# Development and implementation of a flexible system for monitoring a created wetland

**(Great Kills Park, Staten Island, New York)**

by

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## EXECUTIVE SUMMARY

A full understanding of the dynamics of created wetlands requires data of sufficient density to reveal the small-scale fluctuations that give rise to large-scale behavior. Wetland development has historically been investigated using irregular field observations, which often focus on patterns within the vegetal and faunal communities. As the behavior of vegetation and fauna is a result of the physical and chemical properties of the system, a more complete understanding of the whole wetland system could be arrived at if one could continuously monitor the controlling properties of the system.

A flexible multi-hub, web-based continuous monitoring system was designed and implemented for an artificial wetland in Great Kills Park, Staten Island. This system is unique in that it allows for easy reconfiguration of different sensor types over a series of hubs as well as the automated integration of the data in a relational database, which can be queried over the web. The data from this system show the temporal variations of the wetland. The system will be used for studying the long term evolution of the wetland as well as for educational and outreach purposes.

## *ACKNOWLEDGEMENTS*

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# CHAPTER 1
# INTRODUCTION

Wetlands have over the last fifty years been recognized as playing a vital role both as habitat for wildlife and in the cleansing of surface waters. In many urban coastal areas wetlands have been either destroyed or have been severely impacted by development. For example, in the New York metropolitan area 75% of the original wetlands have been lost (HEP, 1996).

While numerous wetland restoration projects have been undertaken in the past ten years, wetland creation and restoration is still a young discipline. Significant difficulties have been encountered in translating wetland science into wetland creation and management practices.

There are several reasons for these difficulties. First, the various components of a wetland interact in extremely complex ways. Current ecological models are not able to fully account for all of the chemical reactions and biological interactions taking place. Second, wetlands are self-organized. They adapt their relationships to the specific hydrological, geochemical and biological constraints imposed by their environment. Even where wetland models can explain an isolated part of the wetland cycle, they encounter difficulty dealing with the complex and subtle feedback involved in the self-organization of an ecosystem. Self-organization is a long and dynamic process. It is often difficult to determine which initial conditions or later interventions would help or frustrate the process.

Due to the lack of understanding of both individual wetland processes and ecosystem development, the current approach to wetland creation focuses on the creation of suitable initial conditions, and primarily on creating appropriate hydrological conditions. The wetland is then seeded with a wide variety of native wetland plants, which allows the system to self-select the most suitable plants for the site. Over time, invertebrates, higher animals and plants are expected to enter into the system naturally. Some of the introduced species will find niches and survive, and others will die out. The ecosystem will gradually evolve to a stable state, in which all major ecological niches are filled.

It has become clear from several wetland creation and remediation efforts that the development of a wetland is strongly dependent on not only the *initial* but also the *interim* conditions. Outside environmental factors, as well as internal fluctuations have the potential to upset equilibrium at any time. A major challenge of establishing a stable ecosystem lies in providing appropriate support for the ecosystem as it develops toward equilibrium.

The knowledge of what types of support are appropriate at each stage of development will require a detailed understanding of wetland behavior and science as well as an accurate understanding of the conditions within the wetland. Current methods of wetland evaluation based on plant cover partially capture this behavior. While the biological behavior of wetlands has been studied extensively (Mitsch and Gosselink, 1993), we do not know much about the underlying causes of this biological behavior and consequently we know relatively little about effective wetland management.

The solution to this problem includes improvements in wetland modeling and science, but the most basic and important element is the accessibility to a continuous, high quality stream of primary information about wetlands.

The information currently available about wetlands falls into three categories: information from field measurements, information from aerial maps and information from permanent monitoring stations.

**Field measurements** (which can be either done on a regular or intermittent schedule) primarily yield information on biological behavior and have the downside that the information derived from these campaigns is often uncalibrated; that is, data may be collected by different observers; observers may apply different classification or measurement criteria during field visits.

**Satellite or airplane based observations** yield information on the gross changes in vegetation coverage and wetland extent and are more and more becoming valuable tools in wetland management. However, they do not provide insight into controlling factors, such as flow velocity, temperature gradient, or water chemistry.

**Permanent monitoring stations** can provide data on the primary physical and chemical parameters that drive the system, such as temperature, pH and dissolved oxygen concentration.

While a large number of off-the-shelf physical and chemical sensor packages exist, the problem with selecting the appropriate sensor package is that little is known about how the temporal and spatial characteristics of a wetland reflect the condition of the ecosystem as a whole. Thus, it is hard to predict the spatial and temporal sampling density required to sufficiently characterize the wetlands.

The development of an appropriate protocol needs to be grounded in both models and field data. Obviously, it is hard to collect super high-density field data for large wetlands. One would ideally want to have a small, well-constrained developing wetland ecosystem which could be used to develop sampling and monitoring techniques. The knowledge gained from the study of this small mesocosm could then be applied to larger systems.

As a small wetland was about to be constructed by the National Park Service in the Great Kills Park on Staten Island, this provided a unique opportunity to design an observational system in tandem with a developing wetland.

# CHAPTER 2
# BACKGROUND

## 2.1 Description of study site

Great Kills Park is part of the Gateway National Recreation Area, which encompasses a number of parks and refuges throughout the New York metropolitan area (Figure 1). Gateway was the first urban national park established by the National Park Service. It is unique among national parks in the extent to which it has been impacted by human activity. As such, it provides an excellent case study of the behavior of ecosystems under stress, and a natural laboratory in which to study how impacted nature can be restored and managed.

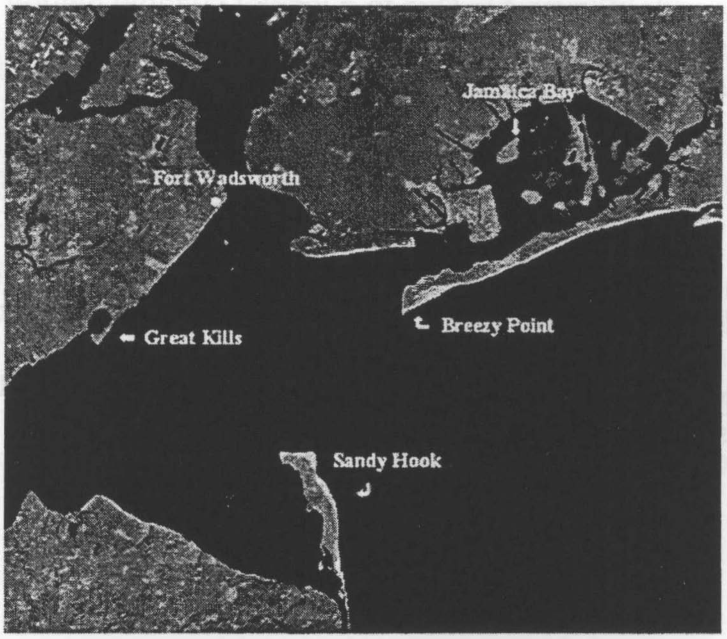


Figure 1. Satellite photo of Gateway National Recreation Area

*(photo courtesy of the Gateway National Recreation Area GIS Implementation Project, University of Rhode Island, http://www.edc.uri.edu/ftsc/gate/)*

As part of an expansion effort by the National Park Service of its education program at Gateway National Recreation Area, plans were made in 1999-2000 for the construction of a field station, and adjacent to this a quarter-acre pond at Great Kills Park. Visiting students and the general public will be able to use the field station for environmental study and special programs. The pond will serve as an integral part of the education program, serving as an example of an evolving ecosystem that can be studied by visiting students. Students will observe the components of the ecosystem and compare the pond with the naturally occurring wetland ecosystems (fresh and saltwater) that occur in the vicinity and to areas located in their communities.

The size of the pond and the timing of its construction made it an ideal site for the development of a monitoring system. The pond would be small enough to make instrumentation feasible. The timing would permit the monitoring system infrastructure to be built into the pond during construction, rather than retrofit later. The system would be able to collect data right from the creation of the pond, allowing the pond's evolution to be tracked from the very beginning. The system would be useful both as a research tool and for educational programming.

## 2.2 Pond design and layout

The pond design went through several iterations. Figure 2 shows the final design and the layout of the pond relative to the field station, and Figure 3 shows the construction and completion of the pond and the field station. The pond is one-quarter acre (approx. 5000 sq ft) in area with a maximum depth of approximately six feet. Figure 4 shows the bathymetry of the pond. The pond is located downhill from the field station, bordered by woodland on the far side (Figure 5). Due to a lack of suitable natural water sources, the pond is fed by a slow trickle of water from a nearby fire hydrant. The water level is maintained by an automated system (Figure 6).

The pond is lined with gunnite. In order to provide varied depths to suit many different plant species, the bottom of the pond is terraced. The gunnite was covered with six inches of topsoil.

Pond construction was completed in the fall of 2000 and was planted in May 2001. A finalized planting list is given in table 1. This planting included a wide variety of native wetland species, including both submergent and emergent plants. It is assumed that amphibians, reptiles, invertebrates, mammals and birds will migrate in on their own. There are no plans as yet to stock the pond with fish.

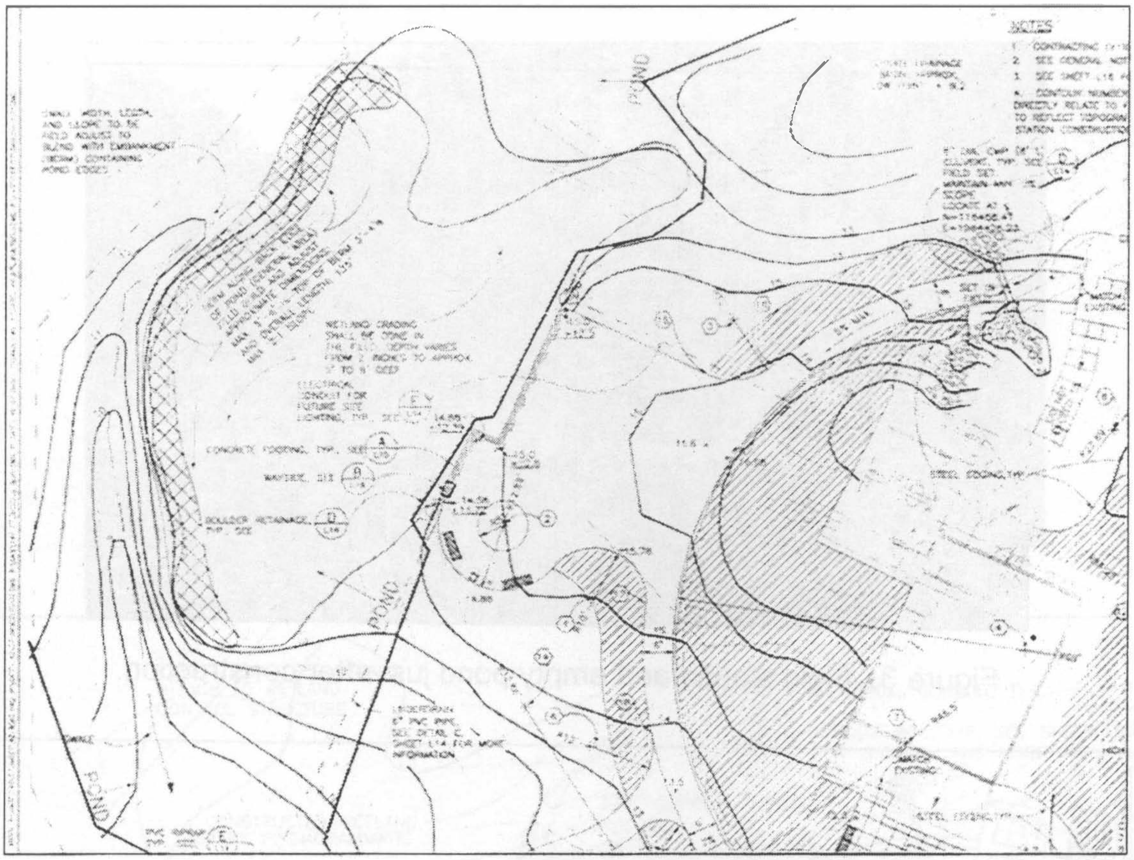


Figure 2. Construction drawings of pond and field station (Petersen, 2000).

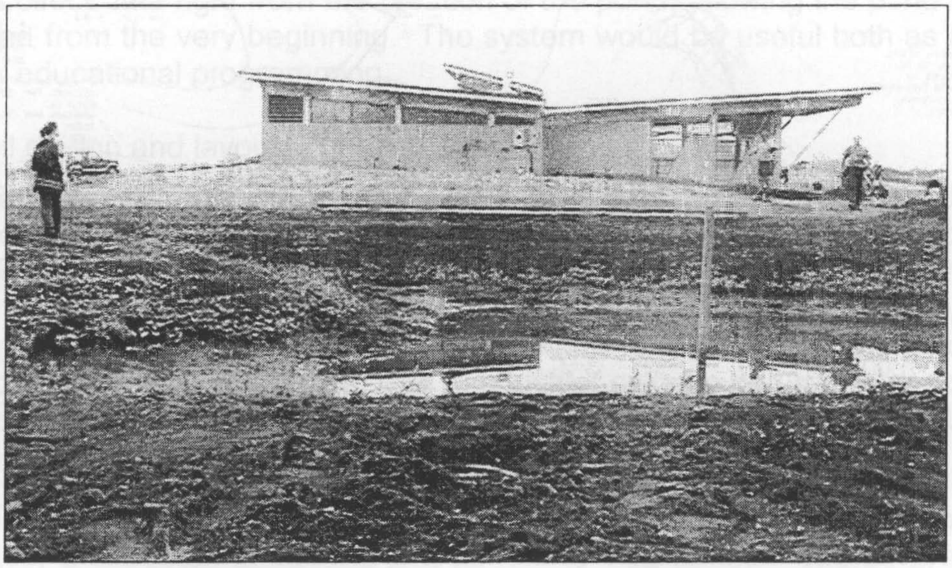

Figure 3. Field station and empty pond just after construction.

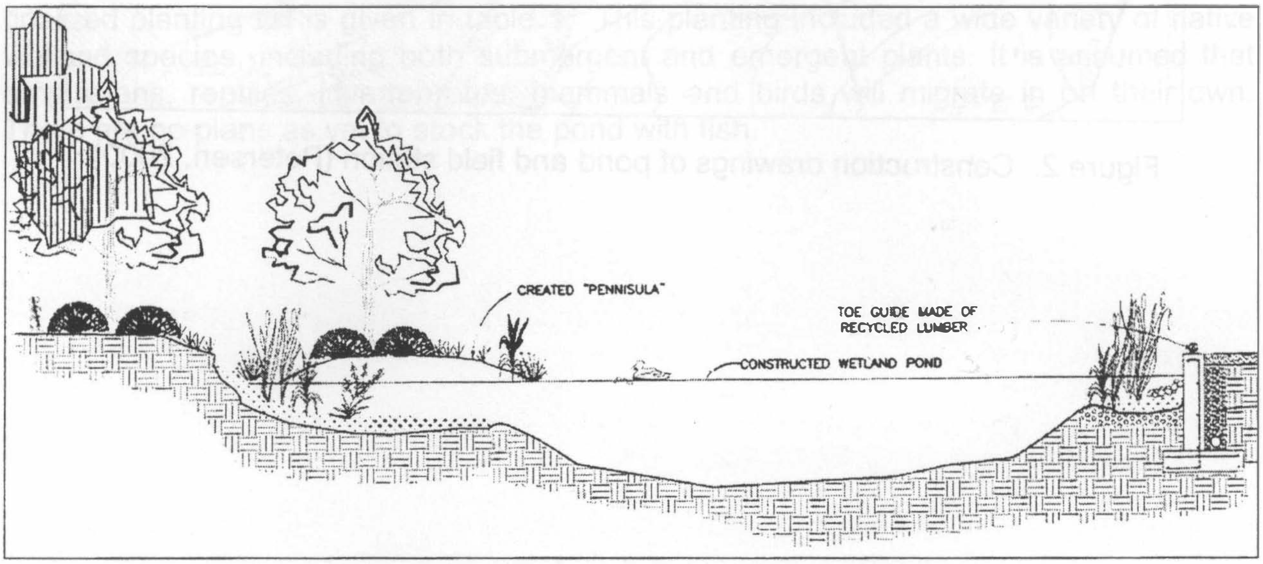


Figure 4. Pond in profile (Petersen, 2000).

Figure 5. Empty pond, facing woods.

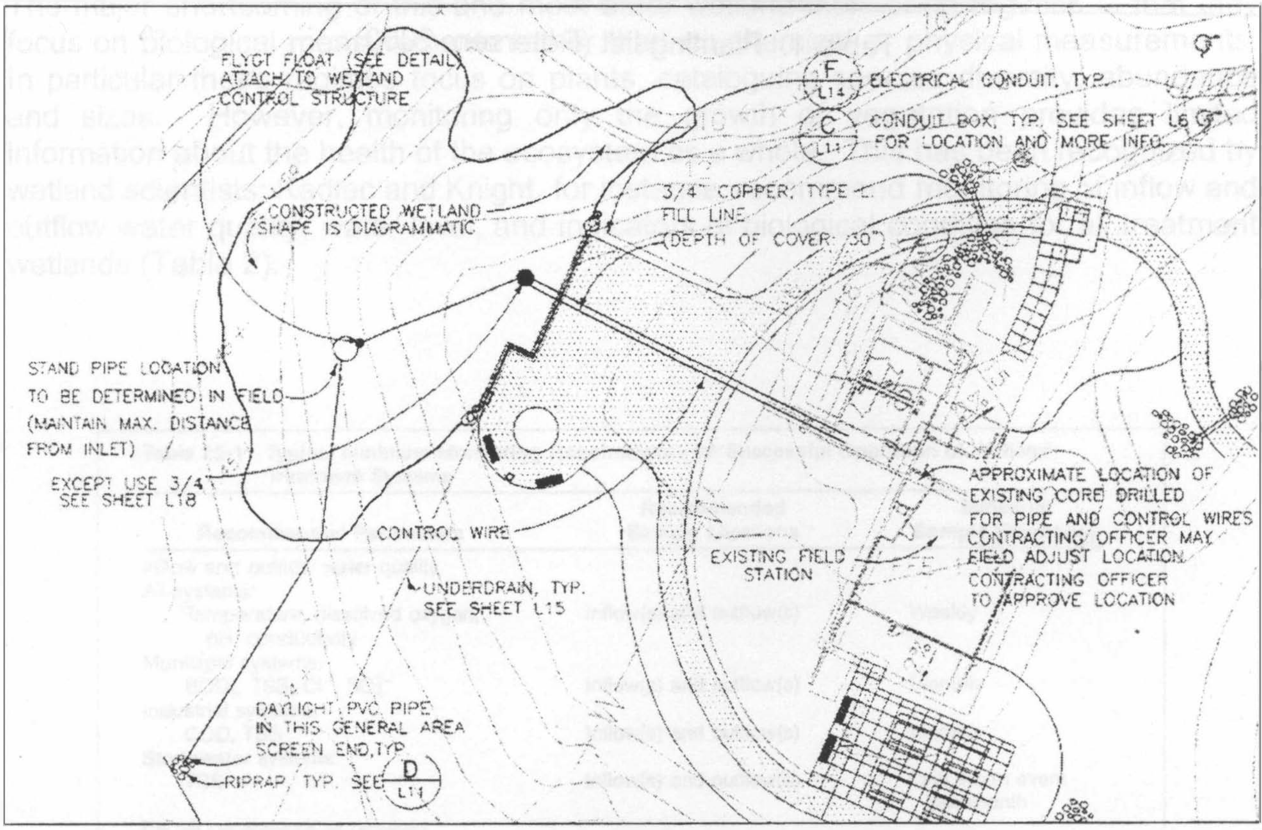


Figure 6. Pond inlet and outlet design (Petersen, 2000).

| | Quantity | Botanical Name | Common Name | Size |
|---|---|---|---|---|
| Zone 3<br>12 - 18" deep | 25 | *Sagittaria latifolia* | Arrowhead | 1 quart |
| | 15 | *Nymphea tuberosa* | White water lily | 1 gallon |
| Zone 2<br>6 - 12" deep | 22 | *Verbena hastate* | Blue Vervain | 1 quart |
| | 32 | *Caltha palustris* | Marsh Marigold | 1 quart |
| | 15 | *Eupatorium perfoliatum* | Boneset | 1 quart |
| | 28 | *Hibiscus palustris* | Swamp Rose Mallow | 1 quart |
| | 35 | *Typha spp.* | Cattail | 1 quart |
| Zone 1<br>3 - 6" deep | 18 | *Symplocarpus foetidus* | Skunk Cabbage | 1 quart |
| | 22 | *Rosa palustris* | Swamp Rose | 1 gallon |
| | 22 | *Clethra alnifolia* | Sweet Pepper Bush | 1 gallon |
| Zone 4<br>0 - 3" deep | 15 | *Iris versicolor* | Blue Flag Iris | 1 gallon |
| | seed | *Juncus tenuis* | Soft Rush | |
| | seed | *Scirpus cyperinus* | Woolgrass | |
| | seed | *Hibiscus mocheutos* | Marsh Mallow | |

Table 1. Planting list (Petersen, 2000).

## 2.3 Current approach to monitoring

Traditional wetland monitoring takes one of two forms: either ground-based bioassays, or satellite-based remote sensing. Remote sensing is useful for very large areas where ground-based monitoring is impractical, but it provides only a partial picture. For a complete picture it is necessary to perform on-site monitoring. Generally speaking, this consists of regular visits to a site during which a number of wetland indicators are measured.

An example of monitoring guidelines can be found in the recently published salt marsh restoration and monitoring guidelines (Niedowski, 2000) from the New York State Department of State. These guidelines recommend annual assessment of various biological factors, including vegetation development, soil properties, colonization by benthic invertebrates and habitat usage by macrofauna. These measurements are made by the establishment of transects and quadrants in the marsh, and then systematically counting individuals and measuring plant sizes.

The major shortcoming of this and most other wetland monitoring regimes is that they focus on biological measurements rather than on chemical or physical measurements. In particular these regimes focus on plants, cataloguing species diversity, abundance and sizes. However, monitoring only the growth of vegetation provides limited information about the health of the ecosystem as a whole. This has been recognized by wetland scientists; Kadlec and Knight, for instance, recommend monitoring of inflow and outflow water quality, water level, and indicators of biological condition for all treatment wetlands (Table 2).

**Table 25-1 Typical Minimum Monitoring Requirements for Successful Operation of Wetland Treatment Systems**

| Recommended Parameters | Recommended Sample Locations | Minimum Sample Frequency |
|---|---|---|
| Inflow and outflow water quality | | |
| All systems: | | |
| Temperature, dissolved oxygen, pH, conductivity | Inflow(s) and outflow(s) | Weekly |
| Municipal systems: | | |
| $BOD_5$, TSS, $Cl^-$, $SO_4^{2-}$ | Inflow(s) and outflow(s) | Monthly |
| Industrial systems: | | |
| COD, TSS | Inflow(s) and outflow(s) | Monthly |
| Stormwater systems: | | |
| TSS | Inflow(s) and outflow(s) | One storm event per month |
| Permit parameters as required: | | |
| $NO_2+NO_3-N$, $NH_4-N$, TKN, TP | Inflow(s) and outflow(s) | Monthly |
| Metals, organics, toxicity | Inflow(s) and outflow(s) | Quarterly |
| Flow | Inflow(s) and outflow(s) | Daily |
| Rainfall | Adjacent to wetland | Daily |
| Water stage | Within wetland | Daily |
| Plant cover for dominant species | Near inflow, near wetland center, near outflow | Annually |

*Note:* $BOD_5$, 5-day biochemical oxygen demand; TSS, total suspended solids; COD, chemical oxygen demand; TKN, total Kjeldahl nitrogen; TP, total phosphorus.

Table 2. Monitoring requirements for wetland treatment systems (Kadlec and Knight, 1996).

It is also important to ensure that spatial and temporal variations within the system are adequately captured by the selected monitoring regime. Thus, there are two important considerations in the selection of a monitoring regime: what to monitor, and how often and how densely to monitor it.

# CHAPTER 3
# CONCEPTUAL DESIGN

## 3.1 Goals and conceptual design

A well-designed monitoring system will allow the investigation of many important scientific questions. It will provide the opportunity to track the self-design and evolution of a constructed ecosystem, compare constructed wetlands to natural wetlands, provide insights into the processes at work during the early development of the pond ecosystem, compare the utility of different measurement regimes, and improve the design of future monitoring systems.

The system will also be useful for the maintenance and management of the pond. It will permit continuous knowledge of the precise water quality conditions in the pond, early detection of serious problems such as eutrophication and Phragmites invasion, comparison between planned and observed ecosystem development, and provide data that can be used as an indicator of ecosystem health and pond evolution. It will also provide the potential for automatic response to deteriorating conditions.

The system should provide data on the pond and at the same time serve as a platform for experimentation with different measurement configurations in order to optimize data collection, as a platform from which educational applications can be developed and as a management tool. In order to achieve these goals, the system must:

1. Measure data from a suite of different sensors with a reconfigurable structure
2. Allow for remote data reporting and querying
3. Allow for the incorporation of manually collected data, and
4. Be self-sustaining and require only minimal maintenance.

From the functional demands we can derive a simple conceptual system (Figure 7) in which we have a suite of sensors in the pond which are sampled on a regular basis. These data would be stored a relational database which is updated from the sensing system, and which can be queried through a standard web browser interface.

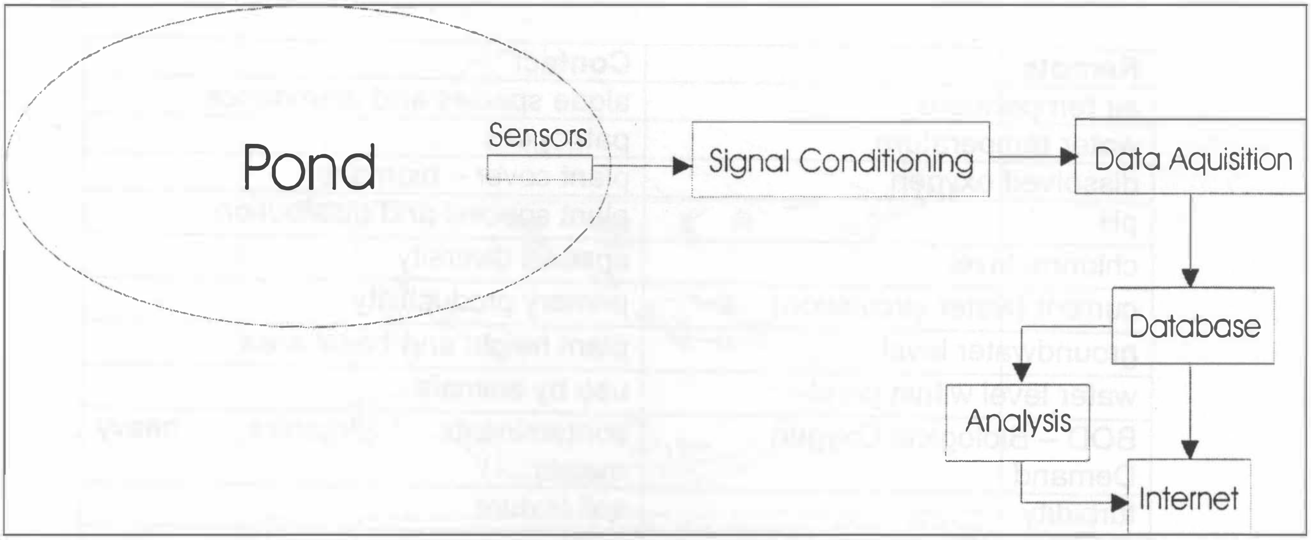


Figure 7. Conceptual design of wetland monitoring system.

### 3.2 Parameters to be measured

Parameters must be selected according to their importance to scientific inquiry, their educational value, and their usefulness for management of the pond. We can divide parameters between those that can be measured using automated sensors (remote) and those that require someone to take samples or make measurements (contact). The table below (obtained after literature studies and discussion with wetland, education and management specialist) gives a list of potential parameters for monitoring.

Ideally, we would like to measure all relevant parameters. Unfortunately, budgetary constraints and lack of manpower require us to select only a few key parameters. In order to decide which parameters are most important it is necessary to consider the ecology and biogeochemistry of the pond as well as the forcing functions which drive the system.

| Remote | Contact |
|---|---|
| air temperature | algae species and abundance |
| water temperature | pathogens |
| dissolved oxygen | plant cover – biomass |
| pH | plant species and distribution |
| chlorine level | species diversity |
| current (water circulation) | primary productivity |
| groundwater level | plant height and basal area |
| water level within pond | use by animals |
| BOD – Biological Oxygen Demand | contaminants (organics, heavy metals….) |
| turbidity | soil texture |
| nitrates, nitrites, ammonia | soil organic content |
| phosphates | |
| water inflow | |
| water outflow | |
| precipitation | |
| humidity | |
| wind speed | |
| dissolved carbon dioxide | |
| alkalinity | |
| total dissolved solids | |
| redox potential | |
| sunlight level | |
| total dissolved gases | |

Table 2. Relevant parameters

## 3.3 Pond ecology

A pond ecosystem is made up of many components, both biotic and abiotic. The abiotic components include water, soil, oxygen, carbon dioxide and nutrients. The major biotic components include microorganisms, invertebrates, amphibians, reptiles, mammals, birds, fish and plants. The pond's organisms can be classified according to their function as producers or consumers. Producers are the autotrophs at the base of the food chain, which provide a food source for consumers and also produce oxygen. Consumers are the heterotrophs. Primary consumers consume producers, secondary consumers consume consumers, and saprophytes consume dead organic matter.

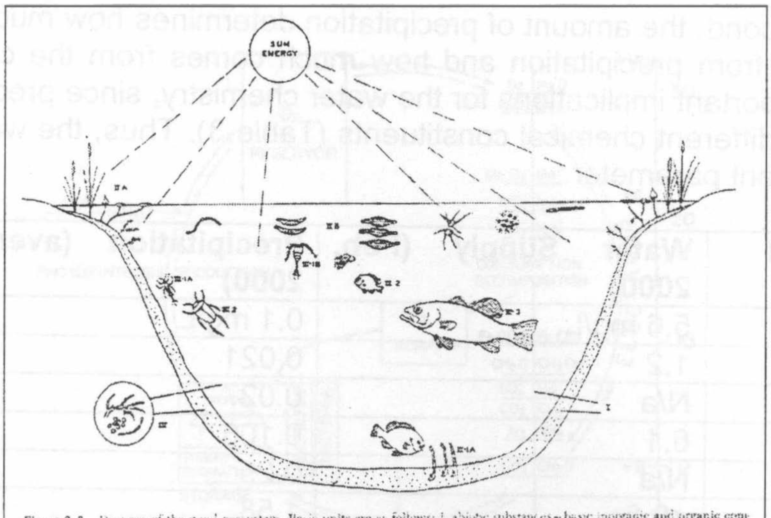


*Figure 2-2.* Diagram of the pond ecosystem. Basic units are as follows: I, abiotic substances – basic inorganic and organic compounds; IIA, producers – rooted vegetation; IIB, producers – phytoplankton; III-1A, primary consumers (herbivores) – bottom forms; III-1B, primary consumers (herbivores) – zooplankton, III-2, secondary consumers (carnivores), III-3, tertiary consumers (secondary carnivores); IV, saprotrophs – bacteria and fungi of decay. The metabolism of the system runs on sun energy, while the rate of metabolism and relative stability of the pond depend on the rate of inflow of materials from rain and from the drainage basin in which the pond is located

Figure 8. The pond ecosystem (Odum, 1971)

Plants in a pond or wetland provide food, habitat and oxygen. Vegetation type changes with water depth. Shallow areas will be dominated by emergent vegetation and as the water gets deeper, the dominant vegetation will change to floating and floating-leaved plants, then to submerged plants, and finally to phytoplankton, which is a food source for many creatures and is the primary source of oxygen in the water. Higher plants generally enter the food web as detritus, which is consumed by microbes. During this process several things happen: organic material dissolves, nutrients are released and organic carbon is released as $CO_2$ (Mitsch and Gosselink, 1993).

## 3.4 External forcing functions

### 3.4.1 Temperature

Temperature is one of the strongest external forces on an ecosystem. It has a direct influence on chemical and biological processes. The kinetics of many reactions are strongly temperature dependent. Temperature determines the solubility of dissolved gases and as such controls pond geochemistry. The activity level of many organisms is also temperature dependent. Many organisms can live only within certain temperature ranges. Temperature is thus a critical parameter which must be monitored in order to understand the processes occurring in the pond.

### 3.5.1 Climate

Diurnal and seasonal changes in temperature, photoperiod and other climatic variables cause changes in plant growth and in community structure. These changes also affect abiotic factors, such as the solubility of oxygen, the rate of release of nutrients, and the rates of chemical reactions.

In this particular pond, the amount of precipitation determines how much of the water in the pond comes from precipitation and how much comes from the city water supply. This will have important implications for the water chemistry, since precipitation and city water have very different chemical constituents (Table 3). Thus, the weather at the site is another important parameter.

| Chemical | Water Supply (Feb. 2000) | Precipitation (average for 2000) |
|---|---|---|
| $Ca^{2+}$ | 5.6 mg/L | 0.1 mg/L |
| $Mg^{2+}$ | 1.2 | 0.021 |
| $K^{+}$ | N/a | 0.027 |
| $Na^{+}$ | 6.1 | 0.106 |
| $NH^{4+}$ | N/a | 0.25 |
| $NO^{3-}$ | <0.5 | 1.58 |
| $Cl^{-}$ | 8 | 0.23 |
| $SO_4^{2-}$ | 7 | 1.85 |
| pH | 6.7 | 4.39 |
| Conductivity | 68 µS/cm | 23.17 µS/cm |

Table 3. Fire hydrant water quality vs. average precipitation water quality.

3.6 Internal forcing functions and processes

Biological and chemical cycles in the pond center around the production and consumption of biomass. During the growing season, higher microbial activity and plant growth will cause the sequestration of nutrients within the plant biomass. Water and soil nutrient levels will subsequently drop. In the fall and winter, the situation will be reversed. Plants translocate their nutrients to their roots during senescence, which returns nutrients to the soil. At this time, nutrients will be released to the water column by plant litter, causing an increase in nutrient concentrations. Wetland soils play an essential role very important in nutrient cycling. Most chemical transformations occur in the soil.

The elements necessary for life (C, O, N, P, S…) are continually cycled within the pond. The most important of these cycles are the carbon and oxygen cycles, which are linked through photosynthesis and respiration.

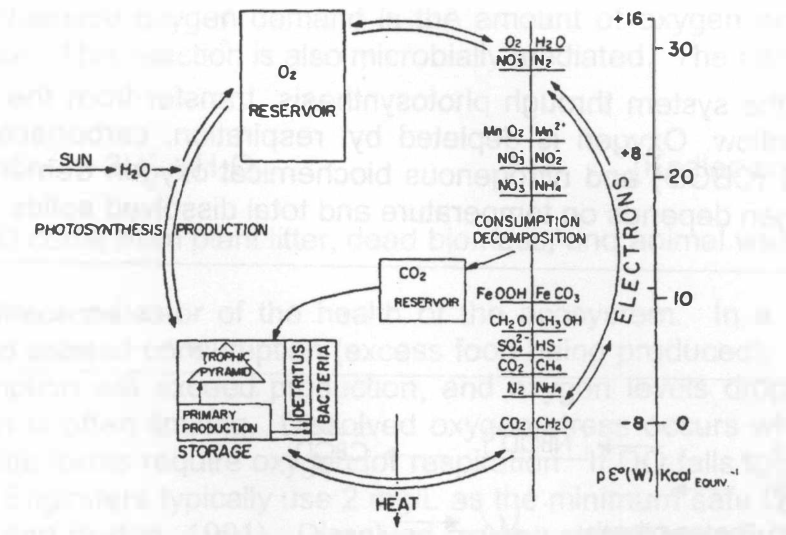


**Figure 8.12.** Photosynthesis and biochemical cycle. Photosynthesis may be interpreted as a disproportionation into an oxygen reservoir and reduced organic matter (biomass containing high-energy bonds made with hydrogen and C, N, S, and P compounds). The nonphotosynthetic organisms tend to restore equilibrium by catalytically decomposing the unstable products of photosynthesis through energy-yielding redox reactions. The $p\varepsilon°(W)$ scale on the right gives the sequence of the redox reactions observed in an aqueous system.

Figure 9. Photosynthesis and the biochemical cycle (Stumm and Morgan, 1996).

### 3.6.1 Carbon dioxide

The aqueous carbonate system constitutes the following reactions:

$H_2O + CO_2(aq) = H_2CO_3(aq)$

$H^+ + CO_3^{2-} = HCO_3^-$

$H^+ + HCO_3^- = H_2CO_3$

Photosynthesis converts $CO_2$ to organic carbon. Respiration converts organic carbon back to $CO_2$. Methanogenesis converts $CO_2$ to $CH_4$. Carbon dioxide participates in chemical reactions involving dissolved carbonate species. These reactions regulate the pH and composition of the water. Carbon dioxide can also participate in the dissolution of calcium carbonate:

$CaCO_3(s) + CO_2(g) + H_2O = Ca^{2+} + 2HCO_3^-$

$CO_2$ also enters the system through diffusion from the atmosphere.

Changes in $CO_2$ concentration due to photosynthesis and respiration shift the dissolved carbonate equilibria, causing a change in pH. Photosynthesis consumes $CO_2$ and produces $O_2$. This causes a shift in the carbonate – bicarbonate – carbon dioxide equilibria to a higher pH. At night, respiration produces $CO_2$, lowering the pH. The diurnal pH cycle is dominated by these processes. Open water with high algal activity can have a very high pH swings. Algal influence is greatly damped by the presence of dense emergent vegetation. Atmospheric diffusion and calcium chemistry modify the cycle by supplementing and removing $CO_2$.

3.6.2 Oxygen

Oxygen enters the system through photosynthesis, transfer from the atmosphere and D.O. in water inflow. Oxygen is depleted by: respiration, carbonaceous biochemical oxygen demand (CBOD) and nitrogenous biochemical oxygen demand (NBOD). The solubility of oxygen depends on temperature and total dissolved solids.

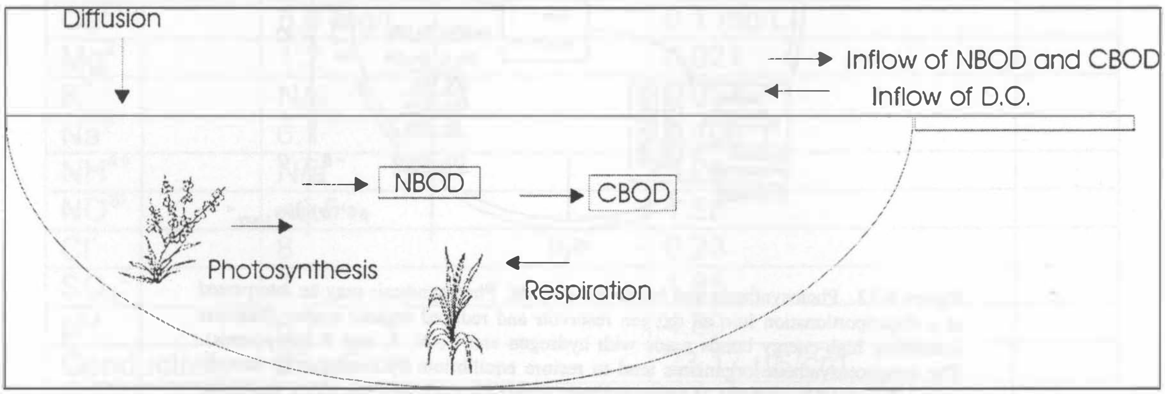


Figure 10. Dissolved oxygen pathways

Photosynthesis is carried out by all plants in the wetland, but only the oxygen produced by plankton, periphyton and submerged aquatics add oxygen to the water column. Oxygen produced by emergent vegetation is released directly to the atmosphere. In unshaded areas, photosynthesis tends to dominate the DO cycle. This results in large diurnal variations in dissolved oxygen concentration. In shaded areas, abiotic processes tend to dominate, so the swings are greatly damped.

There are three routes for transfer from air:

1. Direct mass transfer to the water surface
2. Convective transport down dead stems and leaves
3. Convective transport down live stems and leaves

Routes 2 and 3 are collectively referred to as the Plant Aeration Flux (PAF) (Kadlec and Knight, 1996).

Oxygen is transported to the air-water interface. The surface layer is completely saturated with oxygen. The saturation concentration is determined by temperature and total dissolved solids.
Transfer from the surface to the water column is a combination of molecular diffusion and bulk mixing. In totally stagnant water, diffusion dominates. Rain, wind and even very low currents all promote mixing. The rate of diffusion depends on the concentration gradient between the air and the water, which depends on the rate of oxygen consumption in the water column.
Carbonaceous biochemical oxygen demand (CBOD) is the amount of oxygen used by microbes in the breakdown of organic matter.

Oxidative reduction of BOD: $BOD + O_2 = CO_2 + H_2O$ (Kadlec and Knight, 1996)

Nitrogenous biochemical oxygen demand is the amount of oxygen needed to oxidize ammonia to nitrate. This reaction is also microbially mediated. The nitrification reaction is:

$NH^{4+} + 2O_2 = NO_3^{2-} + 2H^+ + H_2O$ (Kadlec and Knight, 1996).

CBOD and NBOD come from plant litter, dead biomass, and animal wastes.

D.O. is a very direct indicator of the health of the ecosystem. In a healthy system, production should exceed consumption (excess food being produced). If pond is being polluted, consumption will exceed production, and oxygen levels drop (Odum, 1971). Dissolved oxygen is often limiting. Dissolved oxygen stress occurs when DO falls too low. All aerobic life forms require oxygen for respiration. If DO falls too low, organisms begin to die off. Engineers typically use 2 mg/L as the minimum safe DO concentration (Tchobanoglous and Burton, 1991). Dissolved oxygen stress is generally caused by a combination of factors, including excessive CBOD and NBOD, insufficient atmospheric diffusion, and an imbalance between respiration and photosynthesis.

Wetland soils are typically anoxic. Thin layer of oxidized soil a few mm thick at the soil-water interface. This layer is very important for nutrient cycling. Plants have aerenchyma (air ducts) which supply oxygen to the roots. Significant quantities of oxygen are transferred to the root zone (rhizosphere) this way. This creates adjacent aerobic and anaerobic zones separated by only a few microns. This allows for very fast transfer of substances back and forth.

Regular dissolved oxygen measurements are essential to our study. They can serve as an early warning system, allowing detection of the onset of oxygen stress before plants and animals begin to die. Long-term measurements will reveal patterns. These will shed light on the balance between production and consumption in the ecosystem.

### 3.6.3 pH

pH influences biological and chemical reactions, and also reflects the reactions taking place. The pH of a freshwater marsh is usually 6 – 7 (slightly acidic). Most bacteria can survive in a pH between 4.0 and 9.5, but some have more specific pH requirements. For example, denitrifiers prefer pH between 6.5 and 7.5, and nitrifiers prefer pH > 7.2.

In fresh water, pH is largely controlled by dissolved carbonate equilibria, which are controlled by the concentration of dissolved $CO_2$. The pH thus reflects the balance between photosynthesis and respiration.

Other biological reactions influence pH, but to a lesser degree. Denitrification and sulfate reduction increase pH (Stumm and Morgan, 1996). Decomposition produces humic and fulvic acids, which act as a natural buffer against incoming basic substances (such as calcium and magnesium).

Acid rain is also an issue. It adds $H_2SO_4$, $HNO_3$, HCL, $NH_4^+$ and organic acids to the system (Stumm and Morgan, 1996). Figure 11 shows more processes which affect pH.

**Table 15.1. Processes that Modify the $H^+$ Balance in Waters**

| Processes[a] | Changes in Alkalinity $\Delta[Alk] = -\Delta[H\text{-}Acy]$ (equivalents per mole reacted) |
|---|---|
| 1. Weathering reactions: | |
| $\underline{CaCO_3(s)} + 2H^+ \rightleftharpoons Ca^{2+} + CO_2 + H_2O$ | +2 |
| $\underline{CaAl_2Si_2O_8(s)} + 2H^+ \rightleftharpoons Ca^{2+} + H_2O + Al_2Si_2O_5(OH)_4(s)$ | +2 |
| $\underline{KAlSi_3O_8(s)} + H^+ + 4\tfrac{1}{2}H_2O \rightleftharpoons K^+ + 2H_4SiO_4 + \tfrac{1}{2}Al_2Si_2O_5(OH)_4(s)$ | +1 |
| $\underline{Al_2O_3 \cdot 3H_2O} + 6H^+ \rightleftharpoons 2Al^{3+} + 6H_2O$ | +6 |
| 2. Ion exchange: | |
| $2ROH + \underline{SO_4^{2-}} \rightleftharpoons R_2SO_4 + 2OH^-$ | +2 |
| $NaR + \underline{H^+} \rightleftharpoons HR + Na^+$ | +1 |
| 3. Redox processes (microbial mediation): | |
| Nitrification | |
| $\underline{NH_4^+} + 2O_2 \rightleftharpoons NO_3^- + H_2O + 2H^+$ | |
| Denitrification | −2 |
| $1\tfrac{1}{4}CH_2O + \underline{NO_3^-} + H^+ \rightarrow 1\tfrac{1}{4}CO_2 + \tfrac{1}{2}N_2 + 1\tfrac{3}{4}H_2O$ | +1 |
| Oxidation of $H_2S$ | |
| $\underline{H_2S} + 2O_2 \rightarrow SO_4^{2-} + 2H^+$ | −2 |
| $SO_4^{2-}$ reduction | |
| $\underline{SO_4^{2-}} + 2CH_2O + 2H^+ \rightarrow 2CO_2 + H_2S + H_2O$ | +2 |
| Pyrite oxidation | |
| $\underline{FeS_2(s)} + 3\tfrac{3}{4}O_2 + 3\tfrac{1}{2}H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$ | −4 |
| 4. In the *buildup (or breakdown) of biomass*, the uptake (release) of each equivalent of conservative anion causes an equivalent increase (decrease) in alkalinity, and each equivalent of base cations that is taken up (released) results in an equivalent decrease (increase) of alkalinity. The reduction of Fe(III) (hydr)oxides and of Mn(III,IV) (hydr)oxides by biota is particularly efficient in generating alkalinity in the hypolimnion of lakes. | |
| $\{(CH_2O)_{106}(NH_3)_{16}(H_3PO_4)\}_{Biota} + 424\ Fe(OH)_3 + 862\ H^+ \rightarrow 424\ Fe^{2+} + 16\ NH_4^+ + 106\ CO_2 + HPO_4^{2-} + 1166\ H_2O$ (a) | |
| $\{(CH_2O)_{106}(NH_3)_{16}(H_3PO_4)\} + 212\ MnO_2 + 398\ H^+ \rightarrow 212\ Mn^{2+} + 16\ NH_4^+ + 106\ CO_2 + HPO_4^{2-} + 298\ H_2O$ (b) | |

[a]Reactant is underlined.

Figure 11. Processes that modify the $H^+$ balance in waters (Stumm and Morgan, 1996).

CHAPTER 4
SYSTEM DESIGN

There are four main components to the monitoring system: (1) data acquisition (automated acquisition through a suite of fixed sensors and control software, and manual acquisition by NPS personnel and students); (2) data organization into a relational database; (3) data distribution and visualization; and (4) advanced components (data analysis and feedback).

4.1 Automated data acquisition

One of the central goals of this effort was to develop a system with the ability to measure parameters at small and large scales. This of course requires us to be able to deploy multiple sensors over the entire pond. This is hard to do with fixed sensor packages, which monitor only a single location. The solution was to build a system of "hubs" distributed around the pond (Figure 12). Each of these hubs would be able to accommodate multiple sensors, and would be strategically located to ensure that all parts of the pond were accessible. Every sensor would be sampled regularly, and the data would be processed and stored, which requires a software control system.

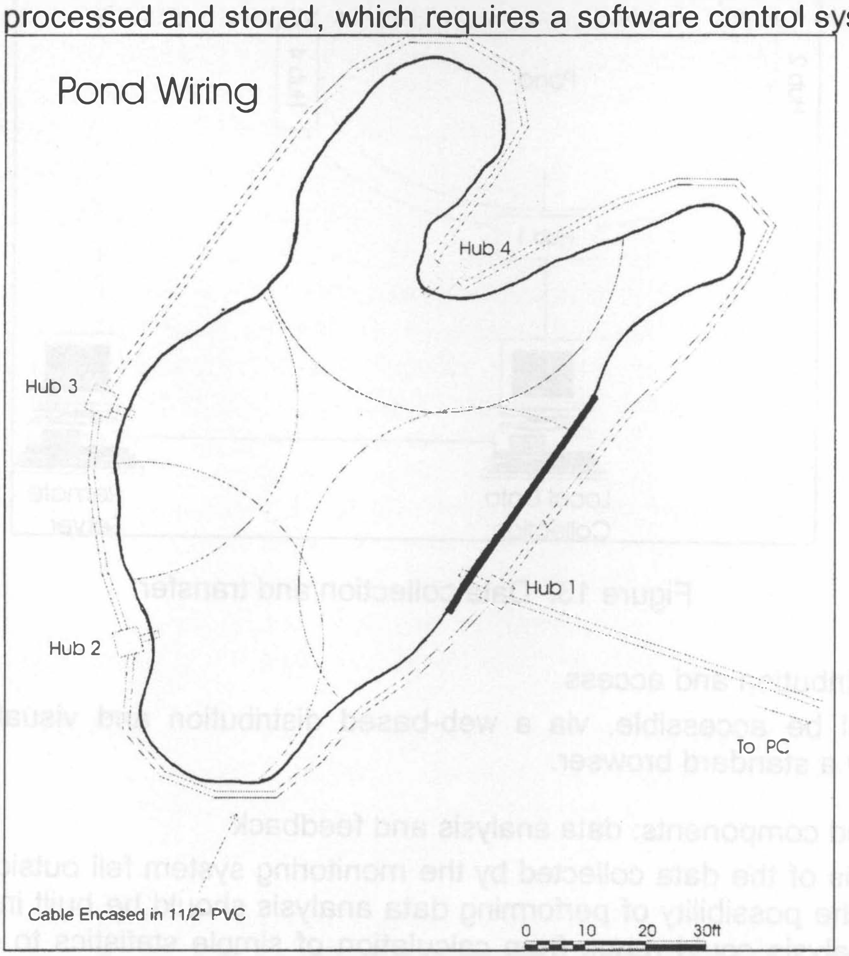


Figure 12. Arrangement of hubs around the pond.

4.2 Manual data acquisition

The focus of the effort was the design of an autonomous monitoring system. However, many important parameters must be measured by hand. Our system design had to allow for manual data to be entered into a database. Instead of an automated data stream, the data would be entered through either submission of web-based forms or by direct entry into the database.

4.3 Data organization in a relational database

Once the data are collected they will need to be stored. This needs to be done in an organized manner, and the most appropriate way is to use a relational database. The database could be housed on a remote server (Figure 13).

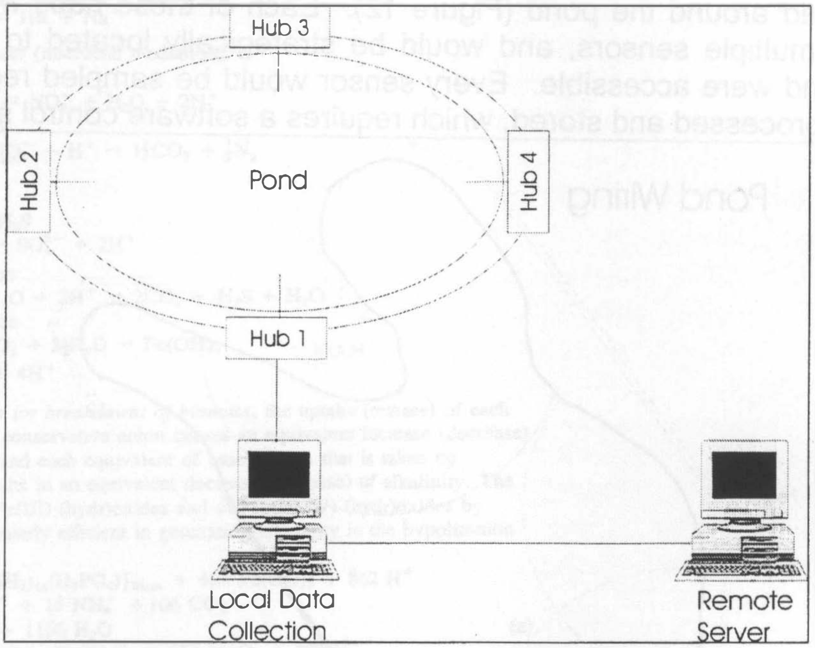


Figure 13. Data collection and transfer.

4.4 Data distribution and access

The data will be accessible, via a web-based distribution and visualization system requiring only a standard browser.

4.5 Advanced components: data analysis and feedback

While analysis of the data collected by the monitoring system fell outside the scope of this project, the possibility of performing data analysis should be built in to the system. This data analysis could range from calculation of simple statistics to coupling of the data to ecosystem models.

The incorporation of data analysis also opens up the possibility of automatic feedback to allow the system to take action in response to its observations. For example, if dissolved oxygen levels were to fall below some threshold value, an aerator could be turned on. It could be turned off automatically once the dissolved oxygen concentration rose to a safe level. The advantage of this approach would be that the system would indicate exactly when intervention was necessary, the extent of the intervention required, and when the desired result was achieved.

While feedback and intervention in the developing ecosystem is an attractive option, it is not central to the monitoring effort. Some level of manual intervention will be necessary to allow the system to take hold and develop. Feedback driven intervention would represent a new way of managing constructed ecosystems. It would allow for maintenance of proper conditions, but in a minimally invasive way. However, significant efforts and an extensive monitoring of the pond over several months to gain an insight into its evolution are required before this can be considered. The system was designed in such a way that a feedback system could be incorporated at a later date.

# CHAPTER 5
# IMPLEMENTATION

## 5.1 System components

### 5.1.1 Data acquisition

Remote measurements are made through an array of sensors, which are distributed throughout the pond. Each of these sensors is plugged into a hub. The maximum cable length for most sensors before amplification is required is about 25 feet. As the pond is about one-quarter acre in size, with a maximum depth of approximately four-and-a-half feet, four hubs suffice to monitor the pond.

The hubs are buried underground in water resistant utility boxes. The purpose of the hub is to serve as a nodal point for the sensors, to amplify and condition the signals, and to convert the signals from analog to digital. The hubs therefore need to be close to the pond, be watertight, be connected to the sensors and the central computer and be belowground (so as to minimize the risk of vandalism). An underground PVC conduit connects the four hubs to the computer, with the cabling guided through the conduit to protect the cables from damage and weather, as well as to allow for more cabling to be installed at a later date, if necessary.

Signal conditioning equipment, including amplifiers and analog-to-digital converters (ADC) are located inside the hubs. The hubs are wired to a computer inside the Field Station. The computer communicates with the ADC converter using the RS-485 protocol, which allows the computer to communicate with all four ADCs on one five-wire cable. Each hub can be used to measure eleven sensors. The design of this hub system allows for maximum flexibility. Sensors can be interchanged between hubs, although some do require specialized signal conditioning, which must also be transferred.

In the first phase of the project eight thermocouples, one pH sensor and one dissolved oxygen sensor were employed, plus four water-detecting sensors to protect the equipment in each hub. In a future phase of the project more sensors will be added.

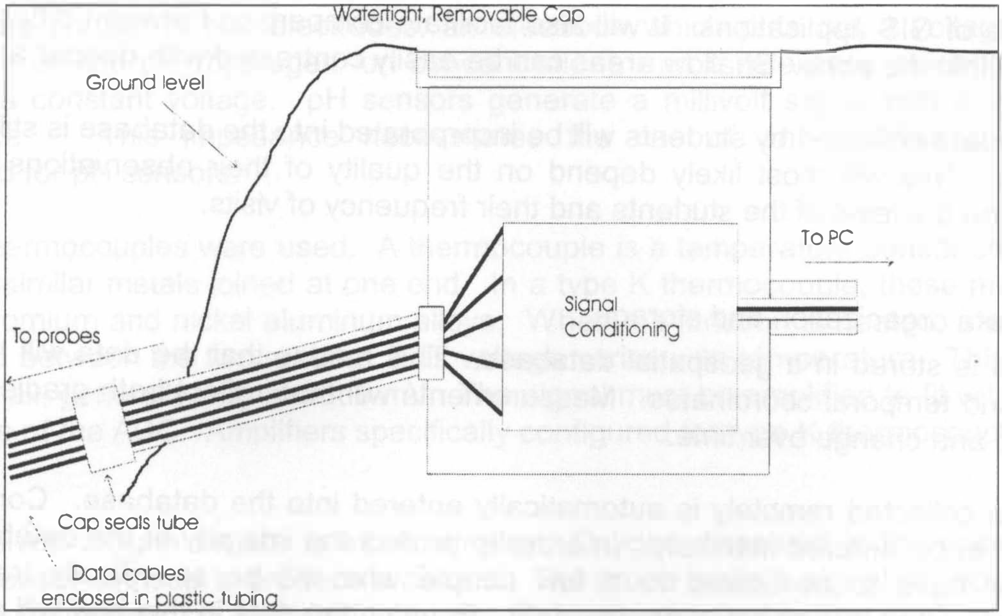


Figure 14. Hub

Data collection is controlled by a custom written Labview™ program. Every 30 minutes, each sensor is polled 100 times. This data is then processed to obtain the most accurate reading possible. These values are written to a Microsoft Access™ database. The data is then made publicly available for analysis through a website.

As mentioned before, the data acquisition network uses the RS-485 protocol. This means that one set of wires can be used to connect the serial port of the central computer to every hub, rather than requiring one set of wires for each hub. The computer is programmed to take a reading from each sensor at a specific interval. To take a reading, the computer sends a command to the hub requesting a reading from a particular sensor. The hub reads the correct sensor, and then formats the data for the computer. The hub then sends the requested data to the computer.

In addition to the sensors, a web camera could be installed to record visual images of the pond. These images could be analyzed to measure such factors as biomass and use by birds and mammals. The images could also be used for security purposes.

Contact measurements, which form an essential part of the monitoring but which are impractical, impossible or too expensive to do remotely, will be made both by NPS staff and by students visiting the site. Very precise protocols must be created in order to ensure the uniformity and accuracy of the data.

All data collected must have space and time coordinates so that it can be properly incorporated into a GIS database. The pond will be divided into several "research sites" in order to ensure clarity and consistency of the time and location of data collection. Dividing the pond into segments will allow us to map gradients within the pond, and to make use of GIS applications. It will also facilitate comparison between different water depths within the pond. Shallow areas can be easily contrasted with deeper areas.

How the data collected by students will be incorporated into the database is still an open question. This will most likely depend on the quality of their observations and also possibly on the level of the students and their frequency of visits.

### 5.1.2 Data organization and storage

The data is stored in a geospatial database. This means that the data will have both spatial and temporal coordinates. Measurements will thus reflect both gradients within the pond and change over time.

The data collected remotely is automatically entered into the database. Contact data will have to be entered manually. In order to protect the integrity of the database, data entry will have to be limited to a few people who will be specifically trained and password coded to properly enter the data. Housing the data in this way will allow data collected by students to be compared with the data collected by the sensors.

### 5.1.3 Data distribution and analysis

Once collected and stored, the data can be used for modeling to predict the pond's evolution, for educational activities, and to evaluate the status of the pond, leading to intervention where it is deemed necessary. As discussed previously, the system can be set up so that equipment is automatically turned on when it is needed. Current plans provide for a situation in which the database, as well as any modeling or analysis that has been done, will be made available in near real time over the internet.

## 5.2 Details

As has been discussed previously, a prefabricated sensor package is not appropriate for this application. A primary goal of this system is to allow maximum flexibility. Sensor packages inhibit this flexibility, because they contain a fixed number of sensors, and poll all sensors at the same time interval. Some parameters display stronger spatial gradients than others. For this reason, it was desirable to have different numbers of sensors for different parameters. Some parameters change rapidly over time. These sensors need to be polled more frequently than sensors measuring parameters that change more gradually. Building a custom system provided the flexibility to optimize the spatial and temporal data density for each parameter. It also preserved the option of adding new sensors as needed.

### 5.2.1 Sensors, amplification and analog-to-digital conversion

Most sensors put out an analog signal of a few millivolts. To be readable by the computer, the signal must be amplified and converted to a digital signal. This is accomplished using amplifiers and an analog-to-digital converter (ADC). The amplifiers must often be tailored to the sensor. For example, pH sensors have special amplification requirements, and thus require specially constructed pH sensor amplifiers.

pH sensors consist of two electrodes: an electrode which puts out a voltage that is dependent on the pH (hydrogen ion concentration), and a reference electrode which puts out a constant voltage. pH sensors generate a millivolt signal with a very high impedance. This impedance necessitates the use of an amplifier specifically configured for pH sensors.

Type K thermocouples were used. A thermocouple is a temperature sensor composed of two dissimilar metals joined at one end. In a type K thermocouple, these metals are nickel-chromium and nickel aluminum alloys. When the junction is heated, a voltage is generated between the two metals. This voltage varies with temperature. This voltage is very small, generally only about 5 mV. The signal must be amplified to fit within the 0 - 5V range of the ADC. Amplifiers specifically configured for type K thermocouples were used.

The dissolved oxygen sensor is much simpler. Oxygen dissolved in the water reacts with the sensor cathode to produce a current. The probe emits a signal of about 50mV, which simply needs to be amplified to the 0 – 5V range required by the ADC.

After amplification, the signals are sent into the analog-to-digital converter (ADC). The ADC converts a 0-5V analog signal to a 12-bit digital signal. The ADCs used are actually small microprocessors. They wait for a request from the main computer, then send back a measurement from the requested channel.

Due to budgetary constraints, a choice was made to develop the infrastructure for the pond completely and purchase only a small number of sensors initially. It is anticipated that additional sensors will be supplied through donations. The core of the system design has been to set up the system in such a way as to allow maximum flexibility in the sensors. The system can accommodate many different types of sensors, with a small number of requirements: the output range of the sensor can be no greater than 5 volts, and the sensor must not require a power source greater than 12VDC. There is an additional constraint on the length of the sensor cables: sensor cables generally cannot be longer than 25 feet. At longer distances, the signal will significantly deteriorate.

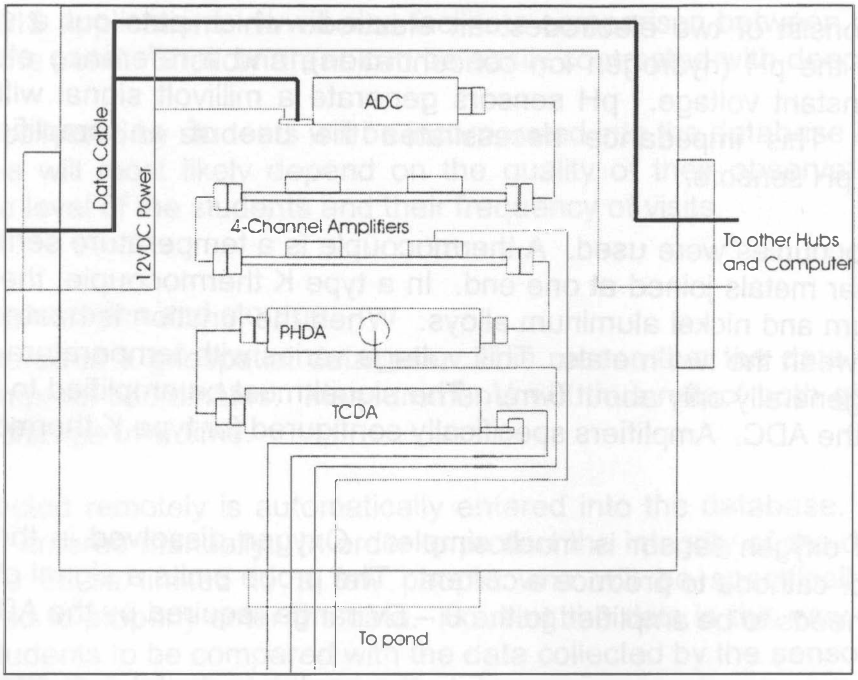

Figure 15. Internal Wiring of Hub.

### 5.2.2 The RS-485 Standard

Communication between the computer and the hubs takes place using the RS-485 standard. This standard allows multiple processors to communicate over the same cable. Each ADC contains a microprocessor, and is assigned a unique address. The circuit is set up in a master-slave configuration, with the main PC acting as the master and the ADCs acting as the slaves. The PC sends out a command addressed to a specific ADC. Only the ADC with the correct address will respond to the PC's request. The PC can request a reading from any of the ADC's channels. The ADC returns the value of the requested channel, followed by the values of each of the lower channels.

### 5.2.3 Relational database

A relational database is employed for two purposes: It is used both to store the collected data and to store information about the type and location of the sensors. All of the information specific to the sensors and their configuration is stored in this database. This information includes:

- which sensors are installed
- what type of sensors they are
- which channel they are assigned to
- where they are physically located within the pond
- how often they should be sampled
- how many data points to collect
- how to average those data points to get a value

This greatly increases the ease of using the system, since these values need only be changed within the database. The central data acquisition program remains unchanged.

5.2.4 Labview™ control software

The program that controls the data acquisition was written in Labview™. Labview™ is a graphical programming environment, in which data flows from one subroutine to another.

Major parts of the program:

1. Initialization. The program queries the database to determine which sensors are currently installed, queries the database to get the protocol for each installed sensor, then matches time of the last measurement to an assigned frequency to determine whether or not it is time to take another measurement.
2. Data collection. For each sensor installed, the program requests measurements from the appropriate channel of the appropriate hub using getdata.vi, then builds an array containing the number of measurements requested along with a time stamp for each measurement.
3. Data processing. The program averages values and assigns a new time stamp, then converts the average voltage to the appropriate value.
4. Data entry. The program writes the new measurement, sensor number and time stamp to the database.
5. If the sensor is a leak detector, the program determines whether or not a leak has been detected. If there is a leak, an email message is sent to the appropriate contact person.

The averaging protocol currently in use takes the array of measurements, removes the outliers and returns the median. It uses the following steps:

1. Remove the 5 highest and lowest values
2. Calculate the standard deviation and the median
3. Remove all values more than two standard deviations from the median
4. Re-calculate the median

5.2.5 Data Reporting

The website is the primary portal for viewing and analyzing the data.
It is set up to perform three main types of analysis.

1. It always displays the most recent values for each sensor
2. The site will allow users to query the database to extract datasets according to their specifications. This data can then be downloaded or viewed online in either table or graphical form.

An application queries the database to determine which sensors are currently installed. For each sensor installed:

1. Generates graphs of the measurements for the last day, week, month and year.
2. Generates an icon displaying the current measurement.

3. If there are multiple sensors of the same type, it also computes the average value and generates an icon to display the average.

Webprep then creates an icon showing the current date and time. It then FTPs these images to the ftp site specified on the front panel. This cycle is repeated as often as is specified on the front panel.

# CHAPTER 6
# DISCUSSION AND CONCLUSIONS

Unfortunately, recurring mechanical difficulties have so far prevented the system from becoming fully operational. Therefore, the following discussion focuses on the challenges encountered during the design and implementation of this system, and the lessons learned. One of the biggest challenges was the transfer of the electronic components from the laboratory into the field. Since the signal conditioning equipment couldn't be more than 25 feet from the sensor, it had to be installed into the four hubs at the edge of the pond. These hubs are relatively waterproof, but still quite damp. Electronic equipment is prone to corrosion in such an environment. Great care had to be taken to keep the equipment as dry as possible. The sensitive components were sealed inside a plastic box along with silica gel to absorb moisture. This ameliorated the situation somewhat, but did not completely solve the problem.

The sensors themselves presented a similar problem. Most of the sensors used were quite delicate instruments. They were not meant for continuous use, especially not in the field, exposed to the elements. Both the pH and DO sensors suffer from the rapid growth of biofilms on their surfaces, which impact the quality of the readings. These sensors need to be cleaned and recalibrated weekly. Incoming data must be carefully scrutinized for signs that the sensors have drifted.

The root of these difficulties lies in budgetary constraints on the project. An attempt was made to adapt inexpensive sensors and electronic components to a fairly sophisticated application. The equipment purchased was designed for laboratory use, not for use in the field. Attempting to use inappropriate equipment created unnecessary problems. Instead of focusing on the experiment itself, a great deal of time was spent troubleshooting mechanical problems.

In addition, the system was over-designed. Such a small pond did not require nearly so many sensors. Designing the system for fewer sensors would have allowed us to spend more money on better-quality equipment.

The system could be fixed by investing in more robust equipment. In recent years very rugged sensors and electronic equipment have been developed for use in outdoor applications. Unfortunately, these components are quite expensive, and will require substantial additional investment in the system.

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