

MODELING PHOSPHORUS REMOVAL IN A CONSTRUCTED WETLAND

**Case Study of the Department of Water Affairs Constructed
Wetland Gaborone, Botswana**

Baboloki Autlwetse

**Master (IWRM) Dissertation
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Wetland Gaborone, Botswana**

**By
Baboloki Autlwetse**

**A Dissertation Submitted in (Partial) Fulfillment of the Requirements for the
Degree of Master in Integrated Water Resources Management (MIWRM) of
the University of Dar es Salaam**

**University of Dar es Salaam
October, 2008**

CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance by the University of Dar es Salaam the dissertation: *Modeling Phosphorus Removal in a Constructed Wetland: Case study of the Department of Water Affairs Constructed Wetland, Botswana*, in fulfillment of the requirements for the degree of Master in Integrated Water Resources Management of the University of Dar es Salaam.

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AND
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I, **Baboloki Autlwetse**, declare that this dissertation is my own original work and that it has not been presented and will not be presented to any other university for similar or any other degree award.

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Lastly I want to say thank you Jehovah, the Lord my provider for your strength and unfailing love towards me. I bless your holy name.

DEDICATION

To my mum
My brothers and sisters

ABSTRACT

This research work is carried out so as to assess the performance of constructed wetland piloted within the Department of Water Affairs, Gaborone, Botswana. The treated effluent is reused for irrigation and people are concerned about the quality of effluent used. The wetland has four cells and each cell has flow rate of 4m³/day and hydraulic retention time of approximately 5 days. The first cell (C1) is set as a control with sand only, the second one (C2) planted with *Typha Latifolia*, the third one (C3) with *Papyrus* *Cyperus* and the last one (C4) with *Phragmites Mauritianus*.

The samples obtained in this pilot system for phosphorus analysis were filtered through a whatman 0.45µm filter paper and analyzed using the IC machine. The data from C1, C2, C3, and C4 showed average effluent phosphorus (PO₄⁻³) concentration of 0.63mg/l, 0.26mg/l, 0.19mg/l and 0.16mg/l of which when translated to percentage removal cells have 93.6%, 97.4%, 98.1% and 98.4% respectively. From the effluents it can be noted that C4 is the best macrophyte to be used in treating wastewater. DWA constructed wetland is in compliance with the Botswana Bureau of Standards (BOBS) BOS 93:2004 which allows 0.5mg/l of phosphorus concentration in the effluent that is to be discharged into the environment.

A model was developed using the Stella 6.0.1 software and it shows that sand adsorption is the main process involved in phosphorus removal, then plants uptake. The model proved to model the processes in the wetland and this was indicated by a good correlation factor of $R^2 = 0.55, 0.74, 0.68$ and 0.72 for C1, C2, C3 and C4 respectively.

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LIST OF ABBREVIATIONS

BOBS	-	Botswana Bureau of Standards
BOD	-	Biochemical Oxygen Demand
COD	-	Chemical Oxygen Demand
CW	-	Constructed Wetland
DO	-	Dissolved Oxygen
DWA	-	Department of Water Affairs
HSSFS	-	Horizontal Subsurface Flow System
P	-	Phosphorus

CHAPTER ONE

INTRODUCTION

1.1 General Introduction

Wastewater management in general has recently been taken on board so as to prevent pollution of water resources. Currently the wastewater technologies used can be categorized in to on-site and off-site facilities. The on-site facilities are used in households where there are no water connections and for off-site facilities it's for the households connected with water. Now due to human development, there are now more water connected households throughout the world and this has led to the construction of large scale off-site technologies (conventional and biological systems) that are used to treat wastewater at a larger scale from diverse places.

Constructed wetland (CW) is one of the systems that can be used for such treatment of wastewater. They have been several studies carried out on CWs in order to see their performance in treating wastewater. Different components of treatment mechanisms taking place in the CW have been studied, such as but not limited to carbon, nitrogen and phosphorus, dissolved oxygen, BOD, COD, total suspended solids dynamics in the system (van der Peijl and Verhoen, 1999).

In Botswana, few of the constructed wetlands have been introduced since they are believed to be low cost technologies. They are built to treat wastewater at institutional

levels, whereas biological systems mainly oxidation ponds and conventional treatment (trickling filter and activated sludge) are used to treat wastewater for villages and towns respectively. It is therefore important that once a treatment facility is constructed; its performance is monitored so as to avoid any pollution that can be caused due to under performance of such a system.

Wastewater Management in Botswana is carried out by the Ministry of Local Government and the ministry deals with policy administration; whereas the Local Authorities are responsible for operation and maintenance of off-site facilities around the country.

The Department of Water Affairs (DWA) is responsible for issuing discharge permits and monitoring compliance to the same. DWA in their endeavor to demonstrate to small scale wastewater generators that they can use low cost technologies to treat their wastewater and comply with the required discharge standards they piloted a constructed wetland within their yard.

This pilot project is the one in which the topic of this research shall be based.

1.1.1 Weather of Botswana

Botswana's climate is semi-arid. Though it is hot and dry for much of the year, there is a rainy season, which runs through the summer months. Rainfall tends to be erratic, unpredictable and highly regional. Showers are often followed by strong sunshine so

that a good deal of the rainfall does not penetrate the ground but is lost to evaporation and transpiration.

The summer season begins in November and ends in March. It usually brings very high temperatures. However, summer is also the rainy season, and cloud coverage and rain can cool things down considerably, although only usually for a short period of time. The winter season begins in May and ends in August. This is also the dry season when virtually no rainfall occurs. Winter days are invariably sunny and cool to warm; however, evening and night temperatures can drop below freezing point in some areas, especially in the south-west. The in-between periods - April/early May and September/October - still tend to be dry, but the days are cooler than in summer and the nights are warmer than in winter (www.sa-venues.com/weather/botswana.htm).

The rainy season is in the summer, with October and April being transitional months. January and February are generally regarded as the peak months. The mean annual rainfall varies from a maximum of over 650mm in the extreme north-east area of the Chobe District to a minimum of less than 250mm in the extreme south-west part of Kgalagadi District. Almost all rainfall occurs during the summer months while the winter period accounts for less than 10 percent of the annual rainfall. Generally, rainfall decreases in amount and increases in variability the further west and south you go (www.sa-venues.com/weather/botswana.htm). The Department of Water Affairs

Constructed Wetland is in the South Eastern Part of Botswana; in Gaborone the capital city, see figure 1 for the location.

1.2 Problem Statement

DWA has piloted a constructed wetland to treat its wastewater in order to demonstrate how low cost technologies can be used to treat wastewater. All the wastewater from the DWA offices is collected into a septic tank and from there it flows into the constructed wetland for treatment.



Figure 1.1: Map of Botswana showing the location of Gaborone

Constructed wetlands have been used to treat raw sewage the world over and different components of it have been studied, now this study focuses on the removal of phosphorus simply because the larger component of the wastewater produced in DWA is from the restrooms, cleaning of the floors and washing machinery in mechanical workshops using chemicals which might contain phosphates that are eventually released into the environment and end up causing eutrophication. Since no research has been carried out on the performance of DWACW, adsorption efficiency of the river sand used in the DWA wetland and the best macrophyte that should be used in other new constructed wetlands in Botswana out of the three that are used in the pilot project, it is in this research that these information can be found and used to advise small wastewater generators accordingly.

This constructed wetland is a horizontal subsurface flow system (HSSF). The treated effluent due to the water demand management initiatives is recycled to irrigate the vegetable garden, the orchard and the lawns that are within the compound offices. This has raised some eye brows to some employees and customers of Water Affairs about the quality of the effluent especially when they are to buy the vegetables. It is in this regard that the project is carried out to study the removal of phosphorus in the system looking at the sand adsorption efficiency and the type of macrophyte used.

1.3 Objectives of Study

The main objective of the research is to study the performance of constructed wetland in the removal of phosphorus (as PO_4) in DWA looking at the river sand adsorption and the type of macrophyte used under the prevailing weather conditions.

1.3.1 Specific objectives

- (a) To determine the performance of the DWA constructed wetland in removing phosphorus.
- (b) To determine how efficient is the river sand used in the constructed wetland in helping to remove phosphorus.
- (c) To determine which of the plants (macrophytes) is performing better in terms of treating wastewater.
- (d) To determine the controlling process, and model the process that is controlling the transformation (mathematical model-equation).

1.4 Significance of the Study

This study focuses on Phosphorus removal and the results are a baseline data since no research of this kind has been carried out in DWA constructed wetland under the prevailing weather conditions.

Phosphorus because it's one of the main elements which when not treated and it ends in water bodies it causes eutrophication. So when removed from the wastewater, eutrophication is reduced.

The study results in knowledge of which of the macrophytes used in the wetland best treats wastewater.

Since the treated effluent from the wetland is used to irrigate the lawns, orchard and vegetables, the study reveals if there is compliance of effluent for reuse.

Modeling the removal of phosphorus helps in designs of other constructed wetlands in the country by providing information for development of design guidelines and standards for constructed wetlands and also in their management.

1.5 Research Questions

- What is the performance status of DWA CW in terms of removing Phosphorus?
- Of the macrophytes used in the DWACW system, which one best remove P?
- What is the P adsorption capacity of the river sand used in the wetland?

How is the DWACW effluent quality as compared to the re use of treated effluent standards in agriculture?

CHAPTER TWO

LITERATURE REVIEW

2.1 Wetlands

Mitsch and Gosselink (1993) described wetlands as the “kidneys of the landscape.” Wetlands filter out pollutants and act as sinks for nutrients by purifying the water through physical (sedimentation, filtration), physical-chemical (adsorption on plants, soil, and organic substrates), and biochemical processes (biochemical degradation, nitrification, denitrification, decomposition, and plant uptake) (Novotny and Olem, 1994). Mitsch and Gosselink (1993) continues to say that a precise definition which satisfactorily describes all wetland types is not possible due to the varying types of wetland and however the U.S. Fish and Wildlife Service have advanced a comprehensive definition as quoted by Cowardin *et al*,(1979).

Wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water. Wetlands must have one or more of the following attributes: (1) at least periodically, the land supports predominately hydrophytes; (2) the substrate is predominately undrained hydric soils; or (3) the substrate is non soil (organic matter) with water or covered by shallow water at some time during the growing season each year (Cowardin *et al*, 1979).

2.2 Wetland Classifications

It has been noted in literature that there are various ways to classify wetlands and there is not yet a consistent method developed to describe wetlands. The easiest way to differentiate wetlands is to divide wetlands between natural and constructed types, but beyond this simplistic categorization, a clear cut classification scheme for wetlands does not exist. Mitsch and Gosselink, (1993), say that the confusion in terminology stems from the vast diversity of wetland types that exist throughout the world and the lack of direct equivalent translations between various languages. They continue to divide wetland types into two initial systems (coastal and inland) and then further subdivide these systems into seven separate categories that encompass most, but not all wetland types (Mitsch and Gosselink, 1993).

2.2.1 Natural Wetlands

As according to Widener, 1995, Natural wetlands originate in geological settings due to water movement and accumulation. The major geological settings in which wetlands form are areas of 1) slope discontinuity, 2) topographic depression, 3) stratigraphic features which inhibit infiltration, and 4) permafrost (Widener, 1995). On the other hand Baker, (1973) says wetlands that are formed in lowland areas tend to be underlain by glacial outwash, clay and silt, or alluvial outwash comprised of sand or a mixture of sand and gravel, while wetlands formed in upland areas tend to be underlain by bedrock and glacial till (Baker, 1973).

2.2.2 Constructed Wetlands (CW)

Constructed wetlands are man-made systems designed to imitate/mimic the functions of natural wetland systems. There are two fundamental types of constructed wetlands, the free water surface (FWS) system and the subsurface flow system (SSF) (Novotny and Olem, 1994). The FWS system usually consists of basins or channels with a natural or subsurface barrier of clay or impervious geotechnical “lining” to prevent seepage (U.S. EPA, 1988).

A SSF system consists of a trench or bed underlain with an impermeable layer of clay. The trench is back filled with media that usually consists of crushed stone, rock fill, gravel, and different soils. Water flows through the medium and is purified through filtration; absorption by microorganisms; and adsorption onto soils, organic matters, and plant roots (U.S. EPA, 1988).

Constructed and natural wetlands have been employed as alternative low cost biological treatment systems for municipal sewage and have been extensively studied over the past decades (Kadlec, 1987; Richardson & Davis, 1987). From this one can see that wetlands play a very important role in treating wastewater, hence protect the limited water resources from pollution.

It has been reported by the US Environmental Protection Agency that wetlands appear to perform, to at least some degree, all of the biochemical transformations of wastewater constituents that take place in conventional wastewater treatment systems,

in septic tanks and their drain fields, and in other forms of land treatment (US EPA, 1987). Wetlands remove pollutants from aquatic systems, through a complex variety of biological, physical and chemical processes. The nutrient uptake by higher plants and retention of heavy metals in roots are considered to be important processes as the higher plants are the most obvious biological components of wetland ecosystems (Orson *et al.*, 1992; Rai *et al.*, 1995).

Different types of constructed wetland can be distinguished based on water flow characteristics and plant species. Systems with above-ground flow are referred to as surface-flow CWs (SFCW), whereas the ones with belowground flow are subsurface-flow CWs (SSFCW). The SSF can further be divided into two categories due to the nature of water flow directions as vertical flow and horizontal flow.

In vertical SSF CWs the wastewater flows vertically through the root zones of the plants within the sand (substrate) and in horizontal SSF CWs the water flows horizontally through the root zones of the plants within the sand. In this SSF system the wastewater flows below the porous surface and is not exposed to the surface.

There are two fundamental types of constructed wetlands, the free water surface (FWS) system, and the subsurface flow system (SSF) (Novotny and Olem, 1994).

2.2.2.1 Free-Water Flow System

In the free-water flow system the flow of water is above the ground, and plants are rooted in the sediment layer at the base of water column. The FWS system usually

consists of basins or channels with a natural or subsurface barrier of clay or impervious geotechnical “lining” to prevent seepage (U.S. EPA, 1988). The basins are then filled with soils to support the accompanying planted vegetation (Figure 2.1).

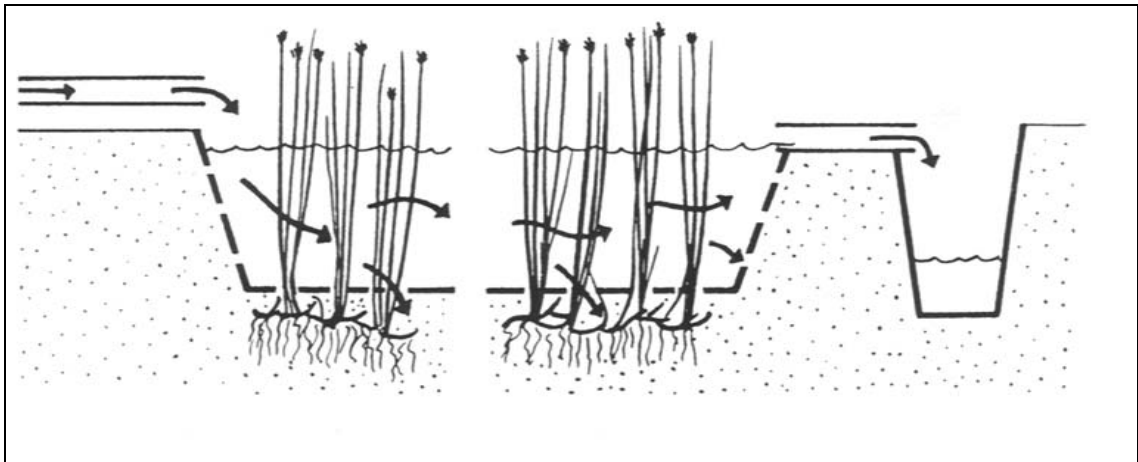


Figure 2.1: Free Water Flow Macrophytes

Source: Brix, (1993)

2.2.2.2 Emergent Macrophytes System/ Subsurface Flow system

In the emergent macrophytes system the plants are attached to the media for their growth see figure 2.2. In this system this is where the two categories of vertical and horizontal flow can be identified. The treatment efficiency in respect of nutrients removal is relatively higher in the subsurface flow system types as compared to free water flow systems.

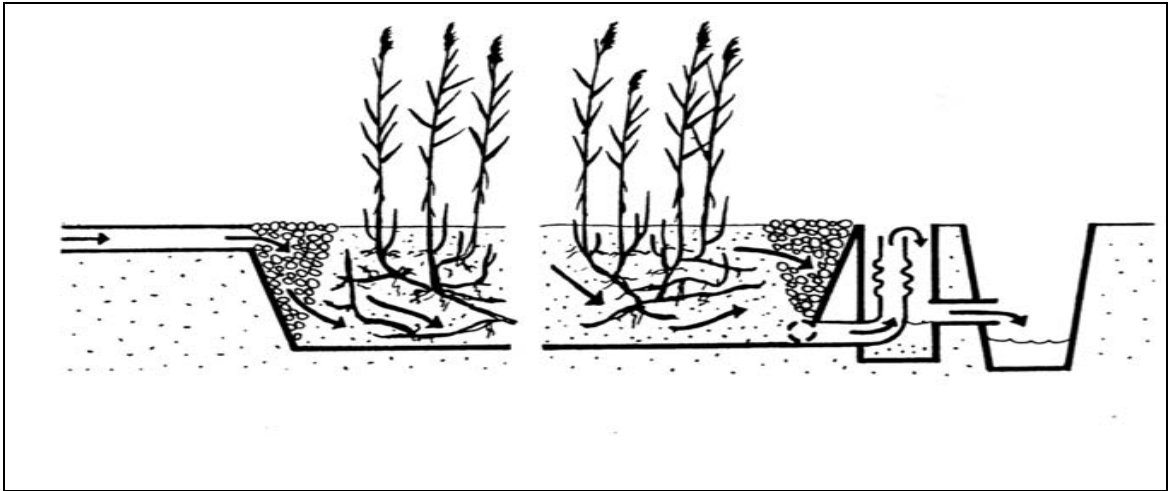


Figure 2.2: Subsurface Flow Emergent Macrophytes

Source: Brix, (1993)

Subsurface constructed wetland types have gained popularity as according to Reed *et al.*, (1995) as compared to surface ones because of the perception of decreased risk of nuisance from flies, mosquitoes and odor. Also it's due to greater efficiency in terms of land use. The major disadvantage in vertical flow systems is clogging of the substratum medium.

2.3 Performance of CW

Gearheart *et al* (1989), quoted by Nzengy'a *et al* (1999) in the Journal of Hydrological Processes, found that from a four-year pilot project on the performance of a free surface freshwater constructed wetland treating and receiving wastewater from the city of Arcata, California, that suspended solids and BOD₅ were effectively removed to less than 10 mg/l as the secondary treated wastewater flowed through the system. Seasonal variation in the performance of the wetland was not detected. Also as found by Cooper

and Findlater (1990), the performance of constructed wetlands undoubtedly compares favorably and even better in some instances to that of conventional wastewater treatment systems. These facts can help to fully support the use of constructed wetlands in treating wastewater since the system is low cost and easy to operate with appealing results.

Watson *et al.*, 1989, attributes the treatment of wastewater in the wetlands to different processes such as sedimentation, filtration, chemical precipitation, adsorption, microbial interaction and uptake by vegetation in the wetland. These processes take place within the CW system hence the need to look at components of the CW and see how they treat the wastewater.

2.4 Macrophytes

There are two broad categories of wetland vegetation. The submerged and emergent macrophytes. The Aquatic macrophytes are plants that live either completely submerged or floating or have some small portion of the plant emerging from the water. They may be attached (for example *Potamogeton* - Pondweed) or unattached to the sediment (for example *Lemna* -Duckweed) whereas Emergent macrophytes are wetland plants which are always rooted in the sediment and whose growth habit results in the plant protruding above the water surface e.g. *Baumea articulata* (Jointed twig rush) and *Typha orientalis* (Bulrush) (www.portal.environment.wa.gov.au).

In a study conducted in Kenya, effluent from the Carnivore and Splash restaurants' septic tanks flows through the trenches filled with graded granular gravel medium. Dense stands of hydrophytic plants such as *Typha* sp., *Papyrus* sp and *Phragmites* sp., established in a thin layer of soil covering the medium, root down into the wastewater and feed on the nutrients. Bacteria colonizing all the surfaces of the medium actively and efficiently breakdown pollutants in the effluent as it flow through. Effluent waters then flow across bottom sediments between stems of emergent macrophytes and through roots of floating aquatic plants in the respective wetland cells. (Journal of Hydrological Processes). From what is discussed in the journal it can be seen that macrophytes that are used in constructed wetlands play a very important role of treating wastewater as they absorb the nutrients in the water. This means that different macrophytes can have different absorption rate there by meaning that those which need more nutrients will be best suitable for use since they will absorb more.

2.5 Substratum Media

Phosphorus exists in the soil largely as P adsorbed on iron and aluminum oxides or in association with calcium. This P is in equilibrium with P in solution. Phosphorus also occurs in organic forms and may be released by microbial activity. Soil pH and the presence of CaCO_3 (lime) in the soil have a major influence on this adsorption relationship.

2.6 Phosphorus

Like nitrogen, phosphorus, P, is an essential nutrient that contributes to the growth of algae and the eutrophication of lakes. Its presence in drinking water has little effect on health. Phosphorus can enter water body from sewage or from agricultural runoff containing fertilizers and animal wastes. Phosphate, PO_4^{3-} , the inorganic form of phosphorus, has been commonly used in detergents in the past, but even with the ban on phosphate-based detergents, the amount of phosphorus occurring in water from other sources poses a significant environmental problem hence the need to find ways of removing it to avoid water pollution (eutrophication).

Phosphorus may enter a water body through the inflows, precipitation, and dry fallout and from the sediments, and it may be removed by sedimentation and through the outflow. A certain reduction of phosphorus input will generally result in a greater reduction in algal biomass compared with the same reduction of nitrogen (<http://lakes.chebucto.org/>). From the statement it can be seen that if wastewater treatment concentrates mostly on phosphorus removal then they will be less algal boom in the lakes since reduction in P results in greater reduction of algal boom. If nitrogen input is reduced without a proportional reduction in phosphorus, this creates low N/P ratio which favors nitrogen fixing nuisance algae, hence no reduction in algal biomass.

2.6.1 Forms of Phosphorus

Forms of total Phosphorus (TP) in water are determined by analytical methods based around: whether the P is in a dissolved or particulate form or whether or not the P is

Molybdate (Mo) reactive, according to the Mo blue reaction (Murphy and Riley, 1962). On the other hand, according to Sheila Murphy, 2007, in the website, she says that phosphorus in natural waters is usually found in the form of phosphates (PO_4^{-3}). Phosphates can be in inorganic form (including orthophosphates and polyphosphates), or organic form (organically-bound phosphates) (<http://bcn.boulder.co.us/>).

2.6.1.1 Organic Phosphate

This is the phosphate that is bound to plant or animal tissue and is formed primarily by biological processes. They contribute to sewage through body waste and food residues, and also may be formed from orthophosphates in biological treatment processes or by receiving water biota. Organic phosphates may occur as a result of the breakdown of organic pesticides which contain phosphates and they may exist in solution, as loose fragments, or in the bodies of aquatic organisms (<http://bcn.boulder.co.us/>).

2.6.1.2 Inorganic Phosphate

Inorganic phosphate is phosphate that is not associated with organic material. Types of inorganic phosphate include orthophosphate and polyphosphates. According to Sheila Murphy, 2007, Orthophosphate is sometimes referred to as "reactive phosphorus" and it's the most stable kind of phosphate, the form used by plants. Orthophosphate is produced by natural processes and is found in sewage. Polyphosphates (also known as metaphosphates or condensed phosphates) are strong complexing agents for some metal

ions. Polyphosphates are used for treating boiler waters and in detergents. In water, polyphosphates are unstable and will eventually convert to orthophosphate.

Total phosphorus (TP) is a measure of phosphorus in all its forms. Specifically, it is orthophosphate plus the phosphorus that is convertible to orthophosphate upon oxidative digestion. Total phosphorus is the measure used in most regulatory guidelines.

For constructed wetlands treating wastewater, the main input of phosphorus is from the wastewater itself. Phosphorus concentrations in rain, snow and runoff from forested land are normally very low (Nichols and Higgins, 2000).

2.7 Phosphorous Cycle in Wetlands

Due to the general scarcity of P in the natural environment and the absence of significant atmospheric inputs, natural ecosystems such as wetlands, have numerous adaptations to sequester this element (Kadlec and Knight, 1996). Phosphorous is not particularly mobile in soils and phosphate ions do not readily leach, thus P transport is mostly from plant uptake or through soil transport (Novotny and Olem, 1994). Figure 2.3 details the basic transport modes and reactions for P in a wetland.

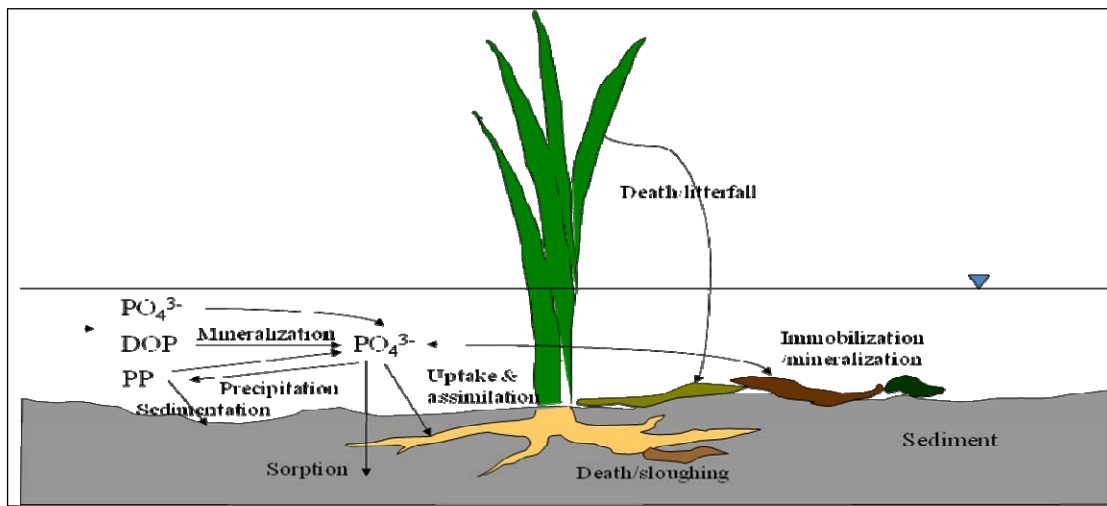


Figure 2.3: Phosphorus Cycle in Constructed Wetland

Source: Sasha Hafner, (2005)

The phosphorous cycle is sedimentary rather than gaseous therefore, commonly a major portion of a wetland's P content is tied up in organic peat and litter and in sediment (Mitsch and Gosselink, 1993).

2.8 Phosphorus removal Mechanisms in Constructed wetlands

Phosphorus removal in wetlands can be attributed to two main processes; plants uptake and sediment/substratum uptake as per Peters *et al.*, (1985). On the other hand some authors (Stowell *et al.*, 1981; Cooper and Boon, 1987) as quoted by Mann, 1996, say the feasibility of using constructed wetland to remove phosphorus present effluent sewage is still inconclusive. Each system has site specific factors which affect its performance including phosphorus adsorption capacity of the substratum, loading rate of effluent, plant management techniques, operational time, type of effluent applied and

substratum type. Of the mechanisms that are discussed they can be divided into biological, chemical and physical removal mechanisms.

2.8.1 Biological Removal Mechanism

Calder, (2001), says that Biological removal of phosphorus occurs through the uptake of phosphorus by plants and microbes while on the other hand Cooke, (1992), say that detritus, or dead vegetation, has also been shown to adsorb phosphorus likely due to the microbes decomposing the dead vegetation. Cooke (1992) found that 11% of phosphorus removed was through plant and detritus uptake, from a wetland receiving sewage effluent, pre-treated with an oxidation pond, for over ten years. The quantity of phosphorus taken up by plants and microbes shows to be small hence biological mechanisms alone will not sufficiently reduce phosphorus concentrations.

Literature shows that the storage of phosphorus in plants and microbes varies seasonally. Phosphorus is taken up during growth in the spring and summer and is released during die-back in the fall. Richardson and Craft (1993) estimates that 35-75% of the phosphorus retained by the plants is released back to the water column during die-back.

One potential method of enhancing sustainability in removing P from the system is through routine harvesting of biomass. Prior studies with productive aquatic macrophytes, however, have shown that this approach can be cost prohibitive unless

there is an economically valuable use for the harvested material (International Symposium on Biochemistry of Wetlands; 2005(9): p. 80; 2005)

2.8.2 Physical Removal Mechanism

Kadlec and Knight, (1996), say that filtration of suspended solids that contain phosphorus and precipitation through the substrate media is a physical means of phosphorus storage within the wetland. However, if the solid matter filtered from the wastewater is planktonic, its decomposition can release dissolved phosphorus into the water column (Kadlec and Knight. 1996).

2.8.3 Chemical Removal Mechanism

Chemical removal of phosphorus occurs through adsorption and precipitation. Adsorption is the process of a substance adhering to the surface of a solid, such as the wetland media, and precipitation is the formation of insoluble products from the combination of soluble reactants.

Precipitation achieved through the addition of chemicals is a common approach in many conventional wastewater systems. With chemical precipitation in constructed wetlands, removal of phosphorus is ultimately achieved through physical storage of phosphorus precipitates within the substrate media

Davies and Cottingham (1993) note some problems with the chemical dosing approach for constructed wetlands: alum, a common chemical used for phosphorus

removal, can be toxic to plants. Rapid mixing is required to preferentially form aluminium phosphate, and is difficult to achieve within a gravel bed or open water zones. For constructed wetlands, the greatest disadvantage to chemical dosing for phosphorus removal is the loss of the operational simplicity inherent in the constructed wetland alternative.

Drizo *et al.*, (1997); Mann, (1990); Wood, (1990); Steiner and Freeman, (1989) say that adsorption to wetland soil media is considered to be the most significant phosphorus removal mechanism in subsurface flow wetlands. The two processes as shown in the literature is unclear as to the distinction between adsorption and precipitation, in terms of their definitions and their respective impacts on phosphorus removal. The two processes are frequently considered together.

Mayer and Jarrell (2000) and Faulkner and Richardson (1990) remark on the difficulty in determining whether adsorption or precipitation is the dominant phosphorus removal mechanism as quoted by Calder, (2000)¹ in his masters' thesis. Since both processes remove phosphorus in a constructed wetland, in this study they will also be considered together.

Richardson and Quian (1991) describe phosphorus storage sinks as the short term for micro-organisms and vegetation and long term for adsorption and stable organic fractions. On the other hand, other authors like Breen, (1990) and Rogers *et al.*,

(1990) say that the main mechanism for P removal is plant uptake. Nicholas (1993) stated that the initial mechanism for removing some of the nutrient load was by filtering and settling of inorganic and organic particulate matter.

2.9 Factors Influencing Phosphorus Removal in Constructed Wetland

Phosphorus removal in CWs as discussed above has been reported to occur via a variety of mechanisms. This includes plant uptake, adsorption onto substratum, microbial assimilation, precipitation and complexation reactions as well as incorporation into biological films (Richardson and Davis, 1987; Faulkner and Richardson, 1989). In this section we will discuss the factors that affect the removal of phosphorus.

2.9.1 Substratum

The soil type has a major impact on the phosphorus efficiency of wetlands (Richardson, 1985; Schwartz *et al.*, 1992). Richardson (1985) has attributed phosphorus adsorption potential of several wetlands to the aluminium and iron contents of the soils. The amorphous acid-extractable aluminium content of the soil was highly correlated to the phosphorus adsorption potential of several wetlands. Wood (1990B) as quoted by Mann, 1996, agrees that local substrata should be evaluated to determine their nutrient adsorption capacities and hydraulic permeability.

Soils containing high clay and organic matter adsorb large amounts of phosphorus and thus the inclusion of soil/ substratum which allows good percolation is paramount in optimizing the phosphorus removal processes (Wood, 1990A). Kalff, 1980 says that

sediments that are labeled with ^{32}P , were shown to constitute significant source of phosphorus to rooted macrophytes. Phosphorus was believed to be taken up directly by plants only in rarely-encountered hypereutrophic waters.

Different substratum have been investigated in Cs include gravel, sand, peat/ bentonite, asphalt, concrete, granite, limestone, gold slime waste, chalk, crushed rock, hydrated calcite lime and power station bottom ash and fly ash (Cooper and Boon, 1987; Steiner and Freeman, 1989). It is realized that as said by Mann, (1996) most of the studies adsorption capacity of the material used was not calculated, therefore it's difficult to attribute any improvement in the phosphorus removal to the use of a particular substratum. It has been realized that regional gravels are normally selected as a substratum in sub surface flow CWs. The advantage of using gravel based systems is their high hydraulic conductivity. They are less likely to clog or experience short-circuiting, compared to soil based systems which may contain large amounts of silt or clay. Findlater *et al.*, 1990 say that though gravel CWs maintains high hydraulic conductivity they have been shown to be largely anaerobic.

The type of gravel employed can affect the phosphorus adsorption characteristics of a CWs. Silica based gravel has lower P adsorption capacity than limestone based gravel (Cooper and Hobson, 1989)

2.9.2 Hydrologic Conditions

Wetland hydrological conditions, whether surface or subsurface flow, are major factors affecting the nutrient removal efficiency. Tchobanoglou (1987) suggested that effluent could be applied in semi-plug flow with step feed application so as to spread out the impact of the added nutrients in an aquatic treatment system. Bowme (1987) on the other hand suggested that constructed wetland could contain baffles to improve mixing.

The immobilization of phosphorus in constructed wetlands is dependent upon the contact time between effluent and substratum. Adequate retention time is often required in CWs to ensure that mineralization and precipitation can take place. Slower water velocities, however, enhance sedimentation and entrainment of solids, containing phosphorus, in the root zones and gravel.

Flow rates of effluent through a CW may be controlled by slope, water depth, vegetation type and baffles. Kadlec (1987) suggested that tracer studies were necessary to more accurately describe overall budget in wetland systems. Higher water velocities are of concern in CWs as these tend scour sediments rich in phosphorus or lead to re-dissolving some phosphorus compounds. Rain events are known to increase the water level in CWs whereas water loss by emergent macrophytes takes place via evapotranspiration.

2.9.3 Aquatic Plants/ Macrophytes

As allude to earlier on, the types of macrophytes in a wetland are generally classified as submerged, floating or emergent. These plants are responsible for many functions in a wetland system used for wastewater treatment. Table 2.1 shows a list of the plants with potential for wastewater treatment as quoted by Mann, (1996).

Table 2.1: List of Plants that have Potential in Wastewater Treatment

Type	Genus	Common Name
Emergent	<i>Baumea</i> <i>Carex</i> <i>Ceratophyllum</i> <i>Cladium</i> <i>Eleocharis</i> <i>Juncus</i> <i>Phragmites</i> <i>Sagittaria</i> <i>Salix</i> <i>Schoenoplectus</i> <i>Spartina</i> <i>Typha</i>	Rush Sedge Hornwort, Coontail Swagrass Spike rush Rush Common reed, cane grass Arrowhead Sedge Rush Saltwater cordgrass Cumbungi, Cattail
Floating	<i>Alternanthera</i> <i>Azolla</i> <i>Cotula</i> <i>Eichhornia</i> <i>Elodea</i> <i>Hydrocotyle</i> <i>Lagarosiphon</i> <i>Ludwigian</i> <i>Pistia</i> <i>Salvania</i> <i>Spirodela</i> <i>Wolfia</i>	Alligator weed Water velvet Water button Water hyacinth Pondweed, oxygen weed Pennywort Lagarosiphon Water primrose Water lettuce Salvanis Duckweed Duckweed
Semi- emergent	<i>Egeria</i> <i>Hyfrilla</i> <i>Myriophyllum</i> <i>Potamogeton</i>	Waterweed Water thyme Parrot feather, milfoil Pondweed

Source: Finlayson, (1983) and Fisher, (1985)

Different authors agree that submerged and floating macrophytes can readily take up nutrient from wastewater (Boyd, 1976; Best and Mantai, 1978; McDonald and Wolverton, 1980; Tanner 1992). Whereas Kadlec (1987) say that generally wetland plants lack large amounts of structural tissues hence breakdown rapidly at senescence, causing a release of most of the nutrients back into the water column. He advocates for harvesting the macrophytes before senescence which will reduce/minimize nutrients release.

Several authors consider that macrophytes do not contribute significantly to the overall nutrient removal efficiency of aquatic treatment system. Richardson (1985) says that plant uptake was not a significant phosphorus removal process, with removal rates often less than 10%. Phosphorus is likely to be released back into water column when plant dies and decays.

In CW treatment systems, macrophytes are said to have two important functions to play (Brix, 1987; Wood 1990A). They supply oxygen to the heterotrophic microorganisms in the rhizosphere and they increase/stabilize the hydraulic conductivity of the soil.

2.9.4 Harvesting

Harvesting wetland plants is one way of removing nutrients. However, the phosphorus removed will depend on the plant employed and its productivity. Some authors like Finlayson, (1983) and Kinhill Stearns, (1986) say that harvesting may not be significant

P removal process and less than 20% of the nutrients in wetland plants were shown to be contained in aerial parts. Howard-Williams, (1985) realized that in almost all temperate wetland species, species with highest nutrients concentrations have been found to be young shoots during the early periods of growth. Whereas Hauser (1984) found that evidence that routine harvesting of water hyacinths every two weeks during growing season was not required to ensure good performance. However, harvesting was thought to cause a significant increase in turbidity and suspended solids. On the other hand Taylor and Stewart, (1978) in the other study they realized that harvesting water hyacinths showed to be necessary to prevent nutrient release from sediment material that forms in a natural environment.

The removal of plant material was found to be the only consistent phosphorus removal mechanism in other study of floating aquatic macrophytes and harvested aquatic plants may have a number of possible uses (De Busk and Reedy, 1987). Table 3.2 shows the possible uses of the harvested macrophytes.

Table 2.2: Uses of Harvested Aquatic Plants

Animal Feeds
Fertilizers
Extraction of Chemicals
Feedstock for Thermal Conversion Process
Feedstock for Biochemical Processes
<ul style="list-style-type: none"> • Methane • Alcohol fuels • Chemicals
Protein source
Compost

Source: Wolverton *et al.*, (1975); Taylor and Stewart, (1978); Hayes *et al.*, (1987)

According to Mitchell and Williams (1983), harvesting submerged macrophytes was not useful for nutrient removal. Similarly Jackson (1982) stated that aquatic plant treatment systems were disappointing with respect to nutrient removal. Reasons advanced were that plant uptake of phosphorus was relatively low and that damaged and dead plants release phosphorus back into the solution.

2.10 Other Factors

2.10.1 Seasonality

Seasonal changes in nutrient removal by wetlands may be due to factors including; temperature, variability in influent characteristics and flows as well as variability in plant uptake of nutrients. Howard-Williams (1985) say that nutrient uptake by wetland vegetation and hydrological conditions vary seasonally. In some tropical wetlands, seasonal changes in water flow or level, causes pulses of nutrients that are to be released by the reflooding of dry soils (Howard-Williams, 1985).

2.10.2 Solids Removal

Phosphorus removal has been reported to be related to solids removal in wetlands. According to Kadlec (1987), more solids are discharged in winter than in summer, which could explain the decrease in phosphorus removal in many wetlands in winter.

2.11 Phosphorus adsorption in Constructed Wetland

The phosphorous cycle is sedimentary rather than gaseous (unlike for N); therefore, commonly a major portion of a wetland's P content is tied up in organic peat and litter and in sediment (Mitsch and Gosselink, 1993). Removal efficiencies range from 0 to 90% (Watson et al., 1989). As said by Lee (1999), phosphorous occurs as insoluble and soluble complexes in both organic and inorganic forms in wetland soils. The principal inorganic form is orthophosphate, which includes the ions PO_4^{3-} , HPO_4^{2-} , and H_2PO_4^- (Mitsch and Gosselink, 1993).

2.11.1 Adsorption Media

Since P cycle is sedimentary, sediment movement plays a vital role in determining P transport and concentrations. Dissolved P in both inorganic and organic forms usually interacts with suspended and bed sediments. Many of these interactions are heterogeneous in nature and it is therefore likely that the kinetics of the processes rather than the chemical equilibrium determine the P division (Grobelaar, and House, 1995).

Mann (1990) says that the inconsistency of wetlands in removing phosphorus is frequently due to the variable capacities of different wetland media to adsorb phosphorus (Mann, 1990). He says that with a properly selected media, and proper consideration of other relevant factors, a constructed wetland can be effective in phosphorus removal. Mann (1990) advocates that selection of a medium must consider the medium's adsorptive properties, permeability and suitability for plant growth.

2.11.2 Adsorptive Properties

The capability of wetlands medium to adsorb phosphorus is generally attributed to the presence of aluminium, iron and calcium oxides.

Literature (Johansson, 1997; Sakadevan and Bavor, 1998; Baker *et al.*, 1998) shows that aluminium oxides are suggested to have greater capacity for phosphorus adsorption than iron oxides. A combination of aluminium and iron oxides has even greater phosphorus adsorption capacity than either of the two mineral oxides alone (Sakadevan and Bavor, 1998; Mann, 1990).

The form of iron oxide greatly affects its capacity to adsorb phosphorus, and the form of iron oxide present in the media is dependent on several factors, including oxidation/reduction conditions, pH and the presence of other ionic compounds.

The quantity of these three metal ions present in a medium can be indicative of the medium's adsorptive capacity. Several studies have shown that phosphorus retention by wetland soils can be predicted by the aluminium content of the soil (Reddy and D'Angelo, 1994; Owusu-Bennoah and Acquaye, 1989; Richardson, 1985). However, environmental factors can significantly affect the adsorptive capabilities of a media, and need to be considered in addition to the chemical make-up of the media.

2.11.3 Media Permeability and Surface Area

In selecting a wetland medium, a compromise needs to be made between permeability and adsorptive capacity due to surface area. A fine grained sample will adsorb more phosphorus than a coarse grained sample, due to the greater surface area available for

adsorption in the fine grained sample. However, fine grained materials have lower permeability's, and are therefore more likely to clog and cause surface flooding or short circuiting (Calder 2001). Unstable media can also cause permeability problems. The gravel medium used by Mann (1990) disintegrated with time, producing fines that would significantly reduce the hydraulic conductivity of the medium.

2.11.4 Suitability for plant growth

Fine grain materials are not only more effective at phosphorus adsorption, but they tend to be more suitable for plant growth. Plants can establish in coarse material, including coarse gravels (Calder 2001). However, the material should not have a sharp edge, and some plant varieties will not easily establish in coarse or silty material (Geller *et al.*, 1990).

2.12 Factors Affecting Phosphorus Adsorption

The adsorption and desorption of phosphorus in constructed wetlands is impacted not only by the chemical characteristics of the substrate media, but by phosphorus loading, temperature effects, dissolved oxygen, pH, hydraulic conditions, and compounds competing for adsorption sites.

2.12.1 Phosphorus loading

High phosphorus concentration in the inflow can result in phosphorus removal by soils, whereas low inflowing phosphorus concentrations can result in phosphorus release by soils (WEF, 1998; Patrick and Khalid, 1974; Holford and Patrick, 1979).

Phosphorus loading impacts processes of both adsorption and precipitation. WEF, (1998) say that for adsorption, diffusion is required for phosphorus to reach micro pores and be sorbed. Diffusion of phosphorus to the micro pores will not occur unless the floodwater phosphorus concentration is greater than the soil pore water phosphorus concentration.

For precipitation, the solubility product (i.e. the concentration of phosphorus and the concentration of metal ions that will precipitate with phosphorus) controls the concentration of phosphorus in solution (Wood, 1990). In both cases, high concentrations of phosphorus will facilitate the removal of phosphorus.

2.12.2 Temperature Effects

Cold temperatures adversely affect reactions, especially biological and chemical reactions and as such it would be expected that phosphorus removal would decrease during the winter. Having said that, literature shows that in several studies conducted it has been noted that cold temperatures do not significantly affect phosphorus removal (Drizo *et al.*, 1997; Wittgren and Maehium, 1997; Kadlec and Knight, 1996; Maehlum *et al.*, 1995; Jenssen *et al.*, 1993).

Dahab and Vanier (1998) conducted a regression analysis of phosphorus removal, which showed a decrease in performance during winter conditions; however, large scatter in the data prevented any definitive conclusions.

On the contrary, some studies showed that biological activity occurs at water temperatures between 0 and 5°C (Jenssen *et al.*, 1993), indicating that biological mechanisms continue to contribute to phosphorus removal in winter periods. Although winter months generally have an insignificant effect on phosphorus removal, large phosphorus exports have been observed in the spring (Tanner *et al.*, 1998; Reinelt and Homer, 1995; Howard-Williams, 1985).

2.12.3 Dissolved Oxygen

Mann 1990; Fillos and Swanson, 1975 say that anaerobic (low redox or reducing) conditions have generally been associated with the release of phosphorus in constructed wetlands whereas aerobic (high redox or oxidative) conditions have been associated with a decrease in phosphorus concentrations in the water column (Fillos and Swanson, 1975; Drizo *et al.*, 1997).

The actual mechanisms involved in the release or uptake of phosphorus due to anaerobic or aerobic conditions are complex. The relationship between redox conditions and phosphorus adsorption is generally attributed to the transformations of iron compounds in the soils (Calder, 2001). Others have likened the removal to other elements like Fillos and Swanson (1975) found that iron is released from soils in a similar pattern to phosphorus release from soils in anaerobic soils.

The complexity of the release and uptake of phosphorus due to redox conditions is consequently related to the diverse phosphorus adsorption capacities of the different forms of iron.

The release of phosphorus during anaerobic conditions occurs from pH 5.5 to 8, except for high reducing conditions at pH 6.5 (Holford and Patrick, 1979). However, for low concentrations of phosphorus (< 4 mg/L), the net effect of anaerobic conditions at pH 6.5 is an increase in solution phosphorus concentration due to the release of native phosphorus from the soils. Consequently, when low concentrations of phosphorus are present in the water column, anaerobic soils at all pH levels will release phosphate to the water column.

Constructed wetlands are generally anaerobic, with some fluctuation in dissolved oxygen concentrations due to fluctuating hydrology (Reddy et al., 1998). However, aerobic conditions can exist in the direct vicinity of root rhizomes except during winter dormancy (Jensen *et al.*, 1993): plants will transport oxygen to their roots. Hiley (1995) notes that very fine roots are more likely to leak oxygen and those very fine roots are only produced in low oxygen demand conditions. However, the small amount of oxygen provided by the roots will likely be insufficient for wastewater with high oxygen demands, let alone to provide oxidative conditions for phosphorus removal (Brix, 1994a).

Calder, 2001 says that, to enhance oxygen concentrations and phosphorus removal year-round, pre-treatment of the wastewater is recommended. Pre-treatment can decrease the organic matter exerting a demand on oxygen, thereby allowing oxygen from root rhizomes to be used more effectively in nutrient removal.

2.12.4 pH

The pH of water controls the mobility of phosphorus and affects which mineral components sorbs phosphorus. For water at a low pH, the main soil components active in phosphorus adsorption and precipitation are iron and aluminium. The optimal pH range for phosphorus removal by aluminium components is pH 6 to 8 (Zhu *et al.*, 1997). Other studies have noted the dominance of aluminium components in phosphorus removal under pH 8 conditions (Diamadopoulos and Benedek, 1984; Robertson and Harman 1999; Richardson and Craft, 1993), and even effective removal at pH values between 8 and 9 (Baker *et al* 1998). Johansson, (1997); Sakadevau and Bavor, (1998) say that the greater capacity of aluminium oxides to adsorb phosphorus relative to iron oxides may be due to its effectiveness under a wide pH range, and stability under redox changes.

For iron oxides, the optimal pH range for removal of phosphorus is pH 5 to 7 (Zhu *et al.*, 1997). Other studies have noted the increase in iron phosphorus adsorption under acidic conditions (Mayer and Jarrell, 2000; Robertson and Harman, 1999; Richardson and Craft, 1993).

It has been noted that water at a high pH (pH greater than 8 or 9, calcium is considered the main phosphorus adsorbing or precipitation component of soils (Zhu *et al.*, 1997; Jenssen *et al.* 1994; Richardson and Craft, 1993; Holford and Patrick, 1979). Diamadopoulos and Benedek (1984) noted that phosphorus bound by calcium is released when pH decreases to below 7.5.

The pH of a wetland is not only a result of the wastewater source, but can be dependent on the wetland media characteristics, pre-treatment of the wastewater and the redox conditions in the wetland. Certain wetland media contribute to decreases or increases in pH. In some cases, the change in pH causes the media to be ineffective in phosphorus adsorption. Media can also be manipulated to provide the desired pH conditions. James *et al.* (1992) used a peat wetland medium to provide the acidic pH conditions required for effective phosphorus removal by steel wool added to the peat medium.

The pH of wetland water can also be impacted by algae blooms in pre-treatment lagoons. Algae remove carbon dioxide and release oxygen during sunlight, increasing the pH of water. The reverse process at night decreases the pH of water by 2 to 3 units (WEF, 1998).

2.12.5 Hydraulic Conditions

Hydraulic conditions in a subsurface wetland relate to the transport of water through the media, including flow schemes, hydraulic loading, retention time, and flow pathways.

- **Flow Schemes**

Wastewater is usually applied to wetland systems in a continuous and horizontal flow scheme. Several studies have determined intermittent flow strategies to be more effective at removing phosphorus than continuous flow strategies (Brix, 1994a; Geller *et al.*, 1990). Wetland designs with a horizontal flow path have some short circuiting and Breen (1990) was able to achieve fully mixed conditions with batch up flow hydraulics. However, Brix (1994a) notes that

intermittent flow systems are more expensive in terms of construction, operation and maintenance. As well, an intermittent flow strategy would likely not be suitable in cold climates, due to increased vulnerability to freezing (Calder, 2001).

- **Hydraulic Loading and Retention Time**

Longer retention times and low hydraulic Loadings are considered to increase phosphorus removal (Sakadevan and Bavor, 1999; Howard-Williams, 1985). Longer retention times allow for increased diffusion, increasing access to sorption sites in micro pores. Low hydraulic loadings are associated with larger areas, which would increase the phosphorus retention capacity of the wetland based on volume alone (Calder, 2001).

- **Flow Pathway**

Kadlec and Knight, (1996) says within a subsurface wetland, preferential channelling can occur on a large scale, potentially resulting in poor phosphorus removal due to decreased retention time. On the other hand Drizo et al. (2000) observed through tracer testing that the majority of flow travelled along the bottom of the trench and this effect in both planted and unplanted tanks and also observed that overall detention times were unaffected by the preferential flow.

2.12.6 Competition Effects

Compounds competing for adsorption sites can decrease the quantity of phosphorus removed from wastewater. Few compounds have been determined to be competitive.

Sakadevan and Bavor, (1998), Sanyal *et al*, (1993); Owusu-Bennoah and Acquaye, (1989) have realised that Organic matter has correlation with increased phosphorus adsorption as well as decreased phosphorus adsorption. Increased adsorption due to organic matter is assumed to be indirect; aluminium and iron hydrous oxides combined with organic matter provides active surfaces for adsorption.

Mayer and Jarrell, (2000) says that Silicon ions may also compete with phosphorus for sorption sites. Based on equilibrium sorption constants, phosphate is sorbed much more strongly than silicate, and significant competition from silicon ions occurs only for silicon ion concentrations greater than two times natural concentration.

Reddy and D'Angelo, (1994) says that Phosphorus may also be prevented from adsorbing to iron compounds if hydrogen sulphide is present, causing the formation of ferrous sulphide.

On the other hand Johansson and Gustafsson (2000), say that the other competing effect is where soluble calcium ions are precipitating with phosphorus, wastewaters with high alkalinity may cause precipitation of calcite, reducing the availability of soluble Ca ions, and therefore reducing phosphorus removal by precipitation.

2.13 Modeling Phosphorus Removal

Calder, (2001) says that modelling of phosphorus removal in subsurface and surface wetlands has been accomplished through sorption isotherms, breakthrough analysis, first-order models, sophisticated deterministic models and stochastic-deterministic models. No one particular model has proved entirely satisfactory; the overall removal of phosphorus is complex, depending on several mechanisms and environmental actors as discussed in the previous section.

Lee (1999) says modelling of the P cycle would seem to be simpler than the N cycle because of the fewer processes involved, yet this is not the case since processes in the P cycle are not entirely understood. He continues by saying that for simplification, high percentages of models simulate total phosphorus, rather than its components. A mass balance is implemented to account for inputs, outputs, and retention of P amounts:

$$\frac{dP_m}{dt} = P_{in} - P_{out} - P_{ret} \dots\dots\dots(1)$$

Where P_m is the mass of Phosphorus per wetland volume

P_{in} is the influent phosphorus

P_{out} is the effluent phosphorus

P_{ret} is the retention phosphorus

Since different modelling approaches differed with respect to how they represent the balance parameters, Mitsch et al (1995) developed a model that accounted for retention

by incorporating the effect of the hydrologic loading on the wetland. The retention was calculated as:

$$P_{ret} = k (aL_h + 1) P_T \dots\dots\dots (2)$$

Where k is the retention coefficient for P ($1/L^3$)

L_h is the hydrologic loading of the wetland (L/T)

a is the coefficient reflecting the magnitude of added hydrologic effect (L/T)

P_T is the total P in the system (M)

Input is the phosphorous concentration of inflow and output is the concentration value of wetland outflow. The retention coefficients were determined through calibration.

Other models were also developed with took into adsorption with more parameters like Mitsch and Reeder (1991) used the same mass balance concept with more details. The model accounted for macrophytes and plankton phosphorous uptake and release, sedimentation and resuspension velocities, and phosphorous concentrations in sediments. Christensen et al. (1994) on the other hand accounted for pools of dissolved TP in the water column, particulate TP in water, bottom soil TP, and macrophytes uptake and release. Mineralization, sedimentation and inflows were all modelled using first order equations.

When adsorption is calculated, it is usually modelled using the Sorption isotherms and breakthrough analysis. Sorption isotherms and breakthrough analysis consider the

adsorption process alone, whereas the other models consider other phosphorus removal mechanisms in a wetland.

2.13.1 Sorption Isotherms

Calder, (2001) says sorption isotherms describe the sorption equilibrium of the wetland material and phosphorus at a constant temperature. Equilibrium occurs when desorption reactions equal adsorption reactions, resulting in an invariable concentration of phosphorus. Specifically an isotherm is a relationship between the amount of phosphorus adsorbed per unit of adsorbent material and an equilibrium pore water phosphorus concentration. The commonly used isotherms are the Langmuir and the Freundlich isotherms.

2.13.1.1 Langmuir Expression

Jorgensen, (1988) says that the Langmuir expression used to calculate the adsorption is valid for monolayer adsorption. The Langmuir model is of the form (Novotny and Olem, 1994):

$$r = \frac{Q^0 b C_e}{1 + b C_e} \dots\dots\dots (3)$$

Where r is the adsorbed concentration of the contaminate ($\mu\text{g/g}$)

Q^0 is the adsorption maximum at a fixed temperature ($\mu\text{g/g}$)

b is the constant related to the net energy enthalpy of adsorption ($1/\mu\text{g}$)

C_e is the dissolved (free) concentration of contaminant water ($\mu\text{g/l}$)

2.13.1.2 Freundlich Equation

Novotny and Olem, (1994) says the other model to use in determining the adsorption of P to particles is the Freundlich equation.

$$r = K * C_e^{1/n} \dots\dots\dots (4)$$

Where K and n are constants and are obtained by plotting r versus C_e on log-log graph paper, where the logarithmic intercept is K and the logarithmic slope equals $1/n$.

For low concentrations of contaminants, the Freundlich and Langmuir isotherms can be simplified to a linear isotherm:

$$r = \Pi C_e \dots\dots\dots (5)$$

Where Π is the partition coefficient (1/g)

Isotherm adsorption capacities do not sufficiently predict full-scale phosphorus removal capacity of a medium. Several studies have noted that phosphorus adsorption can be greater than predicted by adsorption maxima (Cooke *et al.*, 1992; Reddy *et al.*, 1998). Despite their inability to predict field adsorption, isotherms are useful to compare various materials, as illustrated by Rosolen (2000).

2.13.2 First Order Models

First order models have been used to describe the performance of full-scale wetlands in phosphorus removal. Such a model lumps all the removal mechanisms into one rate constant, providing a description of the average phosphorus removal performance of a system over the long term (Kadlec and Knight, 1996).

Wood, (1995), says that Constructed wetlands hydraulics behaves somewhere between plug flow and completely mixed reactor. Within Limitations, the modelling of wetland phosphorus removed can be successfully and conservatively accomplished through a first order plug flow kinetics equation, described as follows:

$$q \frac{dC}{dy} = -k (C - C^*) \dots\dots\dots (6)$$

Where q is the hydraulic Loading (m/d)

C is the concentration (mg/L)

y is the distance along the bed (m)

k is the rate constant (m/d)

C* is the background concentration (mg/L)

Kadlec and Knight, (1996) say that background concentration is usually close to zero, and is assumed to be negligible hence equation (6) becomes:

$$\ln \left(\frac{C}{C_i} \right) = - \frac{k}{q} y \dots\dots\dots (7)$$

Where influent concentration (mg/l)

The first order model assumes that the concentration profile along the transect of the wetland will decrease exponentially. Phosphorus concentrations generally decrease

exponentially along the transect of the filter (Kadlec and Knight, 1996; Drizo *et al.*, 2000) on the same note Mann (1990) did not observe a trend in reactive phosphorus with distance.

The first order model is only appropriate over large time scales, due to the lags and fluctuations in treatment performance caused by senescence cycles and stochastic phenomena such as weather patterns (Kadlec and Knight, 1996; Tanner *et al.*, 1998). Also the equation applied to constructed wetlands also assumes that the system is mature, closed (i.e. inputs from inflow and outputs from outflow only), and that the flow is relatively steady and the concentration of phosphorus is uniform.

Drizo *et al.* (2000) modified the model to differentiate between phosphorus removal by plants and phosphorus removal by the gravel medium. The rate constant was divided into two rate constants, one to describe the contributions of the plants (k_s) and the other the gravel medium (k_p).

$$\frac{dC}{dy} = -(k_s + k_p)(C - C^*) \quad \dots\dots\dots (8)$$

The first order model is simple and comprehensive. It requires little data and incorporates various mechanisms and factors but they are some problems associated with the use of the model. For one, site specific media and environmental factors, as well as fluctuations in inputs and environmental factors can have a large affect on the value of the rate constant. Also the model does not consider the eventual saturation of adsorptive media.

Some other authors say that Phosphorus storage in the plant biomass of emergent vegetation and microorganisms are usually considered short term or temporary, since phosphorus is being released during decomposition detritus tissue (Richardson 1985; Richardson and Craft 1993; Davis 1994; Reddy *et al.* 1999). Researchers have repeatedly attributed the major and long-term retention of phosphorus from water to settling of particles onto the sediments compared to the other mechanisms (Caraco *et al.* 1991; Reddy *et al.* 1999; Braskerud 1998, 2002a). Therefore, efficiency of wetland to store phosphorus on a long-term basis for this model is determined by sediment accumulation (Richardson *et al.* 1997).

2.14 Phosphorus and human Health

Phosphates are not toxic to people or animals unless they are present in very high levels. Digestive problems could occur from extremely high levels of phosphate (Sheila Murphy, 2007).

2.15 Ecological Modeling

According to Jorgensen, 2003 as quoted by Kimwaga, 2003, models are simplification of a real situation in which the most important components are identified and their interactions described. Ecological models are biogeochemical which means their organization is based on conservation of mass and cyclic elements as compared to the

traditional ones. Ecological models that are based on theoretical principles and yet are mathematically simple enough to be parameterized using available data are likely to be the most useful for environmental management and decision-making (Borsuk *et al.*, 2001).

2.15.1 Procedures in Ecological Modeling

Like in any other modeling, they have to be steps to follow even in ecological modeling. These steps are Problem definition, Model selection, Preliminary simulation, Mathematical equations, Model calibration and Model validation. This will be discussed in the following sections.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

The Constructed Wetland understudy is in Gaborone, Botswana within the Department of Water Affairs (see appendix F). The climate of Gaborone is semi-arid, meaning it is hot and dry for most of the year. There is little difference between average summer and winter temperatures. Mean minimum and maximum temperature ranges are approximately 18°C to 32°C in January (wet summer season) and 5°C to 23°C in July (dry winter season) (<http://gaborone.info/php/gabclimate>). November to February are the hottest and the wettest months; although in winter months it can be chilly at night. Rain is erratic, but falls mostly in summer in heavy localized downpours that are followed quickly by a return of strong sunshine. Gaborone receives an average rainfall of 650mm. Summers are extremely hot with high humidity in the mornings (<http://www.wordtravels.com/>).

The constructed wetland in DWA started to operate in the late 2004 and treats wastewater generated by about 1000 employees who are using the offices, wastewater generated from restrooms, cleaning the floors and washing the machinery. All the water is collected into a septic tank and flow into each of the cells for treatment. Four cells were designed and constructed with equal loading rate, a hydraulic retention time (HRT) of about 5 days and a supply through a septic tank. Three of the cells are planted

with emergent macrophytes of different species, whereas the other one is set as a control with sand only.

3.2 Design and Construction of Constructed Wetland Cells

The design parameters for the DWACW were based on the acceptable effluent quality of BOD₅ in accordance with World Health Organization and Botswana Bureau of Standards (BOS 93:2004). This was done bearing in mind the characteristics of wastewater effluent from the septic tank into the cells.

The size of the cells was constructed with the theory of plug flow in the mind. The dimensions of each cell in the DWACW are: Length, $L = 25\text{m}$, Width, $W = 4\text{m}$, Media depth (m) = 0.6m, Area, $A = 125\text{m}^2$, Volume, $V = 75\text{m}^3$. River sand media of varying dimension ranging from 2-7mm was used as a substrate to fill up each cell. Media porosity, $n=0.44$, HRT, $t= 5$ days. The bottom of the cells was constructed with a slope of 1% to help in wastewater flow through the system from the inlet to the outlet as recommended by Billore *et al.*, (1999). Figure 3.1 shows a schematic presentation of the cell planes.

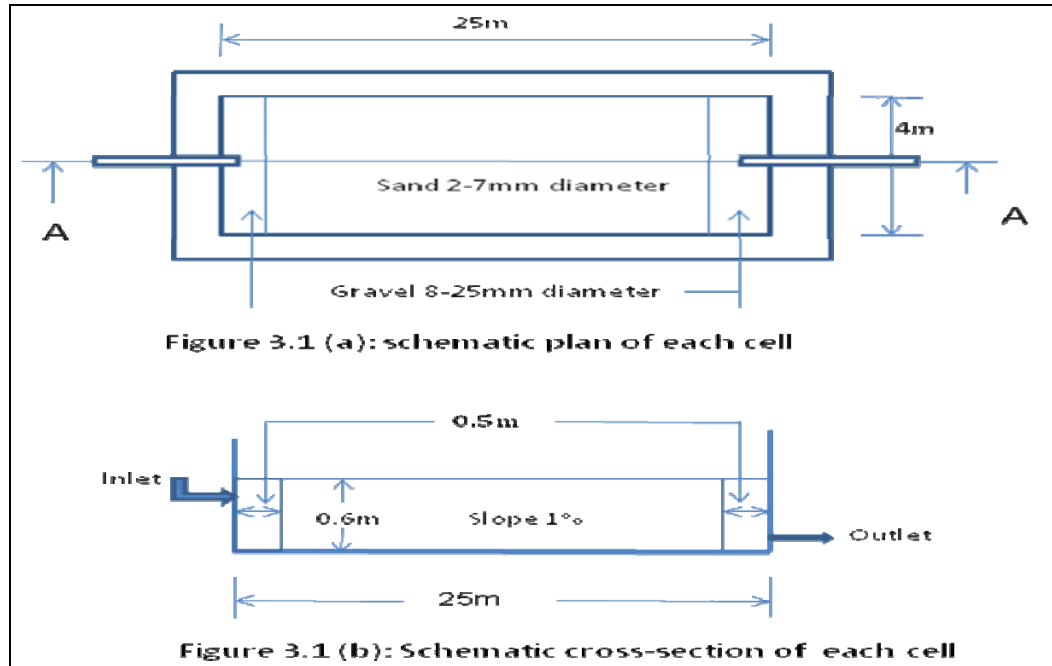


Figure 3.1: Schematic diagram for Cell Planes

Source: Authors own creativity, (2008)

At the inlets and outlets, gravel media of dimensions about 8-25mm was used to allow distribution along the full cross section of the cell. The cells are laid in parallel to each other and three of the cells have sand and a different macrophyte (*phragmites mauritianus*, *typha latipholia*, *cyperus papyrus*); the last cell is set as a control with sand only.

A two compartment septic tank was also designed and constructed, the tank is 60m³ in volume and it has an estimated retention time of about 3 days. Raw sewage from the ablutions and wastewater produced by cleaning the floors is collected in to the septic tank before it's passed into the wetland. This is where primary treatment (sedimentation) of the wastewater takes place.

3.3 Wastewater Sampling Procedures

Wastewater samples were collected at the inlet point into the wetland and at the outlet points as shown in figure 3.2. The samples were collected in 1L distilled water rinsed narrow-mouthed plastic bottles. The water was then transported to the laboratory in cooler boxes packed with ice. Upon arrival at the laboratory, samples were filtered through a 0.45 μ m Whatman filter paper. The samples were all the time kept in a cold room.

For samples collected within the wetland at 5m, 10m, 15m 20m, sampling points were dug within each cell. This was done so as to see how phosphorus is removed as the water column moves across the cells. See figure 3.3 for diagram showing the sampling points. A depth of 15 to 30 cm was dug and the water allowed to settle for some time so as to reduce suspended solids. After settling the wastewater was collected into 1L plastic bottles following same procedure as described above.

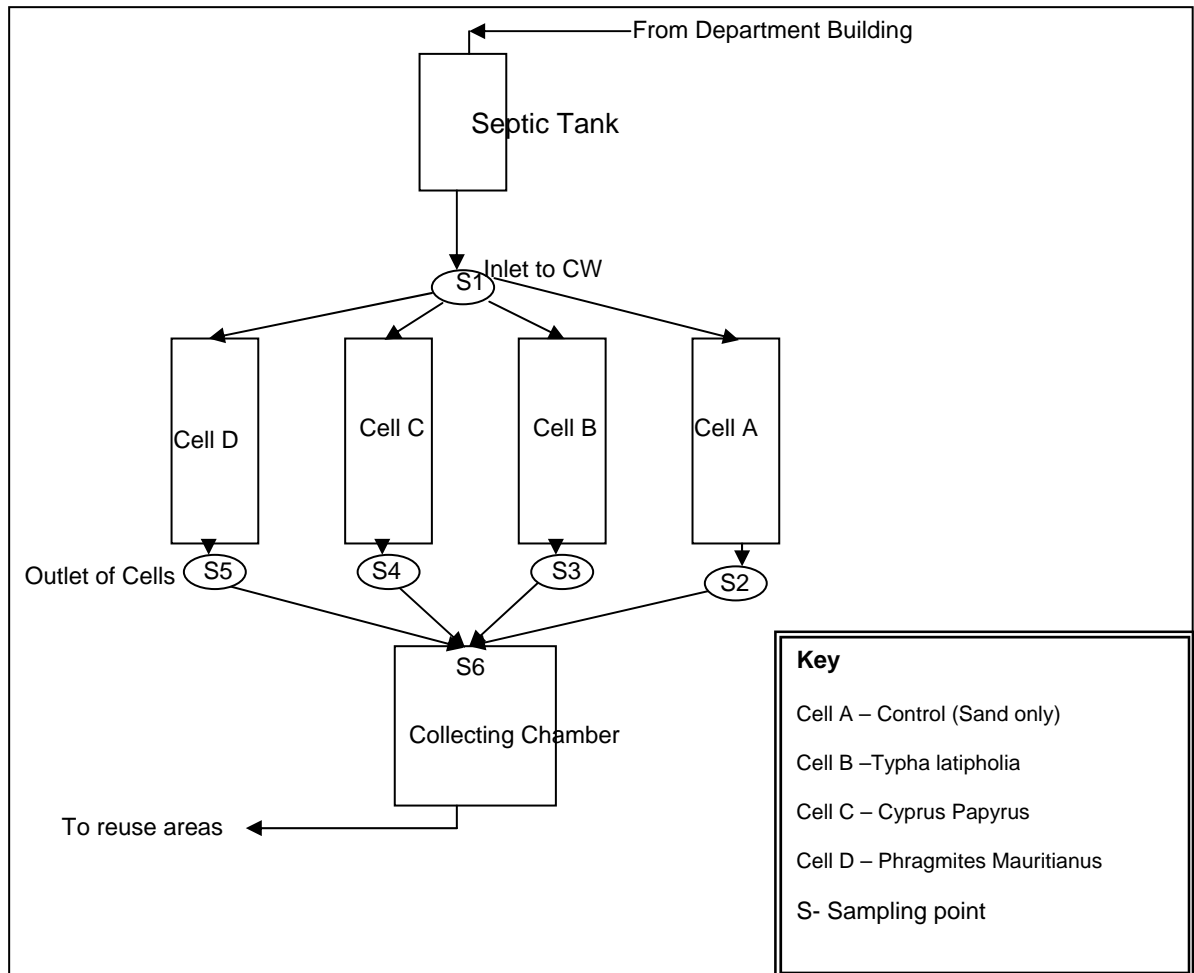


Figure 3.2: Sampling Points for Wastewater Analysis
Source: Authors own creativity, (2008)

3.4 Water Analysis

Field measurements were carried out on the wastewater samples. This included temperature (T), and pH. Field Temperature and pH were measured using a dual EC and pH meter (Denver Instruments, model AP250, Arvada, Colorado, USA). The pH meter was calibrated before and checked after each sampling event. The samples were

analyzed in the laboratory for DO, PO_4 and other parameters that are needed to see if the water does not pollute the environment like BOD, COD.

Phosphates in wastewater were analyzed using Ion Chromatography (Waters 510 HLPC pump, waters IC PAK anion HC column, and water U6K injector), conductivity detector and Hewlett Packard integrator. A borate/gluconate eluant (pH 8.5) can be used at a flow rate of 2.0ml/min.

3.5 River Sand Sampling Procedures

Sand samples were collected from within each cell in clear clean plastics and taken to the soil laboratory for analysis. Samples were collected at a distance of 5m, 10, 15m, and 20m from the inlet point within the cell. See figure 3.3 for the diagram on sand sampling points. Composite sand samples were collected from a depth of approximately zero to 30cm from the media level for all the four sampling points in each cell.

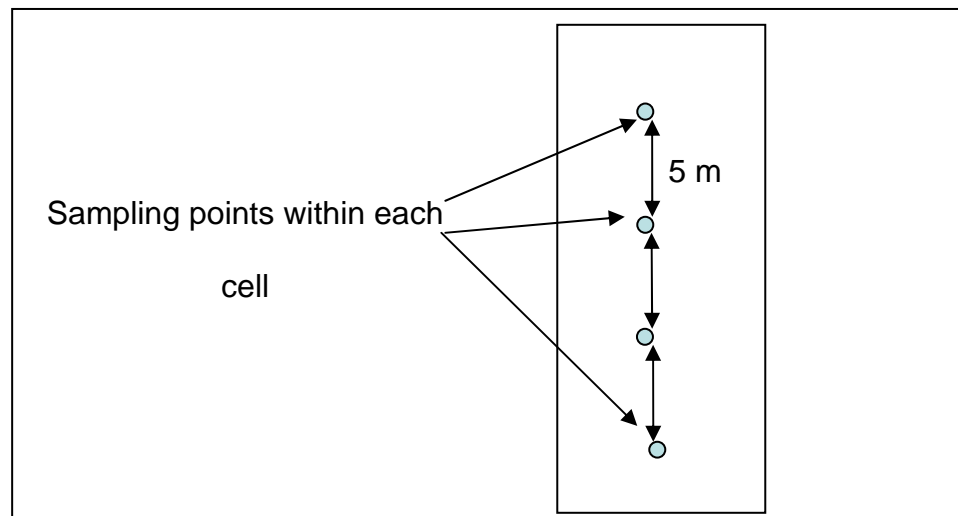


Figure 3.3: Sampling Points within each Cell of the CW

Source: Authors own creativity, (2008)

Sand samples at the laboratory were analyzed using the phosphorus Bray-II method. An HCl/NH₄F mixture extracts the readily available acid-soluble forms of phosphorus. The phosphate in the extract is determined calorimetrically with the blue ammonium molybdate method with ascorbic acid as a reducing agent. This was done so as to see how phosphorus is attached to the sand particles.

3.6 Model Development

STELLA® 6.0, software was used to simulate the processes that take place in the CW during phosphorus removal. Firstly a conceptual model was developed on the major mechanisms of phosphorus removal in the wetland see figure 3.4 below, and then followed by identifying the major mathematical equations which govern the processes.

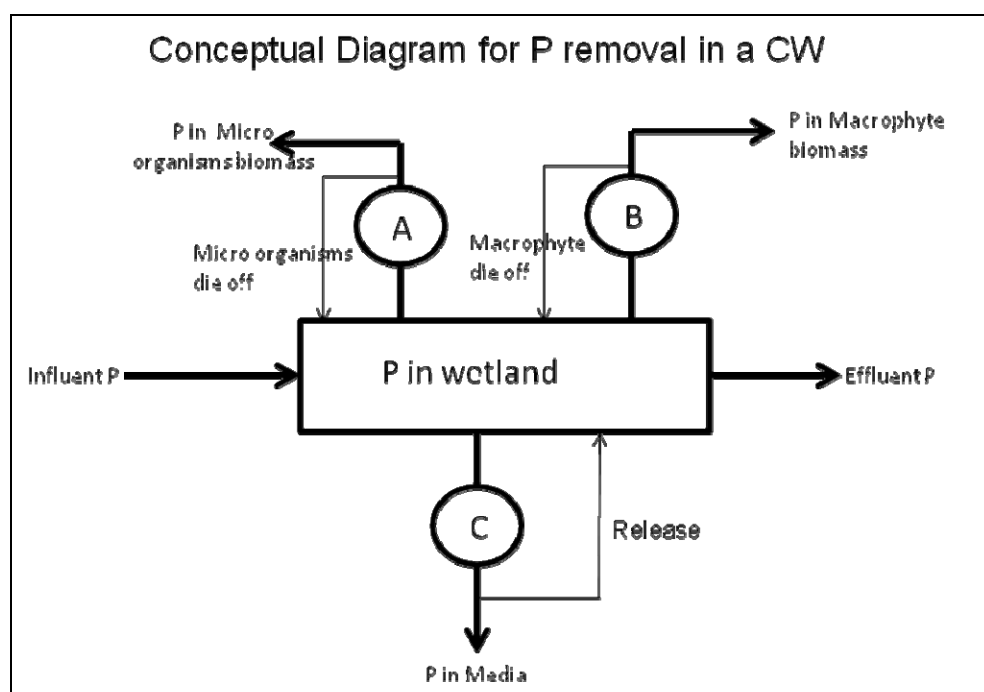


Figure 3.4: A Conceptual Diagram for Phosphorus Removal in a CW
Source: Authors own creativity, (2008)

Processes involved in P removal to be considered in the research include process A, B, and C.

- Process A is the uptake of phosphorus by the microorganisms for their assimilation in body as they growth.

The phosphorus may be returned into the wetland as the micro organisms die off.

- B Processes involves the uptake of phosphorus by the macrophytes planted in the wetland for the biomass production.

The P is returned back into the system as the macrophytes die and fall back into the system. Removal from the system is as when the plants are harvested.

- C Processes involve the adsorption of P by the sand media in the system, also the sedimentation of P at the bottom of the system.

P is released into the system as and when the sand particles desorb the phosphorus.

3.7 Mathematical Equations

The mathematical equations generated from the model were based on the mass balance.

The overall equation for the processes involved in phosphorus removal in the CW modelled can be as follows:

$$\frac{dP_{water}}{dt} = Influent + Plant\ die\ off + P\ release - SandAdsorption - PlantUptake - Effluent.....(3.1)$$

Influent is the wastewater concentration entering each cell in the constructed wetland.

Effluent is the treated effluent leaving each cell of the constructed wetland.

Processes involved in the dynamics of phosphorus removal in the constructed wetlands are presented below.

3.7.1 Sand Adsorption Process Equations

As discussed earlier on, sand adsorption is one of the processes in which phosphorus is removed in CWs. The Langmuir's adsorption isotherm equation was adopted in adsorption process in this study like in Jorgensen (1994). The equation is as follows:

$$\frac{dP_{adsorbed}}{dt} = P_{adsorption} - P_{released} \dots\dots\dots(3.2)$$

$$P_{adsorption} = \left(1 - \frac{P_{adsorbed}}{P_{adcapacity}}\right) \times (P_{adequilibrium} - P_{adsorbed}) \dots\dots\dots(3.3)$$

Where: $P_{adsorbed}$ is the PO_4^- in mg/l adsorbed in the media

$P_{adsorption}$ is the adsorption of PO_4^- in mg/l to the sand particles

$P_{released}$ is the PO_4^- in mg/l desorbed from the sand particles

P adsorption was calculated using the following equation:

$$P_{adequilibrium} = P_{adcapacity} \times \frac{P_{conc\ insand}}{P_{conc\ sand} + P_{conc\ hcapacity}} \dots\dots\dots(3.4)$$

Where: $P_{conc\ insand}$ is the concentration of PO_4^- (mg/l) available in the sand

$P_{conc\ hcapacity}$ is the concentration of PO_4^- (mg/l) at which half of the maximum adsorption capacity of the sand is used

$$P_{conc\ sand} = \frac{P_{water}}{dd} \times 1000 \dots\dots\dots (3.5)$$

Where: dd (amount of water in sand) = Porosity x WFP x depth x 1000.

WFP = Fraction of the gravel that is filled with water.

$$P_{adcapacity} = P_{adCC} \times bulkdensity \times depth \dots\dots\dots (3.6)$$

Where: P_{adCC} is the adsorption capacity of the sand on dry basis.

$$P_{released} = \frac{P_{adsorbed}}{P_{adcapacity}} \times (P_{adsorbed} - P_{adequilibrium}) \dots\dots\dots (3.7)$$

Where parameters are defined as above.

3.7.2 Plant Uptake Process Equations

Plant uptake is one of the processes involved in phosphorus removal hence was considered in this study. It was modelled using the following equation (Jorgensen

$$Plant\ uptake = (P_{influent} - P_{water}) \frac{Q}{V} (\mu - R) \times P_{plant} \dots\dots\dots (3.8)$$

1994):

Where: P_{water} is the PO_4^- in mg/l in the wetland matrix

$P_{influent}$ is the inflow PO_4^- in mg/l

Q is the flow rate entering the CW in m^3/d

V is the volume of the CW in m^3

μ is the plant growth rate

R is the rate Constant (day^{-1})

P_{plant} is the PO_4^- (mg/l) in plants

$$V = L \times W \times D \dots\dots\dots(3.9)$$

Where: L is the length of CW (m)

W is the width of CW (m)

D is the height of CW (m)

$$\mu = \frac{S \times P_{Plant}}{K + P_{water}} \dots\dots\dots(3.10)$$

Where: S is the solar radiation available for photosynthesis

K is the Michaelis Meuten Constant (g/m⁻³)

$$S = S_{max} [1 + \sin(0.008603 \times t)] \dots\dots\dots(3.11)$$

Where: S_{max} is the maximum sun light

T is the time (number of days).

3.7.2.1 Plants die off

There is also the addition of phosphorus back into the wetland as the macrophytes die off. The process is described by first order kinetics (Jorgensen, 1994) and equation is:

$$Plant_{die\ off} = R P_{Plant} \dots\dots\dots(3.12)$$

Where the parameters are defined as above.

3.7.3 Microorganism Uptake Process Equation

Microorganism uptake of phosphates is also one of the processes involved in removal of phosphorus in the CW as they assimilate it into their body mass. The process is described using the Monods equation. The commonly used equation is

$$M = \frac{S \times M_{\max}}{S + K_s} \dots\dots\dots(3.13)$$

Where M is the specific growth rate (hr^{-1})

M_{\max} is the maximum specific growth (hr^{-1})

S is the substrate concentration (g/l)

K_s is the saturation constant for substrate (g/l)

Micro organism growth is then calculated as

$$\text{Microgrowth} = MP_{\text{micro}} \dots\dots\dots(3.14)$$

Where M is specific growth rate (hr^{-1})

P_{micro} is the phosphorus in microorganisms

Micro organism die off is one of those processes that add some phosphorus into the CW when the micro organisms die and the body mass is disintegrated.

$$\text{Microorganisms} = RP_{\text{micro}} \dots\dots\dots(3.14)$$

Where R is the rate Constant (day^{-1})

P_{micro} is the PO_4 (mg/l) in microorganisms

3.8 Preliminary Simulations

In this step, preliminary simulations of the system being modeled are performed. The procedure is useful for identifying data deficiencies, theoretical gaps and the most important parameters.

3.9 Calibration

This is an attempt to find the best accordance between computed and observed data by variation of some selected parameters. It may be carried out by trial and error, or by use of software developed to find the parameters giving the best fit between observed and computed values.

3.10 Verification

This is the stage where a test to see the internal logic of the model is achieved. Questions in the verification phase are: Does the model react as expected? Is the model stable for long periods? Does the model follow the law of mass conservation? Verifications are largely a subjective assessment of the behavior of the model.

3.11 Validation

Validation consists of an objectives test on how well the model outputs fit the data. The selection of possible objectives test is dependent on the aims of the model, but the standard deviations between model predictions and observation and a comparison of observed and predicted minimum or maximum values of a particularly important state variables are frequently used.

3.12 Data Analysis Methodology

Based on the data obtained from DWA, the performance of the wetland was established.

3.12.1 Phosphorus Removal Performance

For each sampling location and date, an analysis of dissolved phosphorus (phosphates) was done. These average phosphorus concentrations of each sampling point were then used for further analysis.

The performance of all the cells was evaluated and compared using both the inflow and outflow dissolved phosphorus concentration, as well as the percent of phosphorus removal. Percent phosphorus removed is calculated according to Equation 3.15. From a regulatory perspective, the outflow concentration is the parameter of importance. However, the percent of phosphorus removed provides a description of the overall system performance, in terms of whether phosphorus removal or export is occurring.

$$\% \text{ removed} = \frac{(C_{in} - C_e)}{C_{in}} \times 100 \quad \dots\dots\dots (3.15)$$

Where C_{in} is the influent P concentration (mg/l)

C_e is the effluent P concentration (mg/l)

Phosphorus removal in the cells was also evaluated by examining the profile of concentrations along the filter lengths, and the performance of individual bed sections. A cell section is defined from the inlet to an effluent sampling point.

3.12.2 Environmental Factor Effects

Several environmental factors were analyzed for their impact on phosphorus removal.

These factors include temperature, pH, DO. Excel graphs were drawn to see their trends in the wetland.

CHAPTER FOUR

RESULTS AND DISCUSSION

In this chapter, results of the DWA Constructed Wetland (DWACW) which has been described in chapter three are presented. Studies on this CW were carried out in order to determine the performance of the constructed wetland in removing phosphorus. Results were obtained from the DWA (Botswana) to be used for analyzing the performance. As already stated in the previous chapter, the sampling points were S1 (Inlet/influent to wetland), S2 (effluent from a cell with sand only), S3 (effluent from a cell planted with *typha latifolia*), S4 (effluent from a cell with *papyrus cyperus*) and S4 (effluent from a cell with *phragmites mauritianus*).

N.B: In the data collected, phosphorus was measured as phosphate (P as PO_4) hence will use the phosphate values to model the removal of phosphorus.

4.1 Performance of the Constructed Wetland

From the results obtained it can be seen that commencement of the monitoring routine was started after some months of the CW commissioning. This is can be that the macrophytes have to establish themselves before they can attain optimum wastewater treatment just like Ciria et al (2005) in their paper, they allowed the cattails to establish

themselves before they start monitoring the quality of the wastewater. Measurements of different parameters were carried out.

4.1.1 Dissolved Oxygen (DO)

The DO influent into the CW varied from 0-3.5 mg/l with a mean of 0.75mg/l. The low DO in the septic tank can be attributed to that in there is anaerobic respiration of bacteria taking place in it. These processes help in preliminary treatment of wastewater. As the wastewater is passed through the CW there is a noticeable trend of DO increase. The increase can be attributed to the presence of the macrophytes in the CW, which might have effected aeration in the substrate and subsequently the wastewater. Also increase in DO in the CW can be due to photosynthesis brought about by the wetlands plants. Brix (1997) says that plants contribute to P removal by increasing P binding ability of sediments by release of oxygen from the roots. Lavrova and Koumanova, 2006, say that rooted macrophytes actively transport oxygen from the atmosphere to the media. Some oxygen leaks from the root hairs into the rizosphere supporting aerobic microorganisms. This contributes to higher oxygen in the planted cells. Figure 4.1 shows the variations of DO in the CW system for all the sampling points.

Figure 4.2 shows the average values of DO from each sampling point and it can be noted that the cell which contained sand and *papyrus cyperus* had a high aeration of the final effluent.

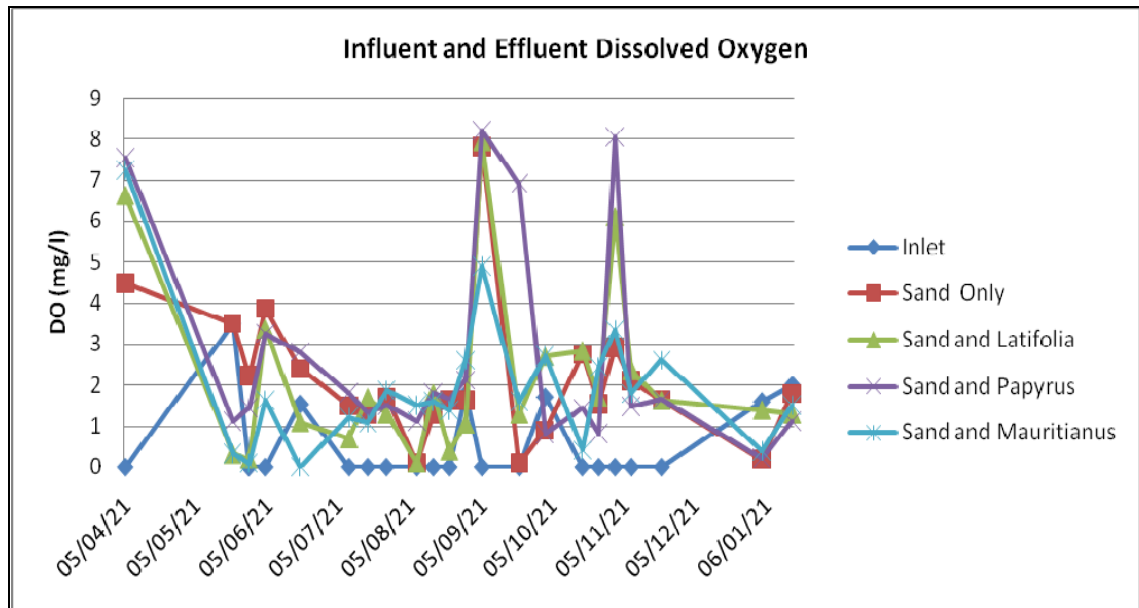


Figure 4.1: Variation of Dissolved Oxygen in the CW

Source: Field work, (2008)

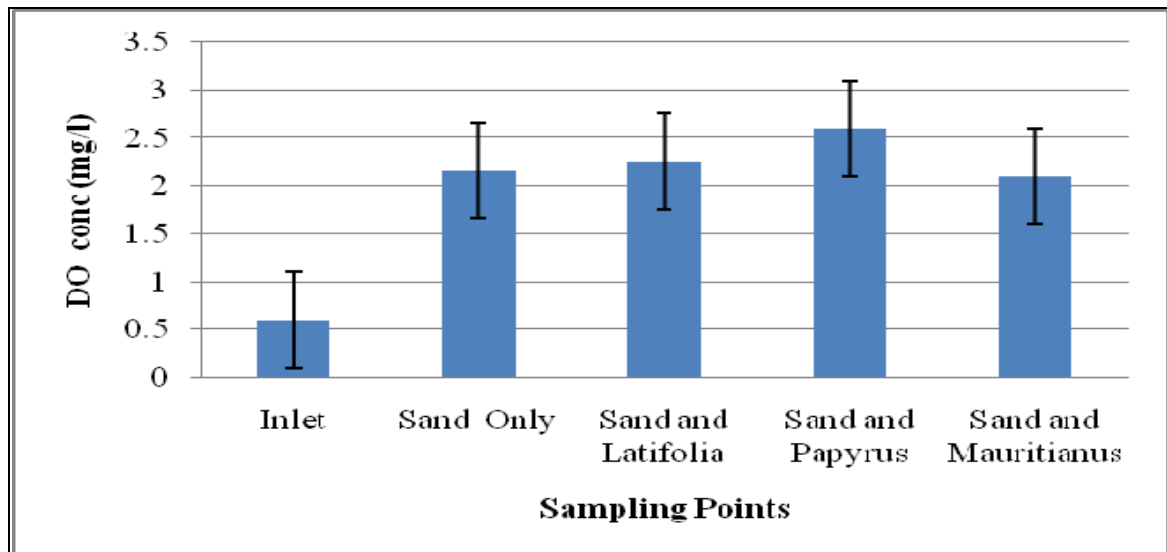


Figure 4.2: Average Dissolved Oxygen from the Sampling Points

Source: Field work, (2008)

4.1.2 pH Variations

From the results that were collected, pH was among them. It is also looked into here because it's one of those parameters that do influence the removal of phosphorus, controls various biological processes and also determines important chemical reactions in the constructed wetland. It can be seen from the results that pH increases from the influent to the effluent. The increase in pH can be attributed the increase in alkalinity as the wastewater passes through the CW cells, possibly due to the oxidation of part of the volatile fatty acids and ammonification of the organic nitrogen as Sousa et al (2001) say.

Also Lavrova and Koumanova, 2006, in their paper say that during photosynthesis plants consume carbon dioxide and release oxygen. Submerged aquatic plants growing within the water column raise the dissolved oxygen level in the wetland water and deplete the dissolved carbon dioxide, resulting in increased pH.

Figure 4.3 which show the mean influent and effluent pHs of the CW. The pH values were largely within the recommended range of $4.0 < \text{pH} < 9.5$ for existence of many treatment bacteria (Kadlec and Knight, 1996).

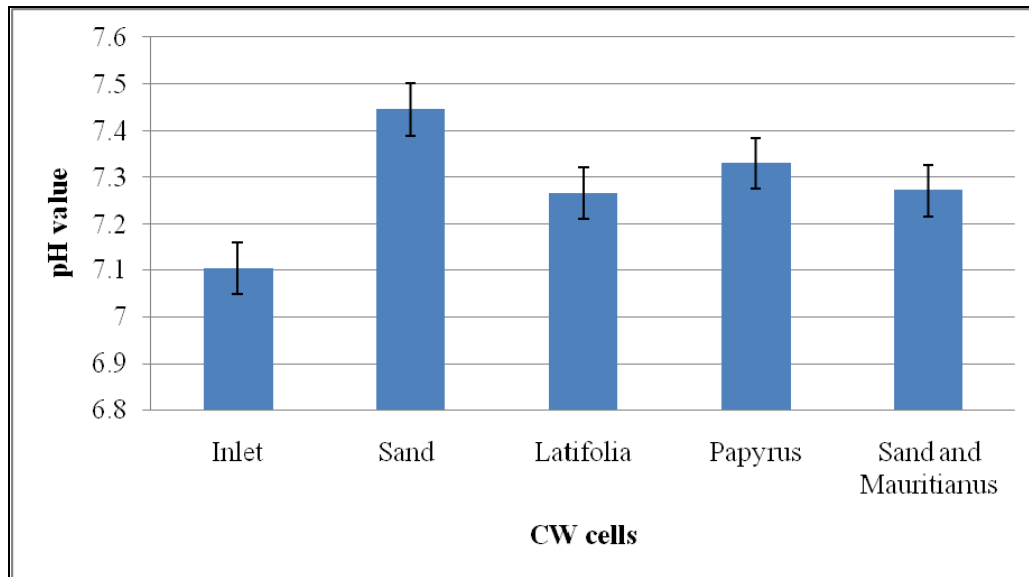


Figure 4.3: Mean Influent and Effluent pH in CW Cells

Source: Field work, (2008)

On the other hand increase in pH can be attributed to the origin of the substrate material used in the CW. If its of the limestone origin there is that possibilty of increase in alkalinity of the wastewater.

The cell which is set as a control with sand only has more pH increase, which can be because where there are no macrophytes, more ammonification of organic nitrogen took place where as in other cells some of the nitrogen is taken up by plants. Sousa et al (2000) reports that ammonification of organic nitrogen in CW results in increase in alkalinity hence high pH in the wastewater which might be happening in this cell leading to higher pH.

4.1.3 Temperature Variations

Temperature is one of the parameters that has been analysed from the results. It's of interest because the thermal conditions especially of the wastewater leaving the system for final disposal have to be monitored. Also temperature is important because many of the bio-chemical processes in the CW are temperature sensitive hence an optimum temperature has to be achieved. From the results there is a decreasing trend in temperature from the influent to the effluent. This can be due to cooling of the wastewater as it moves through the wetland. Wastewater cools as it moves through the sand which is under the shade of the macrophytes and also due to atmospheric cooling. Figure 4.4 show the graph for temperature variations in the constructed wetland.

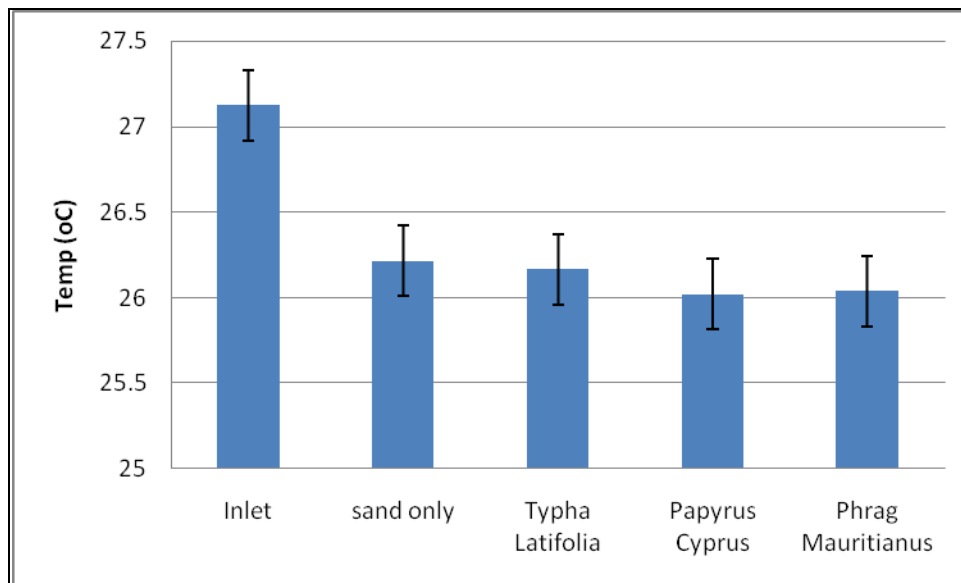


Figure 4.4: Temperature Variations in the Constructed Wetland

Source: Field work, (2008)

Table 4.1: Summary of the Physical Parameters Measured in the CW

Sampling Point	DO			pH			Temperature		
	Range	Mean	Std Err	Range	Mean	Std Err	Range	Mean	Std Err
Inlet	0 - 3.5	0.601	0.189	5.82 - 7.73	7.10	0.090	22.7 - 29.3	27.16	0.401
Sand Effluent	0.1 - 7.81	2.161	0.320	7.03 - 7.91	7.45	0.050	22.4 - 28.9	26.30	0.387
<i>T. Latifolia</i> Effluent	0.1 - 7.93	2.261	0.448	6.4 - 8.00	7.27	0.080	22.1 - 28.2	26.14	0.357
<i>P. Cyperus</i> Effluent	0.2 - 8.2	2.602	0.473	6.36 - 8.1	7.33	0.080	22.4 - 28.1	26.01	0.349
<i>P. Mauritianus</i>	0 - 7.24	2.106	0.347	6.09 - 7.91	7.27	0.090	22 - 28	26.03	0.359

n = 25

Source: Field work, (2008)

4.2 Macrophytes Removal Efficiency

In the study, phosphorus (as PO_4^{3-}) was looked into since it's the bone of contention for the study. Equation 3.15 was used to determine the efficiency of the CW in the removal of nutrients. Table 4.2 shows the results that were obtained during analysis of removal efficiency of the system. From the results it can be seen that phosphorus had means of 9.83 mg/l, 0.63 mg/l, 0.26mg/l, 0.19 mg/l and 0.16 mg/l for inlet, cell with sand only, the one with *typha latifolia*, *papyrus cyperus* and *phragmites mauritianus* respectively.

From the computations, cell with sand only has removal efficiency of 93.6%, *typha latifolia* has 97.4%, cell with *papyrus cyperus* has 98.1% and the last one with *phragmites mauritianus* has 98.4%. Cell with sand only shows that the removal was not high as compared to the other cells that have macrophytes planted on them. This is mainly due to that as said in previous chapters, the mechanisms of phosphorus removal in a constructed wetland involves phosphates uptake by plants. Now that the sand cell does not have macrophytes planted on it to help in removal by uptake, the cell is bound to have lesser phosphorus removal.

Table 4.2: Summary of Concentrations of Phosphorus and Removal Efficiencies

Sample	Phosphorus (mg/l)			
	Range	Mean	Std Dev	% Removal
Inlet	0 - 20.49	9.828	5.635	
Sand Effluent	0 - 2	0.630	0.630	93.59
<i>Typha Latifolia</i> Effluent	0 - 0.7	0.258	0.208	97.37
<i>Papyrus Cyperus</i> Effluent	0 - 0.5	0.188	0.133	98.09
<i>Phragmites Mauritianus</i>	0 - 1.2	0.157	0.249	98.40

Source: Field work, (2008)

In the cell with no macrophytes, the removal is dependent upon adsorption and microbial uptake processes only hence a lower efficiency in phosphorus removal.

It can also be noted in cells that were planted with macrophytes, that they exhibited different removal percentages amongst themselves. The cell which is planted with

phragmites mauritianus showed to be very effective in removing phosphorus as compared to other cells; it was then followed by the cell planted with *papyrus cyperus* and lastly the one with *typha latifolia*.

From the analysis of the performance, it can be seen that the performance of the wetland in phosphorus removal did not seem to portray a straight forward trend when compared between the cells. This may be due to what Vaillant et al. (2003) say that phosphorus reductions display complex seasonal variations that imply that the least efficient phosphorous removal occurs in winter and the most efficient reduction occurs in summer. This may be due to that phosphorus could be presented in various forms and these different forms of phosphorus are not removed or assimilated in the same way by plants and bacteria (Vaillant, *et al* 2003) hence in this study different macrophytes assimilated phosphorus differently.

Macrophytes, by providing a suitable habitat for many decomposing microorganisms in the rhizosphere, play an indirect but important role in reducing organic matter from various types of wastewater. This makes the cells which are planted with macrophytes to be efficient in treating wastewater in constructed wetlands as compared to cells filled with sand only with no macrophytes. Plants also increase soil or other root-bed medium hydraulic conductivity. As roots and rhizomes grow they are thought to disturb and loosen the medium increasing its porosity which may allow more effective fluid movement in the rhizosphere. When roots decay they leave behind pores and channels

known as macropores which are effective in channeling water through the soil (Conway *et al.*, 1991). These processes lead to more surface area hence more adsorption.

In a study done by Okurut, 2000 in Uganda he found that that nitrogen and phosphorus removal via plant uptake is only significant at the exponential growth phase and more so in *P. mauritianus* which had nearly 90% of its total biomass as above ground. This also makes the *P. mauritianus* to have better performance in this study since data used was just after the establishment of the constructed wetland. At this stage plants were on exponential growth phase too.

Figure 4.5 shows the phosphorus means in the constructed wetland as compared to the Botswana Bureau of Standards (BOBS) effluent discharge standards (BOS 93:2004) of 0.5mg/l for phosphorus before the wastewater is discharged into the environment.

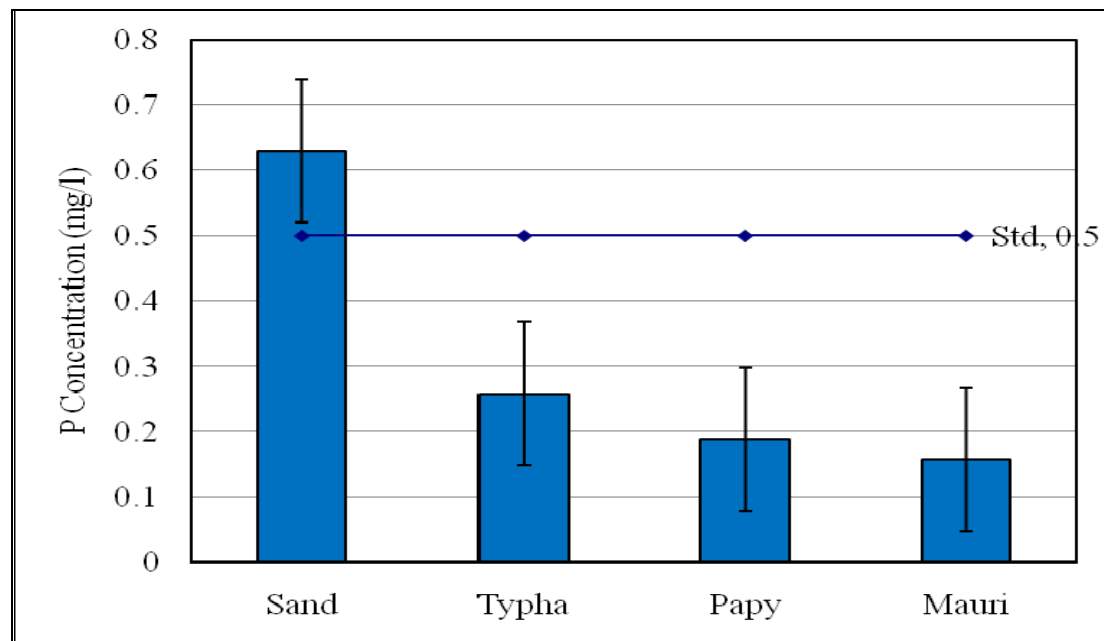


Figure 4.5: Averages of Effluent against the Discharge Standard
Source: Field work, (2008)

All the cell effluents have met the required standard except for the effluent from the cell that is set as a control with sand only. Since the effluents are blended when they get into the collector chamber the average concentration will be 0.31 mg/l which is lower than the required standard and the effluent can be reused for irrigation.

4.3 Trends of Phosphorus removal within cells

During data collection, wastewater samples were collected within each cell at intervals of 5m from the inlet as described in chapter three. The results show that, in all the cells phosphorus is removed at different rates in each cell as wastewater moves through the substratum showing a first order reaction. It can be seen that for cells with *typha latifolia* and sand only phosphates are degraded at a higher rate as compared to other cells.

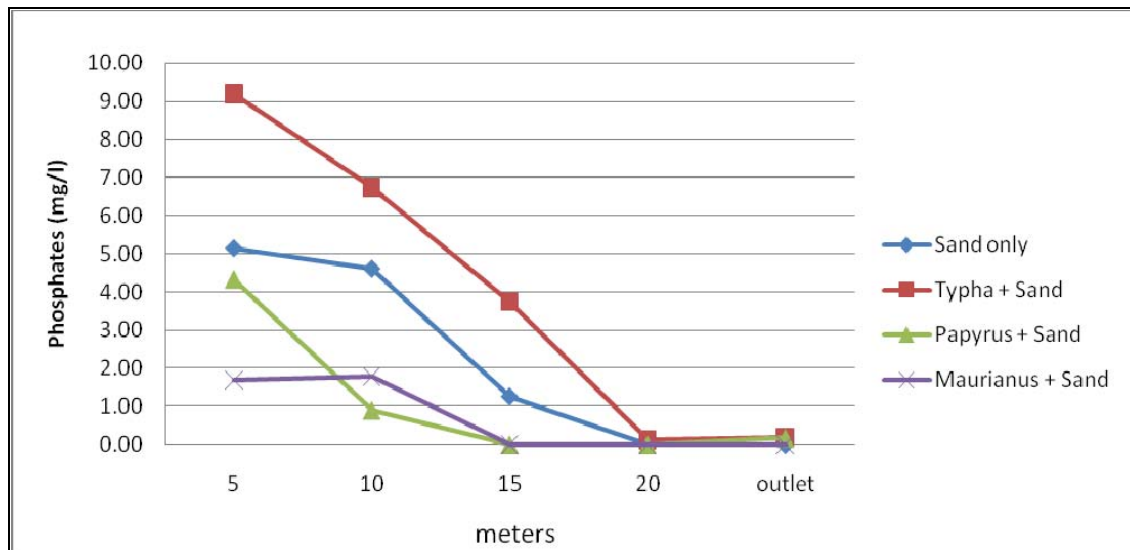


Figure 4.6: Trends in Phosphorus Removal within Cells

Source: Field work, (2008)

This shows that the retention time the wastewater takes in the wetland is more than sufficient as it traverses through the lengthy cell. Though this is good since the wastewater molecules are allowed maximum time of treatment, it also needs more land for the construction of the wetland which can be costly to acquired in some places.

4.4 Process Model Results and Discussion

The section presents the model results and discussions that have been simulated on the performance of the constructed wetland in DWA Gaborone, Botswana. The model is developed for all the cells. Model development details are presented in chapter 3 and performance results for the constructed wetland are presented in the previous section. The mathematical equations were developed using the Stella version 6.0.1 (2000) software.

4.4.1 Model Verification

In this section, the simulated results of the model have been compared with the observed values of the effluent phosphorus in order to verify the relationship described in the model. As according to Jorgensen, (1994), a model is said to be verified if it behaves in a way the modeler wants it to behave.

The input data into the model were the observed phosphates influent and effluent concentration values that were produced over 25 weeks. This is the data collected from

the time monitoring commenced up to when there was no data. This was from April 2005 up to March 2006.

Figure 4.7 shows the Stella diagram for the cell with macrophytes (also in appendix A) and the diagram for the cell with sand only is attached in the appendices, see appendix B. All the processes involved in the model have been simulated as per figure 3.4 which shows the conceptual model of all the processes involved in phosphorus removal in a constructed wetland.

The model was run at time specs of weeks, with a DT of 2 under the Runge-Kutta 4 integration method. Mathematical equations for the Stella model are presented in appendix C.

4.4.2 Model Assumption

- The system was assumed as continuous stirred tank reactor, such that all time the concentration in the CW system assumed is to have spatial distribution. (Metcalf & Eddy, 1991 and Jorgensen 1994).

Source: Authors own creativity, (2008)

In this model, the phosphates release due to desorption and the plant die off loops are not expected to have an input into the wetland since the data used to run the model is for the period when the system is new in operation. The macrophytes/plants are expected to be still growing. As for the sand it is the period when adsorption is expected to be still

taking place. If ever they is plants die off and phosphorus release, there should be very minimal contribution of the same due to some plants leaves falling and some chemical reactions taking place to cause desorption.

Figure 4.8 and 4.9 shows the simulated Phosphorus (PO_4) removed from the cell with *Typha Latifolia* and the correlation analysis between measured and modelled phosphorus in the cell. The simulation for phosphorus was in accordance with the observed values though the simulated peaks were higher than the observed values in all the cells.

The model was largely in accordance with the measured and simulated P values as it is indicated by a good correlation factor of $R^2 = 0.741$ as shown in figure 4.9.

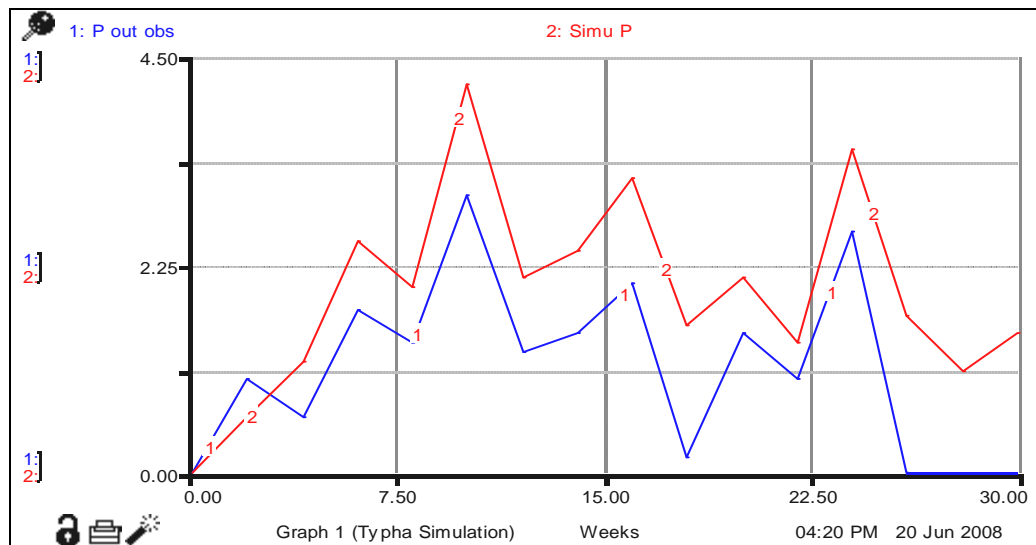


Figure 4.8: Simulated and Observed Phosphorus in the cell with *Typha Latifolia*

Source: Field work, (2008)

The correlation was measured by a plot of measured or observed phosphorus against the simulated phosphorus and a best fit line was attained to get the correlation.

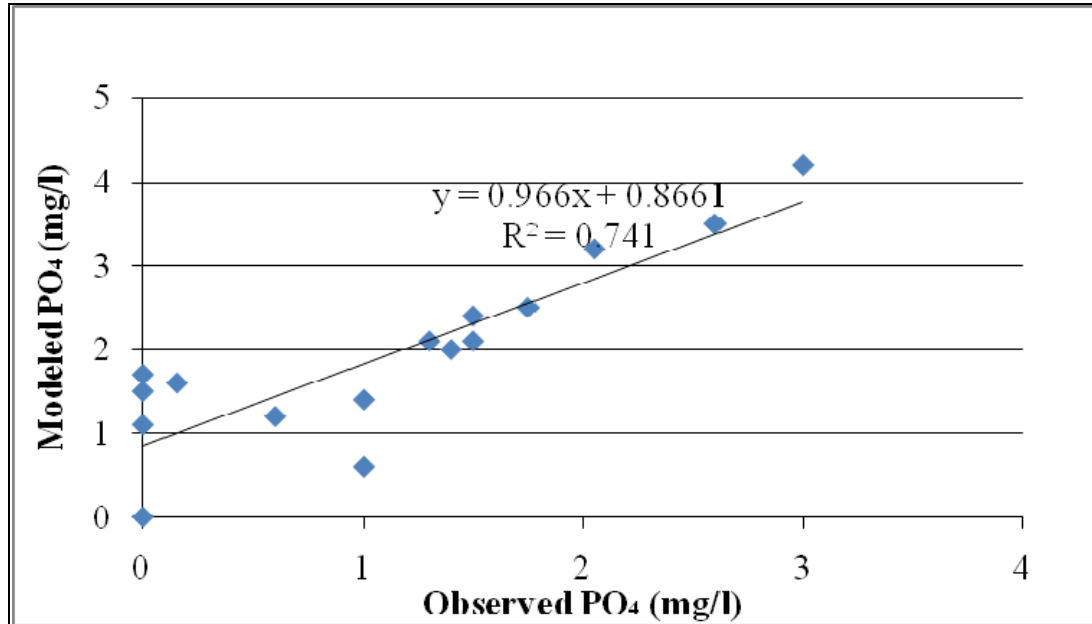


Figure 4.9: Observed and Modelled Correlation in a *Typha latifolia* cell

Source: Field work, (2008)

Figures 4.10 and 4.11 present the simulated phosphorus removal values in comparison with the observed values for cells with *papyrus cyperus* and *phragmites mauritianus* respectively.

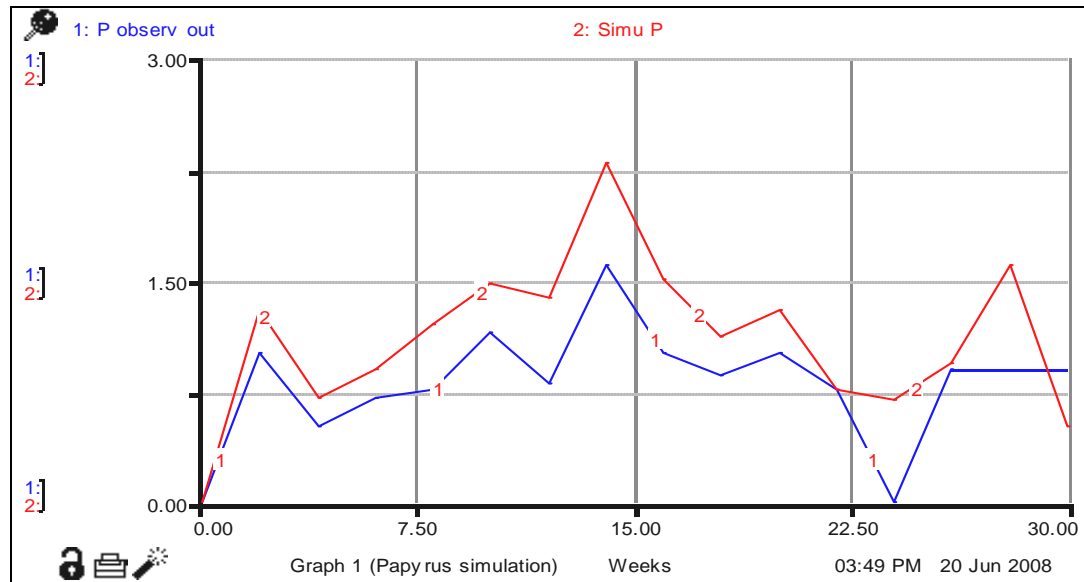


Figure 4.10: Simulated and Observed Phosphorus in the cell with *Papyrus cyperus*

Source: Field work, (2008)

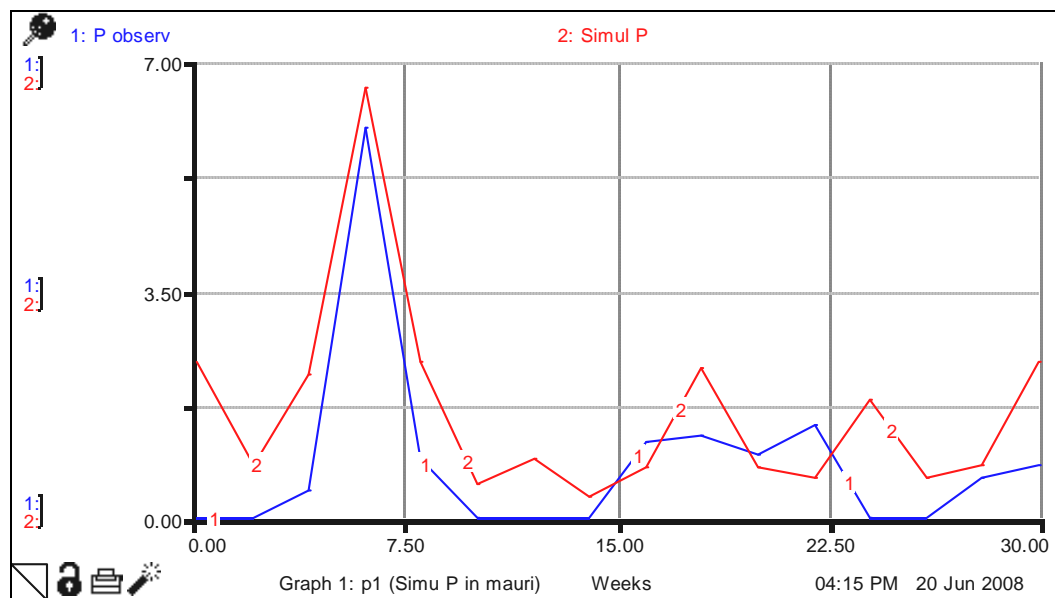


Figure 4.11: Simulated and Observed Phosphorus in the cell with *Phragmites mauritianus*

Source: Field work, (2008)

The graph for the simulation of the cell with *Phragmites mauritianus* show that the timing of the peaks was not totally matched. This may be due to different growth rates of macrophytes hence different phosphates uptake of the macrophytes in the wetland. The cell had a good correlation between modelled and observed values, see figure 4.7. Figures 4.12 and 4.13 present the corresponding correlation analyses between modelled and observed values for *papyrus cyperus* and *phragmites mauritianus* cells respectively.

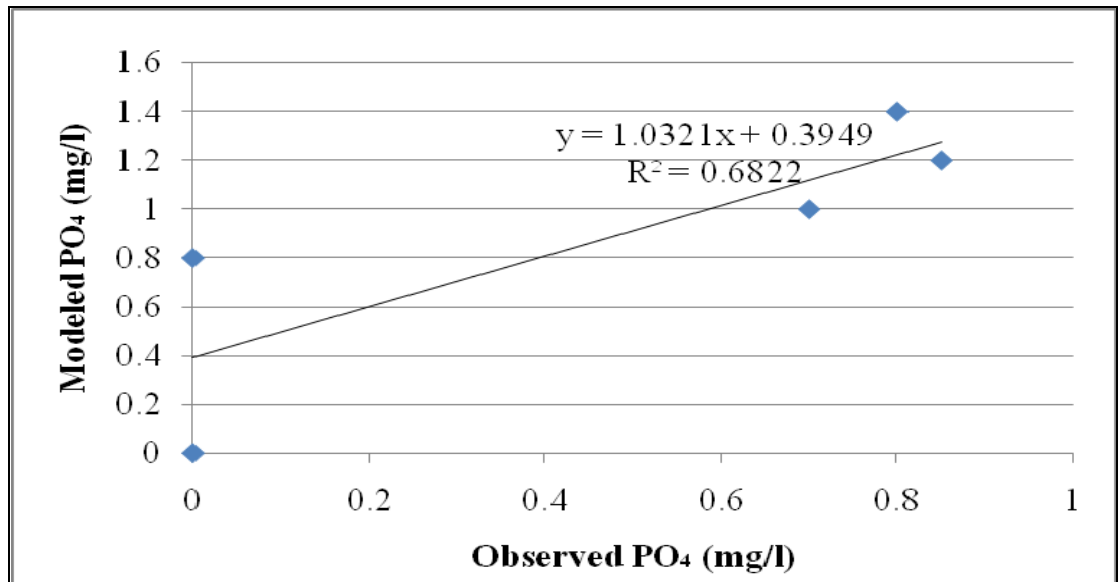


Figure 4.12: Observed and Modelled Correlation in a *Papyrus cyperus* cell

Source: Field work, (2008)

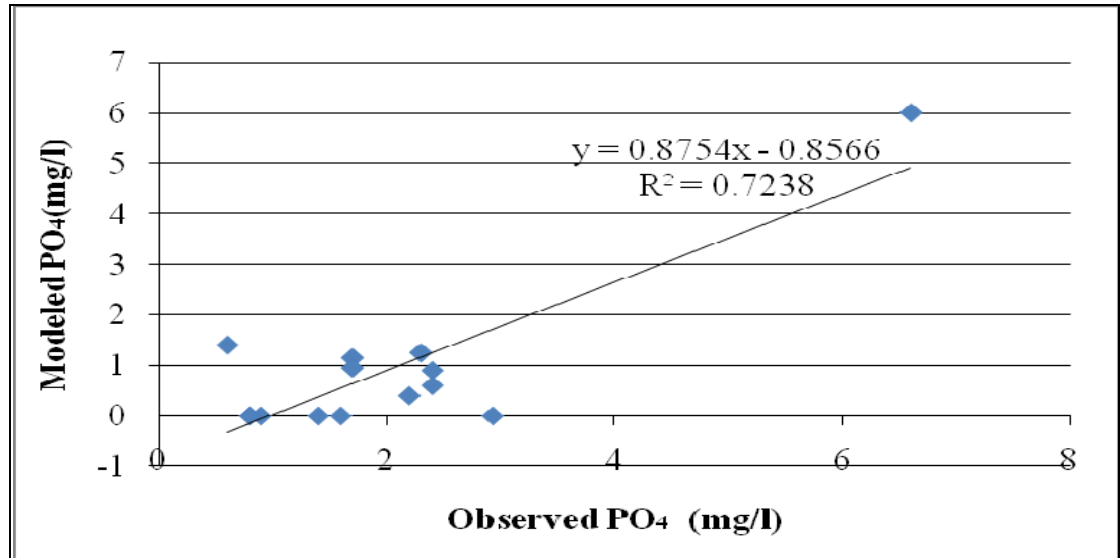


Figure 4.13: Observed and Modelled Correlation in a *Phragmites mauritianus* cell

Source: Field work, (2008)

Since the wetland has another cell which has been set as a control, the model for that cell was also made. In this model since there are no plants in the cell, the mechanisms for phosphorus removal that are modelled include adsorption and microorganism uptake. See the model diagram in Appendix B.

In the model, observed effluent phosphorus values from the cell with sand were modelled. The simulation of the observed phosphorus is presented in figure 4.14 and the correlation between the observed and the modelled phosphorus are presented in figure 4.15.

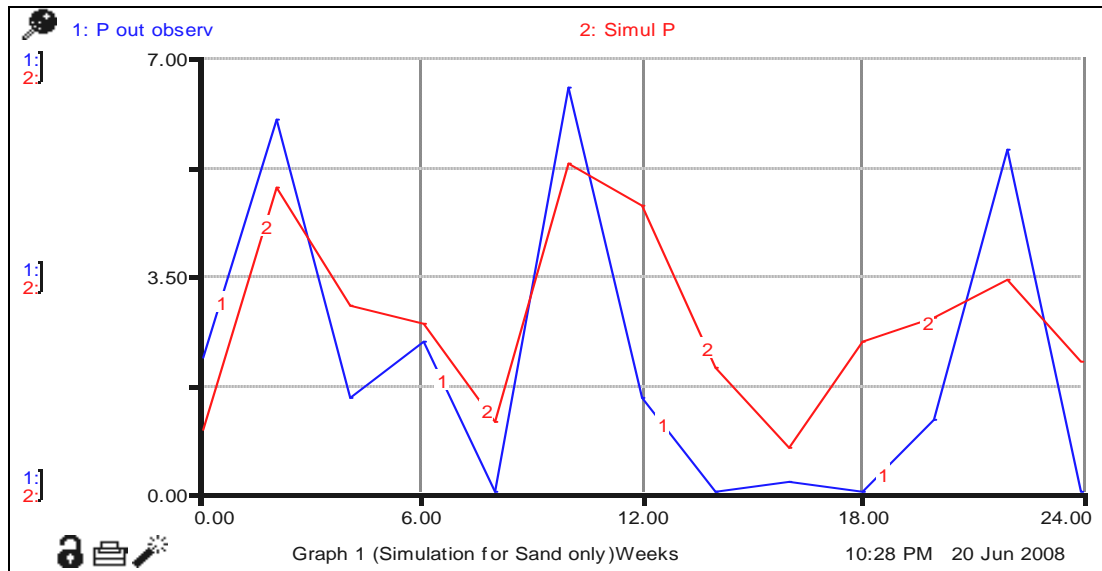


Figure 4.14: Simulated and Observed Phosphorus in the cell with Sand

Source: Field work, (2008)

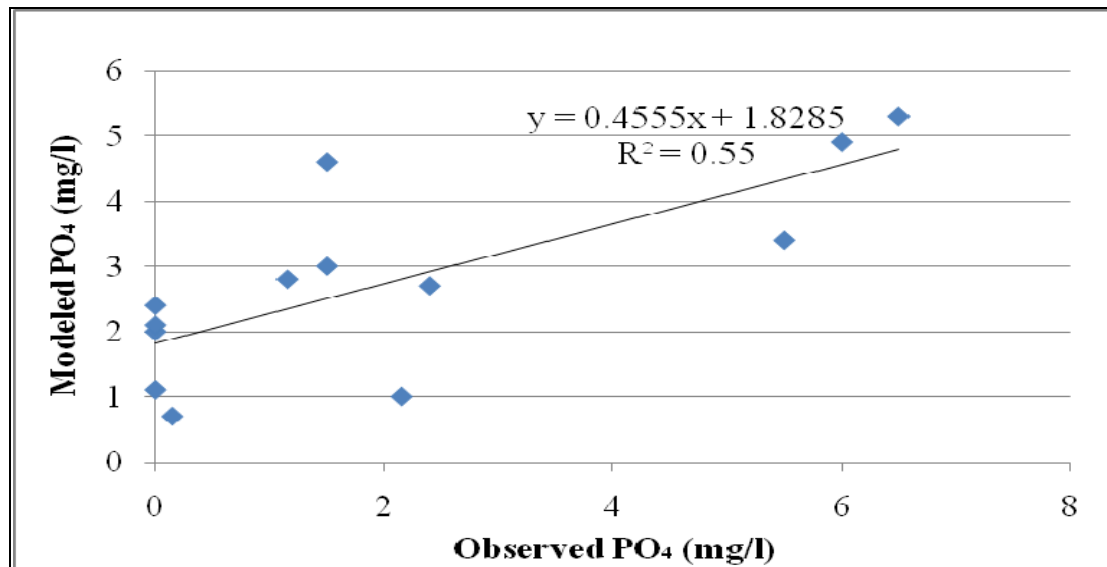


Figure 4.15: Observed and Modelled Correlation in a Sand cell

Source: Field work, (2008)

In figure 4.14 the peaks of the modelled and observed do not tally in magnitude and in time, this shows low performance results in the cell without macrophytes. The correlation coefficient for the modelled and observed is fairly low as compared to other cells. This suggests that the developed equations are more relevant for the cells with macrophytes than those without.

Also the correlation factor is small because adsorption and precipitation of phosphorus in constructed wetlands are very complex phenomena and can occur simultaneously (Del Bubba et al 2003). The media can both adsorb the phosphate ion and/or promote its precipitation by supplying the solution with metals, which can react with phosphorus to produce sparingly soluble phosphates. In addition, calcium present in the wastewater itself can promote phosphorus precipitation (Del Bubba et al 2003). These processes since they were not modelled at individual basis but lumped (as adsorption only) they may cause the correlation factor to be lower.

4.4.3 Model Mass Balance

A mass balance for the major processes taking place in the wetland was also done so as to see the ones that have greater percentages in phosphorus removal.

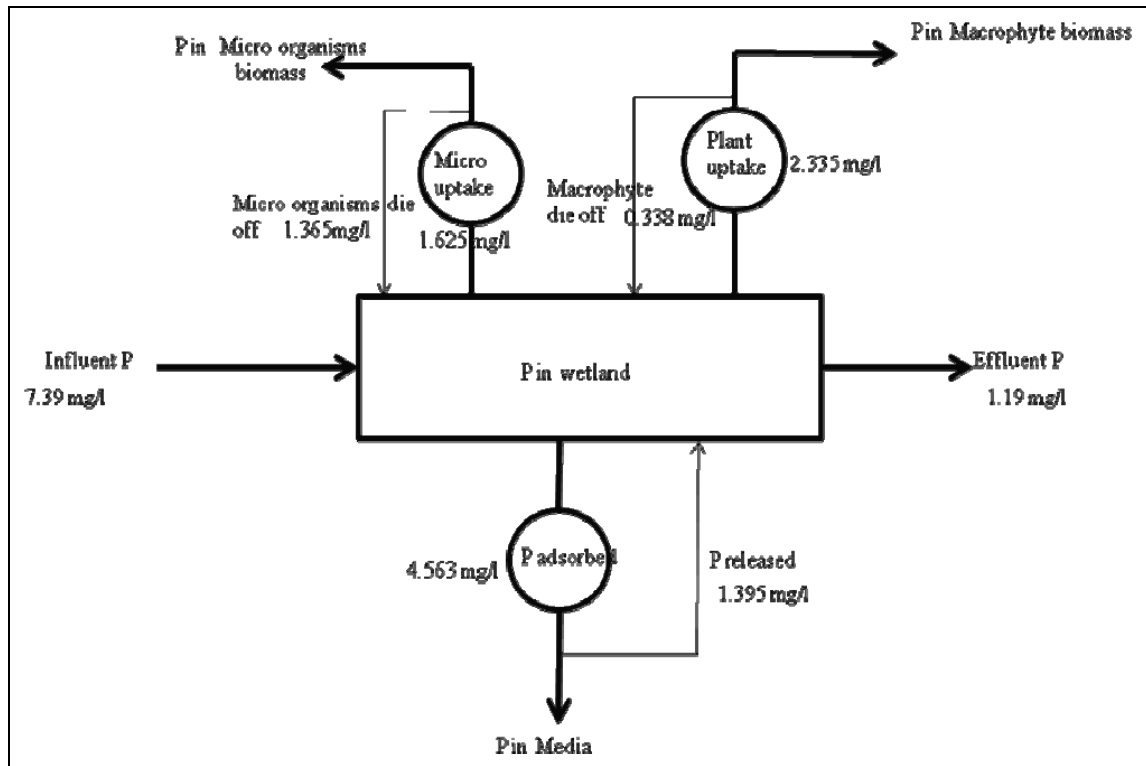


Figure 4.16: Mass Balance of Phosphorus Removal in a *Typha Latifolia* cell

Source: Authors own creativity, (2008)

Figure 4.16 shows the mass balance of major processes which take place in the removal of phosphorus in a cell planted with macrophytes. The major removal of the phosphorus in the wetland was through sand adsorption which accounted for 4.563 mg/l and 1.395mg/l is released back hence removal is 3.168mg/l (42.9%). Plants uptake is 2.335 mg/l with die off release of 0.338mg/l hence phosphorus up taken by plants is 1.997mg/l (27%), lastly the microorganisms accounted for 1.625 mg/l with 1.365 die off release and what is taken microorganisms is (3.5%). This shows that phosphorus

removal is mainly through adsorption and followed by plants uptake, this is in line with what other authors have shown in chapter three (Mann, 1996).

Microorganism show to have an upper uptake of phosphorus from the wetland but the mechanism is not sustainable since the release of phosphorus back into the system due to die off is high (about 84% of what was taken returns) hence the mechanism is more of cycling the nutrients. This is mainly due to that microorganisms have a very short life span as compared to plants, they uptake and release within a short time and the process is cyclic. This process cannot be taken as a major mechanism of phosphorus removal.

Also it can be seen in figure 4.16 that in the model there is some release of phosphorus into the wetland from the sand and plant die off. From the sand it may be due to reactions within the sand which makes the phosphates to desorb. In plants as they grow, they are some leaves/ stalks that fall out and decompose in the wetland which may have accounted for the release of phosphorus back into the system.

From figure 4.16 they has been unaccounted for phosphates values of about 0.775 mg/l (10.5%) in the model, which can be associated with the errors during measurements of the parameters. Also may be because the exact flow rates could not be measured since they was no provision for that in the system hence adopted to use the design flow.

Table 4.3 present the mass balance for the *papyrus cyperus* and the *phragmites mauritianus* computed from the model just like for *typha latifolia*. See appendix D on how it was calculated.

Table 4.3: Mass Balance for *Papyrus Cyperus* and the *Phragmites Mauritianus*

	Influent P	P adsorbed	P released sand	Plant uptake	Plant die off	Micro uptake	Micro die off	Effluent P
<i>Papyrus Cyperus</i>	8.653	2.553	0.408	4.878	2.083	1.463	0.036	0.842
<i>Phragmites Mauritianus</i>	7.530	3.348	0.322	2.817	0.823	1.483	0.045	0.843

Source: Field work, (2008)

Similarly like in the cell for *Typha Latifolia*, the major process for removing phosphorus in the *Phragmites mauritianus* cell is 40.2%, plants uptake is 26.5% and microorganisms contributed 19.1%. Contrary to the trend seen in *Typha latifolia* and *phragmites mauritianus*, *papyrus cyperus* display plants uptake (with 32.3%) as a process that has higher removal percentages as compared to sand adsorption (24.8%). Microorganisms have accounted for (16.5%). Unaccounted for phosphorus, for both *phragmites mauritianus* and *papyrus cyperus* are 3% and 16.7% respectively.

This shows that the major process controlling the removal of phosphorus is sand adsorption followed by plant uptake. Though sand only does remove phosphorus, for thorough wastewater treatment, sand and macrophytes should be used together in a wetland system to enhance wastewater treatment.

4.4.4 Calibration Parameters

In calibrating the model, constants and coefficient were used from available sources. The initial choice of parameters for the model was based on reference from several literatures studied. Table 4.4 present a summary of the calibration parameters used in running the model.

Table 4.4: Calibrated Parameters used in the Model

Parameter	Description	Units	Calibration	Source
b	Bulk density of sand	kg/m ³	0.472	Van der Peijl et al.(1992)
P	Porosity (%)		0.44	Design report.(2004)
Pad Cap	Adsorption capacity of the sand on dry basis	mg/g	0.39	Lab analysis
S _{max}	Maximum sun light		0.5	Jorgensen (1994)
K	Michaelis Meuten Constant	g/m ³	0.9	Jorgensen (1994)
R	Rate Constant	day ⁻¹	0.5	Jorgensen (1994)
Q	Flow rate	m ³ /d	4	Design report.(2004)
V	Volume of the CW	m ³	24	Design report.(2004)
WFP	Fraction of the sand that is filled with water		0.001	Calibration
P con cap	Conc. P at ½ max adsorption cap of sand		18.54	Calibration

Source: Field work, (2008), Van der Peijl *et al.*(1992), Jorgensen (1994), Design report.(2004)

4.4.5 Model Application

The developed model can be applied for the prediction of the phosphorus (PO₄) removal in a domestic based wastewater constructed wetland. The following information is required for the model to run: influent and effluent concentrations of the phosphorus in the wastewater, adsorption capacity of the substratum, the flow rates of the system, and the list of other parameters as per table 4.4.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study was carried out in order to determine the performance of the DWA constructed wetland in removing phosphorus, determine how efficient is the river sand used in the constructed wetland in helping to remove phosphorus, determine which of the plants (macrophytes) is performing better in terms of treating wastewater and finally determine the controlling processes, that are controlling the transformation through modeling (mathematical model-equation).

The data collected show that the wetland is performing very well in removing phosphorus from the wastewater as shown in table 4.2. The effluent quality of 0.63 mg/l from the cell with sand only (control) presents a removal of 93.59%, while the cell with *typha latifolia* with 0.26 mg/l presents a removal of 97.37%, the cell with *papyrus cyperus* with quality of 0.19 mg/l presents a removal of 98.09% and lastly the cell with *phragmites mauritianus* with a quality of 0.16 mg/l presents a removal of 98.40 mg/l.

From this, better performance is in those cells with macrophytes. This is due to the mechanism of plant uptake of nutrients for their biomass production which enhance treatment. Among those cells with macrophytes, the cell planted with *phragmites mauritianus* showed to have better removal percentages as compared to other cells with other macrophytes.

Based on the obtained results in the study, the following conclusions can be made

- The obtained phosphorus removal results show that the DWA constructed wetland is performing well in treating wastewater and the effluent can be reused for irrigation since the quality of effluent (phosphates) meets the required standards (0.5 mg/l) of the wastewater that has to be discharged into the environment.
- The removal efficiencies of the macrophytes supports that out of the three macrophytes used in the wetland, *phragmites mauritianus* is performing better than others.
- The use of sand only in treating wastewater has proved to be performing well and sand can be used as a media (substrate) in wastewater treatment. To enhance the performance, macrophytes should be planted to get the best removal of phosphorus.
- Based on the model results, it can be concluded that substratum adsorption of the wetland plays a very important role in treating wastewater. We can see in the study that the model for each cell show sand adsorption as the major mechanism controlling phosphates removal with higher percentages in mass balance calculations followed by plants uptake.
- This research has also contributed to the body of knowledge in that it has added to the available limited database, the information on performance of CW in

removing phosphorus in Botswana. It is also an eye opener to stakeholders involved with water and wastewater management, who can now opt for the constructed wetland systems in treating domestic wastewater following the results obtained in the study.

5.2 Recommendations

The research was based on one constructed wetland in Gaborone, Botswana, which was constructed to demonstrate to the public that CWs are low cost technologies that can be used in wastewater management in the country. Based on the results it is recommended that:

- Continuous monitoring of the constructed wetland to be done so as to have more data for further research.
- Further research should be carried out on other parameters of the effluent from the pilot DWACW project in order to validate the model and optimize the design of constructed wetlands (HRT) and the applicability of CWs in the country for effluent reuse. This is because the performance of constructed wetlands depends on several factors especially type and size of the substratum used, presence of macrophytes and hydraulic retention time (Sousa et al 2001).
- Education and awareness on the use, benefits and maintenance of constructed wetland be made throughout the country by various stakeholders involved in wastewater management. This will make the public appreciate the system when they are built at large scale in their respective places.

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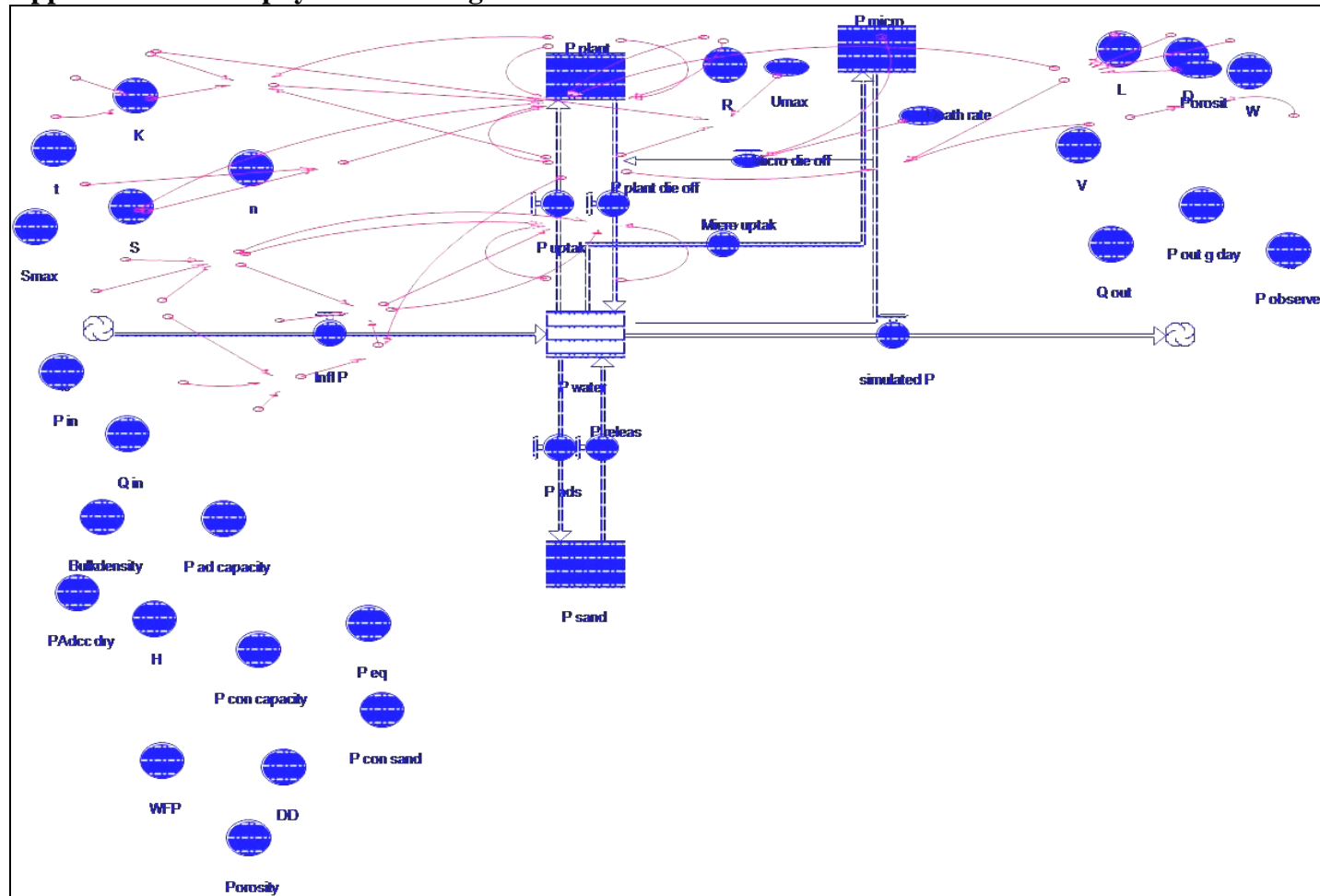
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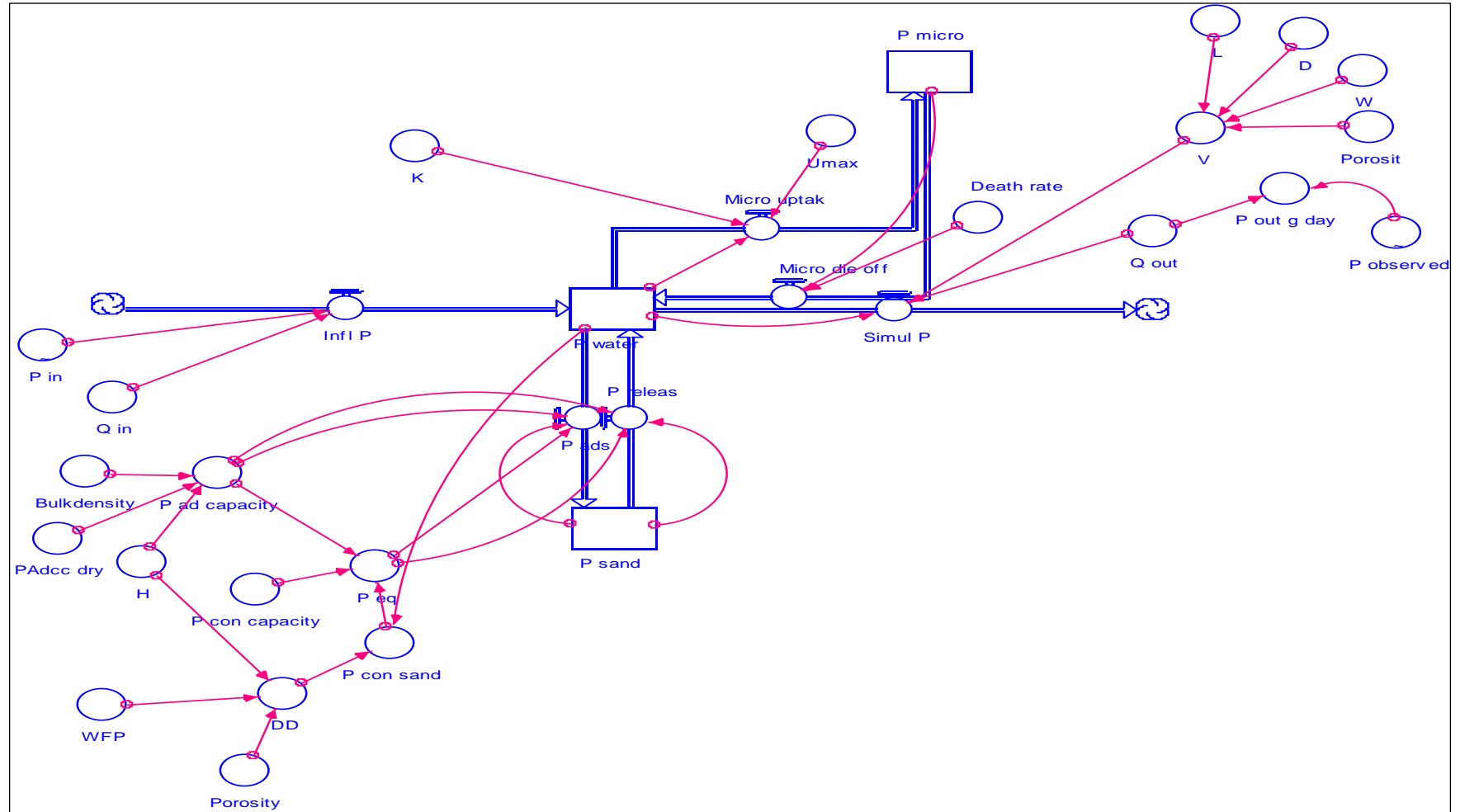
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APPENDICES

Appendix A: Macrophytes Stella diagram



Appendix B: Sand Stella diagram



Appendix C: Stella Equations from the Model

$$P_micro(t) = P_micro(t - dt) + (Micro_uptak - Micro_die_off) * dt$$

$$INIT P_micro = 1$$

INFLOWS:

$$Micro_uptak = Umax * P_water / (K + P_water)$$

OUTFLOWS:

$$Micro_die_off = Death_rate * P_micro$$

$$P_plant(t) = P_plant(t - dt) + (P_uptak - P_plant_die_off) * dt$$

$$INIT P_plant = 19$$

INFLOWS:

$$P_uptak = (Infl_P - P_water) * Q_in / V * (n - R) * P_plant$$

OUTFLOWS:

$$P_plant_die_off = P_plant * R$$

$$P_sand(t) = P_sand(t - dt) + (P_ads - P_releas) * dt$$

$$INIT P_sand = 25$$

INFLOWS:

$$P_ads = (1 - P_sand / P_ad_capacity) * (P_eq - P_sand)$$

OUTFLOWS:

$$P_releas = P_sand / P_ad_capacity * (P_sand - P_eq)$$

$$P_water(t) = P_water(t - dt) + (Infl_P + Micro_die_off + P_plant_die_off + P_releas - Micro_uptak - P_uptak - P_ads - simulated_P) * dt$$

$$INIT P_water = 2$$

INFLOWS:

$$Infl_P = P_in * Q_in$$

$$Micro_die_off = Death_rate * P_micro$$

$$P_plant_die_off = P_plant * R$$

$$P_releas = P_sand / P_ad_capacity * (P_sand - P_eq)$$

OUTFLOWS:

$$Micro_uptak = Umax * P_water / (K + P_water)$$

$$P_uptak = (Infl_P - P_water) * Q_in / V * (n - R) * P_plant$$

$$P_ads = (1 - P_sand / P_ad_capacity) * (P_eq - P_sand)$$

$$\text{simulated_P} = P_{\text{water}}/Q_{\text{out}}*V$$

$$\text{Bulkdensity} = 0.472$$

$$D = 0.6$$

$$DD = \text{Porosity}*H*WFP*1000$$

$$\text{Death_rate} = 0.002$$

$$H = 0.6 \quad K = 0.9 \quad L = 25$$

$$n = S*P_{\text{plant}}/K+P_{\text{water}}$$

$$P_{\text{Adcc_dry}} = 0.39$$

$$\text{Porosity} = 0.44$$

$$P_{\text{ad_capacity}} = \text{Bulkdensity}*P_{\text{Adcc_dry}}*H$$

$$P_{\text{con_capacity}} = 18.54$$

$$P_{\text{con_sand}} = (P_{\text{water}}/DD)*1000$$

$$P_{\text{eq}} = P_{\text{ad_capacity}}*P_{\text{con_sand}}/(P_{\text{con_capacity}}+P_{\text{con_sand}})$$

$$P_{\text{out_obs}} = Q_{\text{out}}*P_{\text{observed}}$$

$$Q_{\text{in}} = 5$$

$$Q_{\text{out}} = 5$$

$$R = 0.01$$

$$S = S_{\text{max}}*(1+\text{SIN}(0.008603)*t)$$

$$S_{\text{max}} = 0.5 \quad t = 1 \quad U_{\text{max}} = 0.001$$

$$V = L*D*W*\text{Porosit} \quad W = 4 \quad WFP = 0.001$$

$$P_{\text{in}} = \text{GRAPH}(\text{time})$$

(0.00, 0.00), (1.00, 5.39), (2.00, 12.4), (3.00, 3.14), (4.00, 0.00), (5.00, 11.0), (6.00, 10.3), (7.00, 7.04), (8.00, 13.1), (9.00, 10.2), (10.0, 15.8), (11.0, 16.8), (12.0, 11.0), (13.0, 17.8), (14.0, 9.90), (15.0, 4.97), (16.0, 8.70), (17.0, 19.5), (18.0, 14.4), (19.0, 19.1), (20.0, 5.20), (21.0, 6.00), (22.0, 3.08), (23.0, 10.8), (24.0, 9.11), (25.0, 0.00)

$$P_{\text{observed}} = \text{GRAPH}(\text{time})$$

(0.00, 0.00), (1.00, 0.11), (2.00, 0.2), (3.00, 0.12), (4.00, 0.12), (5.00, 0.04), (6.00, 0.35), (7.00, 0.1), (8.00, 0.28), (9.00, 0.38), (10.0, 0.6), (11.0, 0.00), (12.0, 0.26), (13.0, 0.5), (14.0, 0.3), (15.0, 0.7), (16.0, 0.41), (17.0, 0.00), (18.0, 0.03), (19.0, 0.49), (20.0, 0.3), (21.0, 0.45), (22.0, 0.2), (23.0, 0.00), (24.0, 0.52), (25.0, 0.00)

Appendix D: Mass balance calculations from the Model*Typha Latifolia* Cell

Weeks	PO4 in	P adsorption	P desorption	Plant uptake	Plant release	Micro uptake	Micro die off	PO4 out
0	0	27.05	14.55	8.13	3.58	1.42	1.22	0
2	12.38	7.06	4.03	4.96	1.2	1.5	1.25	1
4	0	5.01	0	2.33	0	1.85	1.5	0.6
6	10.34	3.7	2.12	4.01	0.02	1.5	1.5	1.75
8	13.09	4.19	0	3.04	0	1.76	1.03	1.4
10	15.82	1.98	0.04	2.32	0.01	2.5	1.41	3
12	10.96	1.34	0	2.86	0	1.5	1.3	1.3
14	7.8	0	0.12	0	0.2	1.5	1.5	1.5
16	8.7	2.03	0	2.31	0	1.5	1.25	2.05
18	14.37	3.6	0	1.74	0.06	1.5	1.5	0.15
20	5.2	2.6	0.06	1.38	0	1.5	1.4	1.5
22	3.08	4.58	0	0.92	0	1.5	1.2	1
24	9.11	5.31	0	1.02	0	1.5	1.5	2.6
26	0	0	0	0	0	1.5	1.41	0
28	0	0	0	0	0	1.85	1.5	0
Average	7.39	4.563	1.395	2.335	0.338	1.625	1.365	1.19

Papyrus Cyperus Cell

Weeks	PO4 in	P adsorption	P desorption	Plant uptake	Plant release	Micro uptake	Micro die off	PO4 out
0	0	4.34	4.84	4.3	0.38	1.23	0	0
2	12.38	0.03	0.04	8.92	8.6	1.47	0.01	1
4	0	2.07	0	11.26	5.42	1.47	0.02	0.5
6	10.34	3.67	0.01	9.45	10.58	1.48	0.02	0.7
8	13.09	4.63	0	7.29	0	1.49	0.03	0.75
10	15.82	5.98	0	5.36	0	1.49	0.03	1.15

Weeks	PO4 in	P adsorption	P desorption	Plant uptake	Plant release	Micro uptake	Micro die off	PO4 out
12	10.96	2.82	0	0	0.01	1.49	0.04	0.8
14	9.9	0	0	6.75	0	1.49	0.04	1.6
16	8.7	1.03	0	0	0	1.49	0.05	1
18	14.37	6.07	0	5.2	0	1.49	0.06	0.85
20	5.2	0	0	0	0	1.49	0.06	1
22	3.08	0	0	0	0	1.48	0.07	0.75
Average	8.653	2.553	0.408	4.878	2.083	1.463	0.036	0.842

Phragmites Mauritianus Cell

Weeks	PO4 in	P adsorption	P desorption	Plant uptake	Plant release	Micro uptake	Micro die off	PO4 out
0	0	4.33	4.83	4.33	0.5	1.25	0	0
2	12.38	0.03	0	3.87	6.03	1.5	0.01	0
4	0	3.29	0	3.65	3.27	1.5	0.02	0.4
6	10.34	0	0	0	2.55	1.5	0.02	6
8	13.09	6.01	0	6.74	0	1.5	0.03	0.9
10	15.82	5.89	0	5.19	0	1.5	0.03	0
12	10.96	0	0	7.29	0	1.5	0.04	0
14	9.9	4.81	0	3.43	0	1.5	0.05	0
16	8.7	5.32	0	0	0	1.5	0.05	1.15
18	14.37	7.32	0	2.02	0	1.5	0.06	1.25
20	5.2	6.51	0	3.67	0	1.5	0.06	0.95
22	3.08	4.33	0	2.07	0	1.5	0.07	1.4
24	9.11	2.38	0	0	0	1.5	0.07	0
26	0	0	0	0	0	1.5	0.08	0
28	0	0	0	0	0	1.5	0.09	0.6
Average	7.530	3.348	0.322	2.817	0.823	1.483	0.045	0.843

Sand Only Cell

Weeks	PO4 in	P adsorption	P desorption	Micro uptake	Micro die off	PO4 out
0	0	7.25	7.75	0.81	0	2.15
2	12.38	0.04	0.02	0.98	0.01	6
4	0	0	0	0.97	0.01	1.5
6	10.34	6.32	0	1.2	0.01	2.4
8	13.09	5.56	0	0.99	0.02	0
10	15.82	8.21	0	0.99	0.02	6.5
12	10.96	7.32	0	1.42	0.03	1.5
14	9.9	6.19	0	0.99	0.03	0
16	8.7	5.38	0	0.99	0.03	0.15
18	14.37	4.94	0	0.99	0.04	0
20	5.2	3.66	0	0.99	0.04	1.15
22	3.08	0	0	0.99	0.05	5.5
Average	8.653	4.573	0.648	1.026	0.024	2.238

Appendix E: Data Used in Simulations and Correlations

Papyrus Cyperus

P out Observed	Simulated P values
0	0
1	1.3
0.5	0.7
0.7	0.9
0.75	1.2
1.15	1.47
0.8	1.38
1.6	2.29
1	1.5
0.85	1.11

Phragmites Mauritianus

P out observed	Simulated P values
0	2.39
0	0.8
0.4	2.2
6	6.6
0.9	2.4
0	0.5
0	0.9
0	0.3
1.15	0.77
1.25	2.3

P out Observed	Simulated P values
1	1.3
0.75	0.75
0	0.69
0.9	0.93
0.9	1.6
0.9	0.5

P out observed	Simulated P values
0.95	0.77
1.4	0.6
0	1.8
0	0.6
0.6	0.8
0.8	2.4

Typha Latifolia

P out observed	Simulated P values
0	0
1	0.6
0.6	1.2
1.75	2.5
1.4	2
3	4.2
1.3	2.1
1.5	2.4
2.05	3.2
0.15	1.6
1.5	2.1
1	1.4
2.6	3.5
0	1.7
0	1.1
0	1.5

Sand Only

P out observed	Simulated P values
2.15	1
6	4.9
1.5	3
2.4	2.7
0	1.1
6.5	5.3
1.5	4.6
0	2
0.15	0.7
0	2.4
1.15	2.8
5.5	3.4
0	2.1

All measurements in g/day

Appendix F: Study Area Photo

Source of photo: Google Earth

In all things...