Influences of Riparian Buffers and Soil Variability on the Hydrology of Seasonal Wetlands in Northern Minnesota

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Daniel P. Tersteeg

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Dr. James C. Bell, Dr. Randall Kolka

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ABSTRACT

Forest management guidelines are generally lacking for seasonal ponds, instead focusing on riparian forests adjacent to stream ecosystems. The objectives of this research were to determine what effect buffering seasonal ponds following harvest of adjacent upland forest has on pond hydrology, as well as to investigate and characterize site specific characteristics and soil morphology associated with these ponds. Hydrologic characteristics, including hydroperiod, water depth, and percent inundation, were examined to distinguish any differences between buffer treatments and pond elevation. Additionally, soil texture and hydraulic conductivity was analyzed to explain the presence of a perched water table. Study areas were established in north central Minnesota in 2000. Buffer treatments were assigned randomly to ponds in each study area and they include: control, uncut buffer, partial buffer, and clearcut buffer. Study areas were instrumented with rain gauges and study ponds with duplicate staff gauges. Additionally, study ponds were instrumented with piezometer nests and shallow groundwater monitoring wells. Measurements were taken from April to October to monitor surface and subsurface hydrology. Other site specific characteristics were measured including soil texture, hydraulic conductivity, soil temperature, and seasonal pond elevation. One year of pre-harvest staff gauge data was collected followed by 5 years of post-harvest data. Regression analysis of water levels based on staff gauge data indicates that all buffer treatments experienced significant increases in pond water depth for 4 years following upland clearcut. The fifth year following upland clearcut did not show significance between water depth in buffer treatments and control. Additional hydrological variables were analyzed by ANOVA and indicate that partial and buffer treatments resulted in significantly greater number of days with water in the pond suggesting increases in annual hydroperiod. Immediately following upland harvest the clearcut buffer treatment had the highest mean annual water depth of the three buffer treatments, subsequently followed by the lowest for the remainder of the study. Changes in evapotranspiration and runoff due to altering upland and riparian vegetation are considered key factors in explaining these hydrological responses. The relationship between pond elevation and percent inundation was not found to be strong, with site specific characteristics influencing hydrological inputs. The existence of lithologic discontinuity as well as clay lenses in soils, defined as the formation of Bt horizons, was found to be strongly related to the presence of a perched water table and the occurrence of seasonal ponds on the landscape. These soil characteristics extend into the uplands causing subsurface lateral flow of infiltrated soils to collect in pond depressions. Because of the presence of both Bt horizon formation and lithologic discontinuity, seasonal pond formation can be attributed to both geogenic and pedogenic processes. Furthermore, the results of this study suggest that different types of riparian buffers do result in different hydrological responses in seasonal ponds. Therefore, by altering riparian vegetation communities it is possible to manipulate the length of saturation and average depth of water in seasonal ponds following upland harvest based on the type of buffer left around the ponds.

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Chapter 1 Hydrological and Soil Considerations Defining Seasonal Pond Function: An Overview

INTRODUCTION

Seasonal ponds occur commonly in temperate forests across the North American landscape, often forming in depressions due to ponding of snowmelt and/or precipitation. Because these systems are geographically and hydrologically isolated, and because they are characterized by an annual wet and dry phase, these systems are considered to provide valuable habitat function and contribute to the ecological biodiversity across the landscape. Yet, even though seasonal ponds are recognized as integral components to the ecological landscape, it is due to their small size and general abundance that makes these systems difficult to manage in a forest setting. Often it is difficult to identify the presence of seasonal ponds during their dry phase and the high density of these ponds in forested regions, such as northern Minnesota, create difficulties when attempting to protect their functional integrity while also managing for forest resources.

Because of these challenges facing forest managers it is important to develop a more complete understanding of these systems. Much of the research centered on these ponds is focused on ecological components and function. Additionally, riparian management guidelines are generally lacking for seasonal ponds and instead focus on stream ecosystems. A better understanding of how forest management practices affect seasonal pond hydrology is needed to determine potential impacts to seasonal ponds from management of adjacent upland forest.

Justification

It is recognized by Cole et al., (1997) that hydrology and hydrologic regime is a principle factor affecting the structure and function of wetlands. Because seasonal ponds have an annual hydroperiod generally consisting of at least one wet phase and one dry phase, they are recognized as providing important habitat for a variety of species, including amphibians (Paton, 1999) and invertebrate communities (Batzer and Sion, 1999; Higgins and Merrit, 1999; Schneider, 1999). Furthermore, there is interest in better understanding the role seasonal ponds play in regional groundwater recharge (Semlitsch and Bodie, 1998). Yet, hydrological function of seasonal ponds is considered by many to be the most poorly understood component of these systems (Sharitz and Gibbons, 1982; LaBaugh, 1986; Cole et al., 1997). Particularly, little is known regarding the effect riparian buffers have on the hydrology of seasonal ponds following harvest of adjacent upland forest.

These concerns and lack of understanding apply directly to the objectives of this study. This study will focus on (i) the effect forest management practices have on seasonal pond hydrology, (ii) determining any significant differences in hydrology based on riparian buffers types, and (iii) soil morphology associated with seasonal ponds.

The anticipated results of these objectives will provide a better understanding of the impacts on seasonal pond hydrology as a result of forest management practices. Specifically, this study will provide insight into whether or not riparian buffers are effective at mitigating adjacent upland harvest impacts on seasonal pond hydrology. Furthermore, characterizing soil morphology in and around seasonal ponds will provide a better understanding of the role pedogenic and geogenic processes play in the formation of these ponds in a forested, upland, palustrine system.

LITERATURE REVIEW

The overall goal of this study involves a better understanding of seasonal pond hydrology; both as it is affected by upland harvest and types of riparian buffers, as well as the influence soil morphology has on formation and occurrence of ponds on the landscape and there role in regional groundwater recharge. To better understand the function of these systems on the landscape we must first understand how a seasonal pond is defined.

Hydrology is perhaps the most important factor involved in defining seasonal ponds. Therefore, it is important that we understand how hydrology sets these wetlands systems apart from others. Seasonal ponds occur on the landscape as a result of temporary ponding of water in geographically and hydrologically isolated depressions.

Brooks and Hayashi (2002) as well as Burne (2001) have noted that the ponding of waters in these depressions occurs most often due to seasonal changes. Spring snowmelt and precipitation collects in these depressions. As summer approaches evapotranspiration increases and begins to deplete these depressions of water, generally becoming dry in mid to late summer. With the senescence of vegetation, precipitation in the fall often recharges these depressions depending on precipitation amounts and antecedent moisture conditions. Ponded waters will freeze over the winter and remain until spring, when the cycle repeats itself.

The following discussion will focus on seasonal pond hydrology as it applies to the concept and definition of isolation, influences from soil and basin morphology, and the role it plays defining the habitat function of these ecosystems.

Isolation

Seasonal ponds (Palik et al., 2001), West Coast vernal pools (Jain, 1976; Zedler, 1987; Keeler-Wolf et al., 1998; Witham et al., 1998; Tiner, 1999), woodland vernal pools (Tiner et al., 2002), and seasonal forest pools (Brooks, 2005) are all similar in function and represent a type of isolated wetland that is common throughout the United States and Canada. Regional differences in physiography, including climate and soils, have led to these differences in nomenclature. It is due to the fact that these systems are considered isolated that sets them apart from other wetland types.

Isolation, as it applies to seasonal ponds, is viewed by geographic and hydrologic terms. Geographic isolation is perhaps the easier of these two terms to define with more certainty. Geographic isolation represents a position on the landscape. Therefore, geographic isolation of a seasonal pond is defined as being completely surrounded by uplands. Tiner (2003) suggests ‘upland’ can be more precisely defined by such indicators as hydrophytic plant communities surrounded by terrestrial plant communities or undrained hydric soils surrounded by nonhydric soils.

Seasonal ponds are considered hydrologically isolated when a well defined surface water connection is not present (Winter and LaBaugh, 2003). Therefore, hydrologic isolation is a reflection of geographic isolation. Since seasonal ponds are generally located in depressions and surrounded on all sides by uplands, they do not exhibit a permanent outlet or inlet for surface waters.

Yet, geographic and hydrologic isolation can be complicated by factors including changes in time and space, as well as the consideration of groundwater connectivity. Variability in hydrology due to changes in climatic conditions over time or the altering of landscapes has the potential to modify existing conditions. For example, increases in hydrologic inputs such as precipitation can cause storage capacities of seasonal ponds to be exceeded, thereby creating a surface outlet for discharge. Yet, this increase must be a prolonged occurrence in order to produce the ‘well defined’ outlet needed to meet the definition. As such, it is not uncommon for seasonal ponds to demonstrate a short period of surface discharge due to short lived, though substantially large inputs of precipitation such as rain on snow events in early spring.

The other consideration is groundwater connectivity. Many otherwise geographically isolated wetlands that display no well defined surface connection have been documented to be in fact connected to regional water tables via groundwater flow (Winter, Rosenberry, Buso, and Merk, 2001). Since the current definition of hydrologically isolated wetland only considers surface connectivity, the relationship to groundwater is presently disregarded.

Yet this is an issue that will continue to be debated among scientist and policy makers. For instance, the ruling of the U.S. Supreme Court on the case of *Solid Waste Agency of Northern Cook County v. U.S. Army Corps of Engineers* in 2001, which limited the protection provided isolated wetlands that are not adjacent to or connected by surface waters to other bodies of water. The debate regarding groundwater connectivity is less of an issue for this study since the majority of study ponds exhibit a perched water table that is localized to the pond depression, consequently meeting both the geographic and hydrologic definition of isolation as it applies to wetland systems.

Soil and Basin Morphology

Seasonal ponds are found in landscapes where local geologic settings and hydrologic processes support the ponding of waters (Kantrud et al., 1989). This is often the case in areas where shallow natural depressions are underlain by soils that are characterized as having impervious or slowly permeable soil horizons.

Such is the case of recent continental glaciations that have left behind poorly sorted tills. These tills are often high in silt and clay content as a result of shale-derived material and are characterized by low permeability. Glacially derived till studied in Massachusetts was calculated having hydraulic conductivities in the order of 1.77×10^{-6} to 7.38×10^{-8} cm/s (Gay, 1998). It was shown by Palik et al., (2003) that seasonal ponds in northern Minnesota were more likely to occur on ground moraines than other land-types, thought to be due to low permeability of the soils and the higher frequency of small ice blocks left following glacial retreat.

Throughout other regions of the country, including Pennsylvania and California, seasonal ponds were found in topographic depressions underlain by an impermeable layer of clay subsoil (O’Driscoll and Parizek, 2003; Zedler, 1987). Additionally, they are not limited by vegetation type and can be found in mid-continental and eastern North American prairies and temperate forests, respectively, as well as in grasslands along coastal California (Brooks, 2005).

The relatively few studies conducted that examine basin morphologies of seasonal ponds indicate they are generally small. Therefore, this would suggest that seasonal ponds are particularly sensitive to change in forest catchments due to their high perimeter-to-area ratio (Millar, 1971; Palik et al., 2001). An inventory of seasonal ponds in northern Minnesota by Palik et al. (2001, 2003) found seasonal ponds to range in size between 0.01-0.25 ha. In South Carolina, a study involving Carolina bays and similar wetland types found the majority were <3 ha in size (Kirkman et al., 1996). Brooks et al. (1998) found seasonal ponds in central Massachusetts to have a median surface area of 0.07 ha.

Habitat Function

As previously discussed, seasonal ponds are characterized by the temporary ponding of water in geographically and hydrologically isolated depressions. It is this temporary ponding of water that is critical to a number of species for reproductive success. Seasonal ponds will generally dry up at some point during the growing season, generally coinciding with peak temperature and evapotranspiration rates in mid-summer. Because of this dry phase, seasonal ponds do not support fish and are therefore ideal breeding grounds for number of species including amphibians (Paton, 1999) and invertebrate communities (Batzer and Sion, 1999; Higgins and Merrit, 1999; Schneider, 1999).

Additionally, seasonal ponds are utilized by turtles, small birds, salamanders, frogs, and small mammals as important habitat refuges during some point in the lifecycle as these species (Gibbs, 1993; Williams, 2005). A number of vegetation communities also prefer or are limited to reproduction in seasonal ponds due to the occurrence of wet and dry phases throughout the growing season (Williams, 2005). It is this wet and dry phase hydrology that is the critical habitat need among both plant and animal communities.

Pond hydrology is driven primarily by inputs of precipitation in the form of rain or snow and hydrological losses due to evapotranspiration combined with lesser amounts of infiltration losses to groundwater. By altering vegetation in and around ponds due to changes in land usage or forest management practices, it is likely that this hydrological balance with be effected, resulting in impacts to the local animal and plant communities. As discussed earlier, the high perimeter-to-area ratio of seasonal ponds across the landscape may also act to magnify these impacts.

OBJECTIVES

The objectives of this research are:

(i) To gain a better understanding of seasonal pond hydrology and determine what effect different types of buffer treatments have on pond hydrology following harvest of adjacent upland forest.

(ii) To better characterize the soils associated with the formation and occurrence of seasonal ponds on the landscape and to investigate the relationship between pond elevation and water depth.

Chapter 2 Effects of Riparian Buffers on Hydrology of Seasonal Ponds

OVERVIEW

Forest management guidelines are generally lacking for seasonal ponds, instead focusing on riparian forests adjacent to stream ecosystems. The abundance of these seasonal ponds in northern, glaciated, forested landscapes and the importance of their habitat function have drawn attention to these systems in recent years. The objective of this research was to determine what effect buffering seasonal ponds following harvest of adjacent upland forest has on pond hydrology. Hydrologic characteristics, including hydroperiod and water depth, were examined to distinguish any differences between buffer treatments. A block design consisting of four treatments, replicated in four study areas was established in north central Minnesota in 2000. Four treatments were assigned randomly to ponds in each study area and they include: control, uncut buffer, partial buffer, and clearcut buffer. Study areas were instrumented with rain gauges and study ponds with duplicate staff gauges. Additionally, a subset of study ponds was instrumented with piezometer nests and shallow groundwater monitoring wells. Measurements were taken from April to October to monitor surface and subsurface hydrology. One year of pre-harvest data was collected followed by 5 years of post-harvest data. Regression analysis of water levels based on staff gauge data indicates that all buffer treatments experienced significant increases in pond water depth for 4 years following upland clearcut. The fifth year following upland clearcut did not show significance between water depth in buffer treatments and control. Additional hydrological variables were analyzed by ANOVA and indicate that partial and uncut buffer treatments resulted in significantly greater number of days with water in the pond suggesting increases in annual hydroperiod. Immediately following upland harvest the clearcut buffer treatment had the highest mean annual water depth of the three buffer treatments, subsequently followed by the lowest for the remainder of the study. Changes in evapotranspiration and runoff due to altering upland and riparian vegetation are considered key factors in explaining these hydrological responses. The results of this study suggest that different types of riparian buffers do result in different hydrological responses in seasonal ponds. Therefore, by altering riparian vegetation communities it is possible to manipulate the length of saturation and average depth of water in seasonal ponds following upland harvest based on the type of buffer left around the ponds.

INTRODUCTION

Seasonal ponds provide valuable habitat function and contribute to the ecological biodiversity across the landscape. Yet, even though seasonal ponds are recognized as integral components to the ecological landscape, little protection is afforded to them due to their small size. Often it is difficult to identify the presence of seasonal ponds during their dry phase and the high density of these ponds in forested regions, such as northern Minnesota, create difficulties when attempting to protect their functional integrity while also managing for forest resources.

Because of these challenges facing forest managers it is important to develop a more complete understanding of these systems. Much of the research centered on these ponds is focused on ecological components and function. Additionally, riparian management guidelines are generally lacking for seasonal ponds and instead focus on stream ecosystems. A better understanding of how forest management practices affect seasonal pond hydrology is needed to determine potential impacts to seasonal ponds from management of adjacent upland forest.

Therefore a study was initiated in the spring of 2000 near Grand Rapids, MN to investigate the effectiveness of buffering seasonal ponds. The objective of this research was to gain a better understanding of seasonal pond hydrology and determine what effect different types of buffers have on pond hydrology following harvest of adjacent upland forest. In order to meet this objective the following hypotheses were tested by analyzing seasonal pond water levels: (i) harvest of adjacent upland forest will impact seasonal pond hydrology causing the increase of water in pond basins and (ii) the uncut buffer will result in water levels closer to control or undisturbed conditions due to minimal disturbance of riparian vegetation.

MATERIALS AND METHODS

Site Description

In 2000, study sites were established in north central Minnesota located along the eastern edge of Cass County and the western edge of Aitkin County (Appendix A: Figure A). The study consisted of 4 experimental units (Willow River, Soo Line, Ashebun Lake, and Dog Lakes) with a total of 16 ponds selected for study; 7 located on Potlatch Corporation land in Aitkin County and the remaining 9 located on Cass County land (Table 2.1). The study areas are characterized by soil parent materials deposited during the Wisconsinan-age glaciations that saw the multiple advance and retreat of up to 4 separate ice lobes; the Wadena Lobe, the Rainy Lobe, the Superior Lobe, and the Des Moines Lobe which also included the St. Louis Sublobe.

Due to these multiple glaciations, Cass and Aitkin County are composed of a variety of different landforms such as drumlins, lake plains, moraines, and outwash plains. Generally, the study areas are located on gently rolling ground moraine (Hobbs & Goebel, 1982). This represents relatively young, low-relief landscapes, where drainage channels have not completely formed and surface drainage is impeded by numerous closed depressions. Soil parent material of the study areas include loess, glaciolacustrine deposits, till, and glacial outwash. Typically, a layer of loess approximately 30-cm thick overlays outwash material mixed with till and/or loess of variable thickness at all study area. This in turn is generally followed by a layer of glaciolacustrine deposits at study areas Willow River, Soo Line and Ashebun Lake ranging in thickness from 40-cm to 127-cm. Dog Lakes lacks these glaciolacustrine deposits and instead dense till continues to depth.

Forested lands comprise over two-thirds of the area in each county. Forestry and forest products are among the counties leading industries, with conifers and aspen representing the majority of commercial forest resources. Upland forests of the study areas are dominated by aspen (*Populus* spp.) with lesser amounts of northern hardwoods: red oak (*Quercus rubra*); maple (*Acer* spp.); and/or basswood (*Tilia americana*). Mean annual precipitation is 71-cm and average snowfall is 137-cm (Nyberg, 1999; Richardson, 1997). Precipitation is distributed fairly evenly throughout the growing season, but generally highest in June and July. Mean annual air temperature is 4.8^{o} C with an average high temperature of 10.6^{o}C and low of -1.7^{o}C (Nyberg, 1999; Richardson, 1997). The length of the growing season based on a daily minimum temperature >0.0^{o}C is approximately 110 days (Nyberg, 1999; Richardson, 1997).

Experimental Design

This experiment was conducted using a randomized block design, where 4 randomly assigned treatments were replicated in 4 blocks resulting in a total of 16 treatments. Each block, or experimental unit, was greater than 6 hectares and consisted primarily of mature, mixed hardwoods (*Populus* spp., *Acer* spp., *Quercus rubra* and/or *Tilia americana*). Seasonal ponds were identified by 1:24,000 leaf-off color infrared air photography. A number of seasonal ponds were located within each experimental unit.

For each unit 4 ponds were randomly chosen based on the following criteria: 1) the surrounding forest was >50 years old; 2) ponds and surrounding forests showed no evidence of recent disturbance; 3) pond area was >0.02 but <0.5 ha; 4) ponds had mineral or muck substrates, as opposed to peat; and 5) water depth in pond basis at the time of selection in spring of 2000 was >15-cm. For each experimental unit the 4 ponds were randomly assigned a treatment as follows: 1) uncut forest; 2) upland clearcut, with 50-ft uncut buffers surrounding ponds; 3) upland clearcut, with 50-ft buffers thinned to 50-ft^2/ac surrounding ponds; and 4) upland clearcut with residual patches of tress left in the upland with no buffers around ponds (Fig. 2.1). These 4 treatments are referred to hereafter as: 1) control; 2) uncut buffer; 3) partial buffer; and 4) clearcut buffer.

Instrumentation and Sampling

Experimental units were instrumented with standard all-weather rain gauges to record precipitation. Gauges were attached to metal posts and placed in clearings where rainfall catch would not be affected. As trees grew and encroached on the gauge they were removed so that the clearing for the gauge was defined by a 30^{o} angle from the top of the gauge to the closest tree top (Brooks et al., 2003).

Duplicate metal staff gauges were used to record water depths and hydroperiods. These were installed in ponds assigned a treatment by driving a metal post approximately 1 meter into the ground. The gauge was then bolted onto the post with the base adjacent to the mineral surface of the pond. For each pond a benchmark was established by driving a metal spike into the base of a tree next to the pond. Using a laser level and the benchmark as a reference the gauges were placed at the lowest points in the pond. After installation of the gauges the initial elevation difference between the benchmark and the base of the gauge was recorded. This elevation difference was checked annually with a laser level after freeze/thaw activity ceased in the spring. It was found that changes in gauge elevation among years was minor based on the reference point.

Soil profiles were described for all 16 study sites to the depth of 185-cm following procedures specified in *Soil Survey Manual* (Soil Survey Division Staff, 1993). Morphological properties were described for each profile including horizon color and thickness, texture, structure, and presence of mottles. At the control treatment for each of the 4 experimental units soil pits were excavated in the pond basin and upland where profiles were described and sampled by horizon. These samples were sealed in paper bags and sent to the University of Minnesota Research Analytical Laboratory where textural analysis was performed on air-dried sieved samples using the hydrometer method (Miller et al., 1997). Hydraulic conductivity of soil horizons was measured at the control treatments using a compact constant head permeameter (Ksat Inc. Amoozometer).

Piezometers and shallow wells were installed along transects running from the pond basin to the upland to monitor water table depth and sub-surface hydrology. A subset of 5 of the original 16 ponds was instrumented due to constraints of available resources and time. This subset included 2 ponds that were assigned the control treatment and 3 ponds that were assigned the clearcut treatment. Transects originated at the pond basin and ran parallel to the hydrologic gradient, terminating at the upper boundary of the immediate catchment area for each individual pond based on surface topography.

Along each transect 3 sets of well/piezometer nests were installed. This represented a nest at the catchment boundary in the upland, followed by a second nest in the wetland-upland boundary and a third nest in the pond basin. Length of transects and spacing of the well/piezometer nests varied depending on topography of specific ponds. Overall, transects ranged between 50 and 80 meters. Piezometers were constructed of 1.9-cm polyvinyl chloride (PVC) pipe with 0.025-cm slotted PVC screen attached to the bottom. Wells were constructed of 5-cm PVC with 6-mm holes drilled throughout the pipe at 5-cm intervals, leaving 30-cm intact at the top to couple a riser onto once installed in the field. After wells were drilled, geofabric was wrapped and zip-tied onto the pipe.

Piezometers and wells were built and installed according to Corps of Engineers guidelines (Appendix A: Figure B) (Sprecher, 2000). Piezometer nests consisted of 4 piezometers installed at the interface of textural changes and/or areas of abundant mottling identified from previous soil profile descriptions and site specific sampling. Generally, these depths were 200, 100, 50, and 25-cm. With each piezometer nest a shallow groundwater monitoring well was installed.

Collection of rain and staff gauge data was done weekly to bi-weekly, recording all 16 ponds within 2 days for each cycle. Rain gauges were read to within 0.03 cm and staff gauges to within 0.30 cm. Similarly, piezometer and well data was also collected weekly to bi-weekly using an electronic water level meter (Solinst Model 101-Mini) and read to within 0.03 cm. The sampling period lasted throughout the ice-free season, generally April 1 to October 31.

One season of pre-harvest sampling was conducted at the onset of the study in 2000. Selected treatment stands were marked in the fall of 2000 and harvested that winter, leaving the designated buffer treatment around selected study ponds. Post-harvest sampling began spring 2001 and continued to 2005.

Pond surface area was determined by using the seasonal high-water level in 2000. Presence of high-water marks, such as sediment-coated or recently saturated leaf litter, was used to establish pond margins. The margin-to-margin pond length was measured in 2 perpendicular dimensions. These dimensions were then used to estimate the surface area using the formula for an ellipse (Table 2.2).

Data Analysis

Staff gauge data was used to record water depth and determine hydroperiods from April 1 to October 31 for the 16 study ponds. These water depth measurements and subsequent hydroperiods were then analyzed to determine any significant difference among ponds based on treatment effect. For each set of duplicate gauges, data was selected corresponding to the deepest water level reading. Gauge readings for all analogous treatments were averaged together for each monitoring cycle, resulting in a mean depth for each treatment. Using the general linear model (GLM) in SAS 9.1 (SAS Institute, 2003) weekly gauge data for the complete, partial, and clearcut buffer treatments were regressed against the control treatment for the 2000 pre-harvest study season; applying this relationship to each post-harvest year and using a paired t-test to determine any significant difference of hydroperiod response based on treatment type.

Variables including maximum depth, average depth, longest dry period, longest wet period, number of dry days, number of wet days, and consecutive wet days were also calculated as a yearly mean value for each treatment type. An analysis of variance (ANOVA) was then completed using the GLM in SAS 9.1 to determine any significant difference between treatment types.

RESULTS AND DISCUSSION

Hydrological Considerations

The general water budget for these seasonal ponds is represented by a perched wetland system. Figure 2.2 illustrates the hydrological inputs and outputs and is represented by the following water budget:

$$\mathbf{P + RO - Q - ET - GW_o = \Delta S} \qquad [1]$$

Where P = precipitation; RO = runoff; Q = surface discharge; ET = evapotranspiration; GW_o = groundwater out; and ΔS = change in storage. Because seasonal ponds are isolated systems completely surrounded by uplands Q is assumed to be 0. There are generally no groundwater inputs from regional water sources and the primary hydrological inputs are P and RO. Table 2.3 shows the annual amount of P for the duration of the study and departure from normal. Since P is assumed to affect all study areas equally, it is assumed to be constant and therefore a controllable variable. Surface RO is a result of sufficient precipitation to reach infiltration capacity of soils, as well as the result of frozen soils following spring snowmelt.

As previously mentioned, water that infiltrates into the soil as a result of rainfall or snowmelt is perched. Figure 2.3, 2.4, and 2.5 represents raingauge, well, and piezometer data from a representative study pond and illustrates the presence of the perched water table found under these ponds. If there is sufficient amount of water that infiltrates in the uplands it is transported to pond depressions via subsurface lateral flow according to Darcy's Law. This subsurface lateral flow is localized and considered interflow and not a result of regional groundwater inputs.

Hydrological losses from seasonal ponds are due to ET and GW_o. Although actual ET rates were not measured for this study, Parson *et al*. (2004) calculated that 70% of water level decline in small seasonal wetlands was due to root uptake and ET by riparian vegetation during the peak of the growing season from June to July. Millar (1971) suggests similar findings, indicating that the majority of water is lost by ET of riparian vegetation, with emergent vegetation in the ponds contributing lesser amounts. Following spring, vegetation begins to grow and transpire more actively causing the depletion of surface waters in these seasonal ponds when ET rates exceed inputs of precipitation during the peak of the growing season. As vegetation decreases its rate of transpiration and senesces in fall, ponds may re-inundate with sufficient fall recharge events.

In general, hydraulic conductivity was found to be higher in the upper 1 meter of the soil profile than material immediately below (Table 2.4). This high conductivity therefore provides a pathway for water to flow laterally to the riparian zone. Furthermore, the low conductivity of soil material under the upper 1 m acts as a significant aquitard, impeding the infiltration of water to more regional groundwater sources. This suggests that much of the GW_o component is subsequently lost to ET instead of contributing to regional groundwater recharge.

These ponds are complex systems and there are exceptions to Equation 1. One of these exceptions involves Q. There is the possibility for the expression of Q for a very short period of time, a matter of days, immediately following spring snowmelt. If there are sufficient quantities of snowmelt runoff and/or the addition of precipitation, storage capacity of these seasonal ponds can be exceeded resulting in Q. The presence of frozen soils inhibiting rapid infiltration plays an integral role (Hayashi *et al*., 2003). Due to impeded rates of infiltration during this period in the uplands, overland transport of RO is greatly increased to the pond basin. Additionally, frozen soils under the pond basin combined with the absence of ET inhibit infiltration of waters stored in the pond as groundwater out (GW_o).

Hydrological Response to Buffer Treatments

Staff gauge data collected from the four replicates of each treatment was averaged each year of the study to determine mean bi-weekly water depth. This data was then used in regression analysis to determine any significant changes in water depth based on the treatment type. Beginning in 2000, one year of pre-harvest data was collected and regression was run on the averaged bi-weekly water depth from each of the treatment types. This served as the baseline response for the hydrological relationship between the three buffer treatments and the control treatment.

The regression relationship including slope and y-intercept for each of the treatment types in 2000 was then used for the following five years; with the control treatment data used as a predictor of water depth observed in each treatment type had there been no upland disturbance. As seen in Table 2.5, the R^2 values for these relationships each year are very strong. This predicted value was then subtracted from the observed value to determine the difference in water level as a result of each of the treatment types. These differences were then imputed in SAS 9.1 using the general linear model (GLM) and a paired t-test was run to determine significant differences between the buffer treatments and the control treatment.

Following the upland harvest in 2000, water level of all buffer treatments significantly differed from that of the control for the years 2001, 2002, 2003, and 2004. By 2005, the fifth year following upland harvest, water levels in buffer treatment ponds begin to rebound to pre-harvest relationships with no significant differences observed among treatments. These results indicate that upland harvest of forest surrounding seasonal ponds does impact pond hydrology, specifically increasing water depth. Therefore, the first hypothesis can be accepted; harvest of adjacent upland forest will impact seasonal pond hydrology causing the increase of water in pond basins.

These results also suggest that five years following upland harvest, the water depth between buffer and control treatments begins to recover to pre-harvest relationships. Yet, based on these results it is difficult to interpret how buffer treatments differ between themselves and which, if any, is more effective at maintaining the pre-harvest hydrology of these seasonal ponds.

To better understand this relationship additional hydrologic variables were examined to attempt to further distinguish any differences in hydrology between buffer treatment types. These variables included maximum depth, average depth, longest dry period, longest wet period, number of dry days, number of wet days, and consecutive wet days. All were calculated as a yearly mean value for each treatment type. An analysis of variance (ANOVA) was then completed using the GLM procedure in SAS 9.1 and least square means were compared to determine any significant difference between buffer treatment types.

As seen in Table 2.6, maximum depth did not significantly differ among treatments. Following upland harvest in the winter of 2000/20001, average water depths in all buffer treatments were greater than the control treatment. Table 2.7 shows the partial and clearcut buffer treatments average annual water depths were significantly different than that of the control. The greatest of this increase was seen in the clearcut buffer treatment in 2001, the year immediately following upland harvest, where the clearcut buffer treatments average annual water depth exceeded all other treatments. Following 2001, the clearcut buffer treatment saw average annual water depths drop below those of the partial and uncut buffer treatments but maintain levels just above those of the control treatment.

Interestingly, the buffer and partial buffer treatments exhibited significantly greater number of wet days (Table 2.8), longest wet periods (Table 2.9), and consecutive wet days (Table 2.10) from that of the control. Not surprisingly, these treatments also had the fewest number of dry days (Table 2.11) and the least amount of longest dry periods (Table 2.12), as the latter two variables are inverses of the former wet days and longest wet periods. This suggests that following upland harvest, these treatments retain surface water in pond basins more consistently and longer into the growing season before drying up.

These results indicate that the partial and uncut buffer treatments were most closely related to each other and exhibited the most significant difference from the control treatment when the response to the additional hydrologic variables is considered, with the partial buffer showing slightly more significance in all cases over the uncut buffer. Additionally, the clearcut buffer treatment differs the least significantly from the control treatments based on these variables and is more closely related to the control treatment than it is to the partial and uncut buffer treatments.

Based on these findings the partial buffer treatment has the advantage of not only maintaining greater average annual water depths, but also maintaining water in pond basins longer into the growing season than both the clearcut and uncut buffer treatments. Excluding 2001, the year immediately following upland harvest, the clearcut buffer treatment reflects pre-harvest hydrology more closely than the uncut and partial buffer treatments. It not only maintains average annual water levels more closely to the control treatment for all years following 2001, it also does not significantly differ from the control treatment when considering longest dry period, longest wet period, number of dry days, number of wet days, and consecutive wet days.

Therefore, based on the results of this data the second hypothesis has been rejected, which stated that the uncut buffer will result in water levels closer to control or undisturbed conditions. Instead the clearcut buffer treatment demonstrates average annual water depths closer to the control treatment, excluding 2001, and differs the least significantly when considering the additional hydrologic variables.

Factors Influencing Hydrological Response of Buffer Treatments

The different hydrological responses seen between the buffer treatments, including changes in water depth and hydroperiod, can be explained by examining the changes to Equation 1. Since P is assumed to be a constant for all study areas and unaffected by the upland harvest, this variable can be eliminated as a possible reason behind the difference of hydrological responses between the buffer treatments. Similarly, Q is assumed to be 0 as these ponds are isolated systems with no established outlet for surface discharge and therefore can be eliminated. It is also assumed that loss of GW_o to regional groundwater systems remains constant for all study areas since upland harvest has no effect on hydraulic conductivity of subsurface soils, especially since harvest is conducted in the winter when soils are frozen.

Assuming that all other external variables are equal, including catchment area, landscape position, dominant vegetation, climate, and soils; the effect of upland harvest on seasonal pond hydrology is primarily due to changes in RO and ET. When considering the clearcut of all upland vegetation, it is plausible to expect changes in these variables. The absence of vegetation decreases interception and storage of precipitation and snow, allowing for increased levels of RO. Similarly, ET is reduced by the clearcut of upland vegetation. This increase in RO and decrease in ET explains why average annual water depths increased in all buffer treatments ponds following upland harvest.

As was previously discussed the clearcut treatment has a much higher annual water depth in 2001 immediately following upland harvest. Factors contributing to this response include the fact that upland harvest was done in the winter of 2000-2001 and allowed no opportunity for vegetative regrowth before spring snowmelt and precipitation, leaving primarily slash and exposed ground surface. This increased the RO to clearcut ponds due to reductions in interception and storage.

This was also the case for the buffer and partial buffer treatments, but due to remaining buffers around these ponds there was still the presence of established riparian vegetation in 2001. The presence of this riparian vegetation not only allowed for ET, but also aided in interception and storage of precipitation throughout the 2001 growing season. Furthermore, this riparian vegetation is likely to have reduced the soil frost depth under the partial and uncut buffer treatment ponds, thereby allowing for the process of infiltration to begin sooner. The complete absence of vegetation in the clearcut buffer treatment ponds immediately following harvest would have promoted deeper soil frost depths causing infiltration rates to be retarded longer into the 2001 growing season, thereby contributing to the overall increase in average annual water depth.

The decline in average annual water depth following 2001 in the clearcut buffer treatment ponds can be attributed to substantial increases in ET due to the subsequent re-growth of riparian vegetation, mainly aspen suckers, throughout the 2001 growing season. With the re-establishment of this dense riparian re-growth by the end of the 2001 growing season, ET rates for following years could exceed that of the established buffers Furthermore, the results that indicate that the clearcut ponds exhibit more dry days and longer dry periods than the partial and uncut buffer treatment ponds further supports this explanation. Due to the high density and rate of growth of this aspen re-growth surrounding the pond riparian area, rapid uptake of water by roots depletes soil moisture faster than the partial and uncut buffer ponds. This causes increased losses of water stored in the pond basin by lateral flow of GW_o to the pond edges because of the lower water potential created by the transpiring riparian roots. Furthermore, the subsequent riparian re-growth of aspen around clearcut ponds following the 2001 growing season also increases interception and storage capacity, thereby reducing RO inputs and resulting in lower average annual water depth.

The close relationship between the partial and uncut buffer treatment ponds is also a result of altering RO and ET rates. These two treatments responded very closes to each other when examining water depth and hydroperiod. Yet the partial buffer treatment consistently showed slightly greater depths of water in the ponds and longer duration of hydroperiod over that of the uncut buffer. This can be attributed to the fact that the riparian vegetation was thinned in the partial buffer treatment, but due to shading and crowding dynamics little to no aspen re-growth was realized in these buffers. This had the effect of reducing ever so slightly the interception, storage, and ET rates around these ponds than those of the uncut buffer. This explains the slight increase seen in average annual water depth and length of hydroperiod over that of the uncut buffer. Yet this thinning of the buffer did not result in substantial significant differences in water level and hydroperiod between the partial and uncut buffer ponds.

CONCLUSIONS

The objective of this study was to gain a better understanding of seasonal pond hydrology and determine what effect different types of buffer treatments have on hydrological variables following harvest of adjacent upland forest. By monitoring water levels in 16 seasonal ponds in North Central Minnesota, we were able to successfully distinguish differences in hydrological responses, including mean water depth and duration of hyrdroperiod, as a result of upland harvest and application of 4 different riparian buffer treatments. Running regression analysis and a t-test on pre-harvest and post-harvest relationships between buffer treatments and control ponds confirmed our first hypothesis, with water depth significantly increasing in all buffer treatment ponds for a period of at least 4 years following upland harvest. This response was not seen in the fifth year suggesting that water levels between buffer and control treatments ponds were beginning to re-establish to the pre-harvest relationship.

Examination of additional hydrologic variables by an ANOVA and comparing least square means between all treatments was successful at determining further differences between buffer treatment types. These results indicate that partial and uncut buffer treatments are closely related and show consistence similarities in hydrological responses, including being significantly wetter on an annual basis and having an overall greater average annual water depth than the control and clearcut treatments. On the other hand, responses seen in the clearcut treatment suggest it is more closely related to the control treatment. This includes average annual water depths closer to control treatment levels following 2001, as well as both the control and clearcut treatment being significantly drier on an annual basis than the partial and uncut treatments. Consequently, these finding caused for the rejection of our second hypothesis, instead suggesting that the clearcut buffer treatment results in water levels closer to control or undisturbed conditions rather than the hypothesized uncut buffer treatment.

Relationships among treatment types and responses in hydrological variables can be explained by examining the water budget for these seasonal ponds. The changes made to ET and RO as a result of treatment type and upland harvest are the primary factors affecting these hydrological responses. By altering riparian vegetation communities, this study suggests it is possible to manipulate the length of saturation and average depth of water following upland harvest based on the type of buffer left around the ponds. Such information is valuable to forest managers who may be concerned with providing a certain type of habitat in seasonal ponds following harvest of adjacent uplands.

Table 2.1). Treatment, ownership, and location of study ponds

Treatment	Location	Pond #	Latitude-Longitude	Ownership, Plat Location
Buffer	Willow River	WR1	46 55’ 48” N; 93 41’ 08” W	Potlach, Aitkin Co. Sec 6 T52N R26W
Partial		WR2	46 55’ 49” N; 93 41’ 02” W	Potlach, Aitkin Co. Sec 7 T52N R26W
Clearcut		WR3	46 55’ 37” N; 93 41’ 10” W	Potlach, Aitkin Co. Sec 7 T52N R26W
Control		WR4	46 55’ 32” N; 93 41’ 10” W	Potlach, Aitkin Co. Sec 7 T52N R26W
Partial		AL1	46 55’ 42” N; 93 46’ 54” W	Cass Co., Sec 24 T140N R25W
Clearcut	Ashebun Lake	AL2	46 55’ 40” N; 93 46’ 50” W	Cass Co., Sec 24 T140N R25W
Partial		AL3	46 55’ 29” N; 93 46’ 42” W	Cass Co., Sec 24 T140N R25W
Control		AL4	46 55’ 03” N; 93 46’ 44” W	Cass Co., Sec 25 T140N R25W
Partial		SL1	46 57’ 58” N; 93 46’ 27” W	Potlach, Aitkin Co. Sec 28 T52N R27W
Clearcut	Soo Line	SL2	46 57’ 57” N; 93 46’ 15” W	Potlach, Aitkin Co. Sec 28 T52N R27W
Partial		SL3	46 58’ 05” N; 93 46’ 21” W	Potlach, Aitkin Co. Sec 28 T52N R27W
Control		SL4	46 58’ 23” N; 93 46’ 41” W	Cass Co., Sec 1 T140N R25W
Buffer		DL1	46 51’ 07” N; 94 04’ 23” W	Cass Co., Sec 15 T139N R27W
Clearcut	Dog Lakes	DL2	46 50’ 42” N; 94 05’ 31” W	Cass Co., Sec 21 T139N R27W
Partial		DL3	46 50’ 07” N; 94 05’ 44” W	Cass Co., Sec 21 T139N R27W
Control		DL4	46 50’ 22” N; 94 05’ 10” W	Cass Co., Sec 21 T139N R27W

Table 2.2). Area of study ponds

Location	Pond #	Area (acres)	Area (m^2)	Area (ft^2)	Area (hectares)
Willow River	WR1	0.143	579	6232	0.058
	WR2	0.081	329	3541	0.033
	WR3	0.091	367	3950	0.037
	WR4	0.089	362	3897	0.036
Ashebun Lake	AL1	0.053	216	2325	0.021
	AL2	0.063	255	2745	0.025
	AL3	0.113	459	4941	0.046
	AL4	0.056	225	2422	0.023
Soo Line	SL1	0.099	400	4306	0.040
	SL2	0.206	832	8956	0.083
	SL3	0.060	241	2594	0.024
	SL4	0.130	528	5683	0.053
Dog Lakes	DL1	0.175	709	7632	0.071
	DL2	0.077	312	3358	0.031
	DL3	0.063	253	2723	0.026
	DL4	0.262	1060	11410	0.106

Table 2.3). Annual precipitation and departure from normal
*From University of Minnesota State Climatology Office

Year	Annual Precipitation for Study Area	Departure from Normal
2000	81 cm	5-10 cm above
2001	71-81 cm	5-10 cm above
2002	61-71 cm	-5 cm below
2003	51 cm	-25 cm below
2004	61-71 cm	-5 cm below
2005	79-84 cm	8-13 cm above

Table 2.4). Soil texture and hydraulic conductivity for Remer ponds

REMER PONDS			Textural Results			
Location	Horizon Depth (cm)	Texture	Sand	Silt	Clay	Hydraulic Conductivity (cm/hr)
Willow River						
Upland	0-10	loam	51.5	39.1	9.4	
	10-41	sandy loam	69	25.2	5.8	
	41-46	sandy loam	57.8	29.1	13.1	
	46-163	clay loam	37	31.1	31.9	
	163-178	clay loam	34.2	31.5	34.3	2.028
	178-193	sandy loam	65.8	24.3	9.9	
	193+	silty clay	3.7	46.6	49.7	
Pond	0-10	organic	LOI = 28.7%			
	10-18	silt loam	23.4	59.7	16.9	
	18-56	silt loam	30.3	61.3	8.4	1.33
	56-91	silt loam	31.9	52.1	15.9	0.193
	91+	sandy loam	78.9	11.7	9.4	
Soo Line						
Upland	0-13	loam	47.2	40.3	12.6	
	13-58	silt loam	23	56.3	20.7	
	58-119	sand	94.6	1	4.4	
	119-165	loamy sand	85	3.2	11.8	
	165+	clay loam	35.5	34.7	29.8	
Pond	0-13	organic	LOI = 30.4%			
	13-23	silt loam	22.7	64.2	13.1	
	23-58	silt loam	25.2	58.9	15.8	0.38
	58-119	loam	15.7	55.4	29	0.014
	119+	loam	49.5	30.4	20.2	
Ashebun Lake						
Upland	0-8	silt loam	33.9	59.9	6.1	
	8-13	silt loam	28.8	63.4	7.9	
	13-43	silt loam	33	60.4	6.7	
	43-79	clay loam	29.1	38.7	32.2	
	79+	loam	41.4	31.8	26.9	
Pond	0-18	organic	LOI = 26.6%			
	18-69	silt loam	21.4	68.4	10.2	0.304
	69-127	silt loam	23.1	61.2	15.7	0.042
	127+	clay loam	28.3	43	28.7	
Dog Lakes						
Upland	0-8	organic	LOI = 25.1%			
	8-13	sandy loam	63.2	31.5	5.3	
	13-25	sandy loam	63.6	28.8	7.6	
	25-61	loamy sand	77.6	16.4	6.1	
	61-91	loamy sand	85.3	9.8	4.8	
	91+	sandy loam	76.6	13.5	9.9	
Pond	0-18	organic	LOI = 20.4%			
	18-38	loam	45	46.7	8.3	
	38-69	silt loam	25.6	54.9	19.5	0.002
	69+	sandy loam	67.4	17.5	15.1	0.756

Table 2.5). Regression analysis of annual mean water level

Regression Analysis of Annual Mean Water Level						
Treatment	Year	R^2	Estimated difference from mean	Standard error	t value	p value
Uncut	2001	0.9474	0.2308	0.0894	2.5800	0.0109
	2002	0.9305	0.5996	0.1066	5.6300	<0.0001
	2003	0.9342	0.8143	0.1099	7.4100	<0.0001
	2004	0.9098	0.7102	0.1255	5.6600	<0.0001
	2005	0.9713	-0.3269	0.0839	-0.3900	0.6973
Partial	2001	0.9554	0.2505	0.1206	2.0800	0.0397
	2002	0.8766	0.7066	0.1533	4.6100	<0.0001
	2003	0.8733	0.9073	0.1581	5.7400	<0.0001
	2004	0.7785	0.7970	0.1805	4.4200	<0.0001
	2005	0.9640	0.2164	0.1285	1.6800	0.0945
Clearcut	2001	0.9592	0.3302	0.1209	2.7300	0.0072
	2002	0.8187	0.5318	0.1537	3.4600	0.0007
	2003	0.9337	0.6581	0.1585	4.1500	<0.0001
	2004	0.8259	0.3709	0.1809	2.0500	0.0423
	2005	0.9456	0.0829	0.1288	0.6400	0.5211

Table 2.6). Maximum Depth: ANOVA and least square means

MD:	R^2=0.7797	mean=1.659	Pr>F=0.0590	
Treatment	Estimated Difference from Mean (cm)	Standard Error (cm)	t Value	p Value
Uncut	4.95	3.46	1.43	0.1725
Clearcut	10.49	3.46	3.04	0.0084
Partial	5.79	3.46	1.68	0.1146

LS Mean				
Treatment	Uncut	Clearcut	Partial	Control
Uncut		0.1299	0.8116	0.1725
Clearcut	0.1299		0.1940	0.0084
Partial	0.8116	0.1940		0.1146
Control	0.1725	0.0084	0.1146	

Table 2.7). Average Depth: ANOVA and least square means

AD:	R^2=0.8739	mean=1.1926	Pr>F=.0248	
Treatment	Estimated Difference from Mean (cm)	Standard Error (cm)	t Value	p Value
Uncut	3.34	2.06	1.62	0.1251
Clearcut	7.07	2.06	3.44	0.0036
Partial	4.80	2.06	2.34	0.0338

LS Mean				
Treatment	Uncut	Clearcut	Partial	Control
Uncut		0.0893	0.4876	0.1251
Clearcut	0.0893		0.2866	0.0036
Partial	0.4876	0.2866		0.0338
Control	0.1251	0.0036	0.0338	

Table 2.8). Number of wet days: ANOVA and least square means

NOWD:	R²=0.8957	mean=101.5729	Pr>F=0.0058	
Treatment	Estimated Difference from Mean (days)	Standard Error	t Value	p Value
Uncut	13.13	4.59	2.86	0.0119
Clearcut	1.46	4.59	0.32	0.7550
Partial	16.04	4.59	3.50	0.0032

LS Mean				
Treatment	Uncut	Clearcut	Partial	Control
Uncut		0.0225	0.5345	0.0119
Clearcut	0.0225		0.0062	0.7550
Partial	0.5345	0.0062		0.0032
Control	0.0119	0.7550	0.0032	

Table 2.9). Longest wet period: ANOVA and least square means

LWP:	R²=0.9124	mean=91.5833	Pr>F=0.0058	
Treatment	Estimated Difference from Mean (days)	Standard Error	t Value	p Value
Uncut	13.42	4.01	3.35	0.0044
Clearcut	3.79	4.01	0.95	0.3591
Partial	14.29	4.01	3.57	0.0028

LS Mean				
Treatment	Uncut	Clearcut	Partial	Control
Uncut		0.0297	0.8301	0.0044
Clearcut	0.0297		0.0193	0.3591
Partial	0.8301	0.0193		0.0028
Control	0.0044	0.3591	0.0028	

Table 2.10). Consecutive wet days: ANOVA and least square means

CONWET:	R^2=0.8921	mean=91.0729	Pr>F=0.0082	
Treatment	Estimated Difference from Mean (days)	Standard Error	t Value	p Value
Uncut	15.46	4.66	3.32	0.0047
Clearcut	5.83	4.66	1.25	0.2298
Partial	16.33	4.66	3.50	0.0032

LS Mean				
Treatment	Uncut	Clearcut	Partial	Control
Uncut		0.0566	0.8536	0.0047
Clearcut	0.0566		0.0397	0.2298
Partial	0.8536	0.0397		0.0032
Control	0.0047	0.2298	0.0032	

Table 2.11). Number of Dry Days: ANOVA and least square means

NODD:	R^2=0.9571	mean=68.8333	Pr>F=0.0070	
Treatment	Estimated Difference from Mean (days)	Standard Error	t Value	p Value
Uncut	-13.13	4.58	-2.87	0.0117
Clearcut	-2.33	4.58	-0.51	0.6175
Partial	-16.04	4.58	-3.51	0.0032

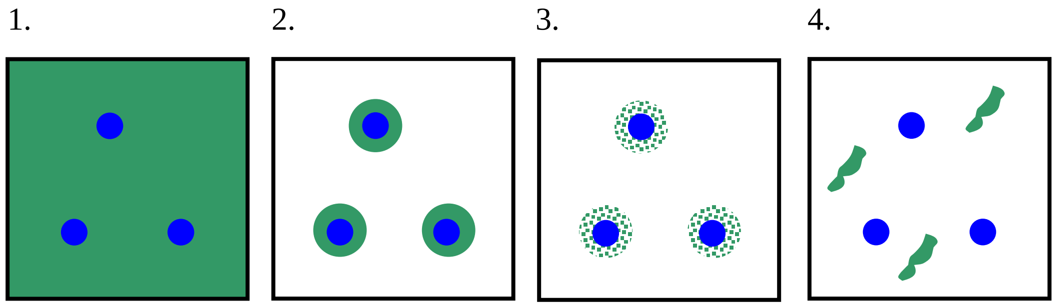
LS Mean				
Treatment	Uncut	Clearcut	Partial	Control
Uncut		0.0323	0.5335	0.0117
Clearcut	0.0323		0.0090	0.6175
Partial	0.5335	0.0090		0.0032
Control	0.0117	0.6175	0.0032	

Table 2.12). Longest Dry Period: ANOVA and least square means

LDP:	R²=0.9569	mean=63.2188	Pr>F=0.0318	
Treatment	Estimated Difference from Mean (days)	Standard Error	t Value	p Value
Uncut	-8.75	4.52	-1.93	0.0721
Clearcut	2.92	4.52	0.64	0.5288
Partial	-9.63	4.52	-2.13	0.0503

LS Mean				
Treatment	Uncut	Clearcut	Partial	Control
Uncut		0.0209	0.8492	0.0721
Clearcut	0.0209		0.0142	0.5288
Partial	0.8492	0.0142		0.0503
Control	0.0721	0.5288	0.0503	

Figure 2.1). Depiction of buffer treatments applied to study ponds



1) Uncut control; 2) Upland clearcut, uncut buffer around pond; 3) Upland clearcut, partially cut buffer around pond; and 4) Upland clearcut leaving residual trees in the upland and no buffer around pond.

Figure 2.2). Generalized depiction of a water budget for a perched system
*Q is excluded as it is assumed to be 0

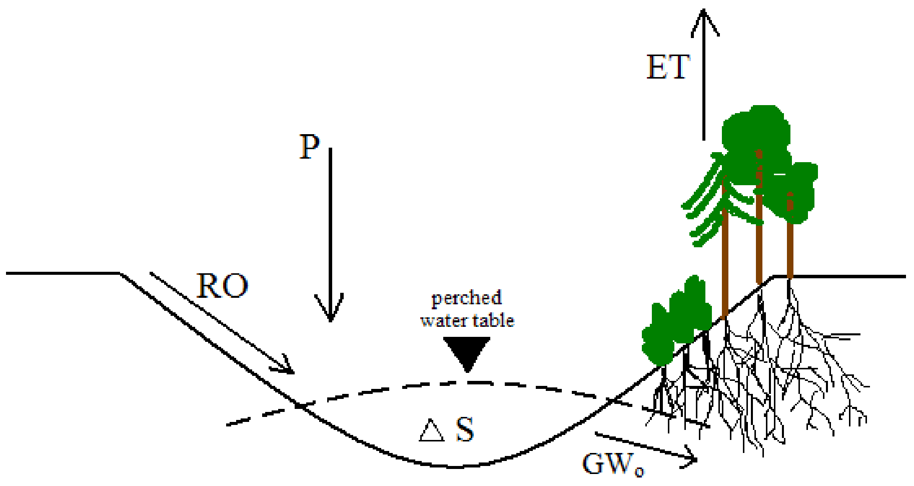


Figure 2.3). Precipitation measurements from Soo Line study area

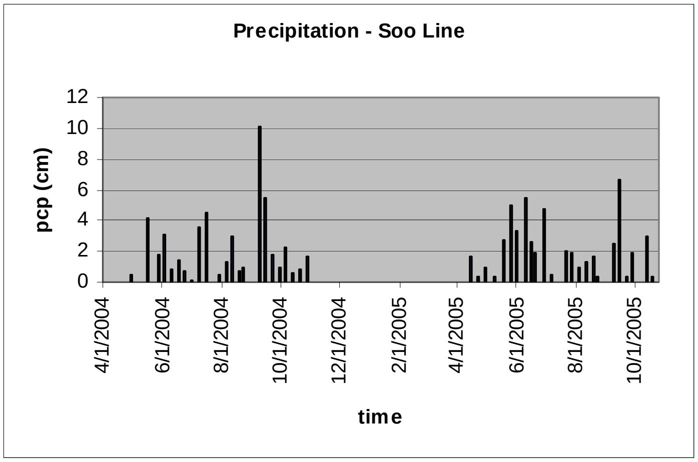


Figure 2.4). Well measurements from Soo Line study area

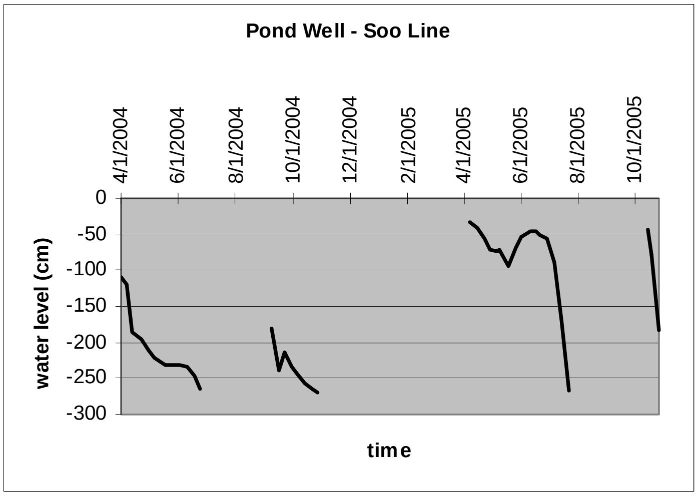


Figure 2.5). Piezometer measurements from Soo Line study area

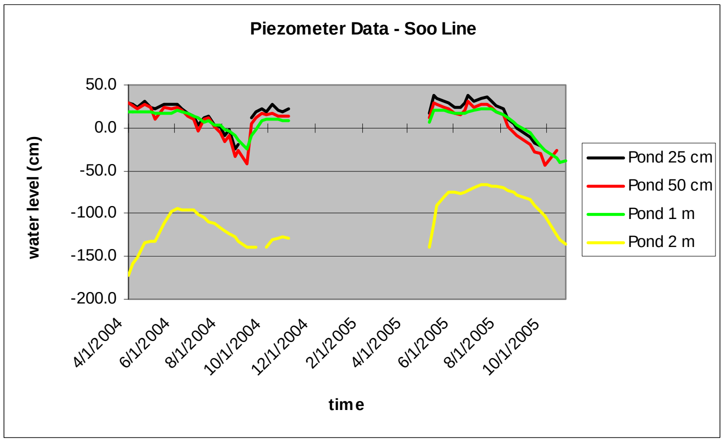


Figure 2.6). Maximum Depth

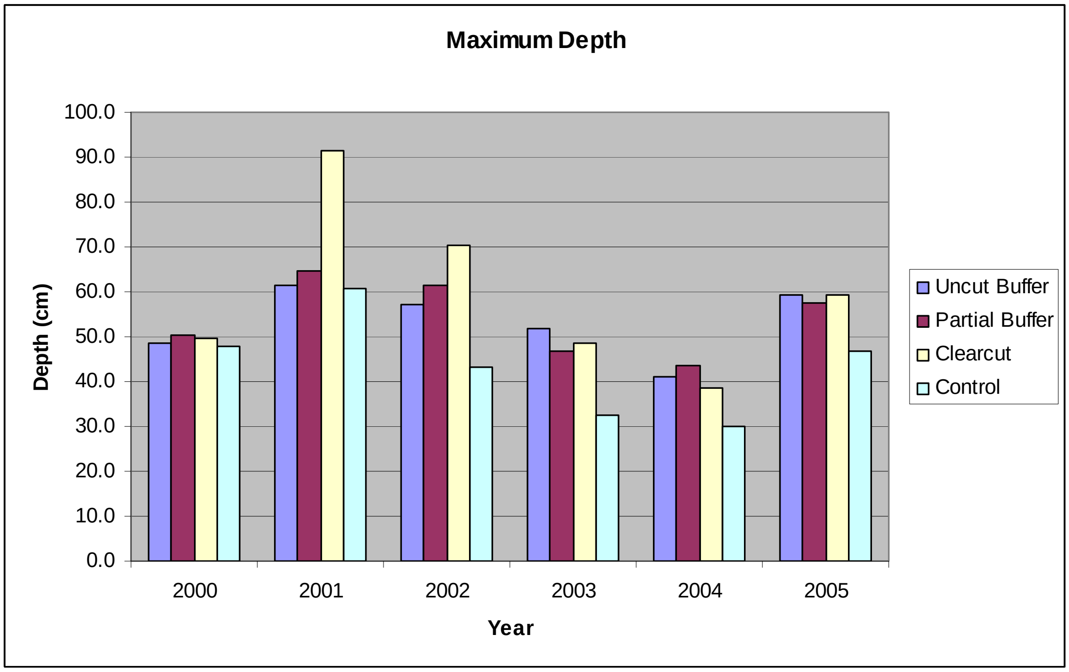


Figure 2.7). Average Depth

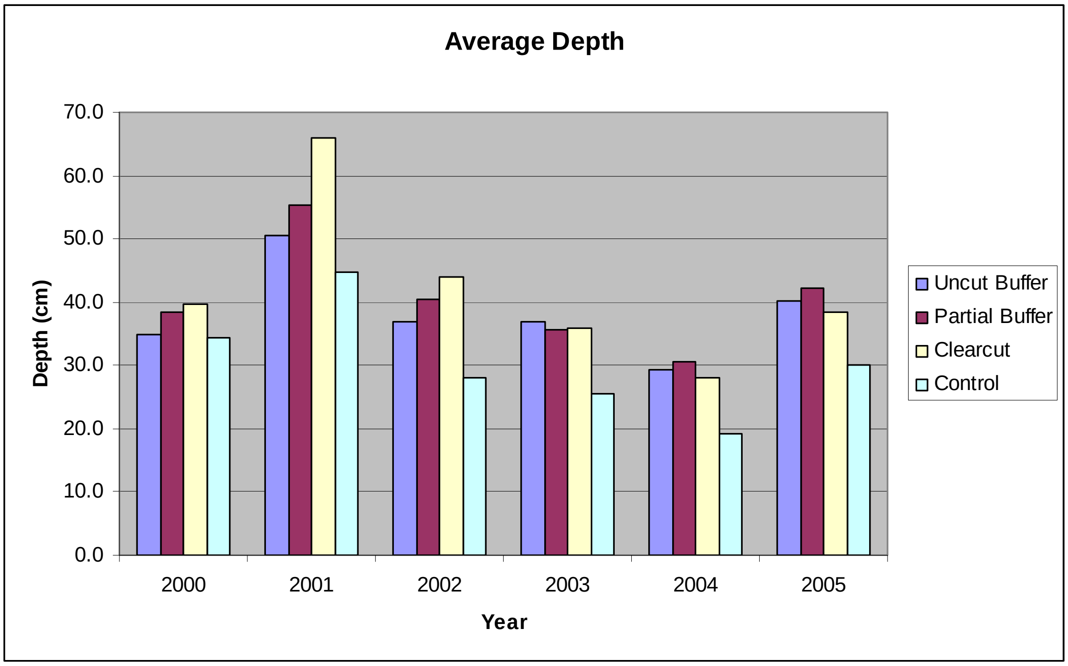


Figure 2.8). Number of Wet Days

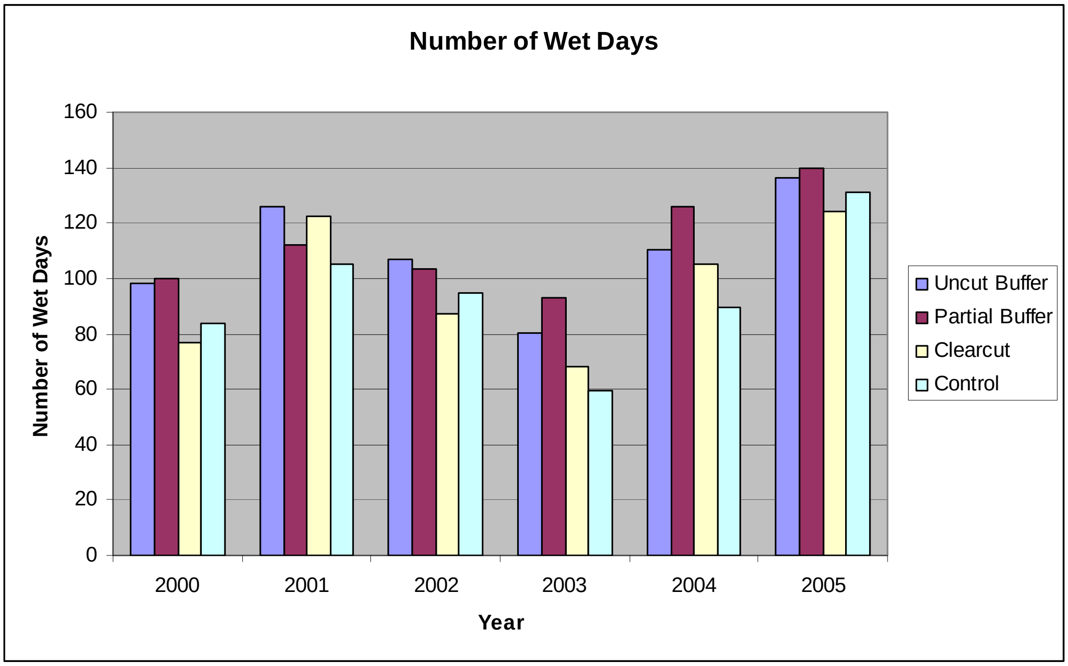


Figure 2.9). Longest Wet Period

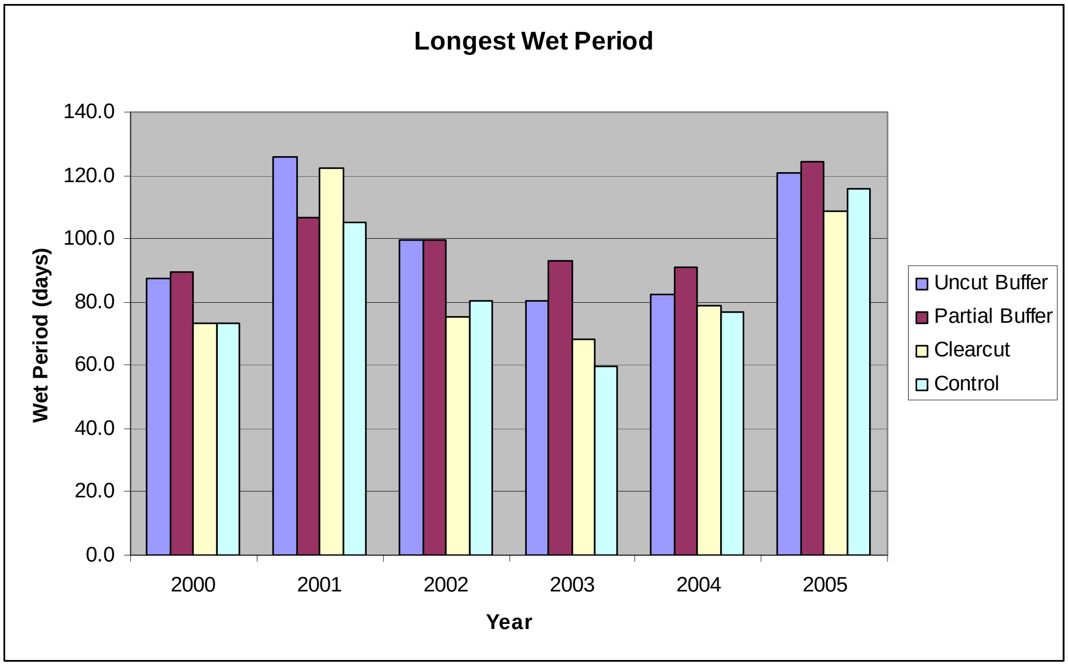


Figure 2.10). Consecutive Wet Days

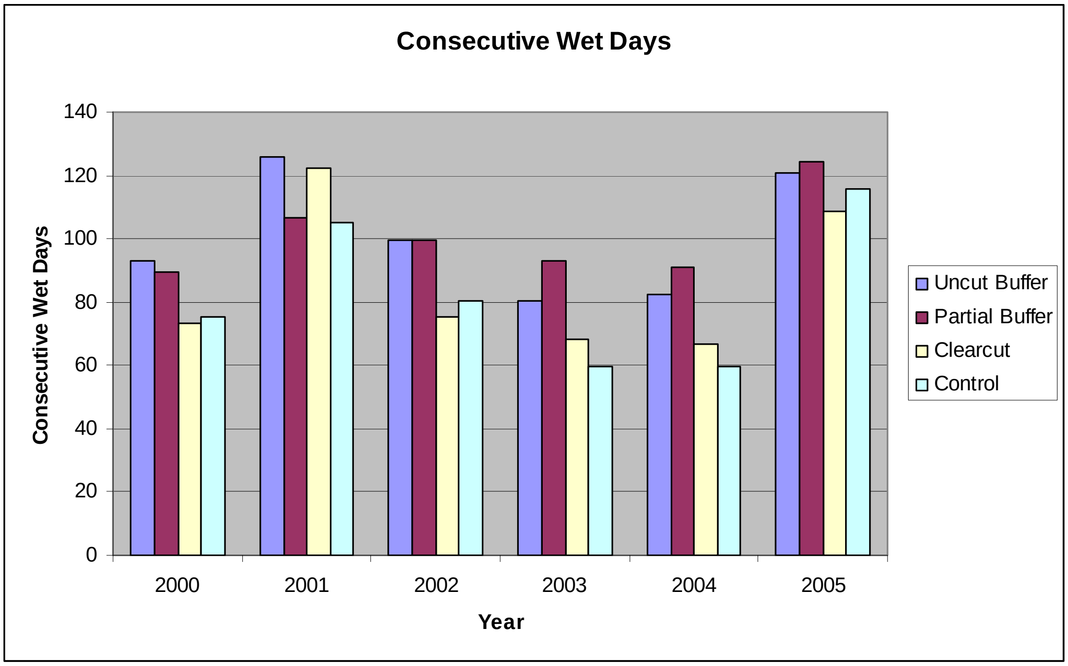


Figure 2.11). Number of Dry Days

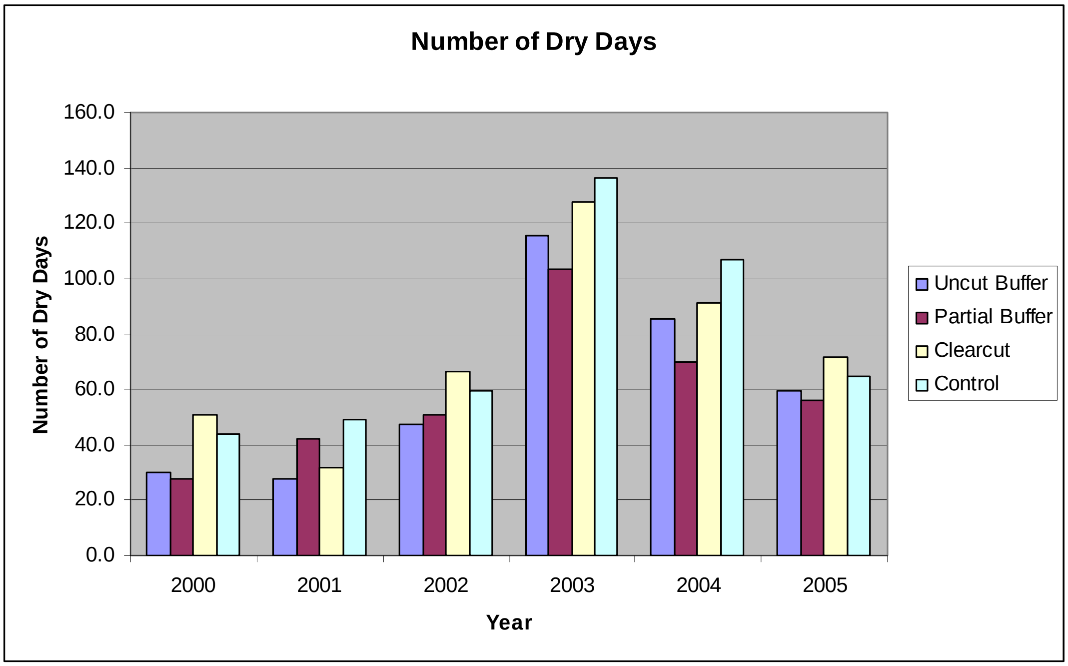
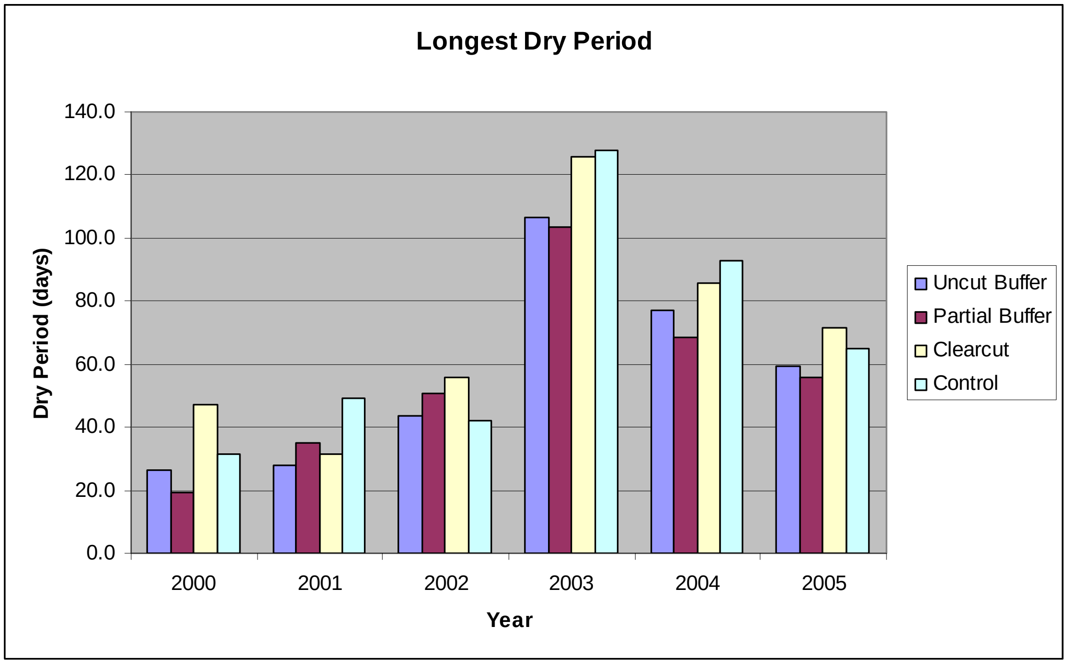


Figure 2.12). Longest Dry Period



Chapter 3 Characterization of Landscape Position and Soil Morphology Associated with Seasonal Ponds Hydrology and Formation

OVERVIEW

Relatively little is known regarding how site specific characteristics and soil morphological processes influence the hydrology and formation of seasonal ponds. The following study was initiated to better characterize the morphology of soils found under seasonal ponds, as well as to examine the relationship pond elevation has on hydrology. Soil morphological features, including clay lenses and lithologic discontinuity, were examined to determine if they exhibit a direct influence on seasonal pond formation. Hydrologic characteristics were also compared to elevation of seasonal ponds to draw any correlation among the two. Experimental units were established in the summer of 2004 in north central Minnesota with 9 seasonal ponds selected for study. Experimental units were instrumented with rain gauges and study ponds with staff gauges, piezometer nests, and shallow groundwater monitoring wells. Measurements were taken from April to October to monitor surface and subsurface hydrology. Additional site specific characteristics were also measured including soil texture, hydraulic conductivity, and pond elevation. Analysis of percent annual inundation and pond elevation on the landscape suggests that localized variability in topography and basin characteristics limit the ability to draw direct correlations between these two. Textural analysis of soils verified the presence of clay lenses, defined as Bt horizons, and lithologic discontinuity in soils under pond basins and surrounding uplands. Hydraulic conductivity tests of soils within pond basins further supported evidence that suggests seasonal pond formation is directly related to the formation of Bt horizons in soils found under ponds. The formation and occurrence of seasonal ponds across the landscape was found to be a result of both geogenic and pedogenic processes that result in slowing the downward infiltration of water, and causing the formation of standing water in localized depressions.

INTRODUCTION

The abundance of seasonal ponds across the north central region of Minnesota is thought to be related to the topography and land formations left behind as a result of multiple glaciations combined with the excess of hydrological inputs over that of outputs. Although seasonal ponds are found in depressional basins across the landscape, the mere presence of a depression does not guarantee it to be a seasonal pond. Site specific characteristics, including topography and soil morphology play an integral role in determining the existence of a seasonal pond on the landscape.

Yet, relatively little is known regarding how site characteristics and soil morphological processes influence the formation of seasonal ponds. Additionally, a better understanding of the influence of geogenic versus pedogenic processes on seasonal pond formation would aid in our understand why seasonal ponds form where they do.

Therefore, a study was initiated in the summer of 2004 near Grand Rapids, MN to investigate the relationship of site specific characteristics and soil morphology to seasonal pond formation. The objectives of this research were to examine the relationship between relative elevation and hydrology of ponds and to gain a better understanding of the processes of soil morphology and its effect on pond formation. In order to meet these objectives the following hypotheses were tested: (i) as elevations of ponds decrease on the landscape the percentage of annual inundation will increase due to the associated increase in upland catchment area contributing to the hydrological inputs to the pond; and (ii) the presence of a seasonal pond in a forested, upland, palustrine system is a result of clay lenses or lithologic discontinuity formed in a soil associated with a depression, thus slowing the downward infiltration of water, and causing the formation of standing water.

MATERIALS AND METHODS

Site Description

Beginning in 2004, study sites were established in north central Minnesota located along the eastern edge of Cass County and the western edge of Aitkin County (Appendix A: Figure A) The study consisted of 5 experimental units (Flow Through, Willow River, Soo Line, Ashebun Lake, and Dog Lakes) with a total of 9 ponds selected for study; 6 located on Potlatch Corporation land in Aitkin County and the remaining 3 located on Cass County land (Table 3.1). The study areas are characterized by soil parent materials deposited during the Wisconsinan-age glaciations that saw the multiple advance and retreat of up to 4 separate ice lobes; the Wadena Lobe, the Rainy Lobe, the Superior Lobe, and the Des Moines Lobe which also included the St. Louis Sublobe.

Due to these multiple glaciations, Cass and Aitkin County are composed of a variety of different landforms such as drumlins, lake plains, moraines, and outwash plains. Generally, the study areas are located on gently rolling ground moraine (Hobbs & Goebel, 1982). This represents relatively young, low-relief landscapes, where drainage channels have not completely formed and surface drainage is impeded by numerous closed depressions. Soil parent material of the study areas include loess, glaciolacustrine deposits, till, and glacial outwash. Typically, a layer of loess approximately 30-cm thick overlays outwash material mixed with till and/or loess of variable thickness at all study area. This in turn is generally followed by a layer of glaciolacustrine deposits at study areas Flow Through, Willow River, Soo Line and Ashebun Lake ranging in thickness from 40-cm to 127-cm. Dog Lakes lacks these glaciolacustrine deposits and instead dense till continues to depth.

Forested lands comprise over two-thirds of the area in each county. Forestry and forest products are among the counties leading industries, with conifers and aspen representing the majority of commercial forest resources. Upland forests of the study areas are dominated by aspen (*Populus* spp.) with lesser amounts of northern hardwoods: red oak (*Quercus rubra*); maple (*Acer* spp.); and/or basswood (*Tilia americana*). Mean annual precipitation is 71-cm and average snowfall is 137-cm (Nyberg, 1999; Richardson, 1997). Precipitation is distributed fairly evenly throughout the growing season, but generally highest in June and July. Mean annual air temperature is 4.8^{o} C with an average high temperature of 10.6^{o}C and low of -1.7^{o}C (Nyberg, 1999; Richardson, 1997). The length of the growing season based on a daily minimum temperature $>0.0^{o}$C is approximately 110 days (Nyberg, 1999; Richardson, 1997).

Experimental Design

In order to study the morphology of soils located in and around seasonal ponds, 9 ponds were chosen based on the following criteria: 1) ponds and surrounding forests showed no evidence of recent disturbance; 2) pond area was >0.02 but <0.5 ha; and 3) ponds had mineral or muck substrates, as opposed to peat. Five of the 9 ponds were selected from a simultaneous study investigating the effect of riparian buffers on pond hydrology. The remaining 4 ponds were selected based on site-specific characteristics that indicated the possibility of representing a flow through system. This flow through system of ponds was composed of 5 ponds in total, the fifth pond coming from the ponds selected from the riparian buffer study.

Instrumentation and Sampling

Experimental units were instrumented with standard all-weather rain gauges to record precipitation. The rain gauge was attached to a metal post and placed in a clearing resulting from upland clearcut where rainfall catch would not be affected. Over time, as trees or vegetation grew and encroached on the gauge they were removed so that the clearing for the gauge was defined by a 30^o angle from the top of the gauge to the closest tree top so rainfall catch would not be affected (Brooks et al., 2003).

Duplicate metal staff gauges were used to record water depths and subsequent hydroperiods. These were installed in ponds assigned a treatment by driving a metal post approximately 1 meter into the ground. The gauge was then bolted onto the post with the base adjacent to the mineral soil surface of the pond. For each instrumented pond a benchmark was established by driving a metal spike into the base of a tree next to the pond. Using a laser level and the benchmark as a reference the gauges were placed at the lowest points in the pond. After installation of the gauges the initial elevation difference between the benchmark and the base of the gauge was recorded. This elevation difference was checked annually with a laser level after freeze/thaw activity ceased in the spring. It was found that changes in gauge elevation among years were minor based on the reference point.

Elevation surveys were conducted on the area surrounding the 5 ponds thought to represent a flow through system in the fall of 2004. Relative elevation was determined corresponding to the location of all well/piezometer nests throughout the study area, using the lowest pond on the landscape as the baseline or 0 elevation.

Soil profiles were described for all 9 study ponds to the depth of 185-cm following procedures specified in *Soil Survey Manual* (Soil Survey Division Staff, 1993). Morphological properties were described for each profile including horizon color and thickness, texture, structure, and presence of mottles. Soil pits were excavated in the pond basin and upland where profiles were described and sampled by horizon. These samples were sealed in paper bags and sent to the University of Minnesota Research Analytical Laboratory where textural analysis was performed on air-dried sieved samples using the hydrometer method (Miller et al., 1997). Hydraulic conductivity was measured as a result of the riparian buffer study using a compact constant head permeameter (Ksat Inc. Amoozometer).

Piezometers and shallow wells were installed along transects running from the pond basin to the upland to monitor water table depth and sub-surface hydrology (Figure 3.1). Transects originated at the pond basin and ran parallel to the hydrologic gradient, terminating at the upper boundary of the immediate catchment area for each individual pond based on surface topography. Additional piezometers and wells were installed between 2 of the 5 ponds thought to represent a flow through system in order to monitor any subsurface flow of waters between ponds.

Along each transect 3 sets of well/piezometer nests were installed. This represented a nest at the catchment boundary in the upland, followed by a second nest in the wetland-upland boundary and a third nest in the pond basin. Length of transects and spacing of the well/piezometer nests varied depending on topography of specific ponds. Overall, transects ranged between 50 and 80 meters. Piezometers were constructed of 1.9-cm polyvinyl chloride (PVC) pipe with 0.025-cm slotted PVC screen attached to the bottom. Wells were constructed of 5-cm PVC with 6-mm holes drilled throughout the pipe at 5-cm intervals, leaving 30-cm intact at the top to couple a riser onto once installed in the field. After wells were drilled, geofabric was wrapped and zip-tied onto the pipe.

Piezometers and wells were built and installed according to Corps of Engineers guidelines (Appendix A: Figure B) (Sprecher, 2000). Piezometer nests consisted of 4 piezometers installed at the interface of textural changes and/or areas of abundant mottling identified from previous soil profile descriptions and site specific sampling. Generally, these depths were 200, 100, 50, and 25-cm. With each piezometer nest a shallow groundwater monitoring well was installed.

Soil temperature probes were installed at depths of 10, 25, 50, and 100 cm in two upland and pond locations on the study area thought to represent a flow through system (Table 3.3).

Collection of rain gauge, staff gauge, and soil temperature data was done weekly to bi-weekly, recording all 9 ponds within 2 days for each cycle. Rain gauges were read to within 0.03 cm and staff gauges to within 0.3 cm. Soil temperatures were read to within one-tenth of a degree Celsius. Piezometer and well data was also collected weekly to bi-weekly using an electronic water level meter (Solinst Model 101-Mini) and read to within 0.03 cm. The sampling period lasted throughout the ice-free season, generally April 1 to October 31.

Pond surface area was determined by using the presence of high-water marks such as sediment-coated or recently saturated leaf litter to establish pond margins. The margin-to-margin pond length was measured in 2 perpendicular dimensions. These dimensions were then used to estimate the surface area using the formula for an ellipse (Table 3.2).

Data Analysis

Staff gauge data was used to record water depth and determine hydroperiods from April 1 to October 31 for the 9 study ponds. Staff gauge measurements for selected ponds were calculated as a percentage of annual inundation and a yearly mean water depth. Additional hydrologic data included piezometer and well data. These hydrological variables were then related to factors including soil texture, hydraulic conductivity, and pond elevation in order to gain a better understanding of soil morphology and its influence on the hydrology and formation of seasonal ponds. Specifically, percentage of annual inundation and mean annual water depth was compared between the Flow Through ponds to determine if elevation has an influence on hydrology. Additionally, soil texture was analyzed along with hydraulic conductivity and piezometer and well data to determine the presence of a clay lenses, defined as the formation of a Bt horizon, and/or lithologic discontinuity.

RESULTS AND DISCUSSION

Site Characteristics

Soils

Generally, soils from the Flow Through, Willow River, Soo Line, and Ashebun Lakes experimental unit are more similar in morphology to each other than those soils found in the Dog Lakes experimental unit. However, soils found throughout all experimental units are similar in the characteristic that they cause perching of hydrological inputs such as precipitation and snowmelt in localized depressions.

All soils representative of the 5 experimental units are generally composed of till as their parent material and associated with moraines are there landform. The following soil series were identified for each experimental unit (Richardson, 1997).

- Dog Lakes experimental unit is represented by the Wabedo Series. These soils are classified as coarse-loamy, mixed, superactive, frigid Aquic Dystric Eutrudepts. These soils exhibit a drainage class of somewhat poorly drained, with moderately rapid permeability in the upper part followed by slow; with very slow permeability associated with dense till in the lower part of the profile.

- Flow Through and Willow River experimental units are represented by the Alstad Series. These soils are classified as fine-loamy, mixed, superactive, frigid Aquic Glossudalfs. These soils exhibit a drainage class of somewhat poorly drained, with moderate permeability in the upper part followed by moderately slow in the lower part of the profile.

- Soo Line and Ashebun Lakes experimental units are represented by the Stuntz Series. These soils are classified as fine-loamy, mixed, superactive, frigid Aeric Glossaqualfs. These soils exhibit a drainage class of somewhat poorly drained, with moderately rapid to moderately slow permeability in the upper part followed by moderately slow in the lower part of the profile.

Influence of Pond Elevation on Water Depth

Five ponds were originally selected based on site specific characteristics, including landscape position, size, shape, and depth; that suggested their relationship to each other may represent a flow through system. The relative elevation of these ponds was surveyed to determine if differences in elevation on the landscape have an influence on pond hydrology, specifically mean annual water depth and percent inundation (Figure 3.2 & Figure 3.3). The results of the elevation survey are shown in Figure 3.4, with pond FT 5 representing the baseline elevation. Because these 5 ponds are situated so closely on the landscape, factors such as temperature, precipitation, and vegetation were assumed to be constant among all ponds.

When comparing percent inundation and mean annual water depth to elevation of each Flow Through pond it was found that generally ponds located lower on the landscape exhibit a higher percentage of annual inundation and higher water depths, while those with higher elevations show the opposite. This can be explained by considering the relationship of catchment area to that of elevation. Generally, catchment area will increase as the relative elevation of a pond on a uniformly sloping landscape decreases. By increasing the amount of catchment area contributing to the pond a greater abundance of water will collect in that pond.

However, when examining the relationship of water depth and elevation more closely, it is apparent that there are exceptions to the relationship between catchment area and elevation. Pond FT 1 is located lower on the landscape than ponds FT 2, 3, and 4 yet is inundated less annually. Similarly, pond FT 4 is the highest pond of the study group yet has greater water depths than that of pond FT 2.

Both of these cases are a result of localized topography that influences the size of each ponds catchment area since these ponds are not located on a uniformly sloping landscape. Because of these differences in local topography, a direct relationship of pond elevation and hydrological variables such as percent annual inundation and mean annual water depth is not possible to predict. Site specific characteristics related to topography must be examined to determine the relative amount of catchment area for each pond, as well as basin characteristics such as size and depth. Additionally, pond interaction with groundwater inputs must be considered as the elevation of ponds decreases on the landscape. Furthermore, slight variation in soil morphology associated with these ponds can have an effect on hydrology and the ability of a pond to retain water.

Influence of Soil Morphology on Seasonal Pond Formation

By examining soil morphological features among the 10 ponds across the 5 experimental units it was possible to gain a better understanding of how seasonal ponds formed on the landscape. Although there was variability seen in soil profiles among and within the experimental units, an attempt was made to distinguish a common soil characteristic that can explain the formation of seasonal ponds within localized depressions on the landscape. Specifically, the presence of a lithologic discontinuity and/or clay lenses, defined as the formation of a Bt horizon, was investigated to determine if a relationship exists between the former or latter and seasonal pond formation. Furthermore, by distinguishing between the presence of a lithologic discontinuity or Bt horizon it is possible to determine if geogenic or pedogenic processes influenced the formation of seasonal ponds.

The presence of a lithologic discontinuity or Bt horizon within the soil profile results in a significant textural change from one horizon to the next. This abrupt change in texture has the effect of slowing the downward infiltration of waters. For both a lithologic discontinuity and Bt horizon, downward infiltration of water is retarded at the interface of the discontinuity or Bt horizon until matric and gravitational forces within the soil are overcome. A Bt horizon, by definition, involves the concentration of clay particles within a horizon. The concentration of these clay particles not only results in a textural change, but can fill in and seal shut soil pores creating an impermeable barrier. Similarly, if the discontinuity involves a clay rich soil this could create an aquitard and severely limit the infiltration of water.

Piezometer and well data collected verified the presence of a perched water table in the study ponds. A representative sample of this data taken from the Soo Line study area is illustrated in Figures 3.5, 3.6, and 3.7. Furthermore, soil textural analysis was performed for profiles representing pond and upland soils surrounding ponds (Table 3.4 & 3.5). The results of these textural analyses confirmed the presence of both lithologic discontinuity and Bt horizons in soils associated with seasonal ponds.

Bt horizons were found in soils beneath ponds in the Willow River, Soo Line, Ashebun Lake, and Dog Lakes experimental units. To determine if the presence of these Bt horizons does in fact slow the infiltration of surface waters, thereby creating a perched water table, hydraulic conductivity measurements were performed for ponds in these study areas. The results of these tests show a significant decrease in the rate at which water infiltrates downward (Table 3.4).

When texture of upland soils surrounding ponds was examined, both Bt horizons and lithologic discontinuity were found in the majority of the experimental units. The presence of either a Bt horizon and/or a lithologic discontinuity in the uplands will result in impeding downward infiltration of hydrological inputs such as snowmelt and rainfall. This water is held up on top of the Bt horizon and/or lithologic discontinuity and is subsequently transported laterally down gradient where it collects in localized depressions. Therefore, these results suggest that hydrology of seasonal ponds is directly influenced by the presence of Bt horizons and/or lithologic discontinuity not only under ponds, but in the uplands as well.

CONCLUSIONS

The objectives of this study were to better characterize the soils associated with the formation and occurrence of seasonal ponds on the landscape and to investigate the relationship between pond elevation and hydrology. By monitoring hydrology in 5 seasonal ponds in north central Minnesota, as well as performing site specific analysis of pond elevation, we were able to reject our first hypothesis that stated as elevations of ponds decrease on the landscape the percentage of annual inundation will increase.

Alternately, by analyzing texture and hydraulic conductivity of soils we were able to confirm our second hypothesis, finding the presence of lithologic discontinuity and Bt horizon formation in soils associated with pond basins and uplands catchment areas.

The fact that pond water depths and the percentage of time inundated are not directly related to a ponds elevation on the landscape was found to be a result of site specific variables. These include differences in local topography that effect catchment areas, differences in pond size and depth, as well as variations in soil properties that have an influence on the permeability of soils beneath ponds. These upland catchment areas were found to have a direct impact on pond hydrology, due to the presence of lithologic discontinuity and/or Bt horizons. Water is restricted from infiltrating and is transported via subsurface lateral flow to pond basins. Because inherent variability across the landscape, local differences in topography affecting pond catchment area will determine relative inputs of hydrology.

Bt horizons formed in soils under pond basins were shown to significantly decrease infiltration rates. This evidence would suggest that the formation of seasonal ponds on the landscape is the result of a pedogenic process. However, this is not completely accurate as both pedogenic and geogenic processes contribute to seasonal pond formation on the landscape. It has been shown that it is a result of geogenic processes, such as the overall topography of the landscape and the formation of lithologic discontinuity that act to restrict downward infiltration, combined with pedogenic processes, including the formation of Bt horizons in localized depressions, that cause the formation of seasonal ponds across the landscape.

Table 3.1) Ownership and location of study ponds

Location	Pond #	Latitude-Longitude	Ownership, Plat Location
Flow Through	FT 1-5	46 55’ 48” N; 93 41’ 08” W	Potlach, Aitkin Co. Sec 6 T52N R26W
Willow River	WR4	46 55’ 32” N; 93 41’ 10” W	Potlach, Aitkin Co. Sec 7 T52N R26W
Ashebun Lake	AL4	46 55’ 03” N; 93 46’ 44” W	Cass Co., Sec 25 T140N R25W
Soo Line	SL4	46 58’ 23” N; 93 46’ 41” W	Cass Co., Sec 1 T140N R25W
Dog Lakes	DL4	46 50’ 22” N; 94 05’ 10” W	Cass Co., Sec 21 T139N R27W

Table 3.2) Area of study ponds

Location	Pond #	Area (acres)	Area (m^2)	Area (ft^2)	Area (hectares)
Flow Through	1	0.139	563	6075	0.056
	2	0.140	567	6126	0.057
	3	0.140	567	6078	0.057
	4	0.321	1299	13964	0.130
	5	0.379	1534	16507	0.153
Ashebun Lake	AL4	0.056	225	2422	0.023
Soo Line	SL4	0.130	528	5683	0.053
Dog Lakes	DL4	0.262	1060	11410	0.106

Table 3.3). Soil temperature readings for Flow Through study area

Average Flow Through Soil Temperatures (ºC)					
Date	Depth (cm)	#1 Pond	#1 Upland	#5 Pond	#5 Upland
January-05	10	7.7	7.7	7.9	7.9
	25	7.9	7.9	8.4	8.4
	50	8.6	8.6	8.9	8.9
	100	9.0	9.0	9.8	9.5
February-05	10	4.2	4.1	5.7	5.6
	25	4.8	4.7	6.7	6.7
	50	6.1	6.1	7.6	7.6
	100	7.8	7.8	8.6	8.5
March-05	10	0.3	0.2	1.5	1.7
	25	1.4	1.3	2.0	2.4
	50	1.9	1.9	3.1	3.2
	100	3.5	3.5	4.8	4.6
April-05	10	0.8	0.8	1.1	0.9
	25	1.0	1.0	1.4	2.1
	50	2.0	1.9	2.7	3.0
	100	3.2	3.1	4.1	4.5
May-05	10	6.1	6.1	5.0	4.5
	25	4.9	4.8	4.0	3.6
	50	4.0	4.0	3.2	2.8
	100	3.0	2.9	2.1	2.2
June-05	10	4.0	4.0	5.7	5.6
	25	4.9	4.9	5.9	5.8
	50	5.6	5.5	5.5	5.6
	100	5.5	5.5	5.3	5.0
July-05	10	7.1	7.0	8.0	7.5
	25	6.2	6.2	7.2	6.3
	50	5.5	5.5	5.9	5.3
	100	4.1	3.9	4.9	4.4
August-05	10	11.1	11.1	11.0	10.2
	25	10.0	10.0	9.3	8.6
	50	8.0	7.9	7.4	6.8
	100	5.9	5.9	5.2	5.1
September-05	10	14.4	14.3	12.9	13.5
	25	13.6	13.7	12.0	12.3
	50	12.6	12.5	10.9	10.8
	100	10.9	10.9	9.3	9.0
October-05	10	13.8	13.8	13.2	13.2
	25	13.7	13.6	13.8	13.6
	50	14.0	14.0	13.8	13.5
	100	13.2	13.2	12.7	12.7

Table 3.4). Soil texture and hydraulic conductivity for Remer ponds

REMER PONDS			Textural Results			
Location	Horizon Depth (cm)	Texture	Sand	Silt	Clay	Hydraulic Conductivity (cm/hr)
Willow River						
Upland	0-10	loam	51.5	39.1	9.4	
	10-41	sandy loam	69	25.2	5.8	
	41-46	sandy loam	57.8	29.1	13.1	
	46-163	clay loam	37	31.1	31.9	
	163-178	clay loam	34.2	31.5	34.3	2.028
	178-193	sandy loam	65.8	24.3	9.9	
	193+	silty clay	3.7	46.6	49.7	
Pond	0-10	organic	LOI = 28.7%			
	10-18	silt loam	23.4	59.7	16.9	
	18-56	silt loam	30.3	61.3	8.4	1.33
	56-91	silt loam	31.9	52.1	15.9	0.193
	91+	sandy loam	78.9	11.7	9.4	
Soo Line						
Upland	0-13	loam	47.2	40.3	12.6	
	13-58	silt loam	23	56.3	20.7	
	58-119	sand	94.6	1	4.4	
	119-165	loamy sand	85	3.2	11.8	
	165+	clay loam	35.5	34.7	29.8	
Pond	0-13	organic	LOI = 30.4%			
	13-23	silt loam	22.7	64.2	13.1	
	23-58	silt loam	25.2	58.9	15.8	0.38
	58-119	loam	15.7	55.4	29	0.014
	119+	loam	49.5	30.4	20.2	
Ashebun Lake						
Upland	0-8	silt loam	33.9	59.9	6.1	
	8-13	silt loam	28.8	63.4	7.9	
	13-43	silt loam	33	60.4	6.7	
	43-79	clay loam	29.1	38.7	32.2	
	79+	loam	41.4	31.8	26.9	
Pond	0-18	organic	LOI = 26.6%			
	18-69	silt loam	21.4	68.4	10.2	0.304
	69-127	silt loam	23.1	61.2	15.7	0.042
	127+	clay loam	28.3	43	28.7	
Dog Lakes						
Upland	0-8	organic	LOI = 25.1%			
	8-13	sandy loam	63.2	31.5	5.3	
	13-25	sandy loam	63.6	28.8	7.6	
	25-61	loamy sand	77.6	16.4	6.1	
	61-91	loamy sand	85.3	9.8	4.8	
	91+	sandy loam	76.6	13.5	9.9	
Pond	0-18	organic	LOI = 20.4%			
	18-38	loam	45	46.7	8.3	
	38-69	silt loam	25.6	54.9	19.5	0.002
	69+	sandy loam	67.4	17.5	15.1	0.756

Table 3.5). Soil texture and hydraulic conductivity for Flow Through ponds

Flowthough Study Site			Textual Results		
Location	Horizon Depth (cm)	Texture	Sand	Silt	Clay
#1 - Upland	0-13	silt loam	33.5	59.9	6.6
	13-43	silt loam	36.4	55.8	7.8
	43-69	loamy sand	82.2	8.5	9.3
	69-132	clay loam	26.8	35.9	37.2
	132-165	silt loam	23.2	58.4	18.4
	165-178	clay	23.4	35.2	41.4
	178+	loamy sand	81.8	9.9	8.3
#1 - Pond	0-3	Organic	Organic: LOI = 44.7%		
	3-8	loam	40.4	46.9	12.6
	8-15	loam	47.5	42.9	9.6
	15-48	sandy loam	65.7	22.5	11.9
	48-81	loam	49.3	25.4	25.4
	81+	clay loam	41.9	29	29.2
#1/2 - Piezometer/Well Nest	0-10	sandy loam	48.1	45.5	6.4
	10-56	silt loam	42.2	51.2	6.6
	56-102	loamy sand	82.4	8.1	9.5
#2 - Pond	0-5	Organic	Organic: LOI = 47.5%		
	5-15	silt loam	26.9	55.8	17.3
	15-86	silt loam	24.9	61.6	13.5
	86-196	loamy sand	85.9	6.9	7.3
	196+	clay loam	28	36.4	35.6
#3 - Pond	0-28	Organic	Organic: LOI = 21.6%		
	28-36	silt loam	32.1	60	7.8
	36-43	loam	36.4	42.5	21.1
	43+	clay loam	30.4	35.4	34.2
#3 - Upland	0-10	sandy loam	59.2	32.9	8
	10-28	sandy loam	67.3	26.4	6.3
	28-71	loamy sand	82.9	12.3	4.8
	71-81	loamy sand	81.9	12.6	5.5
	81-109	loam	45	29.6	25.5
	109-157	sand	91.6	3.8	4.6
	157-178	loamy sand	83.9	5.5	10.6
	178+	sand	90	4.8	5.3
	178+	sandy loam	69.9	20.4	9.7
	178+	sand	97.2	0.6	2.2
#4 - Pond	0-8	Organic	Organic: LOI = 48.2%		
	8-18	silt loam	27.8	52.9	19.3
	18-56	silt loam	36.3	56.6	7.1
	56-79	silt loam	34.7	51.4	14
	79-102	sand	88.5	5.4	6
	102+	clay loam	38	33.5	28.6
#4/5 - Piezometer/Well Nest	0-5	silt loam	27.6	66	6.4
	5-58	silt loam	28.6	66.3	5
	58-89	clay loam	32.3	31.4	36.3
	89-97	sandy loam	69.7	16.7	13.6
	97+	loamy sand	86.3	4.2	9.5
#5 - Uplands	0-8	sandy loam	70.3	21.8	7.9
	8-51	loamy sand	86.2	8.8	5
	51+	loamy sand	83.7	12.3	4
#5 - Pond	0-81	Organic			
	81-91	silt loam	26.1	60.9	13
	91-102	silt loam	31.5	59.7	8.8
	102-152	silt loam	26.7	62.1	11.2

Figure 3.1). Instrumentation layout for Flow Through study ponds

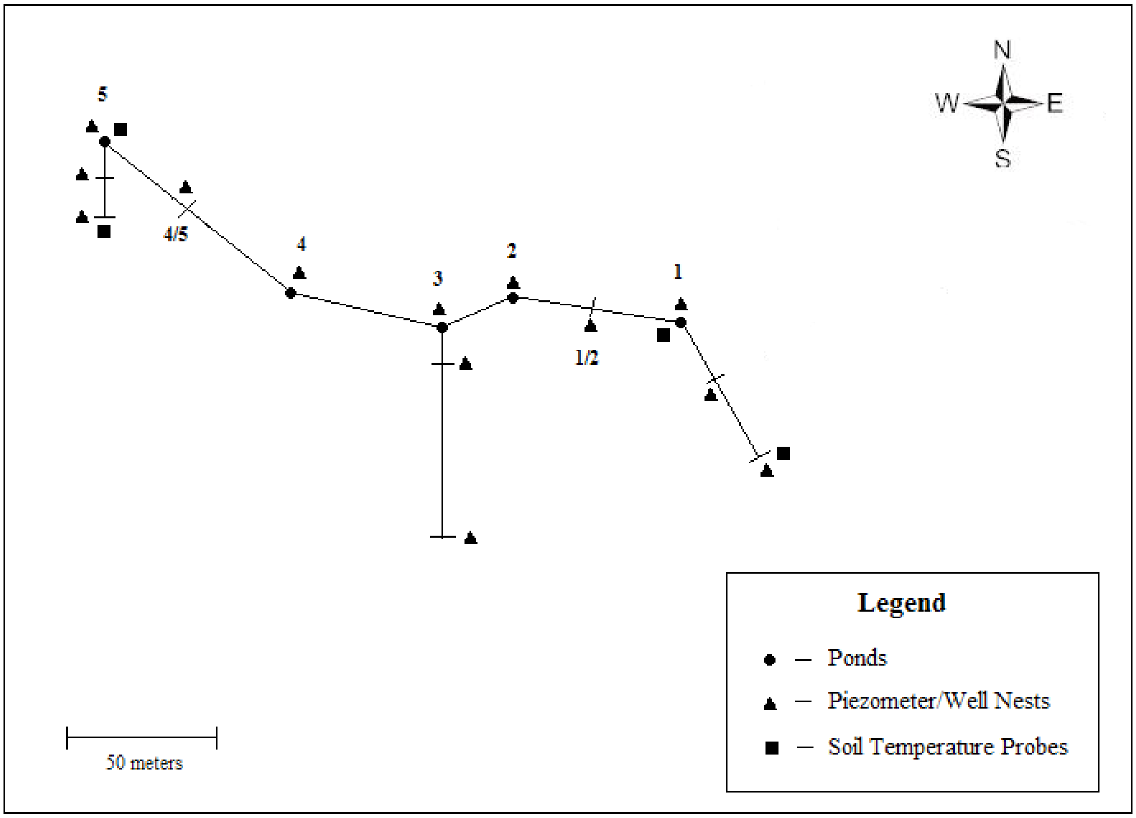


Figure 3.2). Percent inundation on an annual basis

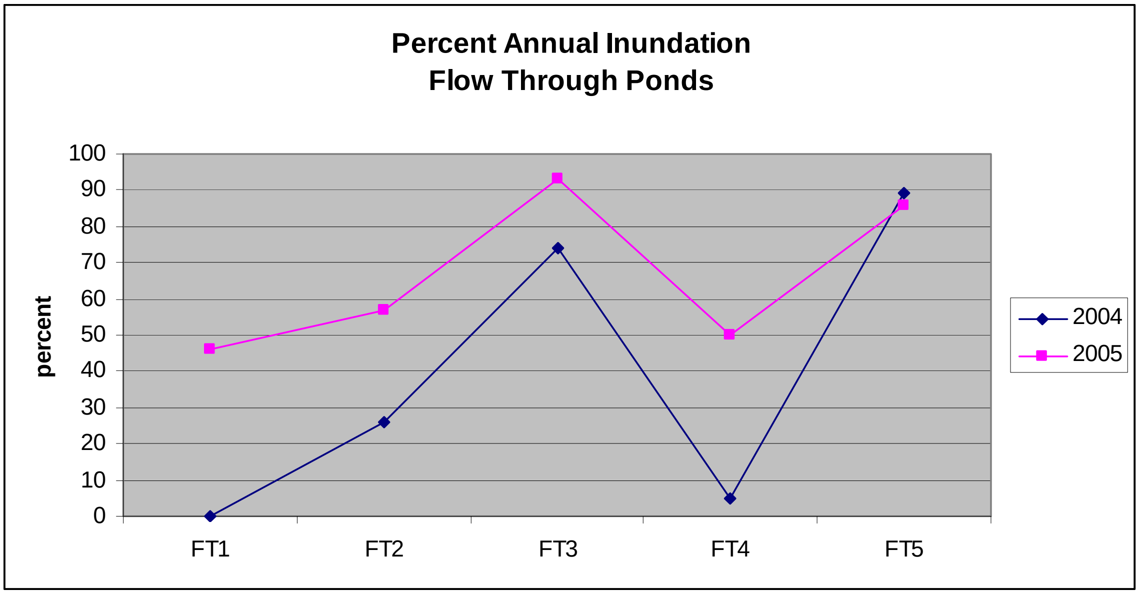


Figure 3.3). Average annual waterlevel depth

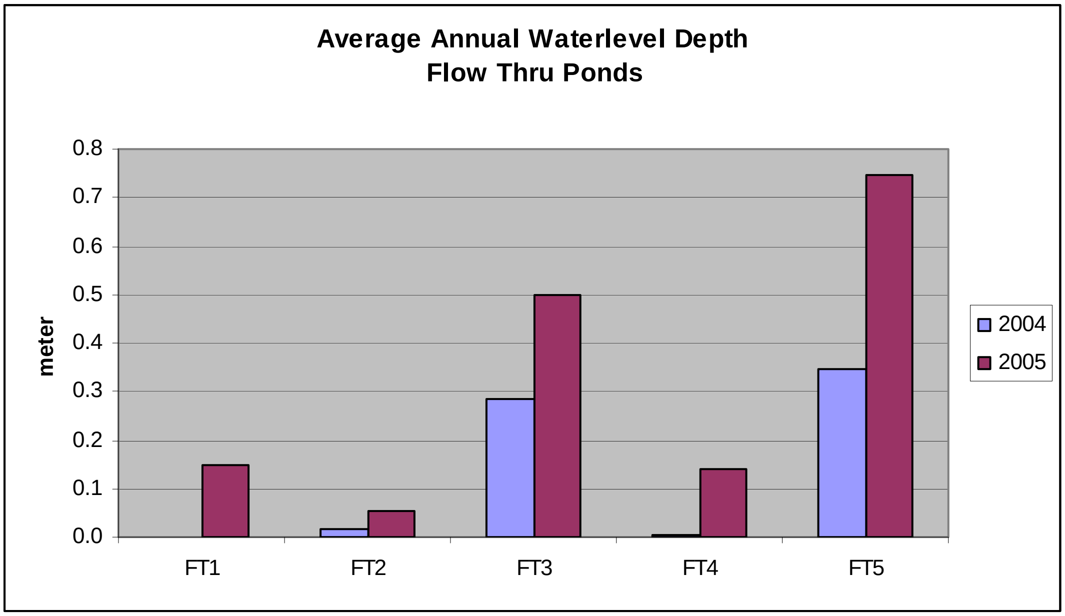


Figure 3.4). Relative elevation of Flow Through study ponds; where FT 5 = 0 or Baseline elevation

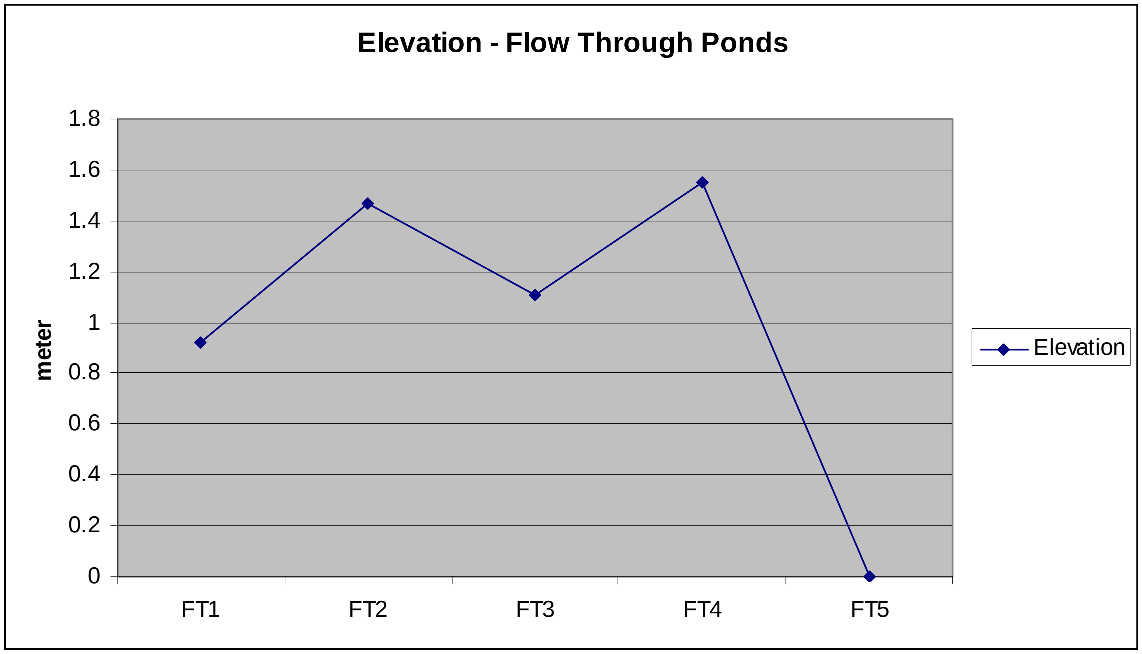


Figure 3.5). Precipitation measurements from Soo Line study area

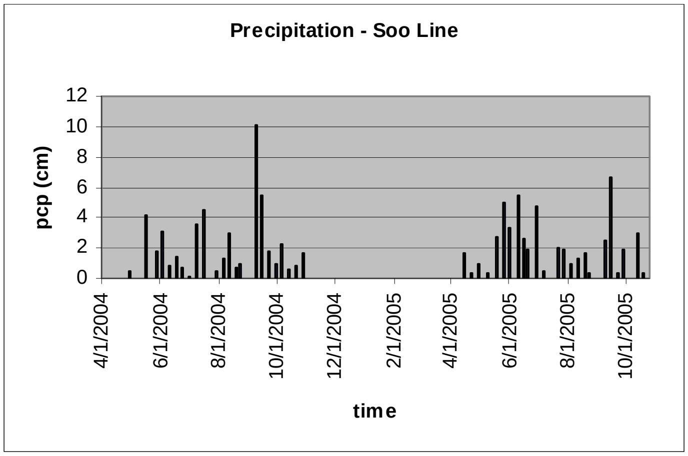


Figure 3.6). Well measurements from Soo Line study area

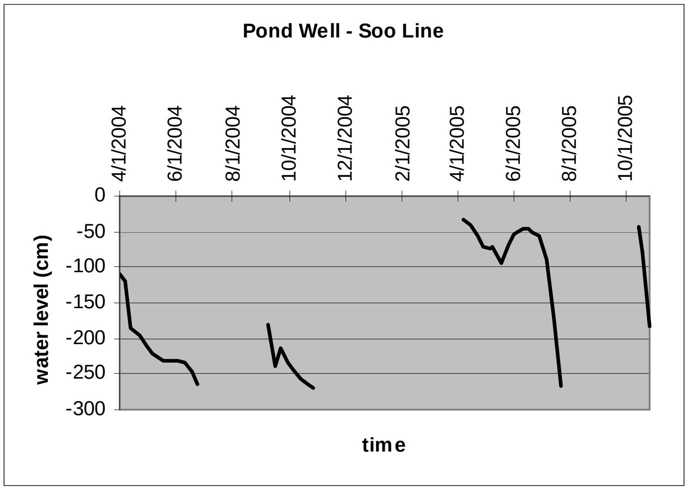
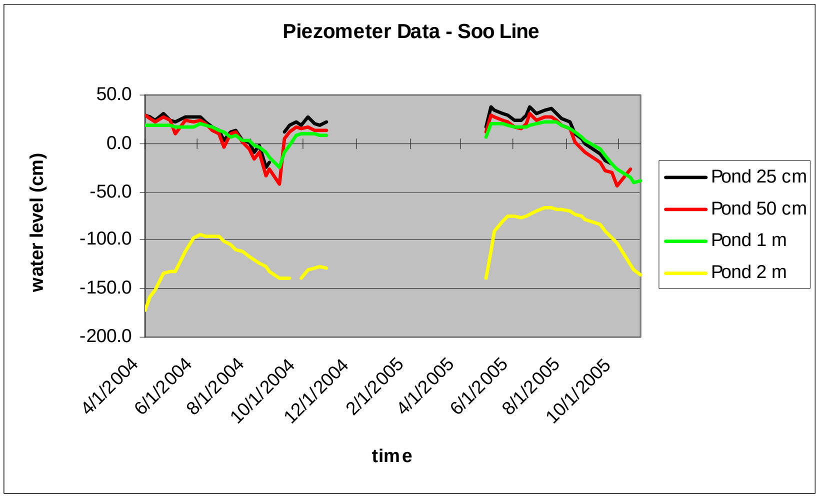


Figure 3.7). Piezometer measurements from Soo Line study area



OVERALL CONCLUSIONS

The results of this study have advanced our knowledge and understanding of hydrological and soil morphological characteristics associated with seasonal ponds found in forested, upland, palustrine systems of north central Minnesota; whereas, the majority of literature associated with seasonal ponds focuses on habitat function and ecological interactions. By studying and analyzing site specific characteristics of seasonal ponds, conclusions were able to be drawn regarding the impact of forest management practices on seasonal pond hydrology; as well as the influence of soil morphological processes on the formation of seasonal ponds on the landscape.

Specifically, it was shown that by altering vegetative buffers following the harvest of adjacent upland forests it is possible to manipulate the length of saturation and average depth of water. Such information is valuable to forest managers who may be concerned with providing a certain type of habitat in seasonal ponds following harvest of adjacent uplands. Furthermore, by examining characteristics of soil morphology, the formation of clay lenses was found to be common in soils under seasonal ponds. Lithologic discontinuity in soils was found in uplands adjacent to seasonal ponds. The presence of these soil morphological features indicate that seasonal pond formation on the landscape is influenced by both geogenic and pedogenic processes.

Because of the abundance of seasonal ponds in north central Minnesota and the valuable habitat function associated with their presence on the landscape, it is imperative that research continues to expand our knowledge of these systems. As management and protection of these systems grows, it is essential to have a solid understanding of how to best manage seasonal ponds to maintain their functional integrity across the landscape.

This includes understanding site specific characteristics, such as those examined in this research, so a more complete picture of why and how seasonal ponds form on the landscape is developed and proper emphasis can be placed on protecting these characteristics.

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APPENDIX A: Additional Figures

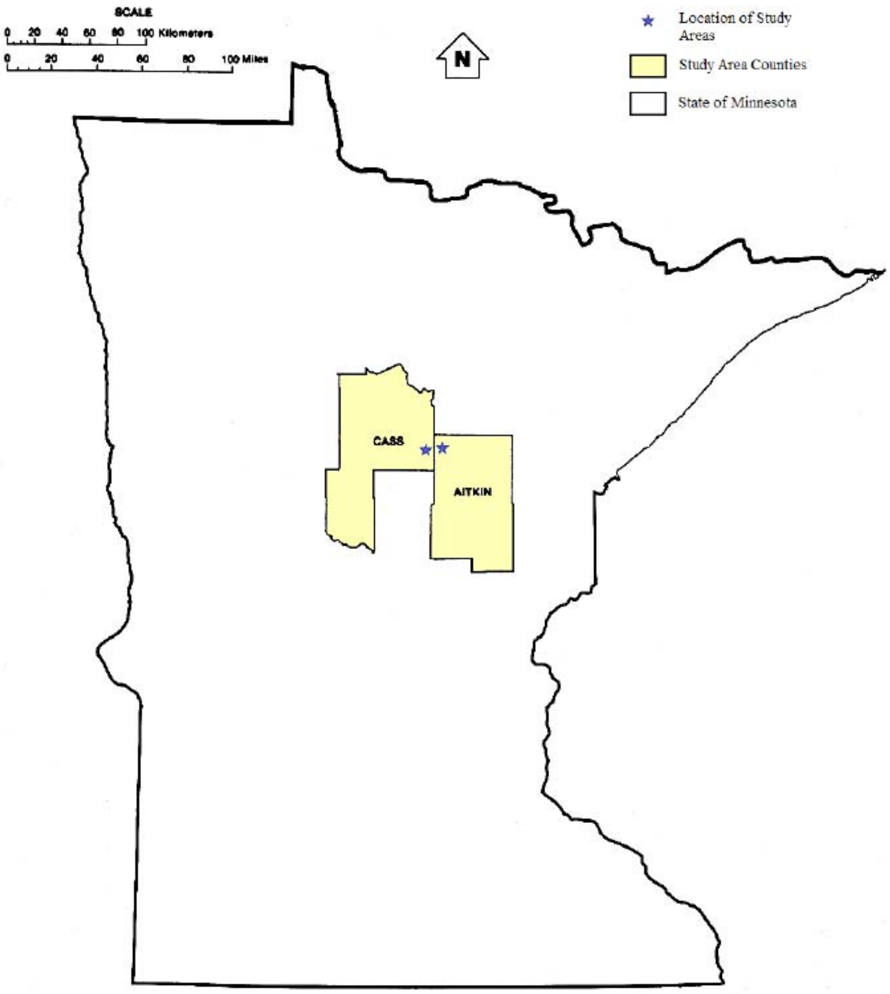

Figure A). Location of study areas

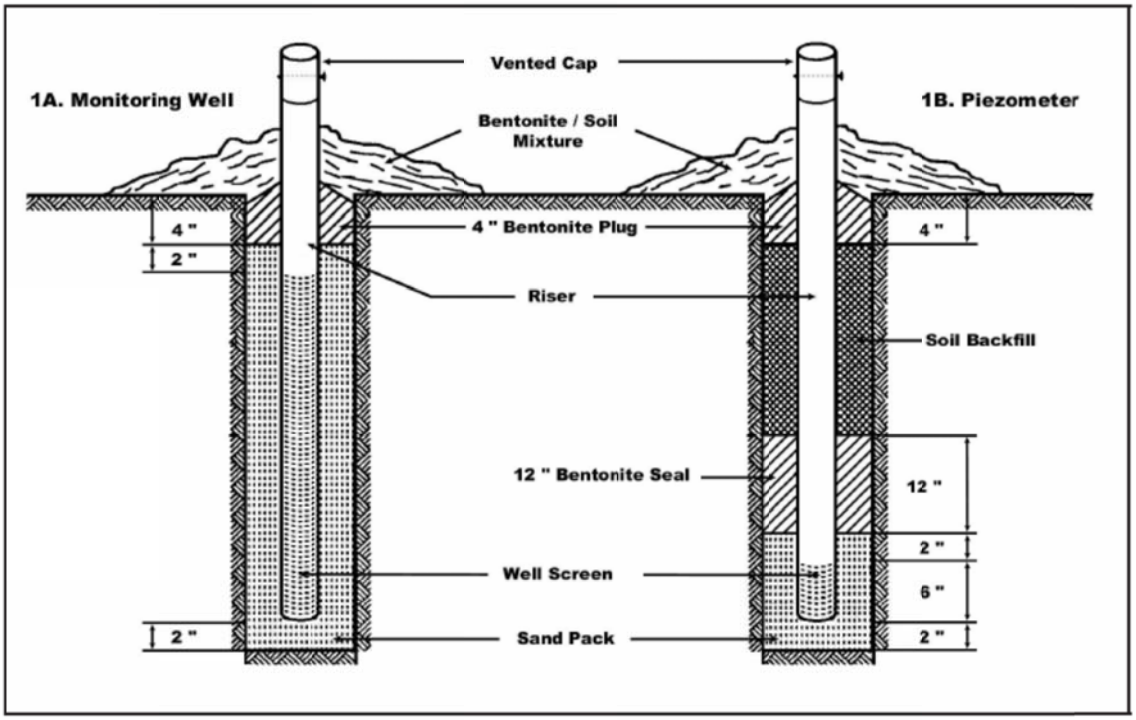

Figure B). Schematic diagram of construction and installation of: 1A) Monitoring well; and 1B) Piezometer (Sprecher, 2000).