
Conductivity was measured in both inlet and outlet all three times that samples were gathered. In the system in San Nicolas elementary school the conductivity increased from inlet to outlet. In the system at the private home there was also an increase in two out of three measurements. In SOS – Aldea infantil the conductivity decreased from inlet to outlet.

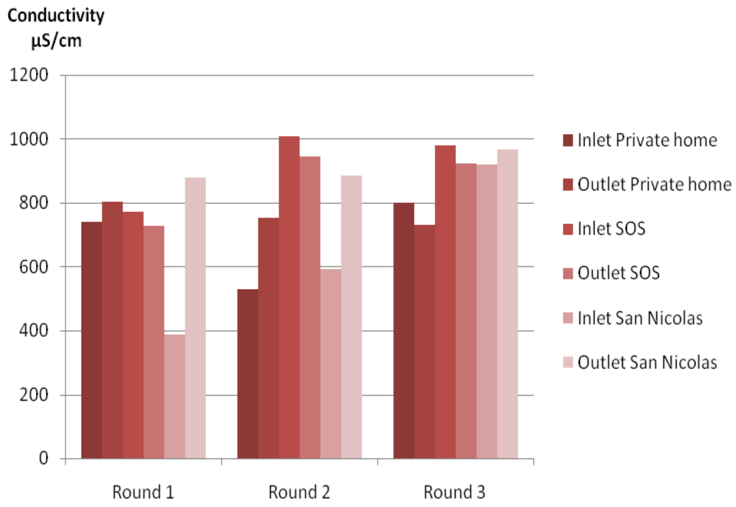

Figure 23 Levels of conductivity in the three systems.

Nitrogen
Total nitrogen and ammonium nitrogen were analyzed for both inlet and outlet at three different occasions with two weeks in between. Both the levels of total nitrogen and ammonium nitrate decreased from inlet to outlet at all of the systems.

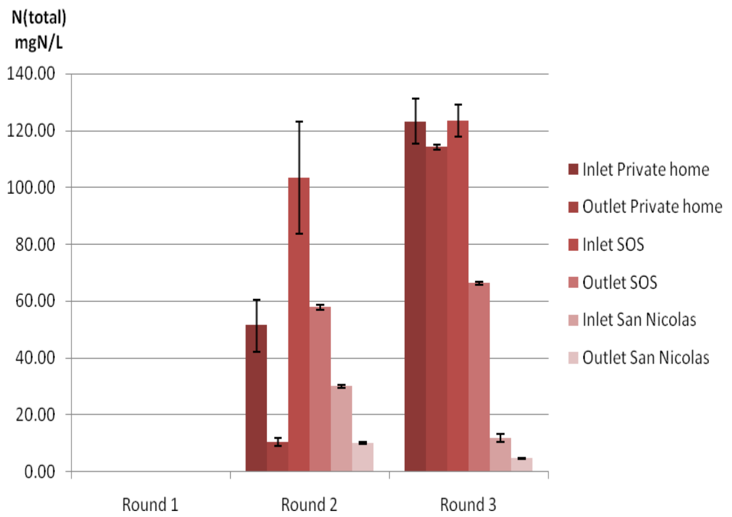

Figure 24 Levels of total nitrogen.

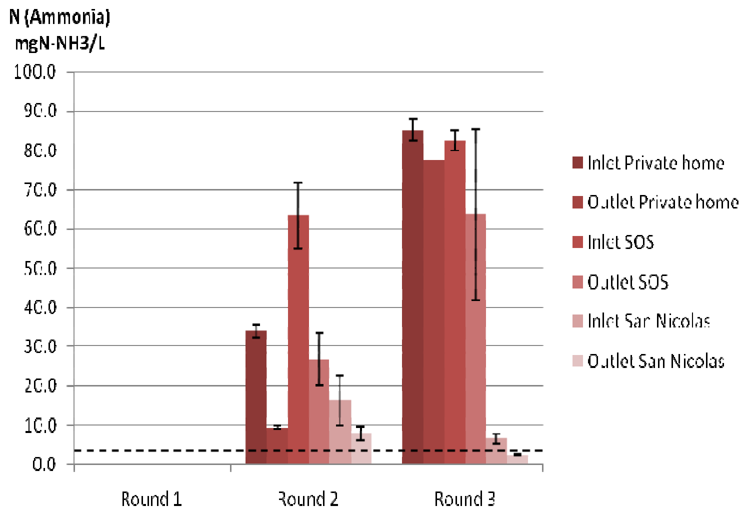

Figure 25 Levels of Ammonia. Dotted line indicates maximum limit for allowed discharge.

Phosphorus

Phosphorus was measured at both inlet and outlet at three different occasions with two weeks in between. Results show that levels of phosphorus decreased for all systems at every occasion except for the first measurement at SOS – Aldea infantil.

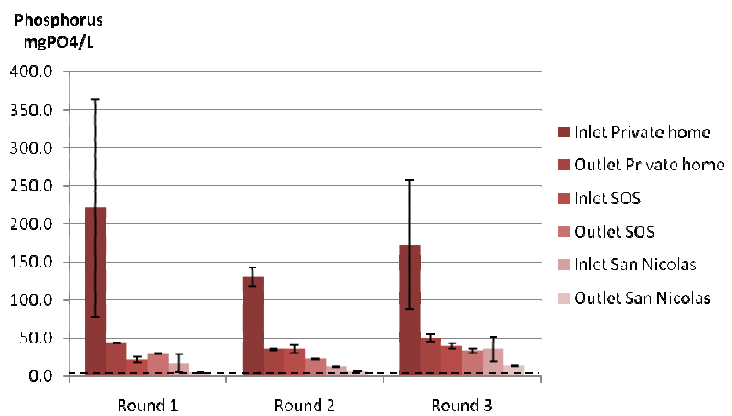

Figure 26 Levels of orthophosphate. Dotted line indicates maximum limit for allowed discharge of total Phosphate (levels of orthophosphate are approximated to be similar).

TSS

Samples for TSS were gathered at both inlet and outlet in all systems at three different occasions with two weeks in between. The results show that levels of TSS are decreasing between inlet and outlet in SOS – Aldea infantil and at the system in the private home. In the system at San Nicolas elementary school the levels are increasing.

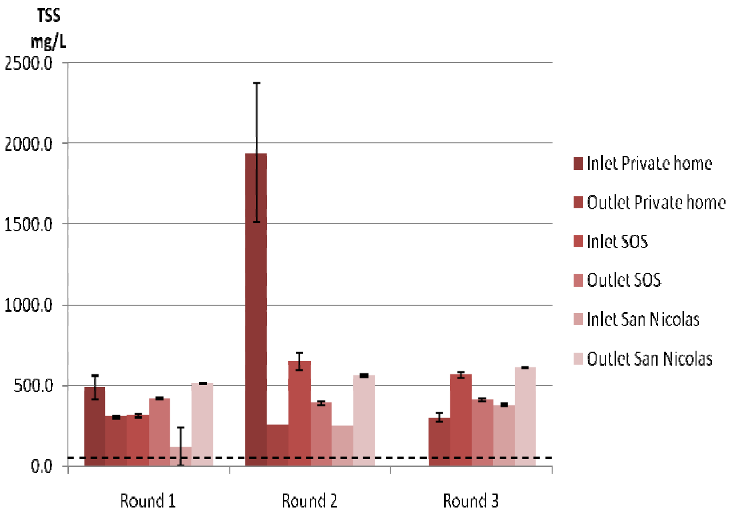

Figure 27 Levels of TSS. Dotted line indicates maximum limits allowed discharging.

DOC

Samples for DOC were gathered at both inlet and outlet in all systems at three different occasions with two weeks in between. The results show that levels of DOC decrease between inlet and outlet in SOS – Aldea infantil and at the system in the private home. In the system at San Nicolas elementary school the levels increase.

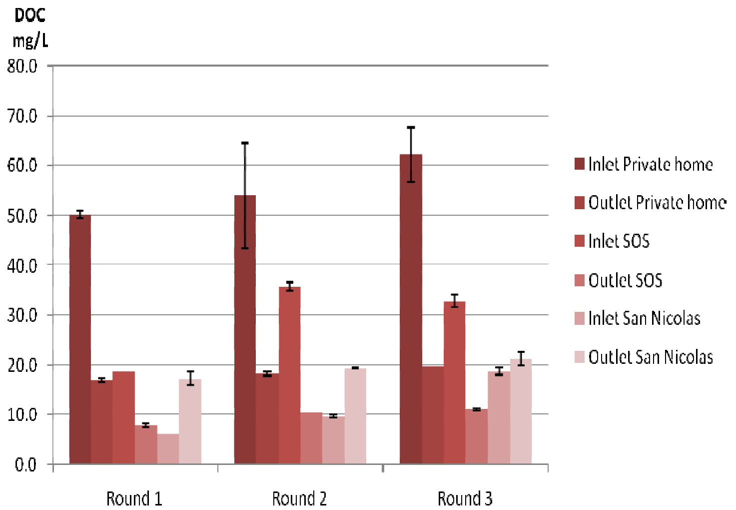

Figure 28 Levels of DOC.

Pathogens

Samples for analyzes of fecal coliforms were gathered at both inlet and outlet in all three systems at three different occasions with two weeks in between. Results show that the levels of fecal coliforms decrease at every occasion for all cases except at the first sample occasion at San Nicolas elementary school. At the private home the reduction has an average of 98 per cent, and at SOS the average reduction is 92 per cent.

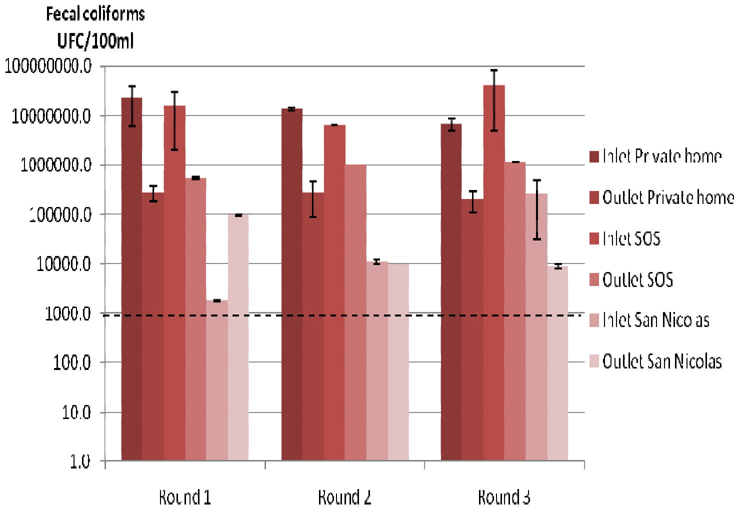

Figure 29 Levels of fecal coliforms. Dotted line indicates maximum limits allowed discharging.

6 DISCUSSION

Water sampling

The equipment borrowed from the Department of Limnology was quite old. It seemed trustable but had some defects. For example every setting was dislocated one step when choosing what to measure. Because of this the first oxygen measurement was misread. Another source of error due to the equipment was that the conductivity meter could not be set to the low pressure that corresponds to the high altitude in Cochabamba. This might have affected the absolute values of the conductivity numbers. However, the relative differences are probably not affected.

Since the wetlands were of SSF (Sub Surface-Flow) character it was hard to collect the water directly from the system without also disturbing the water quality, e.g. TSS. As far as possible the samples were collected from the pipe entering or leaving the wetland, but it often had to be collected in the septic tanks. This could be a source of error since the water might have other characteristics there. Also, the oxygen measurements were taken in the in- and outlets of the systems which often meant a bit more turbulent water and also therefore often a bit more oxygen rich water than in the actual wetland system.

Another source of error was that we did not have the chance to calibrate the oxygen meter for every occasion of sampling since there were strict routines in the laboratory for the person who prepared saturated water. Often that person arrived when we already had to leave for the field. Here we could have brought water, e.g. tap water from the city, to the field site to measure. The tap water would be stored in a dark fridge in between the sample dates.

Laboratory

The results of the analysis performed at the laboratory could be one source of error. First of all the laboratory was not yet certified and therefore the results not quality proofed. The samples were handed in to CASA after each gathering and most of the time analyzed within 24 hours. A period of three weeks passed between the sample rounds, and therefore there might be variations in the analysis that were not discovered. A better strategy, that for practical reasons was not possible in this project, is to freeze the samples until all samples are collected and then thaw them and analyze them all at the same time. In that way the error caused by variations from day to day in the laboratory can be reduced.

The results from analysis at CASA were sometimes mixed up by the personnel in the laboratory and a few times parameters were missing. These problems were however solved quickly and the collaboration with CASA has been working well. Some of the results presented were unrealistic and have been removed. These errors may just as well arrive from the collection of samples as from the laboratory. An extra duplicate of ammonium nitrogen was handed in from one of the sample points, to see if the results would be the same for both analysis. The results responded well with the results from the other samples collected at the same point and time. To further quality proof the analysis we could also have handed in one or two reference samples from each test round to see if these values varied or not.

Retention time
The tracer tests that were performed to get the retention time did not succeed so the real retention time was never measured. There are several possible explanations for this. The tracer used was a natural colouring matter, to make sure that it would not be harmful for the systems. The tracer test would probably work better if a salt had been injected in the inlet and measurements had been performed at the outlet with a conductivity meter. There are also other colouring matters that are more well-tried for this kind of experiment, such as uranin. The colouring matter used might have been diluted too much or absorbed in some way by the wetland.

Theoretical retention times and wetland volumes were calculated before the tracer tests were conducted. Since the retention time was assumed to be five days or more the outlet water was not examined until after three days. At that time it is possible that the tracers had passed the outlet already, since new theoretical retention times were calculated later and approximated to be less than three days. Since the real retention time is often lower than the calculated, the real retention time might still be even shorter than that.

The colouring matter that was used in each wetland was sufficient to give a bright red colour to 40 litres of water. This was assumed to be enough to be possible to discover at the outlets. The outlets were observed one or two times each day, during day time. It is possible that the amount of colouring matter was too small and therefore passed the outlet in night time or between observation times.

Flow
Since all the inlets to the wetlands where placed under the water level the exact volume of water going into the wetland was hard to measure. Therefore most numbers on flow was based on how much the users estimated that their daily use was. At the school of San Nicolas it was possible to dig down to the pipe where the water entered the wetland. In this way it was possible to calculate the inflow from putting plastic bags under the drip system. This gave a good estimation although one source of error was that some of the water stayed in the plastic bag, and another error was that some of the water ended up on the sides. In the private home we measured the outflow of the wetland, but that did not consider possible leakages from the wetland or evapotransporation from the plants. Leakages are in this case not likely to occur since the water starts flowing at the outlet soon after water is being added to the system. This would not happen if there was a leakage since the material underneath the system is rocky. The flow at the private home was measured when the estimated highest flow of the day occurred which meant it was not really comparable with the daily mean values we had from the other systems.

Hydrology
The water in the constructed wetland at SOS – Aldea Infantil was above the surface of the gravel filter at some of the visits. This may influence the treatment in a negative way. However, with a regulation of the outflow or simply by filling up with more gravel this can be adjusted. Surfacing was not observed at the other two sites.

Evapotranspiration was not calculated for the systems, mainly because it is difficult to accurately calculate but also because it was assumed to be small and therefore possible to neglect. Knowing the evapotranspiration would give a more complete picture of the water balances and retention times for the systems.

Plants
Since the wetland at San Nicolas has recently been put in use, there is still no vegetation in the system. One can see the importance of plants in a constructed wetland by comparing the results of the San Nicolas elementary school with the results from the other wetlands that had plants growing on the wetland. Perhaps the rise of conductivity from the inlet water to the outlet water would not be, or at least not so high, if there had been plants taking up these salts and minerals. In both wetlands that had plants growing in the wetland the plants were cut down quite rarely. At the private home they were cut down one year ago and at the SOS – Aldea infantil it was two years ago. Since the plants is an important factor for the cleaning of the water this should probably be done more often to have a better reduction of nutrients by plants in growing stage.

Temperature, oxygen and pH
The values of temperature, oxygen and pH were all in the range which is favourable for most processes to occur. Temperature was never below 15ºC and in all systems 1-3 degrees lower in the outlet than in the inlet water. The oxygen value was at most points over 1.5 mg/l, a limit where normally no denitrification occurs if exceeded (Jennifer Rojas, pers. comm.), although at the SOS – Aldea Infantil it seemed to be some values under this limit. The pH never left the range between pH 6 and 8, within which all nutrients are readily available and most bacteria active.

Phosphorus
The levels of phosphorus all exceed the norms that are given by the EU for discharges from urban waste water plants, both at the inlet and the outlet (Appendix I). The constructed wetlands at SOS – Aldea infantil and in the private home both have values that greatly exceeds the EU norms. The levels at San Nicolas elementary school are not as high but still above the norms (limit values for phosphorus are expressed as total phosphorus and not as orthophosphate, which we determined. However, we have compared our results with the existing limits for total phosphorus, since most of the phosphorus found in sewage water is in the form of orthophosphate).

Comparing the inflow with the outflow indicates that there is a reduction of orthophosphate in the water that passes through the wetland, with an average of 57 percent (disregarding the first measurement at SOS – Aldea infantil where levels of orthophosphate were increasing). Since orthophosphate is in a form available for organisms it is likely that it is being absorbed by these or that it has been adsorbed to mineral complexes. As mentioned above there is, however, some uncertainties in the results from the laboratory.

Nitrogen
There is a trend of reduced levels of nitrogen, with an average reduction of about 50 percent, though the values of the total nitrogen are still very high in the outgoing water. The ammonia values seem generally to follow the reduction of total nitrogen proportionally, with an average reduction of about 46 percent. And since one can see a reduction in the total nitrogen some of the nitrogen must be taken up by plants or the biofilter or transform to N_2. Still the levels are much higher than the Bolivian recommended limit of 4 mg/l for ammonia (Appendix I). Except in San Nicolas elementary school, where the values are reasonable, below 10 mg/l in the outgoing water for both total nitrogen and ammonia. In the other systems, the values are often even higher than 20 mg/l. But the values vary a lot between the sampling days and from

the discussion above about the quality of the laboratory analysis, this could also be a big source of error in the result values.

TSS, DOC and Conductivity

On most test points, the conductivity are rising from the inlet to the outlet water. Except for the wetland at SOS – Aldea Infantil where it is reduced. Most of the values are between 5-900 µS/cm with one value being above 1000. This is not too high for irrigation even if it is in the risk zone of stressing plants. Below 750 µS/cm it is safe for irrigation, but above that the danger of salt stress for the plants can increase, and values over 3000 µS/cm are really not good for the plants (The Department of Sustainability and Environment, Victoria).

TSS is in most of the wetlands decreasing through the system except for the San Nicolas elementary school where the values consequently are rising. But this could be because of the young age of the system and that it has not developed a biofilter yet and also that material on the gravel instead contribute to the value. The TSS values also show the same patterns as DOC and conductivity. The values of TSS are a lot higher than the Bolivian norms on 60 mg/l (Appendix I).

Pathogens

The amounts of pathogens as fecal coliforms are high in the inlets, and though there is a reduction in all systems the amounts in the outlets are still very high and well above the norms that are given by the Bolivian environmental law (Appendix I). This indicated that the treatment in the systems is not efficient enough. An average of above 90%, as most of the results show of the reduction of pathogens, is a good performance of the wetland system although the values leaving the system still are very high.

General discussion

Besides how the water samplings were conducted and the analysis being made at the laboratory there are some more things that could be pointed out about the relevance of the results, first of all the amount of parameters. For a more relevant analysis of the wetland, more parameters, like BOD, could have been analyzed, but due to lack of funding this was not possible. The shortage of funding also made the amount of test points and test days smaller than preferred.

Also one has to take into consideration the whole system. Maybe the pretreatment is not efficient enough and the wetland not constructed for the load that comes in. Compared with recommended maximum values, the influent should not exceed TSS values of 587 mg/l or total Kjeldahl nitrogen of 51 mg/l (Seabloom et al., 2005) and these parameters are higher at some of the test points than in the inlet.

As the water from most wetlands here is used for irrigation the levels of nitrogen and phosphorus do not need any further treatment, although it would need further treatment to be discharged into waters which are subject to eutrophication. Here the sanitary problem is of greater importance. Although pathogens could be spread by the crop the water could still be used for some irrigation where there is no contact between the edible part of the plant and the irrigation water (see 2.2.4). Maybe this would be a good alternative since the pathogens then would be eliminated forever when exposed for direct sun light, but also it leads to a great risk for water reaching crops and humans if not treated right. For an improved pathogen treatment one alternative is to connect a sand filter to the whole system, preferably in the end of the wetland as the level of suspended solids is lower here and therefore the sand filter is less likely to clog up. Another solution to areas in developing countries with a dry climate is to install dry toilets which separate the urine from the faeces. In this way the urine can be directly used as fertilizer and the faeces can be stored in a non-humid alkaline environment for a lengthy storage period before being used as fertilizer (or for biogas production which we saw an example of at the SOS – Aldea infantil). In that way the pathogens can be destroyed. For less attendance one can build two toilets to alter between where the excrement in the toilet not used can be left long time enough to be safe to use as fertilizer. If the water would be let out directly to a recipient another alternative would be to complement the system with a smaller filter with a phosphorus adsorbing substance like filtralite, a lightweight ceramic particle aggregate proven to be a good material for water and wastewater purification.

The richness of wild life in the pond connected to the wetland at the private home is an indicator of a well working system for treated wastewater to enter a water recipient. This Open-Surface Wetland is also a good means to further reduce the levels of nitrogen, phosphorus and pathogens, and the efficiency of that part of the system would have been interesting to include in the study.

7 CONCLUSIONS

One of the biggest problems in Cochabamba is the lack of waste water treatment in combination with a growing population. The municipal treatment plant handles only a small part of the waste water and the treatment does not meet the quality norms of the Bolivian environmental law. The majority of the households only have a septic tank for pre-treatment of the waste water before it is being disposed into surrounding waters. In many cases there is, however, no treatment at all.

Constructed wetlands may be a solution to this problem, especially in rural areas where there is plenty of space. The systems are low in maintenance and cost and are therefore a suitable solution for many developing countries. A few constructed wetlands have been installed in and around the city of Cochabamba.

The results of this study indicate that treatment of domestic waste water performed at the studied three systems take place but depending on the use of the water it should be further improved. Levels of nitrogen, phosphorus and pathogens are too high for safe disposal into rivers and lakes, according to Bolivian and EU norms. But since these waters are mainly used for irrigation the risk for eutrophication is not high. Here the problem is rather the high amounts of pathogens that make it advisable not to use the water for irrigation of food crops eaten raw or at least not where the water is in contact with the crop. The system of these wetlands needs a good understanding of how to use the water to avoid the spread of diseases caused by pathogens.

It is difficult to estimate the credibility of these results based only on relatively few tests. Further and wider studies are needed to make sure that the indications of this study are correct. Even though a good reduction was indicated for most measured parameters, improvements could be made. The retention time was not measured, but calculations indicate that the real retention time is lower than what the systems were constructed for, which could be a likely explanation for the low treatment efficiency. The vegetation in the wetlands should be cut down more often, at least twice each year. It might also be a good idea to complement the treatment in some way, either to put a sand filter at the end of the wetland system so that more pathogens would be absorbed, as this is the critical parameter for water used for irrigation, or to install dry toilets so that the pathogen containing excrement could be treated separately. Or, if the water is going out to a water recipient, another filter could be connected to the wetland, like a sand filter containing a phosphorus adsorbing material like filtralite.

Considering the treatment of domestic waste water as it is today in Cochabamba and its surroundings these systems at least improve the water situation in the city. With a conscious use of the water and maintenance of the system or with improvements of the system it can be a good alternative to the existing treatment techniques.

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APPENDIX

APPENDIX 1 – BOLIVIAN NORMS

Maximum limits allowed to discharge according to Bolivian environmental law (Bolivian Law No. 1333, 2006).

Parameter	Value
pH	6.9
Temperature, ºC	±5
Total Suspended Solids (TSS), mg/l	60
Fecal coliforms, NMP/100 ml	1000
Oil and fats, mg/l	10
BOD5, mg /l	80
DOQ, mg/l	250
Ammonia nitrogen, mg/l	4
Sulphate, mg/l	2

APPENDIX 2 – EU NORMS

Maximum discharge limits allowed according to EU regulation (EU Directive 91/271/EEC).

Parameter	Value [mg/l]
BOD	25
DOQ	125
Total Suspended Solids	35
Phosphorus	2
Total nitrogen	10 - 15