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United Arab Emirates University

College of Engineering

Department of Civil and Environmental Engineering

TREATMENT OF GREYWATER USING BIOFILTRATION AND PERMEABLE PAVEMENT SYSTEMS

Assem Mahn El-Ashkar

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering

Under the Supervision of Dr. Rezaul K. Chowdhury

October 2015

Declaration of Original Work

I, Assem Mahn El-Ashkar, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled *“Treatment of Greywater Using Biofiltration and Permeable Pavement Systems”* hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Dr. Rezaul K. Chowdhury, in the College of Engineering at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

Municipal wastewater can be divided into two categories, greywater and black water. Greywater occupies about 75% of total wastewater and are relatively less polluted than the black water. Reuse of greywater is becoming popular in many arid and semi-arid regions in order to reduce the municipal water demand. They can be reused for groundwater recharge, landscape irrigation and for toilet flushing. However, the main challenges are their collection, storage and selection of the appropriate treatment system. The United Arab Emirates (UAE) is located in a hyper arid region, having an annual average rainfall of less than 100 mm. Reliable survey data for surface water resources are not available here. Three main sources of water resources in the UAE are groundwater, desalinated water and reclaimed wastewater. Despite their scarce water resources, residential water consumption in the UAE is significantly high, of which more than half of the municipal water are used for outdoor activities. The water demand reduction and diversification of water sources are very important for the security of its urban water supply. The study investigated the quantity and characteristics of greywater, and the efficiency of two alternative treatment systems, the biofiltration and the permeable pavement with an underlying reservoir. The study was conducted in the city of Al Ain. Both treatment systems are conventionally used for urban stormwater treatment. They are popularly known as the Water Sensitive Urban Design (WSUD) systems. Laboratory scale prototypes of both systems were prepared and investigated. The estimated greywater generation rate was found about 190 liter/capita/day. The ablution and laundry greywater exhibits the least and most deteriorated greywater, respectively. Both systems performed well in improving the greywater quality, but the vegetative biofiltration unit performed better than the permeable pavement unit. The study revealed that the permeable pavement with an underlying reservoir can be used as a storage unit and subsequent treatment can be achieved in the vegetative biofiltration system. Both systems are well fitted within the urban landscape of UAE.

Keywords: Greywater, treatment, biofiltration, permeable pavement, irrigation.

Title and Abstract (in Arabic)

معالجة المياه الرمادية باستخدام الترشيح البيولوجي و الأرصفه ذات النفاذيه

الملخص

تقسم مياه الصرف الصحي الى فئتين، المياه الرماديه والمياه السوداء. تحتل المياه الرماديه مايقارب 75 % من مياه الصرف الصحي التام وهي نسبيا اقل تلوثا من المياه السوداء.

إن اعاده استخدام المياه الرماديه اصبح شائعا في العديد من المناطق القاحلة وشبه القاحلة من أجل الحد من الطلب على المياه .كما و يمكن إعادة استخدامها لتغذية المياه الجوفية، وري المسطحات الخضراء وغسل المراحيض. ومع ذلك، فإن التحديات الرئيسية تكمن في جمع وتخزين واختيار نظام المعالجة المناسب. تقع دولة الإمارات العربية المتحدة في منطقة ذات درجة قحولة عالية (انخفاض منسوب ومصادر المياه الجوفية) ، مع معدل هطول سنوي للأمطار بأقل من 100 ملم. ولا يتوفرحاليا احصائيات موثقة للموارد المائية السطحية. هناك ثلاثة مصادر رئيسية للموارد المائية في دولة الإمارات العربية المتحدة وهي المياه الجوفية والمياه المحلاة ومياه الصرف الصحي المعالجة. على الرغم من ندرة الموارد المائيه، فان معدلات استهلاك المياه في المناطق السكنيه في دولة الإمارات العربية المتحدة مرتفع و بشكل ملحوظ، بحيث ان اكثر من نصف المياه المزوده للمناطق السكنيه من قبل البلديه تستخدم للأنشطه الخارجيه.ولذلك فأن تخفيض الطلب على المياه وتنويع مصادرها هي امر هام جدا من اجل المحافظة على الأمن المائي - اي امداد وتزويد المناطق الحضرية بالمياه. تبحث هذه الدراسه في كمية وخصائص المياه الرمادية، وكفاءة نظامى الترشيح البيولوجي و الأرصفه ذات النفاذيه مع وضع خزان من تحتها . أجريت الدراسه في مدينة العين. كلا نظامى المعالجه يستخدمان بشكل تقليدي في معالجه مياه الأمطار في المناطق الحضرية، ومن المعروف على أنها أنظمة لمعالجة مياه الأمطار في المناطق الحضرية (WSUD).

تم اعداد نموذجين مخبريين لنظامي المعالجه في المختبر للفحص والتحقق. ووجد ان معدل انتاج المياه الرماديه يبلغ نحو 190 لترللفرد الواحد في اليوم. وقد وجد ان المياه الرماديه الناتجة عن الوضوء تمثل النسبة الاقل بينما المياه الرماديه الناتجة عن غسيل الملابس تمثل النسبة الاعلى.

أداء كلا النظامين كان جيدا في تحسين جودة المياه الرماديه، ولكن وحدة الترشيح البيولوجي الخضري كان ادائها افضل من وحده الأرصفه ذات النفاذيه. وكشفت الدراسه ان

وحدة الأرصفه ذات النفاذيه مع الخزان السفلي يمكن استخدامها كوحدة تخزين، و يمكن لاحقا متابعة المعالجة في نظام الترشيح البيولوجي النباتي. وقد تم تجهيز كلا النظامين ليتماشيا مع المظهر الحضري لدولة الإمارات العربية المتحدة.

مفاهيم البحث الرئيسية: المياه الرمادية، المعالجه، الترشيح البيولوجي، الأرصفه ذات النفاذيه، الري.

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Finally, I would like to acknowledge that the thesis is completed with financial supports from the UAEU-NRF Research Project (31N135) awarded to my supervisor.

Dedication

To my beloved parents and family for their endless love, support and encouragements

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List of Abbreviations

ADSSC	Abu Dhabi Sewage Service Company
ADWEC	Abu Dhabi Water and Electricity Company
AS	Anionic Surfactants
ADRSB	Abu Dhabi Regulation and Supervision Bureau
BOD	Biochemical Oxygen Demand
CR	Costa Rica
cm	centimeters
COD	Chemical Oxygen Demand
Ca^{+2}	Calcium ion
DO	Dissolved Oxygen
EAD	Emirate of Abu Dhabi
E.Coli	Escherichia coli
EC	Electrical Conductivity
C^{o}	Degree Celsius
FR (liter/minute)	Flow rate in liter per minute
FM	Number of Family Members
Fs	Daily frequency of using shower
Ftb	Daily frequency of using tooth brush
Fhw	Daily frequency of using hand wash
Ffw	Daily frequency of using face wash
Fa	Daily frequency of using ablution
Ftf	Daily frequency of using toilet flush
Fl	Daily frequency of using laundry

Fdw	Daily frequency of using dish wash
Fc	Daily frequency of using cleaning
Fp	Daily frequency of using pet water
Fv	Daily frequency of using vehicle cleaning
Fg	Daily frequency of using irrigation to garden
GAC	Granular Activated Carbon
Gw	Greywater generation
g/l	Gram per liter
g	Gram
g/m^3	Gram per cubic meter
K	Potassium
KT (day^{-1})	Reaction rate constant per day
KOH	Potassium Hydroxide
L_{org}	Value of BOD per area per day
L	Length of the system
l	Liter
L_{pcd}	Liter per capita per day
n	Sample size
NTU	Nephelometric Turbidity Unit
NF	Nano-Filtration
Na	Sodium
NO_3	Nitrate
N	Population size
OP	Ortho Phosphate

ORP	Oxidation Reduction Potential
pH	potential Hydrogen
PVC	Poly Vinyl Chloride
ppm	parts per million
ppt	parts per trillion
RO	Reverse Osmosis
SS	Suspended Solids
TSE	Treated Sewage Effluent
TN	Total Nitrogen
TP	Total Phosphorus
TOC	Total Organic Carbon
TDS	Total Dissolved Solids
UAE	United Arab Emiratis
UAEU	United Arab Emiratis University
UF	Ultra-Filtration
WSUD	Water Sensitive Urban Design

Chapter 1: Introduction

1.1 Overview

Water use in the Emirate of Abu Dhabi (EAD) had increased dramatically since the 1960s. Agricultural area reached more than 300,000 ha, which is irrigated mainly by groundwater and expensive desalinated water (Abu Dhabi Water Resources Master Plan, 2009). According to the Plan Abu Dhabi 2030: The Urban Structure Framework Plan (Abu Dhabi Urban Planning Council, 2007), the population of EAD will be more than three millions by 2030 and more than 1.5 million in the Al Ain. Tourism will be increased to almost 8 million visits per year (currently there are 1.8 million visits per year). This additional population will create tremendous pressure on existing water resources and water infrastructures. Currently, about two thirds of EAD’s water resources are used in agriculture and forestry. Agricultural water demand around Al Ain and Liwa exceeds the natural recharge capacity of the groundwater reservoir and groundwater levels have dropped significantly. About three quarters of desalinated water supplies in EAD are used primarily for vegetation – amenity plantations, home gardening, parks and private households (Abu Dhabi Water Resources Master Plan, 2009). To ensure adequate municipal water supply and to reduce the water consumption demand are the most significant challenges in the EAD. As a consequence, the EAD-Environment Agency has prioritized the necessity of improvement of water quantity and quality in EAD; and the Plan Abu Dhabi 2030 has emphasized on sustainable utilization of land and water resources. Water demand reduction and diversification of water sources are considered the two most vital tools for mitigating water crisis in the EAD.

Approximately one fifth of residential water in EAD is used for toilet flushing and about one third is for irrigation to amenity vegetation (Oasis Design, 2008). Though a highly efficient (98% efficiency) centralized wastewater collection sewer network and treatment plants are available in EAD, end uses of treated sewage effluent (TSE) requires development of an expensive distribution network (dual reticulation). This will significantly increase the marginal cost of water supply. Therefore a centralized TSE reuse scheme is not economically viable in the region. The decentralized reuse of greywater has the potential to reduce water demand, however the key challenges are their collection, storage and selection of the appropriate treatment system.

The two types of greywater treatment systems used in this study were vegetative biofiltration and permeable pavement with an underlying reservoir. The biofilter consists of filter media with attached-growth microorganisms to eliminate organic materials and nutrients. A biofiltration greywater treatment system is the best to use wherever a large quantity of greywater is being released. For instance, water from a sink, laundry area, shower, or bath can easily be diverted into the biofiltration system before it enters the receiving environment. The main objectives of the biofiltration greywater treatment system are to provide a better way for greywater disposal, solve the issues of greywater treatment odors around the treatment plants, prevent eutrophication (nutrient overload) of surface waters and preserve groundwater and surface water from any contamination (Yocum, 2006). According to Yocum (2006), treatment of greywater using biofiltration system is low cost for single or group householders, and help to protect fresh water by removing a huge amount of pollutants before it goes to groundwater, rivers or wetlands. Biofiltration system provides healthier ecosystem by eliminating pathogens, bacteria, and non-biodegradable toxins' effects.

Pavements account for a large portion of the impervious area in urban catchments. Permeable pavement is a water sensitive urban design (WSUD) technique that allows infiltration of storm water runoff and is generally constructed in the car parking zones. The base course of permeable pavement can be utilized as a reservoir for greywater storage (Beecham and Chowdhury, 2012). The quantity and quality of greywater harvested and stored using permeable pavement with an underlying reservoir is an important research consideration, particularly for fit-for-purpose reuse. The harvesting, storage and reuse of greywater from permeable pavement reservoirs provide an opportunity to alleviate water shortages in urban areas and to promote amenity plantations. The base course aggregate materials used in permeable pavement provide structural support to the pavement. The materials have the potential to affect the quality of stored greywater.

Permeable pavements are used to allow storm water to infiltrate through the paving surface where it is filtered through various layers and then either harvested for later reuse through an underlying reservoir or released slowly into the underlying soil or downstream storm water drainage system (Beecham and Chowdhury, 2012). There have been numerous research studies outlining the potential water quality benefits of permeable pavements (Myers *et al*., 2009, 2011). Permeable pavements therefore perform the dual functions of supporting traffic loads and intercepting and treating storm water runoff. Previous research on microbial activity in permeable pavements has shown that the base course can develop and maintain a diverse microbial community. Pratt *et al*. (1999) reported that microbial community develops in base course can sufficiently degrade oil pollution in model permeable pavement reservoirs under idealized conditions. Myers *et al*. (2011) observed that permeable pavement with underlying reservoir can reduce heavy metals (copper, zinc and lead) up to 94%-99% when stored for 144 hours. Beecham and Chowdhury (2012) investigated the hydraulic performance of permeable pavement in semi-arid Australian region. While there are some studies on the effectiveness of permeable pavements in improving storm water quality – very little or no information is available for greywater quality enhancement. Since rainfall and urban runoff are not an abundant water resource in UAE, WSUD systems (permeable pavement, biofiltration, etc.) are not commonly seen in UAE. Therefore, this study will investigate the potential of permeable pavement and biofiltration in improving greywater quality for reuse.

1.2 Statement of the Problem

1.2.1 Groundwater and desalinated water consumption in the Abu Dhabi Emirate

Water demand has been increased massively in the past few years in the UAE, about 3% increased from 2011 to 2012, while the rain rate is very low by less than 100 mm per year (Abu Dhabi Environment Agency, 2013). About 24% of desalinated water only goes back to the sewage systems, according to the Abu Dhabi Environment Agency (2013), which is because 74% desalinated water are used for outdoor activities such as gardening and car washing. Approximately 49%, 45% and 48% of generated treated sewage effluent (TSE) were discharged to the sea in the year 2010, 2011 and 2012, respectively. The reason of discharging TSE rather than consuming is due to the low acceptance of TSE to the local farmers or agricultural land owners and to the public to reuse it. In contrary, parks, forests and agricultural lands in the EAD consume the highest amount of fresh water by 2,414 Mm^3 in 2012 and about 92% of this fresh water are groundwater (Abu Dhabi Environment Agency, 2013). Residential water consumption is in the second place by desalinated water consumption of 549 Mm^3 per year. Because of high groundwater consumption and subsequent drawdown of groundwater table and salinity intrusion, desalinated water production increased from 961.5 to 1,059 Mm^3 in 2012, in order to cover the shortage in groundwater levels to meet the required demands.

1.2.2 Wastewater plants in the Abu Dhabi Emirate and Al Ain City

A total of 36 wastewater treatment plants are located in the capital city (Abu Dhabi) and in the Al Ain city. The largest wastewater treatment plant in Abu Dhabi and Al Ain are known is known as the Al-Mafraq (Abu Dhabi) and Zahker wastewater plant (Al Ain) with 93% of all treated wastewater production (265.4 Mm^3) (ADSSC, 2012). Due to the low reuse of treated wastewater, about 25% of raw wastewater is thrown to the sea causing the environmental crisis. Table 1.1 represents the treatment plants' function in the EAD, whereas Table 1.2 shows the future new plants for wastewater treatment in the EAD.

1.2.3 Future wastewater production and consumption in the Abu Dhabi Emirate

It is generally expected that the uses of recycled wastewater (also known as the treated sewage effluent – TSE) will be increased in the Abu Dhabi. This is particularly because of lack of fresh water resources in the region. Figure 1.1 represents the forecast of TSE production and different scenarios for the Abu Dhabi (Dawoud *et al.*, 2012). It displays that the likely and possible TSE available from 2012 to 2025 wouldn't be enough to cover the needed treated sewage water for farming, cooling and irrigation purposes.

Table 1.1: Functional treatment plants in the Abu Dhabi Emirate (Dawoud *et al.*, 2012 and ADSSC, 2009)

Eastern Region		**Abu Dhabi and Western Region**	
Treatment Plant	**Production (million m^3/yr)**	**Treatment Plant**	**Production (million m^3/yr)**
Al Ain - Zakher	43.80	Al Mafraaq	186.40
Al Araad	0.02	Al Khatem	0.27
Al Dhahira	0.16	Ghantout	0.24
Al Faqah	0.20	Al Maraa	2.38
Al Haiar	0.68	Mirfa Cans Factory	0.07
Al Khazna	0.39	Bainounah	0.35
Al Qoaa	0.72	Madient Zaied	3.49
Al waqan	0.46	Liwa	0.28
Al Yahr	0.08	Abu Al Abyad Island	0.12
Bu Keriayah	0.10	Sir Bani Yas Island	0.13
Remah	0.36	Ghuwaifat	0.19
Seih Ghraba 1	0.03	Ghayathi	1.23
Seih Ghraba 2	0.01	Delma	0.38
Al Shweib	0.37	Baaya-Sila	0.98
Sweihan	0.39		
Wadi Fiely	0.44		
Sub Total	28.2		196.5
Total TSE production in the Abu Dhabi Emirate (2011)			244.7

Table 1.2: Future wastewater treatment plants in the Abu Dhabi Emirate (Dawoud *et al*., 2012 and ADSSC, 2009)

Location	**Catchment**	**Capacity (m^3/day)**	**Commissioning**
Al Wathba 1	Abu Dhabi Island & Mainland	345,000	Q1 2011
Al Wathba 2	Abu Dhabi Island & Mainland	345,000	Mid 2012
Al Saad	North Catchment Al Ain City	92,000	Q1 2011
Al Hamah	South Catchment Al Ain City	149,500	Mid 2012
Total Future Additional Capacity		931,000	

Q1 2011: First quarter (January-March) of 2011; Mid 2012: June of 2012

Figure 1.1: Recycled wastewater consumption and production forecast up to 2025 in the Abu Dhabi (Dawoud *et al*., 2012)

1.2.4 Local treated wastewater standards for irrigation purposes

Table 1.3 shows the maximum allowable limits of treated wastewater for the restricted (limited to cereal, industrial and fodder crops) and unrestricted (vegetable and salad crops) irrigation purposes (Dubai Environmental Regulations, 2011).

Table 1.3: Water quality standards for irrigation (Dubai Environmental Regulations, 2011)

Parameters	**Maximum allowable limit**	
	Unrestricted irrigation	**Restricted irrigation**
pH	8.00	8.00
Turbidity (NTU)	5.00	5.00
DO (mg/l)	5.00	3.00
TDS (g/L)	2.00	2.00
Na+ (ppm)	200.00	200.00
NO_3 (ppm)	50.00	50.00
Ammonia (mg/l)	5.00	10.00
Sulfate (mg/l)	400.00	400.00
COD (ppm)	150.00	200.00
Total Coliform (ppm)	-	1
Yeast and Mold (ppm)	-	1

1.3 Purpose of the Study

The purpose of this study is to investigate the efficiency of vegetative biofiltration and permeable pavement with an underlying reservoir system for the treatment of freshwater for their non-potable end uses (irrigation to the plantation). The study also investigates the quality of greywater in the city of Al Ain in UAE. The study investigated the changes in greywater quality through biofiltration system with native vegetations and changes in greywater quality when stored in the base course aggregates of the permeable pavement system. Furthermore, the study investigated the influence of residence time of greywater in the biofiltration and permeable pavement systems on their quality improvement and on the hydraulic design of the systems for greywater treatment. The study considered an urban runoff based WSUD systems into a new application of greywater treatment.

1.4 Scope of the Study

The Abu Dhabi Water Resources Master Plan (2009), the Plan Abu Dhabi 2030 and the Plan Al Ain 2030, all of them have emphasized on the water demand reduction and water source diversification for the security of urban water supply in the UAE. This can be achieved through reuse of alternative sources such as the greywater. Since rainfall and urban runoff is not an abundant water resources in the UAE, treated greywater and treated wastewater are the only potential alternative resources. The challenges for reusing greywater include its capture, storage, appropriate treatment, and supply to end users at cost-effective prices. The conventional greywater treatment systems are generally expensive and requires regular maintenance. Therefore, alternate treatment mechanisms are required to investigate. Through this study, greywater quality in the Al Ain city, treatment efficiencies and hydraulic design of two WSUD systems (biofiltration and permeable pavement) have been explored.

1.5 Objective of the Study

The aim of the study is to explore the performance of two Water Sensitive Urban Design (WSUD) technologies (permeable pavement and biofiltration) in improving the greywater quality for their reuse in household gardening purpose. The study will help to minimize the knowledge gaps in greywater reuse challenges in the UAE. The specific objectives of the study are to:

a. Assess the greywater quality in the Al Ain city of UAE,
b. Assess the changes of greywater quality in the vegetative biofiltration and permeable pavement with an underlying reservoir system,

c. Explore the influence of residence time on greywater quality improvement in the above mentioned systems, and
d. Understand the performance of the permeable pavement and vegetative biofiltration systems in arid regions.

1.6 Need of Resources

The following resources were needed to conduct the study:

a) Laboratory scale vegetative biofiltration unit, which was made available through the UAEU-NRF 31N135 research project,
b) Laboratory scale permeable pavement unit, which was made available through the CE-SEED-13 21N139 research project,
c) A portable multi-parameter water quality meter (HORIBA U-50 model), which was made available through the UAEU-NRF 31N135 research project,
d) Portable ion meters (Ca, Na, K, NO_3, salt), which were made available through the UAEU-NRF 31N135 research project, and
e) Laboratory chemicals for the analyses of COD, BOD, E.Coli, etc., which were made available from the CE-SEED-13 21N139 research project.

1.7 Expected Outcomes of the Study

The expected outcomes of the study are listed below:

a) Greywater generation rate in the city of Al Ain, UAE,
b) Characteristics of greywater in the city of Al Ain, UAE,
c) Identify the factors affecting greywater reuse,
d) Performance of permeable pavement systems in improving greywater quality,
e) Performance of biofiltration system in improving greywater quality,

f) Hydraulic design of permeable pavement and biofiltration systems for the greywater reuse scheme in the arid regions, and

g) Provide recommendation to implement the efficient use of greywater in order to reduce the municipal water demand in the Abu Dhabi Emirate.

1.8 Study Limitation

The study was conducted using two prototypes of permeable pavement and biofiltration systems. The actual field study or the pilot study was not conducted. The greywater quality was measured by investigating 100 villa type houses randomly located in the city of Al Ain, where the total population is about 0.5 million. It is assumed that the 100 villa type houses represent the UAE national population in the region. Two kinds of greywater sources (laundry and ablution) were considered in investigating the performances of treatment systems. The heavy metal removal efficiency of the treatment systems was not investigated.

1.9 Thesis Layout

This thesis comprises of seven chapters. Chapter 1 contains the background and introduction along with the study objectives, scope and limitations. Chapter 2 contains the literature review of greywater reuse, characteristics, greywater literature and greywater treatment systems. Chapter 3 describes the methodologies followed in the study. Chapter 4 includes the greywater characteristics estimated in the study. Chapter 5 and 6 includes the results of the performance of permeable pavement and biofiltration in treating greywater, respectively. The Chapter 7 contains the conclusion and recommendation.

Chapter 2: Literature Review

2.1 Background

The rapid population growth, improvement of living standards, agricultural expansion and desert greening policies in the UAE significantly increase the fresh water demand. In the UAE, there are three main water sources, groundwater, desalinated water and recycled wastewater. Desalinated water is used for residential purposes whereas groundwater is used for agricultural purposes. The recycled wastewater is mainly used for irrigation to street side plantations, however, more than 50% of recycled wastewater are discharged to the Arabian Sea. In the residential premises, municipal water (desalinated water) is used for both indoor and outdoor purposes. In a recent study, Rajput (2015) showed that water demand is more than 2000 liter/capita/day in the villa type houses and more than 80% of this supplied water are used for outdoor uses (irrigation to vegetations and car washing). The Rajput (2015) also showed that about 50% of the generated greywater (at the rate 190 liter/capita/day) can be reused without affecting water supply network and downstream sewer network. Providing fresh water for the upcoming years in the UAE is a challenge since groundwater level is declining and desalination is significant energy and cost intensive along with environmental problems from brine discharge. Therefore, new technologies and researches must be conducted to overcome the issue. The purpose of this chapter is to review previous studies and literatures to understand the greywater reuse, its characteristics, treatment systems and how could be utilized for non-potable uses of treated greywater.

2.2 Greywater

Greywater is the collected residential wastewater excluding that originates from toilets (Eriksson *et al*. 2002; Jefferson *et al*. 1999) and kitchen (Li *et al*. 2009; Al-Jayyousi 2003). The residential or municipal wastewater consist of black and greywater. Black water originates from toilet and kitchen, and mainly contains nitrogen, phosphorus, pathogens, hormones and pharmaceutical residues. Greywater originates from shower, wash basin, laundry and ablution. About 75% of total wastewater are the greywater (Rajput, 2015). Because of their low strength, they can be reused for non-potable water applications such as irrigation and toilet flushing (Otterpohl, 2002).

Greywater generally contains less organic matter and nutrients compared to municipal wastewater. This is because urine, feces and toilet papers are absent in greywater. However, it may contain different xenobiotic organic compounds (XOCs) originating from household chemical products such as soaps, detergents and cosmetics (Eriksson *et al*., 2002). Greywater quality is highly variable because of the variability of the lifestyles of people and the products they use (Li *et al*., 2009). Chemical and microbiological contaminants present in greywater may stimulate microbial growth in the system (Widiastuti *et al*., 2008). Kitchen and laundry greywater are comparatively higher in organics and physical pollutants than other greywater sources (Eriksson *et al*., 2002). The presence of *Escherichia coli.* and faecal enterocci bacteria have been reported in the bath (Laine, 2001), shower (Laine, 2001) and washbasin (Laine, 2001; Birks *et al*., 2004) greywater, which indicates a pathogenic risk associated with reusing greywater without disinfection.

Nutrients present in greywater can support growth of indicator organisms during storage, particularly because the temperature of greywater is typically warm (Birks and Hills, 2007). The major target of greywater recycling and reuse is to reduce the suspended solids, organic matter and pathogens (Li *et al*., 2009). Removal of organics from greywater decreases the chlorine demand and reduces the potential of microbial growth in the distribution system and in toilet cisterns (Winward *et al*., 2008). Because of excessive sodium accumulation, untreated laundry greywater can be unsuitable for irrigation (Misra and Sivongxay, 2009). Untreated greywater in toilet cisterns may cause odors, staining of toilet bowls and potential transport of pathogens (Mourad *et al*., 2011). The problems associated with greywater reuse include the public health risk associated with spreading of diseases due to exposure to pathogens and the risk of pollution of soils and receiving waters due to the presence of various pollutants (Eriksson *et al*., 2002). Previous studies in the United States identified increased sodium and surfactant concentrations in soil after irrigation with greywater, but was not observed in the high concern range for plant growth and soil quality (Negahban-Azar *et al*., 2012).

Greywater quality changes with time during storage (Liu *et al*., 2010). Long residence times can promote bacterial re-growth that may lead to degradation of greywater quality. Rose *et al*. (1991) found that the total fecal coliform count increased during the first 48 hours of storing untreated greywater before stabilizing over the next 12 days. Similarly, Dixon *et al*. (2000) studied the effects on untreated greywater quality when stored. The results of the study found that the dominant processes in the first few hours produced a settlement of suspended particles, which helped the quality of greywater, but there was also a rapid growth of total and fecal Coliforms in all samples observed. To be used for toilet flushing, Li *et al*. (2009)

recommended a storage time of less than 48 hours and the presence of residual chlorine of more than 1 mg/l in the treated greywater. Table 2.1 contains summarized greywater characteristics from different studies in different geographical locations.

2.3 Greywater Treatment

Greywater treatment generally includes physical, chemical and biological processes, often preceded and followed by pre-treatment and disinfection, respectively (Li *et al*., 2009). Coarse sand, soil and membrane filtrations are the commonly applied physical processes. March *et al*. (2004) applied a nylon sock filter followed by sedimentation and disinfection to reuse low strength shower greywater. The treatment system was found to reduce pollutant levels from 171 to 78 mg/l for COD, 20 to 16.5 NTU for turbidity, 44 to 18.6 mg/l for suspended solids and 11.4 to 7.1 mg/l for total nitrogen. The treated greywater was recommended for toilet flushing under controlled conditions of storage time less than 48 hours and residual chlorine of more than 1 mg/l.

A sand filter combined with activated carbon and a disinfection system was found to be less efficient at removing pollutants (48% of suspended solids and 61% of turbidity were removed), but the significant microorganism removal was achieved (Pidou, 2006). Li *et al*. (2008) reported that a direct ultra-filtration (UF) membrane filtration system was able to reduce total organic carbon (TOC) from 161 mg/l to 28.6 mg/l and they observed that the permeate was free from suspended solids (SS) and E. coli and the turbidity was less than 1 NTU.

Table 2.1: Greywater characteristics collected from different previous studies

Greywater source	**Sampling**	**Parameter concentration (mg/l)**						
		COD	**BOD**	**TN**	**NH_4-N**	**OP**	**TP**	**AS**
111 houses, GM (Li, 2003)	4 months	258 -354	-	9.7-6.6	-	-	5.2-9.6	-
111 houses, GM (Elmitwalli *et al*., 2007)	9 months, n = 6	640	-	27.2	42	8	9.8	-
37 houses, SW (Fittschen and Niemczynowicz, 1997)	2 months, n = 8	361	-	18.1	-	-	3.9	-
47 houses, SW (Palmquist and Hanaeus, 2005)	n = 4	588	-	9.7	-	-	7.5	-
150 houses, NL (Hernandez *et al*., 2007)	2 weeks, n =104	425	215	17.2	7.2	2.3	5.7	-
32 houses, NL (Hernandez *et al*., 2007)	4 months, n =10	1583	-	47.8	16.4	2.3	9.9	-
81-room-hotel, SP (March *et al*., 2004)	1 year, n = 24	171	-	11.4	-	-	-	-
6 person-farm, IS (Gross *et al*., 2005)	9 months, n =72	686	270	14	-	-	18	40
1 house, IS (Shafran *et al*., 2005)	1 year, n = 96	474	195	-	-	-	-	17
2 houses, IS (Shafran *et al*., 2005)	1 year, n =96	200	62	-	-	-	-	3
6 houses, IS (Wiel-Shafran *et al*., 2006)	5 weeks, n =5	-	133	19	-	-	31	34
13 families, JO (Al-Jayyousi, 2002)	n =6	1351	873	17	-	-	-	76
Villages, SA (Al-Jayyousi, 2002)	n = 100	4470	-	72	-	-	-	-
University, SA (Jackson *et al*., 2006)	Not indicated	-	-	206	157	40	69	-
4 houses, CR (Dallas *et al*., 2004)	1 year, n = 11	-	167	-	-	6.28	-	-
One family, USA (Rose *et al*., 1991)	n =10	-	-	0.6 -5.2	0.12 - 2.49	1.9 - 16.9	-	-

n =Sample size, AS = Anionic surfactants, TN = Total Nitrogen, TP = Total Phosphorus, OP = Ortho Phosphate, GM = Germany, NL = The Netherlands, SW = Sweden, SA = South Africa, SP = Spain, JR = Jordan, IS = Israel, CR = Costa Rica

For low strength greywater treatment, Ramon *et al*. (2004) found that a nano-filtration (NF) membrane could remove approximately 93% of organic pollutants while Sostar-Turk *et al*. (2005) observed that a reverse osmosis (RO) membrane after the UF membrane was able to reduce BOD levels from 86 to 2 mg/l. While good treatment performance is often achieved, energy consumption and membrane fouling are often considered as key constraints for membrane filtration systems (Li *et al*., 2009).

Chemical treatments used in greywater reuse schemes include coagulation, photo-catalytic oxidation, ion-exchange and granular activated carbon (Li *et al*., 2009). Li *et al*. (2009) reported that electro-coagulation followed by a disinfection step for low strength greywater treatment was efficient in removing COD, BOD, turbidity and SS from 55 to 22 mg/l, 23 to 9 mg/l, 43 to 4 NTU and 29 to 9 mg/l, respectively. The effluent from the system was also found to be free from total Coliforms. A combined coagulation, sand filtration and granular activated carbon (GAC) treatment process for low strength laundry greywater has also been found to reduce COD, BOD and SS from 280 to 20 mg/l, 195 to 10 mg/l and 35 to less than 5 mg/l, respectively (Sostar-Turk *et al*., 2005).

Several biological processes have been applied to greywater reuse schemes. For example, rotating biological contactors (Friedler *et al*., 2005), sequencing batch reactors (Hernandez *et al*., 2008), constructed wetlands (Li *et al*., 2003; Gross *et al*., 2007) and membrane bioreactors (Liu *et al*., 2005) have all been used. Biological processes are generally preceded by a physical pre-treatment process such as sedimentation and screening, and followed by a filtration and disinfection process (Li *et al*., 2009). Among biological processes, the constructed wetland is generally considered the most sustainable and cost effective technology for greywater treatment (Li *et al*., 2009). The removal efficiency of a constructed wetland for high strength greywater recycling has been reported to be 158 to 3 mg/l for TSS, 466 to 0.7 mg/l for BOD, 839 to 157 mg/l for COD, 34.3 to 10.8 mg/l for TN, 22.8 to 6.6 mg/l for TP, 7.9 to 0.6 mg/l for anionic surfactants, 1.6 to 0.6 mg/l for boron and $5x10^7$ to $2x10^7$/100 ml for faecal Coliform (Gross *et al*., 2007). Previous studies have observed that greywater quality changes with time during storage (Liu *et al*., 2010). Long residence times can promote bacterial re-growth that may lead to degradation of greywater quality. During sedimentation of greywater, Dixon *et al*. (2000) observed an increase of BOD after an initial reduction.

2.4 Water Sensitive Urban Design

The water sensitive urban design (WSUD) systems are conventionally used for source control of urban stormwater. Previous studies identified that stormwater stored in WSUD systems generally improves in quality over time (Chowdhury *et al.,* 2015; Myers *et al*., 2011, 2009). The permeable pavement is designed for urban runoff to filter through gaps in the pavement surface into an underlying base course reservoir where it is temporarily stored for reuse or infiltrated to groundwater (Myers *et al,* 2009; Pezzaniti *et al.,* 2009; Pratt, 1999). Their aggregate base course layer can develop and maintain a diverse microbial community (Myers *et al.,* 2009) which can degrade the oil and grease pollution (Pratt *et al.,* 1999; Coupe *et al.,* 2003) and can lower the levels of heavy metals (copper, zinc, lead) from urban runoff (Brattebo and Booth, 2003). The biofiltration basin treats urban runoff by trapping and in some cases by degrading pollutants (Atchison *et al.,* 2006; Kandasamy *et al.,* 2005; Myers *et al.,* 2009). Both permeable pavement and biofiltration basin are suitable to use in the UAE, because most villa type houses in the UAE have the multiple parking space and about 50% of the plot area are kept open for landscaping and plantations.

2.4.1 Permeable pavement system

Permeable pavements are alternative paving surfaces that are generally designed for stormwater runoff to filter through voids in the pavement surface into an underlying stone reservoir, where it is temporarily stored for reuse or infiltrated into groundwater (Myers *et al*., 2009; Pezzaniti *et al*., 2009; Pratt, 1999). They are made up of a matrix of concrete blocks or a plastic web-type structure with voids filled with sand, gravel or soil (Brattebo and Booth, 2003). Permeable pavements provide a unique opportunity to infiltrate stormwater without compromising the above lying land use. A typical permeable pavement system has a surface pavement layer (pervious concrete, porous concrete or permeable interlocking concrete pavers), a thin bedding layer of fine aggregate, an underlying coarse aggregate layer (base course) and sometimes a filter layer or fabric installed on the bottom. Permeable pavements have the potential to harvest and store the urban stormwater (Beecham and Myers, 2007) by enclosing the structurally supportive base course aggregates in an impermeable membrane (Myers *et al*., 2009). With all permeable pavements, careful sediment control is needed to avoid clogging of the down-gradient permeable pavement system. A schematic figure of a typical permeable pavement is shown in Figure 2.1.

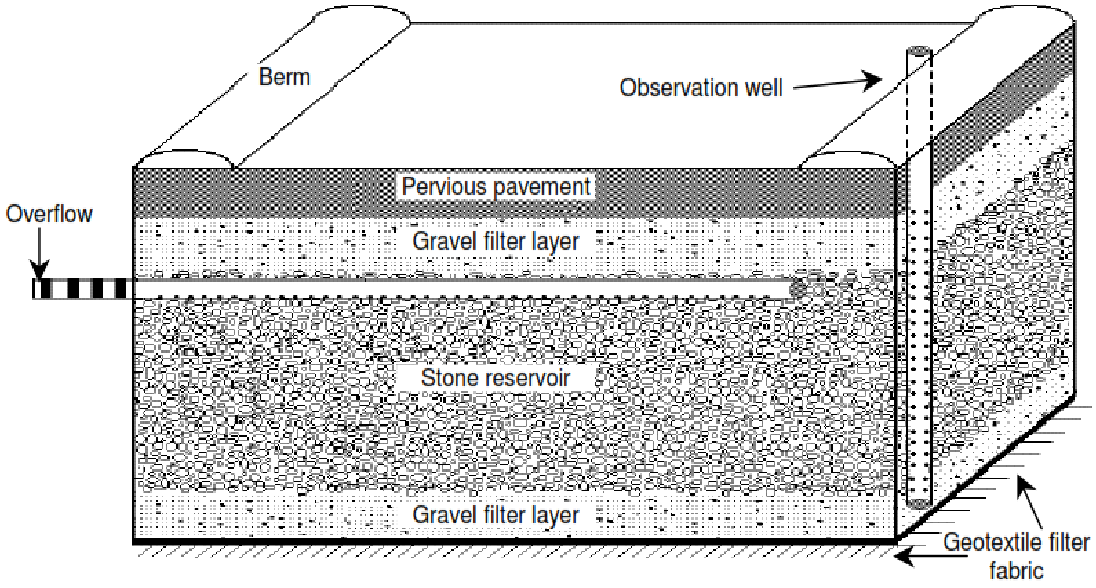

Figure 2.1: A schematic view of a typical permeable pavement system (U.S. Environmental Protection Agency, 1999)

The aggregate base course in permeable pavement can develop and maintain a diverse microbial community (Myers *et al*., 2009). Pratt *et al*. (1999) and Coupe *et al*. (2003) observed that microbial communities developed in permeable pavement reservoirs can sufficiently degrade the oil and grease pollution. They found that protozoa, fungi and bacteria play a vital role in degrading oil in permeable pavement reservoirs. Very few studies have been conducted on the effect of permeable base course media on water quality in short- or long-term storage. Myers *et al*. (2009) observed an inefficient depletion of *Escherichia coli* in dolomite and calcite permeable pavement aggregate storage layer. Brattebo and Booth (2003) evaluated the long-term stormwater quality performance of permeable pavement systems. They found that infiltration of stormwater runoff through a permeable pavement system can lower the levels of copper, zinc, lead, motor oil and diesel fuel significantly (to values less than the minimum detectable limits for motor oil 0.1 mg/l, diesel fuel 0.05 mg/l, copper 1.0 µg/l, zinc 5 µg /l, and lead 1.0 µg /l).

2.4.2 Biofiltration system

A biofiltration system is a landscaped garden in a shallow depression that receives urban runoff (Beecham and Chowdhury 2012). Previous studies showed that they can treat urban runoff by trapping and in some cases by degrading pollutants (Kandasamy *et al*. 2005; Myers *et al*. 2009). They promote infiltration of urban runoff and increase the groundwater recharge rate. The amount of greywater that can be treated is depending on the greywater entering the unit and the rate of Biochemical Oxygen Demand (BOD) that needs to be reduced. Jenkins (2005) observed that a 1 m^3 of wetland can give 135 liters of greywater as in general rules. Greywater must be flowing all year for keeping plants and bacteria in the treatment plant alive and functionally active. Greywater should flow naturally by gravity without using any pump systems and 2 to 10 days is needed for the water to be treated in the system (Jenkins 2005).

The reaction rate constant (k_T (day^{-1})) can be calculated using Equation (2.1) for BOD in a specific temperature. Decomposition depends on the K values, the bigger the K values the larger is the decomposition. Crites and Tchobanoglous (1998) estimated a K_{20} of 1.1 day^{-1}, while Tchobanoglous and Burton (1991) estimated a K_{20} of 1.35 day^{-1} for blackwater treatment wetlands. In Sweden, Olsen *et al*. (1967) estimated the greywater K_{20} value in a wetland was of 4.5 day^{-1}, bigger than the blackwater, because of the organic matter present in greywater.

$$K_T = K_{20} (\theta^{(T-20)}) \qquad (2.1)$$

The detention time t (day), the time the wastewater should remain in the system in order to reach the desired BOD level. Value of θ found to be 1.056 during temperature of 20 and up to 30 oC, while its 1.135 between 4 and 20 oC (George, and Franklin, 1991). However in literature its used as 1.047 (George, and Franklin, 1991).

Calculating the value of BOD per area per day, the following Equation (2.3) can be used L_{org} (g BOD/m^2- day), and the organic value generally does not exceed of 11.2 g BOD/m^2 –day, normally the organic value does not overcome the 11.2 g BOD/m^2 –day with influent applied up to 5 cm per day (Yocum, 2006).

$$L_{org} = \frac{C\, d_w \eta}{t} \qquad (2.3)$$

Where C is the BOD (mg/l = g/m^3) of the influent wastewater, d_w (m) represents the depth of the system which is around 0.4 to 0.85 m. If the medium was too deep, the condition at the bottom may turn to be anaerobic, which may result in incomplete removal of the BOD and nutrients, detention time (t) can be calculated from equation 2.4. The dimensionless parameter (η) represents the percentage of the non-solid volume to the total volume of the material (Yocum, 2006).

$$A_s = \frac{(Q_{ave})\,(t)}{(\eta)(d_w)} \qquad (2.4)$$

Where the Q_{ave} represents the mean daily flow through the system (m^3/day), t represents the retention time and d_w represents the depth of the medium (m). The dimension of the treatment unit can be estimated using equation 2.5 (Yocum, 2006).

$$w = \left(\frac{A_S}{R_A}\right)^{1/2} \qquad (2.5)$$

Where W represents the width (m), A_S is the area of the wetland and R_A represents the aspect ratio which is length/width. Crites and Tchobanoglous (1998) recommended the aspect ratio to be between 2:1 and 4:1, however Bounds *et al.* (1998) discovered no difference in nutrient and BOD removal in three 25 m^2 treatment system with aspect ratio of 4:1, 10:1 and 30:1 over a two year period (quoted in Dallas, 2005). The length L of the system can be calculated by equation 2.6 (Yocum, 2006).

$$l = \frac{A_S}{w} \qquad (2.6)$$

Plants can transport oxygen much faster than water and soil. According to Mitch and Gosselink (2000), plants provide good treatment for removing nutrients and BOD in wastewater. Several locally available plants (Cattails, Bulrushes and Reed grasses, for example) can be considered to use in the biofiltration system. Characteristics of these plants are shown in Table 2.2.

Table 2.2: Characteristics of some selected locally available plants for the biofiltration

Cattails (*Typha spp.*)	**Bulrushes** (*Schoenoplectus spp., Scirpus spp.*)	**Reed Grasses** (*Phragmites australis*)
• Easy to permeate • Strong • Capable of making huge yearly biomass • Good in eliminating big amounts of nitrate and phosphate	• Grow up to 5 cm to 3 cm of water • Grow up as bushes • Has large pollution removal capability	• Distinguish by its tall roots which gives the chance for more oxygen to be transferred throw the soil

2.5 Water Saving through Reuse of Greywater

Recycling and reuse of greywater is receiving significant attention, particularly in water scarce areas around the world because of their relatively low levels of pathogens and nutrients (Li *et al*., 2009). Greywater generally constitutes approximately 50 to 80% of total municipal wastewater (Eriksson *et al*., 2003). The average generation rate of greywater is approximately 90 to 120 liters per capita per day (Morel and Diener, 2006; Li *et al*., 2009; Mourad *et al*., 2011), although the rates vary from country to country depending on living standards, lifestyle and the degree of water abundance (Mourad *et al*., 2011). Chowdhury *et al*. (2014) and Jamrah *et al*. (2008) estimated an average greywater generation rate of 192 lpcd in the city of Al Ain (United Arab Emirates) and in the Sultanate of Oman, respectively. Reuse of greywater can save a substantial amount of municipal water. Sheikh (1993) reported that 12 to 65% of municipal usage can be saved by reusing greywater in irrigation practices in the Los Angeles. Approximately 35% of potable water can be saved by reusing greywater in Brazil (Ghisi and Ferreira, 2007) and in Syria (Mourad *et al*., 2011). Kotwicki and Al-Otaibi (2011) reported that around 25% of potable water savings can be achieved by reusing greywater for toilet flushing and gardening in Kuwait.

Greywater reuse in the United Arab Emirates (UAE) has not yet received much attention. Whilst guidelines are available for reuse of treated sewage effluent, local guidelines for greywater reuse are not available and the evaluation of treatment technologies is scarce. However, there is a growing interest in the reuse of greywater in many arid regions including the UAE. One driving force is water shortage caused by low rainfall in combination with high evaporation rates and large demands for fresh water from communities and industry. Another driving force is to lower the cost of wastewater treatment by reducing the hydraulic load to the facilities (Eriksson *et al*., 2002). The problems associated with greywater reuse include the public health risk associated with spreading of diseases due to exposure to pathogens and the risk of pollution of soils and receiving waters due to the presence in greywater of various pollutants (Eriksson *et al*., 2002). Greywater reuse involves risk of exposure to micro-organisms and pollution of receiving environments (land and water) (Eriksson *et al*. 2002).

Chapter 3: Methodology

3.1 Background

This chapter presents the methodology followed in assessing greywater quality in the city of Al Ain, the construction of prototypes for the permeable pavement and biofiltration system, the laboratory experimental procedures and materials used. The construction of two prototypes required almost six months. The greywater quality assessment was conducted during September to December 2014. The laboratory experiments of treatment efficiencies of both systems were conducted during October 2014 to June 2015. The detail procedures are described below.

3.2 Greywater Quality Monitoring

Greywater characteristics from different end uses (shower, ablution, hand wash, face wash, teeth brush and laundry) were assessed from eleven houses (figure 3.1) randomly located across the Al Ain city. Data were collected during September to December 2014. On an average, about 30 replicates of data were collected for each end use. The Horiba U-50 multi-parameter water quality meter was used to measure several quality parameters (Figure 3.2). These were pH, oxidation reduction potential (ORP), electrical conductivity (EC), turbidity, total dissolved solids (TDS) and salinity. Five portable Horiba LAQUAtwin compact water quality meters were used to measure salt contents (calcium, sodium, potassium and nitrate as NO_3^-) (Figure 3.3). The chemical oxygen demand (COD) of grab samples was measured using a HACH DR/4000U Spectrophotometer (Figure 3.4). The membrane filtration technique and the HACH Paddle Tester (Cat No. 26109-10) were used to estimate the total coliform bacteria (figure 3.5). The municipal water (tap water) sample was also analyzed for comparison purposes.

Figure 3.1 Greywater Characteristics from eleventh different end uses in Al-Ain city (Google map))


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Sensor Probe Unit Features:

- Ultra-sensitive Turbidity Sensor
- Minimum dissolved oxygen sensor maintenance with screw-on type membrane cap
- Chemical resistant materials of construction
- Optional ToupH pH electrode* that is difficult to break
- Field replaceable sensors

*Prevents damage during maintenance.

Figure 3.2: The Horiba U-50 series multi-parameter water quality meter (www.horiba.com)

Compact Water Quality Meter

LAQUAtwin

Your lab-in-a-pocket

- Untuk pengukuran pH, Conductivity, Ion dan Salt
- Praktis dan mudah dibawa
- Mudah dioperasikan
- Dilengkapi dengan *flat sensor technology*
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Figure 3.3: Horiba LAQUAtwin meters for measuring calcium (Ca^{+2}), sodium (Na), potassium (K), nitrate (NO_3) ions (cmsi.indonetwork.co.id)

Figure 3.4: DR/4000U Spectrophotometer (left) and a oven to heat COD bottles (right) used in the experiment for COD test (placed in the Environmental Engineering laboratory, UAEU)

Figure 3.5: HACH Paddle Tester (Cat No. 26109-10) for total aerobic bacteria and total coliform test

One or two residents of each house were convinced to participate in the greywater quality monitoring process. They were requested to close the bathtub and wash basin exit drain during the shower, hand and face wash, teeth brush and ablution, so that greywater was stored in the bathtub and wash basin for their quality measurement. Grab samples were collected from the stored greywater after every end use for subsequent analyses. An equal mixture of ablution, shower and hand wash greywater was also analyzed. The laundry greywater quality varies in different cycles during its operation. Samples were collected from all cycles. An equal mixture of all cycles' greywater was also analyzed. A bucket was used to collect laundry greywater from the discharge pipe of the washing machine.

3.3 Greywater Generation

A field survey was conducted to investigate the social attitudes toward water consumption and reusing greywater in the Al Ain city and to find out a number of parameters affecting water end uses through questionnaire survey and personal consultation. The survey was conducted during February to June 2013. The number of interviewees was estimated by using Equation (3.1), which estimates a population-based representative sample according to Ghisi and Ferreira (2007).

$$n \geq \frac{N/\varepsilon^2}{\frac{1}{\varepsilon^2}+N} \tag{3.1}$$

Where n is the sample size, N is the population size, and ε is the sampling error (from 1% to 20%). Taking the total population of the city (approximately 0.5 million) including peri-urban areas and assuming a 10% sample error, one hundred interviews were conducted. The respondents were chosen randomly with about 50% men and 50% women. The interviews were made at homes, offices, university and in cafeterias. The questions in the interviews included a house and garden area, family members, number of vehicles, social acceptance of reusing greywater for toilet flushing and gardening, and frequency of different water end uses such as shower, face and hand washing, tooth brushing, clothes and dish washing, house cleaning, and toilet use etc. Equations (3.2) to (3.5) were used to estimate the daily water consumption. Greywater generation (G_w) was estimated using Equation (3.6).

$$W_d = W_p + W_f \tag{3.2}$$

$$W_p = F_s Q_s + F_{tb} Q_{tb} + F_{hw} Q_{hw} + F_{fw} Q_{fw} + F_a Q_a + F_{tf} Q_{tf} \tag{3.3}$$

$$W_f = (F_l Q_l + F_{dw} Q_{dw} + F_c Q_c + F_p Q_p + F_v Q_v + F_g Q_g)/FM \tag{3.4}$$

$$Q = TF_R \tag{3.5}$$

$$G_w = F_s Q_s + F_{tb} Q_{tb} + F_{hw} Q_{hw} + F_{fw} Q_{fw} + F_a Q_a + (F_l Q_l + F_c Q_c)/FM \tag{3.6}$$

where W_d is the daily water consumption in Lpcd, W_p is the personal water consumption (Lpcd) and W_f is the water consumption within the family (Lpcd); F_s, F_{tb}, F_{hw}, F_{fw}, F_a, F_{tf}, F_l, F_{dw}, F_c, F_p, F_v and F_g are the daily frequency of using shower, tooth brush, hand wash, face wash, ablution, toilet flush, laundry, dish wash, cleaning, pet water, vehicle cleaning and irrigation to garden, respectively; Q_s, Q_{tb}, Q_{hw}, Q_{fw}, Q_a, Q_{tf}, Q_l, Q_{dw}, Q_c, Q_p, Q_v and Q_g are the water consumption, in liters, for each use of shower, tooth brush, hand wash, face wash, ablution, toilet flush, laundry, dish wash, home cleaning, pet water, vehicle cleaning and gardening, respectively; T indicates time requirements for water uses in minute and F_R indicates flow rate in liter/minute; and FM is a number of family members.

The time requirements (T) for one event of different personal and family water end uses were estimated from a group of twelve volunteers, seven males and five females, having different age classes and marital status. The quantity for each toilet flush was estimated from the volume of the toilet tank. The estimated time for other activities other than toilet flushing was multiplied by their flow rates (F_R). The average flow rate was measured using Volumetric jar and a stop watch.

3.4 Irrigation Water Demand in Landscape Plantation

Two landscape plantation zones were selected within the UAE University campus and their irrigation water demand was measured in the field. One zone is located near the Cresent building and the other zone was located in the female campus of the University. The zones were selected based on the criteria of easy to access, irrigation systems and type and density of plants. In the piped irrigation system, every single plant has to be planted with the same line of pipes and there should be holes for each plant for water supply, but for the sprinkle system one or more sprinkler would considered enough. The sprinkler system is mainly used for plating green weed over a huge size of landscapes.

The Zone-1 (Figure 3.6) has an area of 260 m^2 (13 m width x 20 m long) supplied with water using 45 dripping PVC pipe irrigation system with a horizontal length of each single pipe equal to the horizontal length of the zone (13 m long). The irrigation PVC pipe diameter was 1.25 cm. The space between each single PVC pipe was 27 cm and each dripping point resemble a plant (flower bush) in the zone. Each dripping point was 27 cm apart from each other longitudinally and in the longitudinal direction there were 75 flower bushes.

Figure 3.6: Zone – 1 for the estimation of irrigation water demand (located in the UAE University)

Figure 3.7: Irrigation water demand estimation in urban landscape using a volumetric glass jar and stop watch

The irrigation water was supplied by the Al Ain Municipality and each zone is used irrigate for continuous 15 minutes in a day. The amount of water used was measured using a volumetric glass jar and stopwatch (Figure 3.7). The jar was placed in several pipe holes separately in order to measure average water supply from a drip point in 15 minutes. The total number of drip points in the zone was 50. Therefore, water requirements for the 260 m2 urban landscape zone with flower/small bushes was estimated by multiplying with the number of drip points.

The Zone-2 area was of 573 m^2 (191 m x 3 m) and was supported by water using 11 PVC pipes with 25 cm spacing between each dripping point (plant). The area was irrigated with water for a continuous of 15 minutes in a day. There were a total of 8,415 dripping points in the Zone 2. Small plants were used in the Zone-2. The similar methods were applied as described for the Zone -1.

3.5 Prototype of Permeable Pavement Unit

A permeable pavement unit of size 1 m^3 (length 1 m, width 1 m and height 1 m) was constructed, as shown in Figure 3.8. The unit consisted of three layers, namely an upper layer of 80 mm pavers, then a 40 mm deep bedding course layer of 2 mm to 5 mm crushed gravel and finally a 800 mm deep base course storage layer of 20 mm to 60 mm well mixed stone aggregate. All materials were cleaned and dried before being placed in a 1 m^3 glass container. The unit contained an outlet faucet at the bottom. The void ratio of the base course storage layer was measured at 36% and the volume of the base course storage reservoir was 0.8 m^3, which meant it could store approximately 290 L of greywater. The unit was kept the outdoors in order to simulate the effects of the local arid weather conditions.

Firstly, the pavement unit was filled with municipal supply water (tap water) in order to understand the changes of water quality in the base course storage layer over a period of 7 days. After this period the unit was emptied of water and then filled with ablution greywater for a further period of 11 days. The unit was then back washed and dried before being filled with laundry greywater for a further 7 days. Ablution and laundry greywater were collected from a mosque and a commercial laundry shop, respectively, both being located in the city of Al Ain. A centrifugal automatic pump was used to collect the ablution and laundry greywater in large water tanks and then transported to the location of the permeable pavement unit (at the UAE University). The pump was used again to fill the permeable pavement unit with greywater. The quality of the raw greywater was measured before injecting into the permeable pavement unit. Greywater samples from the permeable pavement unit's lower faucet were collected daily for analysis. The parameters monitored are described in section 3.2.

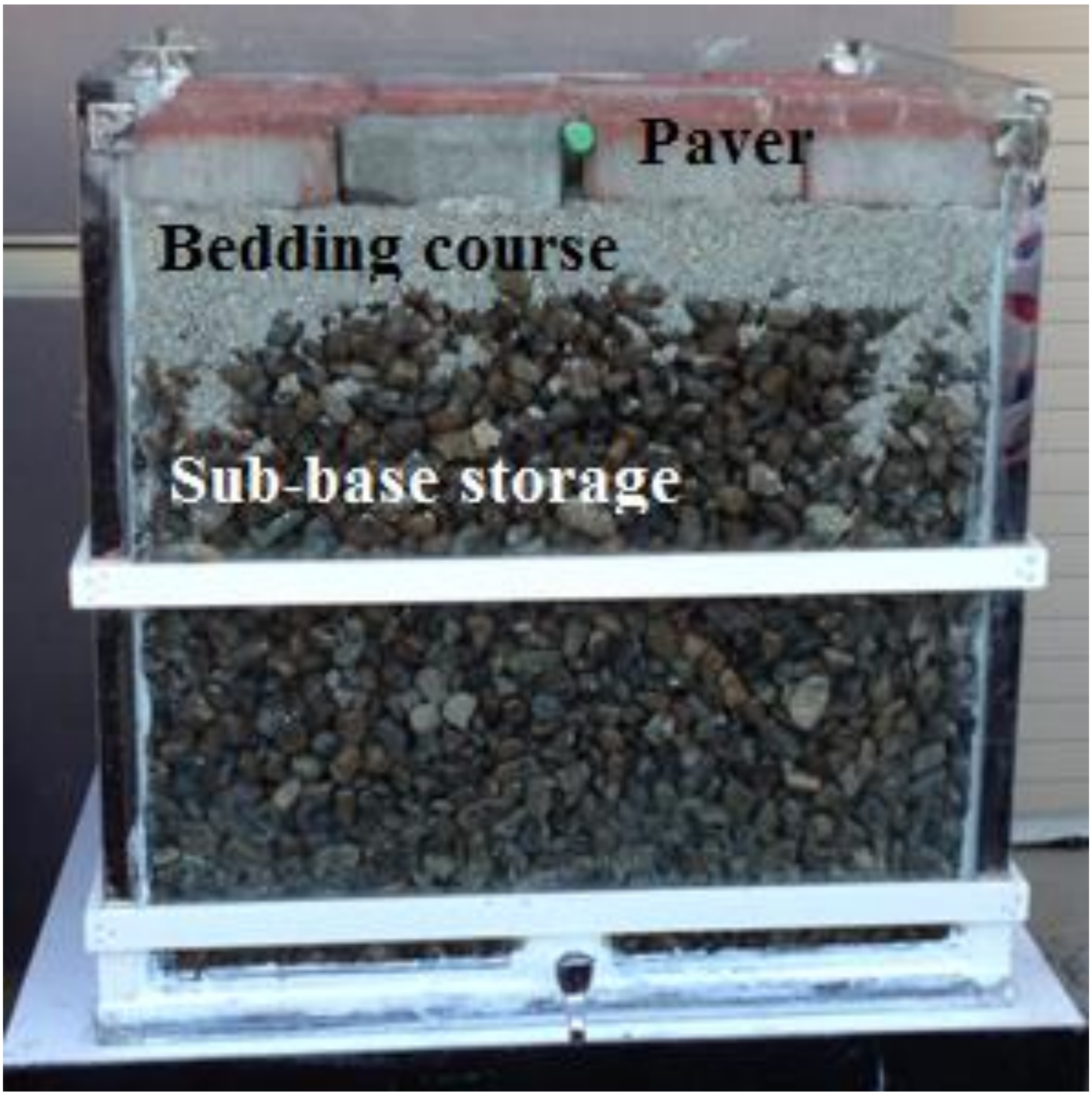

Figure 3.8: Permeable pavement testing unit

3.6 Prototype of Biofiltration Unit

A prototype of a biofiltration system of size 1 m^3 (length 1 m, width 1 m and height 1 m) was constructed, as depicted in Figure 3.9. The prototype consisted of three layers, namely an upper 60 cm layer of well mixed sand and small gravels (0.075 mm to 4.75 mm), then a 12 cm deep well mixed coarse sand (0.5 mm to 2 mm) and finally a 8 cm deep well mixed gravel layer (2 mm to 5 mm). All materials were cleaned and dried before being placed in a 1 m^3 glass container (Figure 3.9).

The prototype was fitted with an outlet faucet at the bottom. The estimated (measured on 10th December 2013) unsaturated and saturated volumes of the biofiltration system were 0.8 m^3 and 0.78 m^3, respectively. The corresponding void ratios were measured by 18% and 18.5%, respectively. The system can hold about 144 L^3 of greywater. The estimated (measured in 12th December 2013) saturated hydraulic conductivity of the system was found of about 203 mm/hour. The prototype was kept outdoors in order to imitate the effects of the local arid weather conditions. A native plant named Reed grass (*Phalaris arundinacea*) was planted in the system as presented in the Figure 3.9. The Reed grass is a tall, coarse grass with an erect, hairless stem, usually standing from 60 to 180 cm tall. The plant is usually found in wetlands, including shallow marshes, stream banks, and swales.

Greywater, collected from ablution and laundry sources, were applied separately in the biofiltration system, for both cases of non-vegetative (without plants) and vegetative (with plants) conditions. These two sources were considered because ablution and laundry greywater were found to exhibit minimum and maximum pollution, respectively, and coliform bacteria were identified in the ablution greywater. Firstly, the non-vegetative system was filled with ablution greywater to evaluate the changes of their quality over a period of 12 days. After this period the unit was being emptied, back washed and dried before being filled with laundry greywater for a further 11 days of observation of their quality. The system was then again emptied, back washed and dried for about four weeks. The Reed grasses were then planted in the system. The vegetated unit was then filled with ablution and laundry greywater separately as described in the non-vegetative system. The storage times of 12 days (non-vegetative) and 11 days (vegetative) were chosen on the basis that the daily greywater quality parameters did not change substantially after the noted timings.

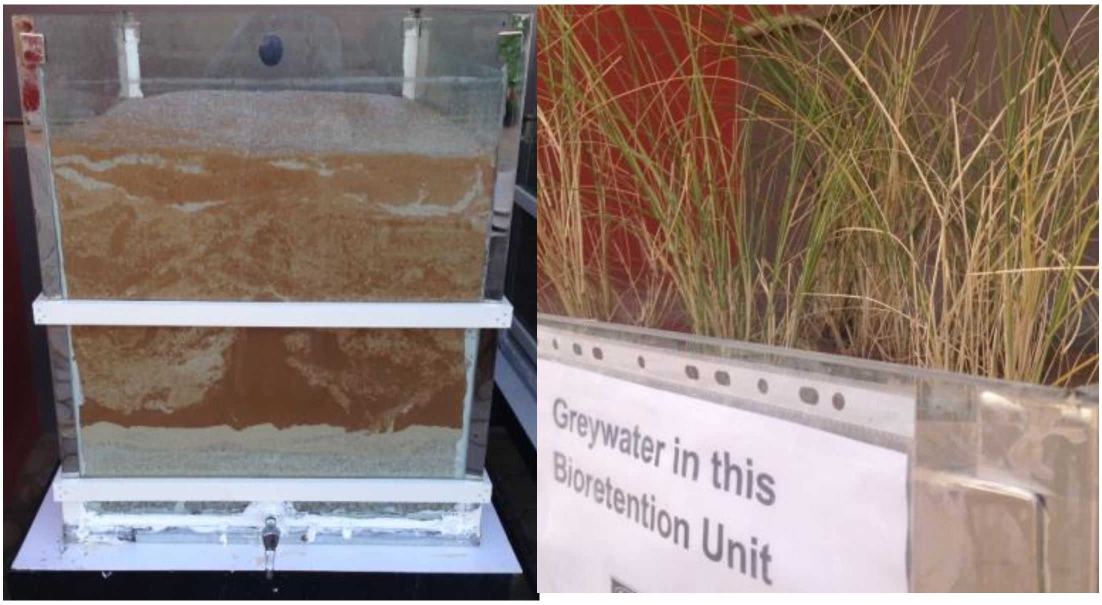

Figure 3.9: Biofiltration testing unit, non-vegetative (left) and vegetative with Reed grasses (right)

The ablution and laundry greywater were collected from a mosque and a commercial laundry shop, respectively, both being located in the city of Al Ain. A centrifugal automatic pump was used to collect the ablution and laundry greywater in large water tanks and then transported to the location of the biofiltration system (at the UAE University). The pump was then used again to fill the biofiltration unit with greywater. The quality of raw greywater was measured before injecting into the biofiltration system. The retained greywater samples from the prototype's lower faucet were collected daily (24 hour interval) for analyses. The samples were analyzed as mentioned in section 3.2. Back wash had to be done to remove any contaminant left over from the ablution water and to rewash the biggest layer in the unit, which is the sand layer that have decomposed organic materials and other contaminants.

Back wash process was done using submerged pump with 0.75 horse power connected to the unit throw the lower tap with a hose, then the tap water was injected into the system from bottom to top for 20 mints. the operation was repeated for 5 times until the unit showed almost clear water exiting the system from the top of the unit (Figure 3.10).

Figure 3.10: Back washing both systems and drilling for almost four weeks

Chapter 4: Greywater Characteristics

4.1 Background

Greywater quantity and quality analysis are needed for the selection of appropriate treatment mechanisms for their reuse. In this study, treated greywater was considered to reuse for irrigation to amenity plantations in villa type houses. In recent studies, it was found that about 80% of municipal water (desalinated water) is used for outdoor activities such as gardening and car washing. Reuse of greywater for outdoor consumptions can save expensive desalinated water. Therefore, greywater samples were taken from different houses across the Al Ain city and analyzed to know their characteristics. Several physical, chemical and biological parameters were monitored. These are pH, TDS, salinity, ORP, conductivity, salt, Ca^{+2}, Na^{+}, K^{+} and NO^{-3}, COD and total coliform bacteria. Different possible greywater sources were considered separately. These were hand washing, shower, ablution, tooth brushing, washing machines, face washing and mix of ablution, shower and hand washing. Frequency and quantity of water uses in these sources were also investigated in order to estimate the generation rate of greywater.

4.2 Factors Affecting Greywater Generation

Several factors affect household water consumptions (e.g., type of toilets, household size, lot size, etc.), and thereby affect the generation of greywater. Residential water end uses and their conservation potential are generally accomplished by empirically estimated parameters affecting water end uses, device turnover rates and regression analysis of their historical trends (Cahill *et al*., 2013). Cahill *et al*. (2013) estimated probability distributions of parameters affecting water end use. Water end uses data along with survey responses and statistically significant parameters affecting end uses were used in regression analysis to estimate water end uses at individual homes (DeOreo 2011; Cahill *et al.*, 2013). Empirical equations are generally developed as a function of these statistically significant parameters. A Monte Carlo approach was applied by Cahill *et al.* (2013) to estimate the distribution of residential water use and their conservation potential considering variability of household physical characteristics and behavior.

Table 4.1 shows the characteristics of houses and frequency of water uses by people in the villa type houses in the Al Ain city. All of the houses surveyed were villa-type detached house and generally occupies provision for amenity plantation. However, area of garden in houses was not estimated. Average family members of around 12 persons per house and their high variance (21.35) are a representation of cultural practices of joint family (brothers and their families live in the same house along with their grandparents) in the region. The five times ablution in a day is a religious practice in the region and an average ablution frequency of 4.42 per person per day indicates that some people perform ablution outside of the home (possible at religious mosque). Mourad *et al.* (2011) estimated per capita frequency of water uses in Syria. Their estimated frequencies (per day) were face washing (4), hand washing (8.6), tooth brushing (1.7), shower (0.6) and toilet flushing (4.1). Their hand washing frequency (8.6) is significantly higher in comparison to our findings (4.71) because ablution water use is separated in our study. Other changes in water use frequency between them are due to changes of climate, geographical settings, lifestyles and an abundance of water availability.

Table 4.1: Statistical characteristics of frequency of water end uses at residential premises in Al Ain

Variable	**Mean**	**St dev**	**Variance**	**Min**	**Median**	**Max**
Bedroom/house	6.76	2.18	4.75	2.00	6.00	12.00
Car/house	4.41	1.81	3.27	2.00	4.00	9.00
People/house	11.60	4.62	21.35	4.00	11.00	24.00
Shower/p/d	1.68	0.73	0.53	1.00	2.00	4.00
Toilet flush/p/d	4.29	1.04	1.09	2.00	4.00	6.00
Tooth brush/p/d	2.15	0.65	0.42	1.00	2.00	4.00
Hand wash/p/d	4.71	1.52	2.32	1.00	5.00	9.00
Face wash/p/d	3.52	1.34	1.79	1.00	3.00	7.00
Ablution/p/d	4.42	0.98	0.96	1.00	5.00	6.00
Laundry/w	6.44	2.91	8.49	1.00	7.00	14.00
Dish wash/d	4.03	1.29	1.65	2.00	4.00	8.00
Home clean/d	1.24	0.65	0.43	0.00	1.00	3.00
Gardening/d	1.56	0.64	0.41	1.00	1.00	4.00
Carwash/w	2.03	1.09	1.19	1.00	2.00	5.00
Pet water/d	0.62	1.20	1.43	0.00	0.00	5.00

St dev= standard deviation, per person per day = /p/d, per week = /w, Min =minimum, Max = maximum

The time requirement for different water end uses were estimated and their statistical characteristics are shown in Table 4.2. Time requirements for different personal water uses (shower, hand wash, ablution, for example) generally depend on cultural practices, the degree of water abundance and on water tariff structures. It is observed from Table 4.2 that shower and dish wash time are highly variable with an average time of 9.71 and 31.67 minutes and a standard deviation of 4.4 and 4.2 minutes, respectively. This is likely due to variation in people's shower water use practices and variation in dish washing techniques. In most of the homes surveyed, there is a hose pipe connection at the garage for car washing and gardening purposes. The car wash time presented in Table 4.2 indicates the hose pipe running time only.

Table 4.2: Statistical characteristics of time requirements for different water uses

Variable (minute)	**Mean**	**St dev**	**Variance**	**Min**	**Median**	**Max**
Toothbrush	1.55	0.82	0.67	0.39	1.44	4.00
Hand wash	1.09	0.86	0.73	0.12	1.02	3.00
Face wash	0.87	0.69	0.47	0.13	1.02	2.03
Shower	9.71	4.40	19.38	5.01	7.73	19.22
Ablution	2.06	0.89	0.79	0.57	2.00	4.00
Dish wash	31.67	4.20	17.65	25.00	30.0	40.00
Carwash	6.76	1.56	2.45	5.00	7.00	10.00

St dev = standard deviation, Min = Minimum, Max = maximum

Table 4.3: Estimated greywater generation rate

Personal water uses	**Average time required (minute)**	**Flow rate (L/minute)**	**Amount of water per end use, Q (Liter)**	**Frequency of use, F (per person day)**	**Average water consumption (Lpcd)**
Shower	9.71	5.75	56	1.68	94
Toothbrush	1.55	4	6	2.15	13
Hand wash	1.09	4	4	4.71	19
Face wash	0.87	4	3	3.52	11
Ablution	2.06	4	8	4.42	35
Family water uses					
Laundry	-	-	255	0.92 (6.44 per week)	20
Average greywater generation (shower, toothbrush, hand wash, face wash, ablution, laundry)					192 Lpcd

Estimated average greywater generation rate of 192 Lpcd is shown in Table 4.3. The estimation is made using average time requirement of individual end users and the average frequency of end uses. The shower consumption (94 Lpcd) is much higher probably because of higher temperature in the region. It is observed from Table 4.3 that greywater originates from shower (49%), ablution (18%), laundry (10%), hand wash (10%), toothbrush (7%) and face wash (6%).

4.3 Greywater Characteristics

4.3.1 Hand wash greywater

Table 4.4 represents the average, median and standard deviation of greywater originates from hand wash basin. The tests were conducted during September and October of 2013. Temperature showed an average of 26.88 C^o considered to be in normal state compared to the warm climate (maximum of 55 C^o). The average pH was found 7.25. The average oxidation reduction potential (ORP) was observed almost 263 mV, whereas in the tap water the ORP value was found 262 mV. A high ORP in greywater may be related to the high amount of positively charged electrons in the greywater. Hand washing frequency was found about 5 times per person per day in the studied areas. The conductivity and TDS were also founded higher than the tap water (municipal water), which is expected since hand washing greywater contains soap and other hand washing liquids. The high value of TDS corresponds to the high level of the conductivity level. The conductivity was found about 0.41.

Turbidity showed a very high value which is understandable since the water considered to be highly polluted with soap, organic and inorganic materials which increase the turbidity in any water. Dissolved oxygen (DO) in the hand washing greywater found normal, but started to decrease every minute by an average amount of 0.45 due to bacterial activities and presence of organic materials in the greywater. Average salinity was found about 0.81 ppm, compare to the municipal salinity value of 0.1 ppm. The increase of salinity is because of presence of soap material that contain some inorganic salts and human perspiration. The average concentration of potassium (K^+), salt, calcium (Ca^{+2}), sodium (Na^+) and nitrate (NO^{-3}) showed a higher level than the tap water due to the contamination particularly from soap and hand wash liquids.

Table 4.4: Characteristics of greywater originates from hand wash basin

Parameters	**Tap Water (Average)**	**Greywater Originates from Hand Wash Basin**		
		Average	**Median**	**Standard Deviation**
Temperature (C^o)	28.63	26.88	27.33	3.01
pH	8.49	7.25	7.41	0.69
ORP (mv)	238.35	262.20	262.00	18.30
Conductivity (mS/cm)	0.266	0.41	0.41	0.10
Turbidity (NTU)	2.14	193.27	211.50	71.75
DO (mg/l)	7.47	7.91	7.93	1.11
TDS (g/L)	0.211	0.25	0.26	0.05
Salinity (ppt)	0.1	0.18	0.20	0.04
Salt (%)	0.01	55.50	57.50	9.91
Ca^{+2} (ppm)	37.8	52.75	55.00	6.57
Na^+ (ppm)	37.4	30.25	31.00	20.58
K^+ (ppm)	2.8	30.50	30.00	2.87
$NO^-{}_3$ (ppm)	11.4	30.5	30	2.87

4.3.2 Shower greywater

Table 4.5 shows the greywater characteristics originates from the shower. The average ORP and turbidity concentrations were observed about 238 mV and 195 NTU, respectively. The turbidity of shower greywater was observed more than the hand wash basin because of more use of soap, shampoo, conditioners and gels, etc., during the shower. The pH of shower greywater was found alkaline (7.41), which is obviously because of the use of alkaline based soaps. The Ca, Na, K and NO3 average concentrations were observed 28 mg/l, 57 mg/l, 17 mg/l and 24 mg/l, respectively. The high concentration of sodium ions may be sourced from different soaps, shampoo, conditioners and hair dye. The increased calcium ions in hand washing greywater indicate that the shower greywater is more hard than showefr water and might need specific treatment for softening specially if the recycled greywater needed to be used for industrial purposes. On average, hand washing greywater was found more hard and alkaline than the greywater originates from shower.

Table 4.5: Characteristics of greywater originates from shower

Parameters	Average	Median	Standard Deviation
Temperature (^oC)	27.97	28.58	2.52
pH	7.41	7.45	0.33
ORP (mV)	237.75	235.50	25.12
Conductivity (mS/cm)	0.28	0.26	0.10
Turbidity (NTU)	195.40	188.50	116.81
DO (mg/l)	9.47	8.90	4.83
TDS (g/l)	0.18	0.17	0.07
Salinity (ppt)	0.13	0.10	0.04
Salt (%)	0.01	0.01	0.00
Ca^{+2} (ppm)	27.57	24.00	17.18
Na^+ (ppm)	56.57	58.00	16.10
K^+ (ppm)	17.00	9.00	23.05
NO^-_3 (ppm)	23.71	22.00	9.10

4.3.3 Ablution greywater

The characteristics of ablution greywater are shown in Table 4.6. The average pH was found 7.56, almost similar to the shower greywater. The ORP and conductivity were observed around 250 mV and 0.32 mS/cm. The turbidity of ablution greywater was found 28 NTU, which is significantly lower than the shower and hand wash greywater. This is because soap or other washing liquids are not generally used during ablution. The concentrations of Ca, Na, K and NO_3 were observed 42 ppm, 44 ppm, 12 ppm and 15 ppm, respectively. The Ca concentration in ablution greywater was found relatively higher than the shower greywater, but close to hand wash greywater. This is because gels or soaps are used sometimes in ablution basin, and some people (workers) have direct or indirect contacts with minerals such as limestone, chalk and dolomite.

Table 4.6: Characteristics of ablution greywater

Parameters	Average	Median	Standard Deviation
Temperature (Co)	29.57	29.75	4.36
pH	7.56	7.34	0.51
ORP (mV)	250.18	262.00	35.00
Conductivity (mS/cm)	0.32	0.32	0.01
Turbidity (NTU)	27.82	29.70	18.43
DO (mg/l)	6.28	6.29	1.86
TDS (g/l)	0.21	0.21	0.01
Salinity (ppt)	0.17	0.20	0.05
Salt (%)	0.01	0.01	0.00
Ca^{+2} (ppm)	41.80	43.00	7.16
Na^{+} (ppm)	44.00	42.00	4.34
K^{+} (ppm)	10.60	5.00	11.32
NO^{-}_{3} (ppm)	15.00	15.00	2.45

4.3.4 Teeth brush greywater

Teeth brush greywater testing was done only in two areas in the Al Ain city due to the lack of sources and sensitivity of the source to the people in the city. However, for each city two tests were done in 2 minutes because teeth brush greywater volume was not enough to conduct more than two tests for each area. Table 4.7 shows the characteristics of greywater originated from teeth brush activities. The pH value of about 8 indicates teeth brush greywater is more alkaline than other sources. This is particularly because of the use of alkaline based tooth brush. Turbidily was found almost similar to ablution greywater. In comparison to ablution greywater, the Ca ion of teeth brush greywater was found almost similar, but the Na ion was found relatively less. The relatively high dissolved oxygen (DO) level was because of mixing of teeth brush greywater with the air.

Table 4.7: Characteristics of greywater originated from teeth brush activities

Parameters	**Average**	**Median**	**Standard Deviation**
Temperature (^oC)	25.6	25.7	1.1
pH	7.9	7.9	0.1
ORP (mV)	211.5	220.5	51.3
Conductivity (mS/cm)	0.3	0.3	0.0
Turbidity (NTU)	36.2	37.2	2.1
DO (mg/l)	12.0	9.7	5.6
TDS (g/l)	0.2	0.2	0.0
Salinity (ppt)	0.1	0.1	0.0
Salt (%)	0.0	0.0	0.0
Ca^{+2} (ppm)	43.0	43.0	4.0
Na^+ (ppm)	33.5	33.5	1.5
K^+ (ppm)	5.0	5.0	1.0
NO^-_3 (ppm)	14.5	14.5	2.5

4.3.5 Washing machine (laundry) greywater

Table 4.8 shows the characteristics of laundry (washing machine) greywater. All washing machines used were of automatic machines that discharge greywater three times for each complete wash. Greywater from the first ringe was of very dark in color indicated highly turbid. Results in figure 4.1 indicate that the high temperature was observed in the 2nd cycle of about 28.35 ^oC in average, while the average pH showed the highest in the 3rd cycle of about 9.52, which indicated that greywater shifted from acidic to base condition. The highest ORP was recorded in the 1st cycle having a value of 181.15 mV, which indicated that the first cycle greywater worked as an oxidizing agent.

Conductivity showed the highest value at the mixed laundry greywater (equal mix of 1st ,2nd and 3rd cycle washing machine discharge) about 3.22 (mS/cm), which indicates that the water at the mix stage has higher ability to pass electrical current because it has more inorganic dissolved solids (chloride, nitrate, sodium and magnesium) than the other stages. Highest average turbidity showed up at the 1st cycle with a value of 394.70 NTU, which indicates that the water has a high total suspended solid. The DO level showed the highest at the mixed laundry greywater of value about 10.37 mg/l, which is considered to be high compared to other stages and which is because of aeration during mixing of greywater.

The TDS value was found the highest at the 3rd cycle with an average of 3.44 g/l, however, as explained earlier TDS has a direct correlation with the conductivity. The conductivity was found the highest in the 3rd cycle. The salinity level was recorded 3.02 ppt at the 1st cycle as the highest average of all ringes. High levels of salinity in the greywater have a serious negative effect on the plants which may go into hydration. The salt, Ca^{+2}, Na, K and No^{-3} values were observed about 0.13 % (1st cycle), 11.8 ppm (3rd cycle), 498.2 ppm (2nd cycle), 19.25 ppm (1st cycle) and 51.6 ppm (2nd cycle), respectively. It was observed that the greywater originated from washing machine is significantly polluted.

Table 4.8: Characteristics of laundry (washing machine) greywater

Parameters	Average	Median	Standard Deviation	
Temperature (^{o}C)	28.30	30.32	3.97	1st cycle
pH	7.94	9.23	2.12	
ORP (mV)	181.15	127.00	87.34	
Conductivity (mS/cm)	3.19	3.76	1.54	
Turbidity (NTU)	394.70	437.00	258.02	
DO (mg/l)	6.33	3.90	4.58	
TDS (g/l)	2.04	2.40	0.98	
Salinity (ppt)	1.70	2.00	0.85	
Salt (%)	0.13	0.10	0.07	
Ca^{+2} (ppm)	6.20	7.00	4.07	
Na^{+} (ppm)	482.00	370.00	291.58	
K^{+} (ppm)	19.25	16.00	13.77	
NO^{-}_{3} (ppm)	46.00	52.00	13.01	

Temperature (^{o}C)	28.35	30.09	4.09	2nd cycle
pH	7.74	7.98	2.09	
ORP (mV)	143.30	167.50	92.38	
Conductivity (mS/cm)	2.99	2.50	3.16	
Turbidity (NTU)	213.57	215.50	166.45	
DO (mg/l)	9.33	7.42	4.35	
TDS (g/l)	3.10	3.53	2.62	
Salinity (ppt)	2.76	2.90	2.41	
Salt (%)	0.12	0.08	0.09	
Ca^{+2} (ppm)	6.60	2.00	8.82	
Na^{+} (ppm)	498.20	450.00	340.40	
K^{+} (ppm)	7.60	5.00	5.28	
NO$^{-}_{3}$ (ppm)	51.60	45.00	24.04	
Temperature (^{o}C)	28.29	29.94	4.19	3rd cycle
pH	9.52	9.99	0.70	
ORP (mV)	168.80	172.50	92.06	
Conductivity (mS /cm)	3.52	2.52	2.90	
Turbidity (NTU)	318.53	299.00	277.36	
DO (mg/l)	9.09	7.05	5.68	
TDS (g/l)	3.44	3.56	2.32	
Salinity (ppt)	3.02	2.90	2.16	
Salt (%)	0.10	0.10	0.10	
Ca^{+2} (ppm)	11.80	21.61	21.61	
Na^{+} (ppm)	436.00	397.52	397.52	
K^{+} (ppm)	5.60	5.46	5.46	
NO$^{-}_{3}$ (ppm)	48.00	23.45	23.45	
Temperature (^{o}C)	25.51	23.53	4.03	Mix of 1st, 2nd and 3rd cycle
pH	7.96	9.06	2.18	
ORP (mV)	171.63	174.00	85.30	
Conductivity (mS /cm)	3.22	3.51	1.95	
Turbidity (NTU)	212.94	244.50	137.64	
DO (mg/l)	10.37	9.01	5.14	
TDS (g/l)	2.72	3.29	1.35	
Salinity (ppt)	2.98	2.90	1.99	
Salt (%)	0.11	0.12	0.09	
Ca^{+2} (ppm)	9.50	8.50	4.15	
Na^{+} (ppm)	315.00	225.00	249.45	
K^{+} (ppm)	14.50	13.50	13.12	
NO$^{-}_{3}$ (ppm)	36.75	35.00	19.79	

4.3.6 Face wash greywater

Table 4.9 shows the average, median and standard deviation of greywater characteristics originated from face washing activities. The average pH and turbidity levels were found 7.27 and 128 NTU, respectively. The Na and Ca concentrations were found about 45 ppm and 34 ppm, respectively. The high levels of Na and Ca were probably sourced from soaps, face wash and other cosmetic products. The characteristics of face wash greywater was found similar to the hand wash greywater.

4.3.7 Characteristics of mixed shower, ablution and hand wash greywater

Table 4.10 shows the characteristics of mixed ablution, shower and hand wash greywater. Equal amount of greywater were mixed together. The pH was found a bit alkaline (7.23) and turbidity was observed about 150 NTU. The Na ion was found relatively high (45 ppm), but definitely the mixed greywater characteristics were better than the shower greywater. Since the ablution greywater is diluted than the shower and hand wash greywater – the overall characteristics of mixed greywater are best for treatment purposes.

Table 4.9: Characteristics of greywater originated from face wash activities

Parameters	**Average**	**Median**	**Standard Deviation**
Temperature (^{o}C)	26.29	25.15	4.43
pH	7.27	7.41	0.60
ORP (mV)	215.10	204.00	36.52
Conductivity (mS/cm)	0.30	0.31	0.05
Turbidity (NTU)	128.30	131.55	72.03
DO (mg/l)	6.47	6.84	1.16
TDS (g/l)	0.28	0.27	0.08
Salinity (ppt)	0.15	0.15	0.05
Salt (%)	0.01	0.01	0.00
Ca^{+2} (ppm)	33.50	32.50	5.94
Na^{+} (ppm)	44.75	44.50	4.32
K^{+} (ppm)	11.25	11.00	4.44
$NO^{-}{}_{3}$ (ppm)	24.00	22.50	4.85

Table 4.10: Characteristics of mixed shower, ablution and hand wash greywater

Parameters	**Average**	**Median**	**Standard Deviation**
Temperature (^oC)	23.76	22.60	1.73
pH	7.23	7.32	0.37
ORP (mV)	263.75	253.00	30.88
Conductivity (mS/cm)	0.32	0.29	0.07
Turbidity (NTU)	150.33	148.00	77.33
DO (mg/l)	6.36	6.09	1.94
TDS (g/l)	0.21	0.19	0.04
Salinity (ppt)	0.13	0.10	0.05
Salt (%)	0.04	0.01	0.04
Ca^{+2} (ppm)	27.33	22.00	8.99
Na^+ (ppm)	44.67	42.00	6.80
K^+ (ppm)	13.33	8.00	8.99
NO^-_3 (ppm)	14.67	12.00	3.77

Chapter 5: Performance of Permeable Pavement

5.1 Background

As mentioned in the methodology (Chapter 3), a permeable pavement unit of size 1 m^3 (length 1 m, width 1 m and height 1 m) was constructed. The unit consisted of three layers, namely an upper layer of 80 mm pavers, then a 40 mm deep bedding course layer of 2 mm to 5 mm crushed gravel and finally a 800 mm deep base course storage layer of 20 mm to 60 mm well mixed stone aggregate. The base course depth of 800 mm was considered in order to increase the storage capacity and to make 1 m of height of the prototype. All materials were cleaned and dried before being placed in a 1 m^3 glass container. The unit contained an outlet faucet at the bottom. The void ratio of the base course storage layer was measured at 36% and the volume of the base course storage reservoir was 0.8 m^3, which meant it could store approximately 290 L of greywater. The unit was kept the outdoors in order to simulate the effects of the local arid weather conditions. The ablution and laundry greywater were considered separately to observe their quality changes during retention in the base course of permeable pavement.

5.2 Changes of Municipal Water Quality

Changes of water quality (municipal water, ablution and laundry greywater) in the permeable pavement base course storage are shown in Figure 5.1. Municipal water pH decreased slightly from 8.64 to 8.35 immediately after filling the base course layer and then it became relatively stable from day 1 to day 7. On average, the pH value was found to increase by between 1% and 1.5% from day 1. The initial decrease of 3.4% was probably due to agitation and mixing of the municipal water with impurities such as soil and crushed fine gravel attached to the pavers, bedding and base course aggregates.

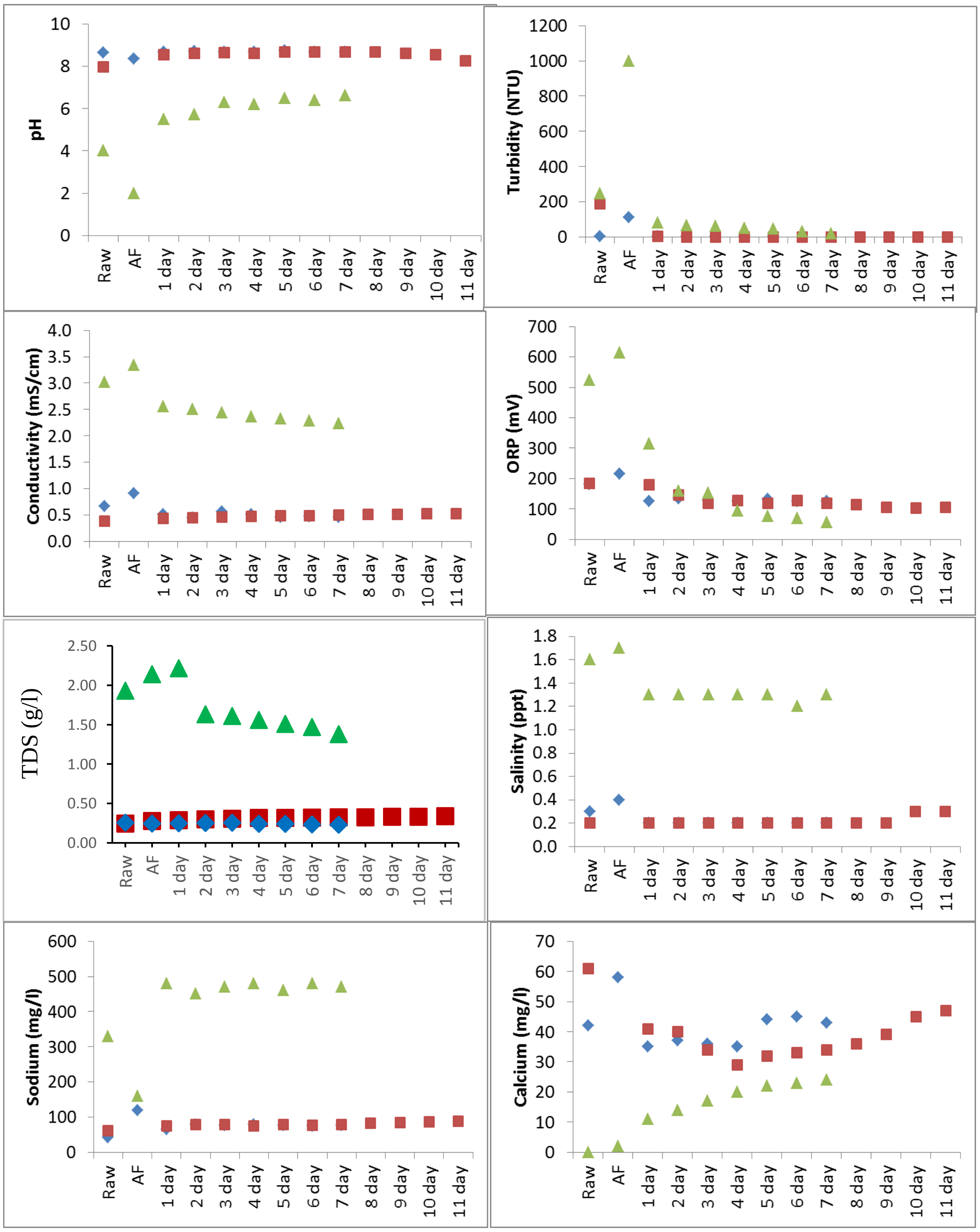

Figure 5.1: Quality changes in municipal water (diamond, blue), ablution greywater (square, red) and laundry greywater (triangle, green) [continue to next page]

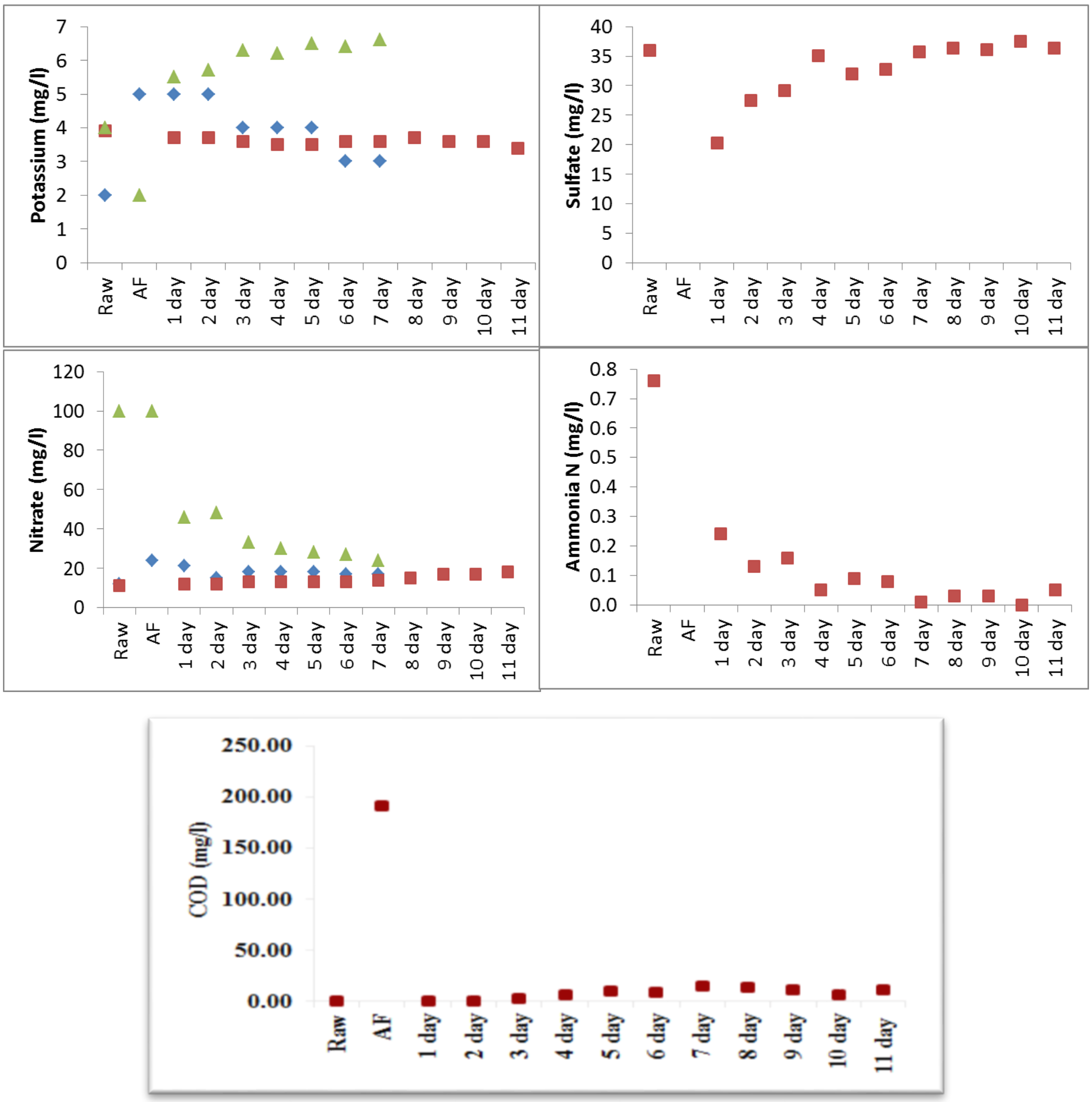

Figure 5.1 (continuing): Quality changes in municipal water (diamond, blue), ablution greywater (square, red) and laundry greywater (triangle, green) in the permeable pavement base course storage layer (*Raw* indicates the quality of raw greywater before entering the unit and *AF* indicates immediately after filling the unit)

The turbidity of municipal water was also observed to increase significantly (111 NTU) after filling the unit and then it decreased to low levels from day 1. From day 1 to day 7, no significant changes in water turbidity were observed. It appears that the initial agitation and mixing of water with impurities in the stone aggregates raised the turbidity immediately after filling.

The TDS of municipal water (4.2 mg/l) was found to improve in the base course storage as shown by a 29% reduction to a relatively stable average level of 3 mg/l from day 1 to day 7.

Changes in the electrical conductivity of water stored in the base course layer were found to follow a similar pattern to that of TDS. The mechanical straining and adsorption of dissolved particles in the surface of base course aggregates may be the reason for lowering TDS and conductivity of greywater during storage. On average, municipal water conductivity reduced from 0.65 mS/cm to 0.5 mS/cm in the storage (23% reduction) at which level it remained relatively constant from day 1 to day 7.

The oxidation reduction potential (ORP) was found to increase after filling of the tank and then decreased from 185 mV to 125 mV (32% reduction) from day 1. The ORP values from day 1 to day 7 were found to be almost invariable.

For salinity, the value increased from 0.3 ppt to 0.4 ppt after filling of the tank. It then decreased to 0.2 ppt from day 1 (33% reduction) after which time it remained relatively constant from day 1 to day 7.

In the case of sodium (Na^+), after filling of the tank the concentration increased significantly from 40 mg/l to 120 mg/l and then decreased to around 65 mg/l after day one and became stable from day 2 with an average concentration of 75 mg/l (87% increase after 2 days).

The calcium (Ca^+) concentration was found to increase from 42 mg/l to 58 mg/l after filling of the tank and it then decreased to around 35 mg/l during the period day 1 to day 4 (17% reduction). From day 5 to day 7, the concentration increased to 43 mg/l. The potassium (K^{++}) concentration increased from 2 mg/l to 5 mg/l after filling of the tank and became constant for the next 2 days. From day 3 to day 5 the concentration decreased to 4 mg/l and reduced further to 3 mg/l during days 6 and 7.

The nitrate (NO_3^-) concentration appeared to increase initially after filling of the tank, but overall remained fairly constant between 15 and 17.5 mg/l over most of the period. This is consistent with the results of Myers *et al*. (2011) who measured nitrate levels in synthetic stormwater stored in two types of base course aggregate for periods of up to 144 hours. Myers *et al*. showed that nitrate levels remained between 25 and 30 mg/l over the entire testing period.

Except for pH, all other parameters showed an increased concentration immediately after filling of the tank which is similar to the first flush phenomenon in stormwater collection systems. This is likely to be due to sediments and other impurities attached to aggregates in the bedding and base course layers mixing with the water in the tank. Within 24 hours, these sediments and impurities settled down, which is very evident from the turbidity graph (Figure 5.1). After storage of at least 24 hours, it can be seen from Figure 5.1 that the quality parameters do not exceed the drinking water quality guideline values for Abu Dhabi (Regulation and Supervision Bureau - Abu Dhabi, 2013), which are: turbidity (4 NTU); TDS (100 to 1000 mg/l); pH (7 to 9.2); conductivity (1.6 to 16 mS/cm); sodium (150 mg/l); potassium (12 mg/l); nitrate (50 mg/l). Total aerobic and coliform bacteria were not identified in the municipal water.

5.3 Changes of Ablution Greywater Quality

The changes in ablution greywater quality in the permeable pavement base course storage were monitored for 11 days, as shown in Figure 5.1. The pH value changed from 7.95 to 8.6 from day 1 to day 10 (8% increase). The standard pH level for drip and spray irrigation water is 6 to 8 (Environment Department – Dubai, 2010), therefore it is seen that the pH level from the permeable pavement storage exceeded the irrigation standard, but falls within the drinking water guideline value (pH 6 to 9).

The turbidity of ablution greywater (initially 188 NTU) decreased to 3 NTU after 24 hours and became zero from day 2. This indicates that the solids in the greywater settled or were adsorbed onto base course aggregates.

The TDS concentration ($2.4\text{x}10^{-3}$ g/l) increased almost linearly up to $3.3\text{x}10^{-3}$ g/l in day 11, which equates to an average increase of $0.08\text{x}10^{-3}$ g/l per day. Therefore, while the TDS concentration decreased over time for municipal water, it increased for ablution greywater.

The conductivity was also found to increase linearly in the base course storage, from 0.38 mS/cm to 0.52 mS/cm after 11 days, with an average increase of 0.013 mS/cm per day. The increase in conductivity may be attributable to the dissolution of salts and carbonates at the mineral surfaces. This process is a well noted phenomenon in aqueous environments, resulting in a number of dissolved and semi-dissolved salts and carbonate constituents as outlined by Chou (1989). This dissolution can be accelerated by repeatedly filling and emptying reservoirs depending on the nature of the base course material (Myers *et al*., 2009). Both TDS and conductivity are interrelated and fall within the acceptable irrigation standard level.

The ORP value decreased from 185 mV to 105 mV after 11 days, which represents an average decrease of 7.3 mV per day. The salinity concentration (initially 0.2 ppt) remained unchanged up to day 9 and then increased to 0.3 ppt during days 10 and 11.

The sodium concentration (initially 60 mg/l) gradually increased in the base course storage at an average rate of approximately 2 mg/l per day. However, the concentration remained well below the allowable limit. The maximum allowable sodium concentrations in drip and spray irrigation are 500 mg/l and 200 mg/l, respectively (Environment Department – Dubai, 2010).

For calcium ions, the concentration (initially 62 mg/l) decreased for the first four days at an average rate of 2.9 mg/l per day and then increased at a rate of 2.4 mg/l per day from 30 mg/l in day 4 to 47 mg/l in day 11.

The nitrate concentration was initially 11.3 mg/l and increased in the base course storage at an average rate of 0.6 mg/l per day. However, the concentration remained below the drinking water quality guideline maximum value of 50 mg/l (Regulation and Supervision Bureau - Abu Dhabi, 2013).

The ammonia nitrogen concentration (initially 0.75 mg/l) decreased significantly to 0.25 mg/l in day one of storage and then gradually further decreased at an average rate of 0.03 mg/l per day, most likely due to the nitrification processes. Even the initial ammonia nitrogen concentration was below the maximum allowable limit of 5 mg/l for drip and 1 mg/l for spray irrigation (Environment Department – Dubai, 2010).

The potassium ion concentration (initially 3.9 mg/l) was observed to decrease up to day 5 at an average rate of 0.08 mg/l per day. From day 5 to day 8, an increasing trend of potassium concentration was observed at an average rate of 0.07

mg/l per day. After the 8th day, the concentration was again observed to decrease at an average rate of 0.1 mg/l per day. The initial potassium concentration was below the water quality guideline maximum value of 12 mg/l (Regulation and Supervision Bureau - Abu Dhabi, 2013).

The sulfate concentration (initially 37 mg/l) decreased significantly to 20 mg/l in 24 hours and then displayed an increasing trend at an average rate of 1.7 mg/l per day. However, it remained considerably below the maximum allowable limit of 200 mg/l for both drip and spray irrigation.

The COD of ablution greywater (initially 0 mg/l) suddenly increased at the first days (192.0 mg/l) which is may due to mixing ablution water the materials in the unit caused that increment. Then remained at a stable level of around 15 mg/l up to day 11. The maximum allowable limit for COD is 100 mg/l for drip and 50 mg/l for spray irrigation (Environment Department – Dubai, 2010).

After comparing with the colony density chart provided with the Peddle Tester, the total aerobic bacteria and total coliform bacteria of raw ablution greywater were found to be approximately 10^6/100ml and 10^4/100ml, respectively. It was observed that storage of ablution greywater in the permeable pavement base course remains the concentrations of the total aerobic bacteria and total coliform bacteria constant at day 3, day 6 and day 9. These results are consistent with those of Myers *et al*. (2009) who investigated whether storage in the base course of a permeable pavement impacts on the survival of E. coli. Myers *et al*. used 12 model permeable pavement storage reservoirs which were filled, in triplicate, with dolomite, calcite and quartzite aggregate. Three reservoirs contained no aggregate. After filling with pathogen spiked rainwater, the concentration of E. coli was examined for 22 days in the reservoirs. The results showed that there was no significant difference in the depletion of E. coli found in reservoirs without aggregate, and those filled with dolomite or calcite. Other researchers have found that storage of greywater results in increases of indicator organisms. Of note, however, is that while the indicator organisms increase during storage, true pathogenic bacteria have been found to survive and not increase while viruses have been found to decrease (Rose *et al.*, 1991).

The irrigation water standard for fecal coliform is 20/100 ml for drip and 0/100 ml for spray irrigation (Environment Department – Dubai, 2010). This indicates the necessity for disinfection of greywater before it is reused for irrigation purposes. From Figure 5.1 it can be postulated that, except for a slightly higher pH level, storage of ablution greywater for three days in a permeable pavement base course together with appropriate disinfection can meet the irrigation standards for recycled water in the UAE. The summarized changes of ablution greywater quality parameters in the permeable pavement base course reservoir are shown in the Table 5.1.

Table 5.1: Summarized changes of greywater quality parameters while stored in the permeable pavement base course storage reservoir (+ and – sign indicates increase and decrease, respectively)

Quality parameters	**Ablution greywater**				**Laundry greywater**			
	Raw	**Day-1**	**Day-3**	**Day-7**	**Raw**	**Day-1**	**Day-3**	**Day-7**
pH	7.95	+8%	+9%	+9%	4	+38%	+58%	+65%
Conductivity (mS/cm)	0.38	+13%	+21%	+32%	3.02	-16%	-19%	-26%
Turbidity (NTU)	188	-98%	-100%	-100%	247	-67%	-76%	-93%
TDS (mg/l)	2.4	+17%	+25%	+33%	19.3	-16%	-19%	-25%
Salinity (ppt)	0.2	0%	0%	0%	1.6	-19%	-19%	-19%
Na (mg/l)	61	+21%	+28%	+28%	330	+45%	+42%	+42%
Ca (mg/l)	61	-33%	-44%	-44%	0	+11%	+17%	+24%
K (mg/l)	3.9	-5%	-8%	-8%	4	+38%	+58%	+65%

NO_3 (mg/l)	11	+9%	+18%	+27%	100	-54%	-67%	-76%
NH_4-N (mg/l)	0.76	-68%	-79%	-99%	Not measured			
SO_4 (mg/l)	36	-44%	-19%	-1%	Not measured			
COD (mg/l)	318	-40%	-94%	-96%	Not measured			
Total aerobic bacteria	10^6	No change			Not identified			
Total coliform bacteria	10^4	No change			Not identified			

5.4 Changes of Laundry Greywater Quality

The changes in laundry greywater quality resulting from storage in the permeable pavement base course are shown in Figure 5.1. The pH of laundry greywater exhibits a high value because of the presence of detergents. The pH value reduced from 10.2 for raw laundry greywater to 9.4 after one day and then this rapidly decreased at an average rate of 0.18 per day up to day 4. After the fourth day of storage, a stable average pH of 8.8 was observed. The pH level exceeded the recommended guideline level of 8 for irrigation, but remained within the acceptable range for drinking water (6 to 9).

The turbidity of laundry greywater (initially 247 NTU) increased significantly to 1000 NTU immediately after filling which was probably due to a first flush effect. The turbidity level then significantly decreased to 82 NTU after day one. For the next six days, a gradual decrease of turbidity was observed at an average rate of 10.5 NTU per day. This trend was also observed by Myers *et al*. (2011) who measured turbidity in stormwater stored in two types of base course aggregate for periods of up to 144 hours.

After an initial increase in TDS value from 19.3 mg/l to 21.4 mg/l because of the first flush, it then decreased by 17% to 16.1 mg/l after day one and then displayed a decreasing trend at an average rate of 0.3 mg/l per day. The TDS concentration falls far below the guideline values for irrigation in the UAE.

The conductivity level showed a similar trend to TDS indicating that they are correlated. A 16% reduction of laundry greywater conductivity is observed per day of storage time.

The ORP level (initially 524 mV) decreased by 40% in the first day and by a further 30% by day 2. The ORP is the activity or strength of oxidizers and reducers in relation to their concentrations. Oxidizers (e.g., chlorine, ozone, chlorine dioxide, etc.) accept electrons and reducers (e.g., sodium sulphite, sodium bisulphate, hydrogen sulfide, etc.) lose electrons. A positive and negative ORP value indicates oxidizing and reducing agent, respectively.

The salinity of laundry greywater (1.6 ppt) decreased by 18% in the first day and then maintained a relatively stable value up to day 7. Unlike for municipal water and ablution greywater, the sodium ion concentration in laundry greywater decreased from 330 mg/l to 160 mg/l after filling the pavement unit. It then increased to 470 mg/l where it remained from day 1 to day 7. This is very close to the maximum allowable limit of 500 mg/l for drip irrigation and exceeds the limit of 200 mg/l for spray irrigation in the UAE.

The calcium ion concentration in raw laundry greywater was not detected. However, its concentration increased to 11 mg/l in day one and then showed a gradual increase at an average rate of 2 mg/l per day. The cause for this could be the dissolution of calcium ion from the pavers, bedding gravel or base course.

On the first day, the nitrate concentration decreased by 54% and then further reduced by 3.7 mg/l per day through the bacterial denitrification process.

Like sodium, the potassium concentration also showed a decrease (from 4 mg/l to 2 mg/l) after filling of the tank and then exhibited an increasing trend from the 1st day of storage onwards. After the first day, the potassium concentration increased to 5.5 mg/l (38% increase) and then further increased at an average rate of 0.18 mg/l per day.

Total aerobic and coliform bacteria were measured, but not identified in laundry greywater. From Figure 5.1, it is evident that while storage in the permeable pavement base course improves the quality of laundry greywater, both the pH and the sodium ion level were found to exceed the respective maximum allowable limits for irrigation.

Chapter 6: Performance of Biofiltration

6.1 Background

As mentioned in the Methodology chapter (Chapter 3), a prototype of a biofiltration system of size 1 m^3 (length 1 m, width 1 m and height 1 m) was constructed. The prototype consisted of three layers, namely an upper 60 cm layer of well mixed sand and small gravels (0.075 mm to 4.75 mm), then a 12 cm deep well mixed coarse sand (0.5 mm to 2 mm) and finally a 8 cm deep well mixed gravel layer (2 mm to 5 mm). All materials were cleaned and dried before being placed in a 1 m^3 glass container. The prototype was fitted with an outlet faucet at the bottom. The system can hold about 144 L^3 of greywater. The prototype was kept outdoors in order to imitate the effects of the local arid weather conditions. A native plant named Reed grass (*Phalaris arundinacea*) was planted in the system. Greywater, collected from ablution and laundry sources, were applied separately in the biofiltration system, for both cases of non-vegetative (without plants) and vegetative (with plants) conditions.

6.2 Changes of Greywater Quality

Changes of greywater quality in the non-vegetative and vegetative biofiltration systems are depicted in Figure 6.1. From Chapter 4, it was found that the laundry greywater generally contains higher levels of organics and physical pollutants compared to other sources of greywater. Greywater needs to be processed based on their end uses quality requirements (toilet flush and gardening, for example). According to Li *et al*. (2009), the major target of greywater reclamation and reuses is to reduce their suspended solids, the organic strength and micro-organisms. Removal of organics decreases the chlorine demand for disinfection and reduces the potential of microbial growth in the greywater distribution system

(Winward *et al*. 2008). The U.S. EPA (2004) noted that the salinity of reclaimed water may be the most important parameter in determining its suitability for irrigation.

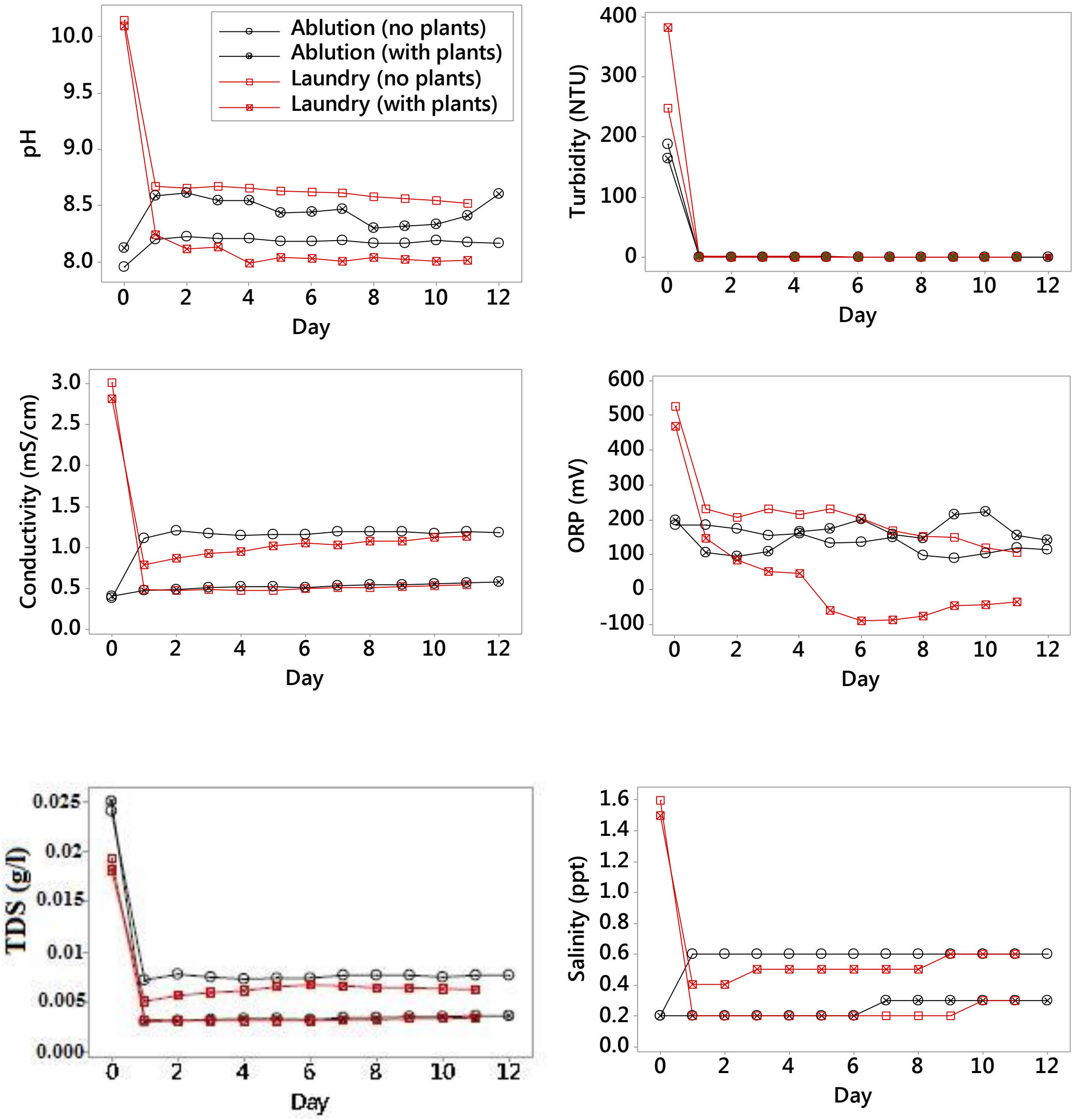

Figure 6.1: (continue to next page): Changes of ablution and laundry greywater qualities in the non-vegetative and vegetative biofiltration systems

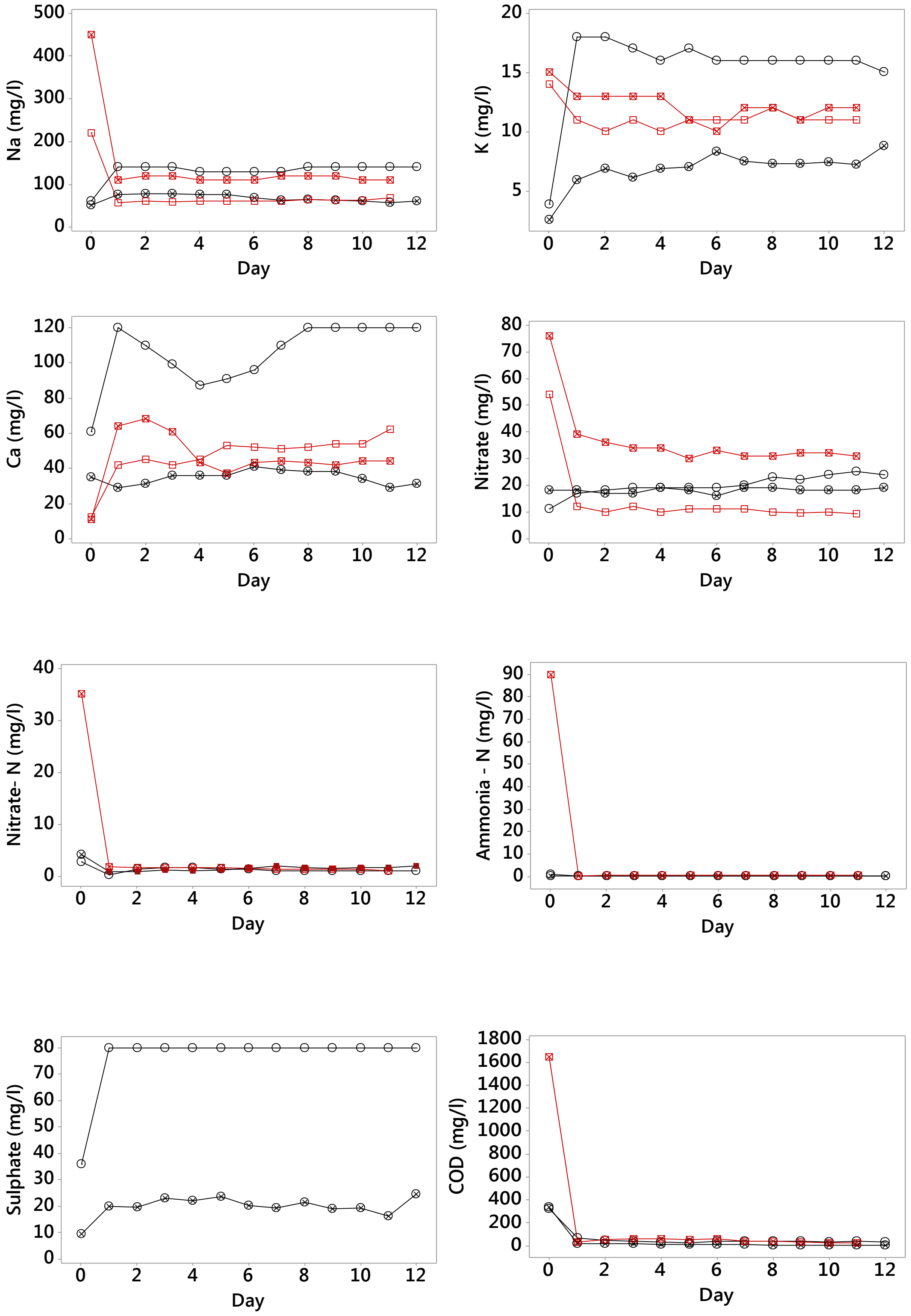

Figure 6.1: Changes of ablution and laundry greywater qualities in the non-vegetative and vegetative biofiltration systems

Broadly, the excessive sodium concentration in laundry greywater makes it unfit for irrigation without proper treatment (Misra and Sivongxay., 2009). The observed changes of greywater quality after retention in the biofiltrartion system are described below.

6.2.1 Hydrogen ion (pH)

The pH level in the ablution greywater was found to increase from 7.95 to 8.2 (increased by 5.8%) after 1 day of retention in the vegetative system, in comparison to the non-vegetative system where pH increased from 8.12 to 8.59, about 3.1 %. In the vegetative system, the pH value was observed to decrease from day 1 to day 8, and then again started to increase, an overall variance of 0.02 was observed. In case of the laundry greywater, the pH value was observed to diminish from 10.15 to 8.67 (15% reduced) in the non-vegetative system and from 10.1 to 8.24 (18% reduced) in the vegetative system, after one day of retention period. A stable pH was observed in both vegetative and non-vegetative conditions for laundry greywater.

The laundry greywater generally possess high pH value in comparison to other sources. Particularly when phosphorous-free detergent are used, less phosphorous and higher pH levels (approximately 8 to 10) were observed (Eriksson *et al.*, 2002). According to the local guidelines (ADRSB, 2010), the pH value of the wholesome water (water supplied for the purposes of drinking, washing, cooking or food production) should be in between 7 and 9.2. Therefore, pH values of both ablution and laundry greywater after retention in the systems met the guideline for wholesome water, but exceeded the irrigation water quality guideline ($6 \leq pH \leq 8$) (Environment Department - Government of Dubai 2010). This shows the requirement of pH adjustment mechanism in the biofiltration systems prior their application for irrigation end uses.

6.2.2 Turbidity

The turbidity of ablution greywater was observed to fall sharply after 1 day retention (reduced by 100% and 99.6% in the non-vegetative and vegetative system, respectively). Further reduction (or increase) was not remarkably notified with longer retention periods. In the case of laundry geywater, for both non-vegetative and vegetative systems, 100% turbidity was observed to remove after one day of retention. The maximum allowable turbidity limit is 4 NTU (ADRSB 2010) and both systems were found excellent in reducing turbidity from greywater. In general, ablution greywater contains less turbidity than the laundry greywater, because soap or hand sanitizers are not generally used for ablution. It was observed that the removal of turbidity from greywater in the biofiltration system does not depend on greywater sources and vegetation features, both vegetative and non-vegetative systems were found almost equally effective. This is because turbidity results from suspended solids and they adsorbed or settled onto the biofiltration filter media (sand).

6.2.3 Electrical Conductivity

The conductivity of ablution greywater was found to increase significantly (approximately 208% increased) after 1 day of retention in the non-vegetative system and the result was remained almost stable during the 12 days of observation (observed variance was about 0.46). In the vegetative system, conductivity was found to increase gradually, on an average about 33% increased in 12 days with a variance of 0.57. Whereas for laundry greywater, an opposite situation was detected. The conductivity of laundry greywater was observed to decrease by 84% and 72% in the non-vegetative and vegetative systems respectively, after one day of retention. The non-vegetative system was found to decrease the conductivity level of laundry greywater more than the vegetative system. The permissible range of conductivity in wholesome water is 160 to 1600 mS/cm (ADRSB 2010), and the observed conductivity in greywater before and after the retention in the biofiltration system was found far below the guideline value.

It is depicted that changes of conductivity in the retained greywater significantly depend on the sources of greywater and on the presence or absence of vegetation in the system. Electrical conductivity is a measure of the ability of water to pass an electrical current. It is affected by the presence of inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions or sodium, magnesium, calcium, iron, and aluminium cations. Consequently, relatively high conductivity in laundry greywater indicates presence of either anions or cations, which may have been driven from different detergents, softeners and whiteners used in cleaning clothes. The increase in conductivity in the biofiltration systems may be attributable to the dissolution of salts and carbonates at the sand (mineral) surfaces. This process is a well noted phenomenon in aqueous environments, resulting in a number of dissolved and semi-dissolved salts and carbonate constituents as outlined by Chou (1989).

6.2.4 Total Dissolved Solids (TDS)

The TDS level in the ablution greywater was observed to decrease sharply after one day of retention in both the vegetated and non-vegetated systems. On an average about 69% and 87% of TDS were removed from the non-vegetated and vegetated condition, respectively. In both conditions, less variability of the TDS level was observed from day 1 to day 12 retention periods with an estimated variance of about 0.005. It was noted that the vegetated biofiltration system showed a better performance in reducing the TDS level from the ablution greywater, about 18% more removal capacity was observed than the non-vegetated condition. In the case of laundry greywater, both systems (vegetated and non-vegetated) were found very effective in reducing the TDS concentration. Nevertheless, the non-vegetated system showed a better performance than that of the vegetated system. After one day of retention, the non-vegetated system removed about 83% of TDS whereas the vegetated system removed about 72% of TDS. For both sources of greywater, the TDS value was found far below the guideline range of 100 to 1000 mg/l (ADRSB 2010). The vegetated system was found to perform better for the TDS removal from ablution greywater, but a bit less performed for laundry greywater.

Comparatively, laundry greywater exhibits high concentration of TDS. Since TDS represents the summation of all anions (chloride, nitrate, sulfate, phosphate, etc.) and cations (sodium, calcium, magnesium etc.), high concentration of TDS in laundry greywater can be attributed to uses of different detergents and other cloth cleaning products. Adsorption of anions in the biofiltration filter media (sand) may be considered as the TDS removal mechanism in the system. From the Figure 6.1, it can be depicted that 24 hours of retention period can achieve the desired removal of TDS from the greywater.

6.2.5 Oxidation Reduction Potential (ORP)

The ORP is the activity or strength of oxidizers and reducers in relation to their concentrations. Oxidizers accept electrons and reducers lose electrons. A positive and negative ORP value indicates presence of oxidizing and reducing agent, respectively. The ORP of ablution greywater was found to diminish gradually in the non-vegetative system; on an average, about 3% was reduced in a day. Whereas in the vegetative system, the ORP was observed to decrease sharply (46% reduced) after 24 hours of retention. A remarkable cyclic variation of ORP was notified of the vegetative system. In the case of laundry greywater, the ORP value of the non-vegetative system was observed to decrease from 524 (mV) to 230 mV (about 56%) after one day of retention, and then showed a decreasing trend with a value of 105 mV after 11 days of retention. In the vegetative system, the ORP value reduced from 468 mV to 147 mV (69%) after one day of retention, and then showed a rapid drop until day 6 (-92 mV ORP was recorded after day 6). After five days of retention, a negative ORP was observed in the vegetative system which indicates presence of reducing agents in greywater. It is noticed that the ORP follows a complex process in the case of laundry greywater in both vegetative and non-vegetative systems.

6.2.6 Salinity

Salinity is the summation of all dissolved salts in water. The salinity concentration of ablution greywater (0.2 ppt) was found to increase by 200% after one day of retention in the non-vegetated system, whereas in the vegetative system the concentration remained constant till day 6 and then increased by 50% from day 7. In the case of laundry greywater, salinity was removed by 88% and 73% after one day of retention in the non-vegetative and vegetative system, respectively. The reduction efficiency was found stable from day 2 to day 11 of retention periods. Both systems (non-vegetative and vegetative) were found effective well in reducing the salinity concentration, however, the non-vegetative system showed a better reduction efficiency than that of the vegetative system. It was observed that most of the reduction of salinity happens after one day of retention and the mechanism may be related to adsorption of dissolved salts in the filter media (sand) of biofiltration system.

6.2.7 Sodium (Na)

The sodium ion concentration in the ablution greywater (61 mg/l) was increased by 130% after one day of retention in the non-vegetative system and then remained stable during 12 days of retention period. In the vegetative condition, the Na concentration (51 mg/l) was increased by 49% and then remained almost unaltered for three days. From day 4, the Na concentration started to decrease gradually. After 12 days of retention, an increase of 20% (of initial concentration) was recorded. While the Na was observed to increase in both conditions (vegetative and non-vegetative), its increase in the vegetative system was found less than the non-vegetative system. In the case of laundry greywater, both vegetative and non-vegetative systems were found effective well in reducing the Na concentration. After one day of retention, the non-vegetative system was observed to reduce Na concentration from 220 mg/l to 57 mg/l (74% reduced), and the vegetative system was observed to reduce from 450 mg/l to 110 mg/l (76% reduced). Further reduction (gain) of Na with increased retention periods was not noticed remarkably.

The Na concentration in the ablution greywater falls below the guideline values of 150 mg/l (ADRSB, 2010), 500 mg/l (drip irrigation) and 200 mg/l (spray irrigation) (Environment Department – Dubai, 2010). However, the Na concentration in laundry greywater exceeded these guideline values. After retention of laundry greywater in the biofiltration system (both vegetative and non-vegetative), the Na concentrations fall below these guideline values. Both the vegetative and non-vegetative systems were found almost equally effective in reducing Na ion from laundry greywater. The process of Na ion reduction may be related to the accumulation in the filter media of biofiltration system. A 24 hour retention period was found optimal for conception purposes.

6.2.8 Potassium (K)

The K ion concentration in the ablution greywater (3.9 mg/l) was found to increase sharply by 362% after one day of retention in the non-vegetative system. From day 2, the K ion concentration was observed to decrease very slowly and after day 12, a value of 3.9 mg/l was observed. Whereas for the vegetative system, the K ion was increased by 127% after one day of retention and then gradually increased to 238% after 12 days of retention. Both the vegetative and non-vegetative systems were found to increase the K concentration of ablution greywater, however, the vegetative system increased the K concentration below to the non-vegetative system. In the case of laundry greywater, the K ion concentration removal was not found significantly higher in both systems. The non-vegetative and vegetative system was observed to remove about 21% and 13% of K concentration after one day of retention. Further removal of K with longer retention periods was not noticed remarkably for both systems.

While the vegetative system performed well for ablution greywater, the non-vegetative system showed a bit better performance in removing K concentration from the laundry greywater. Therefore, it can be postulated that the removal efficiency of K depends on the sources of greywater and the type of system used (non-vegetative or vegetative). According to Arienzo *et al*. (2009), the K ion concentration in domestic wastewater varies between 10 and 30 mg/l, and the greywater K concentration of different sources falls within this range. The potassium hydroxide (KOH) present in soaps and detergents is the main cause of raising K ion in laundry greywater. The K ion concentration in the ablution greywater is generally low because ablution greywater does not contain soaps and detergents. For both systems and for both sources, the K ion concentrations were found below the guideline value of 12 mg/l.

6.2.9 Calcium (Ca)

The calcium ion in the ablution greywater (61 mg/l) was increased by 97% after one day of retention in the non-vegetative system and then decreased to 87 mg/l after four days of retention time. From day 5 to day 8, the Ca ion started to increase again and then remained constant at 120 mg/l. For the vegetative system, the Ca ion decreased by 17% and 11% after one and two days of retention, respectively. The concentration started to increase very slowly from day 3 to day 6 (41 mg/l), and then decreased again gradually. After 12 days of retention, 31 mg/l of Ca was recorded. The vegetative system exhibited a better performance in removing Ca ion from the ablution greywater.

A different situation was observed for the laundry greywater. The Ca ion was observed to increase tremendously in both systems, about 250% and 482% increased after one day of retention in the non-vegetative and vegetative system, respectively. In the non-vegetative system, the Ca concentration increased gradually with longer retention periods and a Ca ion concentration of 62 mg/l was found after 11 days of retention (417% increased). Whereas in the vegetative condition, a decreasing trend of Ca concentration was observed after it reached a value of 68 mg/l after 3 days of retention (518% increased after 3 days). Like the K ion, the Ca ion removal from greywater significantly depends on the sources of greywater and the type of system used (non-vegetative or vegetative).

62.10 Nitrate (as NO_3)

The nitrate (as NO_3) concentration of ablution greywater in the non-vegetative biofiltration system was increased by 55% (from 11 mg/l to 17 mg/l) after one day of retention time. As the retention time increases, NO_3 concentrations showed an increasing trend and reached about 24 mg/l (increased by 118%) after 12 days of retention. In the vegetative system, NO_3 concentrations were found relatively unchanged over the retention period. In the case of laundry greywater, the NO_3 concentration was noted to scale down significantly after one day of retention, about 78% was reduced in the non-vegetative system and about 49% reduced in the vegetative system. Further reduction (or increase) of NO_3 with increased retention periods was not noticed remarkably for both systems. While NO_3 concentration in ablution greywater increased in the biofiltration system, surprisingly NO_3 concentration was observed to decrease for laundry greywater.

For laundry greywater, the non-vegetative system performed well than the vegetative system in reducing the NO_3 concentration. Therefore, it can be postulated that the removal of NO_3 depends on the sources of greywater and on the types of biofiltration system (vegetative or non-vegetative). Though NO_3 is an essential element for plants' growth, their excessive concentration in groundwater and in drinking water may create a health hazard. The recommended guideline value for NO_3 in water is 50 (mg/l) (ADSRB, 2010; WHO, 2006). After retention in the biofiltration system, it was observed that the NO_3 concentration falls below the guideline value.

6.2.11 Nitrate as Nitrogen (NO_3-N)

For the ablution greywater, the NO_3-N concentration was observed to drop significantly after one day of retention in both the vegetative (from 4.2 mg/l to 0.9 mg/l, reduced by 79%) and non-vegetative conditions (from 2.78 mg/l to 0.3 mg/l, reduced by 89%). In the non-vegetative system, the NO_3-N concentration started to increase from day 2 to day 4 and then exhibited a drop onwards (1.1 mg/l of NO_3-N was observed after 12 days retention). Whereas in the vegetative condition, after first day of retention, the NO_3-N concentration showed an increasing trend and 2 mg/l of NO_3-N was observed after 12 days of retention. In the case of laundry greywater, the NO_3-N concentration was significantly removed (from 35 mg/l to 1.8 mg/l, about 95% removed) after one day of retention in the vegetative biofiltration system. Further reduction (or increase) was not observed with a longer retention period. Overall, both the non-vegetative and vegetative biofiltration systems were found effective well in removing NO_3-N from the greywater. However, the vegetative system showed a relatively better performance over the non-vegetative system.

6.2.12 Ammonia Nitrogen (NH_4-N)

The NH_4-N concentration in the ablution greywater (less than 1 mg/l) in both systems (non-vegetative and vegetative) was removed by 100% after one day of retention. For the laundry greywater, the NH_4-N concentration (90 mg/l) was also reduced tremendously (more than 99% removed) after one day of retention in the vegetative biofiltration system. The reduction of NH_4-N concentrations in the vegetative system can be connected to the nitrification processes. In both systems, the NH_4-N concentrations were observed to be far below the maximum recommended value of 5 mg/l (drip irrigation) and 1 mg/l (spray irrigation) (Environment Department – Dubai 2010). The NH_4-N in the ablution greywater in both systems exhibited a non-significant negative correlation with the COD. Whereas for laundry greywater in the vegetative system, the NH_4-N exhibited a positive correlation (95% level) with the SO_4 and a non-significant correlation with the COD.

6.2.13 Chemical Oxygen Demand (COD)

The efficiency of both non-vegetative and vegetative systems was found excellent in removing the COD from the ablution greywater. After one day of retention, the non-vegetative system removed the COD from 318 mg/l to 62 mg/l (by 81%) and the vegetative system removed from 333 mg/l to 17 mg/l (by 95%). While both systems were very efficient in reducing the COD, the vegetative system showed a relatively better performance than the non-vegetative system. Likewise for the laundry greywater, the COD concentration was found to remove tremendously from 1650 mg/l to 26 mg/l (about 98% removed) after one day of retention in the vegetative biofiltration system. Further reductions or increases of the COD concentration with longer retention periods were not noticed remarkably. The maximum allowable limit for COD is 100 mg/l for drip and 50 mg/l for spray irrigation (Environment Department – Dubai, 2010), which indicates that both systems (non-vegetative and vegetative) are very efficient in lowering the greywater COD level after 24 hours of retention period.

6.2.14 Sulfate (SO_4)

The SO_4 concentration was observed to increase by 122% (from 36 mg/l to 80 mg/l) and by 112% (from 9.3 mg/l to 19.7 mg/l) in the non-vegetative and vegetative systems, respectively, after one day of retention of ablution greywater. Further increases (or reductions) of SO_4 concentrations were not observed in both systems during 12 days of retention periods. In both systems, the SO_4 concentrations were found far below the maximum allowable limit for the wholesomeness of water (250 mg/l) and for irrigation (200 mg/l). The monitoring was not executed for the laundry greywater because of some technical problems.

6.2.15 Total Aerobic and Total Coliform Bacteria

The total aerobic and total coliform bacteria were absent in the laundry greywater, however, the ablution greywater exhibits existence of total aerobic bacteria (10^6/100 ml) and total coliform bacteria (1000/100 ml). After three and six days of retention in the vegetative and non-vegetative systems, the total coliform bacteria was not identified and the total aerobic bacteria of 1000/100 ml were estimated. The same results were observed in both systems. This implies that the biofiltration systems are effective in reducing the total coliform and total aerobic bacteria concentration from the greywater and the removal efficiency is independent of existence of plants in the system. Microorganisms in the greywater are removed from the biofiltration system by retaining in their filter media.

Chapter 7: Conclusion and Recommendation

The purpose of the study was to investigate the efficiency of vegetative biofiltration and permeable pavement with an underlying reservoir system for the treatment of greywater for their non-potable end uses for irrigation of home gardening. The Abu Dhabi Emirate is an arid region, where the annual rainfall is less than 100 mm and there is no permanent surface water resources. The groundwater resource is depleting because of excessive extraction and also affected by the saltwater intrusion. Despite these, their residential water demand is significantly high. Particularly in villa type detached houses, recent studies explored that the water consumption rate is more than 2000 liter/capita/day and about 80% of this municipal water are used for outdoor activities like irrigation to amenity plantations and car washing. The municipal water demand reduction and diversification of alternative water sources are the key challenges to secure the water supply in the region. Reuse of greywater has been acknowledged to save about 30% of municipal water consumption. The objectives of the study were to investigate the quantity and quality of greywater in the Al Ain city of the UAE, and to explore the performance of two water sensitive urban design (WSUD) technologies, the permeable pavement and biofiltration systems, to improve the quality of greywater for their possible reuse for irrigation to amenity plantations.

Greywater generation and characteristics differ from country to country depending on age, gender, living standards, habits, lifestyle and the degree of water abundance. The frequency and water requirement for personal water uses (e.g., shower, ablution, toothbrush, hand wash and face wash) and family water uses (e.g., laundry) were estimated from about 100 villa type detached homes randomly distributed across the Al Ain city. The estimated average greywater generation rate was found to be 192 liters per capita per day. The generated greywater originates from the shower (49%), ablution (18%), laundry (10%) and wash basin (23%). The irrigation water consumption of 800 liter/day for 260 m^2 area [about 50 medium size plants] was estimated which can be averaged as 16 liters/plant/day or 3 liters/m^2/day. Therefore, considering the greywater generation rate of 192 liter/day/capita, family size of 10 persons and maximum 50% of greywater can be reused; about 960 liter/day of greywater from a house can accommodate more than 250 m^2 (more than 50 plants) of amenity plantation area. In terms of greywater characteristics, a high variability in greywater quality was observed, which is related to the lifestyles, cultural habits and choices of water uses. In general, greywater quality was found to exceed the local irrigation water quality standards.

Permeable paving is a water sensitive urban design (WSUD) technology that is widely used for source control of urban stormwater runoff. Previous studies have shown that filtration through and storage in the underlying reservoir of a permeable pavement can improve the quality of stormwater runoff, particularly when it is intended for potential reuse. However, in this study, changes in greywater quality were investigated when it is stored in base course aggregate. Greywater in the UAE excludes kitchen waste water and therefore the levels of organics and other pollutants are relatively low. The experimental results show that filtration through and storage in the permeable pavement can reduce some physical and chemical pollutant levels in the ablution and laundry greywater, predominantly through mechanical filtration and adsorption processes, but that pH and sodium ion levels were found to still be beyond the recommended limits for reuse by irrigation. Also, the total coliform and total aerobic bacteria levels were found to remain largely unchanged during their storage in the permeable pavement system. Therefore, appropriate disinfection is required before their reuse for non-potable end uses.

A retention period of 24 hours was found optimal in both the vegetative and non-vegetative biofiltration systems. After retention of 24 hours, the pH of greywater exceeds the local irrigation water quality guideline level of 8. An excellent turbidity removal efficiency was observed after 24 hours of retention. Both the non-vegetative and vegetative systems performed equally well in reducing the turbidity level. More than 70% of TDS were removed after 24 hours of retention of greywater in the biofiltration system. The TDS levels were found far below the guideline levels. The conductivity of greywater was found significantly low, the level was increased in ablution greywater but decrease in laundry greywater after retention in the biofiltration. The significant difference between the vegetative and non-vegetative system was not observed. The salinity of greywater was found significantly low.

The sodium ion concentration in laundry greywater was found higher than the recommended levels and both the vegetative and non-vegetative system performed almost equally well in reducing Na levels (more than 70%) after 24 hours of retention period. The potassium ion concentration was increased in the ablution greywater but decreased in the laundry greywater for both non-vegetative and vegetative systems. The non-vegetative system performed better than the vegetative system in reducing the K from the laundry greywater, however, the concentration exceeded the guideline levels. The calcium ion concentrations were found significantly increased after retention of 24 hours on both systems, but far below the guideline level. The non-vegetative system was found to perform better than the vegetative system in reducing NO_3 concentration from laundry greywater. The concentrations were found below the guideline levels. After 24 hours of retention, the

NO_3-N concentrations were found below the guideline levels. The ammonia nitrogen concentrations were reduced by 100% after 24 hours of retention. The sulfate ion concentrations were found far below the guideline levels. Both systems were found very efficient in reducing the COD levels from greywater after 24 hours of retention. The vegetative system performed better than the non-vegetative system. After retention, the COD levels were found below the guideline levels. The total aerobic and total coliform bacteria in ablution greywater were reduced from 10^6 to 10^3 and from 10^3 to 0, after retention of 24 hours in the non-vegetative and vegetative systems, respectively. Both systems performed equally well in reducing bacterial counts. Total aerobic and coliform bacteria were absent in laundry greywater.

The prototype study revealed that greywater pollutants (without toilet and kitchen sources) can effectively be reduced by 24 hour retention in both permeable pavement and biofiltration system. The disinfection process is required to limit the growth of bacteria. The permeable pavement can store the raw greywater. Selection of a vegetative biofiltration system can serve the dual function of greywater reuse and urban landscape aesthetic. The study did not consider heavy metals and conducted using laboratory scale prototypes. Field investigation is necessary to explore the idea more in details.

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