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# MATHEMATICAL MODELING OF NUTRIENT REMOVAL IN WET DETENTION PONDS

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## ABSTRACT

The model CE-QUAL-W2 (Cole and Buchak 1995) was applied to simulate water quality and pollutant removal in three regional wet detention ponds located in High Point, North Carolina. It was initially calibrated to simulate water quality in each pond, and the simulation results were compared to observed pollutant removal efficiencies over a twelve-month monitoring period. While CE-QUAL-W2 provided adequate predictions of total annual removal efficiency for most pollutants, the model was not able to match the month-to-month variations in outflow concentrations and associated pollutant removals. This suggests that there are fundamental weaknesses in the way CE-QUAL-W2 simulates pollutant dynamics in wet detention ponds.

An evaluation of detention pond design parameters using CE-QUAL-W2 indicated that increasing pond surface area could enhance total phosphorus removal efficiency. The CE-QUAL-W2 model results suggested a very complex and possibly unstable relationship between pond configuration and total nitrogen removal. In certain cases, the model predicted that increasing the pond size could actually reduce the nitrogen removal efficiency. It is not known whether these predicted effects are real or are due to limitations in CE-QUAL-W2 and/or the input kinetic parameters.



(Key Words: BMP, wet detention ponds, nutrient, pollutant removal, modeling)

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## SUMMARY AND CONCLUSIONS


SUMMARY

The model CE-QUAL-W2 (Cole and Buchak 1995) was applied to simulate water quality and pollutant removal in three regional wet detention ponds located in High Point, North Carolina: Davis Pond, Piedmont Pond and Mall Pond A. Twelve months monitoring data were available for each of the ponds, including inflow, outflow, and water quality. Also available were in-pond water quality profiles such as temperature, dissolved oxygen (DO), total suspended solids (TSS), total dissolved solids (TDS), total phosphorus (TP), total nitrogen (TN), dissolved orthophosphate phosphorus ($PO_4$-P), dissolved ammonia nitrogen ($NH_4$-N), dissolved nitrite + nitrate nitrogen ($NO_{2+3}$-N), and a variety of both total and dissolved metals. Different land-use characteristics and precipitation during the monitoring periods had considerable impact on the quantity and quality of runoff entering each pond. These differences were included in the model calibration data sets.

In the process of calibrating the CE-QUAL-W2 model, the input data were separated into three main categories:

1. Data that reflected the physical characteristics of the pond that could be potentially altered by a pond designer. This included the pond size, pond geometry, bathymetry, and configuration of the outflow structure.

2. Data that reflected the watershed characteristics that could not be controlled by a pond designer. This includes meteorological data (light, air temperature, wind speed, and direction) and inflow characteristics (variation in inflow rate and chemical characteristics over the year).

3. Kinetic parameters that were used by the model to simulate the different physical, chemical, and biological processes occurring within the pond.

The first two categories of input data were obtained from the physical characteristics and the measured inflow to each pond. Initial parameter ranges for most kinetic coefficients were taken from Cole and Buchak (1995) or their original sources. During the calibration process, the kinetic parameters were then adjusted within these ranges to match site-specific conditions.

The overall objective of this work was to develop a tool that could be used to evaluate different pond modifications that could be used to enhance pollutant removal. As a consequence, our primary calibration objective was to minimize the error between simulated and observed TSS, TP, and TN removal efficiency. As a secondary check on model performance, simulated and observed temperature, dissolved oxygen, nutrient, and chlorophyll a profiles were visually compared after each model simulation. This was done to ensure the model was providing a reasonable qualitative match with actual conditions in the pond. If there was a dramatic difference between simulated and observed profiles, this information was used to identify specific problems with the calibration and correct them. However, the objective function was used as the primary standard for identifying the "best" set of kinetic parameters.

One of the primary objectives of the model calibration process was to identify a single "best-fit" parameter set that minimized the error in predicted pollutant removal efficiency in all three ponds. Unfortunately, this was not possible. As an alternative, we identified a single parameter set for each pond that minimized the prediction error for pollutant removal efficiency. These parameter sets were then used to define the uncertainty in kinetic parameters.

Pollutant removal efficiencies were calculated as the percentage difference in the total mass entering and discharging from each pond over the one-year simulation period. In general, CE-QUAL-W2 was able to provide a reasonably good match between simulated and observed annual average removal efficiencies for the primary pollutants (TSS, TDS, TP, TN, $PO_4$-P, $NH_4$-N, and $NO_{2+3}$-N). However, this good match is somewhat deceiving since this was the primary calibration objective. To provide a more independent estimate of the model's predictive capability, we compared what the model predicted to observed removal efficiencies month by month. In general, CE-QUAL-W2 did not provide a reliable prediction of monthly variations in pollutant concentrations in the pond outflows. For several parameters, there was essentially no correlation between predicted and observed outflow concentrations. In a few cases, the poor prediction of outflow concentration could be attributed to a specific problem in the way monthly averages were calculated (e.g., when a large storm event extended from one month to the next). However, in most cases, there was no obvious reason for the poor model prediction. The reason for the poor match between simulated and observed concentrations in the outflow from the three ponds is not known. However, the poor match could be related to the absence of zooplankton grazing in CE-QUAL-W2 as a factor potentially limiting algal growth.

To reflect the uncertainties in model input, ten different input parameter sets were identified that reflected the range of uncertainty in the kinetic parameters. All the kinetic parameters fell within the range of best-fit parameters found for the three ponds. Pollutant removal efficiencies calculated using the parameter ranges sets did not match the measured removal efficiencies as closely as the best-fit values. However, in most cases, the differences were not great. In cases where the parameter ranges did not accurately match the field observations, the best-fit values also did not match the field observations.

CE-QUAL-W2 was then used to evaluate alternative pond designs with the goal of maximizing nitrogen and phosphorus removal at the lowest cost. Based on a review of detention pond design criteria and common construction practice, the following design variables were expected to have the greatest potential impact on nutrient removal efficiency.

- Normal pool hydraulic residence time (ratio of storage volume to inflow rate)
- Hydraulic overflow rate (ratio of inflow rate to normal pool surface area)
- Depth of permanent water quality pool
- Length of discharge weir (controls pond outflow rate and time period that stormwater is detained in the pond)

An evaluation of detention pond design parameters showed that, in certain cases, varying the pond hydraulic residence time (HRT) and normal pool surface area could significantly impact total phosphorus removal efficiency. However, the relationship between total nitrogen removal efficiency and pond HRT and/or surface area is much more complex. In Mall Pond A, the calibrated CE-QUAL-W2 model predicted that an increase in pond surface area or HRT would result in a decrease in TN removal efficiency. The model also predicted dramatic changes in TP removal in Davis Pond in response to changing weir length. It is not known whether these predicted effects are real or are due to limitations in CE-QUAL-W2 and/or the input kinetic parameters.

CONCLUSIONS

While CE-QUAL-W2 provided adequate predictions of total annual removal efficiency for most pollutants, the model was not able to match the month-to-month variations in outflow concentrations and associated pollutant removals. This suggests that there are fundamental weaknesses in the way CE-QUAL-W2 simulates pollutant dynamics in wet detention ponds. In many cases, the model was not stable. Small changes in an input parameter could lead to dramatic changes in predicted algal biomass and associated nutrient removals.

An evaluation of detention pond design parameters using CE-QUAL-W2 indicated that increasing pond surface area could enhance total phosphorus removal efficiency. This is consistent with other models and our general understanding of nutrient dynamics in ponds and reservoirs. The CE-QUAL-W2 model results suggested a very complex and possibly unstable relationship between pond configuration and total nitrogen removal. In certain cases, the model predicted that increasing the pond size could actually reduce the nitrogen removal efficiency. It is not known whether these predicted effects are real or are due to limitations in CE-QUAL-W2 and/or the input kinetic parameters.

## RECOMMENDATIONS

1. Designers wishing to increase the total suspended solids (TSS) and total phosphorus (TP) removal efficiency should focus on increasing the surface area of wet detention ponds. Increasing the pond depth is expected to have little effect on TSS and TP removal.
2. Model simulations suggest that it may be very difficult to increase total nitrogen (TN) removal in wet detention ponds beyond the 20 to 30% removal achieved with existing designs. To obtain higher TN removals, designers should consider other BMP alternatives, possibly including two BMPs in series. The first BMP would be designed to oxidize organic nitrogen and ammonia to nitrate while the second BMP would remove nitrate by biological denitrification.
3. Results from this study and prior work indicate that BMP designers should focus on locations that generate high influent pollutant concentrations. Where influent pollutant concentrations are low, pollutant removal efficiencies will also be low.

# INTRODUCTION

Conversion of agricultural and undeveloped areas to residential, commercial, and industrial land uses causes an increase in the total mass of pollutants released and often results in adverse impacts on surface water quality. In response to this problem, many state and local agencies require the construction and operation of Best Management Practices (BMPs) to limit the concentration and total mass of pollutants discharged. For example, the Neuse River Basin Nutrient Sensitive Waters Strategy (15A NCAC 2B .02) requires that: (a) the nitrogen load from existing developed areas be reduced by 30% and (b) new developments maintain a nitrogen loading less than 70% of the existing nitrogen load or offset their loads by paying into the Wetland Restoration Fund. As a consequence, there is a tremendous need for reliable, cost-effective measures to control nutrients in stormwater runoff from urban areas.

Wet detention ponds are the most commonly used BMPs for controlling nitrogen and phosphorus in stormwater runoff. However, current wet detention pond designs often achieve less than 30% total nitrogen removal. Using these designs, it will not be possible to reduce nitrogen loads from urban areas by 30%, even assuming zero new development and 100% coverage of all existing development.

In this report, we describe the use of a two-dimensional reservoir water quality model, CE-QUAL-W2, to simulate thermal stratification, sedimentation, algal growth and nutrient uptake, and pollutant removal in wet detention ponds. Initially, the model was calibrated to simulate water quality and pollutant removal in three regional wet detention ponds in the High Point, North Carolina, that have good monitoring records on pollutant loadings, in-lake water quality, and pollutant removal efficiency. Once calibrated, the model was used to evaluate potential modifications to current wet detention pond design criteria to enhance nutrient removal. An extensive uncertainty analysis was also performed to evaluate the effect of parameter uncertainty on model results and on the reliability of any proposed modifications to current design criteria. Specific objectives of this work are listed below.

1. Calibrate the reservoir water quality model CE-QUAL-W2 to simulate water quality in three regional wet detention ponds.

2. Develop alternative pond designs to maximize nitrogen and phosphorus removal at the lowest cost.

3. Evaluate the effect of parameter uncertainty on the most efficient pond configuration.

## LITERATURE REVIEW

Urbanization and human development have an adverse impact on natural aquatic ecosystems. Erosion from construction sites and agricultural fields, runoff from livestock facilities and urban areas, and many other human activities increase the loading of nutrients, solids, metals, pesticides and bacteria from a watershed into receiving water. These inputs result in the eutrophication of lakes, reservoirs, and estuaries. Common problems associated with eutrophication include toxic algal blooms, nuisance plant growth, a decline in desirable fish and other aquatic species, and undesirable taste and odors.

### WET DETENTION PONDS FOR WATER QUALITY CONTROL

Detention ponds have been widely used to manage the impacts of land development. Early workers advocated the use of dry ponds for combined flood control and water quality enhancement (Amandes and Bedient 1980; Whipple 1981). However, more recent research has shown that dry detention ponds often have little beneficial impact on water quality (Grizzard et al. 1986; U.S. EPA 1983). Many regulatory agencies and municipalities now require the construction of wet detention ponds downstream of intensive development. Wet ponds contain a permanent pool and remove suspended solids and adsorbed pollutants by sedimentation during quiescent periods between storm events. In addition, dissolved nutrients may be removed through algal uptake, growth and subsequent settling.

### NORTH CAROLINA DESIGN REQUIREMENTS

The State of North Carolina requires construction of wet detention ponds or other water quality BMPs for high-intensity development in portions of the coastal zone and water supply watersheds (NCDEHNR 1995). The primary design requirements for these ponds are as follows.

1. The pond will be sized to have a permanent pool sufficient to remove 85% of the influent sediment. The volume of this pool is determined using tables provided by the N.C. Department of Environment and Natural Resources (NCDENR)[1] and is a function of the imperviousness of the contributing watershed and permanent pool depth.

2. The pond will have a temporary pool volume sufficient to retain runoff from a 1-inch rain and release this runoff over a period of two to five days.

In addition, NCDENR has requirements for the average depth of the permanent pool (3 to 6 ft), sediment storage, length-to-width ratio (3 to 1 or greater), aquatic vegetation, and provision of an emergency drain.

### OBSERVED POLLUTANT REMOVAL EFFICIENCY

In the early 1980s, the U.S. Environmental Protection Agency (U.S. EPA 1983) examined pollutant removal in ten different wet detention ponds as part of the Nationwide Urban Runoff Program (NURP). Pollutant removals were highly variable in the NURP study with some of the smaller ponds achieving little or no pollutant removal. However, ponds with long hydraulic

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[1] This agency was formerly known as the N.C. Department of Environment, Health and Natural Resources (NCDEHNR).

residence times and low overflow rates (mean runoff rate/basin surface area) were often very effective in removing both particulate and dissolved pollutants. Particulate removal was attributed to sedimentation and dissolved pollutant removal because of biological processes within the ponds. Removal efficiencies for the four largest ponds varied from 60 to 91% for total suspended solids (TSS), 34 to 79% for total phosphorus (TP), and 0 to 60% for total Kjeldahl nitrogen (U.S. EPA 1983). Each of these ponds, the ratio of permanent pool storage volume to watershed drainage area was 1 cm or greater.

Brown and Schueler (1997) published an extensive review of pollutant removal in water quality BMPs. Their removal efficiency results for wet detention ponds are summarized in Table 1. Brown and Schueler's results clearly show that wet detention ponds (water quality ponds) can be effective in removing both particulate and dissolved pollutants. However, pollutant removal efficiency can vary widely. While the average total nitrogen removal efficiency for all ponds studied was 29%, TN removal efficiency varied from 85% to -12%. At present, the cause of this variability is not known. We believe a significant portion of this variability is due to differences in influent pollutant loads and structural differences between ponds. If physical, chemical, and biological processes controlling pollutant removal are well understood, it should be possible to explain these differences and develop more efficient designs.

## SEDIMENTATION MODELS FOR PREDICTING POLLUTANT REMOVAL EFFICIENCY

Sedimentation or particle settling is commonly assumed to be the primary removal mechanism for particulate substances. Driscoll's sedimentation model, developed in the U.S. EPA NURP (U.S. EPA 1983; Driscoll 1983), and traditional ideal settling models (Camp 1946; Ferrara and Hildick-Smith 1982; Curtis and McCuen 1977; Novotny and Olem 1994) are the most common models used to predict sedimentation. Nutrient removals are often predicted using these sedimentation models in conjunction with the fraction of a nutrient concentration that is associated with particulate matter (Schueler 1987; Hartigan 1989). The key factors used in these models are consistently $V_B/V_R$—the volume of the basin relative to the volume of runoff from the mean storm—or a related parameter such as hydraulic residence time or the surface area of the basin relative to the surface area of the watershed. Driscoll's model includes a short-circuiting coefficient to allow for non-ideal conditions.

Borden (2001) previously showed that these classical sedimentation-based approaches could provide adequate prediction of suspended solids removal under certain conditions. However, in some cases, the models had large prediction errors, presumably due to differences in influent pollutant loads. In general, the empirical trap efficiency curve developed by Brune (1953) provided the best prediction of TSS removal. This may be because Brune's data incorporated the effects of thermal stratification and short circuit that often occur in lakes and ponds.

## EMPIRICAL LAKE MODELS FOR PREDICTING POLLUTANT REMOVAL EFFICIENCY

While it is widely agreed that biological activity has an impact on nutrient removal, there is considerable disagreement over the degree of impact and how to predict removal. Urbonas and Stahre (1993) argued that algae growth and the dissolution of particulate phosphorus remobilized nutrients, so removal was substantially lower than anticipated. They also warned that eutrophication models might not account for these processes. Most other authors, however, are more confident in the ability of wet ponds to remove dissolved nutrients.

Table 1. Pollutant Removal Efficiencies of Four Types of Treatment Systems (%)

| Parameters | Wet Detention Pond | | | | | Wetland | | | | | Water Quality Swale | | | | | Filtering System | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | Avg. | Med. | Max. | Min. | N | Avg. | Med. | Max. | Min. | N | Avg. | Med. | Max. | Min. | N | Avg. | Med. | Max. | Min. |
| Soluble Phosphorus | 20 | 36.9 | 33.5 | 90 | -12 | 15 | 33.2 | 40 | 75 | -34.5 | 8 | 9.2 | 10.7 | 72 | -45 | 2 | -31 | -31 | -25 | -37 |
| Particulate Phosphorus | 4 | 26 | 29 | 35 | 11 | 3 | 14.7 | 17 | 20 | 7.2 | 0 | N/A | N/A | 0 | 0 | 0 | N/A | N/A | 0 | 0 |
| Total Phosphorus | 44 | 47.3 | 45.5 | 91 | 0 | 35 | 49.0 | 51 | 99.5 | -9 | 18 | 14.1 | 14.5 | 99 | -100 | 15 | 42.0 | 45 | 80 | -25 |
| $NH_3$ | 4 | 14.5 | 41.5 | 82 | -107 | 6 | 40.4 | 49 | 72 | -4.4 | 0 | N/A | N/A | 0 | 0 | 0 | N/A | N/A | 0 | 0 |
| Ammonia (as $NH_4$) | 14 | 17.9 | 22.5 | 83 | -107 | 19 | 25.9 | 43 | 72 | -55.5 | 4 | 16 | 2.5 | 78 | -19 | 4 | 68.3 | 68 | 94 | 43 |
| Nitrite | 0 | N/A | N/A | 0 | 0 | 1 | 57.5 | 57.5 | 57.5 | 57.5 | 0 | N/A | N/A | 0 | 0 | 0 | N/A | N/A | 0 | 0 |
| Nitrate | 27 | 28.1 | 23 | 97 | -85 | 30 | 44.4 | 67 | 99 | -100 | 13 | 12.7 | 11 | 99 | -100 | 13 | -24.4 | -13 | 27 | -100 |
| Organic Nitrogen | 6 | 22 | 22.5 | 34 | 2 | 12 | 0.7 | 1 | 43 | -31 | 3 | 45.3 | 39 | 86 | 11 | 2 | 28 | 28 | 56 | 0 |
| Total Kjeldahl Nitrogen | 17 | 32.6 | 27 | 68 | 7 | 10 | 24.2 | 14.5 | 81 | -10.3 | 5 | 16.4 | 17 | 48 | -20 | 9 | 57.0 | 57 | 90 | 32 |
| Total Nitrogen | 24 | 28.8 | 30 | 85 | -12 | 22 | 28 | 20.9 | 83 | -25 | 10 | 13.7 | 10.5 | 99 | -100 | 9 | 36.3 | 32 | 71 | 13 |
| Cadmium | 5 | 25.8 | 47 | 54 | -25 | 6 | 36.3 | 68.9 | 80 | -79.8 | 6 | 55.2 | 48.5 | 89 | 20 | 1 | 26 | 26 | 26 | 26 |
| Chromium | 5 | 42.9 | 49 | 62 | 25 | 3 | 69.5 | 72.6 | 98 | 38 | 5 | 48.4 | 47 | 88 | 14 | 2 | 54 | 54 | 61 | 47 |
| Copper | 18 | 51.5 | 54.5 | 90 | 9.5 | 10 | 40.9 | 39.5 | 84 | 2 | 15 | 31.9 | 41 | 89 | -35 | 9 | 43.7 | 34 | 84 | 22 |
| Iron | 4 | 40.9 | 40.5 | 87 | -4.3 | 3 | 29.0 | 84 | 93 | -90.1 | 0 | N/A | N/A | 0 | 0 | 4 | 75 | 75.5 | 86 | 63 |
| Lead | 34 | 57.8 | 66.5 | 95 | -96.7 | 17 | 62.5 | 63 | 94 | 23 | 19 | 34.7 | 50 | 99 | -100 | 11 | 60.3 | 71 | 89 | -16 |
| Zinc | 32 | 46.7 | 50.5 | 96 | -38 | 16 | 45.2 | 53.5 | 90 | -73.5 | 19 | 27.6 | 49 | 99 | -100 | 15 | 68.3 | 69 | 91 | 33 |
| Total Dissolved Solids | 7 | 3.5 | 5 | 32 | -28 | 3 | -38.7 | -24 | 8 | -100 | 0 | N/A | N/A | 0 | 0 | 6 | 10.5 | 16 | 46 | -37 |
| Total Suspended Solids | 43 | 61.9 | 70 | 99 | -33.3 | 35 | 66.9 | 78 | 99.5 | -29 | 18 | 38.0 | 66 | 99 | -100 | 15 | 74.7 | 81 | 98 | 8 |
| Oil and Grease | 0 | N/A | N/A | 0 | 0 | 0 | N/A | N/A | 0 | 0 | 0 | N/A | N/A | 0 | 0 | 2 | 76.5 | 76.5 | 84 | 69 |
| Turbidity | 0 | N/A | N/A | 0 | 0 | 1 | 68.5 | 68.5 | 68.5 | 68.5 | 3 | 56.4 | 60 | 65 | 44.1 | 2 | -32 | -32 | -17 | -81 |
| | | | | | | | | | | | | | | | | | | | | |
| Bacteria | 10 | 66.5 | 74 | 99 | -5.8 | 3 | 76.7 | 78 | 97 | 55 | 5 | -30 | -25 | 0 | -100 | 5 | 54.8 | 37 | 83 | 36 |
| Organic Carbon | 29 | 36.6 | 35 | 90 | -30 | 15 | 34.5 | 28 | 93 | -31 | 11 | 22.0 | 23 | 99 | -100 | 11 | 54.8 | 57 | 99 | 10 |
| Total Petroleum Hydrocarbons | 1 | 82.5 | 82.5 | 82.5 | 82.5 | 3 | 86.7 | 90 | 90 | 80 | 2 | 62 | 62 | 75 | 49 | 3 | 75.3 | 84 | 87 | 55 |

*Source*: Brown and Schueler 1997.

Empirical lake models are the most common method used in predicting dissolved nutrient removal. The majority of these models were developed to predict phosphorus or chlorophyll-a concentrations in natural northern lakes threatened by eutrophication. However, these models can be rearranged to predict the percent removal of phosphorus by assuming the outflow concentration is roughly the same as the in-lake concentration. These models include Hartigan (1989), Reckhow (1988), Walker (1985), Canfield and Bachman (1981), and Vollenweider (1976). Since these models are generally based on large data sets, they incorporate possible problems related to short-circuiting, thermal stratification, and varying inflow characteristics. The most common parameters used in these models are hydraulic residence time, mean depth, and occasionally the influent phosphorus concentration.

Borden (2001) found that the empirical model developed by Reckhow (1988) for Southeastern lakes and reservoirs provided reasonably good predictions of TP removal efficiency in four regional wet detention ponds near High Point, North Carolina. When the model predicted higher TP removal efficiencies, this was reflected in the measured performance in the field with no significant positive or negative bias. Reckhow's empirical TN model provided a good estimate of the collective average TN removal efficiencies for the four ponds. However, the TN model did not match the observed variation in removal efficiency between the four ponds.

DYNAMIC EUTROPHICATION MODELS TO PREDICT NUTRIENT REMOVAL

Several authors have suggested that dynamic lake eutrophication modeling would be desirable to determine key processes and design factors in wet detention ponds (Goforth et al. 1983; Akan 1992; Novotny and Olem 1994). However, there have been few attempts at the continuous simulation of detention ponds. Nix et al. (1988) simulated long-term suspended solids removal in detention basins using the U.S. EPA's Storm Water Management Model over a wide range of operating characteristics. In particular, they modeled the effect of changes in storage capacity and orifice diameter on solids removal for a hypothetical watershed. They proposed this method as an approach to balance the needs for control of stormwater quantity and quality in designing basins and argued that while the approach is indicative of trends, site-specific data is required to actually apply the results of such an approach to specific situations. They did not model nutrients or metals. They also noted a declining marginal productivity of removal with both storage and orifice diameter. Borden et al. (1997) modeled Davis Pond using MINLAKE (Riley 1988; Riley and Stefan 1988), a dynamic lake eutrophication model. MINLAKE provided reasonably accurate predictions of pollutant removal efficiency and provided very detailed feedback to the pond designer on effects of design changes on projected pollutant removal. However, MINLAKE does not simulate several processes expected to be very important in some wet detention ponds and so would not be broadly applicable as a design tool. Processes not included in MINLAKE include: (1) partitioning of nitrogen and phosphorus species between suspended and dissolved phases; (2) denitrification and inhibition of nitrification at low oxygen levels; (3) nitrogen-fixation by blue-green algae; (4) organic nitrogen in pond influent; and (5) limitation of algal growth by low levels of $CO_2$.

CE-QUAL-W2

CE-QUAL-W2 is a two-dimensional, laterally averaged water quality model developed by the U.S. Army Corps of Engineers for simulating the vertical distribution of thermal energy and biological and chemical materials in an reservoir over time (Cole and Buchak 1995). CE-QUAL-W2 can be used to examine the effects of reservoir management operations on water quality, including eutrophication and development of anaerobic conditions in the reservoir hypolimnion. Chemical and biological processes incorporated into the model include the following.

1. Accumulation and depletion of dissolved oxygen through aeration, photosynthesis, respiration and organic decomposition.

2. Uptake and release of dissolved phosphorus by algae and partitioning of phosphorus between aqueous and inorganic sediment.

3. Nitrogen cycling under aerobic and anaerobic conditions, including algal uptake and nitrification-denitrification.

4. Carbon cycling and alkalinity-pH-$CO_2$ interactions.

5. Dynamics and trophic relationships of three phytoplankton groups and macrophytes.

6. Accumulation, dispersion and decomposition of detritus and sediment.

7. Accumulation, dispersion and reoxidation of manganese, iron and sulfide under anaerobic conditions.

CE-QUAL-W2 requires an extensive input database, including initial conditions for all constituents, geometric and physical coefficients, biological and chemical reaction rates, and time sequence of hydro-meteorological conditions, flow rates, and inflowing water quality concentrations.

## CE-QUAL-W2 SIMULATION OF WATER QUALITY AND POLLUTANT REMOVAL IN THREE REGIONAL WET DETENTION PONDS

CE-QUAL-W2 (Cole and Buchak 1995) is one of the most widely used models for simulation of water quality in lakes and reservoirs. However, CE-QUAL-W2 is also a very complex model that requires a large amount of input data, substantial computing power and a significant effort to achieve an adequate calibration. In this study, we applied CE-QUAL-W2 to simulate water quality and pollutant removal in three regional wet detention ponds located in High Point, North Carolina. Monitoring data for use in model calibration was collected with support from the City of High Point (CHP), the N.C. Urban Water Consortium, and The University of North Carolina Water Resources Research Institute and is reported in Borden et al. (1997) and Borden (2001). In these projects, the regional wet detention ponds were monitored to evaluated pollutant removal efficiency and to gain a better understanding of the physical, chemical, and biological process influencing pollutant removal. Twelve month's monitoring data were available for the three ponds, including inflow, outflow volume, and water quality. Also available were in-pond water quality profiles such as temperature, DO, TSS, TDS, TP, TN, dissolved $PO_4$-P, dissolved $NH_4$-N, dissolved $NO_{2+3}$-N, and a variety of both total and dissolved metals. Using this data set, we attempted to simulate in-pond water quality and pollutant removal efficiency for each of the three regional wet detention ponds using the CE-QUAL-W2 model. One important objective of this work was to obtain a single input parameter set or range of parameters that reasonably simulated water quality and pollutant removal in all of the ponds. This parameter set was later used to evaluate design modifications for enhancing the pollutant removal efficiency of wet detention ponds.

### SITE CHARACTERISTICS AND MONITORING RESULTS

The City of High Point (CHP) is located in the Piedmont Region of North Carolina and operates two water supply reservoirs: City Lake and Oak Hollow Lake. Both reservoirs are experiencing increasing water quality problems because of rapid development in the watersheds. To mitigate the impact of urban development on reservoir water quality, CHP built and operates four regional wet detention ponds and one regional pond-wetland system. Extensive water quality data sets are available for three of the ponds: Davis Pond, Piedmont Pond, and Mall Pond A. Watershed and basin characteristics for each pond are summarized in Table 2.

Davis Pond receives runoff from a 1,258-acre watershed consisting of mainly dairy farms and woodlands, with a small amount of developed land. Water quality conditions in Davis Pond were monitored from December 1993 to November 1994. During this period, Davis Pond was hypereutrophic because of the high concentrations of biologically available nutrients entering the pond. Total precipitation during the monitoring period was 36.5 in. Total runoff (storm and baseflow) entering Davis Pond during this period was 12.9 in. or 36.5% of the precipitation, resulting in an average hydraulic residence time of approximately 17 days.

**Table 2.** Watershed and Basin Characteristics of Davis Pond, Piedmont Pond, and Mall Pond A

| PARAMETER | DAVIS POND | PIEDMONT POND | MALL POND A |
|---|---|---|---|
| Land Use | | | |
| Low-Density Single Family (acre) | 0 | 0 | 26 |
| Medium-Density Single Family (acre) | 0 | 0 | 315 |
| Multi-family Residential (acre) | 0 | 0 | 114 |
| Commercial/Office (acre) | 0 | 0 | 203 |
| Tank Farm (acre) | 0 | 525 | 0 |
| Institutional & Industrial (acre) | 0 | 427 | 70 |
| Woodlands & Open (acre) | 302 | 258 | 6 |
| Farmlands (acre) | 943 | 0 | 0 |
| Pond Area (acre) | 12.7 | 10.0 | 8.2 |
| Total Area (acre) | 1,258 | 1,220 | 742 |
| Watershed Impervious Area | 16% | 30% | 60% |
| Ratio of Permanent Pool Storage Volume to Watershed Drainage Area (inch) | 0.65 | 0.5 | 1.36 |
| Permanent Pool Detention Time (days) | 20.0 | 8.6 | 16.8 |
| Permanent Pool Length: Width Ratio | 3.75:1 | 7:1 | 1.2:1 |
| Permanent Pool Average Depth (ft) | 4.9 ft | 4.1 ft | 10.0 |
| Permanent Pool Surface Area: Drainage Area Ratio | 1.01% | 0.97% | 1.1% |
| Ratio of Temporary Pool Storage Volume to Watershed Drainage Area (inch) | 0.74 | 1.17 | 0.3 |
| Time to 90% Drawdown of Temporary Pool | 2.5 d | 0.3 d | 0.2 d |

Piedmont Pond receives runoff from a 1,220-acre watershed containing a large petroleum tank farm (535-million-gallon storage capacity), commercial development, highway, and some undeveloped forest. Runoff from the petroleum tank farm is treated in a 58-acre-ft detention pond before discharge downstream. Approximately, 48% of the total drainage area of Piedmont Pond is pretreated in this pond. Water quality conditions in Piedmont Pond were monitored from February 1995 to January 1996. During this period, Piedmont pond was mesotrophic to mildly eutrophic because of the low to moderate concentrations of nutrients entering the pond. Total precipitation during this period was 43.4 in., and total runoff (storm and baseflow) entering

Piedmont Pond was 20.2 in. or 47% of the precipitation resulting in an average hydraulic residence time of approximately 8.6 days.

Mall Pond A receives runoff from a 741.5-acre watershed containing a mixture of medium- and high-density residential areas and commercial/office areas. Water quality conditions in Mall Pond A were monitored from March 1998 to February 1999. During this period, Mall Pond A was eutrophic to hypereutrophic because of the high nutrient concentrations in the pond. Total precipitation during this period was 43.85 in. Total runoff (storm and baseflow) entering Mall Pond A was 15.1 inches or 34% of the precipitation during the monitoring period, resulting in an average hydraulic residence time of approximately 16.8 days.

Differing land use characteristics and precipitation during the monitoring periods had considerable impact on the quantity and quality of runoff entering each pond. These differences were included in the model calibration data sets.

## PREPARATION OF CE-QUAL-W2 MODEL

CE-QUAL-W2 model used in this study is version 2.0. The Unix workstation specific code was compiled under Sun UNIX software environment. To aid in model calibration, the code was modified to generate output in a format suitable for use by a MATLAB post-processor. The post-processor allowed both statistical and visual comparison of simulated and observed pollutant concentrations at different depths in the pond and in the pond effluent over time. One of the primary objectives of this work was to develop a reliable tool for predicting TP and TN removal efficiency. The TP and TN concentrations were calculated from the CE-QUAL-W2 output as:

$$TP = PO4 + (LDOM + RDOM + ALGAE + DETRIUS) * A$$

$$TN = NH4\text{-}N + NO3\text{-}N + (LDOM + RDOM + ALGAE + DETRIUS) * B$$

where

| | | |
|---|---|---|
| PO4 | = | dissolved phosphorus |
| LDOM | = | liable dissolved organic matter |
| RDOM | = | refractory organic matter |
| NH4-N | = | dissolved ammonia |
| NO3-N | = | dissolved nitrite and nitrate |
| ALGAE | = | algae growth measured in dry weight |
| DETRIUS | = | particulate organic material in water column |

A and B are stoichiometric coefficients included in the model input file that reflect the phosphorus and nitrogen content of particulate material.

In the standard version of CE-QUAL-W2, the rate of ammonia loss and nitrate production through nitrification are represented by

$$\frac{\partial \Phi_{NH4}}{\partial t}(nitrification) = -K_{NH4}\gamma_{NH4}\Phi_{NH4}$$

$$\frac{\partial \Phi_{NO3}}{\partial t}(nitrification) = +K_{NH4}\gamma_{NH4}\Phi_{NH4}$$

The denitrification rate in the standard version of CE-QUAL-W2 is represented by

$$\frac{\partial \Phi_{NO3}}{\partial t}(denitrification) = -K_{NO3}\gamma_{NO3}\Phi_{NO3}$$

where

| | | |
|---|---|---|
| $\gamma_{NH4}$ | = | temperature rate multiplier for nitrification |
| $\gamma_{NO3}$ | = | temperature rate multiplier for denitrification |
| $K_{NO3}$ | = | nitrate-nitrogen decay rate, $sec^{-1}$ |
| $K_{NH4}$ | = | ammonium-nitrogen decay rate, $sec^{-1}$ |
| $\Phi_{NH4}$ | = | ammonium-nitrogen concentration, $g\ m^{-3}$ |
| $\Phi_{NO3}$ | = | nitrate-nitrogen concentration, $g\ m^{-3}$ |

In both the nitrification and denitrification reactions, the reaction rate is assumed to be independent of dissolved oxygen concentration. However, in reality, dissolved nitrification rates go to zero below some critical DO level, and denitrification rates approach zero when DO exceeds some minimum DO level. To correct this limitation, the nitrification rate terms were modified as shown below based on suggested kinetic formulations in Bowie et al. (1985).

$$\frac{\partial \Phi_{NH4}}{\partial t}(nitrification) = -K_{NH4}\gamma_{NH4}\Phi_{NH4}\left(\frac{\Phi_{O2}}{H_{O2}+\Phi_{O2}}\right)$$

$$\frac{\partial \Phi_{NO3}}{\partial t}(nitrification) = +K_{NH4}\gamma_{NH4}\Phi_{NH4}\left(\frac{\Phi_{O2}}{H_{O2}+\Phi_{O2}}\right)$$

and

$$\frac{\partial \Phi_{NO3}}{\partial t}(denitrification) = -K_{NO3}\gamma_{NO3}\Phi_{NO3}\left(\frac{I_{O2}}{I_{O2}+\Phi_{O2}}\right)$$

where

| | | |
|---|---|---|
| $H_{O2}$ | = | oxygen concentration where nitrification rate is reduced by half, $g\ m^{-3}$ |
| $I_{O2}$ | = | oxygen concentration where denitrification rate is reduced by half, $g\ m^{-3}$ |
| $\Phi_{O2}$ | = | dissolved oxygen concentration, $g\ m^{-3}$ |

The denitrification half saturation constant ($H_{O2}$) was assumed to be equal to 0.1 mg/L, and the nitrification inhibition constant ($I_{O2}$) was assumed to be equal to 0.5 mg/L based on prior published reports (Bowie et al. 1985). After completion of these limited modifications, CE-QUAL-W2 was used to simulate water quality in the three ponds.

MODEL CALIBRATION

CE-QUAL-W2 is a complex model designed to simulate the major physical, chemical and biological processes in a lake. In this project, CE-QUAL-W2 was used to simulate thermal stratification, algal growth, oxygen production and consumption, phosphorus, and nitrogen cycling in each pond. As a consequence, the model required substantial input data. In the calibration process, we separated the input data into three main categories.

1. Data that reflected the physical characteristics of the pond and that could be altered by a pond designer. This included the pond size, pond geometry, bathymetry, and configuration of the outflow structure.

2. Data that reflected the watershed characteristics that could not be controlled by a pond designer. This included meteorological data (light, air temperature, wind speed and direction) and inflow characteristics (variation in inflow rate and chemical characteristics over the year).

3. Kinetic parameters used by the model to simulate the different physical, chemical, and biological processes occurring within the pond.

The first two categories of input data were obtained from the physical characteristics and the measured inflow to each pond. All three ponds are fairly similar in size with a permanent pool surface area ranging from 8.2 to 12.7 acres. Piedmont Pond is long and narrow, whereas Mall Pond A and Davis Pond are roundlike. All three ponds were setup with a computational grid of 22 longitudinal segments and 12 vertical layers. The thickness of each layer was initially 0.4 m, and the length of the longitudinal segments ranged from 15 to 35 m. Water withdrawal from the model grid was set to match the physical characteristics of each pond. Inflow and outflow are given as boundary condition during model calibration. CE-QUAL-W2 requires that outflow rate be specified for each time step. Pond outflow was calculated prior to CE-QUAL-W2 execution using the storage indication method. Input for this procedure included the physical characteristics of the pond (stage: storage data), characteristics of the outflow structure, and inflow rate. The total simulation period was 12 months with a one-day time step. All simulations began in the spring prior to the onset of thermal stratification. To reduce data handling, the flow rates and pollutant loads from each tributary were summed to generate a single inflow for each pond. Meteorological data for each simulation period was obtained from the National Weather Service observations station at the Greensboro Airport, North Carolina.

The last step in model calibration was to identify a single set or range of kinetic parameters that could be used to accurately simulate pollutant removal in all three ponds. Initial parameter ranges for most kinetic coefficients were taken from Cole and Buchak (1995) or their original sources. During the calibration process, the kinetic parameters were then adjusted within these ranges to match site-specific conditions.

The overall objective of this work was to develop a tool that could be used to evaluate different pond modifications that could be used to enhance pollutant removal. As a consequence, our primary calibration objective was to minimize the error between simulated and observed TSS, TP, and TN removal efficiency. Mathematically, the objective function was written:

$$\text{Objective} = \min\{\text{RMSE (TSS)} + \text{RMSE (TP)} + \text{RMSE (TN)}\}$$

where

RMSE = Root Mean Squared Error
= $[\Sigma(\text{Obs} - \text{Sim})^2/n]^{1/2}$

Obs = observed daily pollutant removal efficiency

Sim = simulated daily pollutant removal efficiency

n = number of observations

As a secondary check on model performance, simulated and observed temperature, DO, nutrient, and chlorophyll a profiles were visually compared after each model simulation. This was done to ensure the model was providing a reasonable qualitative match with actual conditions in the pond. If there was a dramatic difference in simulated and observed profiles, this information was used to identify specific problems with the calibration and correct them. However, the objective function was used as the primary standard for identifying the "best" set of kinetic parameters.

The first step in the calibration process was to adjust the light attenuation coefficients to accurately simulate temperature profiles within each pond. Next, the suspended solid setting rate (SSS) was adjusted (within it's reported range) to match the observed TSS removal efficiency. The biological kinetic parameters controlling algal growth were then adjusted to simulate algal growth and its impacts on DO, phosphorus, and nitrogen. Finally, the parameters controlling the exchange with the bottom sediments (partition coefficients, sedimentation rates, and release rates) were adjusted to match the observed variations in DO, phosphorus, and different nitrogen forms.

CE-QUAL-W2 was first calibrated to simulate water quality conditions in Davis Pond. The kinetic parameters from Davis Pond were then used as starting values to calibrate the model for Piedmont Pond and Mall Pond A. Once calibrated, the kinetic parameters from these ponds were used in the Davis Pond simulation. In this manner, we iterated between the three ponds, attempting to find a single "best" parameter set that minimized the error in predicted pollutant removal efficiency in all three ponds. Unfortunately, it was not possible to obtain a single kinetic parameter set that minimized the prediction error for all three ponds.

As an alternative, we identified a single parameter set for each pond that minimized the prediction error for pollutant removal efficiency. In future simulations evaluating potential pond modifications, these parameter sets will be used to define the uncertainty in kinetic parameters. Different aspects of the simulation results for each pond are discussed below.

CE-QUAL-W2 SIMULATION RESULTS

**Temperature and DO**

Figures 1 through 3 show the simulated temperature and DO distributions in Davis Pond, Piedmont Pond and Mall Pond A for the entire simulation period. Also shown in Figures 1 through 3 are comparisons of simulated and observed temperature and DO profiles on three sampling dates. In general, results from temperature and DO simulation were satisfactory with good agreement achieved between field observations and simulation results for both the epilimnion and hypolimnion for each pond. However, the measured contact point between aerobic and anaerobic conditions what somewhat shallower than in the model simulations. The greater depth of oxygen penetration in the model may have been due use of a light attenuation coefficient that was too low. The model predicted pond stratification in mid- or late March and destratification in early October that matched the field monitoring results quite well. Results from the DO simulation were also encouraging. During the period of pond stratification, DO concentrations in the hypolimnion of all these three ponds drop to zero. The model gives very good temperature and DO profiles, respective to seasonal variations.

However, there were some differences between monitored and simulated temperatures and DO concentrations. This is partially because the CE-QUAL-W2 model predicts the average temperature and DO concentration over a 24-hour period, while the monitoring data represent a "snapshot" taken in the early afternoon. For DO, the discrepancies between observation and prediction are also due to nocturnal algal photosynthesis, respiration, and decay. The DO concentration fluctuated much less in the hypolimnion than in the epilimnion because the hypolimnion was devoid of photosynthesizing algae a majority of time. CE-QUAL-W2 predicted the onset of anaerobic conditions in the hypolimnion in late March, shortly after the start of thermal stratification. CE-QUAL-W2 also provided relatively good predictions of the vertical distribution of TP and TN in each pond. The results for dissolved nitrogen ($NH_4$-N, $NO_{2+3}$-N) and phosphorus ($PO_4$-P) were not as good as TP and TN, because of the strong relationship with algal growth.

Figure 1. Temperature and Dissolved Oxygen Profiles in Davis Pond During the Monitoring Period (symbols are measured values and lines are model simulation results)

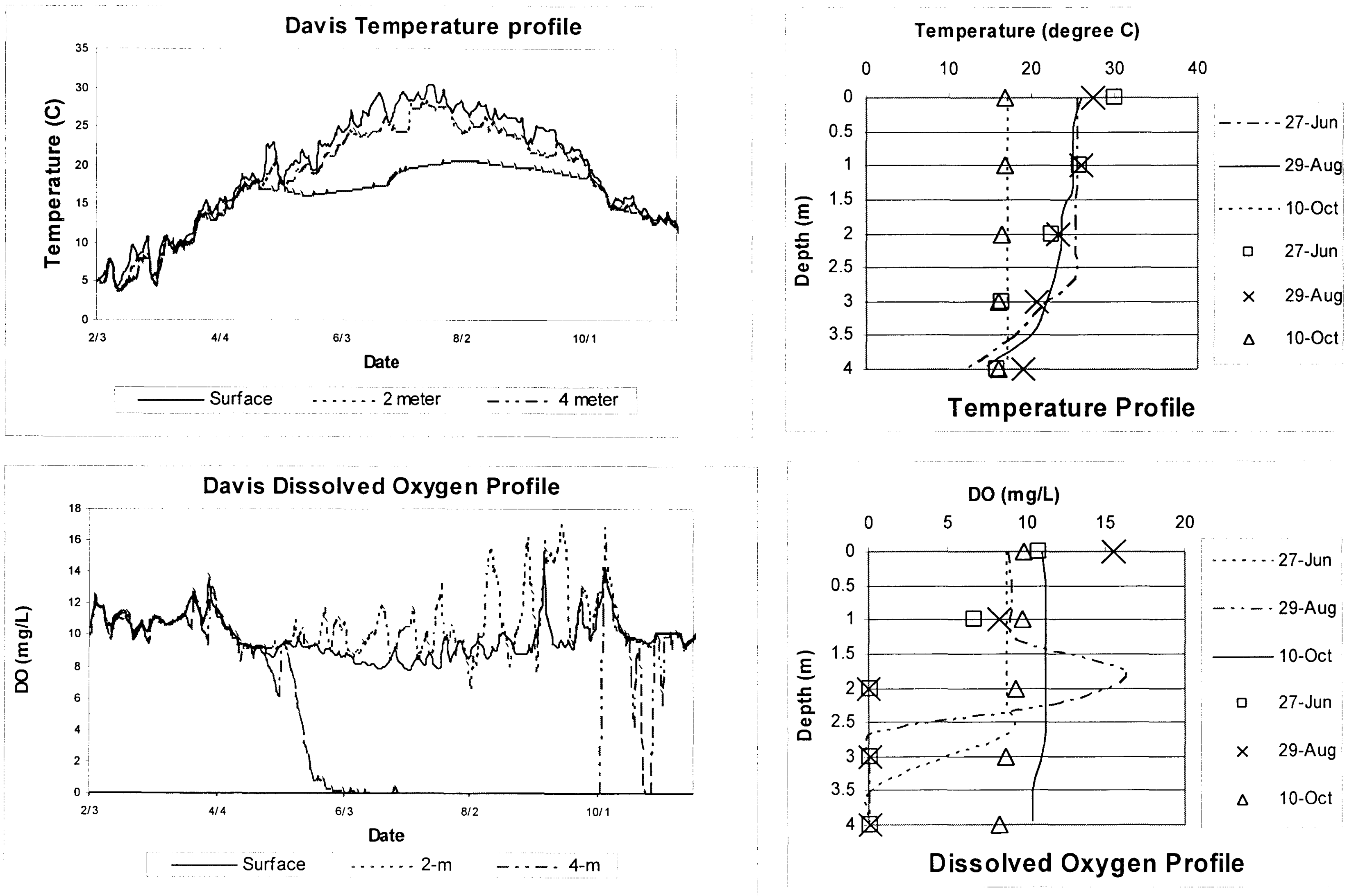


Figure 2. Temperature and Dissolved Oxygen Profiles in Piedmont Pond During the Monitoring Period (symbols are measured values and lines are model simulation results)

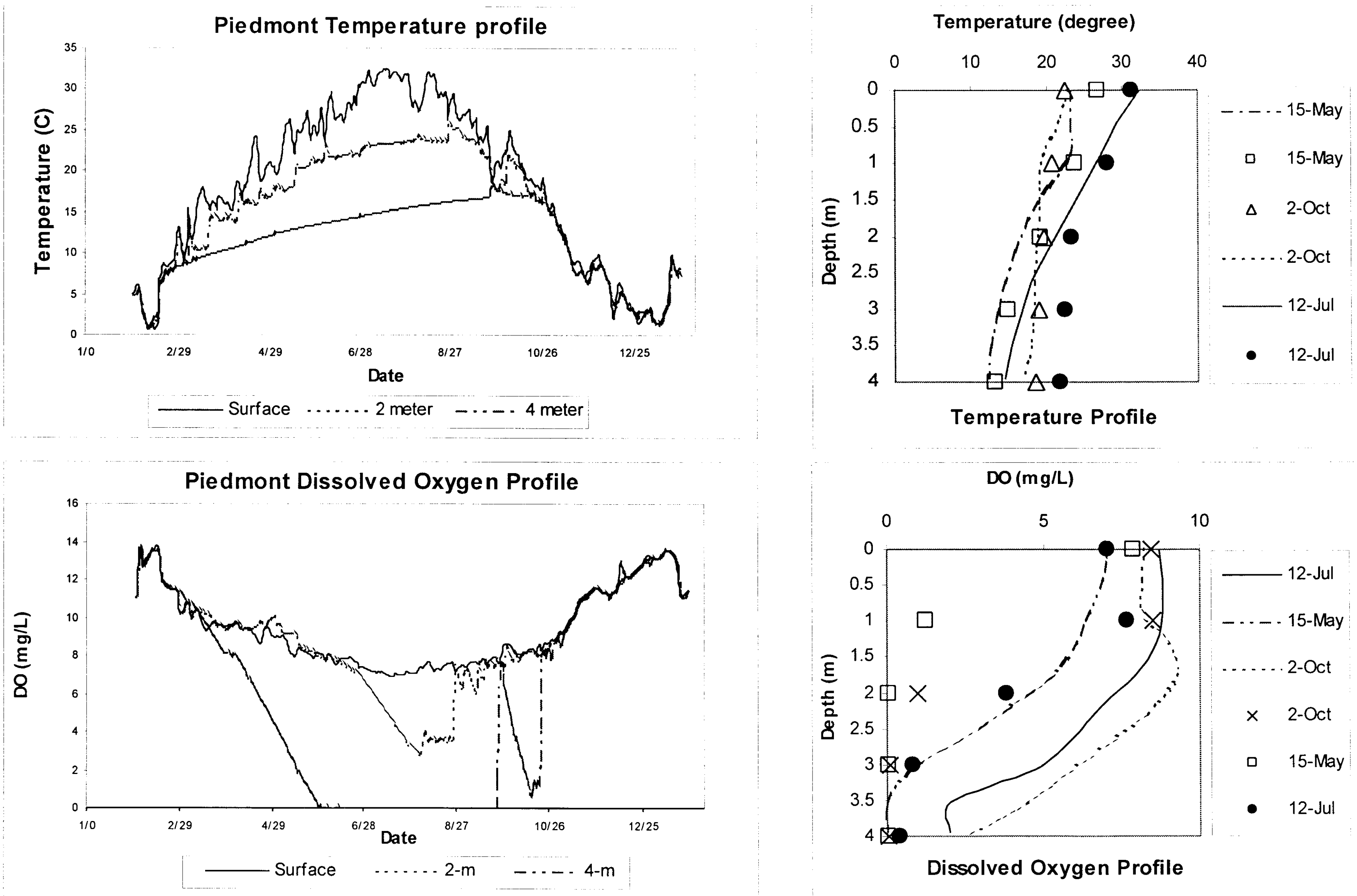
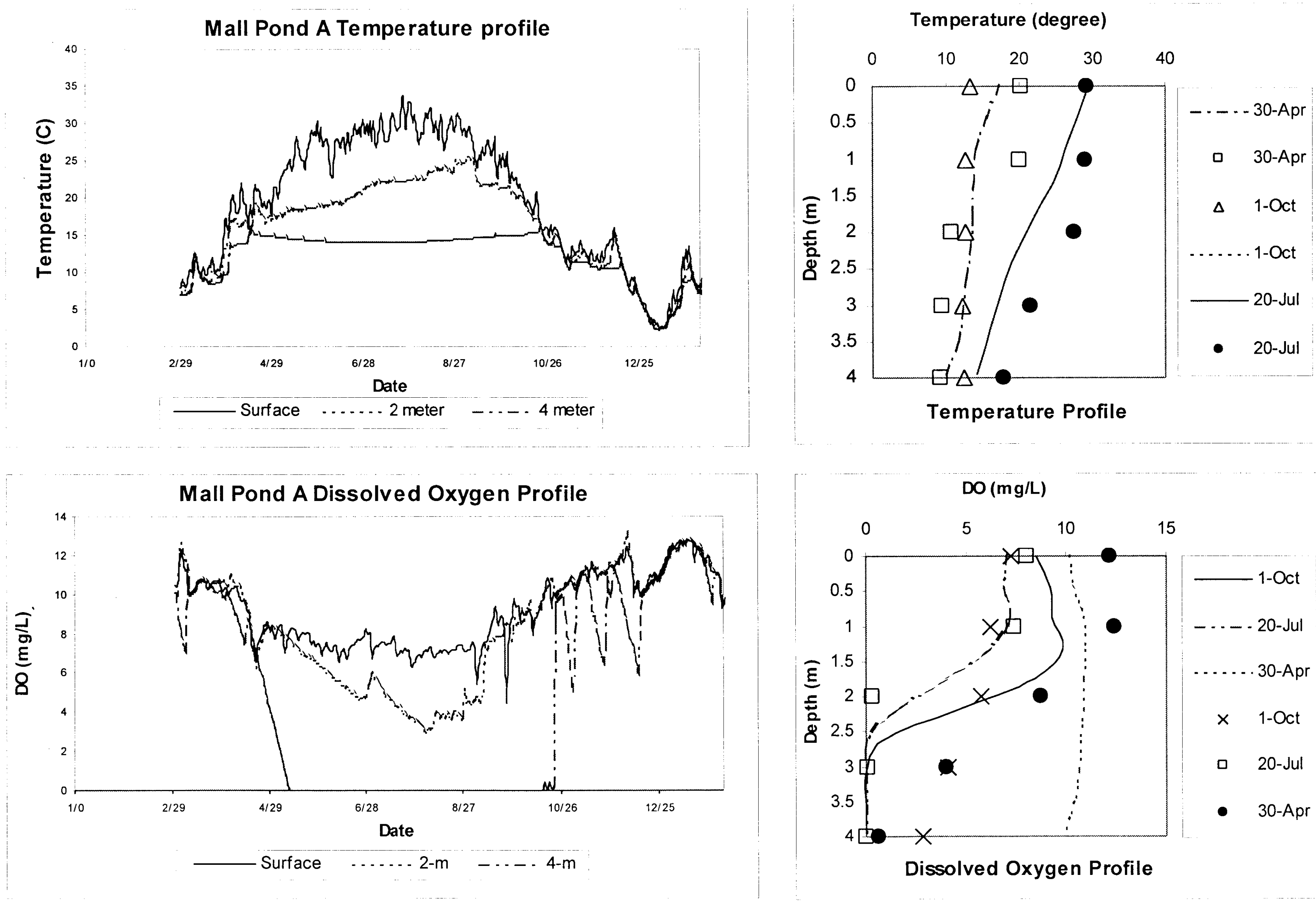


Figure 3. Temperature and Dissolved Oxygen Profiles in Mall Pond A During the Monitoring Period (symbols are measured values and lines are model simulation results)



**Pollutant Removal Efficiency Analysis**
Removal efficiencies were calculated as the percentage difference in the total mass of a pollutant entering and discharging from each pond over the one-year simulation period. Simulated average annual removal efficiencies for the major pollutants are compared to the monitoring results in Table 3. In general, CE-QUAL-W2 was able to provide a reasonably good match between simulated and observed annual average removal efficiencies for the primary pollutants (TSS, TDS, TP, TN, $PO_4$-P, $NH_4$-N, and $NO_{2+3}$-N). However, this good match is somewhat deceiving since this was the primary calibration objective.

**Table 3.** Comparison of Simulated and Observed Pollutant Removal Efficiency (%) for a One-Year Simulation Period

| PARAMETER | DAVIS POND | | PIEDMONT POND | | MALL POND A | |
|---|---|---|---|---|---|---|
| | Observed | Simulated | Observed | Simulated | Observed | Simulated |
| TSS | 60 | 60 | 20 | 21 | 61 | 51 |
| TDS | 2 | 1 | 2 | 2 | 22 | 6 |
| TP | 46 | 44 | 40 | 34 | 45 | 64 |
| $PO_4$-P | 58 | 58 | 15 | 10 | 24 | 6 |
| TN | 16 | 26 | 36 | 29 | 20 | 43 |
| $NH_4$-N | 10 | 9 | -64 | -65 | 23 | 36 |
| $NO_{2+3}$-N | 18 | 40 | 66 | 6 | 38 | 47 |

The primary factor controlling suspended solids removal efficiency is the suspended solids settling (SSS) rate. CE-QUAL-W2 provided a good prediction of TSS removal efficiency for all the three ponds using the same SSS. This suggests that the model is accurately capturing the most important factors controlling TSS removal.

In contrast, we were not able to accurately simulate the removal of nitrogen and phosphorus using a single set of parameters for all three ponds. As a consequence, we made minor changes in the input parameters to achieve a somewhat better fit to the field monitoring results. However, these apparently minor changes sometimes had substantial effects on the model's predicted removal efficiencies. Within CE-QUAL-W2, algae growth has both positive and negative effects on dissolved phosphorus (DP) and dissolved nitrogen (DN) removal—algae consume DP and DN to form biomass that increases DP and DN removal. However, algae also excrete dissolved nutrients when they die and decay. In most cases, high algal growth resulted in high removal efficiencies for TP and DP and TN and DN. However, this relationship was not consistent for all three ponds. For example, when the algae concentration was very low, a very small change in a kinetic parameter could result in a dramatic change in algal growth. This in turn resulted in large changes in predicted DP and DN removal. In contrast, predicted TP and TN removal were more stable and less sensitive to rapid fluctuations in algal biomass.

**Comparison of Simulated and Observed Outflow Concentrations**
When sufficient calibration data was available, CE-QUAL-W2 was able to provide reasonably good estimates of the average annual removal efficiencies for the primary pollutants. However, this was the primary calibration objective so you would expect a reasonably good match given the large number of calibration parameters available.

To provide a more independent estimate of the model's predictive capability, we compared the model predicted and observed removal efficiencies month by month. Simulated monthly average pollutant concentrations in the outflow from each pond are compared to the observed concentrations in Figures 4 to 6. Ideally, the data in these figures should plot on a straight line with a 1:1 slope and a correlation coefficient (R) equal to 1.0. Actual correlation coefficients are summarized in Table 4.

In general, CE-QUAL-W2 did not provide a reliable prediction of monthly variations in pollutant concentrations in the pond outflows. Several of the figures show essentially no relationship between predicted and observed outflow concentrations. Given that inflow concentrations are specified as part of the model input, an error in predicted outflow concentration directly corresponds to an error in predicted removal efficiency. In a few cases, the poor prediction of outflow concentration could be attributed to a specific problem in the way monthly averages were calculated (e.g., when a large storm event extended from one month to the next). However, in most cases, there was no obvious reason for the poor model prediction.

**Table 4.** Correlation Coefficient (R) Between Simulated and Observed Monthly Average Pollutant Concentration in Pond Outflow

| PARAMETER | DAVIS POND | PIEDMONT POND | MALL POND A |
|---|---|---|---|
| TSS | 0.17 | -0.11 | 0.19 |
| TDS | 0.68 | 0.41 | 0.41 |
| TP | 0.49 | 0.25 | -0.52 |
| $PO_4$-P | 0.74 | 0.18 | 0.19 |
| TN | 0.67 | 0.74 | -0.21 |
| NH4-N | -0.32 | 0.64 | 0.39 |
| $NO_{2+3}$-N | 0.71 | 0.14 | 0.50 |

The reason for the poor match between simulated and observed concentrations in the outflow from the three ponds is not known. One potentially very important process not included in CE-QUAL-W2 is zooplankton grazing on algae. In the spring, CE-QUAL-W2 predicts a dramatic increase in algal biomass that results in a rapid drop in DN and DP concentrations. Then in the late summer, the model predicts an increase in DN and DP concentrations when algal growth has declined. In the real wet detention ponds, there was also a relationship between algal growth and dissolved pollutants. However, the changes in algal biomass (as measured by chlorophyll a concentration) were more gradual with slower shifts in dissolved nutrient concentrations. The more gradual shifts in algal biomass and dissolved nutrients in the actual ponds may be due to zooplankton grazing, which limits the algal biomass and recycles dissolved nutrients back into the water column. It may be useful to include zooplankton grazing as a factor limiting algal biomass in future modifications of CE-QUAL-W2.

## UNCERTAINTY ANALYSIS

As described above, we were not able to identify a single set of input parameters that could be used to simulate water quality and pollutant removal in all three ponds: Davis, Piedmont, and Mall Pond A. To reflect the uncertainties in the model kinetic parameters, we identified ten input parameter sets that reflected the range of uncertainty in the kinetic parameters. All the kinetic parameters fell within the range of best-fit parameters found for the three ponds. Table 5 shows a comparison of the pollutant removal efficiencies predicted with the best-fit parameters and removal efficiencies predicted using the ten different sets of input parameters. No ranges are shown for TSS removal because the same parameter values were used for all three ponds.

Figure 4. Comparison of Simulated and Observed Concentrations in the Davis Pond Outflow—Monthly Averages for TSS, TP, $PO_4$-P, TN, $NO_{2+3}$-N, and $NH_4$-N. All concentrations in mg/L.

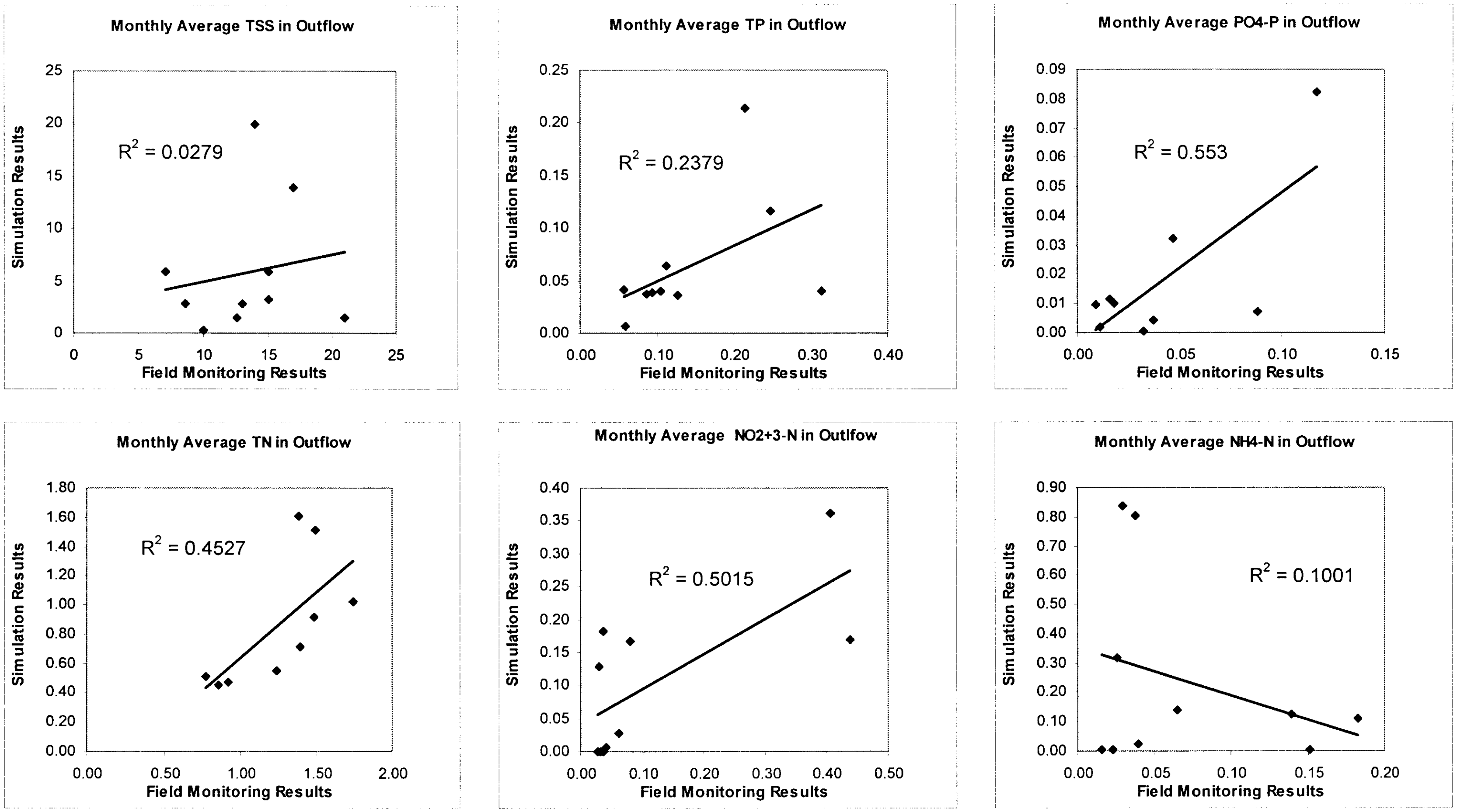


Figure 5. Comparison of Simulated and Observed Concentrations in the Piedmont Pond Outflow—Monthly Averages for TSS, TP, $PO_4$-P, TN, $NO_{2+3}$-N, and $NH_4$-N. All concentrations in mg/L.

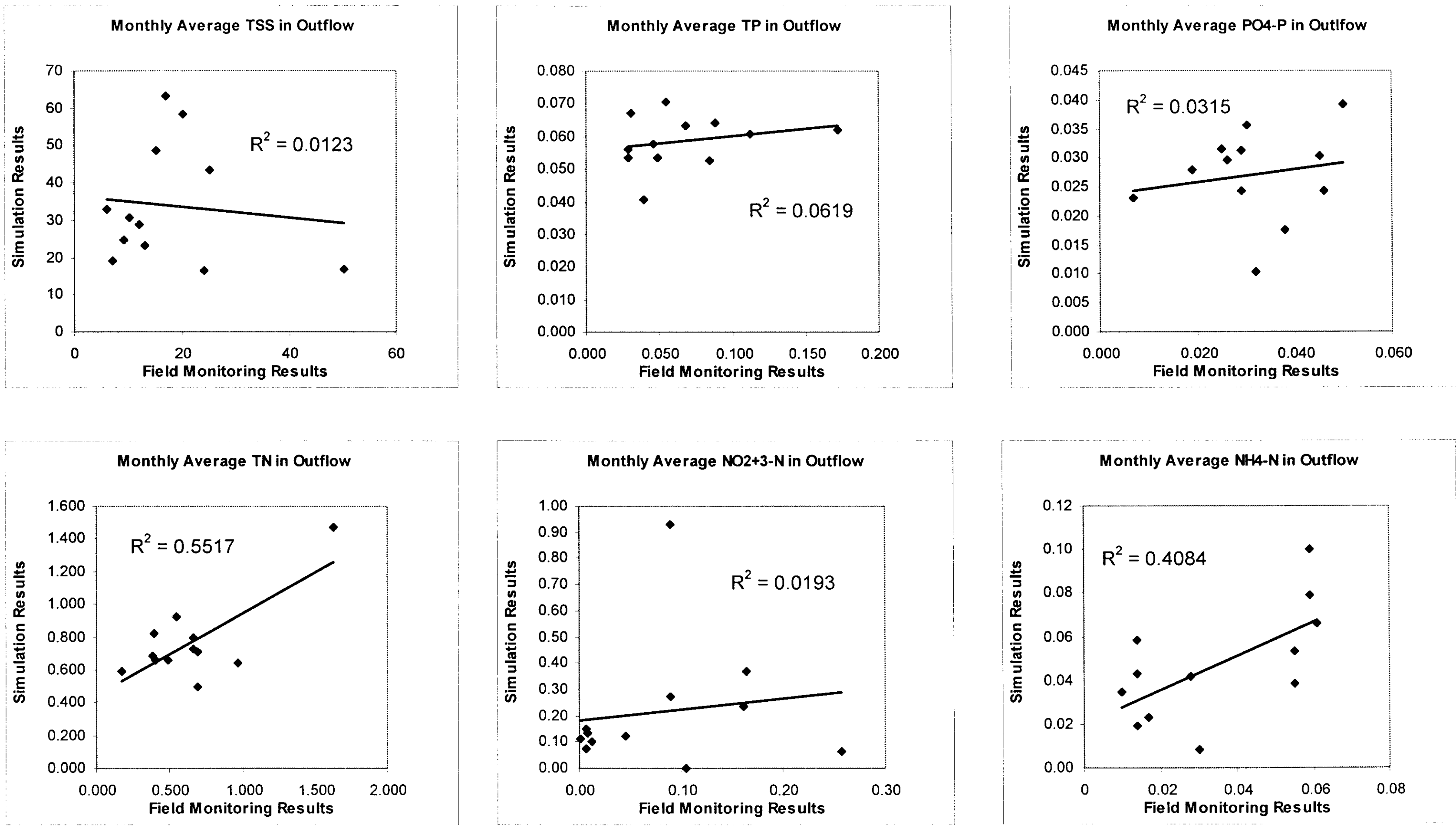


Figure 6. Comparison of Simulated and Observed Concentrations in the Mall Pond A Outflow—Monthly Averages for TSS, TP, $PO_4$-P, TN, $NO_{2+3}$-N, and $NH_4$-N. All concentrations in mg/L.

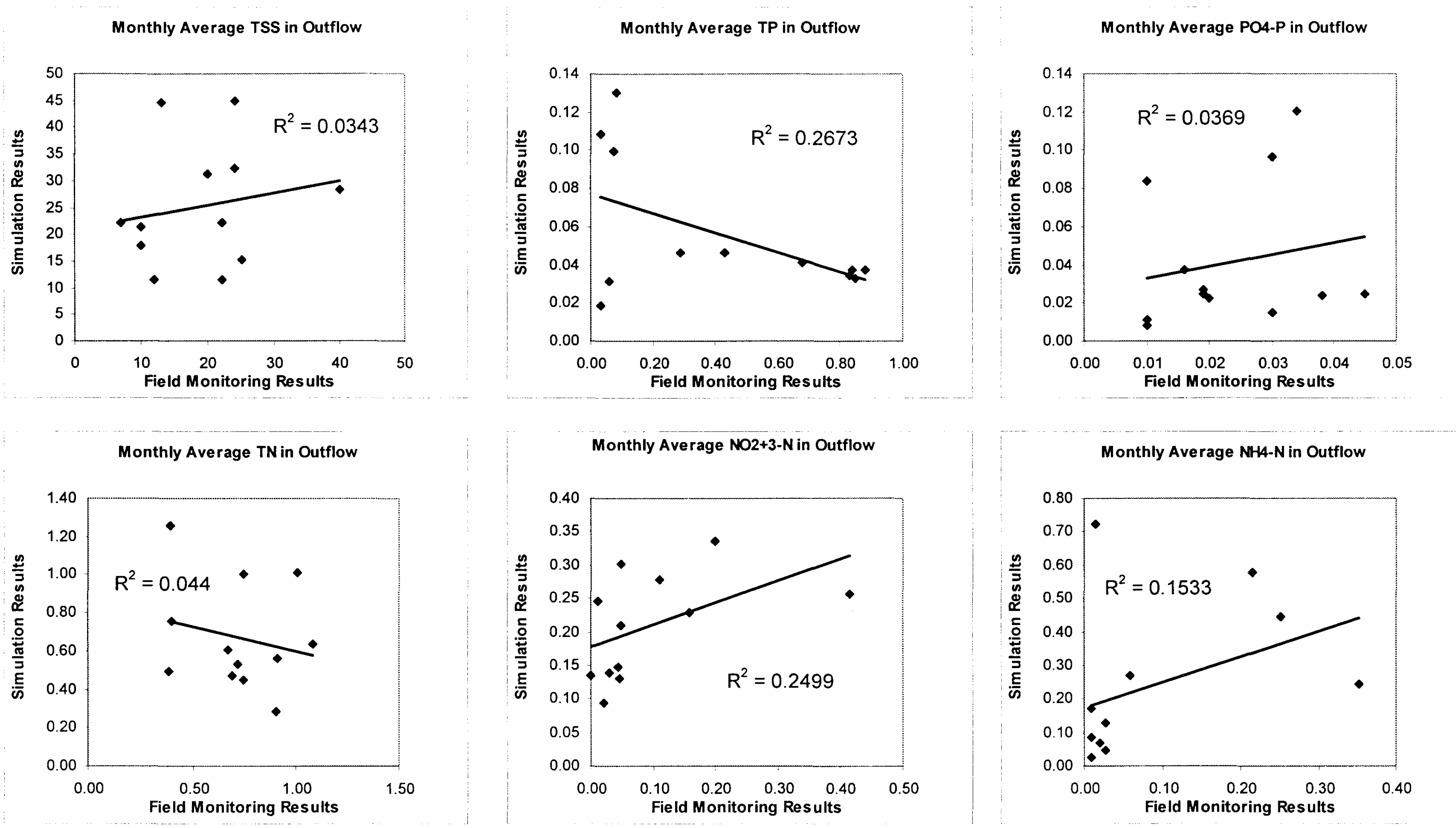


**Table 5.** Predicted Annual Pollutant Removal Efficiencies (%) using Best Fit Values and Parameter Sets Reflecting the Range of Parameter Uncertainty (For parameter ranges, the mean removal efficiency is presented with the standard deviation shown in parentheses)

| | Total Phosphorus | Total Nitrogen | Total Suspended Solids |
|---|---|---|---|
| **Davis Pond** | | | |
| Measured Value | 46 | 16 | 60 |
| Best Fit Parameters | 44 | 26 | 60 |
| Range of Input Parameters | 38.4 (9.3) | 30.3 (5.1) | NA[a] |
| **Piedmont Pond** | | | |
| Measured Value | 40 | 36 | 20 |
| Best Fit Parameters | 34 | 29 | 21 |
| Range of Input Parameters | 26.7 (5.6) | 10.3 (15.8) | NA |
| **Mall Pond A** | | | |
| Measured Value | 45 | 20 | 61 |
| Best Fit Parameters | 64 | 43 | 51 |
| Range of Input Parameters | 63 (2.3) | 46.8 (5.0) | NA |

[a]NA: not applicable.

The pollutant removal efficiencies calculated using the parameter ranges sets did not match the measured removal efficiencies as closely as the best-fit values. However, in most cases, the differences were not great. In cases where the parameter ranges did not accurately match the field observations, the best-fit values also did not match the field observations.

SUMMARY

In general, CE-QUAL-W2 provided adequate predictions of total annual removal efficiency for most pollutants. However, the model was not able to match the month-to-month variations in outflow concentrations and associated pollutant removals. This suggests that there are fundamental weaknesses in the way CE-QUAL-W2 simulates pollutant dynamics in wet detention ponds. In many cases, the model was not stable. Small changes in an input parameter could lead to dramatic changes in predicted algal biomass and associated nutrient removals.

Although CE-QUAL-W2 is not perfect, it is probably the best model for our objective. In the next section, we will examine the effect of different design variables on the pollutant removal efficiencies predicted by CE-QUAL-W2.

## DESIGN RULES SIMULATION BY CE-QUAL-W2 MODEL

CE-QUAL-W2 was used to evaluate alternative pond designs with the goal of maximizing nitrogen and phosphorus removal at the lowest cost. Based on a review of detention pond design criteria and common construction practice, the following design variables were expected to have the greatest potential impact on nutrient removal efficiency.

- Normal pool hydraulic residence time (ratio of storage volume to inflow rate)
- Hydraulic overflow rate (ratio of inflow rate to normal pool surface area)
- Depth of permanent water quality pool
- Length of discharge weir (controls pond outflow rate and time period that stormwater is detained in the pond)

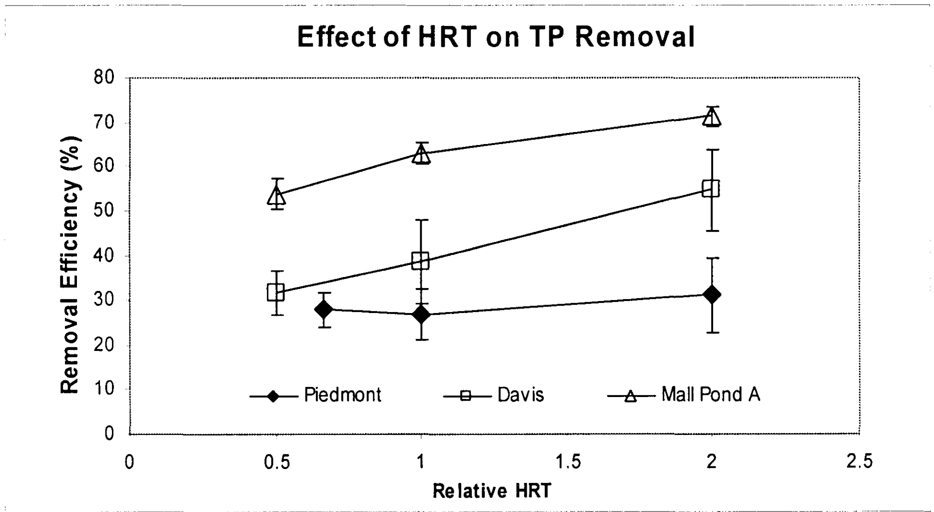
### HYDRAULIC RESIDENCE TIME (HRT)

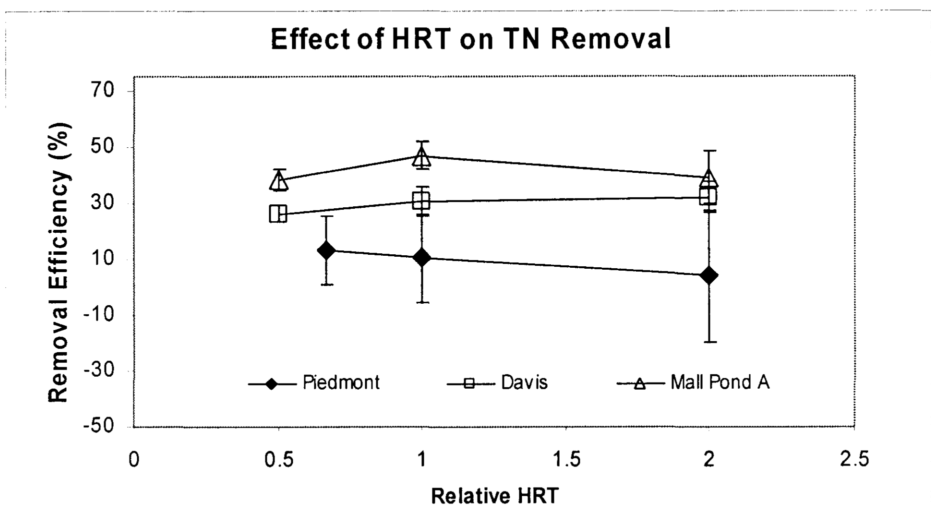
If pollutant removal efficiency is limited by contact or "reaction" time within the pond, a greater HRT should result in greater pollutant removal. To evaluate the effect of HRT on pollutant removal, the inflow rate to each pond was varied to cause a proportional change in HRT while the geometry of the pond remained the same. For all three ponds, the measured inflow rate over the year was used as the base condition. For Davis Pond and Mall Pond A, the inflow rate was reduced to 50% of the base and increased to 200% of the base flow rate. Piedmont Pond was simulated with 50% and 150% of the base inflow rate because of numerical instability problems at the 200% condition. To evaluate the effect of parameter uncertainty, pollutant removal efficiency was calculated using the ten different parameter sets discussed in the previous section. The effect of relative HRT (simulated HRT / base condition HRT) on TP, TN, and TSS removal efficiency is shown in Figure 7.

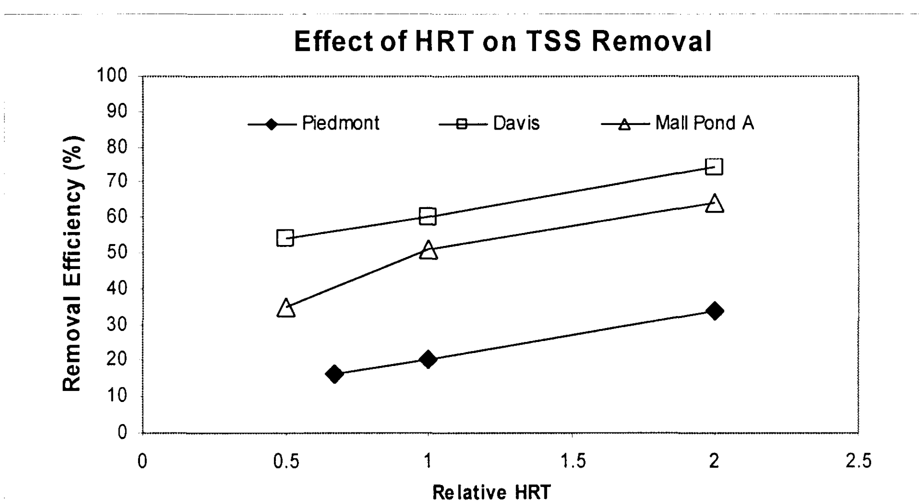
Varying the HRT had a substantial impact on TP removal efficiency in Davis Pond and Mall Pond A, but had little or no effect on TP removal in Piedmont Pond. As expected, increasing HRT increased TP removal and reducing HRT reduced TP removal in both Davis Pond and Mall Pond A. However, in Piedmont pond, changes in HRT had no significant impact on TP removal. The limited impact on TP removal in Piedmont Pond may be due to the very low TP concentration in the pond influent.

Changes in HRT had a negligible impact on TN removal in Davis Pond and Mall Pond A but may have caused a small reduction in TN removal efficiency in Piedmont Pond. Increasing the HRT resulted in a corresponding increase in TSS removal by settling.

Figure 7. Effect of varying Hydraulic Residence (HRT) Time on TP, TN, and TSS Removal Efficiency (Error bars for TP and TN show standard deviation of ten simulations.)



POND SURFACE AREA

If pollutant removal efficiency is primarily due to settling, then a larger surface area and lower hydraulic overflow rate should result in greater pollutant removal. To evaluate the effect of pond surface area on pollutant removal, the model input files that describe the geometry of each pond were modified to alter the normal pool surface area while maintaining a roughly constant total water volume (and constant HRT). For each of the three ponds, the actual pond geometry (surface area to volume relationship) was used as the base condition. The geometry of each pond was then modified to reduce the normal pool surface area to 50% of the base and then increased to 200% of the base condition. To evaluate the effect of parameter uncertainty, pollutant removal efficiency was calculated using the ten different parameter sets discussed in previous section. The effect of effect of relative surface area (simulated pond surface area / base condition area) on TP, TN, and TSS removal efficiency is shown in Figure 8.

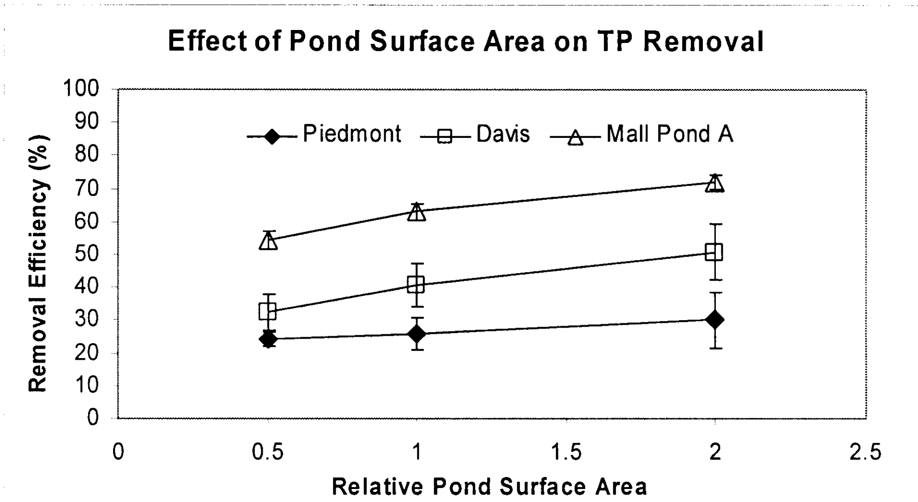
Varying the pond surface area (thereby reducing the overflow rate) had a very similar effect to increasing the HRT. Increasing the pond area, increased TP removal in Davis Pond and Mall Pond A but had negligible impact on TP removal in Piedmont Pond. Increasing the pond area had a negligible impact on TN removal in Davis Pond and Mall Pond A but may have caused a small reduction in TN removal efficiency in Piedmont Pond. Increasing the pond surface area resulted in a corresponding increase in TSS by settling in all three ponds.

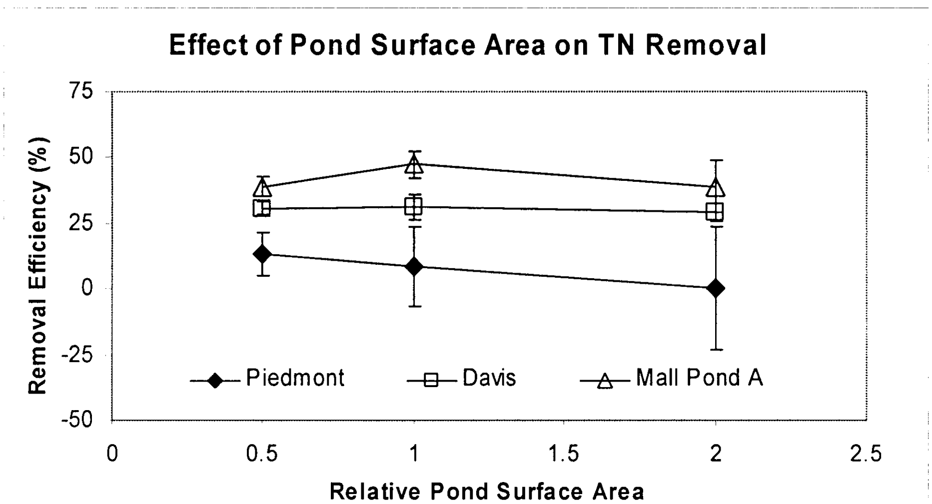
POND DEPTH

The previous simulations have shown that increasing HRT and increasing pond surface area (reducing overflow rate) can result in improved TP and TSS removal efficiencies under certain conditions. However, it is difficult to evaluate which factor is more important since, in the first simulations, changing the HRT resulted in a proportional change in hydraulic overflow rate. To try to separate out this effect, a series of simulations were performed where the pond depths were changed while maintaining a constant water volume. For each of the three ponds, the actual pond geometry (surface area to volume relationship) was used as the base condition. The geometry of each pond was then modified to reduce the average depth to 50% of the base and increase the average depth to 200% of the base. To evaluate the effect of parameter uncertainty, pollutant removal efficiency was calculated using the ten different parameter sets discussed in previous section. The effect of relative pond depth (simulated depth / base condition depth) on TP, TN, and TSS removal efficiency are shown in Figure 9.

Varying the average pond depth had no significant impact on TP, TN or TSS removal efficiency in any of the ponds. This indicates that increasing pond HRT by increasing the average depth will not enhance pollutant removal. However, increasing HRT by increasing pond surface area may enhance TP and TSS removal efficiency under certain conditions.

Figure 8. Effect of Varying Pond Surface Area on TP, TN, and TSS Removal Efficiency (Error bars for TP and TN show standard deviation of ten simulations.)



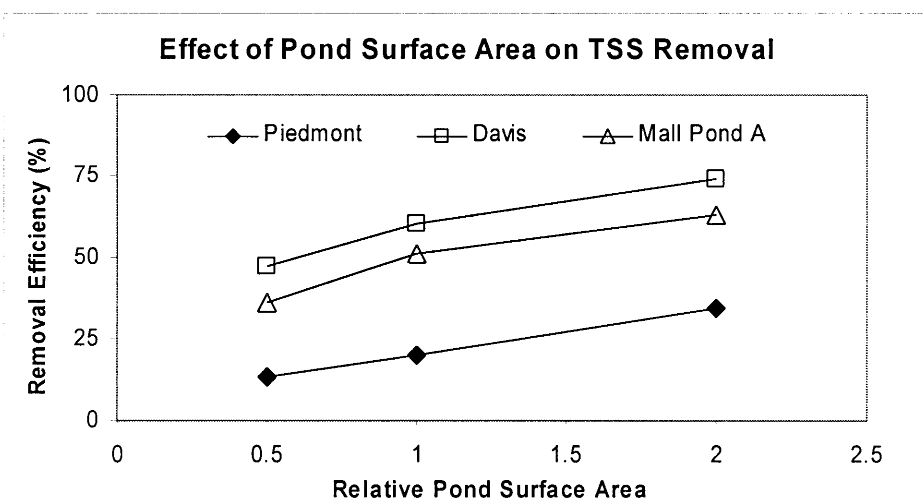
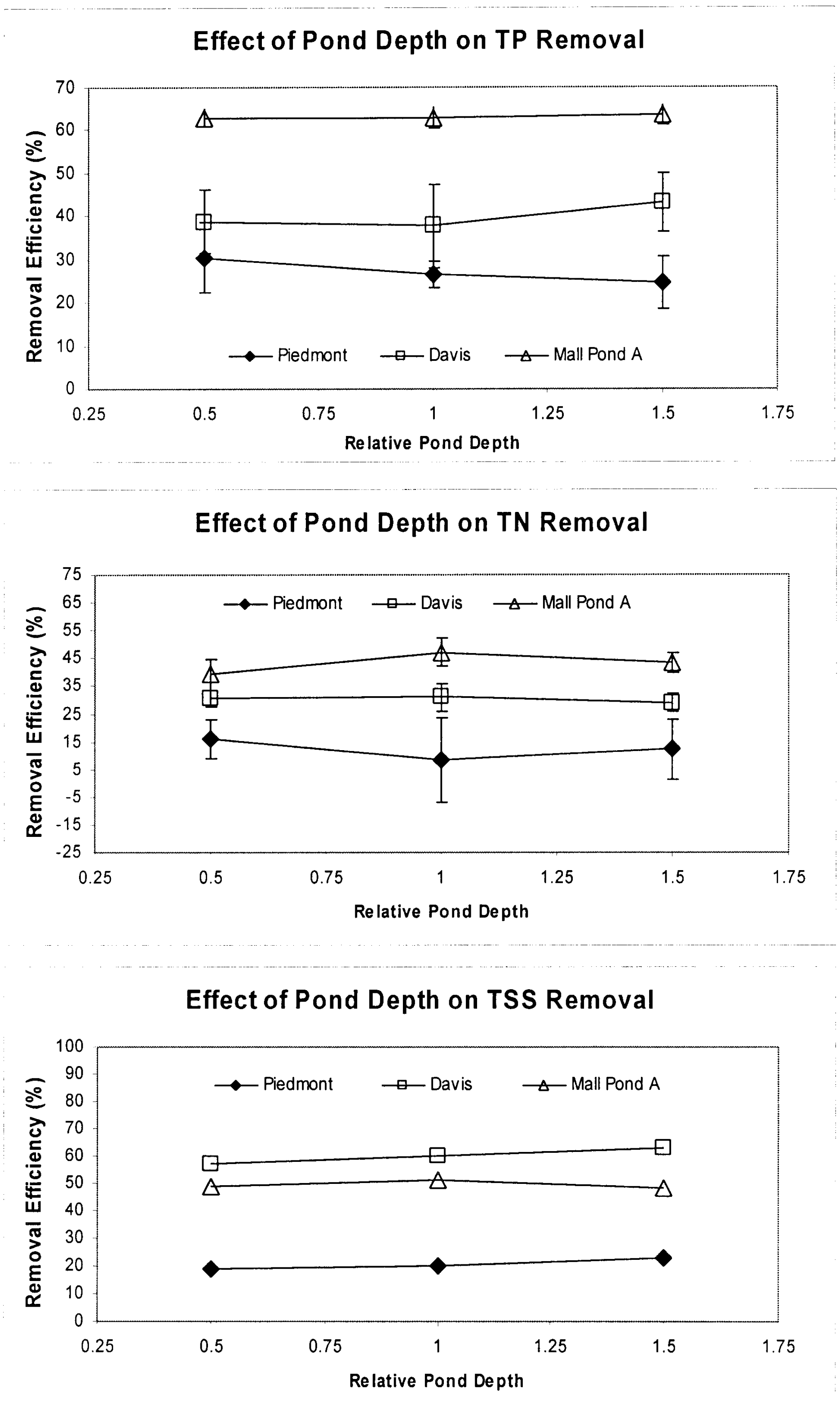



Figure 9. Effect of Varying Pond Depth on TP, TN, and TSS Removal Efficiency (Error bars for TP and TN show standard deviation of ten simulations.)



## OUTFLOW WEIR LENGTH

Discharge from most wet detention ponds are controlled by either riser barrel spillways and/or broad crested weirs. Varying the length of the discharge weir can control discharge rate and the temporary pool detention time.

A series of simulations were performed to evaluate the effect of varying weir length on pollutant removal efficiency of each pond. Outflow hydrographs for different weir lengths were first generated using a spreadsheet-based routing program. These outflow hydrographs were then used in combination with information on the outflow geometry to predict pollutant removal efficiency. In this series of simulations, only the best-fit kinetic parameters were used for each pond. The effects of discharge weir length on TP, TN, and TSS removal efficiency are shown in Figure 10.

In Piedmont Pond and Mall Pond A, reducing the weir length had only a slight impact on pollutant removal. In some parameters, reducing the weir length appeared to slightly enhance pollutant removal, presumably due to the longer HRT immediately after storm events when some water was retained in the temporary storage pool. For other parameters, there may have been a slight decrease in removal related to withdrawal of pollutant rich water from the hypolimnion by the concentrated point outflow.

In Davis Pond, variations in weir length had a dramatic impact on nutrient removal. Predicted TP removal efficiency was highest and TN removal efficiency was lowest for weir lengths between 3.5 and 3.8 m. When the weir length was reduced to 3.2 m or less, predicted TN removal increased and TP was negative. The reason for these dramatic changes in removal efficiency is not known. It may be a real effect resulting from destabilization of the pond thermal stratification or it may be a numerical problem with CE-QUAL-W2.

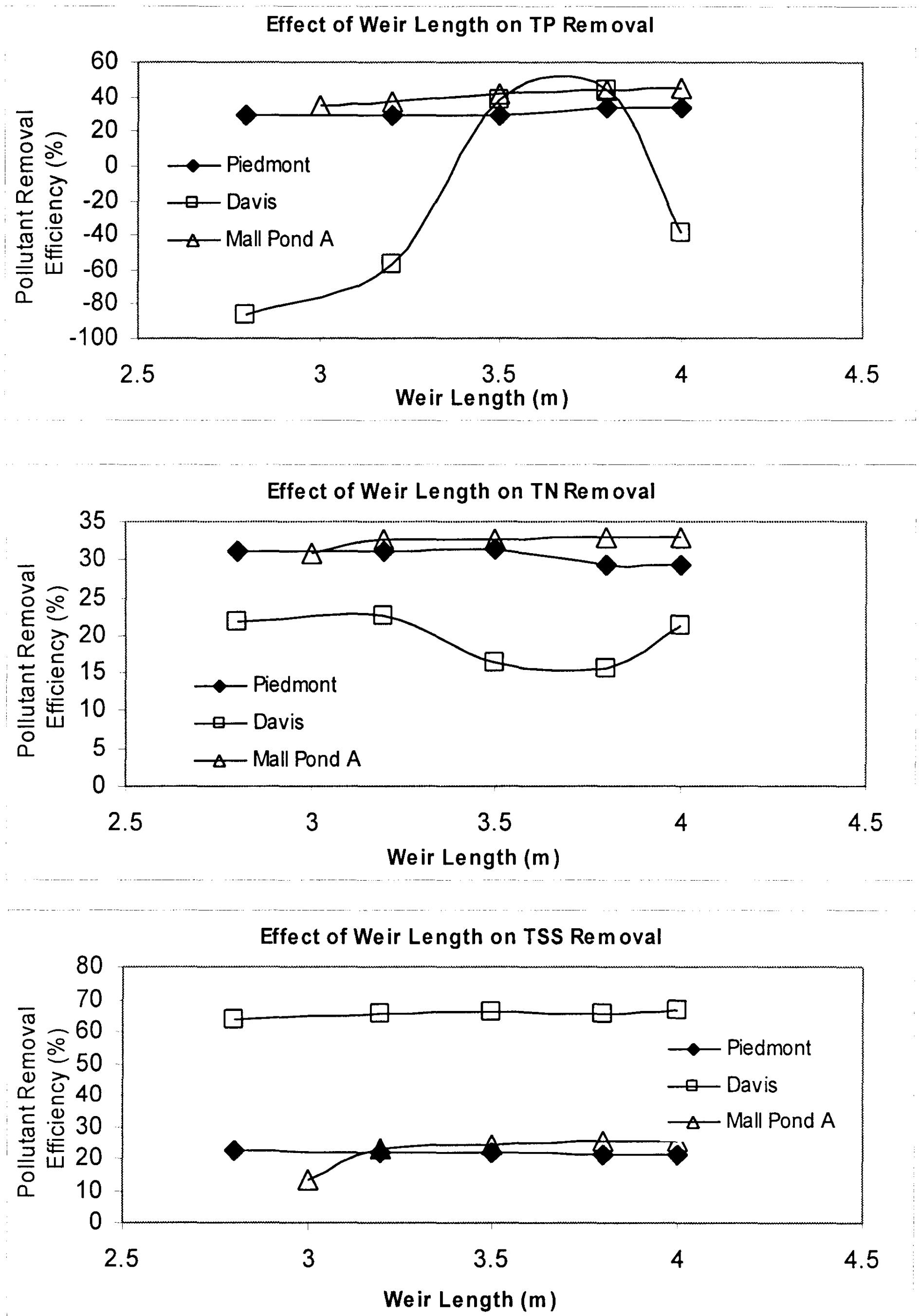
## STATISTICAL ANALYSIS

Two-tailed, paired t-tests were performed to determine if the apparent changes in pollutant removal efficiency in the three ponds were statistically significant. Results from the statistical tests are shown in Table 6.

In Piedmont Pond, none of the changes in pond size or layout had a significant impact on TP or TN removal. This was presumably due to the low phosphorus loading to the pond that resulted in limited algal growth and associated biological activity.

In Davis Pond and Mall Pond A, increasing both the HRT and pond surface area resulted in statistically significant increases in TP removal. Given that increasing the pond depth had essentially no effect on TP removal, increasing pond surface area appears to be most important for TP removal.

Figure 10. Effect of Weir Length on TP, TN, and TSS Removal Efficiency



The impact of varying pond size on TN is more complex. In Davis Pond, a reduction in HRT below the base value reduced TN removal. However, changes in Davis Pond surface area had no significant effect on TN removal, and an increase in HRT had no significant effect on TN removal. In Mall Pond A, either increasing or decreasing the pond HRT or surface area was predicted to reduce TN removal efficiency.

**Table 6.** Effect of Changes in HRT, Depth, and Surface Area from Base Case on Pollutant Removal Efficiency

| Design Criteria | DAVIS POND | | PIEDMONT POND | | MALL POND A | |
|---|---|---|---|---|---|---|
| | TP | TN | TP | TN | TP | TN |
| HRT= 0.5 * base | - | - | NS | NS[a] | - | - |
| HRT = 2.0 * base | + | NS | NS | NS | + | - |
| Depth = 0.5 * base | NS | NS | NS | NS | NS | - |
| Depth = 1.5 * base | NS | NS | NS | NS | NS | - |
| Area = 0.5 * base | - | NS | NS | NS | - | - |
| Area = 2.0 * base | + | NS | NS | NS | + | - |

[a]NS: not significantly different from base case ($\alpha > 0.05$) for two-tailed, paired t-test.

SUMMARY

An evaluation of detention pond design parameters showed that, in certain cases, varying the pond HRT and surface area could significantly impact total phosphorus removal efficiency. However, the relationship between total nitrogen removal efficiency and pond HRT and/or surface area is much more complex. In Mall Pond A, the calibrated CE-QUAL-W2 model predicted that an increase in pond surface area or HRT would result in a decrease in TN removal efficiency. The model also predicted dramatic changes in TP removal in Davis Pond in response to changing weir length. It is not known whether these predicted effects are real or are due to limitations in CE-QUAL-W2 and/or the input kinetic parameters.

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## LIST OF PATENTS AND PUBLICATIONS RESULTING FROM THE PROJECT

None.

## GLOSSARY OF ABBREVIATIONS

| | |
|---|---|
| BMPs | Best Management Practices |
| DN | Dissolved Nitrogen |
| DO | Dissolved Oxygen |
| DP | Dissolved Phosphorus |
| HRT | Hydraulic Residence Time |
| NCDENR | N.C. Department of Environment and Natural Resources |
| $NH_4$-N | Ammonia Nitrogen |
| $NO_{2+3}$-N | Combined Nitrate + Nitrite as Nitrogen |
| NURP | National Urban Runoff Program |
| $PO_4$-P | Orthophosphate Phosphorus |
| SSS | Suspended Solid Setting Rate |
| TDS | Total Dissolved Solids |
| TN | Total Nitrogen |
| TP | Total Phosphorus |
| TSS | Total Suspended Solids |
| U.S. EPA | U.S. Environmental Protection Agency |