NUTRIENT REMOVAL IN A CONSTRUCTED WETLAND, AND IMPACT ON WATER QUALITY IN A DOWNSTREAM POND

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ABSTRACT

Research was conducted on Dick's Pond in Columbiana County, OH. The pond has been affected by high concentrations of nutrients entering the pond, causing heavy growth of algae and duckweed. A constructed wetland was built to remove nutrients from the pond inflow in order to make the pond less productive and more aesthetically appealing. A preliminary monitoring program was conducted to measure the water quality and trophic condition of the pond before wetland construction. Post-construction monitoring was performed to evaluate changes in the pond's water quality after wetland construction and nutrient removal at several points within the wetland. Data were analyzed using statistics, the Student's t-test, and a mathematical model of phosphorus removal in the wetland.

Nutrient and chlorophyll a measurements indicate that the pond is highly eutrophic. Concentrations were highly variable, depending on season and runoff from the watershed. The mean total and soluble phosphorus concentrations after wetland construction were well below the levels observed before construction in the pond's water column. The Student's t-test indicated a high probability that the decrease in phosphorus was due to real changes in the system. A settling pond and wetland cell #1 appear to be removing phosphorus, but not nitrate, from the inflow, while data on the performance of wetland cell #2 are inconclusive. The calculated removal rate constant for phosphorus in wetland cell #1 was much greater than values reported for studies on natural wetlands.

This project is dedicated to my parents and sister. Without their love, support and motivation, I would not be able to endeavor my goals and be able to reach my dreams. I would like to let my family know that whatever I am today and whatever good I may do in my life, I owe it all to them.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Overview of Nutrient Enrichment

Eutrophication of aquatic systems takes place when the environment becomes enriched with nutrients. The entry of nutrients such as nitrogen and phosphorus into the water body causes the growth of algae on the surface, which can reduce its aesthetic appeal and impair the health of the pond ecosystem.

1.1.1 Sources of Nutrients

The two main types of nutrient sources are point sources and non-point sources. Point source contamination enters water bodies at a well defined location, such the discharge from waste water treatment plants and factories. On the other hand, non-point sources come from widespread areas, such as runoff from the land surface or atmospheric deposition. Examples include fertilizers, pesticides, and animal wastes from agricultural and residential lands; about90% of nitrogen and 75% of phosphorus originates from non-point sources, whereas the remaining nutrients come from the point sources (USGS, 1999).

A lake, reservoir, or pond can be naturally eutrophied when situated in a fertile area. However, nutrients from human activity often greatly accelerate productivity. The activity that takes place in the drainage area of the water body reflects directly or indirectly in the water quality. The drainage water coming from agricultural land often contains high concentrations of phosphorus and nitrogen resulting from the excessive use of fertilizers for crop production or runoff of animal waste. Other sources of nutrients to surface waters include precipitation (rain or snow) and municipal or residential wastewater.

Nutrients are present in several forms, such as dissolved inorganic, dissolved organic, particulate inorganic, and particulate organic (including biotic) forms. Nutrients in dissolved inorganic form contribute most directly to primary productivity; however, other forms may also become available for uptake by algae through a variety of nutrient cycling processes.

1.1.2 Effects – High Algal Productivity

High loadings of phosphorus and nitrogen into aquatic systems can cause high algal productivity. The simple inorganic nutrients are converted to more complex organic molecules as algae utilize photosynthesis for the conversion. Algae refer to a wide variety of photosynthetic organisms. If the N:P ratio in a lake is above 15:1-16:1 by weight, the severity of algal blooms will generally be controlled by the excess availability of phosphorus(Schindler,1978; Jaworski, 1981). Heavy growth of algae can result in several negative environmental effects. Algae produce endo or exotoxins which may be harmful to aquatic life. The abundant growth of algae shades deeper parts of the water column, preventing photosynthetic activity. The algae also have impacts on temperature, dissolved oxygen and nutrient cycling.

1.1.3 Effects- Low DO in Hypolimnion

When algae settles to the bottom of a pond or lake and decomposes, dissolved oxygen is depleted. Also, during low light/nighttime periods, algae carry out respiration which consumes dissolved oxygen in the upper part of the water column. Hypolimnetic oxygen depletion is a condition where the dissolved oxygen (DO) in the bottom layer of a lake or pond is gradually consumed through respiration and decomposition faster that it can be replaced over the course of the summer. Low DO is an important result of eutrophication. The decrease in DO causes significant changes in chemistry and biology of a pond. Low DO in the hypolimnion causes the loss of benthic species of plants and animals (Carlson and Simpson, 1996), as well as higher organisms such as fish. The depletion of oxygen in the hypolimnion also leads to the accumulation of phosphate, ammonia, and hydrogen sulfide, which can cause severe odors in the water.

1.2 Use of Constructed Wetlands for Nutrient Removal

The term wetland includes a wide range of ecosystems from areas that are never flooded to areas that are deeply flooded all of the time (Kadlec, and Knight, 1996). Wetlands provide water storage and flood protection during wet periods, water reserve during dry periods, retention of sediments and associated pollutants, retention of nutrients, and provision of recreational areas (Hatterman *et al.,* 2008). Wetlands reduce nutrient loading by encouraging sedimentation (Karr and Schlosser, 1978; Johnston *et al.*, 1984), sorbing nutrients to sediments, taking up nutrients in plant biomass and enhancing denitrification(Lowrence *et al.,*1984). Constructed wetlands have been successful worldwide for treating various types of wastewater, including storm water, industrial, domestic, and agricultural wastewater, mine drainage and landfill leachate (Kadlec and Knight, 1996). For the removal of phosphorus from both point and non-point sources, wetlands can function as active sinks (Reddy *et al.,* 1999; Richardson, 1999; Kadlec, 2005), resulting in lower productivity in downstream lakes. Either constructed or natural wetlands are a low-cost alternative technology for wastewater treatment (Sim, 2003) and water quality improvement. Wetlands can tolerate wide variations in flow and contaminant levels.

1.2.1 Case Study

Fisher and Acreman (2004) conducted a review of nutrient removal in wetlands. They collected data from 57 wetlands around the world to investigate whether wetlands affect the nutrient loading of waters draining through them. The main objective of the research was to answer three questions:

1. Is N or P retained within natural wetlands?
2. Which type of wetland is the most effective at removing N and P?
3. What are the main influences affecting nutrient reduction?

Questions 2 and 3 are most relevant to this research. The authors reported that both man-made and natural wetlands are being used to improve the water quality of road runoff, sewage or agricultural run-off. Marshes or swamps and riparian zones were found to be most effective at removing N and P. Of the wetlands studied, 7% more of the riparian wetlands reduced TP loading than swamps or marshes.

1.3 Site Description

The subject of this study was Dick's Pond, which is located on 41300 Miller Road in Fairfield Township, Columbiana County, Ohio, at an elevation of 1206 ft (368 m). The pond lies on property owned by Dr. Jeffrey Dick, Professor of Geology at Youngstown State University (YSU). The pond has a surface area of about 0.66 acres (0.267 ha) and volume of about 14,700 ft^3 (416 m^3) (Dick, personal communication, 2010). The maximum depth of the pond is approximately 9.5 ft (2.9 m).

Most of the inflow to the pond comes from an intermittent inlet stream that runs through nearby farmland. There is a small stream which joins the inlet stream just before it enters the pond. The characteristics of the pond change often depending on the climatic conditions, after storm events, the pond frequently becomes very turbid due to soil erosion from the farmland. During the summer, the pond exhibits eutrophic conditions, with heavy growth of algae or duckweed. In an effort to improve water quality in the pond, a small constructed wetland was built in October, 2010 to remove suspended solids and nutrients from the inflow.

1.4 Research Goals

The goal of this research was to evaluate the effectiveness of the constructed wetland in improving water quality in Dick's Pond. The project consisted of the following components:

1. Estimate the flow and nutrient (phosphorus and nitrogen) loadings entering the pond from its watershed;
2. Collect background data on water quality in the pond before construction of the wetland;
3. Collect data on water quality in the wetland and the pond after construction of the wetland;
4. Perform statistical analysis of data to evaluate nutrient removal in the wetland; and
5. Evaluate mathematical model of nutrient removal in the wetland.

CHAPTER 2

LITERATURE REVIEW

2.1 Forms and Sources of Phosphorus

2.1.1 Forms of Phosphorus

In water, phosphorus (P) exists in either soluble (dissolved) phase or a particulate phase (Murphy, 2007). The primary dissolved form of phosphorus is orthophosphorus, which is readily available to algae and aquatic plants. In response to a variety of environmental conditions, particulate phosphorus can change from one form to another (Minnesota Pollution Control Agency, 2007). Algae, plant and animal tissue, waste solids, or other organic matter contains a portion of particulate phosphorus. Since phosphorus changes form, to determine the amount of nutrient that can feed the growth of algae, total phosphorus is measured rather than any single form (Minnesota Pollution Control Agency, 2007).

In soils, phosphorus can be thought of as existing in 3 forms: solution P, active P and fixed P (Busman *et al.*, 2009). Solution phosphorus will usually be in the orthophosphate form. The solution P form is very important as this form of phosphorus has the highest mobility and is the only form from which plants take up phosphorus (Busman *et al.*, 2009). Active phosphorus is particulate forms of phosphorus that are relatively easily released to the soil solution (water surrounding soil particles). Active phosphorus is the main source of available phosphorus for crops as solution phosphorus is very small (Busman *et al.*, 2009). The fixed form of phosphorus remains in soils for years and may not be available to plants and may have little impact on the fertility of a soil (Busman *et al.*, 2009).

2.1.2 Sources of Phosphorus

Human and animal wastes, industrial wastes, soil erosion and fertilizers are the main sources of phosphorus. Fertilizers contain phosphorus in the orthophosphate form (Murphy, 2007). As phosphate is not mobile in soil, it tends to be attached to the soil particles instead of dissolving in water. Soil erosion of fertilized fields can also be a source of phosphorus in streams (Murphy, 2007). If fertilizers are applied in large amounts, phosphates will be carried into surface water with storm runoff.

The sources of phosphorus into the water can be either from point sources or non-point sources. Non-point source pollution is often significantly higher than point source pollution (Smolen, 2004). Approximately two thirds of total phosphorus load to lakes and rivers comes from non-point sources such as runoff from croplands, atmospheric deposition and stream bank erosion (Smolen, 2004). Compared to the amount of soluble phosphorus in runoff, sediments often carry higher concentrations of phosphorus.

During conditions when oxygen is depleted in the water column, phosphorus moves readily from the sediment into the water column, resulting in internal recycling of phosphorus and increased growth of algae (Makarewicz, 2010).

2.1.3 Role of Storm Events in Phosphorus Loading

Loading rates of any pollutant can be calculated from the product of pollutant concentration and flow rate of the stream in which it is transported. The loading rates of nutrients are higher during storm events compared with base flow conditions (Figure 2.1). The primary reason for higher loading rates during the storm events is the large disparity in flows. It is not uncommon for flow in natural streams to increase by one, or even two, orders of magnitude after major storm events. To evaluate the effects of land use, loading rates from non-point sources are often expressed in lb/d/mi^2 (pounds of the pollutant per day per square mile of drainage area). Figure 2.1 show that the sampling was done along the mainstem Lackawanna River (LAWR) to measure the loading rates for base flow and storm flow. From Figure 2.1 it can be observed that the loading rates were below 1.0 lb/day/mi^2 for base flow, and the loading rates increased by the factor of three to four during the storm events.

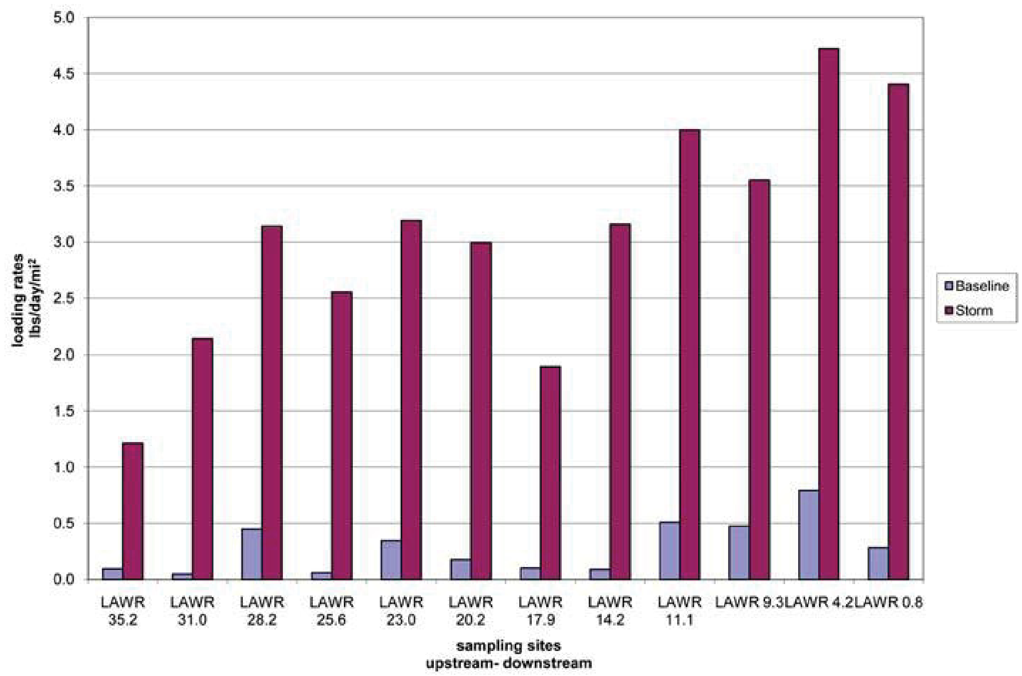

Figure 2.1 Example for Total Phosphorus Loading (Buda, 2009)

2.1.4 Phosphorus Cycling Processes

The phosphorus cycle is different when compared with other nutrient cycles. As phosphorus has no gaseous phase, it has no major atmospheric component to its cycle (Turner; and Raboy, 2003). The processes involved in the cycling of phosphorus are biological, physical and chemical. The geological and biological cycles are considered as long-term and short-term processes, respectively, the latter with terrestrial and aquatic components.

2.1.4.1 Geological Cycle

The geological phosphorus cycle (Figure 2.2) begins with slow dissolution and weathering of phosphate minerals in the environment. The released phosphorus may enter the terrestrial biological cycle (soil-plant-animal system) during the short term. In the long term, phosphorus leaches slowly from the soil and is transported by rivers to lakes or the oceans (Turner; and Raboy, 2003). If the phosphorus is taken up by phytoplankton, then it enters into the aquatic biological cycle. Otherwise, it will precipitate with calcium and settle down to the lake or ocean sediment (Turner; and Raboy, 2003).

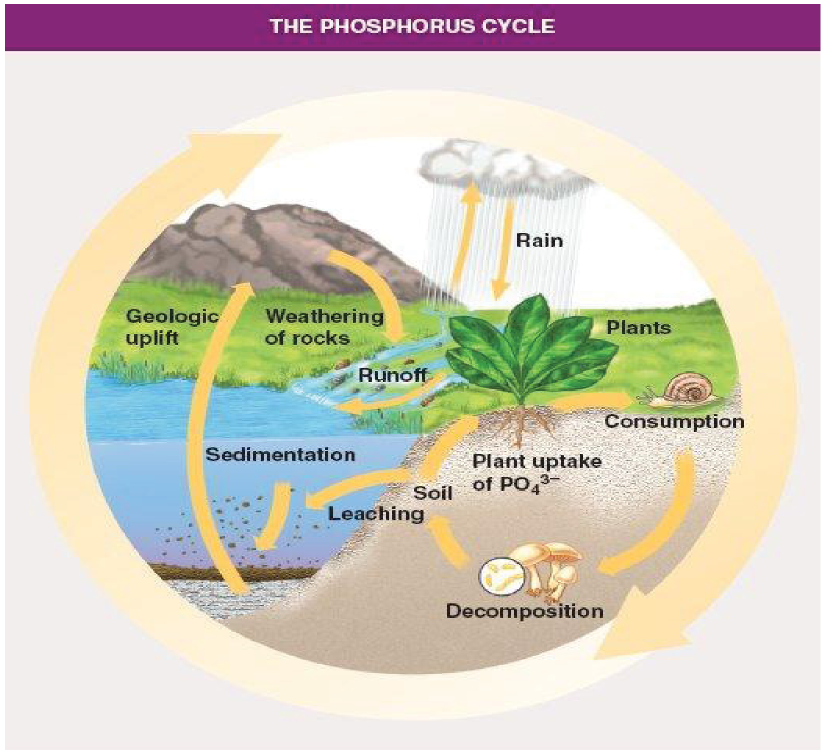

Figure 2.2 Simplified Geological Phosphorus Cycle (Larson, 2011)

2.1.4.2 Biological Cycle

The presence of phosphorus in soil plays a vital role in determining the ecology of terrestrial ecosystems. The availability of orthophosphate in soil is low when plants uptake phosphorus from soil solution in the form of inorganic orthophosphate (Turner; and Raboy, 2003). By the weathering and dissolution of apatite, a group of calcium phosphate minerals, phosphorus is released slowly in the earlier stages of soil formation. Inorganic phosphorus reacts strongly in the soil, forming precipitates with calcium, iron and aluminum (Turner; and Raboy, 2003) and adsorbing to the surface of soil particles. Plants convert inorganic orthophosphate to organic forms of phosphorus after uptake from the soil. The organic compounds present in the soil from plant residue represent the major soil phosphorus fraction in natural terrestrial systems (Turner; and Raboy, 2003).

The conversion of organic phosphorus to inorganic forms through decomposition (hydrolysis) is a key stage in the biological phosphorus cycle (Turner; and Raboy, 2003).

2.1.5 Effects of Phosphorus

Phosphorus is regarded as a multivalent nonmetal of the nitrogen group (Lenntech, 1998). It is an essential element for the life of aquatic and terrestrial organisms. Phosphorus is the most common limiting factor for vegetative productivity in lakes and ponds (Lenntech, 1998). In nature, phosphorus is never found in its pure form; it is usually encountered as phosphate, which consists of a phosphorus atom bonded to four oxygen atoms (Lenntech, 1998). In water, phosphorus does not react quickly with other substances, which allows it to accumulate in the bodies of aquatic organisms.

Even small concentrations of phosphorus in water can accelerate the growth of phosphate dependent organisms, such as algae and duckweed. This phenomenon is known as eutrophication. The growth of these organisms on the surface of the water greatly reduces the transparency of the water, making it less desirable for many uses, including swimming, boating, and drinking. When algae settles and decomposes, oxygen is depleted, which can make the water body unlivable for other organisms, such as fish (Kadlec, 2005; Kadlec and Knight, 1996).

2.2 Trophic Status Classification

Since the ultimate goal in this project was to improve water quality in Dick's Pond, classification of the trophic status of the pond water body must be given consideration. In general, the following terms are used to classify the biological productivity (or trophic status) of lakes:

- Oligotrophic – low productivity
- Mesotrophic – moderate productivity
- Eutrophic – high productivity

Several researchers have developed methods for classifying lake trophic status based on nutrient concentrations, hydraulic and morphometric characteristics, and/or biomass indicators. Since phosphorus most often acts as the growth-limiting factor to algae, and nitrogen cycling complicates the accurate measurement of nitrogen loading into water bodies, the models emphasize phosphorus relationships. For example, in one of the simplest classification systems, Vollenweider (1968) found that lakes with spring total phosphorus (TP) concentrations less than 10 μg/L are typically oligotrophic, and those with TP > 20 μg/L are usually eutrophic. Wetzel (2001) summarized typical values of nitrogen, phosphorus, chlorophyll, and Secchi depth transparency for lakes and reservoirs of different productivity levels, based on data obtained by the Organization for Economic Cooperation and Development (Vollenweider, 1968; Rast and Lee, 1978). This summary is presented in Table 2.1.

An example of a graphical method that incorporates the hydraulics and morphometry of lakes is shown in Figure 2.3. In this model, the boundaries between oligotrophic, mesotrophic, and eutrophic lakes are defined by relating areal TP loading rates to mean depth divided by hydraulic retention time.

Table 2.1 Trophic Classification of lakes and reservoirs in relation to Phosphorus and Nitrogen (Wetzel, 2001)

Parameter(annual mean values)	Oligotrophic	Mesotrophic	Eutrophic
Total Phosphorus (μg/L)	8.0 (3.0-17.7)	26.7 (10.9-95.6)	84.4 (16-386)
Nitrogen (μg/L)	661 (307-1630)	753 (361-1387)	1875 (393-6100)
Chlorophyll *a* (μg/L)	1.7 (0.3-10.6)	4.7 (3-11)	14.3 (3-78)
Secchi transparency depth (m)	9.9 (5.4-28.3)	4.2 (1.5-8.1)	2.45 (0.8-7.0)

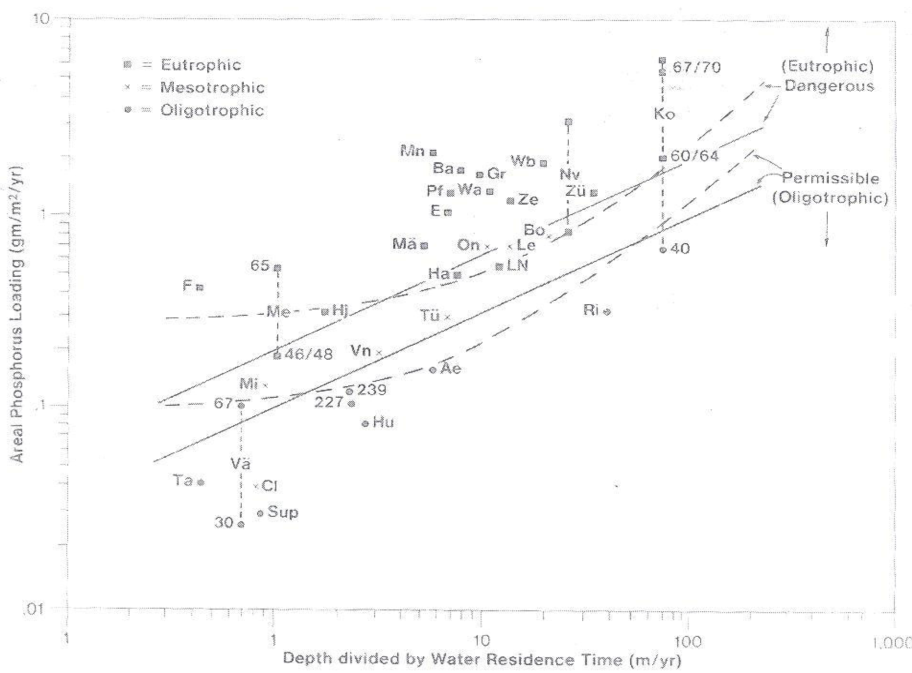

Figure 2.3 Graphical method of trophic status classification incorporating the hydraulics and morphometry of lakes (Reckhow; and Chapra, 1983)

2.3 Characteristics and Types of Wetlands

2.3.1 What are wetlands?

Under the Clean Water Act, the U.S Army Corps of Engineers defined wetlands as “those areas that are inundated or saturated by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions” (U.S. EPA, 2011). Wetlands are considered as the most biologically productive ecosystems on Earth and are composed of a number of physical, biological or chemical components such as soils, water, plant and animal species and nutrients. Wetlands can also be defined as land areas that are wet during part or all of the year because of their location in landscape (N.C. Division of Coastal Management, 2007). Aquatic and terrestrial species can be supported by wetlands (Figure 2.4). Due to the prolonged presence of water, conditions that favor the growth of specially adapted plants and the development of characteristic wetland soils are created. Wetlands provide large quantities of food that attract many animal species. Apart from the fact that various wetland types look and function differently, all wetlands share certain common properties, including characteristic wetland vegetation, hydric soils and hydrologic features (N.C. Division of Coastal Management, 2007). Wetlands help to protect neighboring land, reduce soil erosion, and provide recharge areas for groundwater aquifers, in addition to offering habitat for plants and animals. According to Kadlec and Knight (1996), the technical meaning of the term wetland includes a wide range of ecosystems from areas that are never flooded to areas that are deeply flooded at all times.

Figure 2.4 Wetland (Department of Planning and Development Division of County Development Land and Water Conservation, 2011)

2.3.2 Basic Characteristics of Wetlands

Wetlands can be recognized using three characteristics: vegetation, soil and hydrology. For an area to be a wetland, all three characteristics must be present during some portion of the growing season. The characteristics of these wetland indicators are explained below.

2.3.2.1 Vegetation Indicators

There are nearly 5000 plant types in United States which are known as hydrophytic vegetation that may occur in wetlands. The presence of wetland vegetation can be determined by identifying the plant types in that area. Cattails, bulrushes, cord grass, bald cypress, willows, mangroves, sedges, rushes and water plantains are some of the examples of hydrophytic plants that occur in wetlands. Certain physical properties are exhibited by the plants that grow in wetlands, including shallow root systems, swollen trunks, or roots found growing from the plant stem or trunk above the soil surface (Environmental Laboratory, 1987).

2.3.2.2 Soil Indicators

Hydric soils are the soils that occur in wetlands. The characteristics of hydric soils indicate conditions where soil oxygen is limited by the presence of saturated conditions for prolonged periods during the growing season. Wetland soils fall into two broad categories – organic and mineral. Hydric organic soils are thick, mucky, and dark brown to black in color due to the decomposition of organic material, mostly from plants (Fisher, 1998). Hydric mineral soils are often gleyed (grey colored) with bright mottles and/or iron and manganese concretions (Environmental Laboratory, 1987). The area may be a wetland if the soil in that area is listed as a hydric soil by Natural Resource Conservation Service (NRCS). Soil type for a given location can usually be determined by consulting a county soil survey report.

2.3.2.3 Hydrology Indicators

It's hard to recognize some wetlands as they are dry during part of the year. The presence of water at or above the soil surface for a sufficient period of the year to influence the plant types and soils is referred as wetland hydrology. Hydrologic indicators can be observed during field inspection. Some evidence of the periodic presence of flooding or soil saturation includes (Environmental Laboratory, 1987):

- During the growing season standing or flowing water is observed on the area.

- Soil is waterlogged during the growing season.
- Water marks are present on trees or other erect objects.
- Small piles of debris oriented in the direction of water movement through an area which are known as drift lines, are present.
- Thin layers of sediments are deposited on leaves or other objects.

2.3.3 Types of Wetland

There are several different types of natural wetlands found throughout the world. Some of the wetlands are seasonally aquatic and some are seasonally terrestrial. The four general categories of wetlands are marshes, swamps, bogs and fens.

Marshes: Salt water marshes and fresh water marshes are two types of marshes. Marshes (Figure 2.5) are characterized by poorly drained mineral soils and by plant life dominated by grasses. Nutrient enriched sediments are deposited, as the marsh plants slow down the flow of water. Marshes receive surface water, and some of them are also fed by groundwater (US EPA, 2011)

Figure 2.5 Marsh (US EPA, 2011)

Swamp: Swamps (Figure 2.6) are wetland ecosystems that may hold different types of plants and animals. They are characterized by mineral soils with poor drainage and are dominated by trees or shrubs. Swamps are found in low-lying regions next to rivers, which supply the swamp with water (US EPA, 2011).

Figure 2.6 Swamp (US EPA, 2011).

Bog: Bogs (Figure 2.7) area type of wetland ecosystem usually found in cold regions of the world. These are formed from shallow lakes, slowly moving water and areas with poor drainage. Bogs are characterized by wet, spongy and poorly drained peaty soil, dominated by the growth of bog mosses. The water received by the bogs is entirely from rainfall. Bogs usually have no inflow or outflow. As the water is very acidic, bogs do not usually support a diverse population of animals, other than insects.

Figure 2.7 Carlisle Bog in Alaska. **(US EPA, 2011)**

Fen: Fens (Figure 2.8) are characterized by peaty soil, and dominated by grass like plants, grasses, sedges and reeds. Fens receive water mostly from surface and ground water sources. Compared to bogs, fens are less acidic and have higher nutrient levels. Therefore, they are able to support much more diverse plant and animal communities (US EPA, 2011).

Figure 2.8 Fens (US EPA, 2011)

2.3.4 Constructed Wetlands

Wetlands can also be classified based on their treatment systems. There are three basic types of wetland treatment systems: natural wetlands, constructed surface flow wetlands, and constructed subsurface flow wetlands. Natural wetlands are the wetlands which require high level of pretreatment. Constructed surface flow wetlands are considered into the category which are densely vegetated by a variety of plant species and typically have water depths less than 1.3 ft (0.4 m). The constructed subsurface flow wetlands use a bed of soil or gravel as a substrate for growth of rooted wetland plants.

Treatment wetlands are capable of removing phosphorus from waste waters on both short-term and long-term basis (Kadlec, 2005; Kadlec and Knight, 1996). They are one of the least expensive treatment systems to operate and maintain. The largest constructed treatment wetland is the 4,447 acres (1800-ha) KIS-Balton project in Hungary, which has operated since 1985 (Kadlec, Knight, 1996).

2.4 Phosphorus Removal in Wetlands

2.4.1 Phosphorus Dynamics – Review of a Case Study

Johanneson, *et al.* (2011) conducted a study to determine the efficiency of a constructed wetland in southeast Sweden for retention of sediment-associated phosphorus. The wetland was constructed in 2003 to increase biodiversity and to favor nutrient removal. The wetland surface area is 5.1 acres (2.1 ha) with a catchment area of 237 acres (96 ha). The catchment area covers 84 acres (34 ha) of arable land, 138.3 acres (56 ha) of forest and 14.8 acres (6 ha) of pastures. The catchment consists of three areas, where the largest sub-catchment (Area 1, Figure 2.9) drains to the inlet pipe and other two (Areas 2 and 3) to the sides of the wetland.

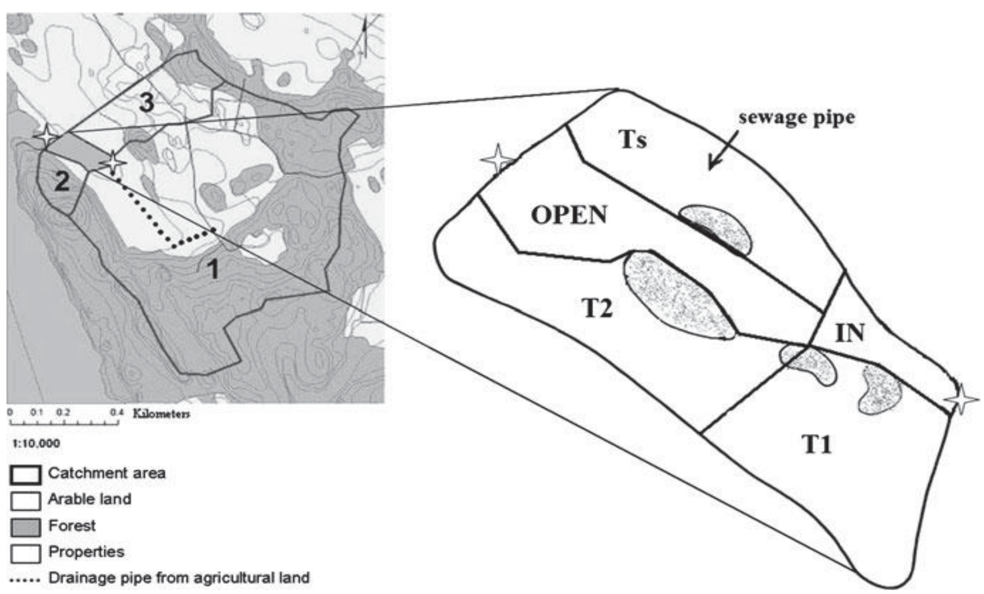

Figure 2.9 Catchment areas for Sodra Stene Wetland studied by Johanneson (Karlsson, 2005)

Using the combined flow meters and water samplers since April 2004, rainfall and flow-proportional water samples were collected. Sampling was done during three high-flow periods (April 2007, Dec 2007, and March 2008) and analyzed for total phosphorus. The results showed that the large sub-catchment contributed 79% of the phosphorus load, while sub-catchments 2 and 3 contributed 21% of P loading, and that 14% of annual P load entered the wetland from arable land (Eriksson *et al*., 2009). The authors found that, during the first 4 years after construction, the wetland acted as a trap for clay-bound phosphorus, as 78% of the total P load was found in sediment near the inlet. There is a need to add measurements of sediment accumulation to inflow-outflow studies for an improved understanding of phosphorus retention in constructed wetlands (Johannesson *et al.*, 2011).

2.4.2 Modeling Approach

Mathematical models for the removal of phosphorus through a constructed wetland can be used to account for site-specific conditions, such as geometry and hydraulics, and to compare the study site to other wetlands. The simple model equation used in this study expresses total phosphorus removal as a first order areal uptake process (Kadlec and Knight, 1996). The equation is as follows:

$$\ln\left(\frac{C}{C_i}\right) = \left(\frac{-k}{q}\right) * y \qquad \textbf{(2.1)}$$

Where C_i = pollutant concentration at start, g/m^3

C = pollutant concentration at time t, g/m^3

q = hydraulic loading rate, m/yr

$$q = \frac{V_r}{A_s} \qquad \textbf{(2.2)}$$

V_r = annual volume of runoff, m^3/yr

A_s = surface area, m^2

y = fraction of distance from inlet to outlet

k = rate constant, m/yr

Compared to typical wastewater concentrations, wetlands are capable of surviving at very low nutrient concentrations. The rate constant "k" can be determined from either transect data or from input-output data. In most of the cases the inlet and outlet concentrations can be measured, but transect concentration measurements are not known. In such cases, the above equation can be used to calculate the rate constant. The values of uptake rate constant change with the type of wetland. For emergent marshes, the value of "k" falls within the range $k = 13.1 \pm 8.5$ m/yr, when averaged at one-point per wetland. The rate constant is lower for wetlands which are occupied by trees. As a result the rate constant for forested wetlands is $k = 3.1 \pm 5.2$ m/yr.

An important model parameter is the flow rate entering the wetland. At higher flow rate, less phosphorus removal will be obtained.

2.5 Watershed Hydrology

2.5.1 Watershed Delineation

A watershed can be defined as the total land area from which water drains into a particular waterway (WDA, 2003). Watershed delineation is the process of using a topographic map to identify the drainage area boundaries.

2.5.1.1 StreamStats

To make it easy for the users to obtain streamflow statistics, basin characteristics and other information for USGS data-collection stations and ungaged sites of interest, USGS developed a map-based web application called StreamStats. StreamStats displays maps and provides previously published information, if any exists, for a user-selected station (Ries *et al.,* 2004). If the user selects a station where no data are available, such as an ungaged site, StreamStats will run a GIS program to obtain and measure the basin characteristics and estimate streamflow statistics for that particular site (Ries *et al.,* 2004). StreamStats was developed cooperatively by the USGS and the Environmental Systems Research Institute, Inc. (ESRI), and was designed for national implementation (Ries *et al.,* 2004).

2.5.1.2 Design of Storm Hydrograph

A hydrograph is a graphical or tabular representation of runoff rate against time. Development of hydrographs is an important step in the design of facilities for handling runoff from non-homogeneous watersheds. The storm hydrograph for ungauged rivers can be determined by three methods:

(a) **Simple Rational Method*:*** The rational method was developed to estimate the peak discharges from drainage areas. The rainfall intensity is assumed to be constant for the duration of the storm. For this method the rainfall distribution is assumed to be uniform over the area of the watershed (McCuen*,* 2005). The rational method is used to estimate the storm peak runoff for areas up to 200 acres.

(b) **Discretized Rational Method**: This method is used for small watersheds. It is increasingly popular with GIS (McCuen, 2005). The watershed is divided into sub-watersheds (Figure 2.10) and a hydrograph is created for each one. By adding all the sub–watershed hydrographs, the final hydrograph can be obtained.

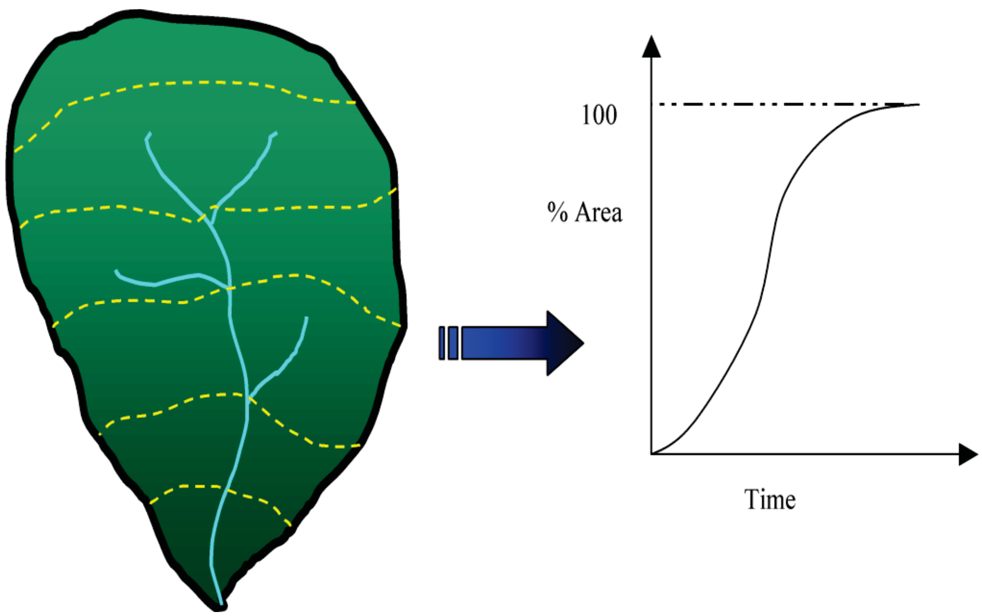

Figure 2.10 Hypothetical Watershed divided into 6 areas of approximately equal travel time to the outlet. Corresponding accumulative time-area curve is also illustrated (NOHRSC, 2011).

(c) **SCS Method**: The SCS (Soil Conservation Service) method is used for large watersheds (up to 2000 acres). This method is based on a dimensionless rainfall distribution curve or a 24 hr storm. The dimensionless unit hydrograph is based on an extensive analysis of measured data (McCuen, 2005). The unit hydrographs are made dimensionless by dividing all discharge ordinates by the peak discharge and all the time ordinates by the time of peak. The base time of the dimensionless hydrograph is approximately equal to five times the time to peak discharge, and 3/8 of runoff volume occurs before the time of peak. The inflection point of recession limb occurs at 1.7 times the time of peak (McCuen, 2005). Figure 2.11 shows the average dimensionless unit hydrograph and Table 2.2 lists the discharge ratios for selected values of the time ratio.

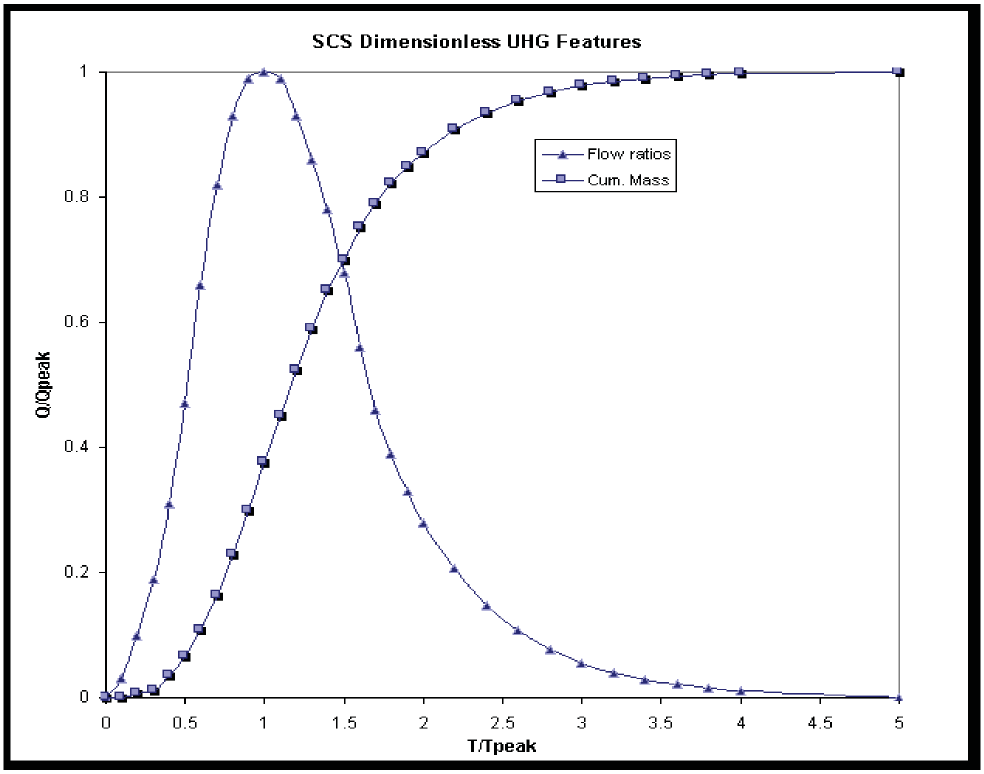

Figure 2.11 SCS Dimensionless Unit Hydrograph (NOHRSC, 2011).

Table 2.2 Ratios for SCS Dimensionless Unit Hydrograph

Time Ratios(t/T_p)	Discharge ratios (q/q_p)
0	0
0.1	0.03
0.2	0.1
0.3	0.19
0.4	0.31
0.5	0.47
0.6	0.66
0.7	0.82
0.8	0.93
0.9	0.99
1	1
1.1	0.99
1.2	0.93
1.3	0.86
1.4	0.78
1.5	0.68
1.6	0.56
1.7	0.46
1.8	0.39
1.9	0.33
2	0.28
2.2	0.207
2.4	0.147
2.6	0.107
2.8	0.077
3	0.055
3.2	0.04
3.4	0.029
3.6	0.021
3.8	0.015
4	0.011
4.5	0.005
5	0

The time of peak is obtained by the equation.

$$T_p = \frac{2}{3}T_c \quad \textbf{(2.3)}$$

Where T_P = time of peak (hrs or min)

T_C = time of concentration (hrs or min)

Time of concentration is calculated by the equation

T_C = travel time of overland flow + travel time in stream channel + travel time in pipe; or

$$T_C = T_{to} + T_{tc} + T_{tp} \quad \textbf{(2.4)}$$

- **Travel Time for Overland Flow**: Overland flow includes sheet flow and concentrated flow. If the depth is less than 0.1 ft (0.03 m), then the flow is sheet flow, and if the depth is greater than 0.1 ft (0.03 m), the flow obtained is concentrated flow. For the watershed of Dick's Pond, the depth obtained is less than 0.1 ft for the entire overland flow.

The depth is calculated by using the equation

$$d = \left[\frac{L*n*i_*}{C_n*S_o}\right]^{3/5} \quad \textbf{(2.5)}$$

Where L = Length of overland flow (ft)

n = Manning's roughness coefficient

i_* = Excess rainfall

Where $i_* = i - E - f$ **(2.6)**

i = Intensity (in/hr)

E = Evaporation

f = Infiltration

C_n = Manning's conversion coefficient

1.486 For $ft^{1/3}$/sec for SI units

1.0 For $m^{1/3}$/sec fr metric units

S_o = Slope of water surface or land.

- **Travel Time of the Stream Channel**: Travel time in a stream channel is obtained by the equation:

  Travel time = (Length of channel / Velocity of channel flow) **(2.7)**

After obtaining the time of concentration and time of peak, the peak flow is calculated using the equation

$$Q_p = \frac{484*A*P}{T_p} \quad \textbf{(2.8)}$$

Where Q_p = peak flow (cfs)

A = area of the watershed in mi^2

T_p = time in hours

P = precipitation in inches (p= c*i*d) **(2.9)**

Where C = runoff coefficient

i = intensity of the rainfall (in/hr)

D= duration of the rainfall (in)

The runoff coefficient, C, is calculated by the following equation.

$$\text{Runoff coefficient} = \frac{\sum \mathrm{Ci}*\mathrm{Ai}}{\sum \mathrm{Ai}} \quad \textbf{(2.10)}$$

The intensity and durations are obtained from the Intesnity–Duration–Frequency (IDF) curves for the closest available location.

2.6 Student's T-Test

The Student's t-test was developed by W.S. Gossett [1876-1937]. To assess whether the means of two groups are statistically different from each other, the t-test can be applied (Trochim, 2006). The formula for the t-test is expressed in ratio. The top part of the ratio implies the difference between the two means or averages. The bottom part, which is called the standard error of the difference, is a measure of variability of the groups (Trochim, 2006).

$$t = \frac{\text{difference between group means}}{\text{variability of means}}$$

The standard error of the difference is computed by taking the variance for each group and dividing it by the number of data points in that group. The two values are added and then their square root is taken (Trochim, 2006). So, the formula for the T-test is

$$t = \frac{X_T - X_C}{\sqrt{\left(\frac{var_T}{n_T}\right) + \left(\frac{var_C}{n_C}\right)}} \quad \textbf{(2.11)}$$

If the first mean is larger than the second, the t-value will be positive, and if it is smaller, t will be negative

CHAPTER 3

METHODS AND PROCEDURES

3.1 Runoff Calculations

For modeling purposes, two flow conditions were investigated– annual average inflow to the pond and the two-year storm. The 2-year storm was arbitrarily chosen to represent typical high flow conditions into the wetland and pond system.

3.1.1 Watershed Delineation

The watershed was delineated by using USGS StreamStats. StreamStats is a stream flow statistics web application that is designed to estimate the stream flow at ungaged locations on streams. Using StreamStats, a point of interest is first selected. To locate Dick's Pond, the latitude and longitude (N 40° 48' 55" and W 80° 43' 21") was used. Once the pond was located, 1:24000 zoom was maintained, the basin delineation button activated, and the desired water body point was checked. Then StreamStats determined and displayed the boundary of the watershed that drains into the stream where the pond is located. Once the watershed boundaries were determined, StreamStats provided the basin characteristic report and StreamStats ungaged site report. The basin characteristic report provided the watershed area that drains to the pond in square miles. The ungaged site report provided the basin characteristics that are used in the regression equations for the hydrologic region where the site is located (USGS StreamStats, 2007). The report also includes the peak-flow basin characteristics and peak-flow statistics. The delineated watershed for the pond is shown in Figure 3.1.

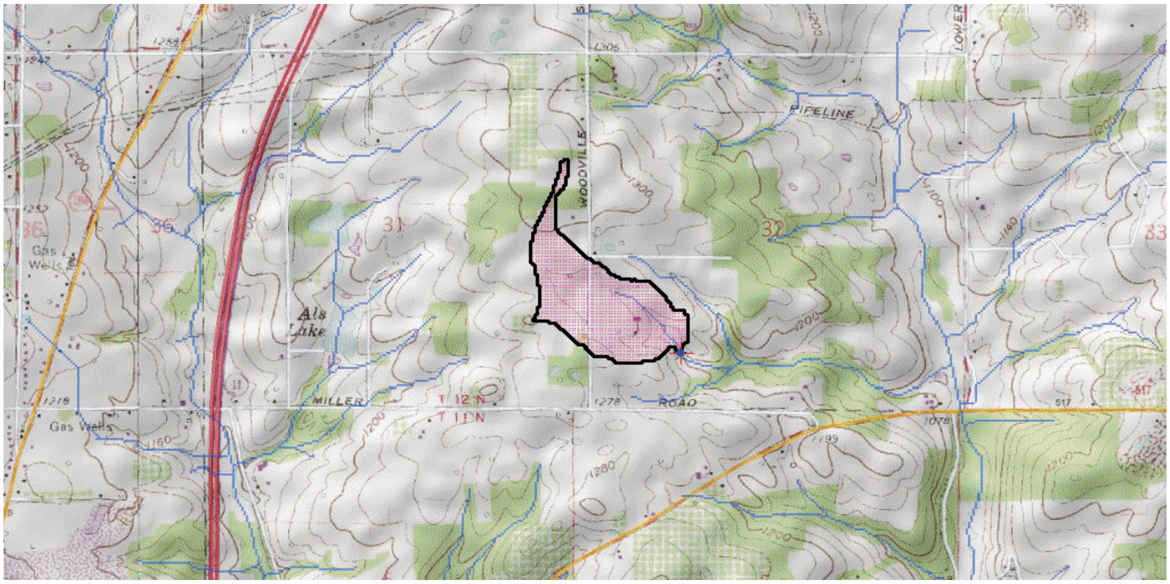

Figure 3.1 Delineated watershed boundary of Dick's Pond using StreamStats

The area of the watershed is 61 acres (24.6 ha). The watershed was divided into two subwatersheds, which are shown in Figure 3.2. The largest, outlined in red and designated as subwatershed #1 (area A_1), drains into the main stream feeding the pond. The smaller drainage area, outlined in black and designated as subwatershed #2 (area A_2), drains into a small intermittent stream that joins the main stream just above the pond. The watershed has several different land covers. The land covers within the watershed are: (a) woods; (b) corn/soy beans crops; (c) grazing land; and (d) hay.

Figure 3.2 Delineated watershed boundaries – subwatershed#1(red); subwatershed#2 (black).

The total areas of the watersheds and the areas for each land use were identified from aerial photography and calculated using a planimeter. The results are shown in Table 3.1.

Table 3.1 The area and land covers of each subwatershed in Dick's Pond watershed.

Land use	A_1 (acres)	A_2 (acres)	A_{total}(acres)
Corn/Soy beans	28.23	----	28.23
Grazing	16.19	5.573	21.763
Hay	2.145	6.805	8.95
Woods	2.073	----	2.073
Total	**48.638**	**12.378**	**61.06**

3.1.1.1 Manual Calculations

These different land covers were used to obtain the runoff coefficient of the watershed. The runoff coefficients for the various land covers in Dick's Pond watershed are shown in Table 3.2.

Table 3.2 Runoff coefficients for different land uses considering the treatment/practice, soil group and slope of the land (McCuen, 2005)

Land use	Treatment (or) practice	Soil group	Slope	Runoff coefficient
Corn/Soy beans	Cultivated land	C	2-6 %	0.19
Grazing	Pasture	C	2-6 %	0.34
Hay	Meadow	C	2-6%	0.28
Woods	Forest	C	0.2 %	0.10

3.1.2 SCS Method

For this project, the SCS method was used to obtain the runoff into the pond. The main reason for using the SCS method is that it is applicable for drainage areas less than 2000 acres (809.37 ha). To find a typical flow rate into the pond following a significant storm event, the hydrograph was desired for a storm that occurs every two years. To determine the storm duration, the following procedure was adopted to obtain the time of concentration (T_C):

1. Assume D (storm duration) = T_C for the worst case flooding which produces the highest peak flow.
2. Assume trial storm duration, D - in this case, 12 hr was assumed.

3. Using the trial storm duration, read off intensity from the Intensity–Duration-Frequency (IDF) curve (Table 4.3) obtained for the project site from http://dipper.nws.noaa.gov Columbiana 2 SE, OHIO (33-1770) 40.8833 N 80.6833 W 1099 ft. .
4. The intensity for the 2 yr, 12 hr storm is obtained.
5. Calculate time of concentration using equation 2.4.
   - **Travel time for overland flow**: For this watershed, the depth obtained by using equation 2.5 is less than 0.1 ft (the obtained depth was 0.03 ft) for the entire overland flow.
   - **Travel time of the stream channel**: The length of the stream channel is 1674 ft (510.2 m). The cross section of the river is considered to be a triangle. The depth of the river is calculated by trial and error, and using the Manning's equation, the velocity of channel flow was calculated. The travel time of the river was calculated to be 8.4 min.
   - **Travel time of pipe**: A pipe was laid underground, running from the neighboring dairy farm to the inlet stream. The length of the pipe is 20 ft (6.096 m), diameter = 2 ft (0.6 m), and slope = 0.6 %. The calculated travel time was T_{tp} = 2.48 s. This does not add significantly to the total time of concentration, so the travel time through the pipe was neglected.
6. After obtaining the time of concentration for the 1st duration, assume the calculated D = T_C.
7. Read new intensity using new D.

8. Continue to iterate until new T_C = previous T_C (i.e., T_C converges to a fixed value).

Using this process, the time of concentration for subwatersheds #1 and #2 were calculated. Substituting T_c into equation 2.3, the time of peak (T_p) for each subwatershed was calculated. After obtaining the peak time, the peak discharge was calculated from equation 2.8.

Hydrographs were obtained by multiplying the peak times and peak flows by dimensionless time and peak discharges (Table 2.2), respectively. Inflow hydrographs were generated for wetland cells #1 and #2. For wetland cell #1, the hydrograph from subwatershed #1was used, and for wetland cell #2, hydrographs from subwatersheds #1 and #2 were combined.

3.2 Wetland Description

Dr. Dick planned and constructed a wetland upstream from the pond to reduce the sediment and nutrient loading to the pond. The main goal is removal of phosphorus from the pond inflow in order to reduce plant and algae growth. After the wetlands were built, the dimensions of the cells were measured using a surveying tape. The wetland is constructed on 0.4 acres (0.16 ha). A 50 ft (15.24 m) wide settling pond was constructed at the inlet pipe. The water from the pipe flows through the settling pond and then enters into wetland cell #1, which is about 2.0 ft (0.6 m) above the pond surface elevation. Cell #1 is a rectangular cell, 41 ft (12.49 m) wide and 55 ft (16.76 m) long. Flow from the small subwatershed (#2) and the outflow from wetland cell #1 enter wetland cell #2, which is about 0.5 ft (0.15 m) in elevation above the pond level. The second cell is shaped like a right triangle having a base of 60 ft (18.28 m) and height of 44 ft (13.41 m). Outflow from cell #2 enters the pond. The settling pond and the constructed wetland cells are shown in Figure 3.3 and the position relative to the pond is shown in Figure 3.4.

Figure 3.3 Settling pond (on right) and the constructed wetland cells.

Figure 3.4 Wetland cells and Dick's Pond

3.3 Water Quality Sampling and Analysis

3.3.1 Overview

To determine the nutrient loading and background water quality in the pond, some pre-construction monitoring was conducted. Frequent monitoring was performed by field measurements and by collecting water samples for laboratory analysis. Subsequently, post-construction monitoring was conducted to measure the reduction in nutrient levels due to the constructed wetland, and to apply a mathematical model of phosphorus removal.

3.3.1.1 Parameters Measured

To assess the water quality and trophic conditions in Dick's Pond, the following parameters were measured during the pre- and post-construction monitoring: depth of the pond, Secchi depth, water temperature, dissolved oxygen, conductivity, soluble reactive phosphorus, total phosphorus, nitrate nitrogen, ammonia nitrogen and chlorophyll a.

3.3.1.2 Sampling Locations

Five water sample locations were selected for the pre-construction monitoring, while nine sample locations were selected for the post-construction monitoring. Tables 3.3 and 3.4 and Figures 3.5 and 3.6 the sample locations for pre- and post-construction monitoring, respectively.

Table 3.3 Water sample locations for pre-construction monitoring

Location	Description
1	Pond outlet
2	Inlet pipe (from farm)
3	Water column - 1.6 ft (0.5 m) depth
4	Water column - 3.2 ft (1 m) depth
5	Water column - 6.56 ft (2 m) depth

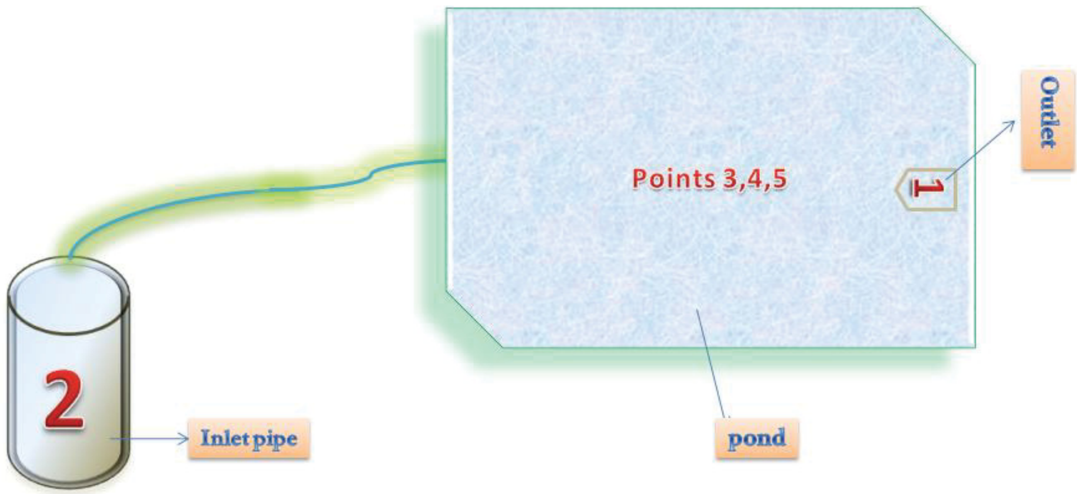

Figure 3.5 Pre-construction sampling locations

Table 3.4 Water sample locations for post-construction monitoring

Location	Description
1	Inlet pipe (from farm)
2	Settling pond outflow
3	Wetland cell #1 outflow
4	Small stream
5	Wetland cell #2 outflow
6	Water column - 1.6ft (0.5 m) depth
7	Water column - 3.2 ft (1m) depth
8	Water column - 6.56 ft (2m) depth
9	Pond outlet

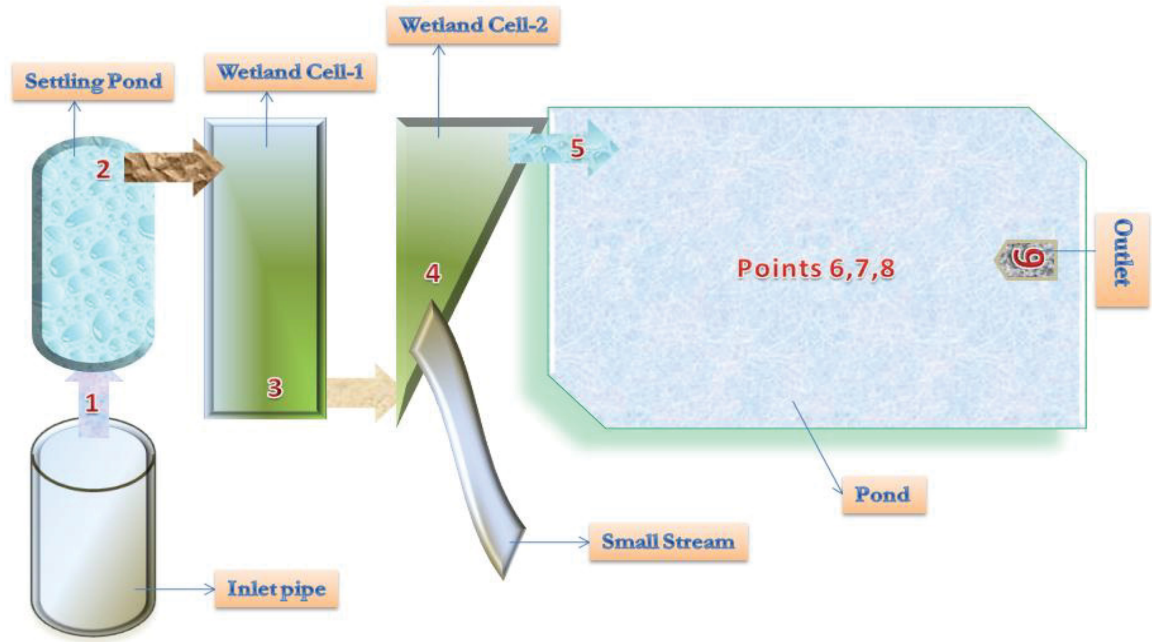

Figure 3.6 Post-construction sampling locations

3.3.1.3 Sampling Dates

The pre-construction monitoring was executed during summer and fall of 2010. Seven samplings were performed in the pre-construction phase of the study. The first six sampling dates ranged from May, 2010 to June, 2010, with a week interval in between. The seventh sampling was performed on September 8, 2010, as the pond experienced a relatively large flow during that week.

The post-construction monitoring was performed during spring, summer and fall of 2011. Eight samplings were conducted during the post-construction phase of the study. The samples were collected in March, April, and July-September 2011.

3.3.1.4 Field Measurements

Secchi depth and profiles of water temperature, dissolved oxygen and conductivity versus depth were routinely measured from a canoe at the deepest spot in the pond during the pre- and post-construction sampling. The Secchi depth was measured using the Secchi disk to determine the transparency of the water in the pond. The Secchi disk was immersed deep into the water until it was invisible, and then brought up slowly until it was just barely visible in the water and the depth of submergence recorded. The profiles of water temperature, dissolved oxygen (DO) and conductivity are measured using an YSI Model 57 oxygen meter (manufactured by Yellow Springs Instrument Co., Inc).

3.3.2 Sample Handling and Analysis

3.3.2.1 Preparation of Sample Containers

Water samples were collected for laboratory analysis in plastic bottles. For every sampling day, two sets of sample bottles were prepared. One set of one liter bottles was used for collecting the samples in the field, and another set of 500 ml plastic bottles was used to store filtered water samples until analysis. As the parameters that are measured are very sensitive to contamination, the containers were acid washed with 20% HCl solution and rinsed thoroughly with deionized water. Along with the sample containers, all glassware used for the laboratory analyses were also acid washed.

3.3.2.2 Sampling Procedure

In the field, the YSI Model 57 meter was calibrated for dissolved oxygen by following the procedure described in the user's manual. Then, DO, temperature and conductivity readings were taken in the water column of the pond at several depths, determined by markings on the cable connecting the sensor to the instrument, and Secchi depth was measured. Water samples were collected at three different depths using an alpha bottle (manufactured by the Wildlife Supply Company). The equipment used during the sampling is shown in Figure 3.7.

The water samples from the inlet pipe, outlet and the wetland cells were collected directly from the flow. During the low flow conditions, the sample from the small stream was collected using the container cap, as there was not enough depth of water to dip the sample bottle. During this process, an attempt was made to prevent suspended sediment from entering the sample.

Figure 3.7 Sampling Equipment

3.3.2.3 Lab Preparations -Filtration and Storage of Samples

Once the samples were collected into the container, they were tightly capped to prevent water spillage during transportation. Later the samples were brought back to the YSU Environmental Engineering Lab for processing and analysis. The first step was to filter the samples through Fisher G4 glass fiber filters. The filtered water was transferred into a 500 ml acid washed container. All samples were stored in a refrigerator at about 40 ^{o}F (4 ^{o}C) until analysis.

3.3.2.4 Analysis and Calculations

After the samples were brought to the lab, analyses were performed for chlorophyll a (Chla), total phosphorus (TP), soluble reactive phosphorus (SRP), ammonia (NH_3-N) and nitrate nitrogen (NO_3-N). The analytical methods were all taken from *Standard Methods for the Examination of Waters and Wastewaters* (21st edition; APHA, *et al.*, 2005). At the end of each analysis, the absorbance levels were measured using a Bausch & Lomb Spectronic 1001 spectrophotometer at wavelengths suggested by Standard Methods.

a) Standard Curves Using Excel

The concentrations corresponding to the measured absorbance levels were calculated by using Microsoft Excel. Standard curves were obtained by plotting concentration versus absorbance of the blanks and standards, and performing linear regression to get an equation of the form (Conc) = a (Absorbance) + b, where a is the slope and b is the y intercept of the straight line. From this equation, the concentration of analyze in each of the samples was calculated.

b) Data Analysis

The main goals of data analysis were to evaluate the trophic condition of Dick's Pond and to determine whether the constructed wetland had improved water quality. First, means and standard deviations were calculated for all measured parameters. Then, the data sets were compared using an online Student's t-test calculator. For each data set, the data were entered into the given box separating values using spaces. The Calculate

Now button was clicked to obtain the results. The data set comparisons performed with the Student's t-test are:

- Compared pre- versus post-construction conditions in the pond for all parameters (TP, SRP, NH_3, NO_3, Chla) at all depths and the pond outlet.
- Compared inlet concentrations to settling pond outflow, wetland cell #1 outflow, and 0.5 m depth in the pond for all parameters.
- Compared settling pond outflow to wetland cell #1 outflow for all parameters.

The results obtained from the student's t-tests are the values of t, standard deviation, degrees of freedom, the probability of the null hypothesis that the two data sets are the same, mean, and the 95% confidence interval for mean.

3.4 Modeling

To calculate the rate constant "k", the first order areal uptake (Kadlec, 2005; Kadlec and Knight, 1996) equation (2.1) was used:

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

Setting $C = C_o$ at $y = 1.0$ and solving for k yields:

$$k = q * ln\left(\frac{C_i}{C_o}\right) \quad \textbf{(3.1)}$$

Where q = The hydraulic loading rate for average flow conditions.

C_i = Concentration entering the cells

C_o= Concentrations leaving the cell.

The rate constant for wetland cell #1 is calculated by taking the TP concentration in outflow from the settling pond as C_i and the TP concentration in outflow from cell #1 as C_o (Figure 3.8). For wetland cell #2, C_i was calculated by assuming instantaneous mixing between the cell #1 outflow and inflow from the small stream. C_o is considered as the TP concentration in outflow from cell #2.

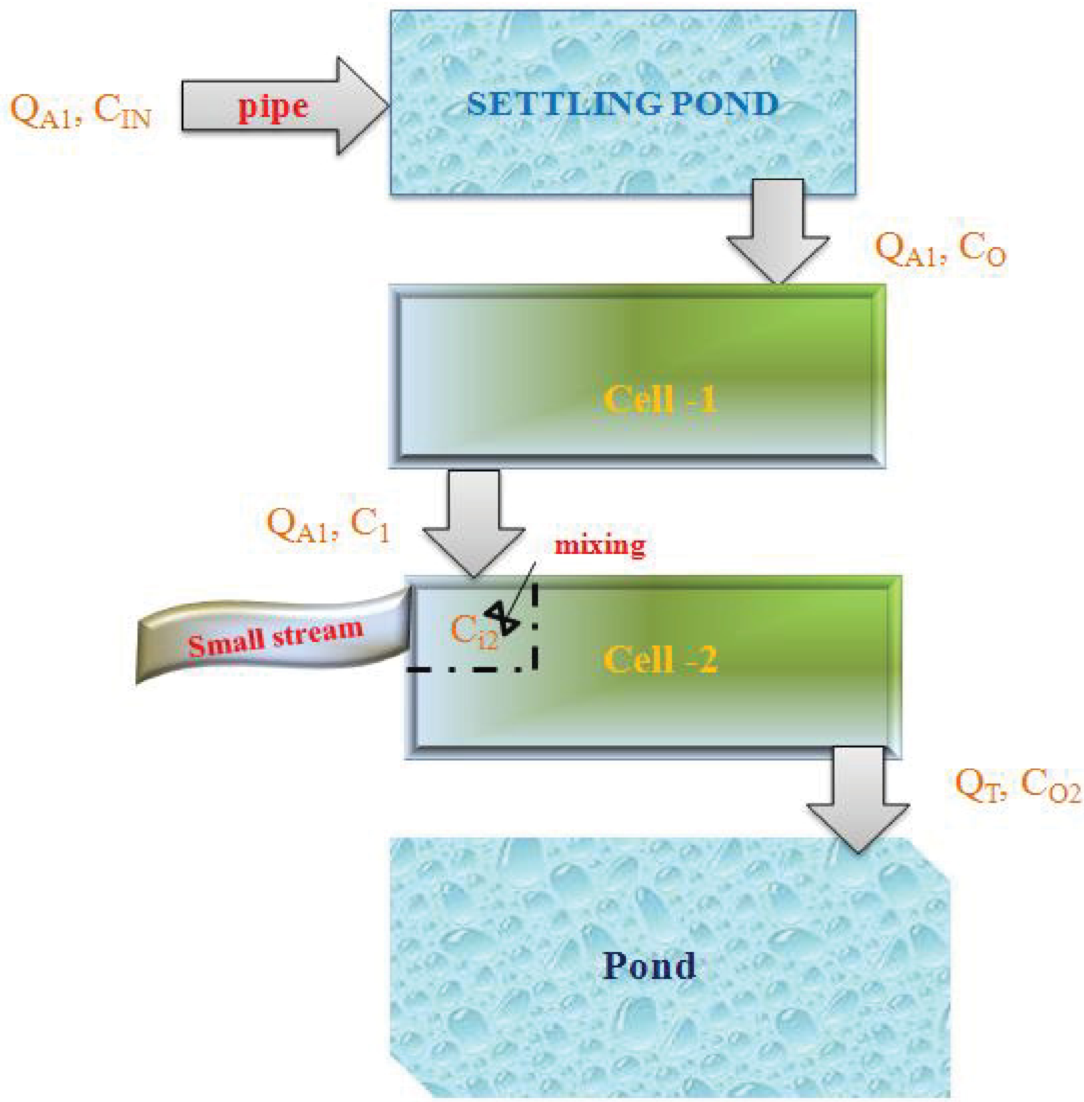

Figure 3.8 Flow Conditions

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Runoff Estimates

4.1.1 Watershed Delineation

The watershed was delineated using USGS StreamStats. Selecting the Ohio interactive map, the pond location was entered using the latitude (N 40° 48' 55") and longitude (E 80° 43' 51"). Figure 4.1 shows the delineated watershed for the pond.

4.1.1.1 USGS Watershed Map

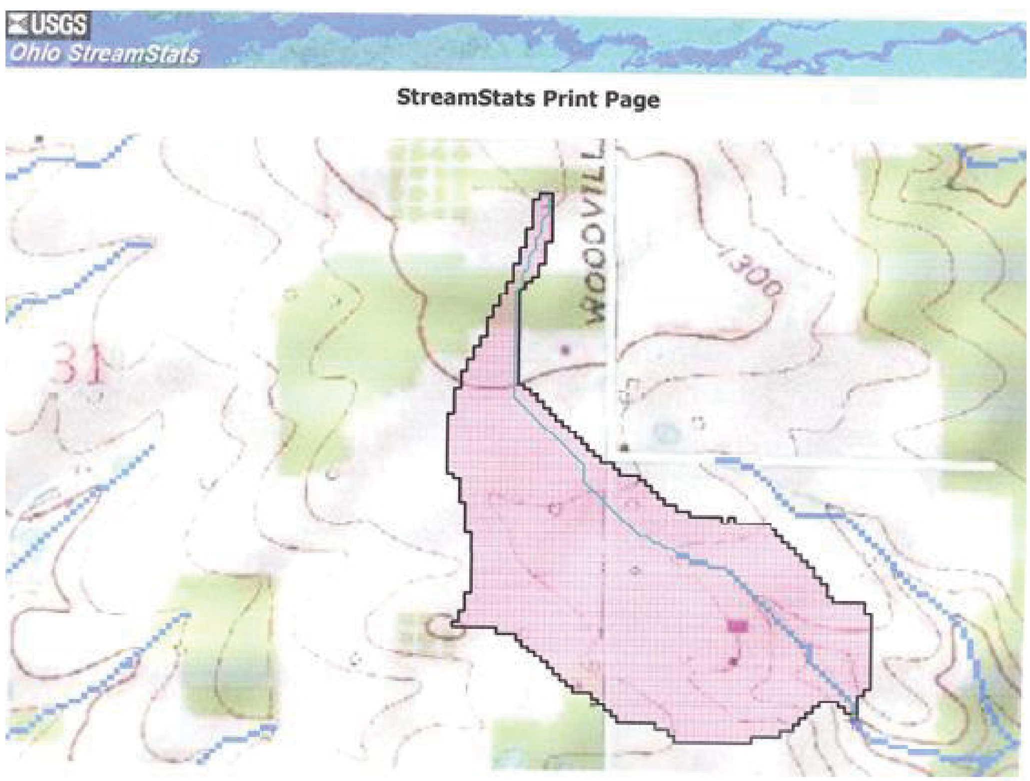

Figure 4.1 Watershed map for Dick's Pond obtained from StreamStats (USGS, 2010)

4.1.1.2 Basin Characteristics

USGS StreamStats provided the drainage area and the mean flow estimate for the watershed. Table 4.1 summarizes the basin characteristics of the watershed including the drainage area and mean annual precipitation of the watershed.

Table 4.1 USGS basin characteristic report for Dick's Pond watershed (USGS StreamStats, 2010)

Basin Characteristics Report	
Date: Wed Nov 23 2011 11:42:48 Mountain Standard Time	
NAD27 Latitude: 40.8163 (40^{o} 48' 59'')	
NAD27 Longitude: -80.7233 (-80 43 24)	
Parameter	**Value**
Area Covered by forest, in percent	8.47
Area in square miles	0.0963
Mean annual precipitation at basin centroid, in inches	36.3
10-85 slope, in feet per mile	153
Area Covered by water and wetlands, in percent	0
Region A indicator for Ohio Peak Flows	1
Mean annual flow in the stream in cfs	0.0903

4.1.2 Manual Calculations

4.1.2.1 Runoff Coefficient Results

Using the runoff coefficient values from Table 3.2, the runoff coefficient values for the subwatersheds #1 and #2 are calculated and shown in Table 4.2.

Table 4.2 Runoff coefficients for Dick's Pond subwatersheds #1 and #2

Land use	C	A_1 (acres)	A_2 (acres)	CA_1	CA_2
Corn/Soy beans	0.19	28.23	----	5.36	-
Grazing	0.34	16.19	5.573	5.50	1.89
Hay	0.28	2.145	6.805	0.60	1.90
Woods	0.10	2.073	----	0.21	-
Total	-	**48.63**	**12.37**	**11.66**	**3.79**
Average				**C_1= 0.24**	**C_2 = 0.30**

Using equation 2.10 and substituting the values from Table 4.2, the following runoff coefficients for subwatersheds #1 and #2 were calculated:

$$C_1 = 0.24$$

$$C_2 = 0.30$$

4.1.3 SCS Method

The SCS method was used to obtain the runoff into the pond. In order to find a typical high flow rate entering the pond, a storm with a return period of two years was chosen. To obtain the intensity of the 2-year storm, the Intensity-Duration-Frequency (IDF) curve for Columbiana County was used (http://dipper.nws.noaa.gov). Table 4.3 summarizes the precipitation estimates in inches for various storm frequencies and durations for Columbiana 2 SE, OHIO (33-1770). Using the storm durations obtained from time of concentration calculations (section 4.1.3.1) and data from Table 4.3, the storm intensities for subwatershed #1 and #2 were obtained. The intensities obtained for the 2-year storm for the watersheds after the iterations were

Intensity for watershed #1 = 0.88 in/hr

Intensity for watershed #2 = 1.46 in/hr

Table 4.3 Intensity-Duration-Frequency data for Columbiana County, OH (http://dipper.nws.noaa.gov).

AEP (1-in-y)	5 min	10 min	15 min	30 min	60 min	120 min	3 hr	6 hr	12 hr
2	0.35	0.54	0.66	0.88	1.08	1.26	1.33	1.58	1.86
5	0.44	0.69	0.85	1.16	1.46	1.69	1.78	2.09	2.44
10	0.51	0.79	0.97	1.35	1.71	1.99	2.1	2.46	2.86
25	0.59	0.9	1.11	1.57	2.04	2.38	2.52	2.96	3.43
50	0.65	0.98	1.22	1.74	2.29	2.68	2.85	3.35	3.89
100	0.71	1.06	1.32	1.91	2.55	2.99	3.18	3.76	4.36

4.1.3.1 Results for Tc and Qp

The time of concentration and the peak flow were calculated individually for subwatersheds #1 and #2. The parameters for subwatersheds #1 and #2 are presented in Table 4.4.

Table 4.4 Physical parameters for subwatersheds #1 and #2

Parameters	Watershed #1	Watershed #2
watershed length (ft)	3252	1208
area (acres)	48.63	12.37
slope	3.30%	2.50%
Length of the pipe (ft)	20	-
diameter of the pipe (ft)	2	-
slope of the pipe	0.60%	-
$L_{overland}$(ft)	1720	550.4
L_{river}(ft)	1674	658.43
C	0.25	0.3
n sheet	0.24	0.15
n conc	0.0475	0.0325

Substituting the parameters in equations 2.4 and 2.8, the times of concentration and peak flows for watershed #1 and #2 are

Watershed #1: T_c = 1.5hr and Q_p = 12 cfs

Watershed #2: T_c = 0.72hr and Q_p = 3.7 cfs

Since T_c for subwatershed #1 is larger, the worst case storm duration was chosen as 1.5 hr.

4.1.3.2 Dimensionless Time and Peak Discharges

The times of concentration and peak discharges were multiplied by the SCS dimensionless time and peak discharge ratios (Table 2.2) to obtain two-year storm runoff hydrographs. Tables 4.5 and 4.6 give the hydrograph data for subwatersheds #1 and #2, respectively. These hydrographs are plotted in Figures 4.2 and 4.3. The runoff hydrograph for subwatershed #1 is assumed to be the same as the inflow to wetland cell #1.

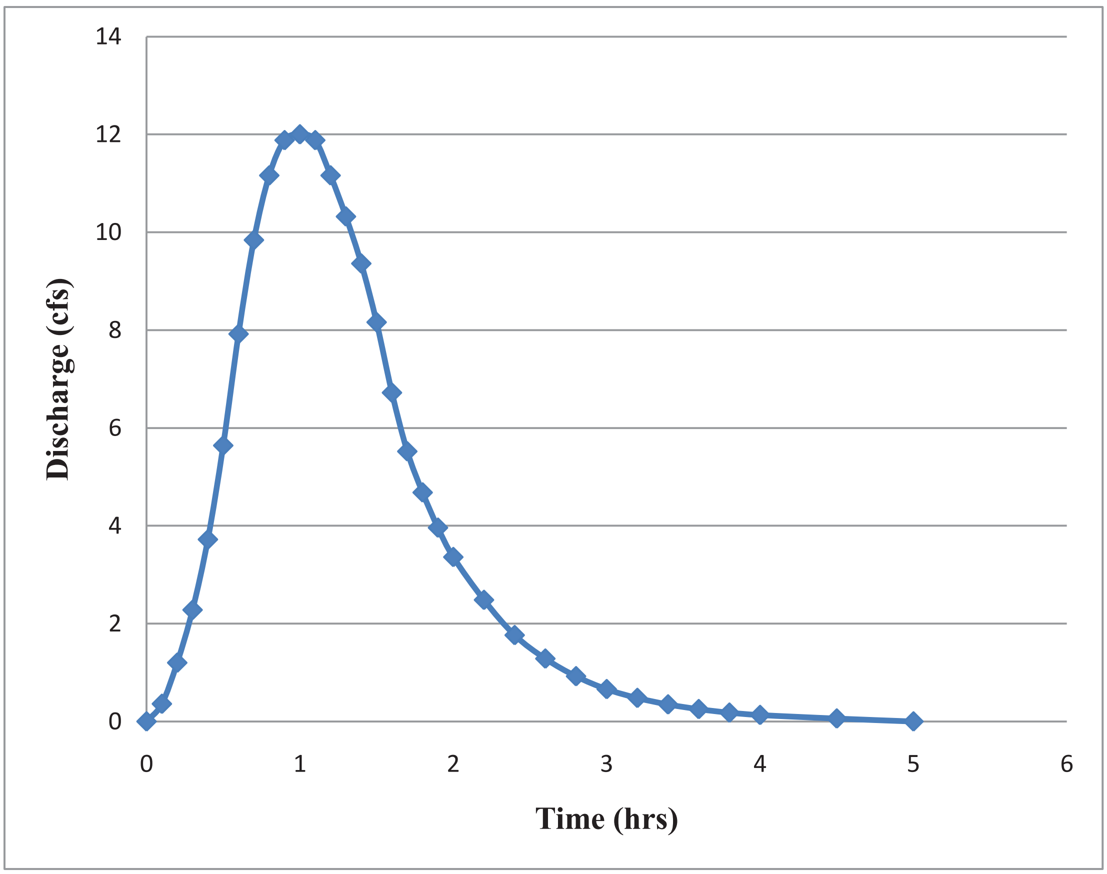

Figure 4.2 Two-year storm hydrograph for subwatershed #1 and wetland cell #1.

Table 4.5 Two-year storm hydrograph for subwatershed #1 and inflow hydrograph for Wetland #1

T (hrs)	Q(cfs)
0	0
0.1	0.36
0.2	1.2
0.3	2.28
0.4	3.72
0.5	5.64
0.6	7.92
0.7	9.84
0.8	11.16
0.9	11.88
1	12
1.1	11.88
1.2	11.16
1.3	10.32
1.4	9.36
1.5	8.16
1.6	6.72
1.7	5.52
1.8	4.68
1.9	3.96
2	3.36
2.2	2.484
2.4	1.764
2.6	1.284
2.8	0.924
3	0.66
3.2	0.48
3.4	0.348
3.6	0.252
3.8	0.18
4	0.132
4.5	0.06
5	0

Table 4.6 Two-year storm hydrograph for subwatershed #2

T (hrs)	Q(cfs)
0	0
0.048	0.111
0.096	0.37
0.144	0.703
0.192	1.147
0.24	1.739
0.288	2.442
0.336	3.034
0.384	3.441
0.432	3.663
0.48	3.7
0.528	3.663
0.576	3.441
0.624	3.182
0.672	2.886
0.72	2.516
0.768	2.072
0.816	1.702
0.864	1.443
0.912	1.221
0.96	1.036
1.056	0.7659
1.152	0.5439
1.248	0.3959
1.344	0.2849
1.44	0.2035
1.536	0.148
1.632	0.1073
1.728	0.0777
1.824	0.0555
1.92	0.0407
2.16	0.0185
2.4	0

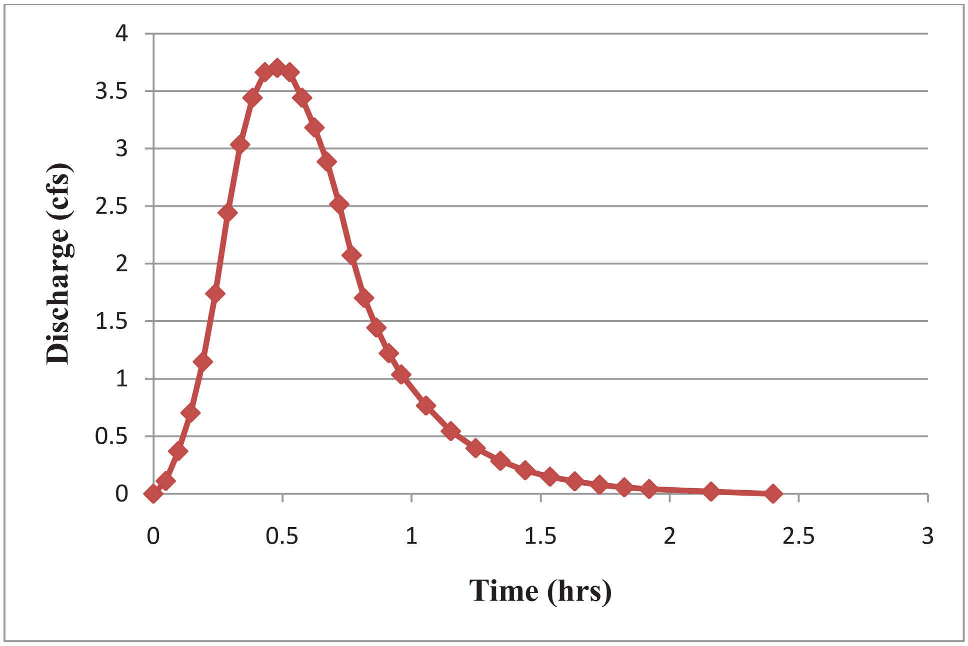

Figure 4.3 Two-year storm hydrograph for subwatershed #2

In order to obtain an inflow hydrograph for wetland cell #2, the hydrograph for subwatershed #2 was first adjusted considering that there is uniform rainfall from 0.48 hr to 1.26 hr at a peak discharge of 3.7cfs. This makes the storm durations for the two subwatersheds equal so the hydrographs can be added. The results are presented in Table 4.7 and Figure 4.4.

Table 4.7 Two-year storm hydrograph for subwatershed #2 adjusted to rainfall duration of 1,5 hours

T (hrs)	Q(cfs)
0	0
0.05	0.11
0.10	0.37
0.14	0.70
0.19	1.15
0.24	1.74
0.29	2.44
0.34	3.03
0.38	3.44
0.43	3.66
0.48	3.70
1.26	3.70
1.31	3.66
1.36	3.44
1.40	3.18
1.45	2.89
1.50	2.52
1.55	2.07
1.60	1.70
1.64	1.44
1.69	1.22
1.74	1.04
1.84	0.77
1.93	0.54
2.03	0.40
2.12	0.28
2.22	0.20
2.32	0.15
2.41	0.11
2.51	0.08
2.60	0.06
2.70	0.04
2.94	0.02
3.18	0.00

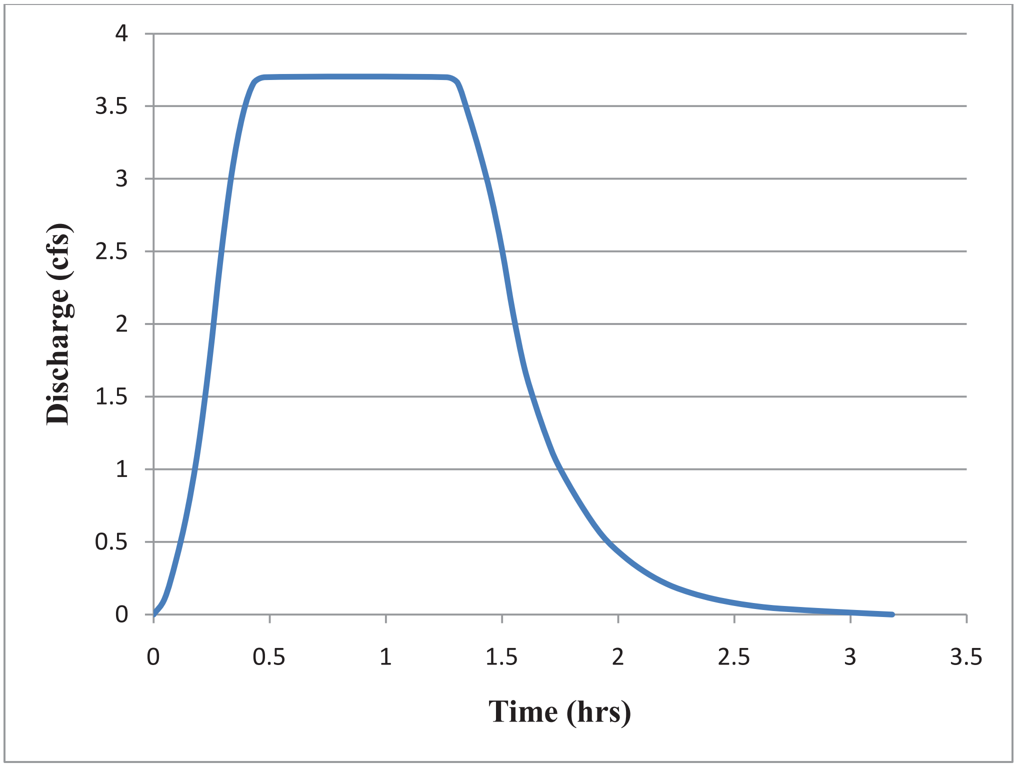

Figure 4.4 Adjusted two-year storm hydrograph for small subwatershed (#2)

The discharge values for each time from the adjusted hydrograph of subwatershed #2 were added to those for large subwatershed (#1) in order to generate and the inflow hydrograph for wetland cell #2. Table 4.8 and Figure 4.5 show the calculated inflow hydrograph for wetland cell #2 resulting from the two-year storm.

Table 4.8 Hydrograph for two-year storm runoff entering wetland cell #2.

Subwatershed #1 Original Hydrograph		Subwatershed #2 Adjusted Hydrograph		Subwatershed #1 Interpolated Flow	Wetland Cell #2 Inflow
T (hrs)	Q(cfs)	T (hrs)	Q(cfs)	Q (cfs)	Q (cfs)
0	0	0.00	0	0	**0.00**
0.1	0.36	0.05	0.11	0.17	**0.28**
0.2	1.2	0.10	0.37	0.35	**0.72**
0.3	2.28	0.14	0.70	0.73	**1.43**
0.4	3.72	0.19	1.15	1.13	**2.28**
0.5	5.64	0.24	1.74	1.63	**3.37**
0.6	7.92	0.29	2.44	2.15	**4.59**
0.7	9.84	0.34	3.03	2.80	**5.83**
0.8	11.16	0.38	3.44	3.49	**6.93**
0.9	11.88	0.43	3.66	4.33	**8.00**
1	12	0.48	3.70	5.26	**8.96**
1.1	11.88	0.53	3.70	6.28	**9.98**
1.2	11.16	0.58	3.70	7.37	**11.07**
1.3	10.32	0.62	3.70	8.38	**12.08**
1.4	9.36	0.67	3.70	9.30	**13.00**
1.5	8.16	0.72	3.70	10.10	**13.80**
1.6	6.72	0.77	3.70	10.74	**14.44**
1.7	5.52	0.82	3.70	11.28	**14.98**
1.8	4.68	0.86	3.70	11.62	**15.32**
1.9	3.96	0.91	3.70	11.89	**15.59**
2	3.36	0.96	3.70	11.95	**15.65**
2.2	2.484	1.06	3.70	11.93	**15.63**
2.4	1.764	1.15	3.70	11.51	**15.21**
2.6	1.284	1.25	3.70	10.76	**14.46**
2.8	0.924	1.26	3.70	10.66	**14.36**
3	0.66	1.31	3.66	10.24	**13.91**
3.2	0.48	1.36	3.44	9.78	**13.22**
3.4	0.348	1.40	3.18	9.31	**12.49**
3.6	0.252	1.45	2.89	8.74	**11.62**
3.8	0.18	1.50	2.52	8.16	**10.68**
4	0.132	1.55	2.07	7.47	**9.54**
4.5	0.06	1.60	1.70	6.78	**8.48**
5	0	1.64	1.44	6.19	**7.64**
		1.69	1.22	5.62	**6.84**
		1.74	1.04	5.18	**6.22**
		1.84	0.77	4.42	**5.19**
		1.93	0.54	3.77	**4.31**
		2.03	0.40	3.24	**3.63**
		2.12	0.28	2.82	**3.10**
		2.22	0.20	2.41	**2.62**
		2.32	0.15	2.07	**2.21**
		2.41	0.11	1.74	**1.84**
		2.51	0.08	1.50	**1.58**
		2.60	0.06	1.27	**1.33**
		2.70	0.04	1.10	**1.14**
		2.94	0.02	0.74	**0.76**
		3.18	0.00	0.50	**0.50**
		3.20	0.00	0.48	**0.48**
		3.40	0.00	0.35	**0.35**
		3.60	0.00	0.25	**0.25**
		3.80	0.00	0.18	**0.18**
		4.00	0.00	0.13	**0.13**
		4.50	0.00	0.06	**0.06**
		5.00	0.00	0.00	**0.00**

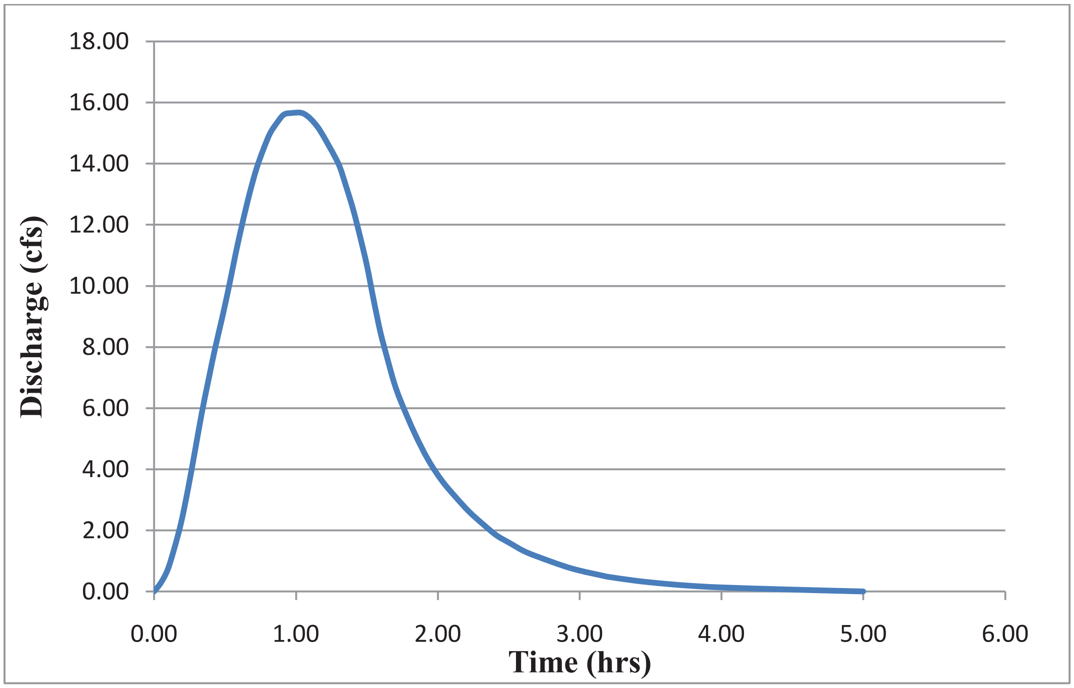

Figure 4.5 Inflow hydrograph for wetland cell #2 for two-year storm.

4.2 Water Quality Results

4.2.1 Climatic Conditions

Weather plays a key role in controlling the condition of the pond observed during sampling. If there is significant rainfall during the past couple of days, the flow into the pond is expected to be high compared to the normal weather conditions. Also the climatic conditions can affect the algal growth in the pond by altering such factors as nutrient concentrations, transparency and temperature. Table 4.9 summarizes the climatic conditions during the pre- and post-construction sampling dates. Both sampling periods included a wide range of weather and flow conditions.

Table 4.9 Climatic conditions on different sampling dates.

	Date	Climatic Conditions
Pre-Construction		
	5/12/2010	Sunny day.no rainfall
	5/19/2010	Sunny day.no rainfall
	5/21/2010	Moderate rain
	5/24/2010	Moderate rain
	5/28/2010	Warm, sunny day- 75 F
	6/1/2010	Very heavy rainfall event on 06/01
	6/4/2010	Heavy storm on 06/02
	6/11/2010	Cloudy, light rain -65 F
	6/14/2010	Rain fall
	6/18/2010	Sunny, light breeze-70 F
	9/8/2010	Sunny day with cold breeze
Post-Construction		
	3/21/2011	Rain for past couple of days
	4/24/2011	Continuous rainfall for a week
	7/13/2011	No flow
	7/27/2011	Lot of duckweed and algae, with good flow
	8/3/2011	Light breeze and cloudy-74 F
	8/18/2011	No rain.breeze-70F
	9/8/2011	Continuous rainfall for couple of days
	9/27/2011	Continuous rainfall for a couple of days

4.2.2 Field Measurements

4.2.2.1 Temperature

Temperature is an important parameter that should be considered during the data analysis. Temperature affects the circulation patterns in the pond. Biological and chemical processes occur at faster rates at higher temperatures. Also, as the temperature in the pond increases, the ability of the water to hold dissolved oxygen decreases. Table4.10 shows the temperature in the pond at different depths.

The pond was thermally stratified in May and June of 2010, with temperature differences of up to 13.6 ^{o}C (May 28, 2010). On the other hand, the overall temperature was higher, with less thermal stratification during the post-construction monitoring in 2011. It is possible that this difference is simply due to the normal seasonal variations in air and water temperatures. In this study, water temperatures were cooler and temperature differences larger in May and June, whereas during July and August, the entire water column was fairly warm with minimal stratification by late summer.

Table 4.10 Temperature profiles in Dick's Pond.

	5/12/10	5/19/10	5/28/10	6/4/10	6/11/10	6/18/10	9/8/10	7/27/11	8/3/11	8/18/11	9/8/11
Depth (ft)	**Temp (^{0}C)**	**Temp (^{0}C)**	**Temp (^{0}C)**	**Temp (^{0}C)**	**Temp (^{0}C)**	**Temp (^{0}C)**	**Temp (^{0}C)**	**Temp (^{0}C)**	**Temp (^{0}C)**	**Temp (^{0}C)**	**Temp (^{0}C)**
surface	-	19.5	24.2	22.1	19.3	21.3	19.2	26.6	26.5	23.1	19.4
1	13.0	18.5	23.5	20.0	19.2	21.1	20.3	26.7	26.5	22.9	19.2
2	12.2	15.1	23.0	19.2	18.6	20.3	20.5	26.8	26.5	22.9	19.2
3	12.0	13.1	19.5	18.6	17.1	20.4	19.5	26.6	26.7	22.5	19.2
4	11.5	12.0	15.0	18.5	17.4	19.6	19.4	26.6	25.6	22.5	19.1
5	11.0	11.0	12.5	17.6	17.1	17.2	19.2	25.1	24.6	22.2	19.1
6	11.5	11.2	11.5	15.6	16.3	15.3	19.0	22.5	23.7	21.6	19.0
7	-	10.0	10.6	13.2	15.3	14.1	18.6	20.5	20.8	20.5	18.5
8	9.5	10.1	10.1	11.5	13.3	13.5	18.2	18.2	18.5	19	18.5
9	-	-	-	10.5	12.2	12.2	16.1	-	-	-	-

4.2.2.2 Dissolved Oxygen

Dissolved oxygen data are summarized in Table 4.11.

Table 4.11 Dissolved oxygen levels in Dick's Pond.

	5/12/10	5/19/10	5/28/10	6/4/10	6/11/10	6/18/10	9/8/10	7/27/11	8/3/11	8/18/11	9/8/11
Depth (ft)	**D.O (mg/l)**	**D.O (mg/l)**	**D.O (mg/l)**	**D.O (mg/l)**	**D.O (mg/l)**	**D.O (mg/l)**	**D.O (mg/l)**	**D.O (mg/l)**	**D.O (mg/l)**	**D.O (mg/l)**	**D.O (mg/l)**
surface	-	14.6	8.1	9.7	5.5	6.9	8.5	4.5	4.3	0.6	0.04
1	11.0	16.7	10.8	13.3	4.5	6.2	8.4	4.6	4.4	0.5	0.0
2	5.4	15.4	14.3	2.6	2.8	6.2	7.1	4.7	4.2	0.5	0.0
3	2.8	1.7	20.0	1.5	2.2	0.7	6.9	4.3	2.2	0.5	0.0
4	3.6	0.2	1.2	0.3	1.1	0.2	3.8	0.3	0.4	0.5	0.0
5	3.6	0.05	0.2	0.1	0.2	0.1	0.8	0.04	0.0	0.25	0.0
6	2.0	0.02	0.1	0.05	0.05	0.05	0.1	0.14	0.02	0.0	0.0
7	-	0.0	0.04	0.03	0.06	0.05	0.05	0.03	0.0	0.0	0.0
8	0.002	0.0	0.01	0.03	0.02	0.04	0.02	0.03	0.0	0.0	0.02
9	-	-	-	0.0	0.0	0.03	0.01	-	-	-	-

The observed dissolved oxygen profiles are typical of highly productive lakes and ponds. The bottom of the pond (below 5 ft) was essentially anaerobic throughout the late spring and summer. During July and August (2011), the dissolved oxygen was well below the saturation level even at the surface. In fact, in late August and September of 2011, there was less than 1 mg/L of dissolved oxygen throughout the entire water column.

4.2.2.3 Conductivity

Conductivity indicates mixing. The conductivity data are presented in Table 4.12. In general the conductivity values within the top 6 ft of the pond are reasonably uniform, which indicates that the pond is fairly well mixed or only weakly stratified.

Table 4.12 Conductivity Profiles in Dick's Pond.

	5/19/10	5/28/10	6/4/10	6/11/10	6/18/10	9/8/10	7/27/11	8/3/11	8/18/11	9/8/11
Depth (ft)	Cond (Us)	Cond (Us)	Cond (Us)	Cond (Us)	Cond (Us)	Cond (Us)	Cond (Us)	Cond (Us)	Cond (Us)	Cond (Us)
surface	-	-	208.7	190.0	250.0	246.6	252.9	237.3	245.6	249.7
2	250.0	320.0	178.4	174.0	241.0	247.0	251.5	247.6	232.1	250.4
4	251.0	270.0	202.6	189.0	211.0	246.8	254.7	252.0	226.8	253.3
6	255.0	264.0	249.8	212.0	229.0	254.2	310.2	340.0	294.5	266.3
8	-	303.0	301.0	272.0	273.0	528.0	487.0	574.0	545.0	516.0

4.2.2.4 Secchi Depth

Table 4.13 lists the Secchi depth transparency measured in the Dick's Pond. Most of the values were less than 1.0 meter. Comparing the results with the values from Table 2.1 indicates that the pond is highly eutrophic. During the pre-construction monitoring, the pond often had a brown or brownish-green appearance, indicating the presence of suspended solids from runoff and algal growth. During the post-construction monitoring, dense blooms of duckweed were observed on the pond surface.

Table 4.13 Secchi depth transparency measured in Dick's Pond

	Date	Secchi Depth
Pre-Construction	5/19/2010	1.9 ft (0.6 m)
	5/28/2010	2.7 ft (0.85 m)
	6/4/2010	0.6 ft (0.2 m)
	6/11/2010	0.9 ft (0.3 m)
	6/14/2010	1.6 ft (0.5 m)
	9/8/2010	2.4 ft (0.75 m)
Post-Construction	07/27/11	2.6 ft (0.8 m)
	08/03/11	3.2 ft (1 m)
	08/18/11	3.93 ft (1.2 m)
	09/08/11	2.9 ft (0.9 m)

4.2.3 Laboratory Analyses

Tables 4.14 through 4.22 lists the concentrations of TP, SRP, NH_3-N, NO_3-N and Chla measured during the pre- and post-construction monitoring at different sample locations.

Table 4.14 Concentrations at inlet pipe from neighboring farm

		Concentration (µg/L)				
	Date	**TP**	**SRP**	**NH_3-N**	**NO_3-N**	**Chla**
Pre-Construction	5/12/2010	339.7	385.0	1473	2124	-
	5/19/2010	82.39	777.5	34.48	1364	-
	5/21/2010	139.7	529.8	0.00	390.8	-
	5/24/2010	55.50	255.9	115.4	733.5	-
	5/28/2010	322.8	118.0	46.49	127.3	-
	6/1/2010	1093	399.9	46.49	1030	-
	6/4/2010	263.5	186.4	170.6	1018	-
	6/11/2010	198.2	117.5	224.0	793.0	-
	6/14/2010	239.2	55.71	27.83	686.3	-
	6/18/2010	172.1	74.27	106.7	30.70	-
Post-Construction						
	3/21/2011	117.1	77.75	1.46	2930	-
	4/24/2011	1377	1371	366.9	1373	-
	7/13/2011	89.93	12.67	11.43	41.55	-
	7/27/2011	119.9	42.19	28.79	61.24	-
	8/3/2011	67.13	3.59	110.6	193.9	-
	8/18/2011	138.3	54.59	381.3	36.27	-
	9/8/2011	498.6	341.1	508.7	274.8	-
	9/27/2011	993.4	781.2	524.3	2375	-

Table 4.15 Concentrations at outflow from settling pond

		Concentration (µg/L)				
	Date	TP	SRP	NH_3-N	NO_3-N	Chla
Post-Construction	3/21/2011	211.7	131.2	52.63	3162	0.00
	4/24/2011	284.7	234.3	270.2	1533	0.00
	7/13/2011	89.93	39.92	57.16	18.47	142.4
	7/27/2011	119.9	31.88	70.18	8.96	0.00
	8/3/2011	67.13	40.46	4.17	14.75	128.6
	8/18/2011	138.3	39.97	113.2	12.09	21.85
	9/8/2011	445.0	245.1	471.4	107.8	0.00
	9/27/2011	992.3	621.7	453.4	3222	8.54

Table 4.16 Concentrations at outflow from wetland cell #1

		Concentration (µg/L)				
	Date	TP	SRP	NH_3-N	NO_3-N	Chla
Post-Construction	3/21/2011	192.9	116.7	35.09	2989	0.00
	4/24/2011	237.0	191.7	247.4	1561	4.27
	7/13/2011	88.57	2.85	13.06	0.00	12.82
	7/27/2011	119.2	11.27	16.19	34.35	22.43
	8/3/2011	138.9	26.10	0.00	6.32	2.14
	8/18/2011	56.47	0.00	141.9	15.11	13.88
	9/8/2011	118.6	23.92	84.78	9.37	11.75
	9/27/2011	931.1	712.1	362.2	3656	2.14

Table 4.17 Concentrations at mouth of small stream

		Concentration (µg/L)				
	Date	**TP**	**SRP**	**NH_3-N**	**NO_3-N**	**Chla**
Post-Construction	3/21/2011	191.6	491.4	301.1	4183	-
	4/24/2011	619.9	46.15	331.0	2457	-
	7/27/2011	34.26	16.75	1.8	14.94	-
	8/3/2011	233.9	16.64	79.29	2.11	-
	8/18/2011	437.2	7.15	35.1	6.04	-
	9/8/2011	768	3.99	68.24	4.67	-

Table 4.18 Concentrations at outflow from wetland cell #2

		Concentration (µg/L)				
	Date	**TP**	**SRP**	**NH_3-N**	**NO_3-N**	**Chla**
Post-Construction	3/21/2011	167.2	87.85	77.48	3292	0.00
	4/24/2011	183.2	141.3	363.6	1824	3.20
	7/13/2011	83.80	10.77	26.13	15.39	0.00
	7/27/2011	177.9	26.73	118.7	143.3	30.97
	8/3/2011	132.9	9.46	37.56	29.51	32.04
	8/18/2011	395.3	3.25	315.8	0.00	9.61
	9/8/2011	1209	69.76	523.1	20.30	45.92
	9/27/2011	728.7	523.1	372.3	2958	10.68

Table 4.19 Concentrations in water column of Dick's Pond at 0.5 meters depth

		Concentration (µg/L)				
	Date	**TP**	**SRP**	**NH_3-N**	**NO_3-N**	**Chl<u>a</u>**
Pre-Construction	5/21/2010	468.1	35.43	0.00	34.12	272.3
	5/28/2010	76.53	27.99	37.49	11.43	55.54
	6/4/2010	661.0	261.2	54.73	573.7	23.50
	6/11/2010	367.9	194.9	190.6	313.8	4.27
	6/18/2010	186.3	32.72	23.40	7.31	22.43
	9/8/2010	117.1	15.01	54.53	6.06	13.88
Post-Construction	07/27/11	93.57	19.65	91.77	276.3	82.24
	08/03/11	83.08	4.24	237.8	35.83	13.88
	08/18/11	130.7	20.47	394.0	19.65	3.20
	09/08/11	157.0	6.31	275.0	0.00	64.08

Table 4.20 Concentrations in water column of Dick's Pond at 1 meter depth

		Concentration (µg/L)				
	Date	**TP**	**SRP**	**NH_3-N**	**NO_3-N**	**Chla**
Pre-Construction	5/12/2010	154.8	41.2	52.0	225.0	44.5
	5/21/2010	284.2	29.5	49.5	9.3	128.2
	5/28/2010	85.3	31.2	19.5	19.6	366.3
	6/4/2010	632.8	260.9	138.1	569.0	9.6
	6/11/2010	407.6	198.6	304.7	279.8	25.6
	6/18/2010	227.1	42.9	124.3	4.4	37.4
	9/8/2010	139.6	21.14	13.3	4.6	1.1
Post-Construction	07/27/11	128.4	8.37	233.9	252.3	205.0
	08/03/11	60.48	2.28	171.1	6.32	13.88
	08/18/11	86.93	13.97	480.2	16.62	0.00
	09/08/11	464	9.63	277.1	0.00	221.0

Table 4.21 Concentrations in water column of Dick's Pond at 2 meter depth

		Concentration (µg/L)				
	Date	**TP**	**SRP**	**NH_3-N**	**NO_3-N**	**Chla**
Pre-Construction	5/12/10	375.0	137.6	1375.9	218.6	8.14
	5/21/10	106.0	177.4	604.1	1.55	37.38
	5/28/10	716.9	262.2	830.7	1.63	366.3
	6/4/10	603.5	267.6	1403	152.6	4.41
	6/11/10	594.0	257.8	1789	35.55	8.54
	6/18/10	752.3	369.0	1569	8.77	33.11
	9/8/10	195.8	106.6	2005	15.15	412.0
Post-Construction	7/27/2011	91.59	23.51	849.3	112.0	102.5
	8/3/2011	292.4	52.21	3733	6.32	28.84
	8/18/2011	125.0	12.67	1340	7.56	42.72
	9/8/2011	116.1	13.29	891.2	0.00	0.00

Table 4.22 Concentrations at outlet of Dick's Pond

		Concentration (μg/L)				
	Date	TP	SRP	NH_3-N	NO_3-N	Chla
Pre-Construction	5/12/2010	31.08	5.41	52.02	39.98	-
	5/19/2010	71.69	76.44	38.98	229.5	-
	5/21/2010	32.73	37.07	0.00	111.6	87.58
	5/24/2010	69.55	38.06	40.48	9.30	-
	5/28/2010	136.3	49.87	23.90	138.7	0.00
	6/1/2010	171.5	62.74	58.48	6.53	-
	6/4/2010	634.2	214.1	24.75	303.7	128.1
	6/11/2010	331.7	209.8	247.6	406.5	16.02
	6/14/2010	208.6	91.67	129.4	60.29	-
	6/18/2010	145.0	43.84	149.2	58.48	10.68
	9/8/2010	619.6	12.87	39.80	140.9	104.1
	03/21/11	154.7	61.59	102.3	2780	2.14
Post-Construction	04/24/11	159.4	108.1	257.2	1523	2.14
	07/13/11	483.7	40.55	78.39	9.23	121.7
	07/27/11	374.9	19.32	735.9	231.5	234.9
	08/03/11	289.7	13.38	219.1	44.26	65.15
	08/18/11	328.0	12.35	231.3	13.60	113.2
	09/08/11	489.2	22.59	177.8	0.00	21.36
	9/27/2011	228.5	66.25	200.1	277.1	59.81

4.2.4 Data Analysis

4.2.4.1 Means and Standard Deviations

The means and standard deviations for the pre- and post-construction monitoring are listed in Table 4.23.

Table 4.23 Mean and standard deviations for pre- and post-construction analyses

		TotalP		SRP		NO_3-N		NH_3-N		Chla	
		Mean	**StDev**	**Mean**	**StDev**	**Mean**	**StDev**	**Mean**	**StDev**	**Mean**	**StDev**
PRE CONSTRUCTION	**Inlet**	290.6	297.2	290.04	233.0	829.9	614.0	223.4	445.2	-	-
	0.5 m	313.0	227.0	94.60	106.0	158.0	237.0	59.90	67.40	65.30	103.0
	1 m	276.0	190.0	89.30	97.90	159.0	215.0	100.0	102.0	87.50	130.0
	2 m	478.0	225.0	226.0	90.30	62.00	87.40	1368	500.0	124.0	182.0
	Outlet	223.0	218.0	76.60	71.50	137.0	128.0	72.90	73.50	56.50	56.90
POST CONSTRUCTION	**Inlet**	425.0	499.0	336.0	495.0	911.0	1171	242.0	227.0	-	-
	Set.Pond	294.0	308.0	173.0	202.0	1010	1444	187.0	188.0	33.40	64.80
	Cell #1	235.0	287.0	136.0	243.0	1034	1521	110.0	133.0	8.41	8.14
	Sm.Str	380.8	278.4	97.02	193.7	1111	1795	136.1	142.3	-	-
	Cell #2	384.7	393.2	109.0	174.0	1035	1432	229.3	187.3	16.42	17.55
	0.5m	116.0	34.10	12.70	8.58	82.20	130.0	250.0	125.0	40.80	38.30
	1 m	185.0	188.0	8.56	4.83	67.60	123.0	291.0	134.0	110.0	120.0
	2 m	156.0	91.90	25.40	18.50	29.90	55.10	1703	1371	41.40	46.20
	Outlet	314.0	131.0	43.00	33.70	610.0	1015	250.0	206.0	77.60	78.40

The results from Table 4.23 indicate that phosphorus and nitrogen concentrations in the runoff entering the pond, and in the pond itself, are sufficient to cause highly eutrophic conditions. The SRP, nitrate, and ammonia concentrations are indications of fertilizers and animal waste in the runoff coming from the neighboring farm. The ratio of SRP to TP in the inlet indicates that most of the phosphorus entering the wetland/pond system is in soluble form, which means that it is readily available for uptake by algae. The mean chlorophyll a concentrations in the pond were several times the typical value of 14.3 μg/L given by Wetzel (2001) for eutrophic lakes (Table 2.1).

The mean total phosphorus (TP) concentrations after wetland construction were well below the levels observed before construction at all three depths in the pond's water column. Due to the low flow in the outlet pipe during the post construction period, the outlet concentration is possibly subjected to sampling error, resulting in a higher mean TP after wetland construction. However, standard deviations are high, indicating highly variable concentrations throughout the entire system.

The ratio of N: P in lakes can be used to indicate whether nitrogen or phosphorus is likely to be the growth-limiting nutrient for algal growth. If the N: P ratio (by mass) is greater than 7:1, phosphorus is generally limiting. If N: P is less than 4:1, nitrogen is usually limiting (Wetzel, 2001). From the data obtained in this study, total N cannot be found because only two soluble forms of nitrogen – nitrate and ammonia – were measured. However, the data in Table 4.23 suggest that a large percentage of both SRP and nitrate in the inflow were consumed by algae in the pond. On the other hand, it does not appear that much nitrate was removed by the wetland.

4.2.4.2 Student's T-Test Results

The Student's t-test can be performed to compare any two sets of data. The t statistic is calculated and used to find the probability, p, that the null hypothesis is valid. The null hypothesis states that the two sets of data are really no different. Since the standard deviations were high for most of the water quality parameters measured, the Student's t-test was used to evaluate the differences between the data sets obtained in pre- versus post-construction monitoring, and the data sets from different locations in the wetland-pond system from post-construction monitoring. Table 4.24 contains the results obtained from the Student's t-test.

The choice of p values representing highly significant differences is arbitrary. In this study, $p< 0.20$ (bold font in Table 4.24) was considered highly significant, $0.20<p<0.50$ (italics in Table 4.24) was considered moderately significant, and $p>0.50$ was considered not significant.

From the results in Table 4.24, the decreases in phosphorus seen in the water column after wetland construction are statistically significant. For example, $p = 0.13$ (highly significant) at the 0.5 m depth in the water column. This means that there is 87% probability that the observed decrease in TP is due to real changes in the system. The results show a 54% probability ($p = 0.46$; moderately significant) of TP decrease at 1 m depth, and 96% probability ($p = 0.04$; highly significant) of an actual decrease in TP at 2 m depth after construction of the wetland. The decreases in SRP in the water column after wetland construction were even more significant.

Table 4.24 Student's t-test results for Dick's Pond water quality data sets.

		TotalP		SRP		NO_3-N		NH_3-N		Chla	
		t	**p**	**t**	**p**	**t**	**p**	**t**	**p**	**t**	**p**
PRE vs. POST	**0.5 m**	1.68	**0.13**	1.51	**0.17**	0.58	0.58	-3.16	**0.01**	0.45	0.67
	1m	0.77	*0.46*	1.61	**0.14**	0.77	*0.46*	-2.67	**0.03**	0.28	0.79
	2m	2.39	**0.04**	4.28	**0.00**	0.66	0.53	0.60	0.56	0.88	*0.40*
	Outlet	-1.04	*0.31*	1.22	*0.24*	-1.54	**0.14**	-2.66	**0.02**	-0.56	0.59
POST-CONSTRUCTION:											
INLET vs.	**Sett. Pond**	0.63	0.54	0.86	*0.40*	-0.15	0.88	0.53	0.60	-	-
	Cel #-1	0.93	*0.37*	1.03	*0.32*	-0.18	0.86	1.41	**0.18**	-	-
	0.5m	1.21	*0.26*	1.27	*0.23*	1.38	**0.20**	-0.06	0.95	-	-
SETT. POND vs.	**Cell #1**	0.39	0.70	0.34	0.74	-0.03	0.97	0.94	*0.36*	-	-

From Table 4.24 it can also be observed that:

1. The probabilities of an actual decrease in nitrate concentration in the pond are not as high as for phosphorus.
2. There is a high probability that the ammonia nitrogen concentrations actually increased between the pre- and post-construction monitoring. This is probably because the post-construction monitoring was done in July and August, when the dissolved oxygen levels in the pond were low. This would slow down the oxidation of ammonia to nitrate in the pond.
3. The probability that chlorophyll a levels at 0.5 m depth in the pond were lower after wetland construction is only 33% ($p = 0.67$; not significant). This is the most direct measure of trophic condition.

Based on the comparisons by sampling location in the post-construction monitoring, there is some weak evidence of decreases in TP and SRP in the settling pond and wetland cell #1. The probabilities of actual decreases from the inlet were 46% ($p = 0.54$) for the settling pond outflow and 63% ($p = 0.37$) for the outflow from wetland cell #1. The corresponding probabilities for SRP decrease were similar but slightly higher. The wetland does not appear to have a significant effect on nitrate concentrations.

Overall, these results suggest that the wetland is removing phosphorus from the inflow and has resulted in decreases in TP and SRP in the pond. The evidence that algal productivity (as measured by chlorophyll a) has decreased is weak and inconclusive. Further monitoring that includes the entire spring and summer, as well as more storm runoff events, would help to clarify the effectiveness of the wetland.

4.3 Modeling Results

Before finding the rate constant using the first order areal uptake model, the surface areas of the wetland and the average flow conditions were calculated.

4.3.1 Surface Area

Wetland Cell #1 is a rectangular cell which is 41 ft (12.49 m) wide and 55 ft (16.74 m) in length. The surface area of the cell is calculated to be 2255 ft^2 (209.4 m^2).

Wetland Cell #2 is shaped like a right triangle having a base width of 60 ft (18.28 m) and height of 44 ft (13.41 m). The surface area is calculated to be 1320 ft^2 (122.6 m^2).

4.3.2 Average Flow Conditions

The annual average flow entering wetland cell #1was calculated by multiplying the average flow determined by StreamStats (0.09 cfs) by the fraction of total watershed area lying within subwatershed#1 (0.797). The average annual inflow to wetland cell #2 was assumed to equal the total average annual flow of both subwatersheds #1 and #2, or 100% of the StreamStats estimate (0.09 cfs). The average flow conditions for wetlands #1 and #2 were calculated to be 2,513,000 ft^3/yr (71,160 m^3/yr) and 3,153,100 ft^3/yr (89,286 m^3/yr), respectively. Using the average flow conditions the hydraulic loading rate (flow divided by surface area) for wetland cells #1 and #2 were found to be 1,114 ft/yr (339.7 m/yr) and 2,388ft/yr (728.1 m/yr), respectively.

Considering the hydraulic loading rates for wetland cells #1 and #2, the rate constants for TP removal were calculated from equation 3.1, using mean TP concentrations from Table 4.24 as C_i and C_o. The resulting rate constants obtained were:

Wetland Cell #1: k = 249.6ft/yr (76.09 m/yr)

Wetland Cell #2: k = -768.0 ft/yr (-234.1 m/yr)

The negative rate constant for wetland cell #2 was obtained due to the assumption that the flow from the small stream is mixing with the outflow coming from cell#1 at the beginning of cell #2. The mean TP concentration measured in cell #2 outflow (384.7μg/L) was higher than the calculated mixed inflow concentration (264.9 μg/L). The measured TP concentrations in the small stream may be high due to sampling error, as there was not enough depth of flow to collect the sample with the 1 L plastic bottle. Due to insufficient flow from the small stream, the samples were collected using the container cap, which may have led to sediment entering the sample, giving higher TP concentrations.

The k value obtained for wetland cell #1 is much higher than the values cited by Kadlec and Knight (1996) for natural wetlands. The reasons for this difference are not clear. Continued monitoring of Dick's Pond and wetland is necessary to determine whether this high removal rate can be maintained.

The impact of storm events on wetland treatment efficiency was investigated by calculating the removal of TP in wetland cell #1 under peak flow conditions of a two-year storm. At peak discharge of 12.0 cfs into wetland cell #1, the hydraulic loading rate (q) would be 148,500 ft/yr (45,260 m/yr). Assuming that the rate constant, k, remains 249.6 ft/yr (76.09 m/yr) and C_i remains at 294 μg/L, equation 3.1 was solved for TP in the outflow of cell #1 (C_o). The result was 293.5 μg/L, compared to 235 μg/L under annual average flow conditions. Thus, the model indicates that TP removal will be minimal during peak flows of two-year or larger storms.

4.4 Wetland Development

Several photographs documenting conditions in the watershed, Dick's Pond, and the wetland are shown in the Appendix. The photos show that dense wetland vegetation was established within the first year after construction. Further growth and establishment of vegetation may improve the filtering and biological uptake processes, improving phosphorus removal. Construction of flow control structures has not been completed yet. Once these are in place and functioning properly, hydraulic residence time in the wetland should increase, which may also enhance phosphorus removal. On the other hand, the accumulation of sediment in the settling pond and wetland, and the seasonal death and decomposition of wetland plant biomass, my act to decrease phosphorus removal, at least temporarily.

CHAPTER 5

SUMMARY, CONCLUSIONS & RECOMMENDATIONS

5.1 Summary and Conclusions

The research was conducted on Dick's Pond to evaluate reduction of nutrient loading and algal biomass with a constructed wetland. The main concern was the amount of phosphorus entering the pond. Phosphorus, in combination with nitrogen, causes heavy growth of algae and duckweed and makes the pond less attractive and less useful for recreation. Pre- and post-construction water quality monitoring, including several field tests and laboratory analyses were conducted. The flow and nutrient loadings entering the pond from its watershed were estimated. The watershed was delineated, the different land uses were identified, and the runoff coefficients were obtained. A 2-yr storm hydrograph was developed to estimate the peak discharge. A mathematical model was applied to calculate the first order areal uptake rate of phosphorus by the wetland.

The following conclusions were drawn from this research:

1. The mean and standard deviation results of the post- and pre-construction monitoring indicate that phosphorus and nitrogen concentrations is the runoff entering the pond, and in the pond itself, are sufficient to cause highly eutrophic conditions.
2. The mean total phosphorus (TP) concentrations after wetland construction were well below the levels observed before construction at all three depths sampled in the pond's water column. Based on the Student's t-test, there is 87% probability that the decrease in TP observed at 0.5 m depth in the water column is due to real changes in the system.

3. The settling pond and wetland cell #1 appear to provide significant removal of phosphorus, but not nitrate.
4. The data provide weak evidence ($p = 0.67$, or 33% probability, at 0.5 m depth) that algal biomass (as measured by chlorophyll a) decreased after construction of the wetland.
5. The annual average inflow to the wetland/pond system is about 0.091 cfs (0.002 m^3/s), while the peak flow for the two-year storm is about 15.6 cfs (0.441 m^3/s).
6. The rate constant calculated for phosphorus removal in wetland cell #1 was significantly higher than literature values reported for natural wetlands.

5.2 Recommendations

In order to improve the understanding of processes in the constructed wetland and further evaluate its impact on water quality in Dick's Pond, the following steps are recommended:

- Further monitoring of the wetlands, including the entire spring and summer, as well as more storm runoff events, would help to clarify the effectiveness of the wetland and its impact on water quality in Dick's Pond.
- Further study of the assumption that flow from the small stream mixes with the outflow from wetland cell #1 at the beginning of cell #2 could improve the accuracy of the wetland model
- Sampling and analysis to find the total nitrogen levels in Dick's Pond could help to confirm whether phosphorus or nitrogen, or both, is the growth-limiting nutrient for algae.

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APPENDIX

Figure A.1 Farm Land

Figure A.2 Agricultural Land

Figure A.3 Pond during Pre-Construction Monitoring

Figure A.4 Pond during Post-Construction Monitoring

Figure A.5 Wetland Cell #1 after Construction

Figure A.6 Wetland Cell #1 with Vegetation

Figure A.7 Small Stream

Figure A.8 Flow in the Small Stream during Post-Construction Monitoring


Figure A.9 Wetland Cell #2 after Construction


Figure A.10 Wetland Cell #2 outflow