SPATIAL AND TEMPORAL VARIATION OF WATER QUALITY AND PHYTOPLANKTON IN THE CONSTRUCTED WETLANDS IN UNIVERSITI SAINS MALAYSIA

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by

SYAFIQ BIN SHAHARUDDIN

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Syafiq Bin Shaharuddin

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C	Total organism counted
A_t	Area of cover slip
A_s	Area of one slip
S	Total strip count
V	Volume of sample under cover slip
H’	Shannon-Wiener Diversity Index
Ni/N	the probability to obtain species ‘i’ in a sample
Ni	Number of individual for species ‘i’
f_i	Percent frequency of species i
D_i	Average relative density of species i

LIST OF ABBREVIATIONS

AN	Ammoniacal Nitrogen
ANOVA	Analysis of variance
APHA	American Public Health Association
ARI	Average Recurrence Interval
BMPs	Best Management Practices
BIOECODS	Bio-Ecological Drainage System
BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CW	Constructed wetland
DID	Department of Irrigation and Drainage
DO	Dissolved oxygen
EIA	Effective Impervious Area
FA	Forebay A
FB	Forebay B
FC	Forebay C
FWS	Free water surface
FFP	Free-floating plants
HSF	Horizontal subsurface flow
HLR	Hydraulic loading rate
HRT	Hydraulic retention time
IF	Inlet Forebay
IAM	Inlet Macrophyte A
IBM	Inlet Macrophyte B
ISI	Important Species Index
LID	Low Impact Development
MA	Macrophyte A
MB	Macrophyte B
MC	Macrophyte C
MCA	Micropool A
MCB	Micropool B
NO_3^--N	Nitrate-Nitrogen

NO_2^--N	Nitrite-Nitrogen
PO_4^{3-}-P	Orthophosphate
OAM	Outlet Macrophyte A
OBM	Outlet Microphyte B
OM	Outlet Micropool
REDAC	River Engineering and Urban Drainage Research Centre
SI	Sub-Index
SUDS	Sustainable Urban Drainage System
TIA	Total Impervious Area
TN	Total Nitrogen
TSS	Total Suspended Solid
USM	Universiti Sains Malaysia
MSMA	Urban Stormwater Management Manual for Malaysia
VF	Vertical flow
VSF	Vertical subsurface flow
WQI	Water quality index

KEVARIASIAN SPATIAL DAN TEMPORAL KUALITI AIR DAN FITOPLANKTON DALAM SISTEM TANAH BENCAH DI UNIVERSITI SAINS MALAYSIA

ABSTRAK

Tanah bencah buatan dibina untuk meningkatkan kualiti air disamping bertindak sebagai salah satu habitat alternatif semulajadi yang mampan untuk kehidupan akuatik. Di Malaysia, tanah bencah buatan direka mengikut garis panduan Manual saliran Mesra Alam (MSMA) Edisi Kedua, tahun 2012. Kajian ini akan menilai prestasi spatial dan temporal reka bentuk bencah buatan yang dibina seperti yang ditetapkan oleh MSMA melalui penilaian kualiti air dan komposisi fitoplankton, yang dipilih sebagai penunjuk biodiversiti untuk kajian ini. Tempoh persampelan selama 13 bulan, bermula November 2014 sehingga November 2015, dengan komposisi fitoplankton dan kelimpahannya dalam tanah bencah buatan ini yang kemudiannya akan dikaitkan dengan hasil pengukuran parameter kualiti air. Tanah bencah yang dibina terdiri daripada tiga zon utama, iaitu zon aliran masuk, zon makrofit dan zon air terbuka. Zon makrofit dan zon aliran masuk menunjukkan purata pencemaran yang secara puratanya lebih tinggi berbanding dengan zon lain. Nilai Indek Kualiti Air (IKA) dipilih supaya dapat mengkelaskan 6 parameter utama kepada satu nilai yang mudah dirujuk, yang kemudiannya dikelaskan dengan kelas yang disediakan. Nilai IKA tertinggi (kualiti air yang baik) diperoleh dari zon air terbuka dengan bacaan tertinggi ialah 82.67 (Kelas II) manakala nilai IKA terendah dikesan di zon makrofit, dengan bacaan terendah direkodkan ialah 65.37 (Kelas III). Pengurangan pencemar yang efektif dan tinggi adalah dari saluran masuk makrofit ke saluran keluar zon air terbuka, dengan peratus pengurangan untuk TSS 76%, TN 35% dan ortofosfat

56% berbanding dengan pengurangan dari saluran zon air masuk ke saluran keluar zon air terbuka. Sejumlah 20 spesies fitoplankton daripada 5 alga phyla yang berbeza telah dikenalpasti di dalam tanah bencah buatan ini. Kumpulan yang dominan adalah kumpulan Chlorophyta dan spesies *Westella botryoides* dan *Coelastrum microporum* didapati dominan di dalam sistem tanah bencah ini. Perubahan taburan kelimpahan fitoplankton dikesan dengan purata sebanyak 15,490.2 cell m^{-3} ± 586 di zon mikrofit berkurang sebaik sahaja di memasuki zon air terbuka, dengan penurunan purata kepada 9,599.3 cell m^{-3} ± 386. Namun terdapat sedikit perbezaan purata kelimpahan fitoplankton ini dikesan semasa musim kering dan musim basah di sepanjang tempoh persempalan ini, 15,765.2 cell m^{-3} ± 567 dan 14,391.3 cell m^{-3} ± 599, dengan musim kering melebihi sedikit berbanding musim basah. Taburan fitoplankton sekiranya dibandingkan dengan rujukan yang lain, bilangannya masih lagi kecil dan tanah bencah ini boleh dikategorikan kelas trofiknya sebagai mesotrofik. Selepas menjalankan analisis keserasian Pearson dan PCA, di dapati taburan fitoplankton berkait rapat dengan kepekatan ortofosfat. Ortofosfat menunjukkan perkaitan yang yang signifikan dengan komposisi fitoplankton, dengan R^2 yang tinggi 0.7 ke 0.9. Pada masa yang sama, reka bentuk zon mikrofit juga mempengaruhi komposisi fitoplankton, yang mana ini menunjukkan potensi dalam zon ini dalam meningkatkan kepelbagaian taburan fitoplankton yang dipengaruhi dengan perubahan kualiti air di setiap zon. Perkaitan perubahan yang dapat dilihat daripada IKA dan ortofosfat dengan kelimpahan fitoplankton menunjukkan fitoplankton adalah indikator biologi yang sesuai, bukan sahaja untuk kualiti air, bahkan untuk pengukuran nilai biodiversiti dan kelestarian habitat.

SPATIAL AND TEMPORAL VARIATION OF WATER QUALITY AND PHYTOPLANKTON IN THE CONSTRUCTED WETLAND IN UNIVERSITI SAINS MALAYSIA

ABSTRACT

Constructed wetlands are built to improve water quality while serving as an alternative sustainable habitat for aquatic life. In Malaysia, constructed wetlands are designed according to the guideline for Urban Stormwater Management Manual for Malaysia (MSMA 2nd ed.) 2012. This study shall evaluate the spatial and temporal performance of the constructed wetland design as stipulated by MSMA through an assessment of water quality and phytoplankton growth, which acts as a biodiversity indicator. The assessment included a 13-month sampling period starting from November 2014 until November 2015 whereby the phytoplankton abundance in a constructed wetland was correlated with the water quality parameters. The constructed wetland consists of three main zones, namely the forebay, macrophytes and micropool zones. The microphyte zone showed the highest average measurement of pollutants as opposed to the other zones. The WQI was chosen as it can group the 6 main parameters into one reference value, which will be further referred to the quality class. The highest WQI value (good water quality) was obtained from the micropool zone at 82.67 (Class II) while the lowest WQI value was collected from the macrophytes zone with 65.37 (Class III). The pollutant reduction was effective and high from the inlet macrophyte to the outlet micropool, with the percentage reduction of TSS at 76%, TN at 35% and orthophosphate at 56% compared to the reduction from the inlet forebay to the outlet micropool. A total of 20 phytoplankton species from 5 different algal phyla were identified in the constructed wetland. The dominant group was Chlorophyta group

while the species of *Westella botryoides* and *Coelastrum microporum* were found to be dominant in the constructed wetland. The changes of total phytoplankton abundance were observed from 15,490.2 cell m-3 ± 586 in the macrophyte zone, and reduced in the micropool zone to 9,599.3 cell m^{-3} ± 386. However there was a slight difference in the total abundance of phytoplankton during dry and wet periods, at 15,765.2 cell m^{-3} ± 567 and 14,391.3 cell m^{-3} ± 599, with the dry season recording more than the wet season. The total abundance of phytoplankton was low compared to other references, thus this constructed wetland can be classified as mesotrophic based on the trophic class. Upon the correlation analysis using Pearson correlation and PCA, the total abundance of phytoplankton was correlated to the orthophosphate concentration. The orthophosphate concentration showed significance correlation with the phytoplankton composition, with the high R^2 value between 0.7 to 0.9. At the same time, the design of the macrophyte zone influences the phytoplankton distribution and abundance. Hence, this zone indicated an increase in the abundance of phytoplankton, which was most likely influenced by the water quality condition. The correlation change from WQI, orthophosphate and phytoplankton abundance showed that the phytoplankton was a good biological indicator, not only for water quality, but also to gauge the biodiversity level and sustainability of habitat.

CHAPTER 1

INTRODUCTION

1.1 Background

It is said that the various problems we face today especially in respect to water security and environmental sustainability are caused by our penchant or strong liking for rapid development. Such a desire to witness development happening quickly has led to the growing percentage of impervious surfaces, which are closely associated with the types of land use (Dinicola,1989). In addition, development happening at a fast pace has also altered land uses; leading rural areas to be transformed into urban industrial areas. This transition has brought significant impacts to the local runoff, in regard to the receiving-water flow, quality and ecology. In addition, urbanization occurring in vast areas will likely result in higher percentage of Total Impervious Area (TIA) and Effective Impervious Area (EIA). Such a situation will therefore lead to more surface runoff or stormwater runoff due to the drastic reduction of infiltration rate.

Rightly so, the issue of stormwater runoff has emerged as the focal point of government and non-government bodies, local authorities, and developers around the world. In the local context, rapid development and urbanization in Malaysia are blamed for regular occurrence of flash floods as well as water pollution. For example, the most populated area in Subang Jaya in Selangor has registered an increase in runoff discharge by about 190% (Abdullah, 2000). Apart from erosion and sedimentation problems associated with development, it has become increasingly apparent that stormwater runoff contributes a significant part of total loads of pollutants such as nutrients (including phosphorus and nitrogen), heavy metals, oil and grease, bacteria and so on to receiving waters.

Nutrient loading containing phosphorus and nitrogen from stormwater runoff flows through the drainage system to lakes, rivers and estuaries. In addition, nutrient loading can even lead to a bigger problem, known as eutrophication. Eutrophication occurs due to the enrichment of water by nutrients which in turn causes structural changes to the ecosystem. This leads to; (i) an increased production of phytoplankton and other invasive aquatic plants, (ii) the decreasing population and diversity of fish species, and more commonly (iii) deterioration of the water quality. Eutrophication can also destroy habitat and may even be harmful to the wildlife population including fish and birds. Recent studies also suggest that eutrophication can kill native vegetation, which is the primary producer in the pyramid chain. In the long run, an area will become unsafe and unpleasant for humans to inhabit due to eutrophication.

Both water quality degradation and habitat loss are impacts of stormwater runoff. To tackle such problems, various efforts and initiatives have been carried out around the world in the past few decades. Among the efforts to manage stormwater runoff include the Best Management Practices (BMPs), Low Impact Development (LID), Sustainable Urban Drainage System (SUDS), Integrated Catchment Planning, and Ecological Stormwater Management. In Malaysia, the Department of Irrigation and Drainage (DID) Malaysia has taken a proactive step by introducing the Urban Stormwater Management Manual for Malaysia (*Manual Saliran Mesra Alam* or MSMA) since 2001. Hence, any new development in the country must comply with the guideline which requires the application of Best Management Practices (BMPs) to control stormwater from the aspect of quantity and quality runoff to achieve zero development impact. With the introduction of this manual, stormwater management in Malaysia is targeted to achieve several objectives including minimizing the environmental impacts of urban runoff on water quality.

Every component in MSMA has been developed with the aim to improve water quality. The Grass Swale (a substitute for conventional concrete drain), for example, will be able to filtrate and control pollutant concentration during the first flush of runoff. Dorman et al., (1998) documented that grass swale was very effective especially in removing heavy metals in the upstream area. In addition, the wet pond and detention pond will remove pollutants through settling and biological uptake. Based on such information, it is believed that almost all BMPs facilities shall play a significant role in improving water quality. However, out of all the facilities, only the constructed wetland has the potential to ensure an improved water quality as well as habitat sustainability.

Being one of the components in BMPs as well as in MSMA, the constructed wetland is built to specifically purify and remove pollutants in a cost-effective manner. Among its many uses include being the secondary treatment of various wastewater such as from municipal and certain industries, as well as polishing secondary effluents and runoff that would be carrying pollution from diffused sources. Aside from treating pollutants, the constructed wetland also serves as a quantity controller of stormwater with its temporary water storage volume significantly above the permanent pool elevation (DID, 2012). The presence of vegetation such as emergent, submerged and floating plants in the constructed wetland also offers a comparative advantage by being an effective biological uptake of pollutants. As a result, the constructed wetland fully utilizes the natural process interaction including the soils and the associated microbial assemblages, which are active agents in the treatment process (Stottmeister et al., 2003)

Further, the constructed wetland not only improves water quality but also provides new ecological and economic sustainability, therefore enhancing the biodiversity in many categories in trophic level (Hsu et al., 2011). The constructed wetland is also capable of modifying the abundance of species structure such as the phytoplankton at its inflow and outflow (Millan et al., 2014). Similarly, Calero et al., (2015) suggest that phytoplankton biomass and assemblages distribution recorded changes after crossing the wetland, and this affected the impact of eutrophication. All these arguments prove that the constructed wetland, which is a man-made "habitat", not only has an impact on the water quality concentration but also affects species distribution from the lowest to the highest trophic level. To justify the capability of a constructed wetland to serve as an alternative habitat for the ecosystem, a biodiversity assessment must be carried out comprising not only the collection and analysis of qualitative and/or quantitative information on the various kinds of organisms, but must also include actual field surveys. Such assessments have often focused on merely one kind of organisms; e.g., phytoplankton, invertebrates, fish, birds, flowering plants (or only aquatic macrophytes), and/or more than one taxonomic group (such as blue-green algae, diatoms, rotifers, molluscs, or grasses).

Nevertheless, there are several reasons to choose phytoplankton as the organism to be assessed to determine the biodiversity influence in the constructed wetland. The phytoplankton assumes several roles such as being the primary producer and bioindicator, and is quick to respond to the change in water chemistry. This will provide a basis for a good comparison as regards the water quality pollutant removal in the constructed wetland. Also, freshwater phytoplankton composition has the potential to change according to varying environmental conditions, with certain biota found in polluted waters and different biota identified in non-polluted water. Thus, by combining water quality assessment as well as phytoplankton assessment in a constructed wetland, both issues of water quality deterioration and habitat loss due to pollutant loading from stormwater runoff can be analyzed in more holistic manner.

1.2 Problem Statement

Since 2001, facilities following BMPs components and MSMA guidelines in Malaysia have been used and tested in various studies as well as systems, for example the Bio-Ecological Drainage System (BIOECODS) (Mohd Sidek et al., 2001; Zakaria et al., 2002; Zakaria et al., 2003; Yusof et al., 2004; Mohd Sidek et al., 2004; Ismail et al., 2008; Ayub et al., 2010; Zakaria et al., 2011; Zakaria, 2013; Sa'id Abdurrasheed et al., 2018). Specifically in studies of constructed wetlands, treatment performances have also been documented in the tropical climate regions especially in Malaysia (Mohammadpour et al., 2014; Mohammadpour et al., 2015; Mohd Noor et al., 2004; Mohd Noor et al., 2014; Shaharuddin et al., 2014; Sim et al., 2008). Most evaluation and assessments pertaining to water quality in BMPs components and constructed wetland were based on the 1st ed. of MSMA, which has been around since 2000. In 2012, the second edition of MSMA was introduced with various improvements in regard to design, monitoring, etc. Being quite new, only a few assessments and studies have been conducted to evaluate the performance of such facilities, including the constructed wetland. In other words, effectiveness of such a guideline to the constructed wetland — in matters relating to its design criteria to water quality improvement — is yet to be ascertained.

Most studies of constructed wetland under MSMA guideline have focused on its design to achieve high pollutant removal efficiency; without considering other important aspects such as biodiversity. As such, it is believed that previous studies are lacking in both information and understanding of biodiversity performance (either focusing on a single taxonomic group or more) and how it influences and affects the treatment performance. The use of freshwater phytoplankton as a biological indicator of water in the constructed wetland is a rarity. Thus, by using phytoplankton as an indicator to co-relate with the water quality performance and biological assessment for a single taxonomic group, this research will become a representative of biodiversity evaluation and a starting point for future higher trophic level monitoring such as invertebrates, fish and birds.

Due to limited information, designing a constructed wetland is quite challenging while knowledge to enhance biodiversity aside from improving water quality has yet to be expanded. Thus, this research seeks to understand the factors affecting biodiversity by starting with the primary producer in the food chain, i.e. the phytoplankton. The research will evaluate freshwater phytoplankton distribution in a particular constructed wetland and correlate such distribution with water quality as an environmental factor. This correlation is important for the initial suggestion to improve constructed wetland design, by including the element of biodiversity.

1.3 Objective of the Study

The specific objectives of this study are as follows:

a) To evaluate the water quality status and performance in the constructed wetland

b) To identify the freshwater phytoplankton community structure through identification, abundance and species diversity index.

c) To determine the correlation between water quality and freshwater phytoplankton distribution through statistical analysis in the constructed wetland

1.4 Potential and Significance of this Study

Although the guideline and design of the constructed wetland in MSMA has been around since 2001 (1st ed.) — and later revised in 2012 (2nd ed.) — there is still limited understanding and data to evaluate the impact of biodiversity in this man-made or artificial wetland. By initiating a study of phytoplankton in a constructed wetland, this research will hopefully bring a significant change to the design concept, by underlining the importance of biodiversity.

This research also has the potential to become a baseline study for future guidelines and design of a sustainable and ecological friendly constructed wetland in

Malaysia. So far, there is an absence of data to prove that a constructed wetland is able to support wildlife species as well as provide them with new habitat. By starting with phytoplankton, this research will take the first step to understand the food chain in this man-made ecosystem, and perhaps suggest improvements to future design.

Furthermore, the outcome of this research can potentially determine whether a constructed wetland is able to solve environmental issues such as eutrophication and habitat loss. So far, there has been limited data in this tropical region on how constructed wetland can improve habitat aside from naturally controlling phytoplankton abundance, which can then overcome the problem of eutrophication.

1.5 Scope of the Study

The scope of this research is mainly concentrated on water quality and phytoplankton study. The details are as follows:

a) Sampling shall be conducted once a month and shall not be subjected to rainfall event. A one-year sampling period starting from November 2014 until November 2015 shall be used as a trend as it reflects both wet and dry periods in the constructed wetland.
b) The research shall only study the surface layer of the water (0.1 meter from the surface) in each zone of the constructed wetland. The bottom layer of water analysis and benthic species of phytoplankton identification shall be excluded.
c) A detailed study of macrophytes plants (which also represent biodiversity) or any other trophic level such as zooplankton, invertebrates, fish or birds shall

also be excluded. The density and types of macrophytes in the constructed wetland shall be controlled into certain plant per area.

d) Secondary data of rainfall shall only be used to determine the dry and wet seasons during the research period. Water quality volume (WQV) and rainfall trends shall not be presented in this research.

e) The water quality index (WQI) parameters shall be used as the primary means of water analysis in the constructed wetland. Other nutrient parameters including orthophosphate, nitrate and so on, are meant to support water quality or phytoplankton distribution data.

f) Several water quality parameter such as chlorophyll-a, Secchi disk and light intensity were not being measured in this study. The reason of not taking this parameters as the main objective of this research was to find the correlation of water quality to the phytoplankton abundance. The understanding on how the constructed wetland treat the water quality from the 2nd ed. MSMA design will help to understand the distribution of phytoplankton in order to improve the design guideline in future.

1.6 Thesis Outline

This thesis shall comprise five (5) main chapters; namely Chapter 1: Introduction, Chapter 2: Literature review, Chapter 3: Methodology, Chapter 4: Result and Discussion, and Chapter 5: Conclusion and Summary. Chapter One provides a brief introduction to the recent issues pertaining to stormwater runoff, basically to provide an understanding of water quality degradation and habitat loss and how the constructed wetland, as a one of the alternative solutions, can tackle these issues.

Chapter Two shall describe in detail the constructed wetland, its functions and feasibility in various regions including in Malaysia. The MSMA guideline will be introduced in this chapter, aside from previous studies on constructed wetland. Further, a review on the use of phytoplankton as a bioindicator as well as biodiversity assessment in the freshwater ecosystem including wetlands shall be included. Chapter Three, on the other hand, shall explain the methodology used including the three main stages; namely Site Preparation, Sampling, Data Collection and Analysis and also Data Interpretation. Description of the laboratory test on water quality and phytoplankton will also be included. Suggested analysis shall also be provided such as water quality index (WQI) and species diversity index. Chapter Four shall present the overall results of water quality analysis, by sampling point and by month, including the identification and enumeration of phytoplankton. Both data shall be correlated using appropriate statistical analysis to find the main parameters influencing the phytoplankton distribution. Finally, Chapter Five shall present a summary of the research findings and provide suitable recommendations on how to improve the design as well as future studies of constructed wetlands.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter shall seek to provide an in-depth understanding of the fundamental characteristics and functions of the natural wetland; in order to establish the significant link between the constructed wetland and biodiversity components. The constructed wetland is among the man-made systems that directly adopt the role of a natural wetland in the earth's ecosystem. The focus of this chapter will later be narrowed down on how previous and present research has been carried out, apart from the actions taken and progress made by Malaysia in preparing a guideline with respect to the country's constructed wetlands.

In addition, this chapter shall provide a review of the overall developments made in research and the current understanding of biodiversity components in a constructed wetland, before solely centering on phytoplankton as the main area of interest. The role of phytoplankton and current research pertaining to both the natural wetland and constructed wetland shall also be reviewed and presented in this chapter. The significance of phytoplankton in various studies of constructed wetland shall also be elaborated to further underline why this research has to be carried out in Malaysia; as there is still a lack of information and documented finding regarding this area of interest.

2.2 Natural Wetlands

The definitions of natural wetland as well as its role shall be dealt with in this section. The aim of this section to exposed as well as to understand the fundamental concept of wetland based on the natural system.

2.2.1 Definitions of natural wetlands

The definitions of a wetland can be obtained from various sources of reference including Kadlec and Knight (1996) and CWA, 1972. According to the Convention on Wetlands (Ramsar, 1971; RCS, 2013), the definitions of a wetland as elucidated in Articles 1.1 and 2.1, are as follows:

Article 1.1:

"For the purpose of this Convention, wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters."

Article 2.1, in addition, provides that wetlands:

"may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six meters at low tide lying within the wetlands".

From these definitions, it can be understood that a wetland constitutes an area where soil is saturated with water or with standing water and dominated by plant species adapted to growing in seasonally or continuously flooded soil, where the condition is anaerobic or has low oxygen. This makes the wetland identified as among the most complex ecosystems on the planet. The wetland possesses highly diverse, productive and great ecosystem value compared with other ecosystems such as terrestrial (Dodds et al., 2008). Further, Mitsch and Gosselink (2015) also described the wetland as *kidneys of the landscape* due to its function as the downstream receivers of water and waste from both natural and man-made sources. In addition, the wetland is sometimes regarded as *nature's supermarkets* due to the extensive food chain and rich biodiversity that it can support.

2.2.2 Wetland zonation and size

The wetland ecosystem such as lake, is an important habitat for a diverse range of plant and animal species. The zones in the wetland ecosystem such as littoral zone, limenetic zone and profundal zone (in the benthic zone) determine the structure of physico-chemical and biodiversity (Figure 2.1). Each zone plays an important role to affect the life cycle of every species, by serving as breeding grounds and nurseries. The zones have different characteristics, thus they support certain species which are favourable to their condition (Cole and Weihe, 2015). Table 2.1 explains the characteristics of each zone in the lake ecosystem, which will later be used as reference to design the constructed wetland. The understanding of this zonation will beneficially help the designer to construct a man-made wetland. At the Putrajaya wetland in Malaysia (Figure 2.2), this lake zonation acted as a reference to create a zonation in the constructed wetland including deep marsh, shallow fringing marsh etc., to help in identifying the plants in constructed wetland, whereby the physical, chemical and biological characteristics in the lake zone were taken into consideration (Lim et al.,1998).

Table 2.1: The characteristics of lake zone (Cole and Weihe, 2015)

Zone	Characteristic
Littoral	The peripheral shallow in which the area occur fluctuate in temperature and erosion through wave action. Due to that, the bottom sediment are normally found in coarse sediment. The area was well lighted and inhabited by a rooted aquatic plants.
Sublittoral	Extend lakeward from the littoral. The sediment is finer grained. Although dimly lighted and lacking a benthic microflora, it is usually well oxygenated. The area contains fewer fauna species than the littoral assemblage; this is a result of e reduced number of niches.
Profundal	Deep enough to exhibit the temperature stratification. The cold reagion is form where current are at a minimum and where light is muched reduced. Under same condition, oxygen is scarce or depleted, although the methane gas and CO_2 are abundant. The hidrogen ion is high (low pH) because of the presence of carbonic acid
Limnetic (open water)	The region where shore and bottom are lessened influence. Habitat of plankton, an assemblage of tiny free-floating, drifting, or swimming plants (phytoplankton) and animals (zooplankton) representing many taxa.

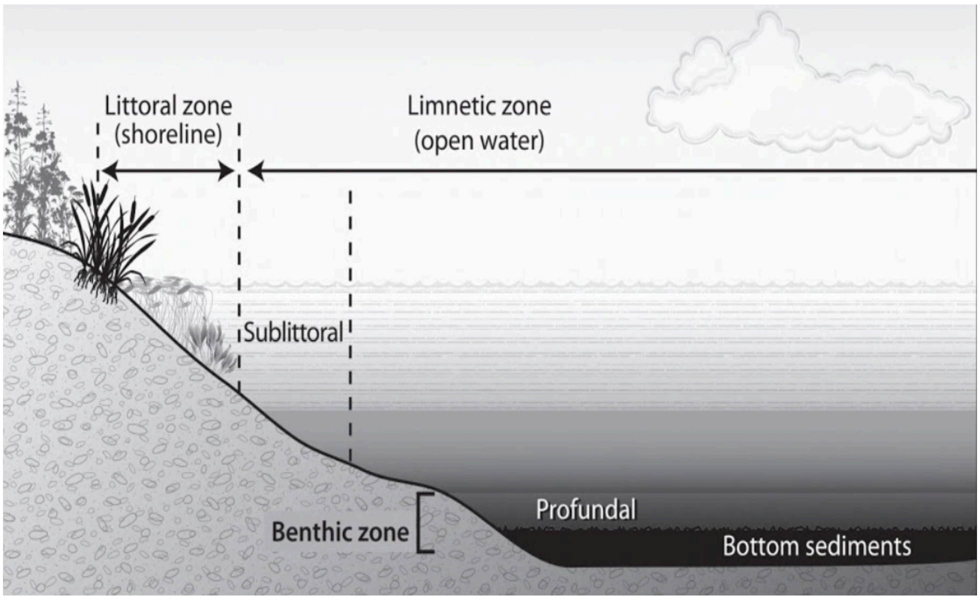

Figure 2.1: Lake zone in wetland ecosystem (Cole and Weihe, 2015)

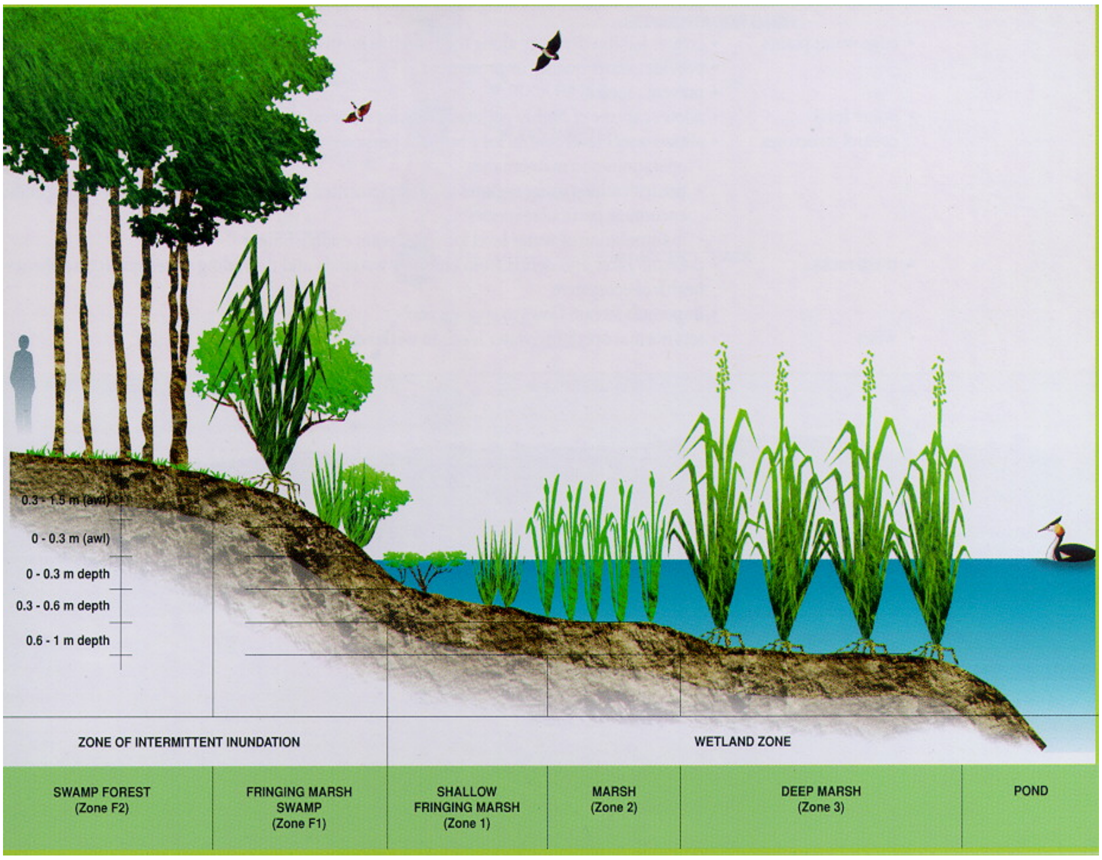

Figure 2.2: The Putrajaya constructed wetland zonation (Lim et al., 1998)

The wetland size has been used as one of the primary criteria for assigning protected status to wetlands as it is related to the hydroperiod and significantly has strong correlation with species richness for certain species such as amphibians (Babbitt 2005). Babbit (2005) demonstrated that the wetland size differed significantly among hydroperiod categories, with wetlands with short hydroperiods being significantly smaller than wetlands with intermediate and long hydroperiods, and wetlands with intermediate hydroperiods were smaller than wetlands with long hydroperiods (Figure 2.3).

This strong correlation between wetland size and hydoperiod also significantly affected the species richness (Figure 2.4-for this case, amphibian species). Thus, the understanding of the wetland size became an important reference in the design of the constructed wetland as it not only impact the retention time, but also the species distribution.

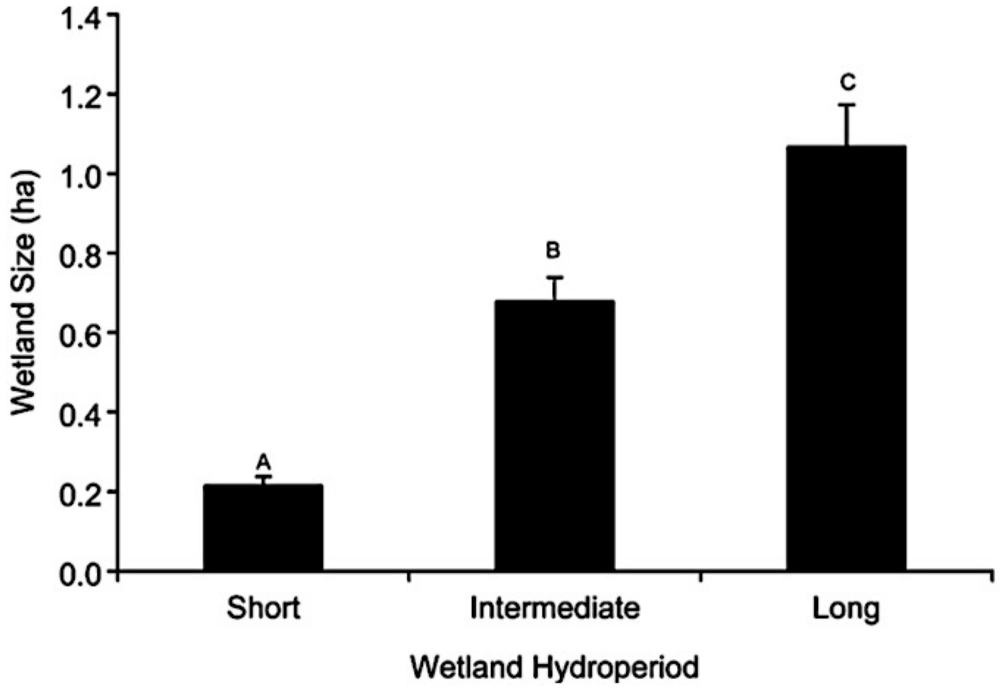

Figure 2.3: Comparison of wetland size for wetlands with short (inundated <4 months), intermediate (inundated >4 months, nonpermanent), and long (permanent) hydroperiods (Babbit, 2005)

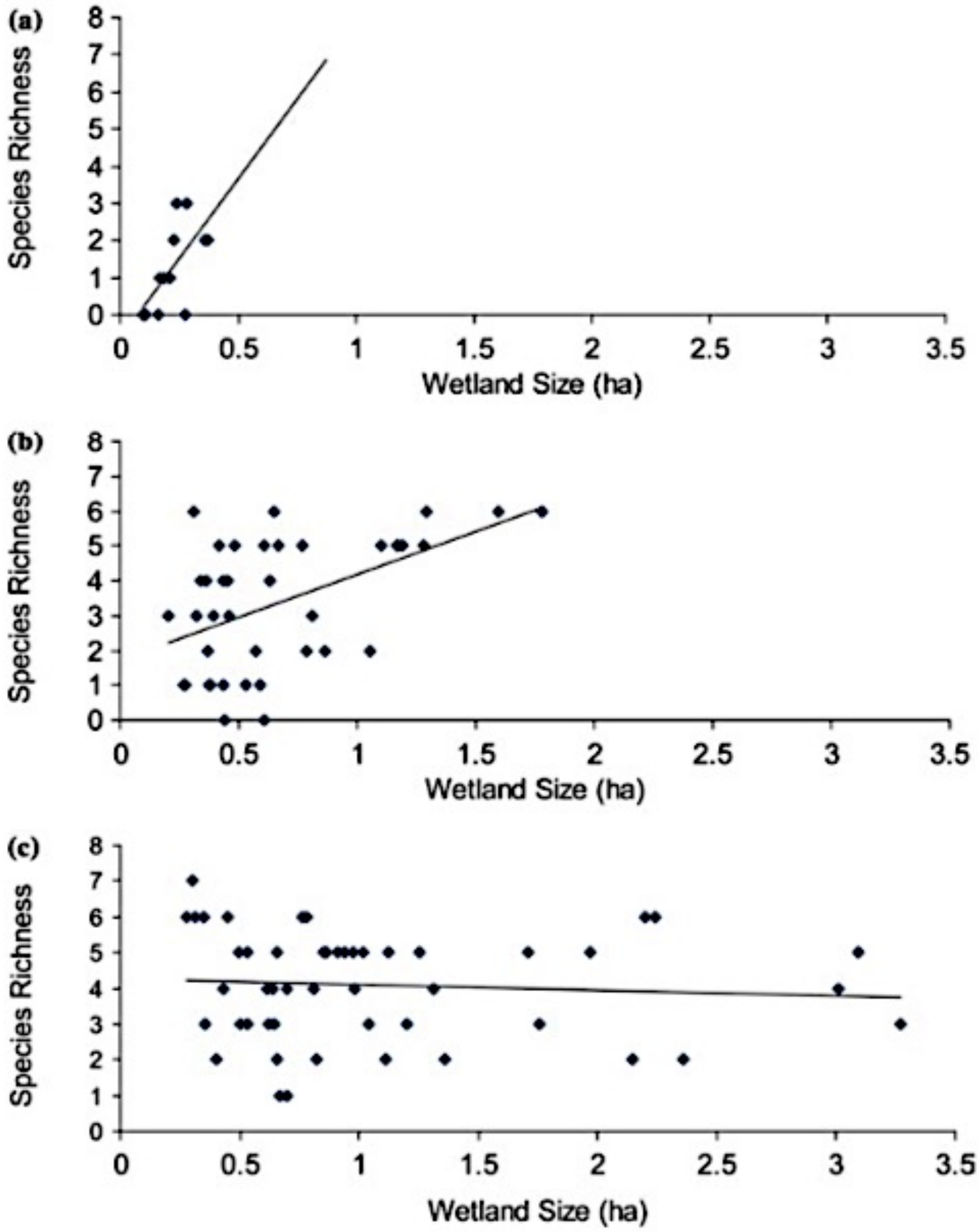

Figure 2.4: Relationship between wetland size and species richness (for this case reference, the author used amphibian species) in (a) wetlands with short (inundated <4 months); (b) intermediate (inundated >4 months); and (c) long hydroperiods (Babbitt, 2005)

2.2.3 The role of natural wetlands

Aside from acting as a habitat for wildlife, the wetland also takes on several important functions such as to mitigate flood, to regulate water quality by reducing nitrogen and phosphorus concentration, to reduce sediment composition and to produce a balanced rate of organic matter with other ecosystems. Table 2.2 below summarizes some of the wetland's natural functions based on past studies conducted around the world. All these functions prove that the wetland not only serves and brings benefits to human beings, but is also significant to wildlife and plants as well. Such natural advantages and characteristics have become a key reference and guide for engineers to mimic and create the artificial man-made wetland, which is also known as the constructed wetland.

Foremost, the engineer has to understand how the natural wetland adapts to several factors such as the climate condition in a certain area, before any treatment can be designed and applied to the constructed wetland. As environment and climate conditions differ between every region (from the tropical to the temperate regions), the same applies to the wetland. The difference between tropical and temperate environment will alter the wetland's functions and affect the wetland's capability to treat wastewater (Tanaka et al*.,* 2011). For example, Pearce and Smith (2000) stated that the ambient temperature in temperate climate region did not change at any time as substantially as it would. This will definitely have an impact on plant growth and also wastewater treatment performance.

Table 2.2: Examples of the natural wetland functions

Functions	References
Support a rich food web	Mitsch and Gosselink (2007, 2015)
Necessary for animal life-cycles (breeding, egg deposition).	Dodd Jr. and Cade (1998) Connor and Gabor (2006)
Biogeochemical cycling involves biologic, physical and chemical transformation of various nutrients within the biota, soils, water and air.	Masscheleyn and Patrick Jr (1993). Reddy & DeLaune (2008)
Atmospheric maintenance, which stores carbon within their live and preserves (peat) plant biomass instead of releasing it to the atmosphere as carbon dioxide, a greenhouse gas.	Whiting and Chanton (2001) Kayranli et al., (2010)
Hydrologic cycle	Bullock and Acreman (2003) Erwin (2009)
Habitat for fish, wildlife and plants	Semlitsch and Bodie (2003) Zimmer et al., (2006)
Improving water quality and hydrology	Whigham et al., (1988) Dhote and Dixit (2009)
Flood protection	Hey and Philippi (1995) Wamsleya et al., (2010)
Protect shoreline and stream banks against erosion	Castelle et al., (1994) Gedan et al., (2011)
Economic benefits of wetland resources	Barbier (1993) Pattison et al. (2011)
Recreation, education and research	Gren et al., (1994) Wang et al., (2012)

In the tropical climate region, the design criteria should take into account the warm temperature and climate conditions before the system can be operated. Such is the key challenge to an engineer. The engineer must also realize that all the functions performed by the natural wetland cannot be simply applied to the constructed wetland. Appropriate selection of functions of the natural wetland to the constructed wetland depends on various factors including land area, catchment, types of native plants and climate. Thus, it is important to gain a prior understanding of the purpose and objective to build a constructed wetland so that its functions (which are based on the natural wetland) can be optimized and be fully put in place.

2.3 Constructed wetlands

Constructed wetlands are part of an engineered system designed to simulate the water quality improvement function of natural wetlands, i.e., to treat and contain surface runoff pollutants and decrease loading to surface water. According to Vymazal (2007), the constructed wetlands are also designed to utilize the natural processes involving wetland vegetation, soils, and their associated microbial assemblages to assist in treating pollutants and wastewater. The types and functions of constructed wetlands as well as Free Water Surface (FWS) constructed wetland shall be discussed further in the following paragraphs. Constructed wetlands are considered to be a low-cost system for treating wastewater discharged from municipal, agricultural, and industrial sources. A schematic process flow for a constructed wetland system is shown in Figure 2.5 below.

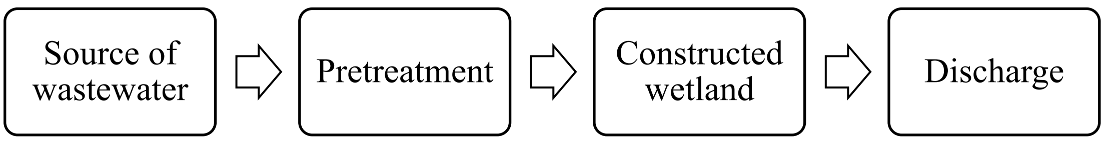

Figure 2.5: A schematic process flow of a constructed wetland system (Azni et al., 2014)

2.3.1 Types and functions of constructed wetland

For the past thirty years, constructed wetlands have been used to treat acidic rain water, factory waste water, water runoff from agricultural areas and waste water from residential areas. Aside from water treatment, the constructed wetlands also boast some unique features because they can tolerate high organic sediments and have low hydraulic retention time (Lim, 2002). All these capabilities originate from simultaneous processes in the system. Greenway (2003) described the process in water quality improvement which constituted 3 different categories, namely physical, biological and chemical. Most of the process is facilitated by wetland vegetation and microbial communities. The specific mechanisms to treat specific pollutants such as sedimentation, plant and microorganism uptake, microbial remediation and natural UV disinfection in the constructed wetland are presented in Table 2.3 The main pollutants include gross sediment, suspended solid, biodegradable particulates, nutrients, metals, hydrocarbon and pathogen.

All these treatment mechanisms involve various biotic (biological) and abiotic (physical and chemical) processes (Kadlec and Knight, l996; Reddy and Angelo, 1997). The biological processes for the removal of pollutants involve microbial metabolic activity, and plants absorption while for physicochemical processes, they involve sedimentation, diffusion and deposition (Reddy and DeBusk, 1987). As a result, the constructed wetland emerges as a tool system that effectively reduces pollutants from surface runoff before it enters rivers, lakes and other water bodies. The mechanism process in the constructed wetland includes (i) the attachment of pollutants with sediment or any biota of wetland components, (ii) degradation, (iii) emission into the atmosphere and (iv) through ground water (Howard-Williams, 1985; Baker, 1992).

Table 2.3: Removal mechanism in constructed wetlands system (Greenway, 2003)

Pollutant	Mechanism process
Gross Sediment	Sedimentation in inlet pond or trapped by dense vegetation
Suspended Solids including biodegradable particulates (BOD)	Sedimentation is facilitated by the vegetation. The vegetation reduces water velocity and turbulence causing settlement. Finer particles adhere to the biofilm surface of the vegetation. The root system binds and stabilizes deposited particulates. The leaf litter and vegetation reduces re-suspension.
Nutrients	Direct uptake by plants and micro-organisms. Inorganic nutrients converted to organic biomass. Microbial processes facilitate the removal and transformation of nutrients, especially nitrogen removal.
Metals	Microbial bioremediation of metals. Metals immobilized by adsorption onto sediments or by precipitation plant uptake.
Hydrocarbons	Microbial hydrocarbon degradation.
Pathogens	Natural UV disinfection. Natural biocontrol by microbial predators in the wetland ecosystem. Adsorption to fine particles and sedimentation. Natural death and decay.

Thus, to make this treatment and mechanism process effective, appropriate design and type of constructed wetland is a must. Vymazal (2001) introduced the basic classification of constructed wetland based on the type of macrophytes growth, and later provided further classification based on the water flow regime (Figure 2.6). The outline design and differentiation of each type of constructed wetlands are shown in the Figure 2.7 below.

The free-floating plants (FFP) constructed wetland involves only floating types of plant as the main macrophytes in the system. On the other hand, the free water surface constructed wetlands with emergent plants (FWS) is the most common type of constructed wetland to treat various wastewater, including stormwater wastewater runoff due to its low cost and easy operation. For the subsurface flow, two types namely the horizontal subsurface flow (HSF) and the vertical flow (VF) have been identified according to the flow direction, level and duration of saturation of the substrate (Economopoulou and Tsihrintzis, 2003; Tsihrintzis, 2017). The HSF is slightly dissimilar to the FWS in the outlet flow, which is located at the substrate level of the system (Figure 2.8). The VF has vertical downflow, whereby the substrate material is the main wastewater treatment component of the system (Figure 2.9).

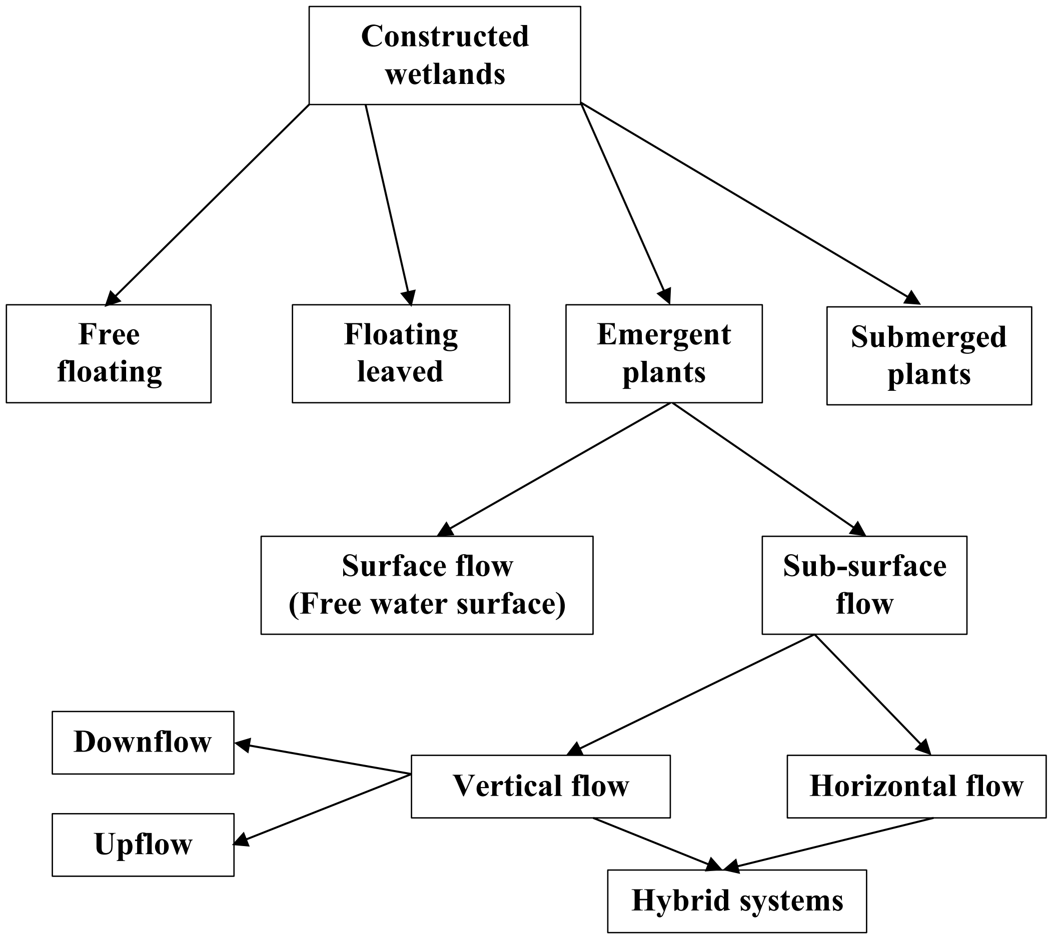

Figure 2.6: Classifications of constructed wetland (Vymazal, 2001)

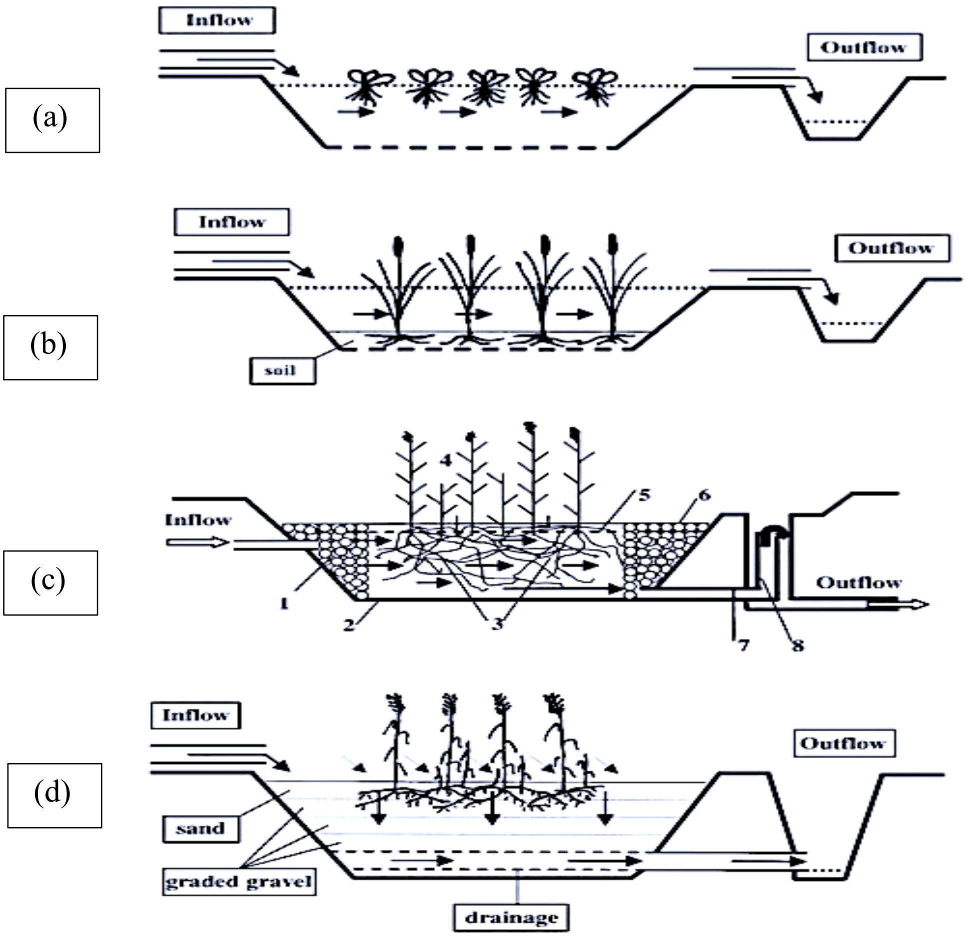

Figure 2.7: Design types of constructed wetland based on the flow and plants: (a) free-floating plants (FFP), (b) free water surface and emergent macrophytes (FWS), (c) horizontal sub-surface flow (HSF, HF) and (d) vertical sub-surface flow (VSF, VF) (Vymazal, 2001)

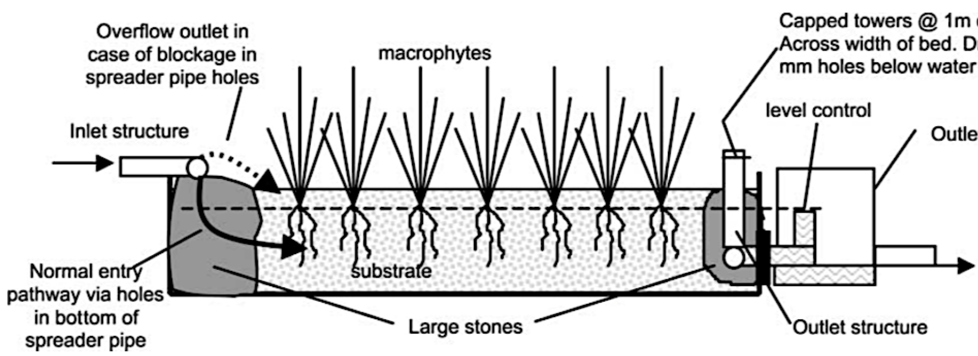

Figure 2.8: Typical design of horizontal subsurface flow (HSF) constructed wetland (Davison et al., 2005)