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Effectiveness of Wastewater Treatment for Selected Contaminants Using Constructed Wetlands in Mediterranean Climates

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This Master's Project

EFFECTIVENESS OF WASTEWATER TREATMENT FOR SELECTED CONTAMINANTS USING CONSTRUCTED WETLANDS IN MEDITERRANEAN CLIMATES

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List of Acronyms

BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
CSO	Combined Sewage Overflow
CWA	Clean Water Act
EDC	Endocrine Disrupting Chemical
FC	Fecal Coliform
FWS	Free Water Surface
HLR	Hydraulic Loading Rate
HRT	Hydraulic Residence Time
HSSF	Horizontal Subsurface flow
NPDES	National Pollutant Discharge Elimination System
OLR	Organic Loading Rate
SFS	Subsurface flow System
TC	Total Coliform
TKN	Total Kjehdahl Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solids
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VSSF	Vertical Subsurface flow
WDRs	Wastewater Discharge Requirements
WWTP	Wastewater Treatment Plant

1.0 Introduction

Wastewater is considered to be any “used” water that contains waste from domestic, commercial, and industrial processes (SFBRWQCB, 2015). Under current standards, storm water is also considered to be a subcategory of wastewater because it can contain pollutants that affect water quality from run-off.

Since early history, people have relied on the natural attenuation of waste either by microbial processes or simple dilution. Throughout the 19^{th} century in the United States, it was not uncommon for wastewater to be directly disposed of into waterways. From the late 1800’s to early 1900’s, 88% of wastewater was dumped into streams and lakes without any form of treatment (Tarr, 1984). As human populations increased due to industrialization, so did the volume of industrial and residential wastewater. During this time period, the primary water sources for many cities were from the very same streams and lakes that were being used as wastewater disposal sites.

When infectious waterborne diseases rapidly increased with the growth of larger cities, engineers began to implement filtration as a means of wastewater treatment. This water filtration marked the beginning of developing regulations for the treatment of wastewater to meet standards in order to be discharged into water bodies. As new technologies for wastewater treatment arose, so did stricter water quality standards. Wastewater effluent is treated to remove various substances as different levels of treatment can allow for recycled water to be reused for irrigation, street cleaning, and watering parks and golf courses.

There are currently many different wastewater treatment technologies. The use of constructed wetlands seems to be a promising “natural” treatment option that also provides ecological benefits. This research will focus on constructed wetlands as a means to treat wastewater for other beneficial uses. The following sections address regulations regarding wastewater, common contaminants of wastewater, basic wastewater treatment, the use of constructed wetlands as a treatment for common contaminants found in wastewater, and the use of constructed wetlands in Mediterranean climate regions around the world.

1.1 Regulation of Wastewater

Even though wastewater treatment systems were prevalent by the 1960s, large quantities of untreated sewage and industrial wastewater were still routinely discharged into rivers, lakes, and streams. It was not until the enactment of the Clean Water Act (CWA) of 1972, that wastewater discharge had to go through a permitting process.

The CWA of 1972 was passed to control water pollution in surface waters and to dictate water quality standards for receiving waters based on criteria for the health of human and aquatic life. The primary goals of the CWA are to regulate point source and nonpoint source water pollution in order to preserve the physical, chemical, and biological health of the nation's waters and to achieve water quality standards that are fishable and swimmable (USEPA, 2015). The CWA's National Pollutant Discharge Elimination System (NPDES) program is designed to manage wastewater discharges from municipal and industrial wastewater treatment plants, and sewage collection systems. While stormwater discharges from municipalities and industrial facilities are regulated separately from wastewater discharges, they can still be subjected to the NPDES regulations (USEPA, 2014a).

Under the CWA, wastewater discharges from sewer collection systems, and municipalities and industrial wastewater treatment plants are regulated as point source pollution (USEPA, 2014b). For point source pollutants, the NPDES regulates the control of toxics, industrial pretreatment, and the disposal of biosolids. Through the NPDES program, wastewater discharges within California are also regulated under the Porter-Cologne Water Quality Control Act (SWRCB, 2015). Under the California law, wastewater discharge requirements (WDRs) are implemented for wastewater discharges to California's surface waters, such as San Francisco Bay. WDRs are also issued for recycling wastewater for reuse and discharging wastewater to land and on-site treatment systems. This category includes septic systems and land disposal systems that could impact groundwater.

1.2 Contaminants in Wastewater

Untreated or improperly treated wastewater effluent can result in negative impacts on human and environmental health. Effects of wastewater pollution include oxygen depletion, impairment to fish and wildlife communities, and contamination to drinking water sources. Wastewater can contain a wide range of contaminants, including a variety of pharmaceuticals and hormones, pesticides, toxic trace elements and metals, total suspended solids (TSS), microorganisms, organic matter, and excess nutrients. (USGS, 2014).

Pharmaceuticals in wastewater can have endocrine disrupting chemical (EDC) properties and compromise the long-term survival of many species (Fuhrman et al., 2015). Hormones and antibiotics in wastewater effluent can result in detrimental ecological consequences. It has been reported that estrogen, anti-androgen, and androgen can interfere with hormones and reproductive health (Filby et al., 2007). However, EDCs are a particular challenge to remove in wastewater effluent because there is still much unknown about their chemical properties and the complexity of synergist effects in effluent (Filby et al., 2007). While wetlands have the ability to perform processes that break down EDCs, pharmaceutical and hormones are unquestionably the most difficult water contaminants to treat in wastewater simply because there is not available treatment technology that specifically targets these contaminants (Chapman, 2012).

Pyrethroids and organophosphate pesticides are ubiquitous throughout waters of the U.S. due to agricultural runoff (Budd, 2009). Pesticides is an all encompassing term that includes inorganic chemicals with the purpose of killing or controlling pests, such as herbicides, insecticides, fungicides, nematocides, and rodenticides (NDMED, 1994). Pesticides can threaten a wide range of species and have major impacts on overall biodiversity. Pesticides in agricultural runoff are a major concern for aquatic ecosystems, but pesticide mitigation through constructed wetlands has only been extensively studied in the past decade. Studies have shown that pesticide removal from wastewater is promising using wetland macrophytes, but there is still much unknown about the processes, and effectiveness can be highly variable based on a variety factors (Vymazal and Brezinova, 2014).

Toxic trace elements can include metals that have a toxic effect on species. Examples of common metal pollutants in aquatic ecosystems are lead, cadmium, mercury, chromium, nickel and arsenic. These are metals of concern because of their biotoxic properties that induce adverse effects in humans and aquatic organisms (Duruibe et al., 2007). Aquatic plants utilized in constructed wetlands have been shown to effectively remove heavy metals from wastewater in several studies. However, the removal efficiency of heavy metals in constructed wetlands is difficult to simplify because it is highly variable and dependent on factors such as plant species and the target trace element (Kara, 2005).

TSS are particles larger than 2 microns in size, which include particulate matter such as silt, clay, plankton, algae, and organic debris (USEPA, 2012). Suspended solids and floating material make up the majority of the residual substances removed from wastewater. Once the residual substances, or sludge is separated from the effluent, federal standards require treatment of the total solids in order to be recycled safely. Local governments make the decisions for the fate of total solids, and decide if it may be composted, used as fertilizer, incinerated or used for other purposes (USEPA, 2014b). TSS in aquatic ecosystems can affect the turbidity in water bodies, thereby affecting the clarity of water. A high amount of TSS limits the penetration of light into the water and can hinder aquatic plant photosynthesis, which can potentially have an affect on aquatic life. TSS not only affects water turbidity, but the suspended particles can also increase the amount of toxins in the water by providing a point of attachment for toxic material (USEPA, 2012). There are several methods used to remove and reduce TSS in wastewater, but one of the most common methods is filtration of effluent to separate particles from the wastewater. Pre-treatment for TSS is an important initial step when using constructed wetlands for treating wastewater because large particles of suspended solids can clog constructed wetlands systems and obstruct flow (Weber and Legge, 2008).

Pathogenic microorganism contamination in wastewater consists of bacteria, viruses, protozoa, fungi, and heminths that can be waterborne (Weber and Legge, 2008). They can cause beach closings and contaminate shellfish, which impacts regional economies, drinking water quality, recreational activities, and the shellfish industry (USEPA, 2013). Traditional wastewater treatment plants (WWTPs) use a variety of methods for pathogen disinfection, such as ultraviolet (UV) radiation, activated sludge, filtration, ozonation, and chlorination. While chlorination is the most commonly used method of pathogen disinfection, there are concerns that chlorination produces carcinogenic trihalomethanes and other organo-chlorine compounds in the presence of organic matter (Weber and Legge, 2008). Studies have shown that constructed wetlands have been able to remove pathogenic microorganism from wastewater. However, there are many mechanisms and factors related to physical, chemical, and biological processes in constructed wetlands that affect the degree of pathogen removal efficiency (Weber and Legge, 2008).

Biological oxygen demand (BOD) and chemical oxygen demand (COD) are the major parameters in measuring the organic content in wastewater (Grismer and Shephard, 2011). In order for microorganisms to decay matter, there needs to be sufficient dissolved oxygen available for decomposition. BOD is the measure of the amount of oxygen microorganisms require in order to degrade the available organic matter, whereas COD is the measure of the amount of oxygen microorganisms require for degrading organic and inorganic matter (University of Georgia, 2011). The typical BOD test is known as the "BOD_5 test", which is measured in a 5-day period to see the change in dissolved oxygen used by aerobic microorganisms (Verma and Singh, 2012). The COD test is an alternative test for estimating the organic matter concentrations in wastewater and can be completed within a few hours. The COD test uses potassium dichromate to "oxidize" organic and inorganic matter in wastewater. Even though the measure of COD is independent of BOD, it is possible to use COD results to estimate BOD results because COD to BOD generally has a constant ratio of ~2:1 in wastewater (University of Georgia, 2011). Even though there are both advantages and disadvantages to each test, measuring organic content is important because the use of oxygen can lead to reduced dissolved oxygen levels and result in fish kills and effects on other biota (Burton et al., 1980). The level of dissolved oxygen is vital for many aquatic organisms because they rely on it to survive.

Nitrogen is present in various forms in wastewater effluent. Humans mainly excrete nitrogen in the form of urea and organic nitrogen, which consists of dead cells, amino acids, and protein. Organic nitrogen gets broken down into ammonia by microorganisms in the form of NH_3, and if oxygen is present, microorganisms break ammonia down into nitrate (NO_3). Forms of nitrogen pose adverse health effects in drinking water and water bodies, especially in coastal regions (Grady and Lim, 1980). Excessive nutrients found in water bodies can lead to eutrophication, where there is a surplus of nutrients such as nitrogen and phosphorous being released into receiving waters. Over-fertilization of waters can reduce dissolved oxygen through the promotion of aquatic plant overgrowth, and subsequent decomposition using up the dissolved oxygen harming aquatic organisms and leading to the decline of their survival rates. Because many forms of nitrogen can have adverse effects on the environment, removing total nitrogen from wastewater is a common treatment method. This method involves biological conversion of ammonia and nitrate into N_2, the gaseous form of nitrogen, which then becomes inert and gets released into the atmosphere (Grady and Lim, 1980). The first step in the process is called nitrification, where ammonia gets converted into nitrite (NO_2) and nitrate under the presence of aerobic conditions. The second step in the process is called denitrification, where nitrate is converted into nitrogen gas through the mediation of bacteria. Anaerobic conditions are required in order for denitrification processes to occur, where bacteria metabolize BOD as a food source and in turn, reduce BOD in the wastewater effluent.

While there are several contaminants found in wastewater, this research focuses on the efficiency of using constructed wetlands for removing selected contaminants, which include TSS, pathogenic microorganisms, organic matter, and excess nutrients. These contaminants were chosen for this research because they have been studied extensively in constructed wetlands for Mediterranean climates.

1.3 Wastewater Treatment

The combination of growing cities and drawing water resources from untreated waters correlated with increased mortality rates from waterborne diseases and typhoid fever in the U.S. in the 1800's (Tarr 1984). When wastewater treatment systems were initially developed, the main concern for engineers was to prevent the spread of diseases. The first municipal sewage system in the U.S. was constructed in the 1850's in Chicago and by the 20th century, 85% of large cities with populations of over 300,000 people were utilizing sewage systems (Tarr, 1984).

Even during the early 1970s, wastewater standards were not consistent throughout the United States. Many treatment systems only treated wastewater for residual substances with the goal of eliminating suspended solids, reducing organic matter, and removing waterborne pathogens through basic disinfection (Tarr, 1984). It was not until the 1980s, under the Clean Water Act, that surrounding environmental concerns were being considered. Wastewater treatment was being managed at a higher level, with nitrogen and phosphorous actively removed since they were the primary nutrients of concern for eutrophication of waters (Conley et al., 2009). Wastewater treatment standards started to include not only human health parameters, but aquatic life requirements as well.

While certain wastewater treatment methods are more effective than others at removing certain contaminants, wastewater treatment types come in many forms: septic systems, settling ponds, industrial wastewater treatment systems, and constructed wetlands. Septic systems are primarily used in unsewered areas, where septic tanks collect suspended solids to be naturally decomposed by anaerobic bacteria (Vymazal, 2005). Liquid waste goes untreated as it is dispersed throughout surrounding substrate via perforated pipes, while the bio-solids have to be used as fertilizer or taken to a municipality. Man-made settling ponds have been used in agricultural settings, construction, and mining projects (USEPA, n.d.). The purpose of the settling pond is to retard water flow to all suspended materials to precipitate out of the water. However, a major disadvantage of utilizing settling ponds is they ultimately reach capacity and require dredging and maintenance. Settling ponds are only a good temporary option, because of these maintenance requirements (USEPA, 1999).

Typical industrial wastewater treatment plant facilities are normally comprised of four main treatment processes: 1) pretreatment, 2) primary treatment, 3) secondary treatment, and 4) tertiary advanced treatment (Gavala et al., 2003). Industrial wastewater plants are necessary for large developed cities, however they are expensive and energy intensive to maintain. Constructed or treatment wetlands are artificial wetlands with the purpose of mitigating organics, inorganics, nutrients, municipal and domestic sewage, industrial effluent, mine drainage, and leachate (USEPA, 2001). Constructed wetlands are being employed more frequently as a means of wastewater treatment facilities for areas with smaller populations because they are less energy intensive and require less maintenance compared to conventional municipal wastewater treatment plants (Karathanasis et al., 2003).

1.4 Constructed Wetland Characteristics

In accordance with USEPA regulations (under 40 CFR Part 122.2), constructed wetlands designed for wastewater treatment purposes are not under the same Clean Water Act jurisdictional group for regulating natural wetlands (USEPA, 2000a). Within constructed wetlands, water quality standards are consistent with state regulations and each state varies in regulations for constructed wetlands for wastewater treatment (Winans et al., 2012). However, in the United States, effluent from constructed wetlands is mainly governed by the CWA, which provides guidance for water quality requirements for discharged waters (Boucher et al., 2011).

Natural wetlands are known to be effective bio-filters and have been utilized for wastewater clarification since ancient times. Both natural wetlands and constructed wetlands clean and filter contaminated water, which includes mitigating the effects of contaminants such as excess nutrient input into water bodies that contribute to hypoxic zones (Jurries, 2003). Even though they share this characteristic, the main distinction between them is that there can be control over the stability of water flow throughout the constructed wetland system, whereas natural wetlands have variable water flow based on precipitation, climate and seasonality (USEPA, 2000a).

The structure of constructed wetlands is designed to mimic the filtration system of naturally occurring wetlands, therefore using the same physical, chemical, and biological processes (Wood, 1995). Not only are constructed wetlands engineered to mimic natural wetland substrate, they are also engineered to mimic the abundance and type of vegetation. A major difference between constructed and natural wetlands is that because hydraulic loadings of constructed wetlands are consistently managed, they can treat wastewater more efficiently than natural wetlands (USEPA, 1988). While constructed wetlands are area intensive based on their land coverage, they can provide similar ancillary ecological services as natural wetlands, such as flood protection and biological habitat (Gearhart, 1992).

The first record of using constructed wetlands for wastewater treatment was in 1904 in Australia (University of Alaska Fairbanks, 2005). The idea did not gain popularity in the U.S. until 1973, where the first pilot constructed wetland was created at

Brookhaven National Laboratory in Brookhaven, New York and called the Marsh Pond Meadow System (Kadlec and Wallace, 2008). Since then, the U.S. has been taking advantage of the technology and research for constructed wetlands is becoming increasingly common for various water pollution reduction purposes.

1.5 Constructed Wetlands in Mediterranean Climates

This research focuses on constructed wetlands studied in Mediterranean climate zones throughout the world. There are five Mediterranean climate regions: California, Central Chile, Mediterranean Basin, Western Cape of South Africa, and Western and South of Australia (Figure 1) (Cowling et al., 2006). Mediterranean regions are characterized based on their northern and southern latitudes approximately between 30°-45° on the western portion of continents (NOAA, n.d.).

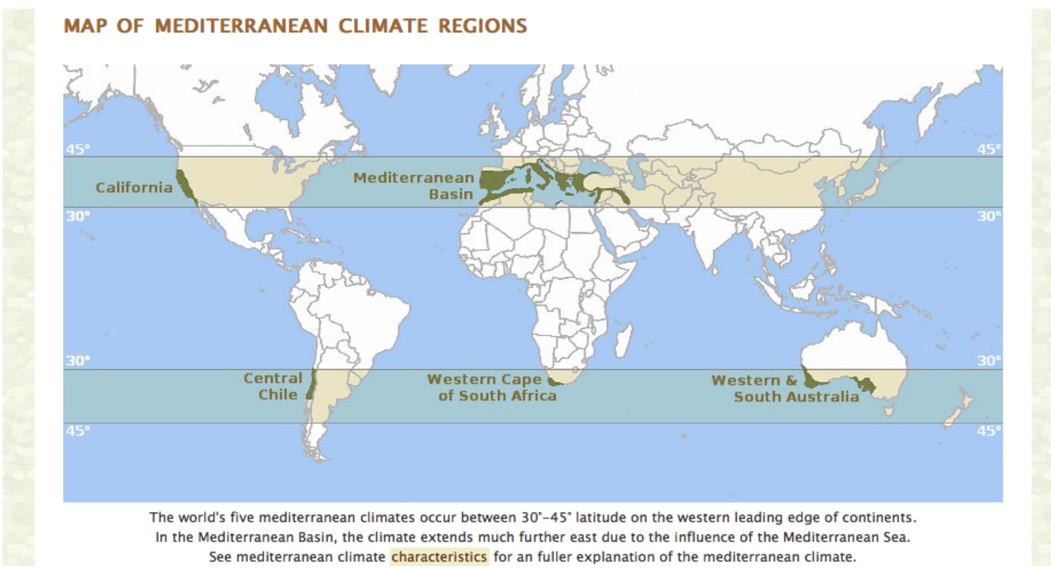

Figure 1: Map of Mediterranean Climate Zones (O'hara, n.d.)

Climate is an important factor in determining particular wetland characteristics. These characteristics include hydrology, soil, and vegetation as the main components that make up wetlands. Based on the Köppen-Geiger-Pohl classification, Mediterranean regions have a distinct climate regime comprised of cool, wet winters and hot, dry summers (Encyclopedia Britannica, 2014). As a generalization, because all Mediterranean zones have similar rainfall cycles, they have similar wetland characteristics as well (Di Paola et al., 2013). This similarity results in dominant vegetation comprised of sclerophyllous trees and evergreen shrubs that are able to withstand water stress during wet seasons and desiccation during dry summers (Di Paola et al., 2013).

Researching the findings of various constructed wetlands studies conducted in Mediterranean climate zones will allow for a better identification of characteristics that result in effective wastewater treatment within constructed wetlands locally. Understanding of the strengths and weaknesses in constructed wetland designs in Mediterranean climate regions throughout the world can be applied to new constructed wetland projects in California.

1.6 Research Summary

This Master's Project evaluated the effectiveness of different types of constructed wetlands in removing TSS, pathogenic microorganisms, organic matter: BOD and COD, and excessive nutrients (i.e., nitrogen and phosphorous) for wastewater treatment in Mediterranean climates. As the topic of water scarcity is becoming more prominent, it is important to develop sustainable treatment methods to reduce water pollution and allow for water reuse.

Chapter 2 of this paper presents the engineering and structure of constructed wetlands to illustrate the various designs that are currently being utilized, and their individual strengths and weaknesses. This chapter also provides details about the diversity of plants that are chosen. Phytoremediation, or using plants to mitigate for contaminants is a crucial aspect of the success of constructed wetlands for wastewater treatment. Understanding processes and phytoremediation methods will assist in understanding the importance of wetland plant types.

There have been a number of effective constructed wetlands for wastewater treatment purposes locally and throughout Mediterranean climate zones. Chapter 3 provides detailed accounts of constructed wetland projects, including the engineering design and wetland plant species. These projects include constructed wetland studies conducted in Greece, Morocco, Portugal, and Turkey. Because wetlands are sensitive ecosystems, climate affects the growth, productivity, and effectiveness of their physical, chemical, and biological processes. Wetlands are heavily influenced by Mediterranean climate conditions, which include periods of rainfall and desiccation (Bottenberg et al., 2006). The studies chosen are based on Mediterranean climates, so they can be applicable regionally to California.

Chapter 4 discusses constructed wetlands projects in Mediterranean climates and compares the effectiveness of each project for removing various contaminants. Chapter 5 presents research conclusions and identifies possible areas for improvement. Chapter 6 provides management recommendations based on research conclusions from the previous chapter.

The primary goal of this research project is to evaluate the effectiveness of constructed wetlands for contaminant removal, specifically TSS, microorganisms, organic matter, and nutrients using known constructed wetland projects to determine their effectiveness for contaminant removal. Based on these findings, this research describes the benefits of each constructed wetland project and possible methods to maximize their efficacy. This research also identifies characteristics of known successful constructed wetland for wastewater treatment, and evaluates the effectiveness and barriers for future projects.

2.0 Constructed Wetlands

Constructed wetlands are distinguished from natural wetlands by the fact that they are man-made engineered systems created from an upland area or an ecosystem that is not considered to be a wetland (Hammer, 1994). As with natural wetlands, constructed wetlands have major components of hydrology, soils, and vegetation (Haberl et al., 2003). Currently, constructed wetlands for wastewater treatment have two main types of engineering, which are surface flow systems and subsurface flow systems. Within subsurface flow systems, there are vertical flow systems (VSSF) and horizontal flow systems (HSSF). These types of constructed wetlands have various levels of efficiency based on the size of the area on which they are built since many of which are designed to be effective wastewater treatment for small populations (Villalobos et al., 2013).

The size of the community the wetland was created for affects the hydrology, which is essentially the input of wastewater entering the system. Hydrology is determined by whether the area is inundated or if the soil is saturated with water. Hydrology is mainly driven by climate in natural wetlands however, with constructed wetlands, controlled amounts of wastewater gets inputted to the system in order for filtration processes to occur. Based on the design of the constructed wetland, wetland hydrology can either be considered free water surface (FSW) or subsurface systems (SFS) (Vymazal, 2010). More importantly, constructed wetland engineering is key to successful wastewater treatment because the soil type, vegetation, and system design are the main factors for the successful removal of certain contaminants.

Constructed wetlands are mainly utilized for secondary or tertiary treatment systems, as primary treatment systems usually involve technical treatment plants or settling tanks (Gauss, 2008). Constructed wetlands are used for further filtration, sedimentation, and biological processes to minimize contaminants entering the receiving water bodies with the effluent. Compared to conventional wastewater treatment plant systems, constructed wetlands require little maintenance and are more cost effective (USEPA, 2000b). Because constructed wetlands emulate natural wetlands, they are robust ecosystems that have the ability to mitigate fluctuations in water flow in a sustainable manner. Constructed wetlands not only treat wastewater, but they can also provide a variety of purposes ranging from aesthetics to creation of wildlife habitat and flood control.

This chapter discusses constructed wetlands in terms of soils and substrates, phytoremediation mechanisms, and wetland designs that are being implemented in the engineering of constructed wetlands for wastewater treatment systems.

2.1 Soils and Substrates in Constructed Wetlands

Soils are an important component in the function of constructed wetlands because they provide nutrients and structure to wetland plants (Mitsch and Jorgenson, 2004). Topsoil is that medium that supports the roots of vegetation and provides habitat for microbes. The efficiency of soils and substrates in constructed wetlands is based on whether the treatment wetland is designed for a free surface flow wetland or a subsurface flow wetland.

Topsoil for free surface flow wetlands is usually similar to natural wetland soils. Their main purpose is to support wetland plants with structure and nutrients, whereas the topsoil for subsurface flow wetlands is important for the permeation of water to flow through the subsoil (Mitsch and Jorgenson, 2004). A common ingredient in the topsoil used for subsurface flow wetlands is gravel because it has high permeability to prevent soil compaction. It is important for soils to be non-compacted to allow space for root development, microbial habitat, water retention during droughts, and room for water infiltration (Jurries, 2003).

The subsoil in constructed wetlands is usually below the root zone and can include sand, gravel, rocks, and other organic material (Jurries, 2003). Various mixtures of substrates are sand, fly ash, shale, gravel consisting of carbonate and igneous rock, bauxite, and zeolite (Singh et al., 2013). The substrate should have enough permeability to allow for water to flow through for saturated soils or retain some standing water in order for microbial action to take place (Mitsch and Jorgenson, 2004). Promoting microbial activity is important in establishing biological processes to treat certain contaminants, so it is vital to have substrate that supports organisms that contribute to the function of the constructed wetland system. Sand and gravel is widely available and efficient at removing solids, but is also highly erodible, which leads to decreased efficiency and clogging over time. Zeolites are commonly used because of their crystalline structures composed to alkali and earth metals and studies have shown they are efficient at removing ammonia nitrogen due to their ammonium cation exchange abilities and structure for microorganism attachment (Singh et al., 2013).

The amount of organic matter is an important part of chemical retention in constructed wetlands. Organic soils have higher cation exchange compared to mineral soils, which allows for more efficient nitrogen removal under anaerobic conditions (Mitsch and Jorgenson, 2004). However, organic soils can have low pH and low nutrients such as clay or sandy soils, which is not ideal for the foundation of wetland plant growth during initial wetland construction.

2.2 Phytoremediation Mechanisms Used in Constructed Wetlands

Phytoremediation in constructed wetlands takes advantage of wetland plants' remediation capabilities for contaminants in sediments, soils, sludge, groundwater, surficial waters, and wastewaters. Plants have natural processes that allow for phytoremediation techniques to eliminate, destroy, and sequester contaminants in the environment (Glick, 2003). Phytoremediation mechanisms performed by wetland plants can be categorized as contaminant accumulation, dissipation, immobilization, or degradation (USEPA, 2001). In order to allow processes to take advantage of phytoremedation of contaminants, the plant has to be able to not only uptake the contaminant, it also has to be able to tolerate its toxicity.

Accumulation is the storage of contaminants, such as inorganic compounds and metals in the plant through phytoextraction or rhizofiltration. Both phytoextraction and rhizofiltration mechanisms allows for plants to contain contaminants for later removal (USEPA, 2001). Phytoextraction occurs as the plant uptakes contaminants through absorption and concentrates contaminants from the soils into the roots and leaves of the plant. Rhizofiltration is using the roots of the plants to uptake contaminants from soils and effluent (Glick, 2003).

Dissipation is the removal of organic and inorganic contaminants by plants releasing them into the atmosphere (USEPA, 2001). Phytoremediation through phytovolatilization are terms used to describe this process of plants uptaking contaminants then volatizing them. This mechanism has mainly been described in studies related to the removal of volatile hazardous substances that contain mercury or arsenic compounds (Glick, 2003).

Immobilization occurs through hydraulic control, by controlling the flow of water in contact with plants to allow for uptake or phytostabilization, where contaminants are immobilized in the soils to prevent the spread of contaminants in the environment (Glick, 2003; USEPA, 2001).

Degradation involves the destruction or transformation of organic compounds through rhizodegradation or phytodegradation. Rhizodegradation is a form of enhanced biodegradation by the root zones of plants, which is due to microbial actions from microorganisms. Phytodegradation is the process of uptaking and metabolizing contaminants within the roots, leaves, or stem of the plant (USEPA, 2001). Studies have shown that there are rhizobacteria, which are beneficial microbes found in the rhizosphere that stimulate plant growth and promote the degradation of organic material in the roots (Glick, 2003).

Despite the various phyotremediation mechanisms utilized by plants, research has shown that it is difficult to identify which mechanism is most effective because different parts of the plants can more successful at accomplishing remediation for different contaminants. Accumulation, dissipation, and immobilization have been extensively studied for metals where studies have shown that the stem, roots, and leaves can play a major role in the transformation, mitigation, or trapping and storing of contaminants through biological processes (Haberl et al., 2003). For the purposes of this research, wetland macrophytes uptake of wastewater contaminants through phytoremediation mechanisms has a minor role. Nevertheless, using macrophytes in constructed wetlands for wastewater treatment is an important aspect in the design because of their contribution to the treatment process. While many of the case studies presented in this research do not discuss the exact mechanism of phytoremediation, it is evident that macrophytes planted in constructed wetland units create a more efficient system for contaminant removal than units that remained unplanted.

2.3 Wetland Macrophytes in Mediterranean Regions

The main purpose of macrophytes in constructed wetlands for treatment of wastewater is the physical effects wetland plants provide (Haberl et al., 2003). Wetland macrophytes can improve wastewater contamination removal through sedimentation, filtration, nutrient absorption, oxygenation, and beneficial microorganism attachment (Karathanasis et al., 2003). The presence of macrophytes in treatment wetlands promotes microbial activity and primarily relies on their rhizomes for contamination removal (Wang et al., 2012). The surface area of the rhizomes provide habitat for microorganisms to attach themselves to and also provide structure for the substrate to maintain hydraulic properties. Vegetation coverage can also help maintain the structure of the substrate by retarding erosion, preventing unwanted algal growth, and providing insulation (Haberl et al., 2003). Insulation from leaf litter is particularly beneficial for constructed wetlands during colder weather.

Native plants that thrive in Mediterranean climates are generally hardy and adapted to summer droughts. These plants are adapted to retain nutrients and have long roots that extend deep into soils. Other adaptations that help plants store water when precipitation is scarce are small leaves, thickened bark, thick stems, waxy outside layers, and growth of hair (Bottenberg et al., 2006). Mediterranean plants are ideal for constructed wetlands because within Mediterranean climates, there will be cycles of flooding and drought when treating wastewater (Jurries, 2003).

The following sections present the three main types of wetland macrophytes commonly used in constructed wetland treatment systems. These wetland macrophytes can be categorized based on their morphology and physiology as free-floating, submerged, and emergent wetland macrophytes (Haberl et al., 2003). The main constructed wetland macrophyte type focused in this research utilizes emergent wetland macrophytic species.

2.3.1 Free-floating Wetland Macrophytes

Free-floating aquatic macrophytes can float as a thin layer covering the water surface or have buoyant adaptations that allow them to float on the surface as opposed to being rooted into the substrate (Headley and Tanner, 2008). Commonly used free-floating wetland macrophytes for wastewater treatment include plants such as *Eichhornia* *crassipes* (water hyacinth) and *Lemna sp.* (duckweed). There have been previous studies showing that *E. crassipes* and *Lemna spp.* have been able to reduce concentrations of total suspended solids (TSS), biological oxygen demand (BOD), phosphorous and nitrogen (Zirschky and Reed, 1988; Kivaisi, 2001). Constructed wetlands that use free-floating plants can vary in water depth without adverse affects on the health of the vegetation (Headley and Tanner, 2008). However, treatment systems that use *E. crassipes* and *Lemna spp.* have rapid colonization, resulting in prolific growth and required harvesting. Free-floating macrophytes tend to create a layer covering the water surface, which prevents light from penetrating to the water column and affecting aquatic organisms. Constructed wetlands with free-floating macrophytes as the dominant species have high maintenance costs because they require routine harvesting to ensure optimum contaminant removal as well as limiting overgrowth (Sim, 2003).

2.3.2 Submerged Wetland Macrophytes

Submerged aquatic macrophytes can be suspended in the photic zone of the water column and/or rooted in the sediment. Their growth usually is limited at the surface of the water due to their submerged photosynthetic parts. Examples of submerged wetland macrophytes used for wastewater treatment are species such as *Elodea spp.* (waterweed), *Ceratophyllum spp.* (coontail), and *Najas spp.* (naiads) (Kadlec and Wallace, 2008; Gumbricht, 1993). There was a previous study conducted in the Netherlands for nutrient removal from a wastewater municipality that showed the potential of submerged macrophytes removing nitrogen by 45%, but overall, the use of submerged aquatic macrophytes for constructed wetland projects has not been extensively studied (Kadlec and Wallace, 2008).

2.3.3 Emergent Wetland Macrophytes

Emergent aquatic macrophytes typically grow above the water surface in saturated soils and are rooted in substrate (Haberl et al., 2003). Common emergent wetland macrophytes used for wastewater treatment are *Arundo donax* (giant reed) (Figure 2), *Scirpus spp.* (bulrush), *Typha latifolia* (common cattail) (Figure 3), and *Phragmites australis* (common reed) (Figure 4). Even though free-floating wetland plants are efficient at nutrient removal, emergent macrophytes have been most frequently used in constructed wetlands studies because they generally require less maintenance (Jurries, 2003). *Phragmites spp.* are commonly used in Europe because they grow rapidly and are not a common food source for wildlife. However, *Phragmites spp.* are not preferred in the U.S. because they are aggressive colonizers that might infiltrate natural ecosystems (USEPA, 2000c). Emergent plants contribute to many beneficial uses of a constructed wetland: they have roots that extend into the sediments that provide structure for substrate, they regulate water velocities and allow for TSS to settle by retarding water flow, they uptake contaminants such as nutrients, they have the ability to exchange gases between the air and soils and allow circulation of oxygen, their stems and rhizosphere zones allow for microbial habitat, and they create a layer of insulation from their debris and leaf litter as they decay (Haberl et al., 2003).

Figure 2. *Arundo donax* (USDA Forest Service, 2004).

Figure 3. *Typha latifolia* (USDA Forest Service, 2008a).

Figure 4. *Phragmites australis* (USDA Forest Service, 2008b).

2.4 Constructed Wetlands Types

Types of constructed wetlands are classified based on their hydrology flow direction. Subsurface water flows can either be vertical or horizontal systems. Free water surface flows are more similar to natural wetlands, where the design is meant to emulate the aesthetics of wetland ecosystems. These three systems are different from each other based on their relative costs, efficiency of removing contaminants, and design complexity (Gauss, 2008). Many constructed wetlands are engineered to create optimal organic loading rates (OLRs) and hydraulic loading rates (HLRs) that maintain a consistent inflow of wastewater into the treatment wetland based on the amount of incoming effluent (Mitsch and Jorgenson, 2004). OLRs and HLRs are typically calculated as runoff (unit/day) divided by constructed wetland surface area (unit) (Blankenberg et al., 2008). The influent, wastewater input is determined using population equivalents (PE), which is used to represent the how much organic material is present in the wastewater. PE is generally computed by dividing BOD_5 from all sources by 60 g of oxygen per day (represents the contribution of BOD_5 per person) (Fox et al. 2002).

The following sections illustrate the basic design of the two subsurface flow systems: vertical subsurface flow (Figure 5) and horizontal subsurface flow (Figure 6), and the basic design of a free water surface flow system (Figure 7). Some of the more complex constructed wetland systems are called hybrid or multi-stage systems, which combines features from two or all three of these primary systems (Vymazal, 2005).

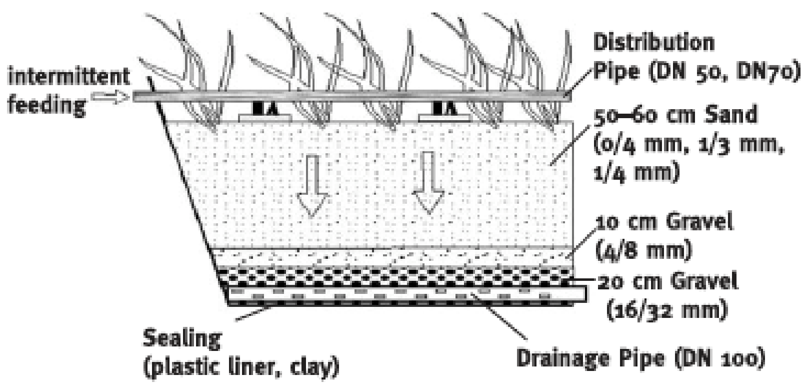

Figure 5. Cross-section of a Typical VSSF Constructed Wetland (Wateraid, 2008).

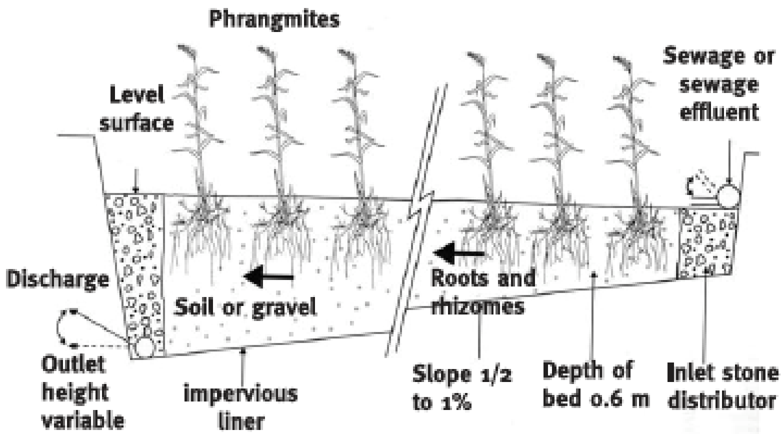

Figure 6. Cross-section of a Typical HSSF Constructed Wetland (Wateraid, 2008)

2.4.1 Subsurface flow Systems

Subsurface flow system (SFS) constructed wetlands are purposely created to improve water quality, but provide little additional benefits. While nesting birds and animals can still be present in SFSs, the water is not exposed in the system and is less accessible for wildlife. SFSs are designed to keep water levels below the surface of the medium, which is an advantage since this design tends to generate lower odor production and have a lower probability of providing insect breeding grounds (Gauss, 2008). Because the water in the process of being treated is not exposed to the atmosphere, it prevents the risk of public and wildlife coming into contact with the wastewater (USEPA, 2000d). The basic design of a SFS consists of an impermeable layer for the lining, then a highly permeable layer for the medium, and water flowing just beneath the medium.

Media in SFS constructed wetlands are typically around 0.6 meters, but can range from 0.3-0.9 meters (USEPA, 2000d). The medium most commonly used in the U.S. and Europe is gravel due to its permeability and high volume of surface area (USEPA, 2000d). Most SFSs in the U.S. use a combination of different sized gravel. Microbial reaction rates are greater in SFS constructed wetlands compared to a free water surface flow constructed wetlands due to the higher surface area in the media. As a result, a SFS does not require the amount of area a FWS system does to achieve similar water quality improvement targets (USEPA, 2000d).

The area inundated with water has a limited amount of oxygen, which reduces the nitrification processes, which remove ammonia nitrogen (NH_3 and NH_4) in wetlands.

Possible solutions could be increasing the size of the area or retention time, but these options can be costly. However, denitrification can be more effective for the removal of nitrate since it requires more anoxic conditions (USEPA, 2000d). SFS constructed wetlands can still remove TSS, organic matter, and pathogenic microorganisms efficiently under anoxic conditions (USEPA, 2000d).

2.4.2 Free Water Surface flow System

Free water surface flow (FWS) or surface flow constructed wetlands were first engineered to mimic natural wetlands and because of this, they are considered to be most aesthetically pleasing out of the three designs. FWS systems can be bogs, swamps, and marshes depending on the primary vegetation. Most operating FWS constructed wetlands closely resemble marshes, which attract wildlife to FWS systems. As a result, it is important to select macrophytes that are not food sources (USEPA, 2000c).

The basic design of a FWS system consists of an impermeable layer, then covered with a soil layer, and water flowing on the surface (USEPA, 2000c). The vegetation generally consists of emergent macrophytes rooted into the soil layer, which adds support to the entire system. In FWS systems, water typically enters the system from an inlet point, then flows on the surface where it is exposed to the atmosphere, and then leaves from an outlet point (USEPA, 2000c). Unlike subsurface flow systems, FWS systems can provide valuable habitat for nesting birds and animals because water is exposed. A particular disadvantage to having surficial water is that it attracts insect vectors such as mosquitoes. Another disadvantage of having water exposed on the surface is that water flow can be inhibited due to water loss from direct evaporation (USEPA, 2000c). Similar to natural marsh wetland ecosystems, water influx enters into the system in a laminar flow fashion over a large area with low velocity. This pathway retards water flow and increases residence time, which is an effective way to remove particulate matter.

The substrate in FWS is usually a soil layer, and the soils can either be completely water saturated or well-drained. These factors greatly influence the amount of available oxygen because in well-drained soils, soils come into contact with the atmosphere and microorganisms in the soils can have access to oxygen in this aerobic environment.

Depending on the climate and selected macrophytes for the FWS system, water depth can range from a few inches to more than 2 feet (USEPA, 2000c). Because a large portion of FWS systems is inundated, it is essentially an anaerobic system, which can limit the nitrification process of ammonia nitrogen, NH_3 and NH_4. A potential solution to this limitation is to increase the retention time by increasing the area of wetland, but this solution can be land intensive (USEPA, 2000c).

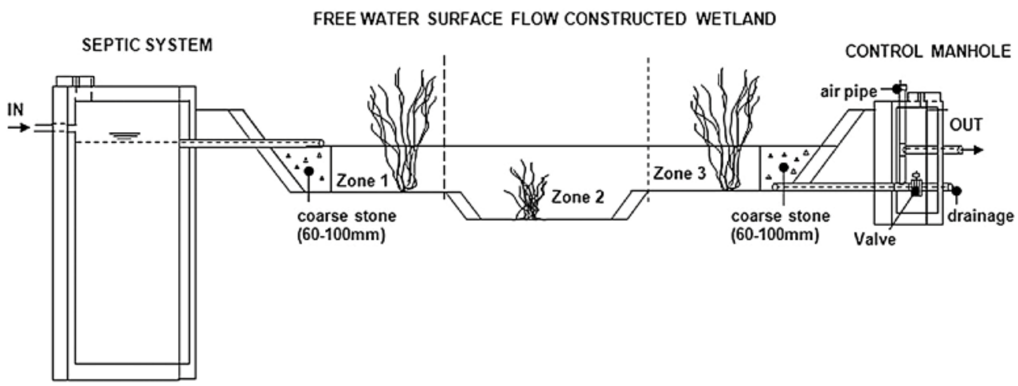

Figure 7. Cross-section of a Typical FWS Constructed Wetland (Gunes et al, 2012)

2.5 Primary Removal Mechanisms in Constructed Wetlands for Selected Contaminants

This section evaluates the basis of removal processes of the selected contaminants in this research. The fundamental principles for contaminant removal are applicable to all constructed wetland system types that are based on physical, chemical, and biological mechanisms (Haberl et al., 2003). Major processes that are vital to all constructed wetland systems involve sedimentation tanks, macrophytes, and microbial activity (Winans et al. 2012).

TSS can affect water turbidity therefore, it is important to remove it from wastewater prior to discharge into a water body. The main removal mechanism for TSS is physical sedimentation and filtration. While gravity aids in allowing TSS to settle, the amount of time it takes for settling to occur is heavily influenced by the size and shape of particles, and properties of the fluid medium. In general, larger particles will settle out faster than smaller particles.

Harmful pathogens can include bacteria, viruses, helminthes, protozoans, and fungi (Weber and Legge, 2008). The main removal mechanism for pathogenic microorganisms is also through sedimentation as pathogens settle out and accumulate as a loose layer on the surface on the sediments. As they settle on the surface, pathogens can be killed off from exposure to UV radiation from the sunlight or through natural die-off. However, if a heavy rainfall event occurs before the UV radiation has had an opportunity to kill off the pathogens, the sedimentation of pathogenic microorganisms might be ineffective and can result in an increased input of pathogens into receiving water bodies.

It is important to remove oxygen-demanding substances in discharged water to prevent reduction of dissolved oxygen in water bodies. Aerobic bacteria break down organic matter through the use of oxygen to produce energy and biomass, and anaerobic bacteria to produce CH_4. If BOD levels are above 300mg/L, the wastewater is considered to be "strong" and if the BOD levels are below 100mg/L, the wastewater is considered to be "weak" (Lindeburg, 2012) (Table 1). The main removal mechanism of organic matter is through physical and biological removal. In physical removal of organic matter sedimentation can occur, where there is a separation process of organic matter or sludge on the surface of the sediments. More importantly biological breakdown of organics require oxygen, which requires the measurement of BOD to understand how much dissolved oxygen is needed to treat the organic matter in the wastewater sample.

Table 1: Concentrations Ranges of BOD and COD in Domestic Wastewater

Concentrations of Organics in Untreated Wastewater (Domestic)			
Contaminant	Concentrations (mg/L)		
	Weak	Medium	Strong
BOD	< 100	~ 200 - 250	> 300
COD	< 250	~ 430	> 800
Adapted from (Lindeburg, 2012; and Metcalf & Eddy, Inc., 2003)			

Nutrients such as nitrogen and phosphorous can have adverse effects like eutrophication if discharged into water bodies without proper treatment. Nitrogen can come in many forms, organic and oxidized (NO_2- and NO_3), ammoniacal nitrogen (NH_3 and NH_4+). The level of nitrogen removal is dependent on the system design, the form of nitrogen being removed, and the abundance of nitrogen in the wastewater (Johnston, 1991). Nitrogen can exist in wetlands as organic and inorganic nitrogen, which is presented in the form of nitrates, nitrites, and ammonium. The measure of nitrogen removal is measured by the Total Kjeldahl Nitrogen (TKN), which is characterized as the amount of total organic nitrogen and ammonia nitrogen. Removal of nitrogen in constructed wetlands can occur through the uptake and storage in wetland plants, volatilization, storage in detritus material or sediments, or through ammonification, nitrification, and denitrification (Sim, 2003). Ammonification converts organic nitrogen into ammonia, where it is removed through other processes such as volatilization and nitrification. Nitrification occurs in aerobic conditions, where ammonia is converted into nitrite and nitrate. After the microbial nitrification processes, nitrate can be reduced to molecular N_2 by denitrification, which is the main step in the nitrogen removal process. Phosphorous can also exist in many forms in a constructed wetland. The removal of phosphorous is measured by the amount of Total Phosphorous (TP) that is remaining after wastewater treatment. The removal mechanism of phosphorous in a constructed wetland is not very effective through biological processes. Phosphorous can be stored in plants and microorganisms through uptake, but this is only temporary because phosphorous gets released once the organisms decays.

2.6 Chapter Summary

This chapter discussed specific aspects of constructed wetlands. Soils and substrates are factors that dictate the effectiveness of constructed wetlands and topsoils containing gravel are the most effective. Phyoremediation mechanisms through the use of appropriate wetland plants are also important and plants should be selected based on contaminants of concern for a particular wastewater stream. There are three primary wetland designs: vertical subsurface flow, horizontal subsurface flow, and free water surface flow, with free water surface flow providing the most additional benefits in terms of creating wildlife habitat.

3.0 Assessment of Constructed Wetlands for Wastewater Decontamination in Mediterranean Climates

This chapter provides an assessment of case studies and discusses in depth about how constructed wetland designs play a role in the efficiency for wastewater treatment. This assessment will allow for a better understanding of which constructed wetland designs can achieve maximum removal of contaminants of concern.

This chapter presents case studies of constructed wetlands used for wastewater treatment in Mediterranean climates. The main contaminants in these studies were Total suspended solids (TSS), pathogenic microorganisms, organic matter: BOD (biological oxygen demand) and COD (chemical oxygen demand), and nutrients (nitrogen and phosphorous). The following sections present two vertical subsurface flow (VSSF) systems in Xanthi, Greece and Western Greece, two horizontal subsurface flow (HSSF) systems in Rabat, Morocco and Lisbon, Portugal, and two free surface (FWS) flow systems in Pompia, Crete, South Greece and Garip, Turkey.

This section also present different species of macrophytes used for each case study and how they supplement the wastewater treatment process. In addition, each case study is assessed independently based on their constructed wetland design and overall effectiveness at treating the selected wastewater contaminants. The focus of each of these case studies is based on parameters related to the overall constructed wetland design such as target contaminants, area of study, materials, macrophyte species, hydraulic loading rates, and the efficiency of contaminant removal. In order to evaluate the performance of a constructed wetland unit, the percentage of concentration reduction and mass removal is reported (Stefanakis and Tsihrintzis, 2012).

3.1 Vertical Subsurface Flow Constructed Wetlands Case Studies

Vertical subsurface flow (VSSF) constructed wetland systems typically have: 1) a sedimentation tank, which is the wastewater pre-treatment aspect, 2) the vertical flow constructed wetland beds, and 3) an effluent collection ditch (Stefanakis and Tsihrintzis, 2012). Wastewater feeds into the system by filling periodically and relies on gravity for drainage. This method is desirable because it is designed to increase oxygen aeration within the different substrates and gradations. The two VSSF constructed wetlands were both pilot-scale studies conducted in Xanthi, Greece and Western Greece.

3.1.1 VSSF Constructed Wetland in Xanthi, Greece (Stefanakis and Tsihrintzis, 2012)

A pilot-scale system operated for three years using a VSSF constructed wetland conducted in Xanthi, Greece for the treatment of synthetic wastewater. Synthetic wastewater was simulated to resemble the characteristics of strong wastewater. The target contaminant for removal were organic matter: BOD and COD, and nutrients: total Kjeldahl nitrogen (TKN) and total phosphorous (TP). The study used ten cylindrical VSSF constructed wetlands units, each with a diameter of 0.82 m and 1.5 m height consisting of a total area of $0.57m^2$. The units either used a substrate that was a mixture of sand, fine carbonate gravel and igneous rock, and zeolite and bauxite with varying gradation and thicknesses of 50, 80, or 90 cm. One unit remained unplanted, while the rest of the nine units were planted with the chosen macrophytes, *Phragmites australis* (common reed) and *Typha latifolia* (cattail) in the units at a density of 14 plant stems/m^2. This study tested 1) three different organic loading rates (OLRs): 107 g COD/m^2d (Year 1), 107 g COD/m^2d (Year 2), and 107 g COD/m^2d (Year 3), and 2) three different HLRs: 0.19 m/d (Year 1), 0.26 m/d (Year 2), and 0.44 m/d (Year 3). The results of these OLRs and HLRs are shown in Table 2.

Table 2: Results of Average Contaminant Removal Over Three Years Using a VSSF Constructed Wetland

Contaminant	Input Averages (mg/L)	Output Averages (mg/L)	Removal Rate (%)
BOD_5	427 ± 61.2	87.5 ± 38.1	82.1
COD	510.4 ± 69.3	124.3 ± 47.5	80.2
TKN	61.1 ± 9.0	25.4 ± 6.9	58.1
TP	9.37 ±2.05	5.88 ± 0.63	37.4

(Stefanakis and Tsihrintzis, 2012)

The study showed that substrate had an effect on contaminant removal efficiency. Units that had a layer of sand on the surface increased treatment performance by decelerating the flow of wastewater, which allowed for a longer contact period between the wastewater and the substrate and plant roots. The slow trickle effect favored nitrification and ammonia adsorption, which meant that ammonia oxidation and microbial decomposition of organic matter was high during the retention periods between hydraulic loads. However, the substrate material showed little differences in the performance of the units.

The presence of macrophytes showed slightly increased efficiency of contaminant removal than the unplanted units. When comparing units planted with *P. australis* and units planted with *T. latifolia*, removal of TKN favored *P. australis*.

The removal rates were consistently high for BOD and COD in all of the units. Despite the higher OLRs and HLRs in Year 2 and Year 3, the study found that efficiency of contaminant removal increased for BOD, COD, and TKN. The system most likely improved in stability once the macrophytes had a chance to establish. Results also show that the VSSF constructed wetland system can handle high OLRs and HLRs. The removal rates for TP decreased in Year 2 and Year 3, which meant the increased OLRs and HLRs had a negative effect on TP removal. However, TP removal increased by 15% when the temperatures were higher than the average temperatures of 16.4ºC, which may suggest that temperature has an affect on phosphorous removal rates.

3.1.2 VSSF Constructed Wetland in Western Greece (Herouvim et al., 2011)

A pilot-scale test using a VSSF constructed wetland was conducted in Amfilochia city in Aitoloakarnania Prefecture, Western Greece for the treatment of pre-treated olive mill wastewater. The study looked at the efficiency of removal of COD and TKN at extremely high concentrations. The study used three series that consisted of four pilot units each, with two of the series planted with *P. australis* and one of the series remaining unplanted. The planted units consisted of 6 stems of *P. australis* per unit. The study used metallic cylindrical VSSF constructed wetlands units, each with a diameter of 1.8 m and 3 m in height. The units used a porous substrate that was filled with a mixture of sand, gravel, and cobble with different gradation. The HLRs for COD ranged from 3,600 mg/L to 14,000 mg/L, and the HLRs for TKN ranged from 100mg/L to 506 mg/L.

The average removal rates of COD were roughly 10% higher in the presence of *P. australis,* which indicates that macrophytes are important for contaminant removal. This pilot-study showed that *P. australis* were capable of receiving higher contamination loads than what was previously studied. Tolerance to high contamination is a desirable characteristic when choosing macrophytes to use in constructed wetland treatment projects.

The study found that even though removal rates were high for COD, TKN, and TP, but the effluent contaminant concentrations still remained high (Table 3), which means it is not suitable for disposal into water bodies based on EU recommended limits. However, the system did treat wastewater influent more efficiently when the concentration of COD was reduced to 3,600 mg/L, the concentration of TKN was reduced to 100mg/L, and the concentration of TP was reduced to 12 mg/L.

While the study did not specifically state output averages, they provided a percent estimate of removal rates of COD at 70%, TKN at 75% and TP at 87%.

Table 3: Results of Initial Contaminant Removal at High Concentrations Using a VSSF Constructed Wetland.

Contaminant	Initial Inputs (mg/L)	Removal Rate (%)
COD	14,120 ± 4321	70
TKN	506 ± 342	75
TP	95 ± 34	87

(Herouvim et al., 2011)

3.2 Horizontal Subsurface Flow Constructed Wetlands Case Studies

Horizontal subsurface flow (HSSF) constructed wetland systems have been commonly used in cold or tropical regions since they are essentially underground systems that are sheltered from the elements. HSSF constructed wetlands typically rely on the slow flow of wastewater to allow contact with the various substrates and vegetation (Villalobos et al., 2013). Even though a large portion of the system is subsurface, temperature still plays a role in plant and microbial activity. The following case studies are two HSSF constructed wetlands conducted on a pilot-scale; one is located in Rabat, Morocco (El Hamouri et al., 2006) and the other is located in Lisbon, Portugal (Amaral et al., 2013).

3.2.1 HSSF Constructed Wetland in Rabat, Morocco (El Hamouri et al., 2006)

A pilot-scale operation using a HSSF constructed wetland was conducted in Rabat, Morocco for the treatment of pre-treated sewage. The target contaminants were organic matter: BOD and COD, nutrients: nitrogen and phosphorous, and fecal coliform (FC) removal. The primary stage consists of a sedimentation tank, then the pre-treated wastewater is fed into three beds: *Arundo donax* (giant reed), *P. australis* (common reed), and an unplanted control. The beds were 8 m in length x 3.5 m in width x 1 m in depth, each totaling an area of 28 m^2. The units were each lined with PVC membrane followed by a layer of mixed limestone aggregates and sand, then a second layer of only limestone aggregate, which allowed for a porosity of 50%. *Arundo donax* was planted in the unit with a density of 25 stems/m^2, and *P. australis* was planted in the unit with a density of 45 stems/m^2. The study tested the OLRs of 70 g COD/m^2d and HLRs of 0.34 m/d in each of the beds.

The study shows that the presence of macrophytes and the species of macrophytes plays a role in contaminant removal efficiency. *Arundo donax* had similar or higher removal rates than *P. australis* for all selected contaminants (Table 4). The planted HSSF constructed wetland beds were efficient for BOD and COD removal, but the removal rates for TKN, TP, and FC were low. It is hypothesized that low oxygen availability resulted in low removal rates of nitrogen due to limited nitrogen oxidation for this type of HSSF system.

Table 4: Results of Contaminant Removal Based on Planted and Unplanted Beds in a HSSF Constructed Wetland

Contaminant	Initial Input (mg/L)	*Arundo donax* Removal Rates (%)	*Phragmites australis* Removal Rates (%)	Unplanted Control (%)
BOD_5	220	82	79	68

COD	385	82	78	66
TKN	60	11	8	8
TP	11	15	15	15
Fecal Coliform* (mL)	10^6	1	1	0

* Initial Input is in mL

(El Hamouri et al., 2006)

3.2.1 HSSF Constructed Wetland in Lisbon, Portugal (Amaral et al., 2013)

A pilot-scale study using a HSSF constructed wetland was conducted in Lisbon, Portugal for the treatment of combined sewer overflow (CSO). CSO is often a problem when inflow of sewage exceeds the capacity WWTPs can handle, which typically occurs during storm events. The target contaminants in this study were TSS, COD, and pathogenic microorganism removal. The study used four constructed wetland beds lined with PVC, followed by a layer of gravel consisting of 4-8 mm sized pieces, which allowed for a porosity of 30%. The beds were reported to be 555 mm in length x 361 mm in width x 400 mm in depth. These measurements are questionable based on the scope of this study and may have been reported inaccurately. Two of the units were planted with *P. australis* and two of the units remained unplanted. These units were analyzed based on Hydraulic Residence Times (HRTs) for day 1, 3, and 7 after inundating the beds with wastewater (Table 5).

Table 5: Results of Contaminant Removal Based on Planted and Unplanted Beds in HSSF Units in Relation to HRTs.

Hydraulic Residence Time (days)	Contaminant	Planted Average Removal Rates (%)	Unplanted Removal Average Rates (%)
1	COD (%)	75.5	76.5
	TSS (%)	84.5	85.5
	Total Coliform (log)	1.7	1.3
	Enterococcus (log)	2.25	1.95
3	COD (%)	81	81.5

	TSS (%)	93.5	96
	Total Coliform (log)	3.7	3.1
	Enterococcus (log)	3.85	3.4
7	COD (%)	87.5	89.5
	TSS (%)	93.5	97
	Total Coliform (log)	4.45	4.3
	Enterococcus (log)	5	4.45

(Amaral et al., 2013)

The study shows that vegetation had no effect on contaminant removal rates. However, this result may be due to the fact that the vegetation has not had a chance to fully mature or establish roots into the substrate. Hydraulic retention time had a significant effect on removal rates for all contaminants. The rate of removal increased as HRTs increased, which indicated that the time in which wastewater is in contact with substrates plays a role in the effectiveness of HSSF constructed wetland systems.

3.3 Free Water Surface Flow Constructed Wetland Case Studies

Free water surface flow (FWS) constructed wetland systems typically have two main components that represent stages. The first stage is a sedimentation tank, which is essentially a septic system, and the second stage is the FWS constructed wetland. Other components that may be found are chambers to regulate water levels, pumps and pipelines for recirculation of effluent, and a compost filter to control odors (Tsihrintzis et al., 2007). The two FWS constructed wetlands in this research are presented in a pilot-scale study conducted in Crete, Southern Greece and a full-scale study conducted in Garip, Turkey. Based on these studies, successful constructed wetland features can be better understood for potential application in Mediterranean regions in California.

3.3.1 FWS Constructed Wetland in Pompia, Crete, South Greece (Tsihrintzis et al., 2007)

A pilot-scale FWS constructed wetland study was conducted in 1999 in Pompia, Crete, South Greece for the treatment of domestic wastewater The system was designed to treat wastewater for 1,200 PE, which is ideally able to support a small community in the Mediterranean. The target contaminants were TSS, BOD, COD, TKN, TP, total coliform (TC), and FC removal. The study used 1) a septic tank with three filters, 2) a compost filter in the septic tank for odor 3) the two basins composing the FWS constructed wetland system, 4) two chambers for controlling water levels in each basin, and 5) pumps and a pipeline for recirculation of effluent. The two basins that make up the FWS system have surface areas of 4300 m^3 and 1200 m^3. The basins were densely planted with two species of macrophytes, *P. australis* and *A. donax* that grew over two meters in height. The study tested approximately 144 m^3/d as the average daily wastewater flow rate.

Results shown in Table 6 are the data that was collected over the course of a 4-year monitoring period from August 1999 to August 2003. Removal efficiencies of TSS, BOD, and COD were extremely high, averaging at about 95% removal rate for the final effluent. Removal rates for TKN and TP was considerably lower, with values of 52.5% and 53.1%, respectively. While the study did not explicitly state the measured concentrations for the input and output averages of TC and FC, they reported an average of over 97% removal of TC and FC without any form of disinfection.

Table 6: Results of Contaminant Removal Based on Average Influent and Effluent Inputs Over 4-years in a Pilot-scale FWS System.

Contaminant mg/L	Input Averages (mg/L)	Output Averages (mg/L)	Removal Rates (%)
TSS	191 ± 40	5.6 ± 0.8	95.5
BOD	165 ± 31	7.7 ± 1.3	94.4
COD	455 ± 31	18 ± 2.7	96.1
TKN	38 ± 3.4	18 ± 1.7	52.5
TP	13 ± 1.5	6.1 ± 1.1	53.1
TC and FC	N/A	N/A	>97

(Tsihrintzis et al., 2007)

3.3.2 FWS Constructed Wetland in Garip, Turkey (Gunes et al., 2012)

A full-scale operating FWS constructed wetland was built in 2005 in Garip, Turkey for treatment of concentrated domestic wastewater (Table 1) from the village population under consideration. The target contaminants were TSS, BOD, TKN, and TP at levels from highly concentrated domestic wastewater. The village of Garip has an estimated population of 625 people and is expected to increase to 868 by 2030. This project was developed with the expectation of treating 74 L/person/day, which equates to approximately 462 m^3/d as the average daily wastewater flow rate.

The entire system design is comprised of three stages. Wastewater feeds into the system through an inflow and reaches the first stage of the septic tank. Once it leaves the septic tank, it enters the second stage, where the wastewater flows through a gravel layer and into the FWS basin and the wastewater remains in the vegetated zone for the recommended HRT. After the HRT, the wastewater flows out through another gravel layer for drainage.

The first stage consisting of the sedimentation tank is 22.1 m in length x 52.4 m in width to allow particles to settle. The second stage is 10.0 m in length x 52.4 m in width and is designed as an open water area for floating and submerged macrophytes as a method of aeration to increase oxygen levels for the nitrification process. The third stage is 22.1 m in length x 52.4 m in width and planted with macrophytes, *T. latifolia* to promote microbial activity and denitrification.

After twelve months of monitoring, the study shows that the septic tank combined with the FWS constructed wetland system removed high rates of TSS, COD and BOD (Table 7). The removal of TSS concentrations in effluent showed an 86% decrease in effluent from the initial inputs, and COD and BOD effluent concentrations showed about a 90% decrease in effluent from the initial inputs of contaminants. The removal rates for TKN and TP were not as high at about 57% and 43%, respectively. The combination of the sedimentation tank and the FWS constructed wetland system allowed for an average removal rate of 57% in TKN because of the alternating aerobic and anaerobic conditions for partial nitrification and partial denitrification processes (Gunes et al., 2012).

Table 7: Results of Contaminant Removal Based on Average Influent and Effluent Inputs in a Full-scale FWS System.

Contaminant (mg/L)	Input Averages (mg/L)	Output Averages (mg/L)	Removal Rates (%)
TSS	222	31	86.0
COD	728	61	91.6

BOD	352	30	91.5
TKN	42	18	57.1
TP	7.6	4.3	43.3

(Gunes et al., 2012)

As shown in Table 8, the researchers found that the recommended HRT is between 28 and 31 days, which is a longer HRT than previous studies that recommend only 4-15 days (Gunes et al., 2012).

Table 8: Effects of HRT on Average Contaminant Removal Rates. The Highlighted Region Represents the Optimum HRTs for Contaminant Removal for the FWS System.

Hydraulic Residence Times (HRTs in Days)	Contaminants (%)	Average Removal Rates (%)
25	TSS	67
	BOD	88
	TKN	48
	TP	31
28	TSS	69
	BOD	92
	TKN	51
	TP	35
31	TSS	66
	BOD	93
	TKN	49
	TP	34
35	TSS	62
	BOD	88
	TKN	45
	TP	35

(Gunes et al., 2012)

After further statistical analysis, it was found that removal rates of TSS, BOD, and TKN were on average, an estimated 4% higher in the summer months than in the winter months. This difference may be due to higher microbial activities associated with warmer temperatures. The removal of TP was higher in the winter months, however this difference may be due to an overall lowering of TP loading rates attributed to colder temperatures. TKN and TP removal rates still remain highly variable based on the FWS constructed wetland system and require further research (Gunes et al., 2012).

3.4 Chapter Summary

This chapter presented an overview of pilot-scale and full-scale constructed wetlands studies conducted in Mediterranean climates around the world. Although these case studies were not conducted in California, these were chosen based on their climatic conditions and possible application to California's Mediterranean climate regions. Based on the studies discussed in this chapter, it is apparent that all three constructed wetland designs share similar characteristics and removal efficiencies. Chapter 4 assesses contamination removal based on the designs and features through the use of case studies. Chapter 4 also discusses other components that contribute to the success and limitations of each of the designs, and other factors that affect contaminant removal effectiveness.

4.0 Discussion of Constructed Wetlands Case Studies for Wastewater Treatment in Mediterranean Climates

This chapter provides further discussion of the case studies presented in Chapter 3. The constructed wetlands discussed in this research were designed to create environments that promote the removal of total suspended solids (TSS), pathogenic microorganisms, organic matter: biological oxygen demand (BOD) and chemical oxygen demand (COD), and excess nutrients however, there are other factors that affect the efficiency of contaminant removal mechanisms such as wetland designs, spatial constraints, climate, hydraulic loading rates (HLRs), hydraulic retention times (HRTs), and the presence of macrophytes.

The case studies were conducted in four countries: three took place in Greece, one in Morocco, one in Portugal, and one in Turkey. Five out of the six case studies were pilot-scale systems and only one was a full-scale operating system. The following sections look at the case studies collectively, based on wetland design, and evaluate features that either makes them effective or ineffective at removing contaminants. This chapter also discusses spatial constraints that may affect the area and size of potential constructed wetland systems, how climate has a major role in the effectiveness of a constructed wetland's ability to remove contaminants, the effects of HLRs and HRTs, and the importance of the presence of macrophytes.

4.1 Vertical Subsurface Flow Constructed Wetlands Case Studies

The vertical subsurface flow (VSSF) pilot-study constructed wetlands in Xanthi, Greece and Amfilochia, Western Greece showed high removal rates for organic matter (Table 9). The VSSF system also shows potential for effective removal of total phosphorous (TP) and total nitrogen (TKN) (Herouvim et al., 2011).

Table 9: Features of Case Studies in Mediterranean Climates. Target Contaminants

Case Study	Design Type	Macrophyte Species	Target Contaminants	Removal Success > 70%	Potential Habitat

Highlighted in Red Represents Low Removal Success < 70%

Xanthi, Greece (Stefanakis and Tsihrintzis, 2012)	Pilot-scale VSSF	*Phragmites australis* and *Typha latifolia*	BOD COD TKN TP	BOD COD	No
Amfilochia City, Western Greece (Herouvim et al., 2011)	Pilot-scale VSSF	*Phragmites australis*	COD TKN	COD TKN	No
Rabat, Morocco (El Hamouri et al., 2006)	Pilot-scale HSSF	*Arundo donax* and *Phragmites australis*	BOD COD TKN TP FC	BOD COD	No
Lisbon, Portugal (Amaral et al., 2013)	Pilot-scale HSSF	*Phragmites australis*	TSS COD FC Enterococcus	TSS COD	No
Pompia, Crete, South Greece (Tsihrintzis et al., 2007)	Pilot-scale FWS	*Arundo donax* and *Phragmites australis*	TSS BOD COD TKN TP TC and FC	TSS BOD COD TC and FC	Maybe
Garip, Turkey (Gunes et al., 2012)	Full-scale FWS	*Typha latifolia*	TSS COD BOD TKN TP	TSS COD BOD	Yes

The main removal mechanism of TSS in VSSF constructed wetlands is through physical suspension, sedimentation, and filtration, and the mechanism for removing organic matter is mainly through microbial activity i.e. biological degradation.

TP removal rates in constructed wetlands are highly variable in both the case studies. In the study conducted by Herouvim et al. (2011), the VSSF system showed high efficiency of TP removal. It was hypothesized that VSSF systems typically have varying layers of substrate with different gradations, and this allows for phosphorous adsorption in the permeable medium. In the Stefanakis and Tsihrintzis (2012) pilot-scale study, there were low removal rates of TP, but they found that factors such as higher organic loading rates (OLRs) and colder temperatures lowered TP removal rates even more. This result suggests that while the VSSF system can handle high OLRs, it may affect the efficiency of TP removal rates and that TP removal rates may be temperature dependent.

The typical design of a VSSF constructed wetland utilizes a trickling method, where water is uniformly distributed at the top of the filter and the wastewater slowly percolates through substrate layers. Vertical drainage can allow aerobic conditions to be restored through cyclic input and output flow (USEPA, 2000d). Because of the vertical drainage feature, the system is never completely inundated with wastewater, which ensures the synchronized flow of oxygen and wastewater. As air and wastewater trickle down the substrate, it does not have a chance to inundate the system so there is no anaerobic factor. A solution for creating anaerobic conditions is to allow the wastewater to be accumulated at the bottom and remain in the system during a period of HRT to allow greater contact with microbes for microbial degradation (Herouvim et al., 2011). This system has been shown to be effective in removing total nitrogen only if there are alternating aerobic conditions for nitrification and anaerobic conditions for denitrification.

4.2 Horizontal Subsurface Flow Constructed Wetlands Case Studies

The horizontal subsurface flow (HSSF) pilot-study constructed wetlands in Rabat, Morocco (El Hamouri et al., 2006) and Lisbon, Portugal (Amaral et al., 2013) showed high removal rates for TSS and organic matter (Table 9). The HSSF constructed wetlands in these case studies showed low removal rates for pathogenic microorganisms and nutrients.

Similar to the VSSF system, the main removal mechanism of TSS in HSSF constructed wetlands is through physical suspension, sedimentation, and filtration. The process for removing organic matter is mainly through microbial activity by biological degradation. The removal of TSS and organic matter increased in the presence of macrophytes (El Hamouri et al., 2006), which suggests that microbial activity plays a role in TSS, BOD and COD removal. In another study that found increased microbial activity in the presence of macrophytes, it was suggested that result was attributed to rhizomes in the macrophytes allowing for greater microbe attachment and more activity to take place (Vymazal, 2010).

Contrary to studies that found high pathogenic microganism removal in HSSF constructed wetlands, the case studies both found low total coliform (TC) and fecal coliform (FC) reductions (Amaral et al., 2013; El Hamouri et al., 2006). The units planted with macrophytes were slightly more effective at removing TC and enterococcus however the different species of macrophytes did not show any significant effects (Amaral et al., 2013).

HSSF systems typically remain as flooded environments and result in low oxygen conditions. Due to the limited amount of oxygen, the nitrification process is extremely limited and the removal of TKN is not an efficient process (Vymazal, 2010). On the other hand, HSSF systems are efficient with the denitification process because of the anaerobic conditions the water-saturated system produces. Because TKN removal requires the nitrification process before denitrification can occur, HSSF systems are missing an aerobic component that hinders the removal processes. The HSSF constructed wetlands showed the lowest amount of TKN removal out of all three systems. The removal of TP was low in both case studies (approximately 30-40%) and may be due to the high influx of wastewater inputs, which does not give the opportunity for phosphorous to be adsorbed into media (Amaral et al., 2013; El Hamouri et al., 2006).

4.3 Free Water Surface flow Constructed Wetland Case Studies

The free water surface (FWS) flow constructed wetlands case studies included a pilot-scale study in Pompia, Crete, South Greece and a full-scale study in Garip, Turkey. The FWS systems were efficient for high removal rates for TSS, BOD, COD, and showed high removal rate potential for TC and FC (Tsihrintzis et al., 2007; Gunes et al., 2012) (Table 9). Similar to the one of the VSSF case studies and both HSSF case studies, the FWS flow systems case studies showed low removal rates for nutrients.

The main mechanism for the removal of TSS in FWS systems in these case studies utilized a pre-treatment septic tank to decrease the amount of particles that enter the constructed wetland portion of the system (Gunes et al., 2012). Using the septic tank reduces the initial amount of TSS through sedimentation and physical suspension, which gets further reduced once the wastewater is filtered in the constructed wetland system. Also similar to VSSF and HSSF systems, the process for removing organic matter is mainly through microbial activity by biological degradation, which increased in the presence of macrophytes. The removal of organic matter in both case studies averaged to approximately 90-95%, showing the highest efficiency for organic matter removal out of all three systems.

One of the FWS case studies also showed the highest removal rates for pathogenic microorganisms, approximately 97% removal rate efficiency for TC and FC (Tsihrintzis et al., 2007). Out of all three systems based on the case studies, the FWS system was the only design to have high potential for removal of pathogenic microorganisms. The other constructed wetland systems that tested for TC, FC, and enterococcus removal showed negligible removal rate results (El Hamouri et al., 2006; Amaral et al., 2013)

The FWS constructed wetlands were not very efficient at removing nutrients. Similar to HSSF systems, the FWS flow systems are also typically flooded environments. There is a major difference in that there is also an open water aspect to the FWS systems created by the surficial water flow. Open water is a particular feature unique to the FWS system that allows for anaerobic conditions around the water-saturated area, but also slightly aerobic conditions at the near-surface layer. While the FWS system creates both aerobic and anaerobic conditions for nitrification and denitrification, it is possible that it is not sufficient enough for the nitrogen removal process to be efficient. The removal of phosphorous was also low, which was to be expected based on the previously mentioned case studies and further research is required.

4.4 Spatial Requirements

The case studies mentioned in the previous chapter were all pilot-scale studies except for one full-scale study conducted in Garip, Turkey for a FWS system. The full-scale FWS constructed wetland for wastewater treatment of this size was the first of its kind operated in the Mediterranean Basin (Gunes et al., 2012). Among the three constructed wetland types, FWS and HSSF systems have the potential to being most land-intensive for treating contaminants in the same amount of wastewater as a VSSF system. In FWS and HSSF systems, the land area required is correlated to the amount of wastewater that needs to be treated, whereas VSSF systems rely more on a dosing system in the trickling method through layers of media (Stefanakis and Tsihrintzis, 2012). While FWS and HSSF can be land-intensive, it is also more likely that these systems can provide ancillary benefits such as wildlife habitat.

Based on the pilot-studies, a major benefit of VSSF constructed wetland systems is that they require less land usage to achieve similar contaminant removal for TSS, BOD and COD. However, because these were pilot-scale studies that treated only limited amounts of wastewater, it is difficult to say if it would be feasible to create a VSSF system solely for the treatment of wastewater produced by a small community. In order to compare the constructed wetland types, it is important to consider spatial requirements of each design as if they were full-scale operating systems.

4.5 Temperature

This research focused on Mediterranean climate regions because temperature has been known to affect the overall function of a wetland system and productivity (Weber and Legge, 2008). While the exact boundaries of the Mediterranean climate region are uncertain, it is generally classified by having mild and wet winters and, hot and dry summers. Wetlands in Mediterranean climate regions can experience long periods of considerable rainfall and also long periods of drought. With such variable climate, it can be useful to understand when constructed wetland treatment systems are more efficient at contaminant removal and are able to handle higher loading rates.

The removal rate of organic matter has the potential to increase during warmer temperatures. In the study conducted by Herouvim et al. (2011), the removal of COD was temperature dependent. At higher temperatures, removal of COD increased, which indicates that removal of organic matter is a result of high microbial activity since they are more active when temperatures are warmer.

One of the main mechanisms for pathogenic microorganism removal is through UV radiation (Weber and Legge, 2008). Along with UV radiation, temperatures also tend to increase in the summer, which can contribute to higher rates of pathogen removal through inactivation and natural die-off.

Warmer temperatures may also affect the efficacy of nutrient removal in constructed wetlands. There were seasonal variations in TP removal rates with higher rates of removal occurring in the summer and fall months and lower rates of removal during winter months. Plant assimilation of phosphorous can be attributed to the increased removal rates of TP in summer and fall months when plant growth may be high (Villalobos et al., 2013). The lowered rates of TP removal in the winter months may be due to a decrease in plant density and plant decay could potentially be an added source of phosphorous (Villalobos et al., 2013).

4.6 Hydraulic Loading Rates and Hydraulic Retention Times

Higher HLRs and water levels allow for less resuspension, but are not ideal environments for vegetation. Lower water levels can lead to anaerobic conditions favoring conditions for denitrification, but are not ideal for vegetation growth. HLRs show that water depths around 30 cm or less are the optimal amount of inflow for a FWS constructed wetland and water depths greater than 30 cm can limit vegetation growth (Mitsch and Jorgenson, 2004).

HRTs in FWS systems can increase contaminant removal rates of TSS and organic matter. After experimenting with HRTs ranging from 25-35 days, the full-scale FWS constructed wetland in Garip, Turkey found the optimal time for contaminant removal was around 28 days (Gunes et al., 2012). After the 28 days, there was no significant increase of removal rate efficiency and this study concluded that for that particular system, 28 days was sufficient for TSS and organic matter removal and increasing HRTs to 35 days would be unnecessary.

HLRs and maintaining water levels for HRTs for wastewater treatment require an intricate balance and adjustments because they are site-specific parameters. It is difficult to predict optimal HLRs and HRTs without expert design and multiple tests, because even if constructed wetlands can handle a high HLR, the removal rate correlates to the amount of wastewater inputs (Herouvim et al., 2011). In other words, high removal rates of HLRs of highly contaminated wastewater can also produce highly contaminated outputs that may not be suitable for discharge. Based on the area the constructed wetland system is built on, it can be unique to various conditions such as the population size the system is designed for and if there are space or topography constraints. Understanding the optimal contaminant removal efficiency based on HLRs and HRTs, in relation to the strength and input rates of wastewater, can allow for significant time and land reduction.

4.7 Macrophyte Species

Macrophytes are an integral part of constructed wetlands. Not only do they present aesthetic and ecological benefits, the units planted with macrophytes were more effective at contaminant removal than units that were unplanted (Stefanakis and Tsihrintzis, 2012; Herouvim et al., 2011; El Hamouri et al., 2006). *Phragmites australis* (common reed) was a common species utilized in the case studies and this may be because it is native to Europe, where five out of the six case studies took place.

In Mediterranean climates, macrophytes should be selected to be able to survive in periods of drought and heat as well as hydric stress (Amaral et al., 2013). In the case studies, macrophytes contributed to TSS removal because they added an extra filtration component. Macrophytes also prove to play an important role in removal of contaminants because their roots can transfer oxygen into various substrates to promote microbial activity (Herouvim et al., 2011). There was also evidence of FC removal rates increasing in planted bed compared to unplanted beds (El Hamouri et al, 2007) and this result may be due to that extra filtration component in the system similar to the mechanism for TSS removal.

Different macrophyte species may have an effect on removal efficiencies for certain contaminants. Units planted with *Arundo donax* (giant reed) showed greater removal rates of BOD, COD, and TKN when compared to *Phragmites australis* (common reed), but had similar removal rates for phosphorous and FC (El Hamouri et al., 2006). *Typha latifolia* (cattails) have been shown to be efficient at removing phosphorous and contaminants from wastewater, but they also have several negative qualities. They have the ability to spread vigorously and tend to require more maintenance than other species (U.S. Forest Service, n.d.). Because vegetation is not often harvested due to maintenance costs, macrophytes that overgrow quickly are not desirable.

Some desirable characteristics when choosing plant species for constructed wetland systems: tolerant to high concentrations of nutrients and contaminants, ability to uptake contaminants, adaptable to local and various climates, high oxygen transport capability, high photosynthetic rates, easy to maintain, and resilient to pests and herbivores (Reddy and DeBusk, 1987). Macrophyte root characteristics are also important when choosing species for constructed wastewater treatment systems. Roots with deep penetration and large surface areas can increase microbial attachment and activity. Other desirable root characteristics are hard stems because harvesting macrophytes is not ideal for maintenance reasons. Hard stems do not add much to detritus material in water column that may further lower oxygen levels in saturated zones (Reed, 1990).

4.8 Chapter Summary

Chapter 4 discusses the many factors that affect the rates and capabilities of a constructed wetland designed for wastewater treatment. There are different levels of efficiency for contaminant removal depending on many factors. These factors include constructed wetland design and water flow directions, site-specific conditions such as spatial constraints, temperature fluctuations, HLRs and HRTs that control the input and output rates of wastewater, and the importance of the presence of macrophytes.

The next chapter will present research conclusions, including contaminants constructed wetlands have a high potential of treating and which contaminants constructed wetlands may not be suitable to treat. Chapter 5 also discusses the advantages and disadvantages of the constructed wetland types, and possible applications to California's Mediterranean climate regions.

5.0 Research Conclusions

Because constructed wetlands are outdoor systems that have unavoidable contact with the elements, it is important to consider which constructed wetland types are best suited for particular climate regions and wastewater treatment goals. All the systems had some level of effectiveness and ineffectiveness for certain contaminant removal. This chapter presents the advantages and disadvantages of each constructed wetland types, which designs were best suited for the reduction of selected contaminants and areas where there needs to be further research due to limitations. This chapter also mentions potential application to California, and data gaps and findings of this research.

5.1 Removal Successes

All three systems showed high removal rates of total suspended solids (TSS) and organic matter: BOD and COD (Table 10). The removal success of TSS is mainly through physical suspension and filtration, whereas the removal success of organic matter can be attributed to microbial activity. There was also some success in the free water surface (FWS) system for the removal of pathogenic microorganisms such as FC (fecal coliform) and enterococcus, and mechanisms that may have attributed to their removal effectiveness are also discussed in this section.

Constructed wetlands that created units with macrophytes and employed a sedimentation or septic tank for the pre-treatment step had an overall higher removal rate of TSS (El Hamouri et al., 2006; Tsihrintzis et al., 2007; Gunes et al., 2012). Macrophytes were important in that their roots and structures were able to add an extra filtration component to further reduce TSS. The pre-treatment stage from the sedimentation tank is also effective in decreasing the overloading of the system and can prevent clogging in the future. The pilot-scale studies were relatively short-term experiments, lasting from a few days to four years, but clogging is particularly an issue in horizontal subsurface flow (HSSF) constructed wetlands. Without proper monitoring and maintenance, clogging can become problematic overtime from the accumulation of TSS and this can result in the retirement of the system unless there is some form of mitigation using a pre-treatment stage. Organic matter was efficiently reduced in all three constructed wetland types. The mechanism for BOD and COD removal is primarily through microbial activity, which generally increased during summer months when temperatures were higher. The presence of microbes is facilitated by attachment to substrate and roots, which increased in the presence of macrophytes (Stefanakis and Tsihrintzis, 2012; Herouvim et al., 2011; El Hamouri et al., 2006). This result suggests that microbial activity is high in all three of the design systems and is able to remove organic matter effectively.

The reduction of pathogenic microorganisms was successful in the FWS constructed wetland system at an over 97% removal rate (Tsihrintzis et al., 2007), but similar removal could not be achieved effectively through the subsurface systems. The presence of macrophytes in constructed wetland units resulted in a slight increase of TC and FC removal compared to unplanted constructed wetland units (Amaral et al., 2013). It is possible that the mechanism to remove pathogens is primarily through UV radiation and higher temperatures, and these parameters correspond with the design of a FWS system where the surface is exposed.

5.2 Removal Limitations

In all three systems, there were limited removal rates of nutrients for total Kjeldahl nitrogen (TKN) and total phosphorous (TP). While the mechanisms for TKN removal are well studied, the individual constructed wetland types are not effective at reducing TKN concentrations. The removal of TP was ineffective in all three systems and requires more research in this area.

The mechanisms for removal require alternating aerobic or anaerobic conditions for nitrification and denitrification, respectively. Based on the case studies, each system creates either a primarily aerobic condition or a primarily anaerobic condition, but not both, which is ideally the conditions for TKN removal. Typical vertical subsurface flow (VSSF) systems create completely aerobic conditions, which is beneficial for nitrification, but not for denitrification. In HSSF systems, the opposite conditions occur and the system is water-saturated and anaerobic, which is beneficial for denitrification, but not for nitrification. In FWS systems, it is similar to HSSF systems in which it is permanently water-saturated, but small amounts of nitrogen can be removed through volatilization via the open water. When comparing these three systems individually, FWS systems should be most capable of removing nitrogen because of the anaerobic conditions created in the water-saturated zone and the slightly aerobic conditions at the water surface. Further studies are required to improve the effectiveness of nitrogen removal.

The reduction of TP is low in constructed wetland systems and extremely variable unless special media is utilized in the system (Vymazal, 2010). The primary mechanism that removes phosphorous is adsorption from the media, but other mechanisms include macrophyte assimilation, and retention and precipitation in sediments (Villalobos et al., 2013). These mechanisms suggest that there may be synergistic effects with media and macrophytes that work together to increase TP removal. Based on the case studies, the mechanisms of phosphorous adsorption in the systems alone cannot efficiently remove TP and may require a separate component with special media. Advantages and disadvantages in removal effectiveness for selected contaminants by constructed wetland types are shown in Table 10.

Table 10: General Description of Advantages and Disadvantages of Constructed Wetland Types for Wastewater Treatment

Constructed Wetland Type	Advantages	Disadvantages
Vertical Subsurface flow	- High removal rates of TSS and organic matter - High potential for nitrification abilities due to aeration - Not land-intensive - Low odor and mosquito issues - Not as prone to clogging as HSSF systems	- Requires precise measurements of wastewater inputs - May require an electrical energy source for the trickling method - Requires more maintenance than HSSF and FWS systems - Low removal of pathogenic microorganisms and nutrients
Horizontal Subsurface flow	- High removal rates of TSS and organic matter - High potential for denitrification abilities due to anaerobic conditions - Low odor and mosquito issues - Low operating costs	- Land-intensive - Low removal of pathogenic microorganisms and nutrients - High risk of clogging
Free Water Surface flow	- High removal rates of TSS, organic matter, and pathogenic microorganisms - Aesthetically desirable - Provides ancillary benefits (wildlife habitat, flood protection)	- Long startup time - Land-intensive - May provide breeding grounds for mosquitoes - Odor can be an issue - Low removal of nutrients

	- Low operating costs	

5.3 Potential Application to California

One goal of this research is to look at potential application of constructed wetland design to Mediterranean climate regions in California based on available case studies with similar climate. Basing constructed wetland studies on Mediterranean climates narrows the research down to factors such as temperature, macrophyte species, and hydrology, as these are major characteristics that affect the constructed wetland for wastewater treatment (CWWT) processes. As water scarcity and microhabitat loss are becoming more imminent issues in California, it is important to understand how to combat water quality concerns while considering environmental factors.

Based on this research, the general trend shows that all the constructed wetland types have a high contaminant removal rate for TSS and organic matter, and low removal rates for pathogenic microorganisms and nutrients. There were some exceptions that showed that VSSF has the ability to remove nitrogen with high efficiency and that FWS systems can have high potential for pathogenic microorganism removal rates. For the most part, removal rates were similar for most contaminants and it is difficult to say which particular individual system is the best application to Mediterranean regions in California.

In general, with wetland loss in California, it might be useful to consider the ancillary benefits FWS systems offer towards the creation of microhabitats. FWS constructed wetlands have shown to be effective in removing suspended solids, pathogenic microorganisms, organic matter and excess nutrients while also creating habitat for wildlife. While startup costs and land usage may be the most expensive aspects of constructed wetlands, there are many advantages to using constructed wetlands as natural wastewater treatment systems that allow them to be effective. Operation and maintenance costs are low compared to conventional wastewater treatment systems due to the utilization of natural biochemical processes, minimal external energy costs, and no need for additional chemicals (Gauss, 2008).

5.4 Data Gaps and Findings

There were many data gaps and findings in this research. A goal of this research is to suggest potential application of constructed wetland design to Mediterranean climate regions in California, so the case studies were restricted to a particular climate and their availability in published work. Major data gaps include information about other countries' water quality standards and the amount of published work in the United States.

The entirety of this research is based on other countries and whether wastewater treatment for selected contaminants was effective. Other countries and their water quality standards may not measure up to water qualities standards in California and the U.S., so not knowing guidelines for wastewater discharge standards is a large data gap. Another data gap is that the majority of published work about CWWT is not written by the engineers that build the constructed wetland systems, it is mainly scientists that are experimenting with different designs for testing. It is known that CWWT systems are utilized in the U.S. and in particular, California such as that Mt. View Sanitary District in Martinez, California and the Pacifica Wastewater Treatment Plant, but there is simply not enough scientific research and information about the design for these plants to conduct the evaluation required for this research.

One particular finding is that the determination of a Mediterranean climate is not clearly delineated. The Mediterranean climate region is defined as approximately 30°-45° in latitudes on the western part of continents (NOAA, n.d.) however with climate change implications, this definition is not representative of precipitation rate, temperature fluctuations, and rising sea levels. Because temperature plays a role in the effectiveness of CWWT, the usefulness of certain case studies may be limited.

The final chapter of this paper presents management recommendations that will identify possible solutions for improving constructed wetland design and considerations for further research.

6.0 Management Recommendations

It is important to consider which target contaminants are of particular concern when deciding on the design and features of creating a successful constructed wetland treatment system. Some management recommendations include considering hybrid design systems, recognizing site-specific constraints, estimating costs of operation, monitoring and maintenance, and conducting further research on other contaminants that can be removed through constructed wetlands for wastewater treatment (CWWT).

6.1 Hybrid Design

A possible solution for total Kjeldahl nitrogen (TKN) removal is to consider the creation of hybrid constructed wetland systems. In order to produce aerobic and anaerobic conditions for nitrification and denitrification processes to occur, creating complex systems that integrate a combination of a vertical subsurface flow (VSSF) and a horizontal subsurface flow (HSSF) system can produce ideal conditions for the removal of TKN. While the removal of TKN may be achieved through hybrid systems, it can also be potentially applied to other target contaminants.

Utilizing hybrid systems can result in more land-intensive costs, but it may also increase removal rates of other contaminants in wastewater. Individually the systems were not efficient at removing all the contaminants, but combining different constructed wetland types can result in more complex systems that can remove contaminants more effectively.

6.2 Site Specific Constraints

Consideration of site-specific conditions should occur whether or not there are constraints that prevent the suitability of building a CWWT. It is important to conduct preliminary environmental impact assessments such as topography in the area and depth to groundwater. This effort is especially important for free water surface (FWS) designs because topography is the driving force for water flow in the system and if groundwater sources are in proximity, leakage and infiltration may be concerns for potential groundwater contamination.

Another concern related to site-specific conditions is deciding if the climate is suitable for utilizing a CWWT and if space is an issue. It may not be feasible to use

CWWT in places where temperatures can drop to below freezing many months of the year since the treatment plant would essentially be out of commission during these times. Space can be an issue if the land available is not sufficient for the amount of wastewater that needs to be treated. Example: If nitrogen is a concern, engineers may consider using a VSSF system, but will also have to consider the fact that applications of a VSSF constructed wetland system may not be ideal on a full-scale operation because they cannot handle continuously high hydraulic loading rates (HLRs) for wastewater treatment for large communities.

6.3 Operation, Monitoring, and Maintenance

Operation of constructed wetlands is important because the size of the CWWT should correlate to the population the system is designed for. Operations need to take cost into consideration for land usage, initial startup costs, and maintenance costs. Monitoring and maintenance is also essential to comply with regulatory requirements such as the water quality standards for inputs and outputs of wastewater. There needs to be a greater understanding about the acceptable hydraulic loadings that maximizes the use of constructed wetlands. This understanding can improve the designs of treatment wetlands since it helps determine the appropriate wetland size for the input of wastewater instead of detrimental effects from overloading.

6.4 Further Research

Most of the case studies in this research were pilot-scale studies and is difficult to conduct parallel comparisons to full-scale operations. In general, the topic of CWWT requires more research in order to fully understand how this research can be applied to larger scale units for municipal wastewater treatment systems. While research has shown that CWWT systems are efficient at removal of total suspended solids (TSS) and organic matter, there are many other contaminants in wastewater that affect water quality such as metals, pharmaceuticals and pesticides that need to be studied more in-depth. Further studies are required to understand exactly how other contaminants of concern gets removed in a constructed wetland in order to implement designs that create optimum performance for reducing contaminants, including, but not limited to TSS and organic matter.

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