Effect of wastewater quality on the performance of constructed wetland in an arid region

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تأثير نوعية مياه الصرف الصحي المعالجة بشكل أولي على أداء الأراضي الرطبة المنشأة

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Thesis was prepared under the supervision of Dr. Nidal Mahmoud and has been approved by all members of the Examination Committee

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The findings, interpretations and conclusions expressed in this study do not necessary express the views of Birzeit University, the views of the individual members of the MSc-committee or the views of their respective employers.

Abstract

Treated wastewater effluent quality in Palestine is very stringent imposing extremely low Biochemical Oxygen demand (BOD), Nitrogen (N) and Fecal coliform effluent quality, that vary with the final disposal, (10,10,10) of BOD, TN and TSS values for discharge in wadi. This is the reason that makes treated effluent in need for further polishing to meet those stringent requirements.

Constructed wetland relies on the removal or degradation of contaminants as water moves through the media, using physical, chemical and biological processes for water treatment. However, the performances of these systems depend on the site characteristics, sources water quality and the process conditions applied. Therefore, this study focused on analyzing the potential of constructed wetland for removal of organic matter, nutrients and pathogens from three different pre-treated source waters.

Horizontal subsurface flow constructed wetlands (HSSFCWs) are being used worldwide to treat wastewater from a variety of sources. An extensive literature review was conducted to update the current state of scientific knowledge on the performance of constructed wetlands for domestic wastewater treatment. This review documented good treatment efficiency for the following commonly measured parameters (BOD, COD and nitrogen).

Three horizontal subsurface flow constructed wetlands were operated in parallel outdoor for almost seven months and fed with different water influents. Wastewater were collected from Al-Mazr'a anaerobically pre treated grey water,

Al-Bireh tertiary treated effluent and Birzeit secondary treated effluent. For the constructed wetland, gravel of 40% porosity was used as filter media. After 98 days of starting operation the system, effluents were analyzed for DOC, BOD, COD, NH4, NO3, TKN, TDS, TSS, pH, EC and fecal coliform until the end of the experiment.

Average DOC removal of 31.8%, 34.4% and 30.8%, COD removal of 36, 27 and 35, BOD removal of 43.4, 18.7 and 47.2, Ammonia removal of 94, 87 and 96, Nitrate removal of 84, 92 and 90, TKN removal of 53, 35 and 50, phosphate removal of 51, 49 and 44, sulphate removal of 15.2, 15.5 and 18.8, TSS removal of 16.4, 21.9 and 23.3 were achieved by the constructed wetlands with Al-Mazr'a greywater, Al-Bireh tertiary treated wastewater and Birzeit secondary treated wastewater, respectively.

The constructed wetland was efficient in terms of NH_4-N, NO_3-N and BOD and achieved the Palestinian standards for using treated effluent for reuse and discharge to wadis. But, in terms of PO_4-P, TSS and fecal coliform the constructed wetland didn't achieve those standards. Also, the results revealed that constructed wetlands can be used as a post treatment for the secondary treated wastewater and for anaerobically treated grey water. In general, constructed wetlands technology has the capacity for removing organic matter and nutrients and to less instant pathogenic micro-organisms and TSS from the different source water.

الخلاصة

تخضع نوعية المياه العادمة المعالجة لمتطلبات صارمة في حالة استخدامها للري أو لتغذية الأحواض الجوفية, بحيث تكون نسب النيتروجين الكلي, الأكسجين المستهلك هوائيا ومجموع المواد الصلبة العالقة 10و 10و 10 ملغم /لتر. هذه المعالجة تجعل المياه المعالجة في المحطات مثل محطة البيرة ومحطة بيرزيت لمعالجة المياه بحاجة الى مزيد من الصقل. ويهدف هذا البحث الى دراسة تأثير نوعية المياه المعاجة بشكل أولي على قدرة الأراضي الرطبة المنشأة في معالجة المياه العادمة وازالة الملوثات العضوية والمغذية ومسببات المرض, كما ويهدف الى دراسة امكانية استخدام تكنولوجيا الأراضي الرطبة لمعالجة المياه المعالجة بشكل أولي لتصبح ملائمة لتغذية الحوض الجوفي . تعمل الأراضي الرطبة المنشأة على إزالة الملوثات من المياه العادمة وذلك باستخدام العمليات الفيزيائية والكيميائية والعمليات الحيوية. ومع ذلك، يعتمد أداء هذه االأنظمة خصائص الموقع و نوعية المياه والظروف التشغيلية. وتستخدم الاراضي الرطبة المنشأة في مختلف دول العالم لمعالجة المياه العادمة. يتضمن هذا البحث دراسة واسعة النطاق تستعرض المعرفة العلمية المتعلقة بهذه التكنولوجيا

تم تصميم وتشغيل ثلاثة أنظمة متماثلة من الأراضي الرطبة المنشأة وتزيدها بمياه معالجة أوليا من ثلاث مصادر مختلفة وهي: المياه المعاجة من محطة البيرة لمعاجة المياه العادمة, المياه المعالجة من محطة بيرزيت لمعالجة المياه العادمة ومياه رمادية معالجة بشكل أولي لاهوائيا. تم تزويدها بمصدر للهواء وتعبئتها بحصمة مساميتها 40%. تم تحليل عينات من مدخل ومخرج الاراضي الرطبة بعد 45 يوما من التشغيل, تم تمت متابعة عملية التحليل لكل الملوثات وذلك بعد مرور 98 يوما من التشغيل

نتائج هذه الدراسة تعكس قدرة الأراضي الرطبة على معالجة مختلف أنواع المياه العادمة المعالجة بشكل أولي. وجدت الدراسة انخفاضا واضحا في تركيز الملوثات التالية: الكربون المذاب عضويا, الاكسجين المستهلك حيويا وكيميائا, النيتروجين الكلي, النترات. حيث سجلت القيم التالية لكل من المياه الرمادية, مياه البيرة وبيرزيت على الترتيب: (31.8,34.4, 30.8)% للكربون المذاب عضويا, (36,27,35)% للأكسجين المستهلك كيميائيا, (94,87,96)% للأمونيا, (84, 92, 90)% للنيترات. على الصعيد الآخر لم يتم تحقيق نتائج جيدة لكل من الكبيريتات (15.2, 15.5,18.8)%, والفوسفات(51, 49, 44)%, والمواد الصلبة المعلقة (16.4, 21.8, 23.3)% والبكتيريا القولونية البرازية التي لم تتجاوز نسب ازالتها 25%.

حققت المياه العادمة المعالجة باستخدام الأراضي الرطبة المنشاة متطلبات المواصفات الفلسطينية فيما يتعلق بتركيز كل من التيترات والاكسجين المستهلك كيميائا والأمونيا لكن لم تنجح في تحقيق المتطلبات المتعلقة بتركيز المواد الصلبة المعلقة والبكتيريا القولونية البرازية.

Dedication

I Dedicate My Work

To Whom I Belong

To My Parents

To My Husband

To My sisters and brothers

For their help, support and encouragement

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Most of all, I acknowledge the incessant blessings for God Almighty granted me wisdom and made everything successful.

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I would like to forward my heartfelt love and thanks to my husband Ahmad Rob

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Scope of Study

The scope of this study includes: set-up subsurface flow constructed wetland (SSFCW) for treating three wastewater types. The experiments were carried out in Birzeit University/ Palestine. Wastewater samples were taken from the inlet and outlet of the three wetland systems. The plants used in this study are commom reed (Phragmites Austrails). The performance of constructed wetland was evaluated using water quality parameters: pH, Electrical Conductivity (EC), Total Suspended Solid (TSS), Total Dissolved Solids (TDS), Ammonia Nitrogen (NH_3-N), Nitrate Nitrogen (NO_3-N) and Phosphate (PO_4-P), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Dissolved Organic Carbon (DOC) and fecal coliform.

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Abbreviations

COD Chemical Oxygen Demand

CWS Constructed Wetland System

DO Dissolved Oxygen

DOC Dissolved Organic Carbon

HRT Hydraulic Retention Time

HSSFCWs Horizontal Subsurface Flow Constructed Wetlands

TDS Total Dissolved Solids

TKN Total Kjeldahl Nitrogen

TN Total Nitrogen

TSS Total Suspended Solids

Chapter One

Introduction

1.1 Background

Water availability is not only a problem in terms of quantity, but also in terms of quality. At present still about 1 billion people in the world lack access to improved water supply and some 2.6 billion people lack access to proper sanitation. In combination with agricultural and industrial waste generation, this lack of wastewater collection and treatment facilities results in serious quality deterioration of both surface and groundwater resources, hampering their exploitation. It has been estimated that, by 2025, 1800 million people will be living in countries or regions with absolute water scarcity, and two thirds of the world population could be under water stress conditions (WHO, 2007). It is therefore of most important to search for alternative water resources and water treatment technologies.

It is important for the developing countries to use a proper wastewater treatment system which meets the local requirements in terms of water quality, costs and operational skills required, maximize the potential for local reuse (non-potable or potable) and have least impact on the environment. Natural treatment systems fit these requirements, i.e. constructed treatment wetlands (Hoffmann and Platzer, 2010).

Constructed wetlands are manmade engineered, marsh like area designed to treat wastewater depending on physical, chemical and biological processes of natural ecosystems. They can remove multiple aquatic pollutants by making use of natural, biological processes driven by solar energy, requiring minimal maintenance and external energy inputs.

These systems can be either free water surface or subsurface wetlands. Free water systems include a shallow basin where water is exposed to atmosphere and flows horizontally. Subsurface systems consist of a basin with porous media with water level below the surface of the media and the water flows horizontally (Converse, 1999).

Constructed wetlands are wetlands intentionally created from non-wetland sites for wastewater or storm water treatment. These are being used worldwide to treat wastewater, including that from mines, animal and fish farms, highway runoff, industry of all types, and municipal and domestic sewage (Hoddinott, 2006).

Natural wastewater treatment systems like soil aquifer (SAT) and constructed wetlands (CW) are robust barriers, can remove multiple contaminants, minimize the use of chemicals, use relatively less energy and have a small carbon footprint. Natural treatment systems rely on natural processes comprising different physical, chemical and biological removal mechanisms and combinations thereof for improvement in water quality. These systems have been applied for wastewater treatment and reuse in different parts of the world. These systems are very

appropriate for developing countries and countries in transition and at the same time equally applicable in developed countries (Khalili, 2007).

The suitability and performance of such natural treatment systems however depend on source water quality, process conditions applied, hydro geological conditions and water quality goals to be achieved by treatment. It is expected that with further improvement of these systems, a comprehensive system for wastewater treatment and reuse can be developed which can be applied for treatment of different types of wastewater, at different-scales and in different regions of the world.

Constructed wetlands are man-made analogs of natural wetlands that optimally exploit the biogeochemical cycles that normally occur in these systems for the purpose of wastewater treatment. Systems can be surface flow or subsurface flow (the latter one to avoid odor problems and mosquito proliferation). CWs are attractive for wastewater treatment at a household or community level and at a larger scale also for the recovery of nutrients to minimize the eutrophication potential of the receiving water bodies (Davis, 1989).

A variety of applications for constructed wetland technology for water quality improvement has started to be implemented in developing countries like India, Nepal, Iran, Thailand and Egypt. All constructed wetlands are attached growth biological reactors. Flow regime may be free water surface and sub-surface flow. The removal mechanisms associated with wetlands include sedimentation, coagulation, adsorption, filtration, biological uptake and microbial transformation.

Constructed wetlands are not recommended for treatment of raw wastewater so that it must be preceded by a pre-treatment step (El-Khateeb *et al.*, 2008)

The current research was conducted within the frameworks of the NATSYS project at the IEWS Institute in Birzeit University, Palestine. The NATSYS project investigates sustainable urban water management, including a focus on the role of natural treatment options.

NATSYS project aims to investigate the potential for CW treatment as a pretreatment for Soil Aquifer Treatment (SAT). The major constraints of SAT are also space use and nutrient removal, so the project aims to optimize space efficiency and nutrient removal in CWs before water is discharged to SAT treatment. In this project, artificial aeration is one novel method that has been used to increase nitrification rates in CWs. The research also aimed to track several pollutant removal performances to investigate whether different water sources may have an impact on the removal efficiency in the wetland.

1.2 Problem statement

Constructed wetlands need to be further adapted to increase their performance under local circumstances (such as climate, wastewater quality and quantity) in terms of pre-treatment to obtain the desired removal efficiencies. Furthermore, there is potential for their optimization in terms of removal efficiency and costs by implementing proper pre-treatment. Under the climatic conditions in Palestine, this MSc research project aims to investigate the treatment capability of main vegetation- based natural systems for wastewater treatment for the removal of different contaminants (organics, pathogens and nutrients) under different water

quality (**Al Bireh tertiary treated wastewater, Al- Mazra'a grey water and Birzeit secondary treated wastewater**). In this context, analysis of the performance of these treatment systems for the removal of multiple contaminants is very relevant to obtain more insight into their capabilities so that these can be successfully implemented in developing countries.

A clear understanding of the performance of constructed wetlands for removal of different contaminants from various types of wastewaters (effluents) still need to be elucidated.

Many researches with regard to constructed wetlands in general and horizontal subsurface flow constructed wetland in particular were conducted. Also, many of these researches were summarized by other authors such vymazal (2005) who studied those experiments and summarized them. Many constructed wetland were examined in different operating conditions i.e, they were operated with different plant types, different influents with and without aeration and with different types of media such as gravel and volcanic tofa. This research is conducted on horizontal subsurface flow constructed wetlands which were fed with different source water with the same plant type (reed). The three wetlands were operated under the same conditions, same loading rate and same hydraulic retention time. In other words, the variables were the influent type and aeration.

1.3 Research Objectives

The main objective of this research is to investigate the effect of source water quality on the performance of constructed wetlands (CW) with respect to the removal of organic matter, solids, pathogens and nutrients. Different types of wastewater effluents were examined during the study including (I) secondary effluent from a contact process activated sludge serving of Birzeit University treatment plant; (II) tertiary treated effluent of Al-Bireh municipal wastewater treatment plant) and (III) anaerobically pre-treated grey water.

The specific objective is:

To investigate the potential of constructed wetland for further treating/ polishing various types of wastewater under the arid to semi arid climatic conditions of Palestine;

1.4 Research Question and Hypotheses

The research questions were:

What is the impact of water source on the removal efficiency of the subsurface flow constructed wetlands?

Does the construed wetland effluent met the Palestinian standards for recharge?

The research hypothesis is:

The constructed wetland will be able to treat efficiently the secondary treated wastewater, tertiary treated and anaerobically pretreated grey water to fit ground water recharge requirements.

1.5 Thesis structure

This thesis is divided into 5 chapters as follows:

- Chapter one is an introduction provides a general background about the Thesis subject, statement of the problem and objectives.
- Chapter two provides comprehensive literature review on the state of the art of CW
- Chapter three describes the materials and methods used.
- Chapter four includes a discussion for the main results
- Chapter five contains conclusions and recommendations.

1.6 Research methodology

The research was conducted outdoor in Birzeit Universitty and involved three HSSFCWs consisting of beds filled with gravel, planted with *Phragmites Australis* reed and fed with three source waters from Borzois University treatment plant, Al-Bireh municipal treatment plant and Al-Mazra'a onsite treatment plant.

During the experiment period, the system was operated and maintained including feeding the wetlands and maintaining the system. The influent and effluent of the constructed wetland were analyzed for several parameters, namely biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved organic carbon (DOC), Nitrogenous compounds (NH_4, NKj, NO_3), phosphate, Fecal Coliform, electrical conductivity, pH, total suspended solids (TSS), Total

dissolved solids (TDS) and dissolved oxygen. During the start up phase, COD, NH_4 and PO_4 concentrations were measured twice weekly for the influent and effluent. Once steady state was reached, the influent and effluent were analyzed for the whole set of parameters once weekly for five months. Also, during all phases, the flow rate was measured daily in order to ensure a hydraulic retention time of 1.3 day.

Chapter Two

Literature Review

2.1 Background

Excessive nitrogen and phosphorous loading to natural watercourses due to urbanization and intensive farming highlight the need to protect these ecosystems from eutrophication by reducing nutrient inputs. Constructed Wetland research has been ongoing firstly in Europe with urban waste streams. Research investigations spread to other countries and since the mid 80's, constructed wetlands have been examined in greater detail (Forbes *et al*., 2004).

Constructed wetlands are used for purification of industrial wastewater, agricultural wastewater and storm waters. Also, they are applied to strip nutrients of eutrophied surface waters before these are discharged into nature reserves (Rousseau *et al.*, 2004). Constructed wetlands have been used to treat acid mine drainage, storm water runoff, municipal wastewater, industrial wastewater and agricultural effluent form livestock operations. Constructed wetlands can remove significant amounts of suspended solids, organic matter, nitrogen, phosphorus, trace elements, heavy metals and microorganisms contained in wastewater (Sa'at, 2006).

The first full-scale constructed wetland for wastewater treatment was built in the Czech Republic in 1989. By the end of 1999, about 100 constructed wetlands were put in operation. Most of these systems are horizontal subsurface flow and are designed for the secondary treatment of domestic or municipal wastewater.

The size of constructed wetlands ranges between (18 - 4500) m² and between (4 – 1100) population equivalents. *Phragmites australis* is the most commonly used plant. The treatment efficiency is high in terms of BOD_5 and suspended solids. However, the removal of nutrients is lower for vegetated beds. The early systems, built in 1970s and early 1980s used mostly soil materials which failed to maintain high hydraulic conductivity. This resulted in surface flow and lower treatment efficiency. In the late 1980s, the coarse materials with high hydraulic conductivity were introduced and were found to meet the other requirements. The experience from operational systems has shown that the 8/16 mm gravel size fraction provides sufficient hydraulic conductivity while supporting a healthy macrophyte growth and good treatment efficiency (Vymazal, 2002).

In 1953, the first experiments using wetland macrophytes for wastewater treatment were carried out by K¨athe Seidel in Germany. The horizontal sub surface flow constructed wetlands were initiated by Seidel in the early 1960s and improved by Reinhold Kickuth under the name Root Zone Method in late 1960s and early 1970s. In the late 1980s, the first horizontal subsurface constructed wetlands were built in many European countries. By the end of 1986, the major change in the design was the use of very coarse filtration material to ensure sub-surface flow (Vymazal, 2005).

The first full technology assessment was published by the USEPA in 1993. Hans Brix authored a 1994 article that presented a large worldwide database of results that showed impressive wastewater treatment by subsurface flow wetlands. In 2002, Jan Vymazal published a summary of ten years experience in the use of

constructed wetlands for wastewater treatment in the Czech Republic. Vymazal stated that there are over 100 constructed wetlands in the Czech Republic. All of these are horizontal subsurface flow constructed wetlands treating municipal or domestic wastewater. Vymazal admitted that his data is somewhat limited by Czech legislation which requires standards only for suspended solids and biological oxygen demand parameters for sources of pollution from less than 500 PE (Hoddinott, 2006).

Original hybrid constructed wetland systems were developed by Seidel in Germany. The process is known as the Seidel system. The Seidel design consisted of two stages of several parallel vertical flow beds followed by two or three horizontal flow beds in series. The vertical beds were planted with *P. australis* and the horizontal beds were planted with a number of other emergent macrophytes. By 1980s, several hybrid systems of Seidel's type were built in France with a system at Saint Bohaire, which was put in operation in 1982. It consisted of four and two parallel vertical flow beds in the first and second stages, respectively. A similar system was built in 1987 in UK. The first stage consisted of six vertical beds (8m² each) intermittently fed and planted with *P. australis*. The second stage consisted of three vertical beds (5m² each) planted with. *P. australis, Schoenoplectus lacustris (bulrush) and Iris pseudacorus*. Hybrid systems have the advantage of producing effluent low in BOD which is fully nitrified and partly denitrified and so that has a much lower total-N outflow concentrations (Vymazal, 2005).

The first subsurface flow constructed wetland for treatment of domestic wastewater was built in Norway in 1991. The Norwegian concept for small constructed wetlands is based on the use of a septic tank followed by an aerobic vertical down-flow biofilter succeeded by a subsurface horizontal-flow constructed wetland. This aerobic biofilter is essential to remove BOD and achieve nitrification in a climate where the plants are dormant during the cold season. Nitrogen removal in the range of 40 to 60% is achieved. Removal of indicator bacteria is high and < 1000 thermo-tolerant coliforms/100 ml is normally achieved (Niyonzima, 2007)

Constructed wetlands are planted with emergent vegetation such as bulrushes, cattails and reeds. A fundamental characteristic of wetlands is that their functions are largely regulated by microorganisms and their metabolism. Microorganisms include bacteria, yeasts, fungi, protozoa, and algae. Microbial activity transforms a great number of organic and inorganic substances into insoluble substances, alters the redox conditions of the substrate and affects the processing capacity of the wetland (Davis, 1989).

The capital costs of subsurface flow constructed wetlands depend on the costs of the bed media in addition to the cost of land. Financial decisions on treatment processes should be made on net present value or whole-of-life costs, which includes the annual costs for operation and maintenance (Hoffmann and Winker, 2011).

2.1.1 Advantages and disadvantages of Constructed Wetland System

Constructed wetlands are designed to take advantage of many of the same processes that occur in natural wetlands within a more controlled environment. Advantages of constructed wetlands include:

* Site location flexibility,

* No alteration of natural wetlands,

* Process stability under varying environmental conditions,

* Constructed wetlands do not produce sludge as the constructed wetland's influent is already pre- treated and contains low concentrations of pollutants. Subsurface flow constructed wetlands have many advantages over ponds. Where in ponds sludge accumulates over time, and the sludge has to be removed after approximately 10 years (Hoffmann and Winker, 2011).

* Horizontal subsurface flow constructed wetlands (HSSFCW) for wastewater treatment can be easily adapted to cold climate. In these systems, risks of hydraulic failure due to freezing are reduced because water flows under the bed surface. Natural or artificial insulation layer can also protect them from freezing (Plamondon *et al.,* 2006).

* Other benefits of treatment using constructed wetlands are decreased potential for spills by eliminating the need for offsite transportation, sharp reduction in use of transportation fuel and decreased energy consumption by using natural processes (Basham, 2003).

The need for use of constructed wetlands in grey water treatment may provide a simple and inexpensive solution for controlling many water pollution problems facing small communities, industries, and agricultural operations (Niyonzima, 2007). Grey water after treatment in a constructed wetland tends to have no colour (Hoffmann and Winker, 2011).

The potential problems with Free Water Surface constructed wetlands include mosquito, start-up problems in establishing the desired aquatic plant species with free water surface and subsurface Flow wetlands (Niyonzima, 2007). Other problem in constructed wetland is the high surface area demand (in the order of 2-10 m^2 per person for domestic wastewater, depending on the type of CW used, the climatic conditions, pre-treatment, etc.). This restricts the use of constructed wetland technology in urban and rural areas where land is scarce and expensive (Stefanakis and Tsihrintzis, 2009).

2.1.2 Types and functions of Constructed Wetlands

Constructed wetlands can be classified according to the flow direction into vertical and horizontal flow. Also, other two types of constructed wetlands have been carried out. They are the free water surface systems and the subsurface flow systems which also called root zone, rock-reed filters or Vegetated submerged bed systems as presented in Fig. 2.1 (Niyonzima, 2007).

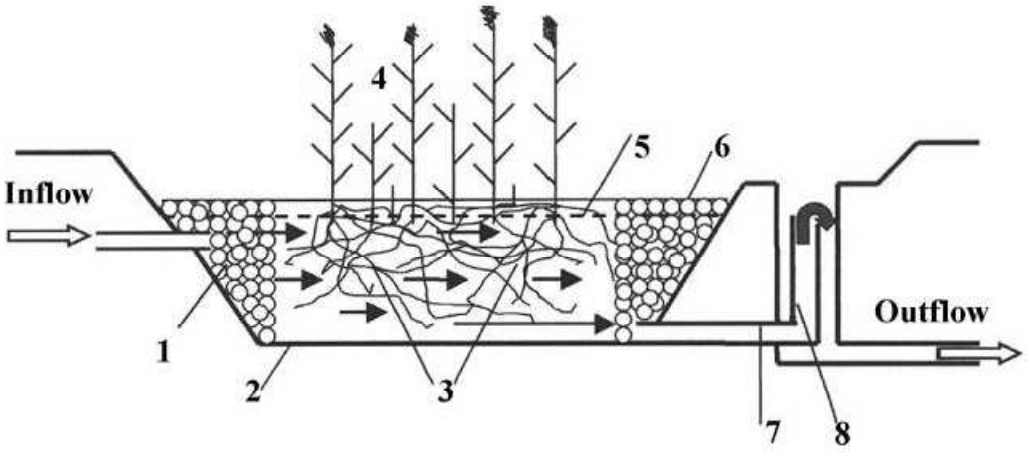

Figure 2.1 Constructed wetland with horizontal sub-surface flow. 1, distribution zone filled with large stones; 2, impermeable liner; 3, filtration medium (gravel, crushed rock); 4, vegetation; 5, water level in the bed; 6, collection zone filled with large stones; 7, collection drainage pipe; 8, outlet structure for maintaining of water level in the bed. The arrows indicate only a general flow pattern (Borst, 2011)

Combination of aerobic and anaerobic processes can upgrade constructed wetlands to treat industrial wastewater containing less-degradable organic pollutants (Yamagiwa et al., 2008).

Anaerobic and aerobic activities in a vertical constructed wetland were investigated with and without supplementary aeration which boosted the carbon removal and nitrification. Constructed wetlands may be classified according to the life form of the dominating macrophyte into systems with free-floating, rooted emergent and submerged macrophytes (Vymazal, 2005).

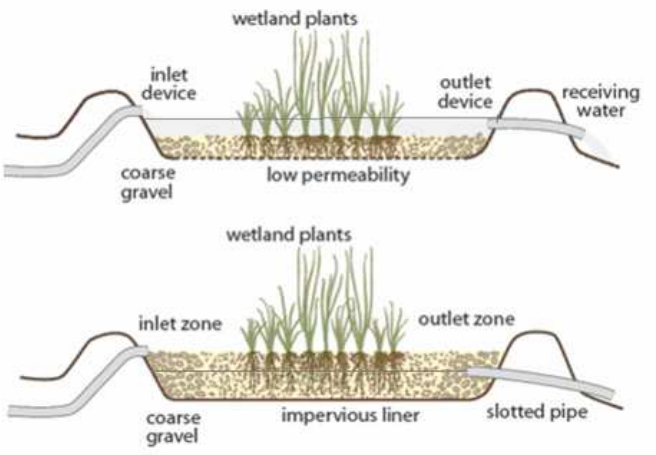

Figure 2.2 Type of constructed wetland (a) free water surface (b) Subsurface flow (Sa'at, 2006).

2.2 History and presentation of constructed wetlands

Pollutant removal in constructed wetlands is a function of several physical, chemical and biological processes. The biological microbial processing drives the removal of organic matter and nitrogen. The microbial transformations involved generation of greenhouse gases: carbon dioxide, nitrous oxide, and methane. Green house gases production in constructed wetland systems deserve increasing attention as the area covered by them increases. Constructed wetlands lose their treatment capacity when they are overloaded for an extended time period (Hoffmann and Winker, 2011). Results obtained by several authors regarding constructed wetlands are presented in Table 2.1.

Table 2.1 Comparison between different constructed wetland setups

Comparison between different constructed wetlands							
Constructed wetland type	HSSFCW	HSSFCW	HSSFCW	HSSFCW	Up-flow constructed wetland	HSSFCW	HSSFCW
Dimensions	3.5, 0.8, 0.8 deep	1.3, 0.5 and 0.4m	1.3, 0.5 and 0.4m	0.45, 0.54, 0.15m	70x18 cm	(10,20, 0.8) for HSSFCW	length: 70cm , 40 cm depth
Aeration					aerated		
Media	coarse sand	Gravel	zeolite	sandy loamy soil with compost	gravel	Gravel	volcanic tofa
Wastewater type	grey water	Agricultural wastewater	Agricultural wastewater	municipal wastewater	industrial waste water	Domestic wastewater	Domestic wastewater
Flow rate	0.48 m3/days	0.078m³/d	0.078m³/d		1.04 ml/min	$17m^3$/	26 l/day
Hydraulic retention time	15 days HRT	1.2 d	1.2 d	5days	3	3days	5 days
DOC				72%			
BOD	72-79%					85.40%	
COD	72-79%				94%	42.70%	71.80%
SS	72-79%						92.90%
Fecal	72-79%						
Grease	72-79%						
Nitrogen	34-53%				69%	TN: 7.1%	
NH4-N				95%	98%		63.80%
NO3		82%	86%		45%		
TKN				62%			
phosphate	34-53%	89%	93%	72%, (TP: 52%)	TP :43%	38%	
E.coli (logFU/100ml)						0.35	
Reference	Niyonzima (2007)	Sarafraz (2009)	Sarafraz (2009)	Chung et al.(2008)	Ong *et al*., 2010	Ghrabi et al., 2011	Avsar et al.,2007

Oxygen and Carbon availability controls the rate of methanogenesis. The Factors regulating the oxygen delivery to the wetland matrix are critical in controlling green house gases emissions in constructed wetlands. Also, nitrous oxide production is a function of O2 and C, as it is a by-product of nitrification and denitrification, a chemo-autotrophic aerobic and an anaerobic heterotrophic microbial process, respectively. Plant presence may reduce or increase CH4 fluxes (Landry *et al.*, 2009).

Landry *et al.* (2009) identified the effects of three species of macrophytes (Phragmites australis, Typha angustifolia, Phalaris arundinacea) and artificial aeration on the variation of greenhouse gases production (Nitrous oxide) over three different seasons using experimental constructed wetland. They found that total nitrogen removal was higher in summer and in planted and aerated units, with the highest mean removal in units planted with Typha angustifolia. Export of ammonium was higher in winter and in unplanted and non-aerated units. Planted and aerated units had the highest export of oxidized nitrogen. Also, results showed that denitrification was the main nitrogen sink in most treatments accounting for 47–62% of TN removal, while sediment storage was dominant in unplanted non-aerated units and units planted with P. arundinacea. Plant uptake accounted for less than 20% of the removal. They concluded that greenhouse gases fluxes were higher in unplanted and non-aerated treatments and during the summer. In addition, the addition of artificial aeration reduced CH4 fluxes and CO2-equivalents.

Niyonzima (2007) designed and operated a Horizontal Sub-surface Flow pilot-scale constructed wetland on the Kwame Nkrumah University of Science and Technology (KNUST) Kumasi, Ghana. The study was carried out in a sedimentation tank of 3.65 x 0.65 x 0.4 m deep and a Horizontal Sub-surface constructed wetland of 3.5m x 0.8m x 0.8m deep. The grey water flow rate of (0.48) m^3/d was flowed through vegetated wetland and sandy pilot plant. The filter media consisted of 0.6 to 2 mm of coarse sand, 368.78 cm^3/d of hydraulic conductivity and cattails (*Typha latifolia spp)* were used as plants species. The

effluent flow rate of the plant was 0.327 m^3/ day and the retention time was 15hrs. 72% to 79% of BOD, COD, SS, Grease, and Faecal Coliform removal were achieved, while the nutrients (Nitrogen and Phosphate) removal was the range of 34% to 53%.

Sarafraz (2009) examined the performance of four horizontal subsurface flow wetlands which were constructed at the Research Station of Tehran University, Iran. Gravel and *zeoilte* were used in this study as substrate. The results indicated that the system had acceptable pollutant removal efficiency. The examined system achieved the NO_3-N removal of (79%) in Planted wetland with zeolite substrate (ZP), (86%) in zeolite constructed wetlands (Z), (82%) in planted wetland with gravel bed (GP) and finally (87.94%) in gravel bed (P) wetlands. Results for P removal were 93, 89, 81 and 76% were respectively achieved for ZP, GP, Z and G. Moreover, results showed that constructed wetlands are efficient in removing Zn, Pb and Cd from agricultural wastewater. Plants types such as Phragmites Australis and *Juncus Inflexus* can contribute in treating wastewater, while *Zeolite* and gravel materials provide a suitable plant growth medium to replace conventional sand and gravel substrates.

Ong *et al.* (2010) found that the organic matter and NH_4-N removal efficiencies in the aerated wetland reactors were better than the non-aerated wetland reactors. The supplementary aeration has enhanced the aerobic biodegradation of organic matter and nitrification.

Vymazal (2009) evaluated the treatment performance of Constructed wetland Ondrˇejov in Czech Republic and constructed wetland in Spalene Porici near Pilsen in western Bohemia, these systems were operated over a period of 15-year**.** The first wetland consisted of a horizontal grit chamber, Imhoff tank and a single 806 m² bed filled with gravel (3–15 mm) and planted with common reed. It is designed for 362 PE, and the average measured flow over the monitored period was 56.3m³/d. The second wetland consisted of Vortex-type grit chamber, Imhoff tank and four beds (2500m² total area, 625m² each) filled with gravel (2–4 mm) and planted with P. australis and reed canary grass (Phalaris arundinacea) planted in bands perpendicular to water flow. Both constructed wetlands were sampled for BOD5, COD, TSS, TP, ammonia-N, and TN; CW Ondrˇejov was also sampled for nitrate-N and TKN**.** Also, aboveground biomass was sampled during the peak standing crop. Results for Constructed wetland Ondrˇejov showed that removal of phosphorus is steady but low with average raw, inflow and outflow concentrations of 11.6 mg/l, 10.1mg/l and 7.0 mg/l, respectively. Also, average BOD_5 raw, inflow and outflow concentrations were as follows, 192 mg/l, 157 mg/l and 18 mg/l, respectively. For the other wetland, the annual average inflow BOD_5 concentrations were mostly < 30 mg/l. The average inflow BOD_5 concentrations were 24.5 mg/l and 122 mg/l in the first and second periods, respectively. The corresponding outflow concentrations were 4.2 mg/l and 10.3 mg/l.

Plant uptake could account for less than10% of nitrogen removal and denitrification seemed to be the dominant process removing nitrogen within a wetland. Lin *et a.,* (2001) compared waste material from coal refuse, fly ash soil

and gravel as a growth substrate for a constructed wetland planted with vetiver grass and receiving landfill leachate. Results showed that cinder substrate treatment showed the best performance in removing COD, NO_3-N and TSS. While the coal refuse treatment showed best performance in removing NH_4 +-N and TP. However, fly ash and soil showed a low hydraulic conductivity and poor pollutant removal performance. Also, they concluded that, the factor controlling denitrification is the C: N ratio. So that, to achieve a much better removal efficiency of nitrate, the ratio of C: N - 5:1 is a must. NO_3-N removal efficiency increased with additional sawdust concentration.

Kimwaga *et al.* (2003) introduced an alternative approach of improving further the waste stabilization ponds effluent by coupling them to Dynamic Roughing Filters and Horizontal Subsurface Flow Constructed Wetlands. They found that a coupled Dynamic Roughing filters and HSSFCW gave the fecal coliform concentrations of 790 FC/100ml suggesting that effluents guidelines of less than 1×10^{3} FC/100ml would be met for restricted irrigation without endangering the health of both farmers and the end users of the irrigated crops.

Mantovi *et al.* (2003) evaluated the performance of two horizontal subsurface flow reed beds treating dairy parlor effluent and domestic sewage. Removal of suspended solids and organic load constantly remained at levels above 90%, while those of the nutrients N and P were about 50% and 60%, respectively. The total number of coliform bacteria and Escherichia Coli was reduced by more than 99% and faecal streptococci by more than 98%. Nitrates, chlorides, sulfates, anionic

and non-ionic surface-active agents and heavy metals were detected only in low concentrations.

Luederitz *et al.* (2001) compared the purification performances of constructed horizontal flow wetlands and vertical flow wetlands including a small horizontal flow wetland, a sloped HFW, larger HFW, a stratified vertical flow wetland and an unstratified VFW. Results showed that both the horizontal flow and vertical flow systems can remove more than 90% of organic load and of total N and P, if there is a pretreatment step, and if the specific treatment area is great enough (50 m^2/m^3 per d). HFWs have an advantage in long-term removal of P because it is bound to organic substances to a high degree.

The effect of six experimental hydraulic retention times in subsurface flow constructed wetlands was examined by Chazarenc *et al.* (2003). They found that the major factor affects HRT was evapo-transpiration. Also, they examined the influence of flow paths on the efficiency of wastewater treatment in constructed wetlands.

Ghrabi *et al.* (2011) monitored the performance of wastewater treatment plant in Tunisia for three months. It is consisted of one imhoff tank, HSSFCW, subsurface vertical flow CW and horizontal flow CW. The removal efficiencies from the SSFCW equal to 85.4% for Biological oxygen Demand, 42.7 % for chemical oxygen demand, 7.1% for total nitrogen and 38.08 % for P-PO4.

One of the best methods for determining and analyzing constructed wetland flow paths is using the evaluation of hydraulic residence time (HRT) distribution by the

impulsion tracer method. This method is usually employed for determining non-ideal flow in chemical reactors. The resulting HRT distribution gives information about mixing and dispersion in a given filter. Two ideal reactors are commonly used: the plug flow reactor (PFR) and the continuous flow steady-state reactor (CFSTR).

The saturated flow of a constructed wetland has non-ideal flow behavior. Chazarenc *et al.* (2003) determined the practical HRT for SSFCW with the classical method of a stimulus-response experiment. They aimed to compare hydraulic behavior variations, due to season, with inflow characteristics. The use of classical models gave a first approach of the dispersion and mixing levels in the reed bed. The presence of plants improved the flow by creating connection between the surface and rhizosphere. Influence of precipitation or snow melt have a direct influence on treatment performances and general flow paths. Evapotranspiration is more beneficial and seems to improve all performances. They concluded that, at the filter inlet, mixing zones and a wide centered effluent injection is recommended to prevent dead volumes from occurring.

Stefanakis *et al.* (2011) examined the effect of wastewater step feeding (the gradational inflow of the wastewater into the wetland, the wastewater inflow at more than one input points along the wetland length) on the performance of pilot scale horizontal subsurface flow constructed wetlands operated for 3 years planted with common reed. During the first two years of operation, one inflow point was

used at the upstream end of the unit. During the third year of operation, wastewater step-feeding was adopted. Wastewater was introduced to the unit through three inlet points: one at the upstream end of the unit length and the other two at 1/3 and 2/3 of the unit length. Two wastewater step-feeding schemes were examined during the second working period: 33%, 33%, 33% and 60%, 25%, 15%. Three HRTs (6, 8 and 14 days) were applied. Results showed that the removal of organic matter (BOD5 and COD), TKN, ammonia and phosphorus (Total Phosphorus and ortho-phosphate) was improved under the step-feeding Scheme 60:25:15, while the other scheme affected negatively the wetland performance.

Step-feeding makes it possible to utilize more effectively the whole wetland surface area by distributing suspended solids and organic loading in the influent along a greater portion of the wetland. Also, it helps avoiding rapid clogging of the substrate; avoid influent overloading, expansion of the useful life time of the substrate material and results in better aeration of the Wastewater (Stefanakis *et al.*, 2011).

Results showed that for conductivity and pH there is no significant variations during the stage operated with step-feeding. For DO, seasonal variations occurred with higher values during the winter, when oxygen solubility in water is higher, and lower values during the summer. It seems that the step-feeding application did not alter dramatically the behavior of the physicochemical parameters (Stefanakis *et al.*, 2011).

Zurita *et al.* (2009) investigated four commercial-valuable ornamental species (*Zantedeschia aethiopica*, *Strelitzia reginae*, *Anturium andreanum* and *Agapanthus africanus*) in two types of subsurface wetlands (Horizontal and Vertical wetlands) for domestic wastewater treatment. Several water quality parameters were evaluated at the inlet and outlets of a pilot-scale system. The results for pollutant removal were significantly higher in the vertical subsurface-flow constructed wetlands for most pollutants. The average removals were more than 80% for BOD and COD; 50.6% for Org-N; 72.2% for NH4+, 50% for Total-P and 96.9% for TC. Nitrate (NO3) and Total suspended solids (TSS) were removed in higher percentages in the horizontal subsurface-flow constructed wetlands (NO3, 47.7% and TSS, 82%). Also, the study showed that it is possible to produce commercial flowers in constructed wetlands without reducing the efficiency of the treatment system.

2.3 Comparison of subsurface flow constructed wetlands with vertical flow constructed wetlands

Larger surface area of horizontal flow constructed wetlands made increase the water loss due to evapo-transpiration. Vertical flow beds are preferable to horizontal flow beds because they have an unsaturated upper layer in the bed and a shorter retention time than horizontal flow beds (Hoffmann and Winker, 2011).

2.3.1 Advantages of VFCW

- Vertical flow constructed wetlands systems can achieve higher oxygen transfer rate as wastewater percolates through the wetland by gravity and this enhances aeration and the microbial activity.

- They are used to achieve more intensive oxidation of ammonia.
- These systems were used for treating municipal and domestic, industrial, dairy and oil refinery wastewater.
- In the case of municipal wastewater mean removals reach 95% for BOD5 and suspended solids, 90% for TKN and more than 50% for phosphorous (Stefanakis and Tsihrintzis, 2009).

2.3.2 Disadvantages of VFCW

- Inadequate removal of phosphorous may be achieved due to inadequate contact time between the wastewater and the substrate (Stefanakis and Tsihrintzis, 2009).

The typical hydraulic loading rates for CW range from 10-20 m/year for secondary treatment and 50-100 m/year for tertiary treatment. Different loading rates are applied depending on the type of constructed wetland. In general, constructed wetlands have proven to be very efficient in removing organic matter (>90%), solids (>90%) and pathogens (3-4 log units). But nitrogen (40-60%) and phosphate removal (20-40%) reach medium levels (Stefanakis and Tsihrintzis, 2009).

According to Stefanakis and Tsihrintzis, (2009) ten pilot scale vertical flow constructed wetland units were constructed and operated for one year. Each unit has its settings (substrate thickness, porous media, ventilation tubes and vegetation). The unit with the thickest substrate material and the existence of fine material resulted in significant removal efficiency for all pollutants (organic matter, nitrogen and phosphorous). Pollutant removal efficiencies in all units were

dependent on temperature and seasonal variation. Also, the presence of ventilation affects the removal of these pollutants positively. The vegetation improved the nutrient removal rates while cattails contributed to nitrogen removal.

Preceding the horizontal subsurface flow constructed wetlands with a vertical flow filter increases organic matter and total nitrogen removal. But, vertical bed requires more careful construction and operation (Plamondon, et al., 2006).

2.4 Comparison of subsurface flow constructed wetlands with ponds

Ponds are difficult to integrate in urban areas due to their open water surface, mosquitoes and odour. On the other hand, ponds are easier to design and construct and they do not need a substrate and have lower capital costs for large-scale plants. Constructed wetlands have significantly lower operation and maintenance costs compared to high-rate aerobic processes for energy use and operator time. For large scale treatment plants of more than 10 000 person equivalents in areas where land is available cheaply, ponds have lower capital costs than constructed wetlands (Hoffmann and Winker, 2011).

2.5 Horizontal Subsurface Flow Constructed Wetlands

2.5.1 Design parameters

Constructed wetland design may be based on several models such as rules of thumb and regression equations, the first-order k - C model, Monod-type equations and complex dynamic, compartmental model. Rules of thumb are the fastest but it's the roughest design methods. They are based on observations from a wide range of systems, climatic conditions and wastewater types. Rules of

thumb show a large variation and uncertainty. Regression equations are a useful tool in applying input–output I/O data. However, important factors such as climate, bed material, bed design, etc. are neglected, leading to a wide variety of regression equations and thus a large uncertainty in the design. Most of the regression equations rely on wastewater concentrations. Where only a limited number of regression equations rely on both influent concentration and HLR as inputs to predict the effluent concentration (Rousseau *et al.*, 2004).

Constructed wetlands requires a low hydraulic loading rate and a long HRT to achieve efficient pollutant removal taking in consideration the fact of a lack of criteria to define what is meant by high or low HLR. Chang *et al.* (2007) examined the effect of increasing hydraulic loading rate on the removal rate of several pollutants in a vertical flow constructed wetland fed with agricultural and domestic wastewater. They found a slightly increase in removal rate for ammonia as a result of increasing HLR from 200 to 1200 ($L/m^2/d$). On the other hand, for COD and TP the removal rates decreases with 16 and 27%, respectively. For BOD removal rates there were no change.

Major drawbacks of the first-order models are that equations are based on the assumptions of plugflow and steady-state conditions. However, small scale wastewater treatment plants under which most treatment wetlands can be ranged are subject to large influent variations whereas the larger ones are subject to hydrological influences thus causing in both cases non steady-state conditions. Short-circuiting and dead zones are common phenomena in constructed treatment wetlands causing non-ideal plug-flow conditions. The rate constants vary

according to the influent concentrations, the HLR and the water depth. Another impossibility of the first-order model is the fact that the removal rates continue to increase with increasing loading rates (Rousseau *et al.*, 2004).

a) Pretreatment

Subsurface flow constructed wetlands are primarily designed for secondary or tertiary treatment of wastewater proceeded by a septic tank as a pre-treatment step. This step removes most solids (measured as Total Suspended Solids) which settle to the bottom and are degraded by anaerobic bacteria (Hoddinott, 2006).

The major removal mechanisms of suspended solids in constructed wetlands are filtration and sedimentation. Pretreatment is essential because high concentrations of suspended solids may speed up the clogging process in the beds resulting in lower treatment efficiency. The average removal of suspended solids in the Czech constructed wetlands amounts to 84.3% with the average effluent concentration of 10.2 mg/l (Vymazal, 2002).

Suspended solids that are not removed in pretreatment system are effectively removed by filtration and settlement. The accumulation of trapped solids is a major threat for good performance of horizontal flow systems as the solids may clogg the bed. Therefore, the effective pretreatment is necessary for HF systems (Vymazal, 2005).

b) Surface area and bed configuration

A simple formula to determine the surface area of the wetlands given by Vymazal has resulted in a general rule of thumb for total area of cells of 4.64 m² (50 ft²) per PE (Hoddinott, 2006).

Kickuth proposed the following equation which was used for sizing of horizontal subsurface flow systems for domestic sewage treatment (Vymazal, 2005):

$$Ah = Qd(ln\ Cin - ln\ Cout)/KBOD$$

Where:

*A*h is the surface area of the bed (m^2),

*Q*d the average flow (m^3/day),

*C*in the influent BOD_5 (mg/l),

*C*out the effluent BOD_5 (mg/l)

and *K*BOD is the rate constant (m/day).

The field measurements showed that the value of *K*BOD is usually lower than 0.19 m/day. Rate constant is increased with hydraulic loading rate and BOD_5 mass loading rate. The average *K*BOD value for 66 village systems after 2 years of operation was 0.118 ± 0.022 m/day (Vymazal, 2005).

Cross sectional area for the bed can be calculated using Darcy's Law: (Converse, 1999)

$$Ac = Q / (KsXS)$$

Where:

Ac = cross sectional area of bed (m^2)

Q= design flow (m^3/d)

K_s = hydraulic conductivity (259 $m^3/d/m^2$ for gravel)

S = hydraulic gradient (0.01 – 0.02 for 1% and 2% bottom slope)

CW design has been mainly based on rule of thumb approaches using specific surface area requirements or simple first order decay models. It have been reported that first order models are inadequate for the design of treatment wetlands (Langergraber, 2008)

c) Aspect Ratio

The aspect ratio is the length to width ratio and it is calculated from Darcy's Law.This ratio has been considered to be of critical importance in maintaining adequate flow through the wetland (Hoddinott, 2006).

$$Ac = Qs/(Kf(dH/ds))$$

Where:

A_c: cross sectional area of the bed (m^2)

Q_s: average flow (m^3/s)

K_f: hydraulic conductivity of the media (m/s)

dH/ds: slope (m/m)

Czech constructed wetlands are designed with an aspect ratio of less than two to achieve a wider inflow rather than a long, narrow bed. This optimizes flow and avoids clogging of the inlet. Clogging is minimized by using larger gravel at the inlet. On the other hand, experiments in Spain indicate that aspect ratio is not a critical element in bed flow mechanics as previously thought. This conclusion for the warm weather of Spain may not necessarily apply to colder climates; because warm climate constructed wetlands sometimes have a high rate of water loss through evapotranspiration which can change flow characteristics (Hoddinott, 2006).

d) Depth and Bottom Slope

The (0.6-0.8) m depth of Czech beds was derived from the maximum depth of the Macropites root of the frequently used common reed. When coarse filtration materials are used, the wetlands beds have a slope of less than 2.5%. Recently, slopes are less than 1% with the use of finer gravel. A water depth of (0.27) m yields the best removal efficiencies in a bed (0.6 -0.8) m deep. The improved efficiency of shallower water depth was directly related to increased oxygen flux from the plants resulting in much higher rates of nitrification/denitrification. The downward pull of surface water by plant roots assured adequate mixing of water in deeper beds. Taking in consideration that almost all of the aerobic processes occur within 35 mm of the plant roots. A minimal bottom slope is necessary if substrate with suitable flow characteristics is used (Hoddinott, 2006).

e) Filtration Media

In constructed wetlands, soil materials that facilitate the plant growth and providing high filtration effect must be used. But they were deficient in maintaining high hydraulic conductivity. The use of (10) mm gravel has fulfilled these requirements. Many studies showed that coarser gravel at the inlet and outlet helps prevent clogging (Hoddinott, 2006).

Suliman (2007) examined the effect of packing patterns using the four filling strategies. They found that dividing the constructed wetland into several sections when filling the filter medium into the constructed wetland basin will improve the treatment efficiency. The filling strategies were based on dividing the constructed wetland into several sections prior to filling the filter medium into the constructed wetland.

Filtration beds of subsurface horizontal-flow constructed wetlands are generally considered as anoxic or anaerobic. So that, it is assumed that the outflow concentration of dissolved oxygen is usually very low (<2 mg/l). However, some systems provided relatively high concentration of DO (>5 mg l−1) (Vymazal and Kröpfelová, 2008).

f) Sealing the bed

Most countries including USA require sealing with plastic liners between 0.8 and 2.0 mm thickness. These liners must be protected on both sides by geotextile or sand to prevent root penetration and damage by sharp edges. Clay liners were used in early Czech and North American constructed wetlands. The sealing of the

bed allows constructed wetlands to be placed in areas with relatively high water tables where drain fields cannot function (Hoddinott, 2006). The fine-grained soils always show better nitrogen removal through adsorption than the coarse-grained soil. This can be explained by the higher cation exchange capacity of the fine-grained soils (Vymazal, 2005).

g) Vegetation

The plants of constructed wetlands are an essential part of a constructed wetland. They serve as a habitat for animals like birds and frogs, and act as a local "green space" (Hoffmann and Winker, 2011). There are three types of wetland plant which is floating plant, emergent plant and submerged plant as shows in Figure 1. Pretreatment may be necessary to ensure vegetation survival where these plants have an acceptable range of water quality. The plants used in constructed wetlands should be tolerant to high organic and nutrient loadings and have rich belowground organs (roots and rhizomes) in order to provide substrate for attached bacteria and oxygenation of areas adjacent to roots and rhizomes (Sa'at, 2006).

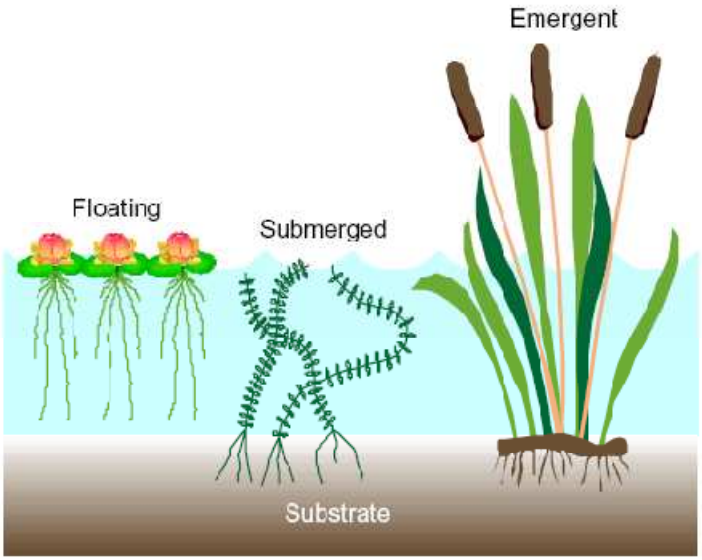

Figure 2.3 Types of Wetland Plants (Sa'at, 2006).

The most frequently used plant in horizontal flow subsurface flow around the world is *Phragmites australis* (common reed). Other species frequently used are *Phalaris arundinacea* (reed canarygrass), *Glyceria maxima* (sweet managrass), *Typha* spp.(cattails) and *Scirpus* spp. (bulrush) (Sa'at, 2006).

Nitrogen and phosphorous are key nutrients in the life cycles of weland plants. Therefore, the proper nitrogen and phosphoros availability are of principle concern in the growth of wetland plants in constructed wetlands (Ong et al., 2010).

The plants chosen for constructed wetlands are usually metal tolerant, fast growing, and of high biomass, such as Phragmites australis and Typha latifolia. Many wetland plants could colonize both uncontaminated and heavily metal-polluted areas. Some wetland plants have the ability to take up> 0.5% dry weight

of a given element and bioconcentrate the element in its tissues to 1000-fold the initial element supply concentration. For example, duck weed (Lemna minor) and water hyacinths (Eichhornia crassipes) are excellent accumulators of Cd and Cu. Other wetland plants can tolerate high concentrations of several metals in their tissues, which do not show negative effects on plant growth (Yang and Ye, 2009).

Plant growth can contribute to reduce nutrients. The reduction of ammonia and phosphate from domestic wastewater by growing plants is about 10-20% (during the vegetation period) (Hoffmann and Winker, 2011)

Reed beds have high efficiency in reducing the total amount of sludge; the much higher quality of the final product and the very long sludge retention times (7 – 10 years), there has been built an increasing number of sludge treatment plants. The use of sludge drying reed beds has been a real success for years (Platzer, 2000).

Sirianuntapiboon and Jitvimolnimit (2007) found that subsurface flow constructed wetland system with both mono- and mixed-cultures of *T. latifolia* and *C. siamensis* could be applied to treat domestic wastewater with high SS, BOD5 nitrogen and phosphorus removal efficiencies of about 90, 90, 85 - 88 and 85 - 90%, respectively under HRT of 6 days. The SFCW with mixed culture was most suitable to apply for the treatment of wastewater under high organic loading of 15.71 g/m²-day according to the ammonium- N_2 and total phosphorus removal efficiencies of 88.3 % and 90.0%, respectively.

Several processes are effective in pollutant reduction: phytoextraction, phytostabilization, transpiration, and rhizofiltration. Vegetation provides several storage and reduction mechanisms.

- Phytoextraction refers to plant uptake of toxicants. Metals are taken up by plants, and may be stored in the roots and rhizomes. The plant need to be harvested frequently and processed to reclaim the metals.
- Phytostabilization refers to the use of plants as a physical means of holding soils and treated matrices in place. It relates to sediment trapping and erosion prevention in those systems.
- Wetland plants possess the ability to transfer significant quantities of gases to and from their root zone and the atmosphere. Stems and leaves of wetland plants contain airways that transport oxygen to the roots and vent water vapor, methane, and carbon dioxide to the atmosphere. The dominant gas outflow is water vapor, creating a transpiration flux upward through the plant. Rhizofiltration refers to a set of processes that occur in the root zone, resulting in the transformation and immobilization of some contaminants. Plants help create the vertical redox gradients that foster degrading organisms (Sa'at, 2006).

Different plant species could influence nitrogen removal through variation in rates of oxidation of the wetland matrix, supply of labile carbon and transpiration. Also, different plant species can respond differently to seasonal changes and artificial aeration (Landry *et al.*, 2009).

Macrophytes stabilize the surface of beds, provide good conditions for physical filtration, insulate against frost during winter, and provide surface area for attached microbial growth. The flow of water in horizontal subsurface flow is intended to be subsurface through channels created by the living and dead roots and rhizomes as well as through soil pores. Also, when roots and rhizomes die and decay, they may leave behined tubular pores and macropores (Vymazal, 2005).

The oxygen flux from the plant is important for nitrogen removal. Oxygen flux fell off rapidly after 35 mm from the root, so plants with rhizosomes wider apart than that will not be as efficient in nitrogen removal. Allen showed that all plants enhanced treatment capacity of SSFCWs compared to unplanted (Allen *et al.*, 2002).

The plants have an important role in the treatment process. They provide an appropriate environment for microbial growth and improve the transfer of oxygen into the root zone which is part of the filter bed. In moderate climate zones dead plant material provides an insulation layer, which has a positive effect for the operation of subsurface flow constructed wetlands in winter (Hoffmann and Winker, 2011)

Reed grows commonly in the West Bank and it is particularly abundant in and around streams that carry waste water. The treatment wetlands already constructed in the West Bank have all used reed as wetland vegetation (Khalili, 2007).

h) Treatment Efficiency

Constructed wetlands could act as primary buffers between pollution sources and adjacent aquatic ecosystems. Constructed wetlands are more complex than conventional treatment processes due to the diffusive flow and the large number of processes involved in wastewater degradation. So that, removal efficiency is less easily predictable with the influence of these varying hydraulics and with the influence of internal environment (Hoddinott, 2006).

There are many factors that can influence the performance of constructed wetlands such as hydraulic properties, temperature, vegetation, wind, shape of the system, inlet–outlet configuration, width-to-length ratio, depth and baffles. Reduced treatment efficiency can occur when wetlands are constructed without considering the influence of the filter medium heterogeneity on the hydraulic parameters and the hydraulic performance of the system. The heterogeneity in the hydraulic parameters of the filter bed can lead to non-uniform flow patterns and dispersion that will cause variations in the hydraulic retention time and poor treatment efficiency (Suliman *et al.,* 2007).

Vymazal and Kröpfelová (2008) concluded that dissolved oxygen concentration at the effluent of horizontal subsurface flow does not provide good information about the processes occurring in the filtration beds. They focused on nitrification and sulfate-reduction as processes occurring under strictly aerobic and anaerobic conditions, respectively. The obtained data showed that in systems with very low outflow concentrations of dissolved oxygen, nitrification was frequently very limited but in some systems a substantial reduction of ammonia occurred. Also,

several systems with relatively high effluent oxygen concentrations provided nearly zero removal of ammonia. For sulfate, high effluent oxygen concentrations were sometimes connected with high reduction of sulfate. But, low effluent oxygen concentrations were not connected with sulfate reduction.

Nitrogen processing in constructed wetlands is often variable. Landry *et al*. (2009) examined the effect of artificial aeration and type of macrophyte on nitrogen loss and retention. They found that removal of total nitrogen was higher in summer and in planted and aerated units, with the highest mean removal in units planted with T. angustifolia. Also, denitrification was the main nitrogen sink in most treatments accounting for 47–62% of total nitrogen removal, plant uptake accounted for less than 20% of the removal while sediment storage was dominant in unplanted non-aerated units and units planted with P. arundinacea.

The horizontal flow constructed wetlands can provide a reliable secondary level of treatment with regard to biochemical oxygen demand and total suspended solids. These systems are less effective for nitrogen removal unless a longer hydraulic retention time and enough oxygenation are provided (Zurita *et al*., 2009).

Nitrogen removal rates reported for horizontal subsurface flow constructed wetlands are variable, ranging from high removals of over 90% to removals as low as 11%. Nitrogen retention in constructed wetlands is thought to occur by ammonification, followed by nitrification (Landry *et al*., 2009). Nitrification is usually the limiting step of nitrogen removal in horizontal subsurface flow constructed wetlands, as it is an aerobic chemo-autotrophic microbial process and

oxygen diffusion is limited in these systems. Oxygen must be provided to the nitrifying microbes through oxygenation of the wetland with the presence of plants in order to enhance nitrogen removal efficiency. Plants provide oxygen to the rhizosphere via passive or active oxygen transport through their stems from the atmosphere to the roots. Aerated constructed wetlands have higher nitrogen removal rates than non-aerated wetlands. Nitrification is a temperature dependent process and it depends on season and become inhibited below 10°C, reducing the efficiency of constructed wetlands in colder climates (Landry *et al*., 2009).

The mechanisms involved in nitrogen removal in constructed wetlands include volatilization, ammonification, nitrification/denitrification, plant uptake, and matrix adsorption. Ammonification and nitrification/ denitrification are the major nitrogen removal mechanisms. Low rate of nitrification are achieved in horizontal subsurface flow wetlands due to anoxic, anaerobic conditions in the wetlands (Vymazal, 2002).

Denitrification can be limited in constructed wetlands by lack of carbon, lack of excessive oxygenation. Estimations of denitrification rates remain difficult, as direct (stable isotopes, acetylene blockage and membrane inlet mass spectrometry) and indirect measurements based on mass balance are often divergent. In general, denitrification accounts for more than half of nitrogen removal in constructed wetlands (Landry *et al*., 2009).

Plamondon *et al*. (2006) examined the effects of artificial aeration on the removal efficiency of horizontal flow constructed wetlands. They found that artificial

aeration enhanced total suspended solids removal. In winter, the reduction in COD removal in non-aerated wetlands compared to summer was totally compensated for in aerated wetlands, in both planted and unplanted units. Artificial aeration improved TKN removal in planted units, but to a lower extent than for unplanted units.

The performance of horizontal subsurface flow constructed wetlands for nitrogen and soluble organic matter which highly driven by biological activity may be reduced in winter where biological processes are temperature dependant. Lower winter temperatures, low oxygen availability are a common limiting factor in horizontal subsurface flow constructed wetlands during the growing season. Oxygen solubility is higher in colder water, but gas exchange in horizontal subsurface flow constructed wetlands may be reduced by the additional insulation layer (Plamondon *et al.*, 2006).

Plamondon *et al.* (2006) found that more than 95% of TSS was removed during the experiment regardless of season, presence of plant or aeration. There was no apparent difference in TSS removal between planted and unplanted wetlands as expected from a pollutant whose removal is mainly due to physical processes. On the other hand, there was a slight but significant improvement in TSS removal in aerated systems both in summer and winter. Also, COD removal was above 90% in all treatments except for unplanted non-aerated wetlands (88%). During summer, there was a slight improvement in COD removal in planted wetlands compared to unplanted, but no effect of artificial aeration, regardless of the presence of plants.

Factors that enhanced electron acceptor availability or root zone oxidation status can be at least as important as temperature in ensuring organic matter removal. When oxidation decreases, amount of residual inert organic matter accumulated increases and aggregates in filtration matrix, reducing HRT. Increasing oxygen availability with artificial aeration could enhance mineralization and reduce hydraulic clogging due to increased organic matter accumulation (Plamondon et al., 2006).

TKN removal in non-aerated units was significantly higher in planted wetlands than in unplanted ones, both in summer and winter. Artificial aeration improved summer TKN removal in unplanted wetlands but the additional aeration did not fully compensate for the absence of plants. TKN removal in winter was lower than in summer because of the lower winter temperature which was under optimal temperature for nitrifying activity. In winter, artificial aeration improved TKN removal for all wetlands. However, artificial aeration didn't compensate for the absence of plants. There was less soluble ammonia at outlet in aerated than in non aerated basins, both in summer and winter. There was no significant difference between NO3 content at outlet of planted and unplanted aerated beds, suggesting that there was no limitation of denitrification due to artificial aeration. Also, as with TSS and COD, there was no difference in TKN removal between common reed and cattail, suggesting that either plant species are equally efficient for horizontal subsurface flow constructed wetland..There was no difference in TKN removal between common reed and cattail for TSS and COD removal (Plamondon et al., 2006).

Organic compounds are degraded in horizontal subsurface flow constructed wetlands both aerobically and anaerobically. The numbers of aerobic heterotrophic bacteria in wastewater entering vegetated beds are higher than aerobic ones but anaerobic bacteria prevail in the out flowing water. As a result, that aerobic bacteria naturally die-off due to of unfavorable anaerobic or anoxic conditions during the passage through the filtration medium of vegetated beds (Vymazal, 2002).

Constructed wetland bed is the major long term phosphorous storage. The adsorption and retention of phosphorus in wetlands is controlled by the interaction of redox potential, pH value, Fe, Ca. Horizontal subsurface flow usually does not remove higher amounts of phosphorus from the wastewater because suitable conditions for phosphorus removal are lacking in these systems. The most important removal mechanisms are chemical precipitation and physico-chemical sorption, processes that are not temperature dependent. However, biological influences on P removal, which are temperature-dependent, are relatively unimportant. Field experience suggests that the amount of phosphorus which could be removed by harvesting accounts only for small percentages which usually less than 10% and in most cases less than 5% (Vymazal, 2002).

High microbial biodiversity, the low flow velocities, the heterogeneity of plant stocks and the redox conditions impede successful evaluation of the different transformation processes being responsible for achieving the total removal efficiency of the treatment wetland. Inhibition of beneficial microbial processes such as ammonium oxidation by sulphur compounds like H2S and also correlation

of sulphur dynamics and generation of greenhouse gases are known but insufficiently investigated (Wiessner, 2010).

The wetland system may influence the sulphur cycling by releasing oxygen and/or organics by the plant roots, and sulphur cycling can influence nitrogen removal and other removal processes in the wetland system due to the toxicity of reduced sulphur compounds, as well as carbon and oxygen competition. Redox processes of the sulphur cycle such as sulphate reduction influence the conditions for the biochemical processes, changing the pH and redox conditions, which in turn mobilize the fixed phosphate in the sediment for its use by plants and microorganisms. sulphide concentrations of 0.5 mg/l are known to be toxic for microbial nitrification. Studies on laboratory scale systems showed highly efficient sulphate reduction and indicated a correlation of sulphur transformation processes with nitrogen and carbon removal. The deposition of elemental sulphur inside constructed wetlands, the precipitation of heavy metals and metalloids such as arsenic may provide redox buffering or potential sources for further redox processes influencing the system (Wiessner, 2010).

Wiessner (2010) found that sulphate reduction occurred in laboratory scale planted wetlands and unplanted control units depending on the availability of organic carbon. The main part of the reduced sulphur was found to be immobilized inside the planted and unplanted gravel beds. Only small amounts of dissolved sulphide and thiosulphate were generated. Removal of organic carbon and ammonium was found to be more efficient inside the planted wetlands compared to the unplanted control unit.

The wastewater treatment plant located in Sakhnin (which treats water with conventional wastewater treatment technology i,e. anaerobic pond and facultative ponds) was redesigned and upgraded by adding six new constructed wetlands having different operating conditions at the end of the treatment plant. These wetlands were operated from August 2005 to February 2006. Avsar *et al.* (2007) found that the most appropriate constructed wetlands was that planted with Phragmites and with volcanic tufa as media material. The maximum removal efficiencies were 71.8% on COD, 92.9% on TSS, 63.8% on ammonia. Also, the phosphorus uptake capacity of plants increases with phosphorus load up to a concentration limit. Ammonium reduction was observed at low levels for all the constructed wetlands. Nitrogen uptake decreased with high concentrations and high loads in the wastewater.

Yang (2001) found that the removals of ammonia, nitrate, and soluble reactive phosphorus were related to three factors (presence of vegetation, medium types, and time period for the test). Also, they found that the main removal mechanism for ammonia was nitrification while nitrate was removed mainly by denitrification and plant uptake in vegetated systems. The main removal mechanism for soluble reactive phosphorus was chemical adsorption in the unsaturated soil bed systems. Also, the results showed that the subsurface flow gravel bed constructed wetland system with vegetation was the optimal one for the removal of total inorganic nitrogen.

Removal mechanisms of Horizontal subsurface flow constructed wetlands

Several physical, chemical and biological processes (microbial metabolic activity and plant uptake) take place in a wetland system. Physical-chemical processes such as sedimentation, adsorption and precipitation (Sa'at, 2006).

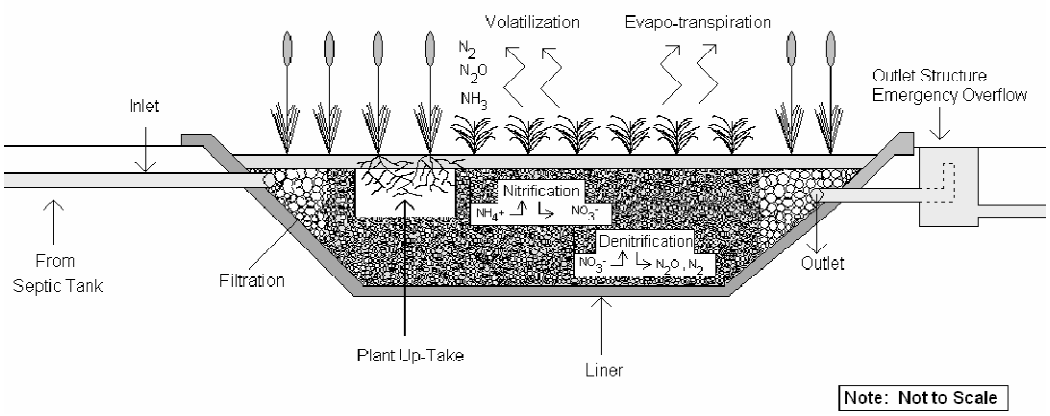

Figure 2.4 Process through the constructed wetland body (Sa'at, 2006).

As the wastewater flows through the constructed wetland cell, plants up-take the wastewater in a process called transpiration. This process will somewhat reduce the overall volume of wastewater. Lower portions of the constructed wetland cells do not receive enough oxygen to maintain aerobic conditions and become anaerobic. This zone will transform the nitrates (produced by the nitrification process), into compounds that are easily removed. Denitrification breaks those components down into nitrogen and nitrous oxide gas. These gases are then released into the atmosphere through a process called volatilization. Depending on the level of phosphorus removal desired, the constructed wetland may be designed to optimize its removal. Removal can occur by the adsorption of phosphorus to

the gravel media, precipitation of insoluble phosphates with ferric iron, calcium, and aluminum found in media, or small amounts will be absorbed by the constructed wetland vegetation. Fecal coliform reductions in the constructed wetland cell systems depend on the hydraulic residence time. Fecal coliform reduction in wastewater is attributed to natural die-off of the pathogens while passing through the media (State of Ohio Environmental Protection Agency (OHIOEPA), 2007).

Table 2.2 Overview of pollutant removal mechanisms (Sa'at, 2006)

Pollutant	**Removal Process**
Organic Material (measured as BOD)	biological degradation, sedimentation, microbial uptake
Organic Contaminants (e.g. pesticides)	adsorption, volatilization, photolysis, biotic/abiotic degradation
Suspended solids	sedimentation, filtration
Nitrogen	sedimentation, nitrification/denitrification, microbial uptake, plant uptake, volatilization
Phosphorus	sedimentation, filtration, adsorption, plant & microbial uptake
Pathogens	natural die-off, sedimentation, filtration, adsorption
Heavy metals	sedimentation, adsorption, plant uptake

Biodegradable Organic Matter Removal

Microbial degradation plays a main role in the removal of biodegradable organic matter. Plants in the constructed wetlands supply oxygen to the wetland ensuring the aerobic degradation of organic material. At the same time, anaerobic degradation of organic material takes place in the bottom sediments. Both free water surface and subsurface flow wetland function as attached growth biological reactor or known as biofilms. Biofilms are formed as microorganisms attach themselves to the plant and to the substrate. Wastewater is exposed to this biofilm when it passes through the wetland (Sa'at, 2006).

The removal of organic are generally very high in horizontal flow constructed wetlands. Aerobic degradation of soluble organic matter is governed by the aerobic heterotrophic bacteria. Also, ammonifying bacteria degrade organic compounds containing nitrogen under aerobic conditions. Heterotrophs are responsible for the reduction in the BOD_5 of the system because it has faster metabolic rate. Insufficient supply of oxygen to this group will greatly reduce the performance of aerobic biological oxidation. In most systems designed for the treatment of domestic or municipal sewage the supply of dissolved organic matter is sufficient and aerobic degradation is limited by oxygen availability. Nitrifying bacteria also utilize oxygen to cover their physiological needs. However, it is generally agreed that heterotrophic bacteria outcompete nitrifying bacteria for oxygen (Vymazal, 2005).

When oxygen is limiting at high organic loadings, anaerobic degradation will predominate. In the first step of anaerobic degradation, the primary end products of fermentation are fatty acids, such as acetic, butyric and lactic acids, alcohols and the gases CO_2 and H_2. Strictly anaerobic sulfate reducing bacteria and methane-forming bacteria then utilize the end-products of fermentation depend on the complex community of fermentative bacteria to supply substrate for their metabolic activities (Vymazal, 2005).

Suspended Solids Removal

Most of the solids are removed through sedimentation and filtration. Suspended solids removal is not a design variable in the normal sense, though solids accumulation must be considered during system design. A sedimentation pond is added prior to the wetland system to remove larger sediment and avoid clogging in the wetland (Sa'at, 2006).

Nutrients Removal

Considerable amounts of nutrients can be bound in the biomass. The uptake capacity of emergent macrophytes is roughly in the range 50 to 150 Kg P ha-1 year-1 and 1000 to 2500 Kg N ha-1/yr (Vymazal, 2005).

Reduction of nitrogen and phosphorus compounds requires the long detention times. Nitrification/ denitrification are the main removal mechanism for nitrogen. The Nitrosomonas bacteria oxidize ammonia to nitrite aerobically. The nitrite is then oxidized aerobically by Nitrobacter bacteria to produce nitrate. Nitrate is reduced to gaseous forms under anaerobic conditions (denitrification). Volatilization, adsorption and plant uptake play much less important role in nitrogen removal in horizontal subsurface flow constructed wetlands (Vymazal, 2005).

Nitrification which is performed by strictly aerobic bacteria is mostly restricted to areas adjacent to roots and rhizomes where oxygen leaks to the filtration media. Prevailing anoxic and anaerobic conditions offer suitable conditions for

denitrification but the supply of nitrate is limited as the major portion of nitrogen in sewage is in the form of ammonia (Vymazal, 2005).

Vipat *et al.* (2008) evaluated the treatment efficiency of a field scale constructed wetland. It was constructed in an area of 700 m^2 having 0.7 m depth and lined with clay and filled with gravels (0.7 cm to 2.5 cm diameter). The constructed wetland showed a removal of NH_4-N up to 78.6 and TKN 59%, organic nitrogen 67.5% where the turbidity removal efficiency ranges was (83.8 to 88.4%).

Phosphorus is stored in new constructed wetland sediments. Phosphorus removal can involve a number of processes such as adsorption, filtration, sedimentation, complexation/precipitation and assimilation/ plant uptake (Sa'at, 2006).

Phosphorus is removed primarily by ligand exchange reactions, where phosphate displaces water or hydroxyls from the surface of Fe and Al hydrous oxides. Gravel used in horizontal subsurface flow constructed wetlands does not contain great quantities of Fe, Al or Ca so that removal of phosphorus is generally low. Aerobic conditions are more favorable for P sorption and co-precipitation. Removal of nitrogen and phosphorus through plant harvesting removes small fraction of the phosphor content (Vymazal, 2005).

Metal Removal

The physiological reasons for heavy metal uptake in constructed wetlands depend on the plant species. In grey water and domestic wastewater heavy metals are not an issue, because their concentration is relatively low. On the other hand,

Industrial effluent could contain significant amounts of heavy metals depending on the industry type (Hoffmann and Winker, 2011).

Metals are removed in treatment wetlands by three major mechanisms (i) Binding to soil, sediments, particulates and soluble organic by cation exhange and chelation(ii) Precipitation as insoluble salts, principally sulfides and oxyhydroxides and (iii) Uptake by plants, including algae and by bacteria. The predominant removal mechanisms in the constructed wetlands were attributed to precipitation-absorption phenomena. Precipitation was enhanced by wetlands metabolism, which increased the pH of inflowing acidic waters to near neutrality. Trace metals have a high affinity for adsorption and complication with organic material and are accumulated in wetlands ecosystem. Plant uptake and microbial transformations may contribute to metal removal (Sa'at, 2006).

Reuse for irrigation

Subsurface flow constructed wetlands treat wastewater to a standard suitable for discharge to surface water or suitable for various reuse applications according to WHO guidelines. The design of the subsurface flow constructed wetlands depends on the desired effluent quality for disposal or reuse. The most common type of reuse is irrigation (Hoffmann and Winker, 2011).

Color aspects

The effluent from constructed wetland can have a yellow or brown color due to the presence of humic substances, such as humic acids which are a result of biological degradation of organic matter. This color may reduce the social

acceptance of wastewater reuse. Humic acids have a negative impact on disinfection processes with chlorine or UV radiation (Hoffmann and Winker, 2011).

Chapter Three

Material and methods

3.1 Introduction

Constructed wetland experimental setup was placed inside the campus of Birzeit University near the university wastewater treatment plant. During the research period, data was collected from the experimental constructed wetlands. Then the collected data was analyzed. The methods and experimental procedures used for data collection are explained below.

3.2 Preliminary Laboratory Tests

Sieve analysis and hydraulic conductivity of different gravel was carried out in order to determine the suitability of the filter medium to be used in constructed wetland. The gravel sieved between (12.5-19) mm gave a good flow and a reasonable hydraulic conductivity. The identification of plants species in the wetland were done by Technicians from the University where they confirmed that common reeds (*Phragmites*), was available. They have capacity to grow quickly and carry enough oxygen through their roots. Ten reed plants were planted into each constructed wetland at the beginning of the experiment but some of them dried up and died in the two weeks of operation. The death of reed in the initial stage did not affect the rapid increase of young plants during the experimental period. The constructed wetland was designed for influent flow rate of 0.36 m^3/day. The wetlands were constructed in 15/March/2010. Also, they were put in operation on the same day with influent water from Birzeit University treatment

plant effluent. This influent was used at the beginning of the experiment in order to provide an accessible and near influent source to irrigate the plants. After one month, one of the wetlands (S3) was continued to be irrigated with this type of treated wastewater but the other two system were fed with Al-Bireh teriary treated wastewater and Al-Mazra'a wastewater. Then, the systems were kept in operations with these influents for three weeks from the date of operation and then samples from influent and effluent were analyzed weekly for a limited set of parameters (COD, NH_4, NO_3, PO_4 and pH).

Photo 1 HSSFCW in operation, photo date (23/July, 2011)/ Birzeit University/ Palestine

3.3 Experimental Setup

3.3.1 Constructed wetland setup

Constructed wetland setup was used to simulate the removal efficiency of natural treatment system for organic matter. The pilot-scale constructed wetlands were operated outdoor under prevailing environmental conditions. The setup was constructed to suit the operation under three water types. This setup was made of stainless steel (60cm length, 45 width and 45 depth). Wastewater depth was 35 cm and gravel depth was 40 cm. There were three such setups to run the tests with different influent water quality at the same time. A valve to control the hydraulic loading rate under gravity was installed at the inlet point.

Waste water was collected from Al-Bireh wastewater treatment plan, Birzeit University treatment plant and Al-Mazra'a onsite treatment twice a week at least. These effluents were stored in refrigerator. The constructed wetlands were fed with wastewater daily using plastic containers which were cleaned every 10 days.

Photo 2 Small scale constructed wetland experimental setup, photo date (27/August/2011)/ Birzeit University/ Palestine

Photo 3 Small scale constructed wetland experimental setup, photo date (12/Sep/2011)/ Birzeit University/Palestine

Three horizontal subsurface flow Constructed wetlands were located inside the campus of Birzeit University, Palestine. Three tanks were used to store the effluent. The influent was distributed at the inlet of each system by gravity. At the outflow of each unit, there was a level control to keep the water level at 35cm from the base. Also, a graduated beaker was used to collect and measure the quantity of treated effluent being discharged daily. The three systems were filled with gravel (12.5-19 mm, porosity 0.4). The water table was kept 5 cm below the substrate surface. The effluents were artificially aerated by an air pump.

3.4 Design parameters

3.4.1 Flow pattern

All constructed wetland systems were designed as horizontal subsurface flow (HSF) systems.

3.4.2 Types of wastewater

Three types of treated waste water were used to feed the constructed wetland system. These types are:

1. Al-Bireh tertiary treated effluent
2. Al-Mazra'a anaerobically pre treated grey water
3. Birzeit University secondary treated effluent

3.4.3 Hydraulic retention time

Hydraulic retention time was monitored daily and kept around 1.3 days.

3.4.4 Aspect ratio

Aspect ratio (length: width ratio) must be less than 2 in order to distribute wastewater to as wide a profile as possible in order to avoid local clogging of the inlet zone.

Calculation of aspect ratio:

Volume = 0.6*0.45*0. 45*0.4 = **0.054** m^3

HRT = **1.3** days

Flow = V/HRT= **37.38** l/d

To account for evaporation Q= **38** l/d will be supplied to the system

Then,

Aspect ratio = length/ width = 0.6/0.45 = 1.33 <2 ok.

3.5 Measurement of water quality parameters

The treatment system began to operate at the beginning of March 2011 and the system was allowed to stabilize for two months. After this stabilization period, the wetlands were monitored for six months for all parameters presented in Table 3.1. The samples were collected weekly at the inlet and outlet of each wetland. Physical, chemical and biological water quality parameters were measured as described in the Standard Methods for the examination of Water and Wastewater (APHA, 2005).

Samples were filtered by 0.45µm membrane for dissolved organic carbon which was measured by the wet chemistry method on an OI Analytical Aurora 1030 TOC analyzer. For all the measured parameters composite samples which is

composed of three samples were taken at the inlet and outlet of each system. Water samples were taken for total phosphorus, NH_4, NO_3, and chemical oxygen demand (COD) after six week of operation. In 15/June/2011, samples were pre-filtered (Whatman 934-AH) for total suspended solids measurements (TSS) and filtered by 0.45µm membrane for DOC. $N\text{-}NH_4$ was measured using Nesselarization method. PO_4 was measured using Ascorbic acid method. COD was measured by the closed reflux colorimetric method (method#5220 D) and TSS was measured using the total suspended solids dried at 103–105 °C (method#2540 D). Temperature, pH and redox potential were measured using an YSI multi-probe (YSI model 556) in the piezometers.

3.5.1 Laboratory analysis

Analysis of several parameters was carried out at the Birzeit University Testing Laboratories, Birzeit, Palestine, except DOC which was analyzed in Jerusalem Company for medical products. Among the major anions, NO_3 was analyzed using Capillary Ion Analyzer (CIA) method. The methods used to analyze the other parameters are shown in Table 3.1.

During the experiment, new calibration curves were drawn each month or in the case at which new reagents were prepared.

3.5.2 Process conditions

a) Oxic conditions

Oxic conditions were maintained by aeration of influent water. During aeration dissolved oxygen concentration was maintained around 4 mg/l.

b) Hydraulic loading rate

Constructed wetlands requires a low hydraulic loading rate and a long hydraulic retention time to achieve efficient pollutant removal taking in consideration the fact of a lack of criteria to define what is meant by high or low HLR. Values of 135l/m^2/d, 1540 and 1950l/m^2/d were all considered by authors to be very high. Chang et al. (2007) examined the effect of increasing HLR on the removal rate at several pollutants in a vertical flow constructed wetland fed with agricultural and domestic wastewater. They found a slightly increase in removal rate for ammonia (variation range 10%) when increasing HLR from 200 to 1200l/m^2/d. But for COD and TP, the removal rate decreases with 16 and 27%, respectively. On the other hand, there was no change for BOD removal rate.

$$HLR = Q/A$$

Where:

HLR: hydraulic loading rate (m/d)

Q: flow (m^3/d)

A: Surface area of the constructed wetland (m^2)

HLR for the horizontal subsurface flow constructed wetlands fed with Q = 38 L/d and has a cross sectional area of (0.45 x 0.6) m^2 equals:

$$HLR = 0.038 / (0.45x0.6) = 0.14 \text{ m/d}$$

3.6 Analytical Method and Equipment

The methods, reagents and equipments used to measure different parameter during the study are presented below.

3.6.1 Measurement of physical parameters (EC, DO and pH)

The electrical conductivity and temperature of all effluent water was measured with conductivity meter. During measurement the probe of the meter was inserted in the sample, the sample was stirred to ensure uniform mixing and when stable reading obtained, the reading was recorded.

Dissolved oxygen was measured with the specific HACK HQ10 oxygen meter. The DO was measured in the lab immediately after taking the samples to limit the time at which the sample will be with contact with air as much as possible.

Measurement of pH was carried out by using Metrohm-691 pH meter which was calibrated prior to the measurement. Samples were collected in glass bottles from the influent and effluent. The samples were mixed with a magnetic stirrer to ensure uniformity. Then the meter probe or the electrode was immersed in the sample after rinsing it thoroughly by spouting de-mineralized water from plastic wash bottle. The stable final reading was then taken.

3.6.2 Chemical parameters

Biological Oxygen Demand, Chemical Oxygen Demand, Ammonia, Nitrate, Phosphate were measured according to Standard methods (APHA, 2005).

Ammonia (NH_4-N)

Measurements of ammonia were carried out by using Nesslarization method. In order to prepare calibration curve (NH_4-N versus Absorbance), a series of

standards were made by diluting a prepared standard solutions to 50ml. also, a calibration curve were prepared for other parameters such as COD and PO_4.

Nitrate (NO_3- N)

Measurements of Nitrate were carried out by using Capillary Ion Analyzer (CIA) method. The method used to measure the concentration of other parameters are listed in Table 3.1

3.6.3 Biological parameters

Fecal coliform were analyzed according to 9221-E methods (APHA, 2005).

3.7 Sampling

Samples were analyzed for both influent and effluent of the constructed wetland during the project period. On 1/May/2010, they were analyzed for COD, NH_4, NO_3, PO_4, pH and DO. From 15/June/2011 to 11/Oct/2011, water samples were analyzed weekly for the same parameters mentioned in addition to TKN, BOD, DOC, SO_4, TSS, TDS, DO, EC, pH and fecal coliform).

3.7.1 Sample collection

Composite samples from the inlet and outlet of the constructed wetland units were collected in sterile plastic bottles and stored at 4°C. Composite samples from both the influent and effluent were analyzed. Each sample is composed of three samples collected between 7:30 am and 11:00 am and kept in the refrigerator until collecting all of the three samples. The sample size was 200 ml which took about 10 minutes to be collected. It was collected in glass bottles and then mixed to

form a composite sample. The composite samples were analyzed for the all the parameters presented in Table 3.1

3.7.2 Water sampling methods

The parameters used for the determination of the efficiency of the system were Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD) Nitrate (NO_3-N), Ammonium (NH_4-N), Ortho-phosphate (PO_4-P), pH, Temperature, Electrical conductivity (EC), Dissolved oxygen (DO) and fecal coliform. The characteristic parameters were measured according to Standard Methods of Analysis (APHA, 2005).

The samples were collected and filtered through a standard 0.45 μm pore filter for major anion analysis, was placed into a Nansen plastic bottle and stored at 4º C. Samples fractions were analyzed as soon as they arrived to the laboratory. Water samples were collected between 7:30AM and 11:00 AM. Samples were collected over the period May/ 2011 to October/ 2011.

Table 3.1 Methods used and water quality parameters measured for the wetland samples

Element	Analytical method	Instrument used for analysis
NO_3	Capillary Ion Analyzer (CIA)	UV 300/ UV-Visible spectrophotometer/ UNICAM (λ=220 nm)
NH_4	Nesslerization method (direct and following distillation)	UV 300/ UV-Visible spectrophotometer/ UNICAM (λ=225 nm)
PO_4	Ascorbic acid method	Automated ascorbic acid reduction
TSS		
TDS	Total dissolved solid dried at 105 ˚C (Gravimetric method)	Filtration Apparatus
Conductivity	Laboratory method pH-meter 3320, Jenway	Conductivity meter, 4320, Jenway
DO	Membrane electrode method	DO meter/ Fluroprobe (FL-3-H)Luminefcent oxygen analyzer
DOC	Persulfate-ultraviolet oxidation method	TOC analyzer
pH	Electrometric method	pH-meter 3320, Jenway
Fecal coliform	9222-B 9221-E	
Organic material COD BOD_5		Hach COD reactor DO meter – Oxi 197

Chapter Four: Results and Discussion

4.1 General

The three systems were planted with 11 healthy plants of Phragmites (common reed) which were distributed uniformly on the wetland surface. Some of these plants dried and replaced by new reed plants from a wetland near the Birzeit university treatment plant. Growth for phragmites decreased and started to dry from late July/2011. The main physical, chemical and biological results for these samples are presented in the following sections.

4.2 Wastewater treatment

4.2.1 Physical parameters

In the case of pH, no significant variations occurred during the wetland operation period. On the whole, pH values showed a trend to be kept on a slightly basic range. These interactions may have resulted in release of salts from the substrate to the water, explaining the slight increase of conductivity, observed along the unit during all periods. The average pH values in the influent were 8.21, 8.3 and 8.32 and in the effluent were 7.57, 7.64 and 7.82 for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively during the steady state period. Similar results was achieved by Zurita et al. (2009) who reported a 7.7 average pH concentration in the effluent treated in a HSSFCW.

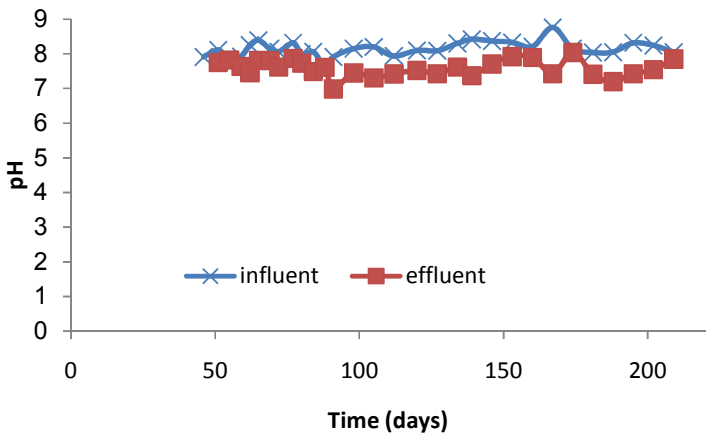

Figure 4.1 Influent and effluent pH concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

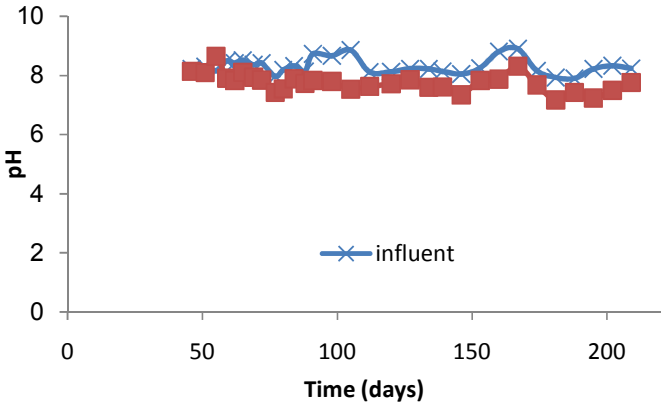

Figure 4.2 Influent and effluent pH concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh city/Palestine

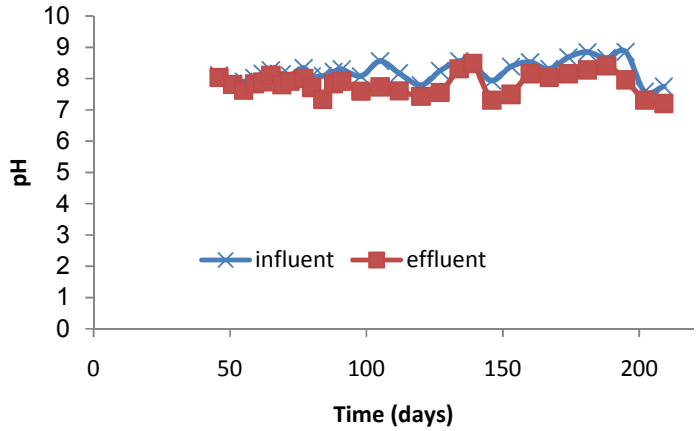

Figure 4.3 Influent and effluent pH concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

Dissolved oxygen

A constructed wetland with shallow depth was created in this study to increase the oxygen level in the substrate and wastewater. Dissolved oxygen concentrations were slightly decreased in the wetland, indicating oxygen consumption by pollutants (Fig.4.4). Artificial aeration improved the removal efficiency in the wetland as Landry et al. (2009) concluded The role of plants goes beyond the sole addition of oxygen, probably by enabling a more diversified and active micro fauna development near the root zone (Plandom *et al.*, 2006). Also, Ong *et al.* (2010) concluded that aerated reactors resulted in a better performance in the biodegradation of organic matter and nitrification.

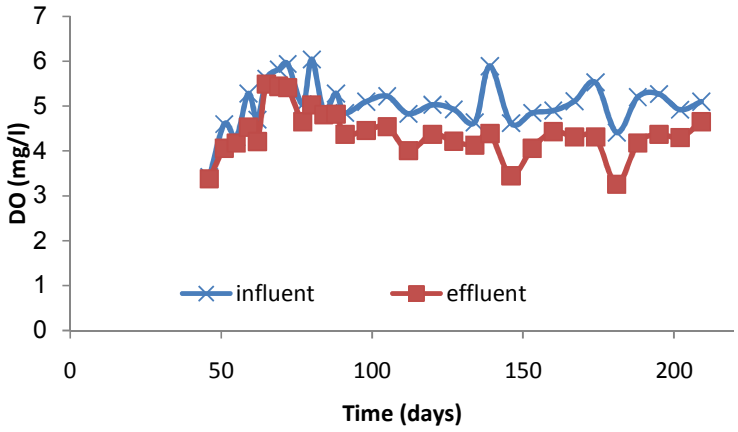

Figure 4.4 Influent and effluent DO concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

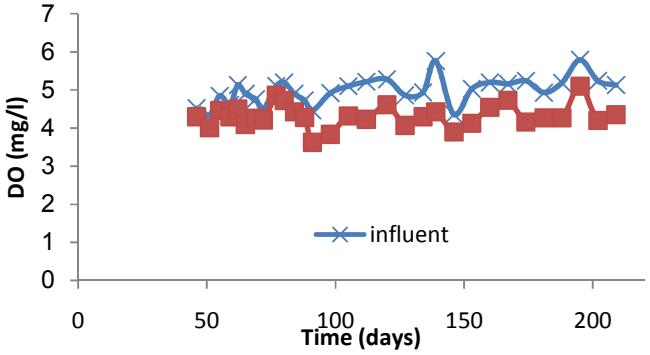

Figure 4.5 Influent and effluent DO concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh city/Palestine

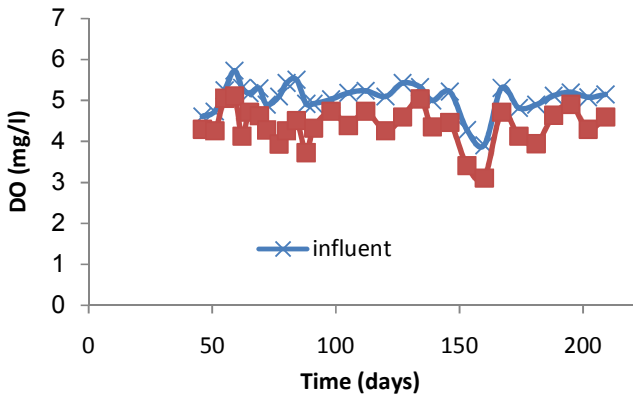

Figure 4.6 Influent and effluent DO concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

4.2.2 Chemical parameters

Chemical parameters for the wetland during the ripening and steady state periods are presented in Table 4.1.

Table 4.1 Average influent, effluent concentrations and removal for three wastewater influents during the project period (1/May/2011- 11/Oct/2011) for both ripening and steady state periods.

Parameter	# of samples	Source water	Concentration (mg/l)		
			Al-Mazra'a	Al-Bireh	Birzeit
BOD (mg/l)	18	Influent	20.3 (5.13)	7.2 (1.5)	16.1 (2.33)
		Effluent	11.1 (5.13)	5.7 (0.78)	8.6 (2.73)
		Removal (%)	43.4 (25.3)	18.6 (10.4)	47.2 (12)
COD (mg/l)	30	Influent	52.1 (8.6)	34.2 (7.06)	45.7 (6.89)
		Effluent	34.1 (9.27)	24.2 (7.26)	31.1 (7.82)
		Removal (%)	34 (18.26)	29 (16.2)	32 (15.3)
DOC (mg/l)	18	Influent	3.1 (0.7)	4.4 (0.76)	5.3 (0.61)
		Effluent	2.1 (0.4)	2.9 (0.78)	3.6 (0.45)
		Removal (%)	32 (6)	34 (3.4)	31 (4.1)
NH_4-N (mg/l)	30	Influent	7.1 (1.33)	3.3 (1.73)	6.2 (1.47)
		Effluent	1.7 (1.92)	0.63 (0.79)	1.1 (1.7)
		Removal (%)	77 (25)	83 (14.5)	84 (23.2)
NO_3-N (mg/l)	30	Influent	11.9 (3.14)	14.6 (4.15)	11.7 (3.45)
		Effluent	2.7 (1.44)	3.02 (2.97)	2.1 (1.78)
		Removal (%)	75 (15.41)	79 (18.1)	81 (17)
TKN (mg/l)	18	Influent	29.1 (6.94)	18.5 (3.96)	27.1 (9.16)
		Effluent	13.4 (4.08)	12.05 (3.69)	13.7 (4.45)
		Removal (%)	53 (11.1)	35 (12.34)	50 (12.4)
TN (mg/l)	18	Influent	41 (5)	33.2 (3.9)	38.8 (6.3)
		effluent	16.1(2.8)	15 (3.3)	15.8 (3.1)
PO_4-P (mg/l)	30	Influent	4.6 (2.02)	6.2 (1.63)	6.9 (1.8)
		Effluent	2.2 (1.09)	3.3 (1.69)	3.4 (1.13)
		Removal (%)	50 (16.13)	47 (24.25)	49 (14.7)
SO_4 (mg/l)	18	Influent	135.5 (31.85)	45.02 (18.87)	26.7 (8.79)
		Effluent	115.2 (29.9)	37.5 (15.87)	21.7 (7.86)
		Removal (%)	15.2 (8.15)	15.5 (11.25)	18.8 (13.4)
pH	30	Influent	8.1 (0.21)	8.3 (0.26)	8.2 (0.32)

		Effluent	7.6 (0.23)	7.8 (0.31)	7.8 (0.34)
		Removal (%)	6.5 (2.45)	6.6 (3.7)	4.9 (2.9)
TDS (mg/l)	18	Influent	337.2 (66.68)	327.1 (23.04)	298.6 (52.45)
		Effluent	366.4 (63.76)	351.4 (22.94)	325.6 (37.27)
		Removal (%)	-9.2 (3.82)	-7.6 (4.8)	-11.1 (16.1)
TSS (mg/l)	18	Influent	95.1 (22.08)	33.3 (6.77)	42.2 (9.91)
		Effluent	80.2 (23.44)	26.05 (6.82)	32.4 (8.77)
		Removal (%)	16.4 (7.7)	21.9 (11.1)	23.3 (9.4)
EC (µs/cm)	18	Influent	736.5 (127.68)	695.3 (61.73)	652.8 (76.63)
		Effluent	679.5 (135.56)	658.4 (47.08)	602.8 (104.06)
		Removal (%)	-8.9 (3.64)	-5.6 (5.8)	-10.2 (15.4)
Fecal coliform (cfu/100ml)	18	Influent	4.4*10^9 (8.68x10^9)	1.6*10^8 (4.29x10^8)	9.3*10^9 (1.8x10^10)
		Effluent	1.2*10^8 (1.69x10^8)	5.7*10^7 (1.75x10^8)	2.6*10^8 (6.16x10^8)
		Removal (%)	14 (6.52)	16 (9.8)	16.6 (6.1)

*The influent and effluent of the constructed wetlands were analyzed for NH_4, NO_3, PO_4, COD, DO and pH after 46 days of operation from 1/May/2011 to 15/July/2011.

* The influent and effluent of the constructed wetlands were analyzed for other parameters after 91 days of operation.

* Standard deviation values are presented between brackets.

Table 4.2 Average influent, effluent concentrations and removal for three wastewater influents during the steady state period (22/June/2011- 11/Oct/2011)

Parameter	# of samples	Source water	Concentration (mg/l)		
			Al-Mazra'a	Al-Bireh	Birzeit
COD (mg/l)	17	Influent	54.4 (8.86)	33 (6.4)	45.8 (6.7)
		Effluent	34.75 (11.53)	23.5 (4.7)	29.6 (5.42)
		Removal (%)	36 (20.5)	27 (15.4)	35 (1.22)
NH_4-N (mg/l)	17	Influent	6.78 (1.38)	3 (1.7)	6.04 (1.48)
		Effluent	0.41 (0.31)	0.29 (0.17)	0.22 (0.09)
		Removal (%)	94 (3.66)	87 (8.45)	96 (1.22)
NO_3-N (mg/l)	17	Influent	13.3 (3.2)	14.7 (4.8)	13 (4.07)
		Effluent	2 (1.2)	1.1 (0.45)	1.2 (0.7)
		Removal (%)	84 (9.8)	92 (4.3)	90 (4.51)
PO_4-P (mg/l)	17	Influent	3.3 (1.2)	5.51 (1.13)	6.3 (1.64)
		Effluent	1.5 (0.86)	2.8 (0.94)	3.5 (1.3)
		Removal (%)	51 (18.3)	49 (18.8)	44 (14.5)
pH	17	Influent	8.21 (0.19)	8.3 (0.31)	8.32 (0.38)
		Effluent	7.57 (0.24)	7.64 (0.27)	7.83 (0.42)
		Removal (%)	7.88 (2.14)	7.92 (2.86)	5.8 (2.95)

There were no clear differentiations occurred for DOC in the constructed wetland through the experiment period except a decrease in removal efficiency of DOC in the system fed with anaerobically pretreated grey water.

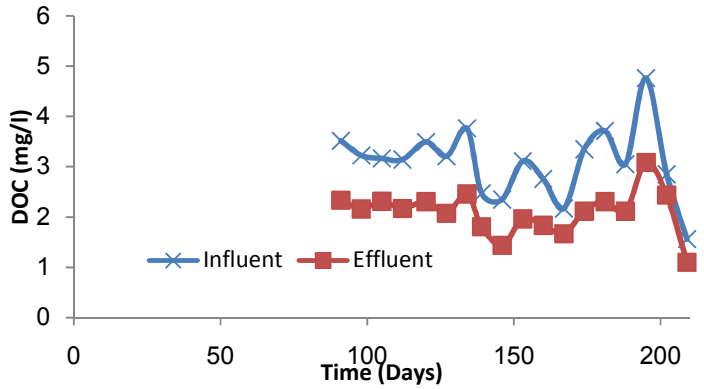

Figure 4.7 Influent and effluent DOC concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

The zero labels in all figures stand for the first day of operation (15/March/2011). The average DOC concentration in the influent was 3.09 (0.7), 4.38 (0.76) and 5.26 (0.61) mg/l for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively. DOC effluent concentrations were almost stable around 2.1, 2.8 and 3.6 mg/l for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively. This indicates that this portion is apparently non biodegradable.

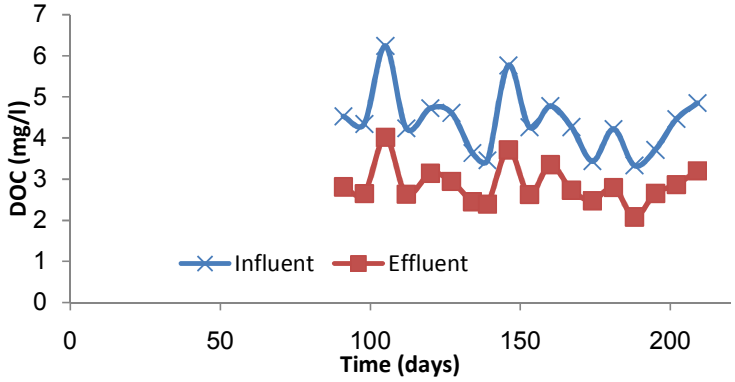

Figure 4.8 Influent and effluent DOC concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh city/Palestine

All systems removed on average less than half of DOC, with mean percentage removals of 31.8%, 34.4% and 30.8% for Al-Mazra'a, Al-Bireh and Birzeit, respectively (Table 4.1 and Figures (4.3,4,5). A higher removal rate of 72% was achieved in a HSSFCW fed with municipal wastewater and filled with sandy soil (Chung *et al*., 2008).

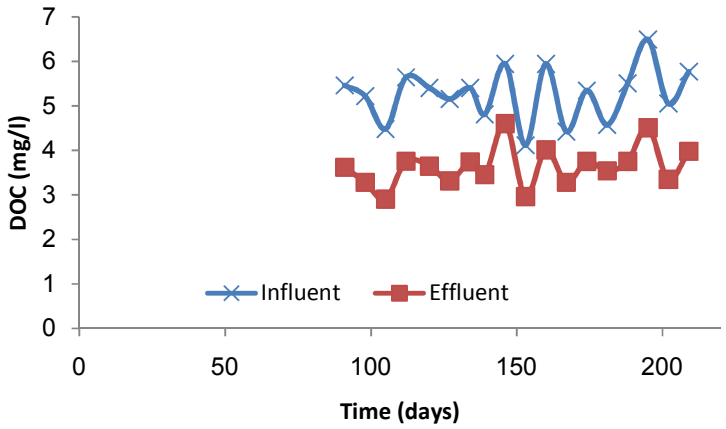

Figure 4.9 Influent and effluent DOC concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

About 35% of DOC influent concentrations were removed in the constructed wetlands. This indicates that organic matter wasn't efficiently removed. Although DOC cannot be directly taken up by plants, the presence of plants can degrade DOC into inorganic carbon for plant uptake. Shackle et al. (2000) found that the main mechanism of reducing DOC is in the activity of microorganisms in gravel. The presence of plants provides a huge surface area and medium for attached microbial growth, and therefore the planted treatments could remove a larger quantity of DOC. In addition, wetlands with shorter hydraulic retention times would reduce leaching of DOC from plant material.

Biochemical Oxygen Demand (BOD)

BOD undergoes aerobic/ anaerobic decomposition in the constructed wetlands depending on the oxygen status at the deposition point (Vipat et al., 2008). As presented in Fig. 4.10, a stable period for BOD removal started after about 135 days from operation. After these days, BOD was improved from 21.2 to 8.11 mg/l during (23/August/2011-11/October/2011) for Al-Mazra'a water.

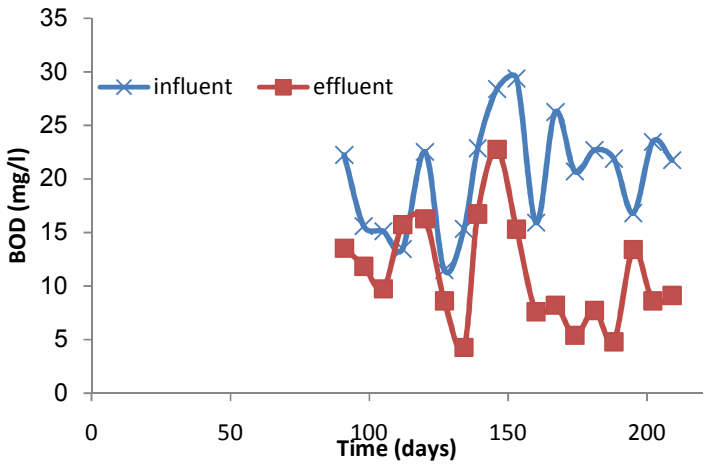

Figure 4.10 Influent and effluent BOD concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

For the system fed with Al-Bireh secondary treated wastewater and after a period of 102 days, average BOD value in the influent was 7.4 mg/l and in effluent was 6 mg/l over the period (21/July/2011-11/October/2011). The results presented in Fig. 4.5 reveals that the BOD concentration was marginally improved.

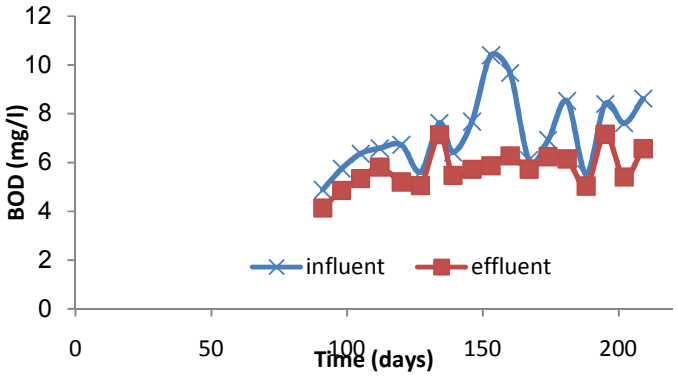

Figure 4.11 Influent and effluent BOD concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh city/Palestine

After 87 days from operation for Birzeit waters, average BOD value in the effluent was 7.63 mg/l during (6/July/2011-11/October/2011). The average influent concentration during the same period was 15.6 mg/l. The results presented in Figures 4.11 and 4.12 reveal that the constructed wetland noticeably improved the effluent quality in terms of BOD for both systems fed with grey water and secondary treated wastewater.

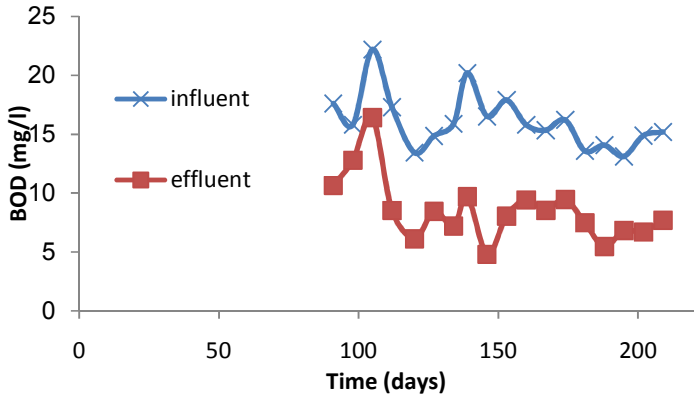

Figure 4.12 Influent and effluent BOD concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

The BOD removal efficiency obtained from experiment were 43, 19 and 47% for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively, are lower than that reported by Zurita et al. (2009) who found a 78.2% BOD removal for a HSSFCW planted with one species (Zantedeschia aethiopica) treating domestic wastewater and a higher removal of 81.5% for the same system planted with three different species. These results were referred to the effective distribution of roots which can be achieved when three species are used in addition to the increased opportunity of creating a great diversity of microbial communities. BOD removal efficiency for a HSSFCW fed with grey water was in the range of (72-79) % as found by (Niyonizima, 2007) with 250 and 71mg/l influent and effluent concentrations, respectively. A BOD removal efficiency of 85.4% was achieved in HSSFCW filled with gravel (Ghrabi *et al.*, 2011). In addition, BOD removal rate of 65.7% was reported by Vipat et al. (2008) with 46.7 and 19.5 mg/l influent and effluent BOD concentrations, respectively.

Depending on the above results, the rate constant (KBOD) for the three influent wastewaters were calculated, Table 4.2. The calculated KBOD for both Al-Mazr'a and Birzeit influents cope with the assumed KBOD (0.11m/d). For Al-Bireh influent, average calculated KBOD was equal to 0.03 m/d which differs from the assumption.

Table 4.3 Calculated rate constant (KBOD) for the three investigated wastewaters

Investigated wastewater	Al-Mazr'a water	Al-Bireh water	Birzeit water
KBOD (m/d)	0.1 (0.07)	0.03 (0.02)	0.1 (0.03)

In this experiment, KBOD was assumed 0.11 m/d. Table 8 presented the average calculated KBOD for three investigated wastewaters. These values were calculated depending on measured concentration influent and effluent BOD using the following equation:

$$Ah = Qd(ln\,Cin - ln\,Cout)/KBOD$$

Where:

A_h: surface area of the constructed wetland

Cin is influent BOD concentration

Cout is effluent COD concentration.

Chemical Oxygen Demand (COD)

COD removal efficiencies were 36% for Al-Mazra'a water and 27% for Al-Bireh water and 35% for Birzeit water during the steady state period which is considered after 100 days of operation. Higher COD removal rates were achieved

for horizontal flow wetlands such as 42.7% (Ghrabi *et al.*, 2011), 71.8% (Avsar *et al.*, 2007) and 72-79% for a wetland treating grey water (Niyonizima, 2007), 93.6% for a wetland treating dairy and agricultural wastewater (Pucci *et al.*, 1998), 77.8% for a wetland treating domestic wastewater (Vipat *et al.*, 2008) , 76% (Zurita *et al.*, 2009) and 90-94% removal rate in upflow constructed wetlands (Ong *et al.*, 2010). In up-flow systems, COD concentration dropped drastically at the aeration points where the aerobic conditions facilitated the growth of aerobic microbes and boosted the degradation of organic matters (Ong *et al.*, 2010).

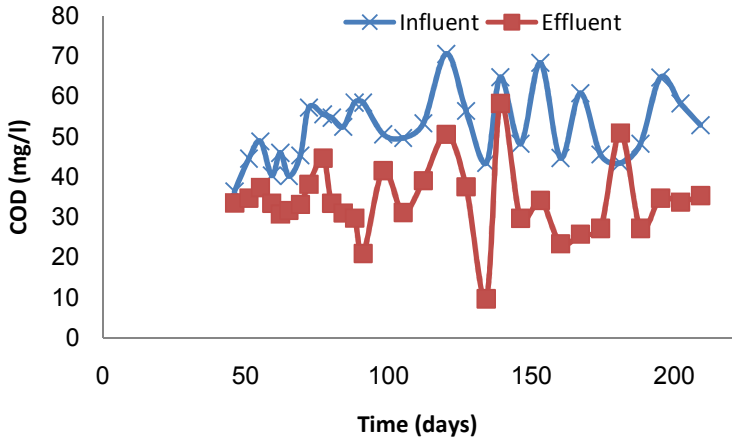

Figure 4.13 Influent and effluent COD concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

The results presented in Fig 4.13, the constructed wetland fed with anaerobically pre-treated grey water have a stable removal of COD after 95 days of operation. The plant growth and the period at which the pant reached maximum growth explain this stable removal of COD.

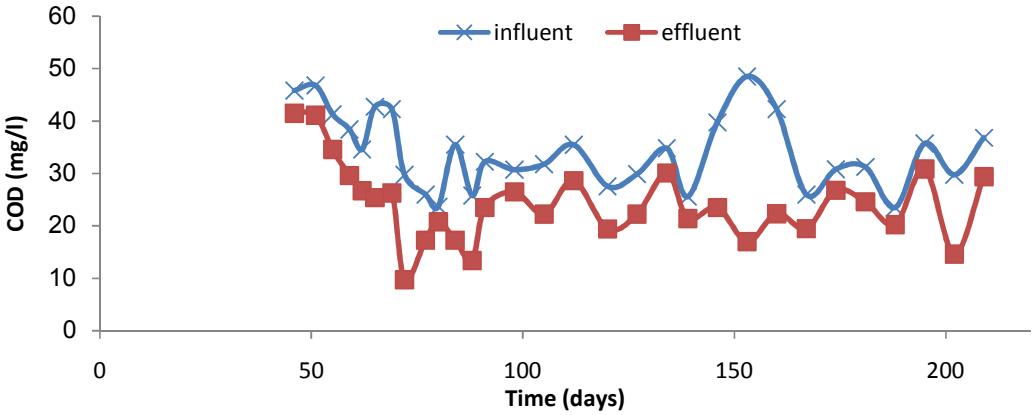

Figure 4.14 Influent and effluent COD concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh city/Palestine

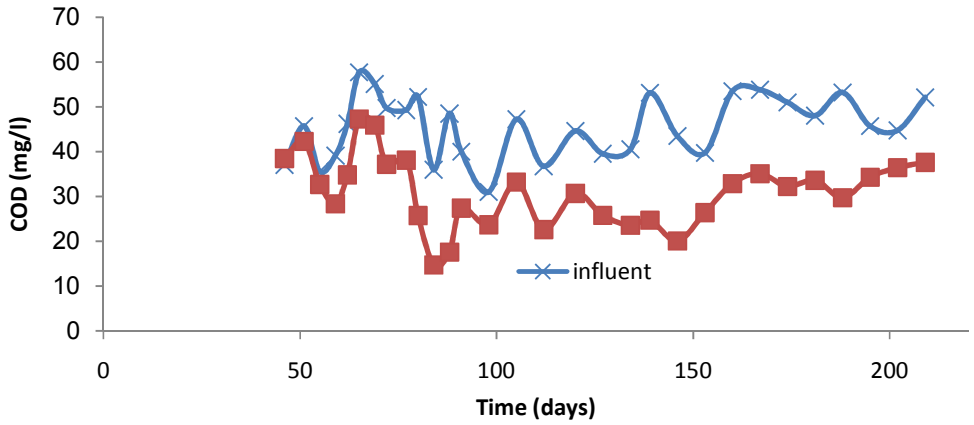

Figure 4.15 Influent and effluent COD concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

BOD and COD associated with settelable solids in wastewater is removed by sedimentation while that in colloidal and soluble form is removed as a metabolic activity of microorganisms and physical and chemical interactions with the root zone/substrate (Vipat *et al*., 2008).

Removal of nitrogen

a) Ammonium Nitrogen (NH_4-N)

As can be seen from Figures (4.16, 4.17 and 4.18), nitrogen removal efficiency is high. This shows the ability of nitrogen uptake by the plants as Lin *et al.* (2001) concluded that plant uptake could account for less than 10% of nitrogen removal in a HSSFCW treating landfill leachate. Also, Mayo and Bigambo (2005) reported that HSSECW achieve a total nitrogen removal of 48.9%. Moreover, they found that significant nitrogen transformation was observed through denitrification and nitrification in addition to plants which has a contribution in nitrogen removal. However, nitrogen removal through plant uptake requires harvesting from the wetlands. The main nitrogen removal process in low nitrogen loads is plant uptake, yet in high loads, different physical and chemical processes take place.

The average pH in the influent wastewater was 8.21 (0.19), 8.3 (0.31) and 8.32 (0.38), showing that ammonium was abundant in the plants as NH_4, which is the favorable form of nitrogen uptake by the plants.

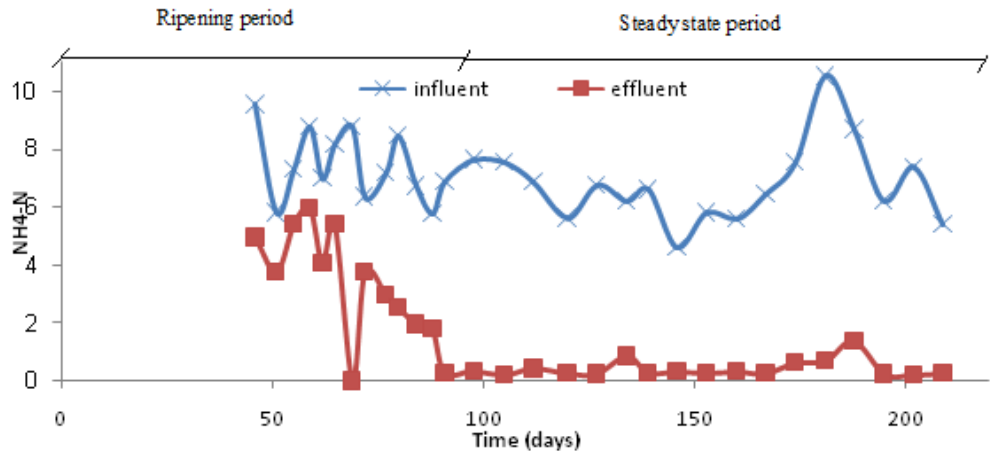

Figure 4.16 Influent and effluent ammonia concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

The average NH_4-N influent concentrations were 6.78 (1.38), 3 (1.7) and 6.04 (1.48) mg/l for AL-Mazra'a, AL –Bireh and Birzeit waters, respectively. However, there was no clear difference in the removal efficiencies detected between the three types of water influents.

It is clear that ammonia was almost removed from all types of investigated waters due to plant growth. Also, the results reveal that NH_4 effluent reached stable low level of concentration after 66, 34 and 44 days for Al-Mazra'a, Al-Bireh and Birzeit wastewaters, respectively.

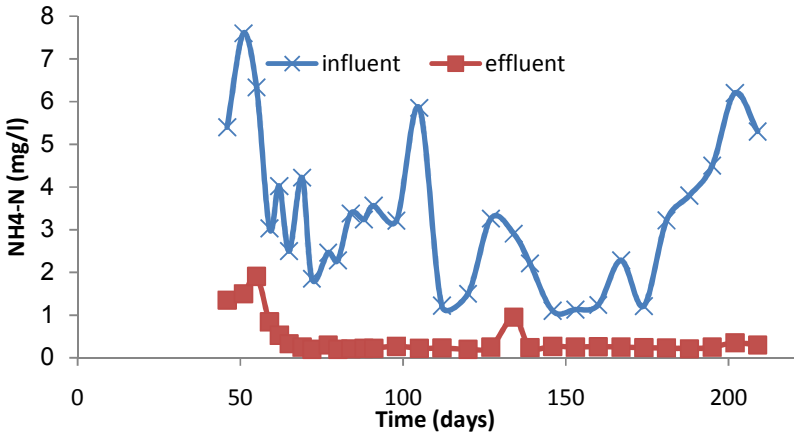

Figure 4.17 Influent and effluent ammonia concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh city/Palestine

The average ammonia-N removal efficiencies were 94% (3.6), 87% (8.45) and 96% (1.2) for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively over the project period. In this context, results reveal that after about two months of operation, average ammonia removal rates was 94, 88, and 96% for al-Mazra'a, Al-Bireh and Birzeit wastewaters. Although the NH_4 removals were quiet low during the first month of monitoring period. The average removals throughout the study were higher than the reported as average values in other countries, such as, ammonia removal rate (63.8%) was recorded by Avsar *et al*. (2007), 55% (Pucci *et al*., 1998) and 53.3% (Vipat *et al*., 2008). On the other hand, high removal efficiency was recorded by Chung *et al*. (2008) with 95%. In addition, Zurita *et al*. (2009) reported a relatively low nitrate removal in HFCWs and referred that to the good nitrification, the nitrate removed by denitrification was immediately substituted by nitrate produced by nitrification. Yang et al. (2001) had observed a relatively good amount of removal of NH_3-N up to about 50% on average in a

constructed wetland. Also, by the end of his experiment results showed that removal efficiency was increased up to 80%.

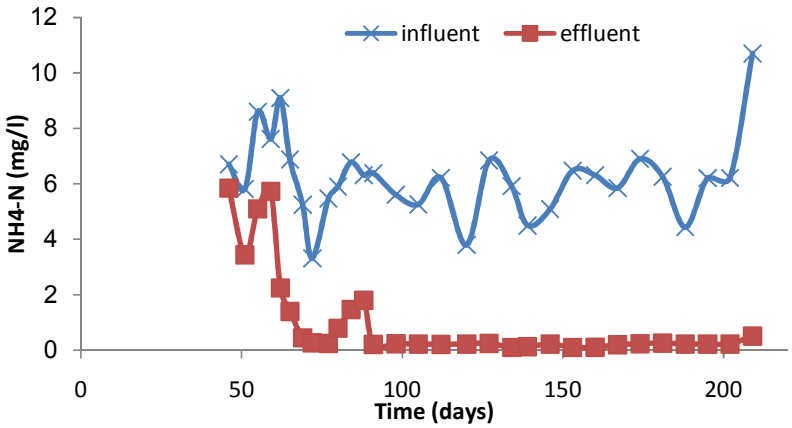

Figure 4.18 Influent and effluent ammonia concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

It is clear that NH_4-N removal efficiency in the three systems operated with different waters consistently achieved near-complete NH_4 removal.

It is expected that the total nitrogen removal observed in this study is the result of these main processes: plant uptake, sediment storage, N_2O production via nitrification and incomplete denitrification (Landry *et al*., 2009). Also, they concluded that, artificial aeration strongly influenced and increased nitrogen removal up to 11%. In this context, Ong *et al*. (2010) concluded that nitrogen removal in constructed wetlands thought to occur mainly due a pathway of ammonification followed by coupled nitrification and denitrification. Vipat *et al*. (2008) also suggested that nitrogen removal takes place through several processes via plant uptake, ionic exchange, ammonia volatilization, nitrification and

denitrification. In this field, NH_4 is removed through adsorption on the substrate but once the available attachment sites were saturated the process will be revised and more endurable process such as nitrification and plant uptake become more important (Zurita *et al.*, 2009).

Table 4.4 Average influent and effluent concentrations (with standard deviation) in mg/l of NH_4-N, NO_3-N and PO_4-P over the project period (1/May/2011-11/Oct/2011).

Influent wastewater	**Al-Mazra'a Water**		**Al-Bireh Water**		**Birzeit Water**	
Parameter	**Influent**	**effluent**	**Influent**	**effluent**	**Influent**	**effluent**
NH_4-N	7.06(1.33)	1.66(1.92)	3.33(1.73)	0.62(0.79)	6.23 (1.47)	1.09(1.7)
NO_3-N	11.86 (3.14)	2.74(1.44)	14.65 (4.15)	3.02 (2.97)	11.7 (3.45)	2.08 (1.78)
PO_4-P	4.55(2.02)	2.22(1.09)	6.22(1.63)	3.26(1.69)	6.88(1.8)	3.39(1.13)

*All units are in mg/l

Table 4.5 Percentages of nutrient removal efficiencies (%) of three constructed wetlands during the project period (1/May/2011-11/Oct/2011).

Parameter	**Al-Mazra'a water**	**Al-Bireh water**	**Birzeit water**
NH_4-N	77(25)	83(14.5)	84(23.2)
NO_3-N	75(15.4)	79(18.1)	81(17)
PO_4-P	50(16.1)	47(24.2)	49(14.7)

* # of samples = 30

* All units in mg/l

* The numbers between brackets stand for standard deviation

b) Nitrate Nitrogen (NO_3-N)

Positive removal efficiencies of nitrate were achieved in all waters, indicating a decrease of nitrate concentration in the effluent. The average influent nitrate concentrations in the three types of investigated waters were very close of 13.3 (3.2), 14.7 (4.8) and 13 (4.1) mg/l for Al-Mazra'a, Al-Bireh and Birzeit waters respectively. A high concentration (20.82, 26.6 and 20.91 mg/l) of nitrate was detected in the influent when compared with the low nitrate (1.7, 0.72 and 1.7 mg/l) concentration in the effluent. Less fluctuation was detected towards the end of experiment, with a high nitrate removal in the wetlands after day-121, 102 and 80 for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively.

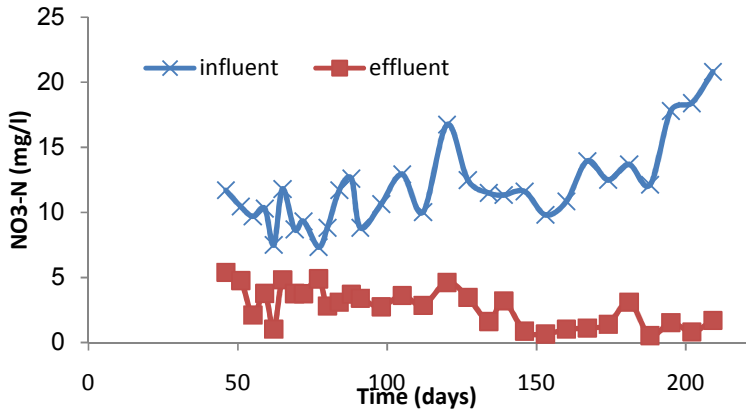

Figure 4.19 Influent and effluent nitrate concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

Nitrate concentration in the anaerobically pre-treated grey water was unexpectedly high. This is attributed to the low organic content of the influent raw grey water, as also suggested by the rather low BOD effluent content of the septic tank.

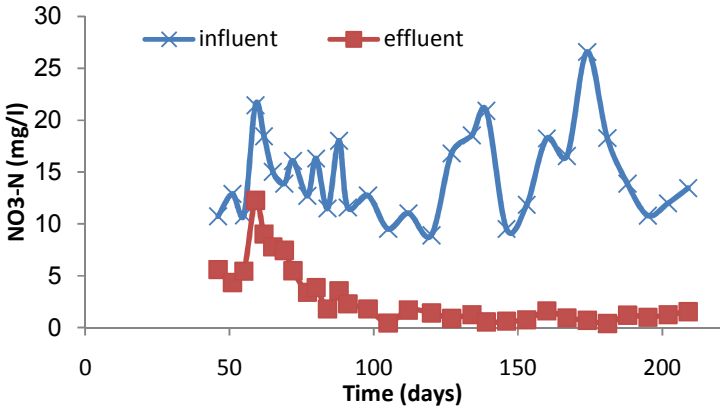

Figure 4.20 Influent and effluent nitrate concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh city/Palestine

The effluent NO3-N concentration for the constructed wetland fed with Al-Bireh water after around 100 days of operation was stable regardless of the influent fluctuations. Nitrate was removed efficiently from all investigated wastewaters as the nitrate was detected in low levels; same result was reported by Mantovi et al. (2003).

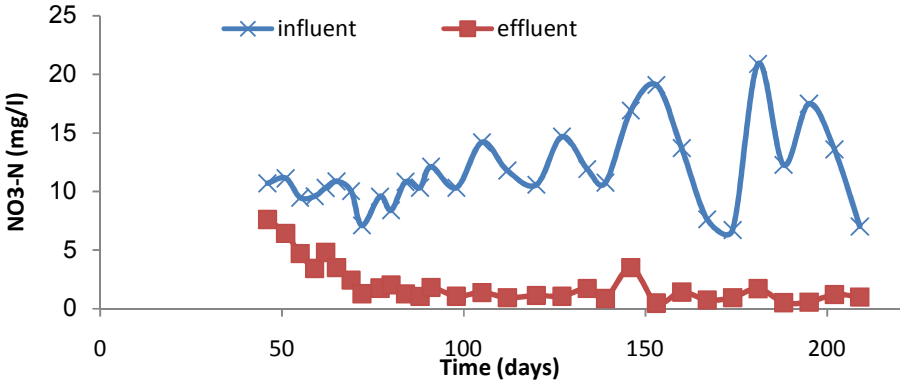

Figure 4.21 Influent and effluent nitrate concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

Low concentrations of NO_3 were observed throughout the experimental period because of plant uptake and denitrification (Yang et al., 2001). This means that – under this configuration – ammonification and nitrification proceeded simultaneously, since the operation period included summer months (higher temperatures) which favor these two processes. This explanation is also supported by the low effluent concentration of nitrate after a period of 120, 60 and 50 days for AL-Mazra'a, Al-Bireh and Birzeit, respectively. At this point, it has to be mentioned that most of effluent nitrate concentrations measured during the May/2011 were lower than the limit of detection.

Mayo and Bigambo (2005) reported that the major pathways leading to permanent removal of nitrogen in HSSFCW system are denitrification (29.9%), plant uptake (10.2%) and net sedimentation (8.2%). The average removal rates for nitrate were 84, 92 and 90 for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively. The overall removals were higher than those found by other authors for example, a removal rates of 40%, 62% and 49.3% were recorded by Pucci et al. (1998), Vipat et al. (2008) and Zurita et al. (2009).

Total kjheldahl nitrogen (TKN)

High concentrations in TKN were detected in the influent throughout the experimental period; the average influent concentration was 29.11, 18.5 and 27.1mg/L for Al-mazr'a, Al-Bireh and Birzeit waters, respectively. However, the average concentration for TKN in the effluent was 13.4, 12.1 and 13.7 mg/l for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively. The removal efficiencies

for the three water sources were 53.4, 35.2 and 46.5%. In the constructed wetlands that was fed with Birzeit water, the removal efficiencies increased after day-102 but decrease of TKN removal was observed in the systems fed with Al-Bireh water. Within the experimental period, fluctuation was detected in the removal of TKN.

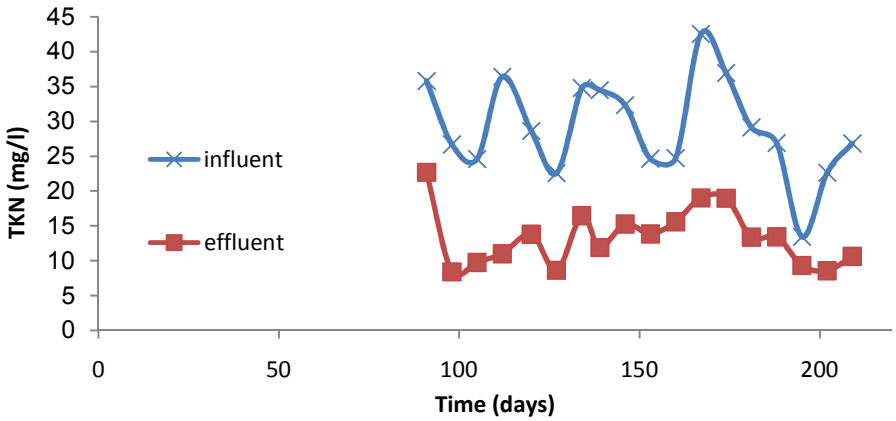

Figure 4.22 Influent and effluent TKN concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

TKN removal efficiency for the system fed with Al-Mazra'a water was 53% which cope with that obtained by Chung et al. (2008) as 62% removal. Also, it is obvious that nitrogen removal was not only due to ammonia removal but also due to organic nitrogen removal. Plandom et al. (2006) concluded that TKN removal was very high in HSSFCW when a low organic load is used. A removal rate of 8.9% was recorded by Vipet et al. (2008).

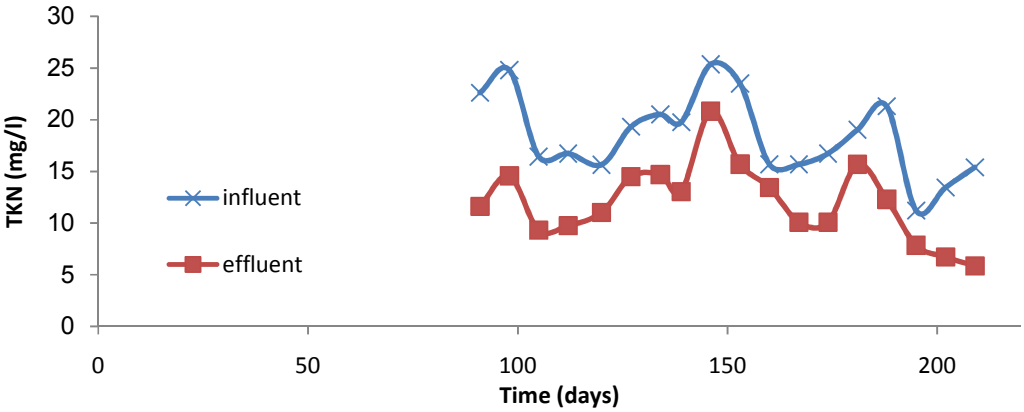

Figure 4.23 Influent and effluent TKN concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh city/Palestine

The rapid decrease of TKN in the effluent indicated the degradation of organic N through ammonification. The average pH in both influent and effluent was within (8.14 - 7.6), (8.31 - 7.76) and (8.23- 7.83) for Al-Mazra'a, Al-Bireh and Birzeit wastewaters, respectively, which lay between the optimal pH ranges for ammonification. Ammonification was then followed by nitrification, so NH_4 concentration did not increase in the effluent. The presence of plants could significantly reduce NH_4. Fraser et al. (2004) showed that plants could reduce total nitrogen to significantly lower levels than unplanted treatments. As he included that the high removal rate of NH_4 in planted treatments showed that nitrification was very active.

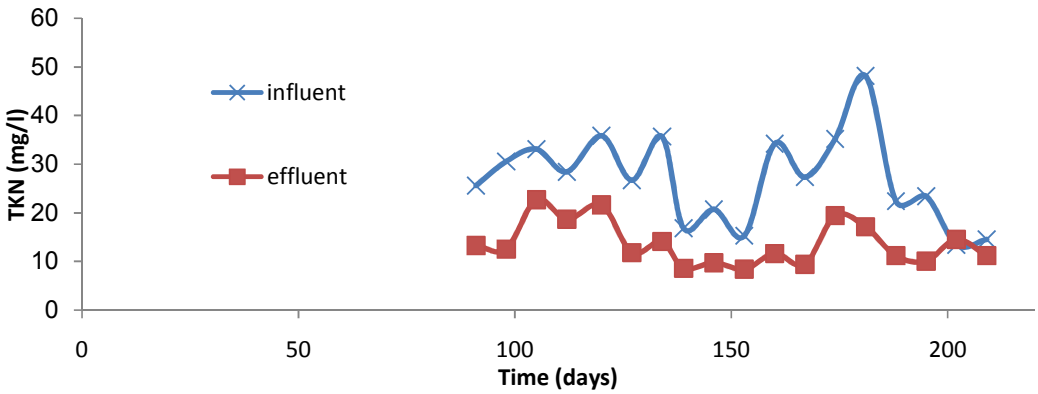

Figure 4.24 Influent and effluent TKN concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

Organic nitrogen

Moreover, the organic nitrogen effluent concentration was similar for all systems as also was its gradual removal. Table 10 presented the calculated concentrations of organic nitrogen influent and effluent through the project period.

Table 4.6 Average organic nitrogen concentration for the three wetlands after 91 days of operation during the period of (15/June/2011- 11/Oct/2011)

	Unit	Al-Mazra'a	Al-Bireh	Birzeit
Influent	mg/l	22.3 (7.06)	15.6(4.6)	21 (9.6)
Effluent	mg/l	13 (4)	11.5 (4.2)	13.5 (4.4)
Removal	%	38.7 (20)	27.8 (14.2)	18.7 (60.3)

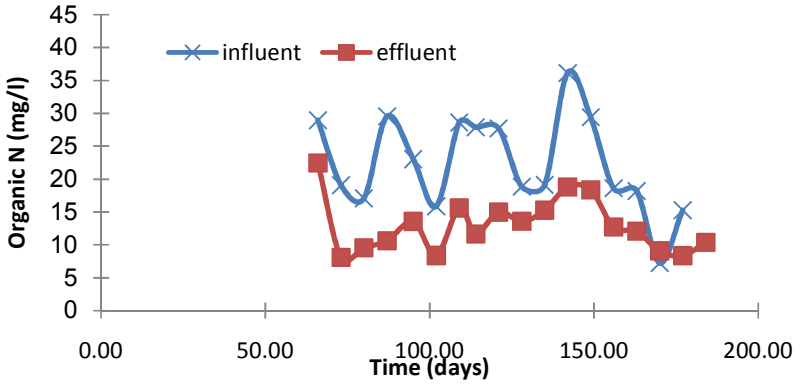

Figure 4.25 Influent and effluent organic nitrogen concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

Increase of organic nitrogen in the effluent was detected; negative values were obtained for the removal efficiency in both systems fed with Al-mazr'a and Birzeit waters during the last weeks of the experiment. The average influent and effluent concentration of organic nitrogen were (22.3, 13), (15.6, 11.5) and (21.03, 13.4) mg/l for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively.

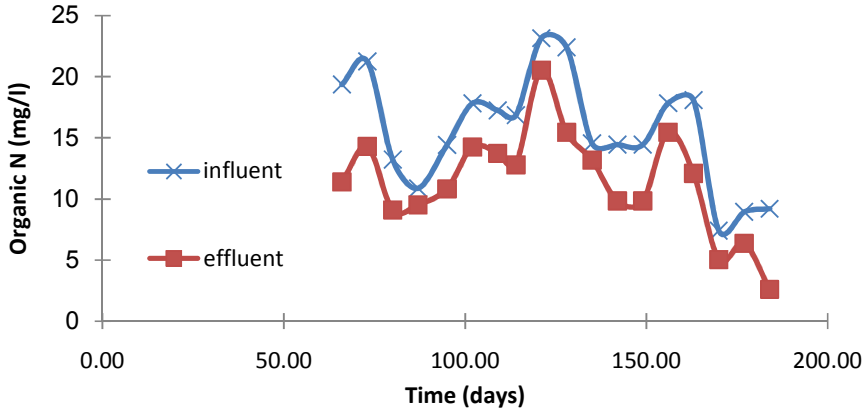

Figure 4.26 Influent and effluent organic nitrogen concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh city/Palestine

It is clear from Fig. 21 that organic nitrogen is not removed efficiently almost over the whole project period. On the other hand, a low removal rates were achieved for both systems fed with Al-Bireh and Birzeit wastewaters as presented in Figures 4.21 and 4.22.

Organic nitrogen removals in this study were 39, 28 and 19% for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively. These results agreed with those obtained by Zurita et al. (2009) who reported removal efficiences in the range (39-46) %. However, they contrast with other study in which the author concluded that the organic nitrogen removal efficiences was 100% (Vipat et al., 2008).

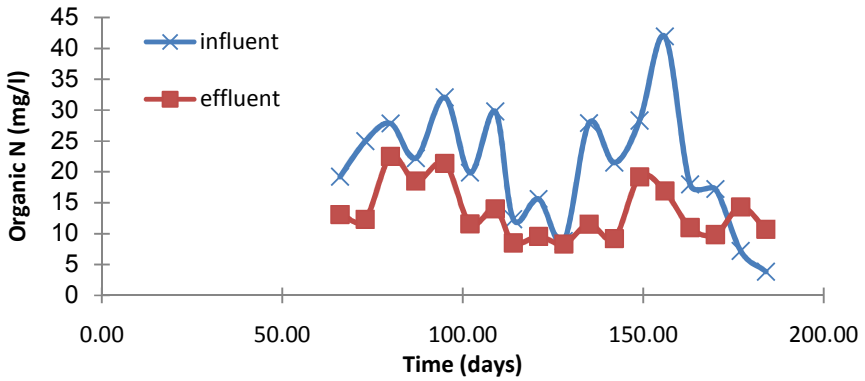

Figure 4.27 Influent and effluent organic nitrogen concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

Phosphate (PO_4-P)

Phosphorus concentrations were low in both influents and effluents- around 5mg/l- and varied little over time. Mean phosphorus concentrations (PO_4-P) concentrations in the influent were 3.3 (1.2), 5.51 (1.13) and 6.3 (1.64) mg/l for

Al-Mazra'a, Al-Bireh and Birzeit wastewaters, respectively. The systems achieved a PO_4-P removal of 51% (18.3), 49% (18.8) and 44% (14.5) for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively. Phosphate is poorly removed in constructed wetlands; Ghrabi et al. (2011) reported a 38% removal rate. In this context, Vymazal (2009) concluded that the removal of phosphorous is steady but low in horizontal subsurface flow constructed wetlands. The results obtained in this study for phosphorous removal are close to that obtained by Mantovi et al. (2003) who recorded a 60% removal. Although phosphorus concentrations in effluent are less than the influent for all the source waters, the system does not remove the phosphorus effectively as other systems such as that examined by (Chung et al., 2008) with 72% PO_4-P removal and 89% removal reported by (Sarafraz, 2009).

Regarding phosphorus retention, the performance of the constructed wetland unit proved to be considerably enhanced during period (20/Sep/2011-4/Oct/2011) for Al-Mazra'a water. For the system fed with Al-Bireh water, the system reached the maximum efficiency in (12/June- 6/July/2011). Also, in 12/June/2011 maximum phosphate removal efficiency was reached in the system fed with Birzeit water. Higher influent values were reached in the system fed with Al-Bireh water during the period (1/May/2011-2/August/2011). Figures (4.28, 4.29 and 4.30) show that effluent phosphate concentration in the constructed wetland fed with al-Mazra'a wastewater is always lower in the last two months of the experiment compared to same period in the other two systems.

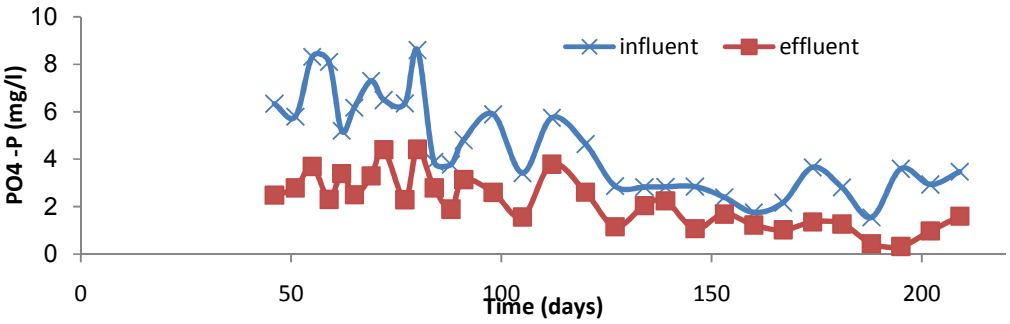

Figure 4.28 Influent and effluent phosphate concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

For Phosphorous removal, contact time may play a major role in the distribution within a constructed wetland. Presence of plants effectively removes PO_4 because it is readily available for plant uptake. It has been suggested that vegetation, detritus, fauna and microorganisms are an important sink for phosphorous in the short term but substrate is the main sink for Phosphorous in the long term. In longer term, the removal of phosphorous will be decreased in the planted treatment due to the saturation of Phosphorous adsorption in the substrate. It can be assumed that phosphorus adsorption was the main removal mechanism (Yang *et al*., 2001).

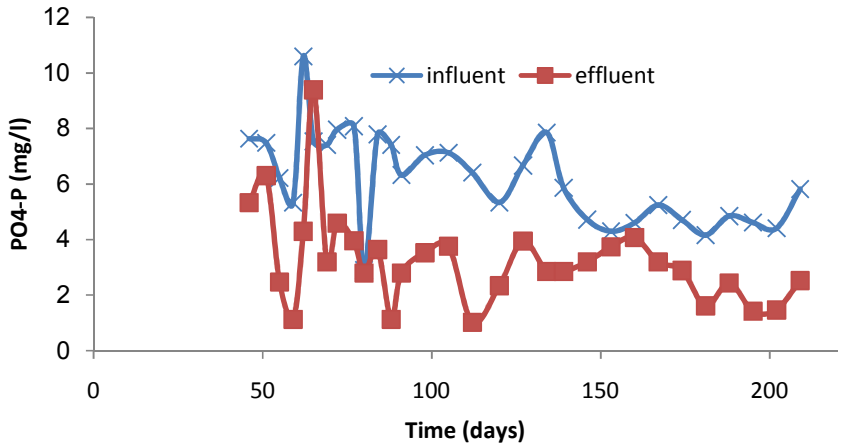

Figure 4.29 Influent and effluent phosphate concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh city/Palestine

Phosphorus removal was found to be at low levels. In the constructed wetland fed with Birzeit secondary treated wastewater, phosphorus removal was the lowest as of 44%. The maximum phosphorus removal was obtained in the constructed wetland fed with Al-Mazra'a water as of 51%. A total phosphorous removal of 20% was recorded by Pucci et al. (1998) in a HSSFCW treating wastewaters produced by an organic farming activity in Tuscany.

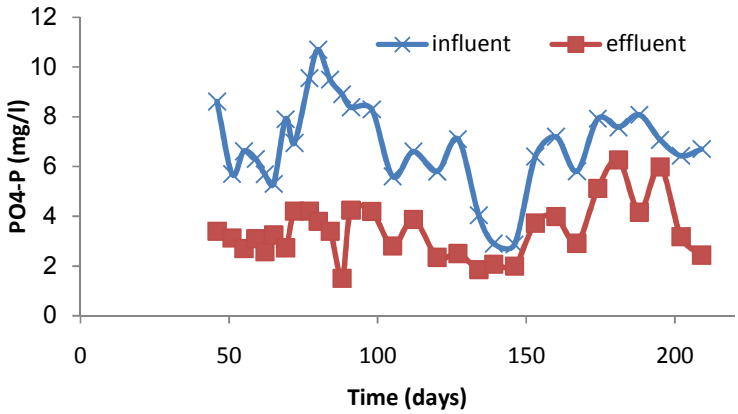

Figure 4.30 Influent and effluent phosphate concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

Most wetland studies have shown that the soil compartment is the major long-term Phosphorous storage pool. Removal of phosphorus in constructed wetlands is not temperature-dependent. Temperature has little influence on Phosphorous removal because the most important removal mechanisms are chemical precipitation and physico-chemical sorption, processes that are not temperature-dependent. Biological influences on Phosphorous removal, which are temperature-dependent, are relatively unimportant.

Removal of Sulphate (SO_4):

As can be noticed in Fig. 4.31, the reduction in sulphate content was low. That reflects the aerobic conditions through the wetland.

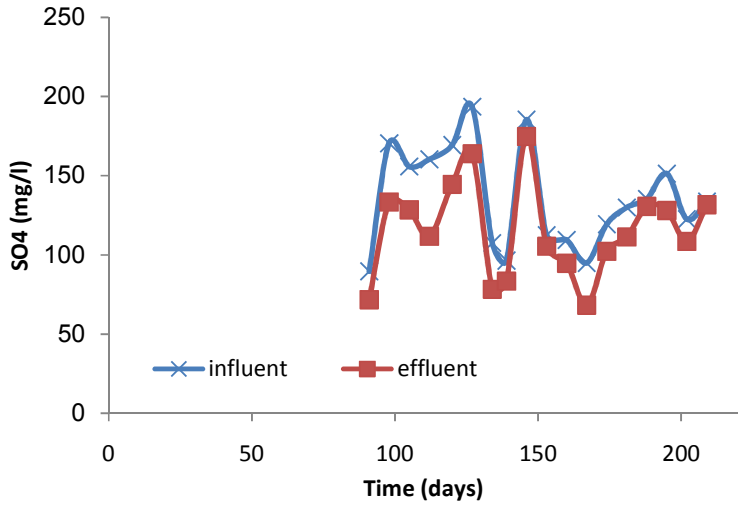

Figure 4.31 Influent and effluent sulphate concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

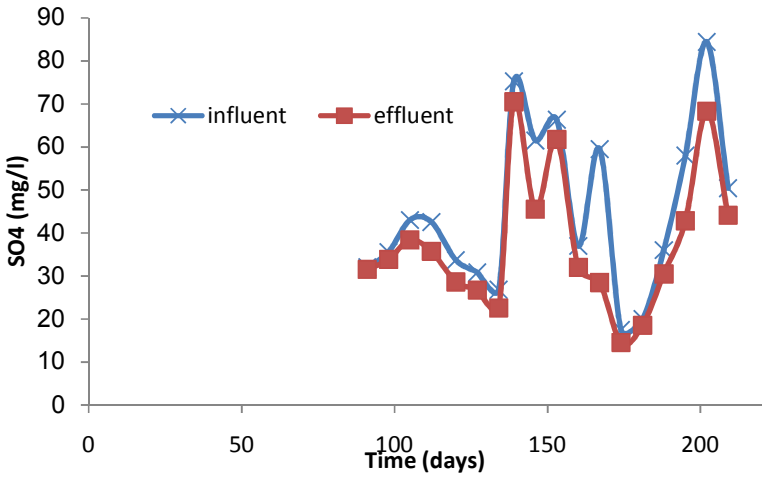

Figure 4.32 Influent and effluent sulphate concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment, Al-Bireh city/Palestine

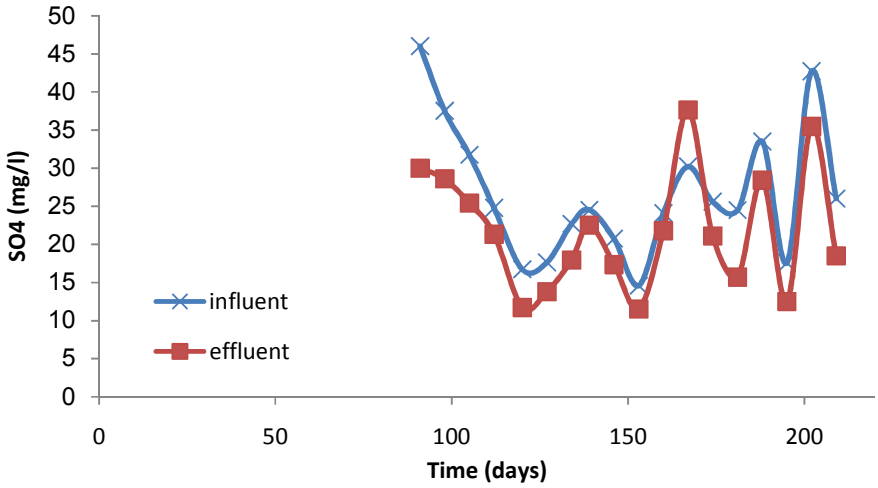

Figure 4.33 Influent and effluent sulphate concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

Total Suspended Solids (TSS)

In general, TSS removal rates in all the systems are close to one another as 16.5% (7.7), 21.9% (11.1) and 23.3% (9.4) as an average for Al-Mazra'a, Al-Bireh and Birzeit water respectively. These results contrast with other studies, for example, Zurita et al. (2009) reported that the TSS removals for HSSFCW planted with one species and fed with domestic wastewater was in the range of (80-84) % with 57 and 11 mg/l influents and effluent TSS concentrations. It is clear that total suspended solids (TSS) were not reduced effectively in the constructed wetlands. The constructed wetland fed with Birzeit water has a maximum removal rate of 23.3%. Niyonizima (2007) reported TSS removal rate in the range (34- 53) %. Also, high removal efficiency of 92.9% was recorded by Avsar et al. (2007) and 79% removal of TSS (Vipa et al. (2008). Similar TSS removal of 79.2% was

reported by Zurita et al. (2009). Also, 81% TSS removal rate was recorded by (Pucci et al., 1998).

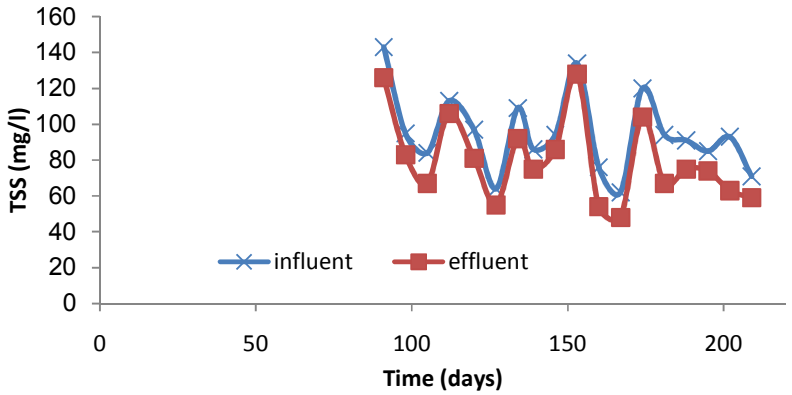

Figure 4.34 Influent and effluent TSS concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah/Palestine

As presented in Figures (4.29, 4.30 and 4.31), hardly any TSS has been removed. This result will have an adverse effect on the opportunity of the effluent reuse as it will cause a problem if used in agriculture that use drip irrigation technology. So that, it is clear that physical removal step of TSS is needed to assure the required low TSS concentrations.

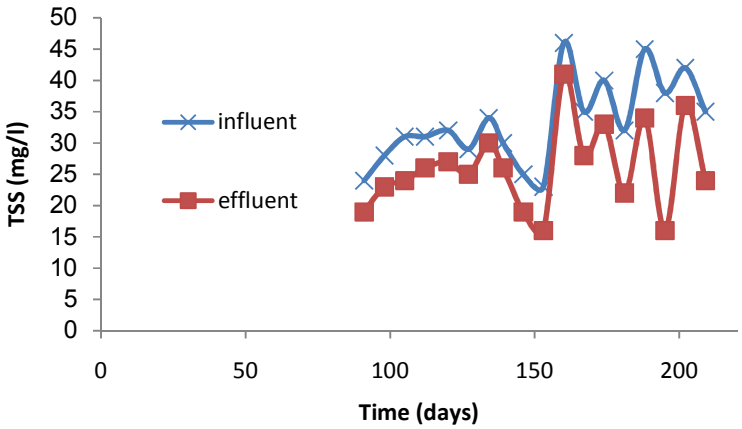

Figure 4.35 Influent and effluent TSS concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh City/Palestine

As can be seen from Figures 33, 34 and 35, TSS was not reduced effectively and the removal rate is lower in comparison to other pollution parameters. Variation between influent and effluent concentrations of TSS is rather low and unchanged during most of the experiment. With regard to the lower TSS removal efficiencies reported, they were probably as a result of the (1.2-1.9) cm diameter substrate which induced the rapid seepage of the wastewater through the wetland reducing the retention of TSS as suggested by Zurita et al. (2009).

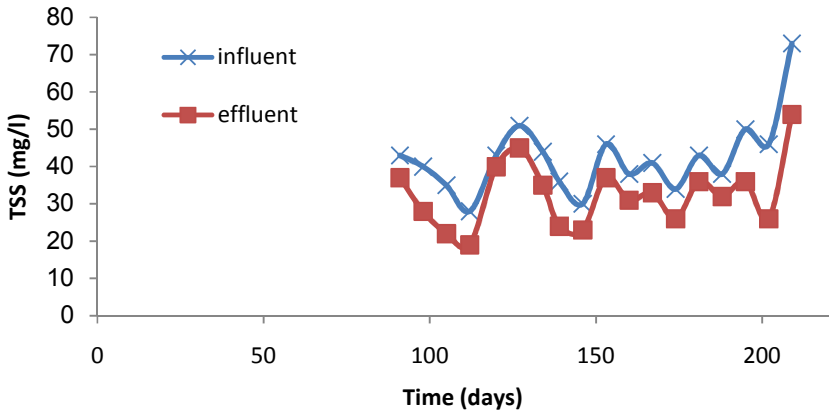

Figure 4.36 Influent and effluent TSS concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah City/ Palestine

Suspended solids are mainly removed by physical processes such as sedimentation and filtration followed by aerobic or anaerobic microbial degradation in the substrate. TSS is removed by wetlands due to the filtering action of the bed media. Filtration occurs by impaction of particles onto the roots and stems of the phragmites or onto the gravel particles in the constructed wetland systems (Zurita et al., 2009).

Total Dissolved Solids (TDS)

There was an increase in TDS concentrations and EC for all water sources. Total dissolved solids (TDS) were increased due to mineralization process. The plants degrade and produce TDS at the same time, the system removes TDS but the first process is dominated and causes the increase in TDS as well as EC concentrations.

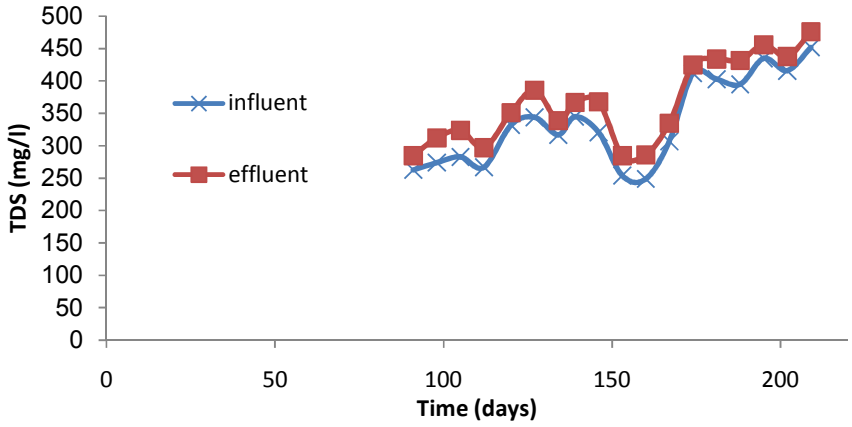

Figure 4.37 Influent and effluent TDS concentrations in a constructed wetland treating anaerobically pretreated wastewater in Al-Mazra'a, Ramallah City/ Palestine

TDS content was almost stable; the influent concentrations are very close to the effluent concentration.

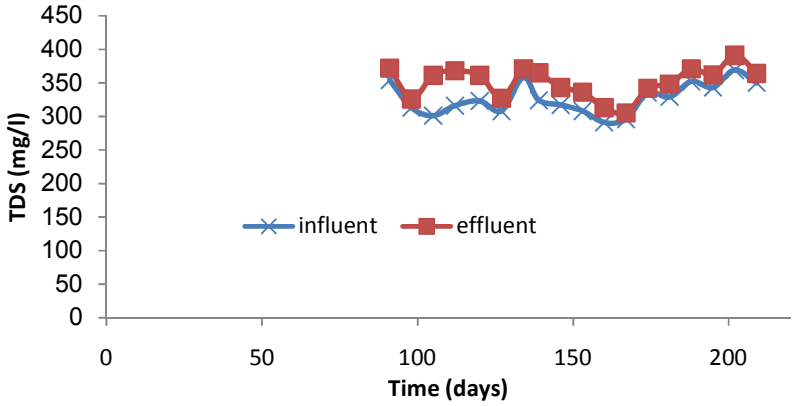

Figure 4.38 Influent and effluent TDS concentrations in a constructed wetland treating tertiary treated municipal wastewater in an extended aeration wastewater treatment plant, Al-Bireh City/Palestine

A TDS removal rate of 91.2% was obtained by Vipat et al. (2008).

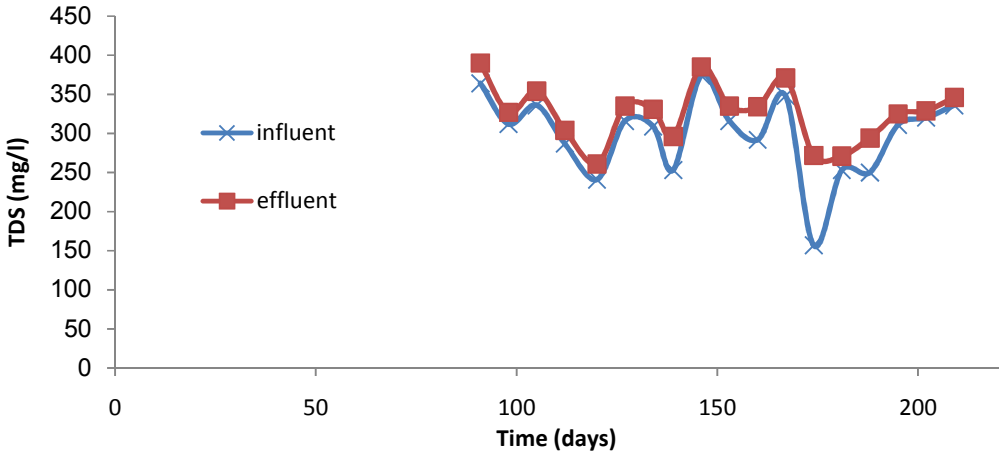

Figure 4.39 Influent and effluent TDS concentrations in a constructed wetland treating secondary treated wastewater in Birzeit University treatment plant, Ramallah/Palestine

4.2.3 Biological parameter

Influent and effluent fecal coliform concentrations are presented in Table 4.7.

Table 4.7 Average fecal coliform concentrations for the influent and effluent in (cfu/100ml)of the three constructed wetland during the period (15/June/2011-11/Oct/2011)

	Unit	Al-Mazra'a water	Al-Bireh water	Birzeit Water
Influent	CFU/100ml	4.4E+09 (8.68E+09)	1.6E+08 (4.29E+08)	9.3E+09 (1.8E+10)
Effluent	CFU/100ml	1.2E+08 (1.69E+08)	5.7E+07 (1.75E+08)	2.6E+08 (6.16E+08)
Removal	%	14 (6.52)	16 (9.8)	16.6 (6.1)

* Fecal coliform removal efficiencies were calculated using log 10

It can be noticed that this stable removal didn't apply perfectly to the system fed with tertiary treated wastewater. The total number of coliform bacteria was reduced by more than 99% as Mantovi et al. (2003) recorded. Fecal coliform removal in the range of (72-79) % was recorded by Niyonzima (2007). Also, a

99.7% removal was recorded (Pucci et al., 1998). A removal rate of coliform bacteria of 98.7% was recorded by Viapt et al. (2008).

Table 4.8 The estimated uptake capacity in Kg/ha/year of reed in the constructed wetland

Water source	parameter		
	Phosphate	Nitrogen	BOD
Al-Mazra'a	858	12791	4752
Al-Bireh	1418	9349	770
Birzeit	1423	11815	3889

The uptake capacity presented in Table was calculated using the following equation:

$$uptake\ capacity\ = \frac{Qd(\ Cin - Cout)}{A}$$

Where:

Q: flow rate in L/day

C_{in} and C_{out}: influent and effluent concentrations in mg/l

A: surface area of the constructed wetland

Discussion

Three horizontal subsurface flow constructed wetlands were constructed outdoor in the campus of Birzeit University, Palestine. They were planted with reed and filled with gravel. In midsummer (July), *reed biomass* reached maximum growth. In this study, the HRT was 1.3 days which was sufficient enough for plants to filter and nutrients uptake in the wastewater. The system was artificially aerated in

order to enhance nitrogen removal efficiency (landry et al. 2009). The difference in the results of this study may not agree with other authors' findings due to the difference in experimental setup, substrate, and plant species.

Reed (phragmites Australis) has been shown to survive and perform well in treating the three investigated wastewaters while gravel material provides a suitable plant growth medium in constructed wetlands.

The constructed wetland has a depth of filtration bed of 0.4 m in order to allow roots of wetland plants (phragmites Austrailis) to penetrate the whole bed and ensure oxygenation of the bed through oxygen release from roots. In this context, roots and rhizomes of reed and other wetland plants are hollow and contain air filled channels that are connected to the atmosphere for the purpose of transporting oxygen to the root system. As the roots are not completely gas tight, some oxygen is lost to the rhizosphere. However, many studies have shown that the oxygen release from the roots of different plants is far less than the amount needed for aerobic degradation of the oxygen consuming substances delivered with wastewater. As a result, organic compounds are degraded aerobically as well as anaerobically by bacteria attached to plant roots and rhizomes and media surface.

The constructed wetland showed a good potential for the reduction of ammonia and nitrate. Also, the constructed wetland was efficient in terms of total nitrogen removal and achieved the Palestinian requirements for using treated effluent for recharging the aquifers. The characteristics of the media type selected in this

system (gravel) were inferred to be a factor causing such high removal of phosphorous by adsorption. The constructed wetlands were operated in the summer season. Landry et al. (2009) found that summer and fall removals were generally higher than the winter removal. The treatment in the constructed wetlands has shown tolerance to different influent concentration (Pucci *et al.*, 1998).

Hence the algal activity is negligible, pH values do not increase. In TSS **r**emoval, constructed wetlands did not give the best result, although it has a good reduction efficiency level for COD and NH_4-N. Effluent concentrations of COD and NH_4 also have positive results in constructed wetlands. NH_4 concentration in effluent also decreased significantly, from Figures 4.16, 4.17 and 4.18 it is obvious that the effluent concentration of NH_4 decreased and was almost stable. Also, the removal efficiencies for NO_3 and NH_4 in the constructed wetlands were generally on the high end of the ranges reported in constructed wetlands for domestic wastewater. Removal of Ammonia (NH_4) was the most effective in the constructed wetlands when compared to Phosphorous and DOC. The average removal efficiencies in NH_4-N were 77, 83 and 84%, and TKN were 53, 35 and 50%, PO_4-P were 50, 47 and 49%, DOC were 32, 34 and 31% for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively. It is suggested that nitrogen retention in constructed wetlands is thought to occur mainly as a result of ammonification where dissolved organic converted to ammonia NH_4, followed by nitrification and denitrification (Landry et al., 2009). In general, nitrification which is performed by strictly aerobic bacteria is mostly restricted to areas adjacent to roots and

rhizomes where oxygen leaks to the filtration media. On the other hand, prevailing anoxic and anaerobic conditions offer suitable conditions for denitrification but the supply of nitrate is limited as the major portion of nitrogen in sewage is in the form of ammonia. Also, mineralization of organic nitrogen (ammonification) which precedes both under aerobic and anaerobic conditions, actually add ammonia to the system. Volatilization, adsorption and plant uptake play much less important role in nitrogen removal in HSSFCW. Volatilization is limited by the fact that the HSSFCW do not have a free water surface. In this research, it is expected that plant uptake is the main removal mechanism. Depending on the obtained results, there is almost no value added for using constructed wetland as a polishing step for Al-Bireh tertiary treated wastewater. That's due to the already low concentration of this effluent.

Table 4.9 Wastewater characteristic for constructed wetlands effluents and specifications for treated water for reuse

parameter	Constructed wetland effluents			Wastewater characteristics for reuse				Wastewater characteristics Aquifer for recharge
	Al-Mazra'a water	Al-Bireh water	Birzeit water	Class A	Class B	Class C	Class D	
BOD5	11.1	5.73	8.58	20	20	40	60	
COD	34.13	24.2	31.1	50	50	100	150	150
NO3-N	2.74	3.02	2.08	20	20	30	40	15
NH4-N	1.7	0.63	1.09	5	5	10	15	10
TN	16.1	15.1	15.8	30	30	45	60	
TSS	80.2	26.05	32.44	30	30	50	90	
FC	1.2x10^8	5.7x10^7	2.6x10^8	200	1000	1000	1000	

References: Palestinian specification No. 34-2012 and Palestinian Specification 742-2003.

- Despite the fact that Al-Bireh treatment plant's effluent is well treated but there still a need to protect the harmful effect on the environment. In other words, constructed wetlands can be used as a disposal option for that water. From the table above, the results reveal that constructed wetland effluents achieve most of class A requirements expect TSS and fecal coliform requirements. In this case, the constructed wetland can be followed with a sand filter.
- The systems operated with Al-Mazra'a and Birzeit wastewaters showed a higher removal rates for COD than that obtained for Al-Bireh. Similar results were found for BOD and TKN.
- The DOC and PO_4-P removal rates for all waters were similar to each other. Removal rate of 32, 34 and 31% for DOC and 50, 47 and 49 % for PO4-P.
- For ammonia and nitrate, the constructed wetland achieved high removal rates for all waters. The average removal rates for NH_4-N were 77, 83 and 84% and for NO_3-N were 75, 79 and 81% for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively.
- The constructed wetland showed a low removal for SO_4 and TSS with SO_4 removal rates of 15.2, 15.5 and 18.8% and 16.4, 21.9 and 23.3% removals for TSS.
- Also, the constructed wetland achieved poor results regarding fecal coliform removal.

Chapter five

Conclusions and recommendations

5.1 Conclusions

- The pollutant removal rates in the constructed wetlands were positive for all the pollutants, except TDS, EC. The removal efficiencies in all wetlands were generally on the high end of the ranges reported in constructed wetlands for domestic wastewater and grey water.
- The constructed wetland was efficient for total nitrogen removal with removals efficiencies of 64, 57 and 65.5% for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively.
- Sulphate wasn't removed in the constructed wetland an achieved 15, 15.5 and 18.8% removal efficiencies for Al-Mazra'a, Al-Bireh and Birzeit waters, respectively.
- The results reveal that that constructed wetland effluents achieve most of class A requirements expect TSS and fecal coliform requirements for reuse in irrigations or to recharge the aquifer.

The results of the water analyses performed on the influent and the effluents of the system are:

- The removal rates for COD were 34, 29 and 32% on average for the Al-Maza'a, Al-Bireh and Birzeit waters, respectively. However, percentage reduction for COD was generally lower than some removal percentages reported in the literature.

- The average BOD removal efficiencies were high in all constructed wetlands. The removal efficiencies observed in the wetlands waters fall within the range of results found in the literature. For the HFCWs, the BOD removals are slightly lower than the average value of 85% BOD removal for different countries reported by other authors.
- Organic matter and nitrogen removal rates improved significantly. Ammonium reduction was observed at high levels for all the constructed wetlands. The maximum ammonium reduction was observed as 84% in the system fed in Birzeit water.
- The presented results indicated that nitrification and denitrification remained high in constructed wetlands with shallow depth, and therefore ammonium and nitrate is effectively removed in the wastewater. The role of plants could promote the removal efficiency of nitrogen and phosphorous in the constructed wetlands.
- The final concentration of nitrate was not sensitive to nitrification because the NH_4 concentration was lower than the NO_3 concentration in the inflow. The development of anoxic zones in the HSSFCWs along their performance was probably due to the high porosity of the rocks which caused the retention of a bigger amount of water inside their porous; in this way it was not possible for the rocks to get completely dry as the performance advanced.
- Phosphorus removal also was found in low levels. In the three waters, phosphorus removals were the highest as 50% in wetland fed with Al-Mazr'a

water. In phosphorus removal, wetland fed with Al-Bireh water did not give the best result;

- In contrast to the results obtained for BOD and COD, TSS removal was not high. In constructed wetlands, TSS are removed mainly by physical processes such as sedimentation and filtration followed by aerobic or anaerobic microbial degradation inside the substrate. These processes are achieved when the wastewater passes through the system at a low velocity because of the presence of vegetation and the substrate.
- The VFCWs were more effective at reducing total coliform than the HFCWs. Such results agree with those reported by Vacca et al. (2005) who found a higher reduction of total coliform in VFCWs. The main difference between the two types of wetlands was the higher oxygen concentration in the VFCW, as well as a slightly higher temperature. Different works have demonstrated that anaerobic conditions prolong the survival of coliforms in constructed wetlands and in contrast, aerobic conditions, such as those predominant in VFCWs, are unfavorable for them conducting to a higher removal efficiencies (Vymazal, 2005).

Recommendations

- Further research is required on the subject, including the study of these treatment systems under a controlled environment and the evaluation of the performance during longer period of time.
- As the research into artificial aeration treatment in CWs is very new, economic and energy analysis are lacking and should be investigated

- Further research is required on the subject, including the study of these treatment systems under a controlled environment and the evaluation of the performance during longer period of time.

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Annexes

Annex A:Influent and effluent concentrations, removals efficiencies and rate constant

Table 1 DOC removal efficiencies (%) of the three constructed wetlands during the period (15/July/2011- 11/Oct/2011)

# of days	Al-Mazr'a water	Al-Bireh water	Birzeit water
91	34	38	34
98	33	39	37
105	27	36	35
112	31	38	33
120	34	33	33
127	35	36	36
134	35	33	31
139	27	31	28
146	39	36	23
153	37	39	28
160	34	30	33
167	23	36	26
174	37	28	30
181	38	34	23
188	31	38	32
195	35	29	31
202	15	36	34
209	30	34	31

Table 2 Calculated rate constant (KBOD) for the three water influents

Date	# of days	Al-Mazr'a water			Al-Bireh water			Birzeit water		
		BOD in (mg/l)	BOD out (mg/l)	KBOD	BODin (mg/l)	BODout (mg/l)	KBOD	BODin (mg/l)	BODout (mg/l)	KBOD
15/6/2011	66	22.25	13.54	0.07	4.88	4.13	0.03	17.62	10.65	0.08
22/06/2011	73	15.6	11.85	0.04	5.75	4.86	0.03	15.82	12.8	0.03
29/06/2011	80	15.12	9.75	0.07	6.36	5.34	0.03	22.2	16.42	0.05
06/07/2011	87	13.46	15.74	-0.02	6.58	5.81	0.02	17.31	8.53	0.11
14/07/2011	95	22.53	16.3	0.05	6.72	5.2	0.04	13.44	6.12	0.12
21/07/2011	102	11.5	8.62	0.04	5.61	5.06	0.02	14.86	8.46	0.08
28/07/2011	109	15.35	4.28	0.19	7.62	7.14	0.01	15.9	7.21	0.12
02/08/2011	114	22.86	16.73	0.05	6.43	5.48	0.02	20.2	9.7	0.11
09/08/2011	121	28.4	22.75	0.03	7.68	5.72	0.04	16.52	4.8	0.19
16/08/2011	128	29.37	15.32	0.10	10.4	5.87	0.09	17.91	8.04	0.12
23/08/2011	135	15.94	7.61	0.11	9.67	6.28	0.06	15.82	9.43	0.08
30/08/2011	142	26.25	8.22	0.17	6.1	5.73	0.01	15.34	8.55	0.09
06/09/2011	149	20.7	5.4	0.20	6.92	6.24	0.02	16.22	9.47	0.08
13/09/2011	156	22.69	7.72	0.16	8.52	6.15	0.05	13.6	7.48	0.09
20/09/2011	163	21.9	4.8	0.23	5.53	5.04	0.01	14.08	5.46	0.14
27/09/2011	170	16.82	13.4	0.03	8.4	7.16	0.02	13.12	6.83	0.10
04/10/2011	177	23.46	8.62	0.15	7.61	5.4	0.05	14.88	6.7	0.12
11/10/2011	184	21.75	9.13	0.13	8.62	6.57	0.04	15.2	7.7	0.10
Average KBOD		0.10			0.03			0.10		

Table 3 Organic nitrogen concentration for the three constructed wetlands after 91 days of operation during the period of (15/June/2011- 11/Oct/2011)

# of days	Al-Mazr'a		Al-Bireh		Birzeit	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
91	28.95	22.44	19.36	11.39	19.21	13.09
98	19.08	8.08	21.25	14.29	24.96	12.32
105	17.08	9.56	13.22	9.1	27.84	22.5
112	29.55	10.61	10.87	9.52	22.21	18.49
120	23.03	13.55	14.42	10.83	32.05	21.4
127	15.84	8.39	17.82	14.25	19.87	11.6
134	28.6	15.62	17.25	13.73	29.78	14.02
139	27.88	11.66	16.85	12.8	12.34	8.48
146	27.71	14.97	23.15	20.55	15.62	9.54
153	18.84	13.59	22.4	15.45	8.8	8.32
160	19.12	15.27	14.55	13.18	27.89	11.53
167	36.13	18.78	14.44	9.83	21.49	9.21
174	29.41	18.38	14.44	9.84	28.3	19.19
181	18.62	12.7	17.83	15.45	41.9	16.9
188	18.21	12.06	18.08	12.09	17.96	10.97
195	7.24	9.09	7.4	5.04	17.23	9.85
202	15.27	8.36	8.94	6.37	7.22	14.33
209	21.43	10.39	9.2	2.6	3.86	10.69

*All units are in mg/l

Table 4 Fecal coliform concentrations in both influent and effluent in (cfu/100ml) during the period (15/June/2011- 11/Oct/2011)

Date	# of days	AL-Mazr'a water		Al-Bireh water		Birzeit water	
		Influent	Effluent	Influent	Effluent	Influent	Efflent
15/6/2011	91	2.0E+08	2.0E+07	3.0E+06	2.5E+06	5.0E+08	2.5E+07
22/06/2011	98	2.8E+08	5.5E+07	1.0E+07	3.0E+05	3.5E+09	5.0E+08
29/06/2011	105	3.0E+07	2.0E+07	1.0E+07	4.6E+06	6.0E+10	1.6E+09
06/07/2011	112	3.0E+08	5.2E+07	5.0E+06	4.0E+04	4.0E+09	1.2E+07
14/07/2011	120	2.0E+06	3.0E+05	5.2E+07	1.0E+06	3.0E+08	4.0E+07
21/07/2011	127	2.0E+08	3.5E+07	1.4E+07	1.5E+06	1.2E+08	2.0E+06
28/07/2011	134	9.0E+08	4.2E+08	2.0E+07	2.3E+06	2.2E+10	2.2E+09
02/08/2011	139	3.0E+08	2.4E+07	5.0E+06	4.0E+05	2.5E+08	3.0E+07
09/08/2011	146	2.0E+10	4.5E+08	1.8E+05	1.0E+05	1.6E+07	3.2E+06
16/08/2011	153	4.0E+08	3.3E+06	3.4E+05	1.0E+04	5.2E+07	1.0E+07
23/08/2011	160	1.0E+10	2.0E+08	2.5E+08	3.0E+06	3.0E+07	1.6E+06
30/08/2011	167	1.5E+08	2.0E+06	5.0E+08	3.0E+08	2.0E+07	1.4E+06
06/09/2011	174	1.5E+10	1.3E+08	1.0E+08	2.0E+06	2.0E+08	3.5E+06
13/09/2011	181	3.0E+10	2.6E+08	1.8E+09	7.0E+08	5.0E+10	6.0E+07
20/09/2011	188	3.0E+08	4.0E+06	5.0E+06	3.0E+05	5.0E+09	3.0E+07
27/09/2011	195	5.0E+08	2.2E+07	1.0E+07	2.3E+06	2.0E+10	1.5E+08
04/10/2011	202	2.0E+08	5.0E+08	6.0E+06	4.4E+04	4.0E+08	5.0E+06
11/10/2011	209	3.0E+08	4.2E+07	2.0E+06	1.0E+05	3.0E+08	1.7E+07

*for Al-Mazra'a wastewater: STD_{in} = 8.68xE9, STD_{eff} = 1.69xE8, average fecal removal = 73% (58%)

*for Al-Bireh tertiary treated wastewater: STD_{in} = 4.29xE8, STD_{eff} = 1.75xE8, average fecal removal = 77% (25.4%)

*for Birzeit secondary treated wastewater: STD_{in} = 1.8xE10, STD_{eff} = 6.16xE8, average fecal removal = 89% (65.6%).

Annex B: Calculations

The land requirements to polish the effluent of Ak-Bireh wastewater treatment plant to fit recharge requirements of 10, 10 and 10 mg/l for BOD, TN and TSS:

Kickuth proposed the following equation which was used for sizing of horizontal subsurface flow systems for domestic sewage treatment (Vymazal, 2005):

$$Ah = Qd(ln\ Cin - ln\ Cout)/KBOD$$

Where:

*A*h is the surface area of the bed (m^2),

*Q*d the average flow (m^3/day),

*C*in the influent BOD_5 (mg/l),

*C*out the effluent BOD_5 (mg/l)

and *K*BOD is the rate constant (m/day).

The required area depending on TSS, TN requirements is:

Ah = 5000 x (ln 33- ln 10)/0.1= 59696

Ah = 5000 x (ln 33- ln 10)/0.1 = 59696

The field measurements showed that the value of *K*BOD is usually lower than 0.19 m/day. Rate constant is increased with hydraulic loading rate and BOD_5 mass loading rate. The average *K*BOD value for 66 village systems after 2 years of operation was 0.118 ± 0.022 m/day (Vymazal, 2005).

Cross sectional area for the bed can be calculated using Darcy's Law: (Converse, 1999)

$$Ac = Q / (KsXS)$$

Where:

Ac = cross sectional area of bed (m^2)

Q= design flow (m^3/d)

K_s = hydraulic conductivity (259 $m^3/d/m^2$ for gravel)

S = hydraulic gradient (0.01 – 0.02 for 1% and 2% bottom slope)

CW design has been mainly based on rule of thumb approaches using specific surface area requirements or simple first order decay models. It have been reported that first order models are inadequate for the design of treatment wetlands (Langergraber, 2008)

$$A_c = 5000/ (259*0.02) = 965$$

If we use a constructed wetland with 45 cm depth,

Width = Ac/depth = 965/0.45= 2145 m

Length of the wetland = Ah/ width = 59696 / 2145 = 27 m