Final Report

Using Geospatial Technologies to Detect Closed Basin Wetland Changes and their Causes Over Time: A Case Study from the Waterville Plateau, Washington

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4 July 2009

Abstract

The U.S. Geological Survey recently made all historical and current Landsat Thematic Mapper (TM) imagery freely available for download. The ready and free availability of this imagery thus opens the door to a variety of possible projects not previously undertaken. Little is known about fluctuations of the open water portions of wetlands on Washington state's semiarid Waterville Plateau on the northwest margin of the larger Columbia Plateau (Figure 1). We used Landsat Thematic Mapper (TM) satellite imagery of 52 wetland ponds and their associated watersheds to identify seasonal, annual, and interannual pond areas on the eastern Waterville Plateau over a 22 year period from 1986 through 2007. Specifically, we: 1) selected imagery; 2) selected pond study areas; 3) acquired imagery; 4) processed imagery; 5) classified images and mapped pond areas; 6) mapped pond watersheds; 7) acquired climate data; 8) determined geomorphic surface types; 9) determined land use types; and 10) correlated over time pond changes to climate, geomorphic surface, and land use patterns. We chose to use Landsat Thematic Mapper (TM) data because historical and current scenes became freely available beginning in late 2008, and because of its high spectral resolution, repeat imagery (16 day return interval) (Campbell, 1987) characteristics. However, the relatively coarse spatial resolution of TM imagery (30 m pixel) as compared to the high spatial resolution of aerial photography (1-3 m) prevented us from analyzed stream and very small pond fluctuations. Also, the large size of the datasets forced us to develop automated techniques for the retrieval and analysis of the images.

Maximum open water areas of individual wetland ponds range up to nearly 4.1 hectares. Minimums range to 0 ha–i.e., ponds disappear, often leaving a salt encrusted, high albedo surface. Wetland pond areas fluctuate markedly over a particular year, generally reached their

maxima in March and April at the end of the wettest months. Minima were more dispersed throughout the year. Slightly more wetland pond minima occurred in April (12%), May (14%), June (16%), July (15%), and August (16%). The slight increase in wetland pond minima occurrences in the late spring and summer months generally coincides with the typical warmer and drier months of the year. Sixteen of the wetland pond watersheds were located on end moraine, 15 on ground moraine, and 21 on scabland surfaces. When stratified by geomorphic surface type, cumulative annual end moraine and ground moraine maximum wetland pond area patterns appear quite similar while scabland pond fluctuations differ markedly. Spearman rank correlation analysis of geomorphically stratified cumulative maximum wetland pond areas supports the relationship between end and ground moraine ponds. Mean annual water year precipitation and snowfall patterns show some similarities to pond fluctuations, especially those on scabland surfaces. This suggests that the thinly till mantled scablands may respond more closely to precipitation than do the till covered end and ground moraine surfaces. However, statistical analysis does not support this hypothesis. Further, land use patterns do not visually or statistically follow pond area patterns on any of the geomorphic surface types. These results suggest that other variables may play a role in Waterville Plateau pond area fluctuations including groundwater input, basin size, and substrate. This study is significant for its scientific results in a Pacific Northwest analog setting to the Northern Great Plains Prairie Potholes region, and for its development of new geospatial techniques centered on now readily and freely available satellite imagery.

Introduction

Closed hydrologic basins (i.e., closed basins) are characterized by surface inlets but lack surface outflow. Wetlands, often associated with open water ponds or lakes, may occupy closed basins, if only seasonally. Such basins result from a variety of processes including tectonics, mass wasting, eolian activity, and glaciation. Closed basin wetlands are especially common in glaciated regions throughout the northern hemisphere because of the hummocky terrain associated with glacial deposits. Water levels, hence water areas, in these glacial depressions fluctuate depending on the balance between surface and subsurface run-in versus evaporative losses (Langbein, 1961). Because glaciated terrain typically does not have well-organized stream networks, wetlands in such settings get little of their flow from streams. Instead, direct precipitation, groundwater, and seasonal overland flow (especially when soils are frozen during the early spring) provides the bulk of water input to wetlands (Winter 2000). Closed basin wetland hydrology therefore responds to a variety of variables including local climate (especially precipitation and evapotranspiration), substrate, groundwater flow, and basin size (Meyboom, 1966; Shjeflo, 1968; Winter 1989; Poiani and Johnson, 1991; Larson, 1995). Because of variable topography, substrate permeability, and groundwater influences on hummocky terrain wetlands, the impacts of climate change may or may not be seen in such wetlands (Winter, 2000). Agricultural land use, combined with weather and climate, also plays a major role in surface runoff hence semiarid, closed basin wetland dynamics (e.g., Detenbeck et al, 2002).

Open water areas within wetlands change seasonally, annually, and interannually (van der Valk and Davis, 1978). Because open water portions of semiarid, hummocky wetlands fluctuate as a result of weather and climate, land use, and subsurface flow, it is important to monitor seasonal and long-term trends of individual wetlands as well as regional assemblages so to better understand the causes of such fluctuations (Beeri and Phillips, 2007). Remote sensing is a way to accomplish such dual scale analyses but the task demands ample, medium to high resolution imagery. Fortuitously, the U.S. Geological Survey recently made all historical and current Landsat Thematic Mapper (TM) imagery freely available for download. The ready and free availability of this imagery thus opens the door to a variety of possible projects not previously undertaken. While the Prairie Pothole Region wetlands of glaciated and prairie-like portions of the North Dakota, South Dakota, Alberta, Manitoba, and Saskatchewan (Larson, 1995) have been studied in detail (e.g., Beeri and Phillips, 2007), little is known about fluctuations of the open water portions of wetlands on Washington state's semiarid Waterville Plateau on the northwest margin of the larger Columbia Plateau (Figure 1). This region, like the Prairie Potholes, was glaciated and is currently characterized by a semiarid climate.

In this study, we test the utility of various geospatial techniques in assessing fluctuations in the open water portions of wetlands over time on the Waterville Plateau. Specifically, we used Landsat Thematic Mapper (TM) satellite imagery of 52 wetland ponds to identify seasonal, annual, and interannual pond area fluctuations and trends over a 22 year period from 1986 through 2007 . Once complete, we attempted to correlate these changes to weather/climate patterns, agricultural land uses, and geomorphic surface types. This latter variable has not been examined previously and has the potential to play a major role in wetland pond area variations because of its likely influence on rapidity of runoff. The original proposal for this research indicated that we would focus on more widespread hydrological changes on the Waterville Plateau. However, the selection of Landsat TM satellite imagery, for all of its advantages (see Methods section) prevented us from analyzing very small hydrologic units such as streams.

Therefore, we focused on wetland ponds of sufficient size that they could be resolved on the imagery.

This research is significant for its technological research as well as its addition to local and regional knowledge. This study develops and tests various geospatial techniques that may be useful for local rural land managers who are faced with assessing long-term environmental change. Because wetland ponds have long-term significance to migratory and resident waterfowl, and because area waterfowl numbers appear to fluctuate based on pond levels, it is important to understand the overall trend of ponds and the causes in their area fluctuations. Finally, this research serves as a baseline for future climate- and land use- driven changes to depressional wetland ponds on the eastern Waterville Plateau.

Study Area

The study area lies within a ~892 km^2 area on Washington state's Waterville Plateau. The Waterville Plateau is bounded by the Columbia River on the north and west, the Quincy Basin on the south, and the Grand Coulee on the east (Figure 1). The study area lies entirely within Douglas County.

Jurassic granitics presumably underlie the entire plateau but are only visible in deep exposures on the western and northern margins. Three members of the Wanapum Basalts–Priest Rapids, Roza, and Frenchman Springs– and the Grand Ronde Basalts of the Columbia River Basalt Group overlie the granitics and are sporadically visible throughout the study area. Late Quaternary glacial drift (undifferentiated), alluvium, and loess often mantle the bedrock in the study area (Gulick and Korosec, 1990). The plateau is a result of uplift associated with the Coulee Monocline and incision by glacial outburst flooding forming the Grand Coulee and likely deepening the main Columbia River Channel. The Withrow Moraine, marking the southern extent of the Cordilleran Icesheet, arcs across the central Waterville Plateau (Figure 1).

Hummocky, yet generally low relief, undifferentiated drift deposits associated with Late Quaternary glaciation harbor numerous closed depressions occupied by wetlands north of the Withrow Moraine. Outburst flooding, and associated erosional and depositional patterns also resulted in closed depressions on the northeastern portion of the plateau. Early geologists in the area commented on the presence of depressions on the Withrow moraine and the ground moraine behind it. These depressions date to the late Pleistocene, likely 13,500-14,000 yr BP (Easterbrook, 1979, p. 177). A deranged drainage pattern throughout much of the area reflects the glacial and outburst flood modifications of the bedrock surfaces. Ephemeral streams characterize the numerous small, closed watersheds of the plateau.

Cold, moist winters and hot, dry summers characterize the overall semiarid climate of the plateau. The only long-term weather station is located in Waterville at 800 m elevation on the western margin of the Waterville Plateau. Over the 1971-2000 climate normal, the mean annual temperature was 8^{o}C with July typically the hottest month averaging 21^{o}C and December and

January having the coolest average temperatures of -4°C. Annual precipitation averaged 29 centimeters. The wettest months are November, December, January, and February. Conversely, the driest months are July-October. Sixty-five percent of all precipitation falls between November-April. Much of this occurs as snowfall. Waterville averaged 109 centimeters of snowfall/year over the 1971-2000 climate normal. Long term measurements at Quincy (69 km SW) and Wenatchee (74 km WSW), suggest that evapotranspiration is between 102 and 127centimeters/year in the study area (Western Regional Climate Center, n.d.).

The native vegetation of the upland portions of the study area is shrub steppe. Riparian vegetation is found in each of the hummocky wetlands.

Land use in the study area ranges from traditional dryland summer fallow/winter wheat, minimum tillage wheat, Conservation Reserve Program (CRP), and range lands. North of the Withrow moraine, the glacial and outburst flood heritage has greatly diminished the amount of farmland and increased rangeland acreage as compared to the area south of the moraine. This is especially true in the northeastern portion of the plateau where outburst floods scoured much of the surface to bedrock. As a result of rainfed agriculture and ranching, and few other economic opportunities, the Waterville Plateau is sparsely populated with farmsteads scattered about the area.

Literature Review

Wetland Pond and Lakes

No classification scheme exists for Waterville Plateau wetland ponds. However, research done on well-studied Prairie Potholes Region wetlands should be applicable to those of the Waterville Plateau because of similarities between the environments–i.e., each lie in semi-arid regions and each occupy small glacial depressions underlain by low permeability glacial till. Prairie Potholes Region wetlands occupy topographic depressions with ponds that are the inundated central portions of wetlands (Hayashi et al, 1998). There, non-fluvial wetlands with open water areas smaller than 50 acres (i.e., 20 hectares) in area are "ponds" while features larger than 50 acres are "lakes" (Stewart and Kantrud, 1971). These may be further subdivided as: Class I-Ephemeral ponds; Class II– Temporary ponds; Class III–Seasonal ponds and lakes; Class IV–Semipermanent ponds and lakes; Class V–Permanent ponds and lakes; Class IV–Alkali ponds and lakes; and Class VII–Fen (alkaline bog) ponds (Stewart and Kantrud, 1971).

Pond and Lake Open Water Changes Over Time

As noted above, wetland pond and lake open water levels, hence areas, vary over time as a result of weather and climate, substrate, groundwater flow, and basin size. Northern Great Plains ponds typically fill in spring as a result of direct precipitation and runoff from rainfall and snowmelt. Because of winter precipitation and spring rainfall, Prairie Pothole Region wetland water levels typically reach their levels in April and May (Winter, 2003). Winter precipitation plays the greatest role in impacting the hydrology of Prairie Pothole wetlands (Winter and Rosenberry, 1995) including summer water levels. Hayashi et al (1998) had similar results finding that 30-60% of winter precipitation reached the wetland as snowmelt runoff. Frozen ground is a major factor in surface runoff in northern settings (Zuzel et al, 1982; McCool, 1990) that ultimately makes its way to depressions (Lissey, 1971; Winter and Rosenberry, 1995). By extension, frozen ground should also play a key role in delivering water to hummocky depression wetlands. Saturated soils also lead to the enhanced delivery of water to depression wetlands (Poiani and Johnson, 1991). Summer precipitation has its greatest impact on wetland water levels when it falls directly on the wetlands or when prolonged or intense precipitation leads to runoff (Winter and Rosenberry, 1995; Hayashi et al, 1998; van der Kamp et al, 1999; Winter 2003).

Evaporation is the greatest cause of water loss in the wetlands. Studies in the Northern Great Plains have shown that 0.8 m of water may be lost from a wetland in an extremely warm, dry summer (Winter and Rosenberry, 1995). Increased evaporation coinciding with rising summer temperatures typically results in falling wetland water levels (Winter, 2003).

As a result of the above inputs and losses, some wetland water levels respond to changes in temperature and precipitation on seasonal, annual, and interannual bases (Winter 2003). Other wetland waterbodies, possibly more influenced by groundwater flow, have more stable water levels (Rosenberry and Winter, 1997, p. 267).

Land uses also appear to impact ponds over time (van der Kamp and Hayashi, 1998). Euliss and Mushet (1996) demonstrated that wetland water levels in farmed watersheds fluctuate more than those in grass covered watersheds within the Prairie Potholes Region. In fact, van der Kamp et al (1999) reported that small prairie wetlands in central Saskatchewan dried up following conversion of farmland to permanent grassland. Vegetation height impacts the amount of snow trapped in a particular area hence the amount of snowmelt runoff into a prairie pothole (Hayashi et al, 1998) or the amount of snow blown into depressions (van der Kamp et al, 1999). The type and height of vegetation complicates these results (van der Kamp et al (1999). It appears that grass vegetation that traps snowfall leads to increased run-in (i.e., infiltration) and reduced runoff (van der Kamp et al, 1999; van der Kamp et al, 2003). Summer fallow may lead to less groundwater uptake than does winter or spring wheat thus Prairie Pothole wetlands may gain water in watersheds dominated by fallow land (Hayashi et al, 1998).

The agricultural land use, combined with weather/climate, plays a major role in surface runoff hence wetland, pond, and stream dynamics in rural watersheds (e.g., Detenbeck et al, 2002). Land use and weather/climate patterns may result in similar hydrologic responses in settings that are further complicated by different geomorphic surfaces. Different geomorphic surfaces may further impact these dynamics as may groundwater flow regime, soil permeability, and basin size (Larson, 1995).

Remote Sensing and Pond Area Changes

Remote sensing has long been used to analyze wetlands, and the water quality and quantity of these settings (e.g., (Lyon, 1993; Johnston and Barson, 1993; Gluck et al, 1996). However, suspended sediments and aquatic vegetation may alter spectral signatures sufficiently to make differentiating terrestrial and aquatic systems difficult (Melack and Gistil, 2001; Ritchie et al, 2003). Wetland analysis is made even more difficult by the typically small size of these features. Overall, mapping accuracy of various types of wetland is hampered by spectral overlap between different wetland types (Gluck et al, 1996).

Mapping of open water portions of wetlands offers the possibility of better accuracy, especially when no other wetland types have similar spectral signatures. Previous researchers have assessed water quantity changes in a variety of settings using remote sensing (e.g., Boland and Blackwell, 1975; White, 1978; Johnston and Barson, 1993; Nellis et al, 1998). Accuracy of water area measurements is a function of the sensor's spatial resolution and the topography of the area (Gupta and Banerji, 1985). Boland and Blackwell (1975) demonstrated that measurements of lake surface areas with Landsat MSS data (79 m spatial resolution) were within 10% of those made from topographic maps. White (1978), also using Landsat MSS data, showed that accuracy should improve as water body size increases beyond 2.5 ha. Steep terrain complicates interpretation of waterbody surface area changes because it diminishes the amount of surface area change despite marked volume changes (Gupta and Banerji, 1985).

Methods

This research involved the innovative use of common geospatial software and freely available geospatial data sets. Specifically, we: 1) selected imagery; 2) selected pond study areas; 3) acquired imagery; 4) processed imagery; 5) classified images and mapped pond areas; 6) mapped pond watersheds; 7) acquired climate data; 8) determined geomorphic surface types; 9) determined land use types; and 10) correlated over time pond changes to climate, geomorphic surface, and land use patterns.

Imagery Selection

We chose to use Landsat Thematic Mapper (TM) data because historical and current scenes became freely available beginning in late 2008, and because of its high spectral resolution, repeat imagery (16 day return interval) (Campbell, 1987) characteristics. However, the relatively coarse spatial resolution of TM imagery (30 m pixel) as compared to the high spatial resolution of aerial photography (1-3 m) prevented us from analyzed stream and very small pond fluctuations.

Pond Selection

As noted earlier, we expect that pond levels vary depending on climate and weather, geomorphic surface type, and land use. We therefore chose our study area watersheds based on presence of ponds sufficiently large to be measured on Landsat TM imagery, and based on the presence of a variety of representative land use and geomorphic surface types. Based on these criteria, we initially chose 62 closed basin wetland ponds and their associated watersheds.

We then obtained digital National Agriculture Imagery Program (NAIP) airphotos of the area to use in initial identification of study area ponds. Once ponds were identified on this imagery, approximate pond boundaries were digitized to serve as bookmarks and areas of interest (AOI's) for the subsequent TM imagery. These initial, approximate pond boundaries were also attributed with a name (if available), a qualitative description of the presence or absence of water in the NAIP image, and the appropriate USGS 24K topographic quadrangle (Table 1).

Imagery Acquisition

Once imagery type and study area ponds were determined, the next step was to procure Landsat imagery through the USGS' EarthExplorer data exploration site (http://edcsns17.cr.usgs.gov/EarthExplorer/). This site makes use of a graphical user interface (GUI) to specify and select Landsat images for download but is not geared well for batch downloading (Figure 4). After some trial and error, a routine was formed to extract the 400 plus images needed for the study. The steps for this routine are as follows:

a. Create a user account in order to obtain data.

b. Based on study area location, identify the appropriate Landsat path(s) and row(s) for streamlined searching. Once these have been identified, they may be specified in the ‘additional search criteria’ at the lower left of the GUI.

c. Specify the dates for your imagery. For the purpose of this study the date range was 1984-2008. By limiting the search criteria by path and row, the returned results numbered 471. While it is possible to specify an acceptable cloud presence, this option was not utilized for 2 reasons: 1) 50% or higher cloud coverage does not necessarily discount the image’s utility; and 2) the cloud coverage values for each image were not reliable.

d. One can then preview the images 10 at a time and select to download them if they have been previously downloaded by another user. Since this research was performed soon after the release of the imagery, many of the images had not been previously requested so were unavailable for immediate downloading. Instead, the request was logged and an email was sent when the imagery became available. This usually took less than 48 hours.

e. Since clicking on over 450 links and waiting for each to download was time-prohibitive, a program was written to create a “gallery” of links which, in turn, enabled a download manager to work around the clock downloading images.

Image Processing

Once the 450+ images were obtained, several decompression programs were needed to expose the seven spectral bands and associated metadata. These files cumulatively totaled nearly one-half of a terabyte (1000gb) in size.

A series of preprocessing routines were performed using Feature Manipulation Engine (FME)^{R} and ArcGIS Desktop^{R} and included: name simplification, clipping to study area, and band stacking. Bands 1,2,3,4,5, and 7 were chosen for the analysis. Band 6, the thermal band, was not chosen because of its low (120 m) spatial resolution.

The stacked, clipped images were then brought into ERDAS Imagine^{R} for spectral analysis and signature creation. While only a rudimentary classification (water, not water) was required (akin to Johnston and Barson, 1993; Beeri and Phillips, 2007), the spectral signature was repeatedly tested for accuracy. We used a spectral euclidian region growing tool to create AOI's of a sample of six ponds. When applied to the other ponds in a particular scene, it was found that the spectral signature was too large therefore taking in wetland that was not open water. Therefore, the spectral signature was visually calibrated to take in only open water areas. All Thematic Mapper bands except thermal band 6 were used in the identification of water. Band 6 was not used because of its low spatial resolution.

At this point, it was necessary to identify each lake's bounding area for the change detection algorithm. Rectangular envelopes were produced for each of the lakes in ArcGIS^{R}, and were then converted to bookmarks bearing the name of their corresponding lake ID number (Figure 4).

In order to visually inspect the data later, it was necessary to output thumbnail, natural-color images of each lake for each Landsat image (Figure 5). Directories were created numbering 1-52 to hold the images. All 420 clipped Landsat scenes were added to the ArcMap^{R} project containing the bookmarks from the latter step. A script was then employed to zoom in to each bookmark in the list, export a thumbnail image for each, turn off the current Landsat image, and turn on the next layer in the table of contents and repeat. The name of the bookmark was used to guide the image to the proper directory and the name of the Landsat image was used for naming the image within said directory. This step resulted in approximately 22,680 true color images.

<u>Image Classification and Pond Area Mapping</u>

With the natural color images thus produced it was now time to classify the images using the spectral signature created above. A simple program was written in Visual Basic^{R} to create ERDAS^{R} command lines which, similar to that of the step above, would be used to classify each lake's bounding box in each of the 420 Landsat scenes. This step resulted in an additional 22,260 bi-color images.

Visual inspection was then performed using the thumbnail view available in Windows Explorer^{R}. Since the classified TIFF images generated by ERDAS^{R} were not viewable as thumbnails in Windows XP^{R}, Irfanview^{R} was used to batch convert the TIFFs to viewable JPEGS. Bad classifications due to cloud interference were immediately obvious using both the natural-color and classified thumbnails and were deleted. Ultimately, this supervised classification

Upon completion of the visual inspection, each lake's classified TIFF images were added to ArcMap[R] and a script was written to cycle through each layer, extract the grid cell count values from the attribute table, multiply them by the Landsat ground resolution (30 meters) and add the value to a separate table (Table 2). This would provide us with the lake area at a particular time. Since different ponds would have different images included, it was not possible to cycle sequentially through the layers but was rather necessary to use the layer name to ensure the value be placed in the correct cell. It was also necessary to discriminate 0 area from no data or "null" values.

With the statistical lake area data organized in tabular format it was now possible to derive graphs and trending lines summarizing the pond area changes over the study period (Figure 6). Because the 1984 and 1985 data sets were very incomplete, they were deleted from the study period.

Watershed Boundary Mapping

Watersheds were delineated for each of the pond polygons using the 10-meter National Elevation Dataset (NED) (available from USDA and USGS) and the basin function in ArcGIS[R] Spatial Analyst toolset. We then visually checked each boundary and made adjustments based on our interpretations of the 1:24,000 topographic maps.

Climate Data Acquisition

As noted above, only one long term weather station is present on the Waterville Plateau. Unfortunately, this station data is not as representative of the study area as we wanted. This stems from Waterville's location ~27 miles west of the western-most portion of the study area, and it location at least 400 feet above that of the study area. Further, the Waterville site has missing data in varying months during the 1986-2008 study period. As a result, we chose to use PRISM climate data. The PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate mapping system uses point measurements of precipitation, temperature, and other climatic factors combined with a digital elevation model and knowledge of local climatic features, to produce continuous, digital grid estimates of monthly, yearly, and event-based temperature and precipitation (see http://www.prism.oregonstate.edu/). For this study, we chose one grid cell in the center of the study area (to be representative of the entire ~892 km^2 area. From this cell, we retrieved monthly precipitation and temperature data for each month beginning in January 1984 and extending through December 2007. Data was not available for only part of 2008. This ultimately limited our study period to 1986-2007.

Geomorphic Surface Type Mapping

Based on previous research (Waggoner, 1992), airphoto and topographic map observations, and previous field experience, geomorphic surface types were mapped in each of the pond watersheds. These surface types included end moraine, ground moraine, and scabland (associated with outburst flooding). Surface types were determined by viewing the area including and immediately surrounding each pond on topographic maps and stereo airphotos. Each watershed had only one geomorphic surface type.

Land Use Mapping

Land use types present in the area over the study period include rainfed (i.e., dryland) wheat farmland and rangeland. Rainfed farmland is typically managed as a summer fallow system where crops are grown on a particular land parcel every other year with a fallow year lying between crop years. Wheat is the most common crop grown on these lands but occasionally oats or barley are also raised. Because it was assumed that runoff differs little from crop to fallow lands, we did not differentiate between these. Rangeland was all land not currently growing crops. It included Conservation Reserve Program (CRP) lands that were taken out of crop production beginning in 1986 (Hellerstein, 2006). In Douglas County, Washington, lands entered the program from 1986 through 1996. Because CRP lands could not be accurately discerned from rangeland, we lumped these uses together.

Once identified on TM imagery, we digitized the boundaries of each land use in each year of imagery to calculate the proportion of each watershed in particular land use because watersheds may have more than one land use type.

Statistical Correlation

Once pond areas, geomorphic surface types, and land uses were determined for each watershed over time, we attempted to correlate geomorphically stratified pond groups to climate and land use using Spearman rank correlation.

Results and Discussion

Wetland Pond Watershed Areas

Fifty-two wetland watersheds were investigated in this study. These watersheds range from 10 to 3,160 ha in area. The median watershed area is 74 ha (Table 3). Total relief in each watershed ranges from 10 to 107 m with median total relief 28 m. All wetland pond watersheds terminate in closed basins on the Waterville Plateau.

Wetland Ponds and Their Areas

Fifty-two wetland ponds were identified in this study (Table 3). Maximum open water areas of individual wetland ponds range up to nearly 4.1 hectares. Minimums range to 0 ha–i.e., ponds disappear, often leaving a salt encrusted, high albedo surface.

This suggests, and the satellite imagery supports the fact, that wetland pond areas fluctuate markedly over a particular year. Over the 22 year study period, wetland pond areas generally reached their maxima in March and April (Figure 7). Thirty-three percent of all wetland ponds over time reached their maxima in March while 30% were at maximum levels in April. Conversely, only 1% of all wetland ponds over time reached their maximum levels in each August and September. These data support the various Prairie Pothole Region research that identifies the highest pond levels occurring in Spring. The slightly earlier maxima (March-April instead of April-May) may reflect the earlier onset of spring-like weather in the Waterville Plateau's slightly more marine climate.

Wetland pond area minima patterns were more dispersed throughout the year (Figure 8) as opposed to the pond area maxima. Slightly more wetland pond minima occurred in April (12%), May (14%), June (16%), July (15%), and August (16). March, September, and October each contained 9% of the total wetland pond minima. The slight increase in wetland pond minima occurrences in the late spring and summer months generally coincides with the typical warmer and drier months of the year.

Geomorphic Surface Areas and Wetland Pond Fluctuations

The entire study area southward to the Withrow Moraine was glaciated in the late Pleistocene. The direct effects of glaciation are clearly evident in two of the three geomorphic surface types--end moraine, ground moraine, and scablands. Each of these surface types are capable having closed depressions with the potential of holding wetland ponds. Depressions and associated wetland ponds are located primarily within (near the crest and on the upglacier side) of the Withrow Moraine. Where the moraine is prominent, depressions and ponds are pervasive, especially on the southeastern portions of the study area. Conversely, poorly developed end moraine results in few depressions and ponds. Depressions and associated ponds are also associated with ground moraine behind (i.e., north) of the moraine. Finally, closed depressions and wetland ponds are also found in scablands formed by early glacial outburst floods that passed over the northeastern portion of the plateau. These floods created a chaotic landscape of non-integrated drainages in a basalt surface. It is also likely that small amounts of ground moraine enhance the creation of wetland ponds on scabland surfaces given that the scabland surfaces were glaciated following their creation. Sixteen of the wetland pond watersheds were located on end moraine, 15 on ground moraine, and 21 on scabland surfaces (Table 3).

When stratified by geomorphic surface type, cumulative annual end moraine and ground moraine maximum wetland pond area patterns appear quite similar while scabland pond fluctuations differ markedly (Figures 9, 10 and 11). For the end moraine and ground moraine, generally high pond levels persisted from 1986 through 1990, and again from 1995 through 2000. Generally smaller pond areas occurred in 1991-1994, and since 2001. The end moraine surface wetland ponds show lower high levels in the 1991-1994 and since 2001. The end moraine dataset also shows 1987-1988 as low years. Scabland wetland ponds show a less distinct pattern of cumulative area fluctuation; instead, one can detect generally high but dropping pond levels from 1986-1990, and again from 1998-2005 with rising periods in between.

Spearman rank correlation analysis of geomorphically stratified cumulative maximum wetland pond areas supports the relationship between end and ground moraine ponds (Table 4)–i.e., end and ground moraine maximum pond areas are strongly correlated while scabland pond areas are less well correlated to ground and end moraine pond areas.

Wetland Pond Area Fluctuations and Climate

As shown earlier, weather and climate patterns play a strong role in wetland pond areas elsewhere. It is logical that such patterns would be reflected in Waterville Plateau wetland pond areas. Climate on the Waterville Plateau showed strong variations in maximum and minimum temperatures as well as precipitation and snowfall over the study period (Figures 12, 13, 14 and 12). Maximum and minimum average annual temperatures fluctuated by as much as 2^{o}C between years. However, it is difficult to match up cool temperatures with large pond areas, and vice versa. A cooling trend in the 1993-1996 maximum and minimum temperature data does correspond with an overall trend of increasing wetland pond areas on the scabland surfaces.

Precipitation over the study period generally rose from 1988 to 1997, then fell until 2001. Since then, it has generally risen. Snowfall follows a similar pattern as expected because it results in the bulk of annual precipitation. Of the three geomorphic surface types, scabland wetland pond areas most closely follow this precipitation pattern.

In comparison to the 1971-2000 climate normal, study period maximum and minimum temperatures were warmer by 1 and 1.6^{o}C respectively. Precipitation was 1 cm drier.

Unfortunately, Spearman rank correlation did not show significant, strong to moderate correlations among the geomorphically stratified ponds and the various climate variables.

Therefore, statistical analysis did little to support the qualitative observations of wetland pond - climate relations noted above, especially for the scabland wetland ponds.

Land Uses

Two land use types were identified in the study area–farmland and rangeland. Farmland included wheat/small grain fields as well as summer fallow. Rangeland encompassed all lands not actively farmed including land not previously farmed as well as Conservation Reserve Program lands. As of 2007, rangeland dominated most watersheds (Table 3). At that time, 40 watersheds had more than 50% rangeland while only 12 watersheds were dominated by wheat. Rangeland dominated all scabland watersheds with many near 100%. Of the 15 ground moraine surfaces, 12 had a preponderance of rangeland. Rangeland characterized only seven of the sixteen end moraine surfaces. This is surprising because of the hummocky, relatively high relief, rocky nature of the Withrow Moraine in much of the study area suggests that it would not be good farmland.

Cumulatively, the majority of area in the watersheds in 1986 was in farmland (6,302 hectares farmland vs. 3,589 hectares rangeland). However, by 2007, the land use dominance had reversed–4,760 hectares farmland vs. 5,122 hectares rangeland. This reflects the placement of marginal farmlands into CRP beginning in the mid-1980's and persisting through present. Over time, changes in land use mostly occurred only in end and ground moraine (Figures 16, 17 and 18). Soils on scabland surfaces are too thin to farm so most of these areas have never been farmed.

Visually, farmland trends do not match up with pond trends on each of the geomorphic surfaces. Further, Spearman rank correlation did not show significant, strong to moderate correlations among the geomorphically stratified ponds and the percentages of farmland over time. While the literature shows that runoff should be higher therefore ponds should be larger in farmed watersheds, we were not able to detect this pattern in the study area despite the conversion of farmland to CRP land (i.e., rangeland) over time.

Conclusions

This study has shown that innovative geospatial techniques can be used to select, retrieve, and analyze extensive satellite imagery datasets for the purpose of identifying and better understanding wetland pond changes over time. The techniques detailed in this report should be useful for others wishing to utilize the recently freely available, worldwide coverage of Landsat Thematic Mapper imagery to study rural watersheds. Analysis of over 450 Landsat Thematic Mapper scenes over a 22 year period shows that wetland ponds can be successfully identified and mapped on satellite imagery. Pond areas can also be determined at different time scales thereby permitting analysis of multi-scalar temporal change. This study revealed that wetland pond areas on till-covered end and ground moraine surfaces fluctuated similarly on an annual scale. Wetland pond areas on thinly mantled, basalt-underlain, scabland surfaces responded differently than the moraine surface ponds. The strong correlation between end and ground moraine wetland pond areas, as opposed to the moderate correlation between ponds on these surfaces and ponds on scablands suggests that substrate plays a significant role in determining the response of ponds to climate fluctuations. While climate and land use are each logical variables in affecting pond area fluctuations, their effects were not readily seen in the data. Further study may focus on teasing out the effects of climate and land use, as well as examining groundwater, basin size, and soil permeability and thickness as a variables in affecting wetland pond areas. Further study is important because of the implications given projected climate change and the implications of significant CRP ground going back into farm production as contracts expire in the next two years.

References

Beeri, O. And R. L. Phillips. 2007. Tracking palustrine water seasonal and annual variability in agricultural wetland landscapes using Landsat from 1997 to 2005. *Global Change Biology* 13: 897–912.

Boland, D.H.P. and R.J. Blackwell. 1975. The Landsat-1 multispectral scanner as a tool in classification of inland lakes. Proceedings of Earth Resources Survey Symposium, NASA. Houston, TX, 1A: 419-442.

Campbell, J.B. 1987. *Introduction to Remote Sensing*. The Guilford Press. New York.

Detenbeck, N.E., C.M. Elonen, D.L. Taylor, A.M. Cotter, F.A. Puglisi and W.D. Sanville. 2002. Effects of Agricultural Activities and Best Management Practices on Water Quality of Seasonal Prairie Pothole Wetlands. *Wetlands Ecology and Management*, 10: 335-354.

Euliss, N.H. and D.M. Mushet. 1996. Water-level fluctuation in wetlands as a function of landscape condition in the Prairie Pothole region. Wetlands 16 (4): 587-593.

Gluck, M., R. Rempel and P.W.C. Uhlig. 1996. An Evaluation of Remote Sensing for Regional Wetland Mapping Applications. Forest Research Report #137, Ontario Mininstry of Natural Resources, Sault Ste. Marie, Ontario. 33p.

Gulick, C.W. and M.A. Korosec. 1990. Geologic Map of the Banks Lake 1:100,000 Quadrangle, Washington. *Washington Division of Geology and Earth Resources Open File Report* 90-6.

Gupta, R.P. and S. Banerji. 1985. Monitoring of reservoir volume using Landsat data. *Journal of Hydrology* 77: 159-170.

Hayashi, M., G. van der Kamp and D.L. Rudolph. 1998. Water and solute transfer between a prairie wetland and adjacent uplands, 1. Water balance. *Journal of Hydrology* 207: 42-55.

Hellerstein, D. 2006. Agricultural Resources and Environmental Indicators, 2006 edition. US Department of Agriculture Economic Research Service. Accessed on 16 June 2009 at http://www.ers.usda.gov/publications/arei/eib16/.

Johnston, R.M. and M.M. Barson. 1993. Remote sensing of Australian wetlands: An evaluation of Landsat TM data for inventory and classification. *Australian Journal of Marine and Freshwater Research* 44: 235-252.

Kovanen, D.J. and O. Slaymaker. 2004. Glacial imprints of the Okanogan Lobe, southern margin of the Cordilleran Ice Sheet. *Journal of Quaternary Science* 19 (6):547-565.

Larson, D.L. 1995. Effects of climate change on numbers of northern prairie wetlands. *Climatic Change* 30: 169-180.

Lillesand, T.M. and R.W. Kiefer. 2000. *Remote Sensing and Image Interpretation*. John Wiley and Sons, Inc. New York. 724 p.

Lissey, A. 1971. Depression-focused transient groundwater flow patterns in Manitoba. p. 333-341. In A.C. Turnock (ed), Geoscience Studies in Manitoba. *Geological Association of Canada Special Paper* #9. Toronto.

Lyon, J.G. 1993. *Practical Handbook for Wetland Identification and Delineation. Lewis Publishers*. Boca Raton, Florida. 121 p.

McCool, D.K. 1990. Crop management effects on runoff and soil loss from thawing soil. Pp. 171-176 in K.R. Cooley, ed., *Proceedings International Symposium Frozen Soil Impacts on Agricultural, Range, and Forest Lands*. Special Report 90-1, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire.

Melack, J.M. and M. Gastil. 2001. Airpborne remote sensing of chlorphyll distributions in Mono Lake, California. *Hydrobiologia* 466: 31-38.

Meyboom, P. 1966. Unsteady groundwater flow near a willow ring in hummocky terrain. *Journal of Hydrology* 4: 38-62.

Nellis, M.D., J.A. Harrington, Jr. and J. Wu. 1998. Remote sensing of temporal and spatial variations in pool size, suspended sediment, turbidity, and Secchi depth in Tuttle Creek Reservoir, Kansas: 1993. *Geomorphology* 21: 281-293.

Poiani, K.A. and W.C. Johnson. 1991. Global warming and prairie wetlands. *BioScience* 41 99: 611-618.

Ritchie, J.C., P.V. Zimba, and J.H. Everit. 2003. Remote sensing techniques to assess water quality. *Photogrammetric Engineering and Remote Sensing* 69: 695-704.

Rosenberry, D.O. and T.C. Winter. 1997. Dynamics of water-table fluctuations in an upland between two prairie-pothole wetlands in North Dakota. *Journal of Hydrology* 191: 266-289.

Shjeflo. J.B. 1968. Evapotranspiration and the water budget of prairie potholes in North Dakota. *U.S. Geological Survey Professional Paper* 585-B.

Stewart, Robert E., and Harold A. Kantrud. 1971. Classification of natural ponds and lakes in the glaciated prairie region. Resource Publication 92, Bureau of Sport Fisheries and Wildlife, U.S. Fish and Wildlife Service, Washington, D.C. Jamestown, ND: Northern Prairie Wildlife Research Center Online. http://www.npwrc.usgs.gov/resource/wetlands/pondlake/index.htm (Version 16APR1998).

van der Valk, A.G. and C.B. Davis. 1978. The fole of seed banks in the vegetation dynamics of prairie glacial marshes. *Ecology* 59: 322-335.

van der Kamp, G. and M. Hayashi. 1998. The groundwater recharge function of small wetland in the semi-arid Northern Prairies. *Great Plains Research* 8: 39-56.

van der Kamp, G., W.J. Stolte, and R.G. Clark. 1999. Drying out of small prairie wetlands after conversion of their catchments to permanent brome grass. *Hydrological Sciences Journal* 44 (3): 387-397.

van der Kamp, G., M. Hayashi and D. Gallen. 2003. Comparing the hydrology of grassed and cultivated catchments in the semi-arid Canadian Prairies. *Hydrological Processes* 17: 559-575.

Waggoner, S.AZ. 1992. Geologic map of the Coulee Dam 1:100,000 quadrangle, Washington. Open File Report 90-15. Washington Division of Geology and Earth Resources.

Western Regional Climate Center. n.d. Evaporation Stations–Washington. Average Pan Evaporation by State. Tables: Wind, Evaporation, Amount of Sky Cover Information by State for the Western U.S. (Comparative). http://www.wrcc.dri.edu/htmlfiles/westevap.final.html. Accessed 27 June 2009.

White, M.E. 1978. Reservoir surface area from Landsat imagery. *Photogrammetric Enginnering and Remote Sensing* 44(1): 1421-1426.

Winter, T.C. 1989. Hydrologic studies of wetlands in the northern prairie. In p. 16-54 in A. Van der Valk (ed), *Northern Prairie Wetlands*, Iowa State University Press, Ames, IA.

Winter, T.C. 2000. The vulnerability of wetlands to climate change: A hydrologic landscape perspective. *Journal of the American Water Resources Association* 36 (2): 305-311.

Winter, T.C. 2003. Geohydrologic setting of the Cottonwood Lake Area. Pp. 1-24 in T.C. Winter, ed, Hydrological, Chemical, and Biological Characteristics of a Prairie Pothole Wetland Complex Under Highly Variable Climate Conditions–The Cottonwood Lake Area, East-Centerl North Dakota. *U.S. Geological Survey Professional Paper* 1675.

Winter, T.C. and D.O. Rosenberry. 1995. The interaction of ground water with prairie pothole wetlands in the Cottonwood Lake area, east-central North Dakota, 1979-1990. *Wetlands* 15 (3): 193-211.

White, M.E. 1978. Reservoir surface area from Landsat imagery. *Photogrammetric Engineering & Remote Sensing.*
Zuzel, J.F., R.R. Allmaras and R. Greenwalt. 1982. Runoff and soil erosion on frozen soils in northeastern Oregon. *Journal of Soil and Water Conservation*, 37 (6): 351-354.

Figure 1. The Waterville Plateau of the northwestern Columbia Plateau, Washington State. Image from Arc Reader[R].

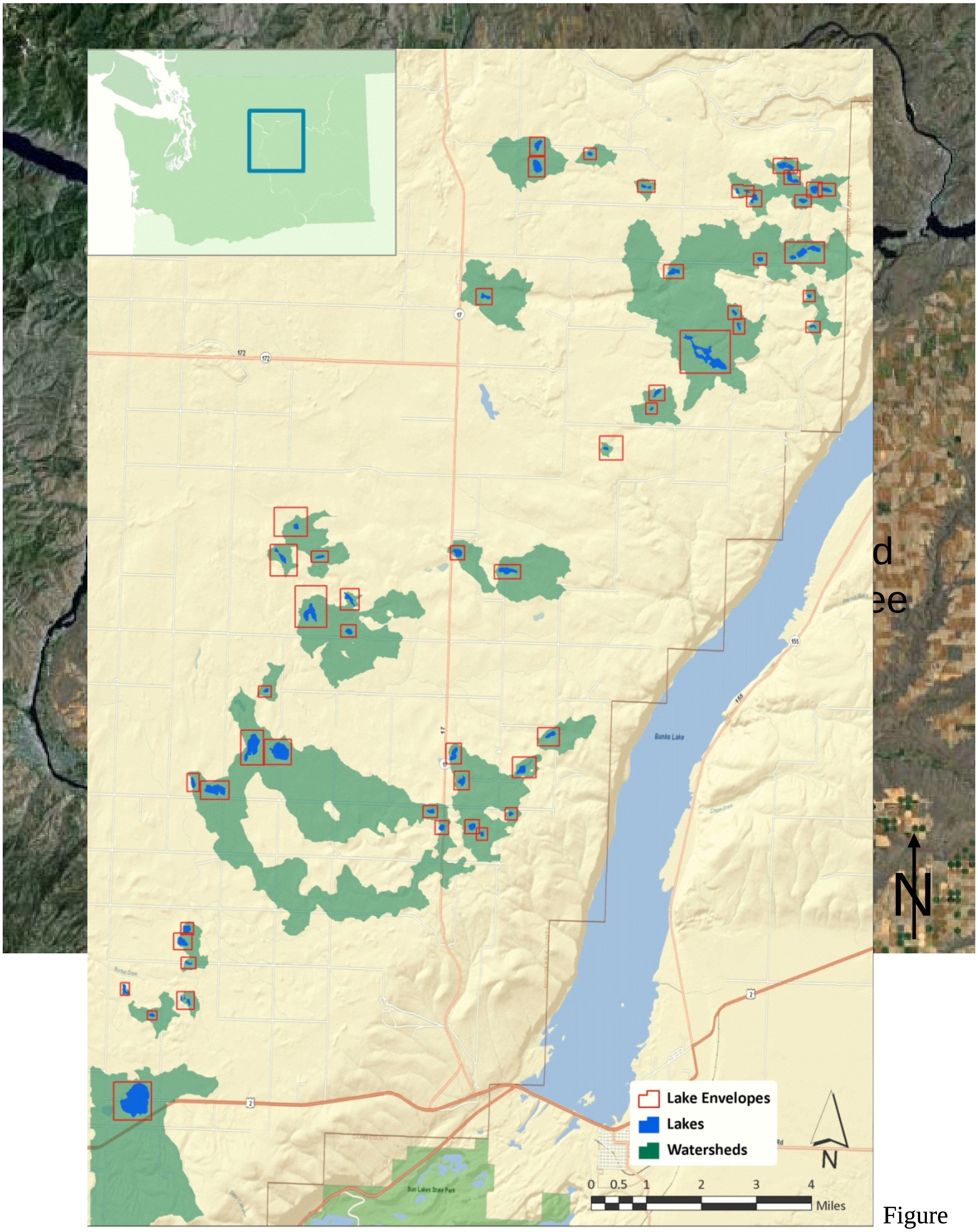


Figure 2.

Eastern Waterville Plateau study area.

Table 1. Excerpt from Lakes table.

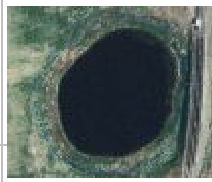
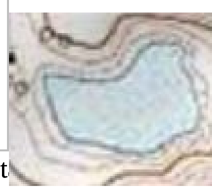
ID	NAIP Thumbnail	USGS 24K Thumbnail	Lake Name	USGS 24K Topo Status	2006 NAIP Status	Lake to Basin Ratio	Approx. Lake Area	Hectare s	Annu Tem
1			None	Dry	Wet	1:10	278263	2.58	47
2			None	Dry	Wet	1:9	152913	1.42	47
3			None	Dry	Wet	1:7	603677	5.6	47

Table 1. E t

Figure 3. Image of the EarthExplorer website. Notice the additional search criteria at the lower left and the inputs for date range.

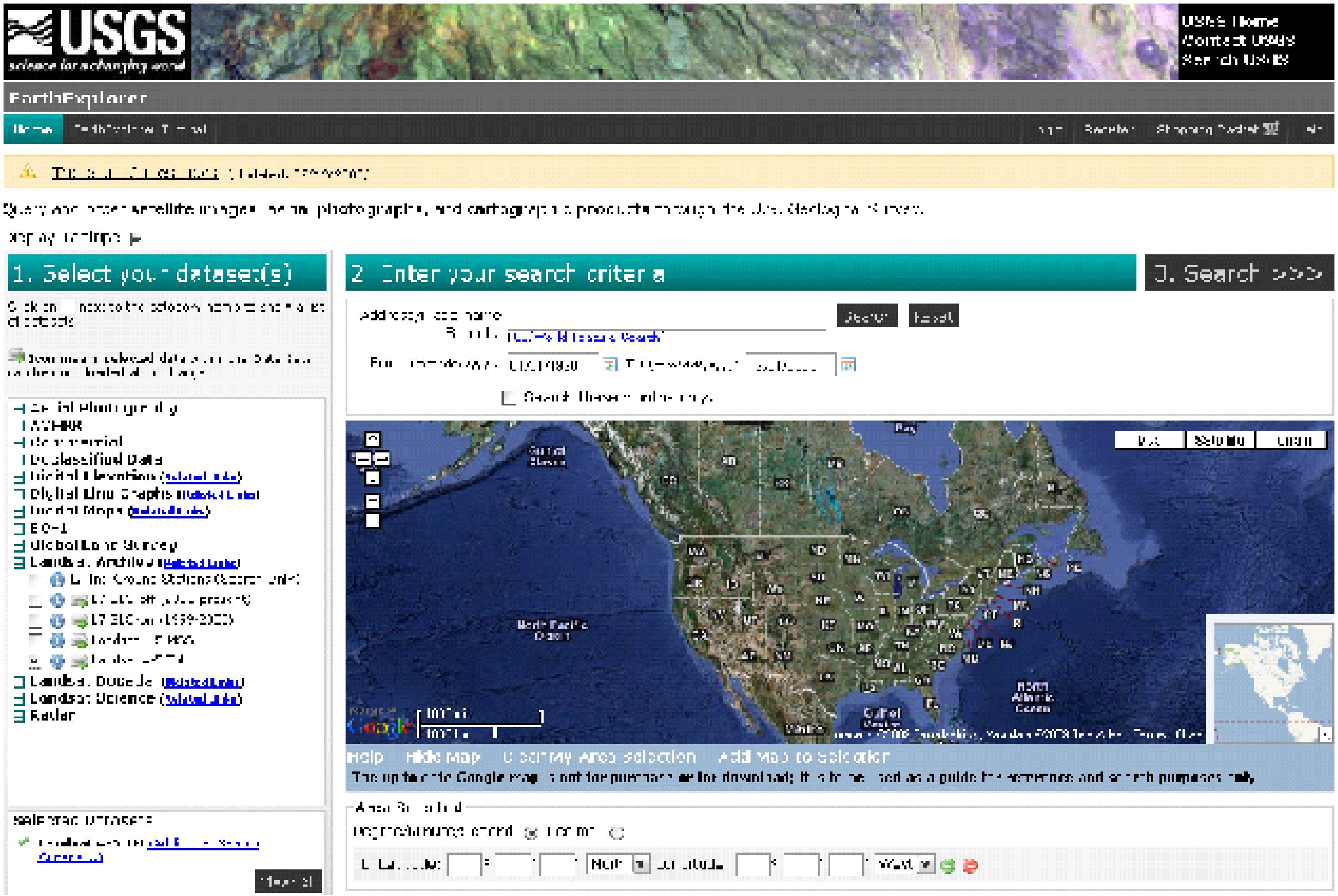


Figure 4. Lake 32 ERDAS Imagine area of interest (AOI).

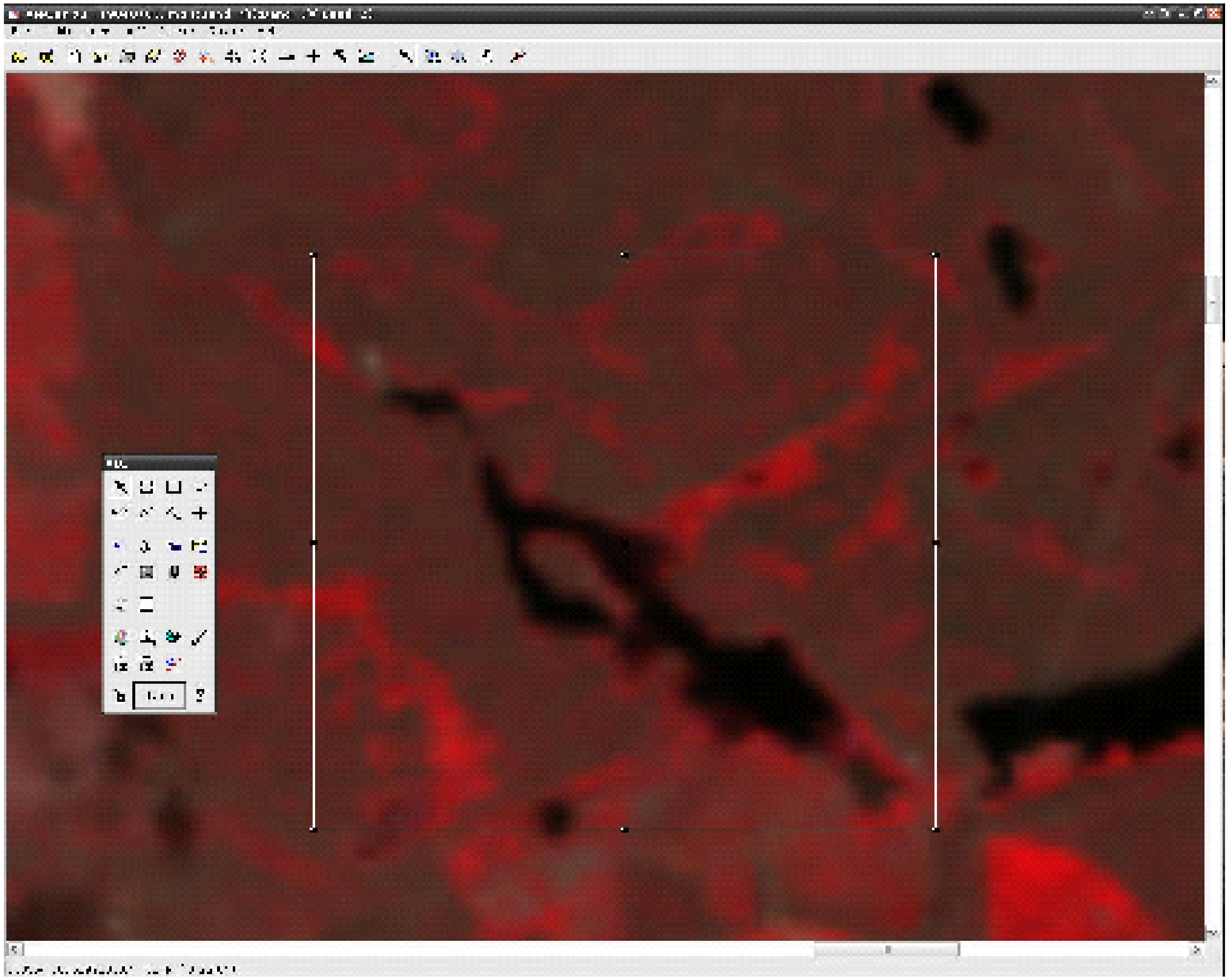


Figure 5. View of the visual inspection stage.

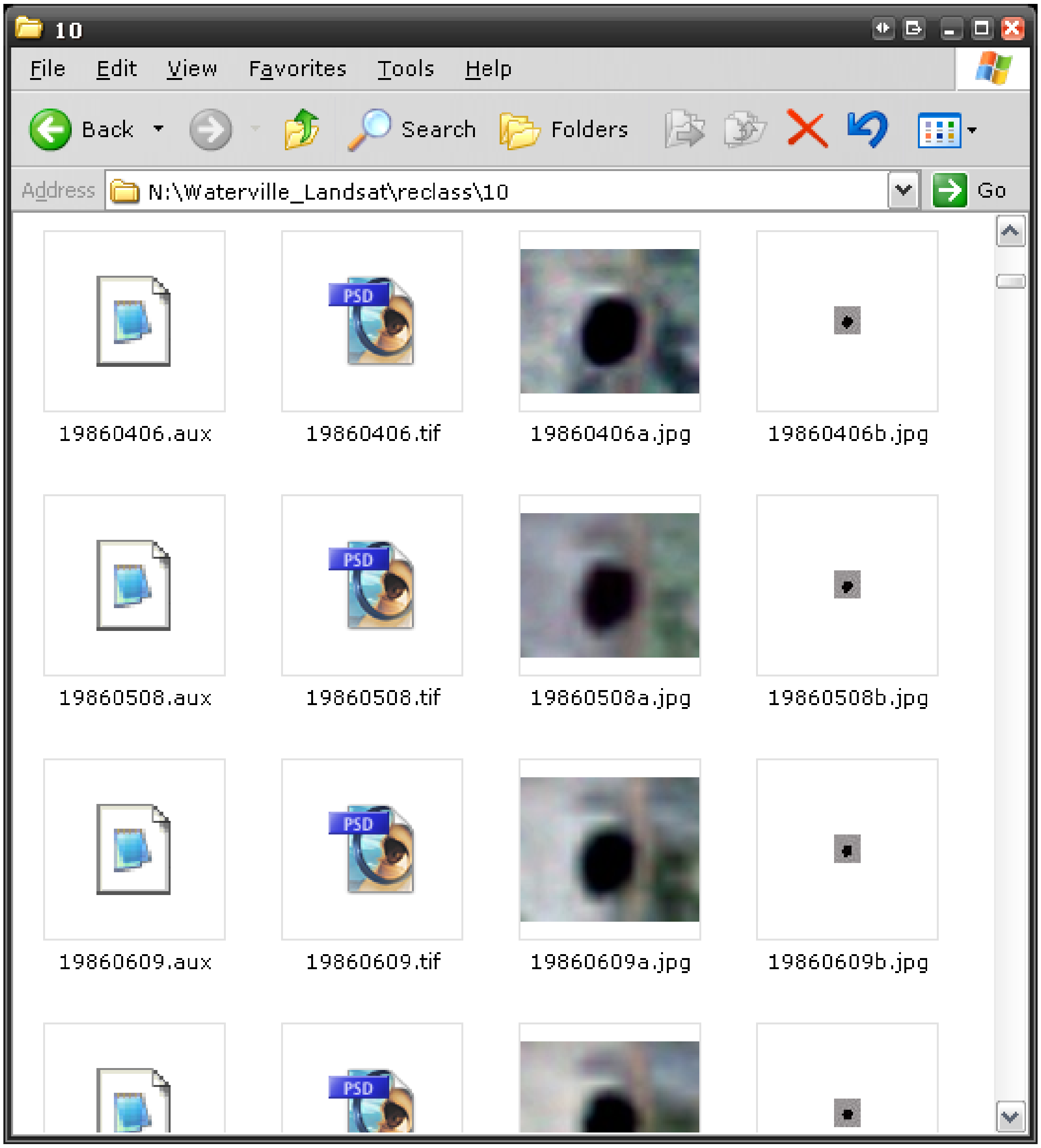


Table 2. Excerpt from the lake area table. Values are in hectares.

Image Date	Lake1	Lake2	Lake3	Lake4	Lake5	Lake6	Lake7
19840705	870	0	210		0	810	6990
19841025			330			2460	
19841212							
19850318		0			0		
19850403		0			0	0	0
19850419		0	0		0	0	0
19850809					0		
19850825	810		180		480	420	6120
19850926	1200	0	300		600	0	6900
19851012	1110	0	330		540	120	6990
19851028	1320	0	360		600	1230	7200
19860201							
19860406	1050	150	510		720	3630	6870
19860422							
19860508	1050	60	420		780	3570	7470
19860524							
19860609	810	0	90		780	3030	7110
19860625	510	0	0		600	2130	6240
19860711	510	0	30		540	1860	6600
19860727	450	0	0		450	1590	6450
19860812	630	0	210		540	1650	6750
19860828							
19860913							
19860929							
19861015	1470	0	390		600	2070	8010
19861031					660	2700	
19861116							

Figure 6. Graph of analysis output for Lake 1.

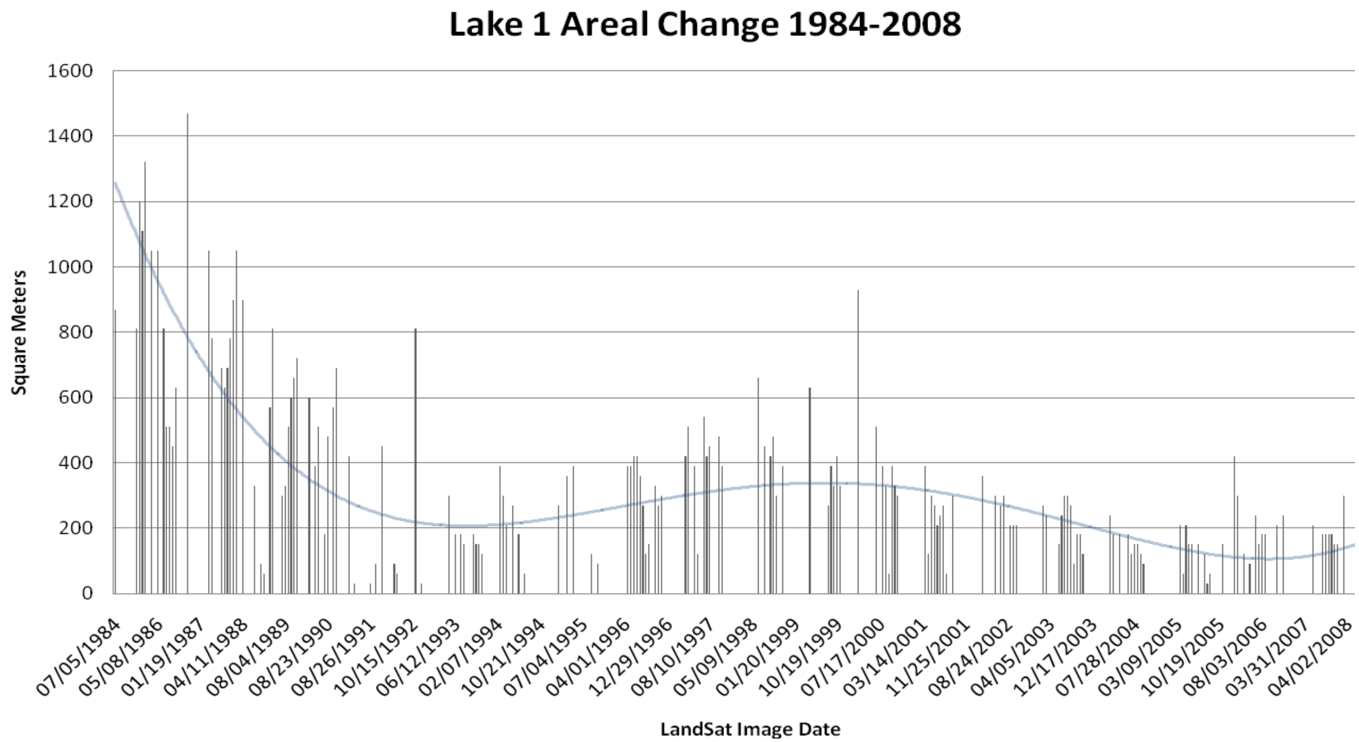


Table 3. Watershed area, pond elevation, watershed relief, geomorphic surface type, and main land use (as of 2007).

Watershed & Pond	Watershed Area (ha)	Pond Elev. (m)	Watershed Relief (m)	Geomorphic Surface Type	Main Land Use (%)
1	25.32	703	19	end moraine	wheat (58)
2	12.85	701	10	end moraine	range (57)
3	36.72	685	25	end moraine	range (59)
5	28.51	665	16	ground moraine	range (64)
6	901.91	667	107	ground moraine	range (77)
7	228.62	662	18	ground moraine	range (98)
8	807.04	668	77	ground moraine	wheat (66)
9	87.68	659	18	ground moraine	range (100)
10	35.85	742	30	end moraine	range (75)
11	33.81	723	37	end moraine	wheat (100)
12	37.80	750	42	end moraine	range (100)
13	84.15	744	44	end moraine	range (78)
14	16.90	766	25	end moraine	range (97)
15	129.88	720	47	end moraine	wheat (96)
17	161.44	707	70	end moraine	wheat (99)
18	74.53	735	34	end moraine	wheat (100)
19	108.48	726	37	end moraine	wheat (100)
21	268.35	671	59	ground moraine	wheat (57)
23	13.56	658	20	ground moraine	range (100)
24	77.16	653	25	ground moraine	range (100)
25	43.36	655	23	ground moraine	range (100)
26	107.82	634	40	ground moraine	range (82)

Watershed & Pond	Watershed Area (ha)	Pond Elev. (m)	Watershed Relief (m)	Geomorphic Surface Type	Dominant Land Use
27	10.64	689	29	ground moraine	range (100)
30	78.97	693	24	scabland	range (98)
31	31.73	692	16	scabland	range (100)
32	882.33	622	95	scabland	range (92)
33	14.29	693	21	scabland	range (100)
34	26.46	700	18	scabland	range (100)
36	367.16	646	64	scabland	range (100)
37	73.65	666	40	scabland	range (98)
38	31.40	683	38	scabland	range (100)
39	48.38	701	28	scabland	range (64)
40	241.91	662	57	scabland	range (91)
42	100.68	684	23	scabland	range (100)
43	47.51	680	26	scabland	range (95)
44	26.76	683	26	scabland	range (94)
45	25.82	681	27	scabland	range (100)
46	51.65	671	27	scabland	range (89)
48	21.28	672	15	scabland	range (100)
49	24.5	662	21	scabland	range (100)
50	50.03	659	19	scabland	range (100)
51	148.31	640	35	scabland	range (66)
52	117.11	645	31	scabland	range (80)
53	3159.54	720	84	end moraine	wheat (93)
54	455.08	659	38	ground moraine	range (98)
55	88.62	664	56	ground moraine	range (79)
57	71.74	684	14	scabland	range (100)

Watershed & Pond	Watershed Area (ha)	Pond Elev. (m)	Watershed Relief (m)	Geomorphic Surface Type	Dominant Land Use
58	9.95	703	13	end moraine	wheat (54)
59	83.48	705	24	end moraine	range (93)
60	24.84	683	17	end moraine	wheat (100)
61	126.81	659	29	ground moraine	range (100)
62	128.62	626	52	ground moraine	wheat (53)

Figure 7. Timing of wetland pond area maxima. Represents the number of ponds at their maximum levels over the 1986-2007 period.

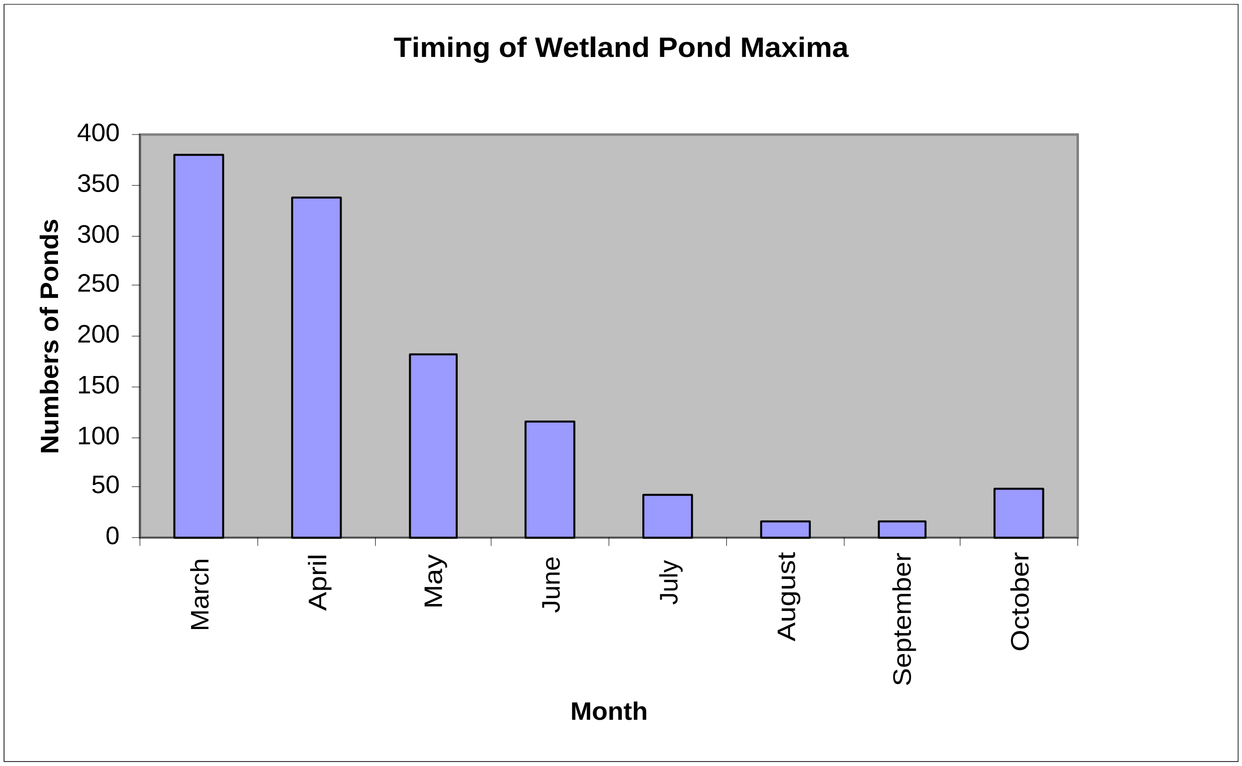


Figure 8. Timing of wetland pond area minima. Represents the number of ponds at their minimum levels over the 1986-2007 period.

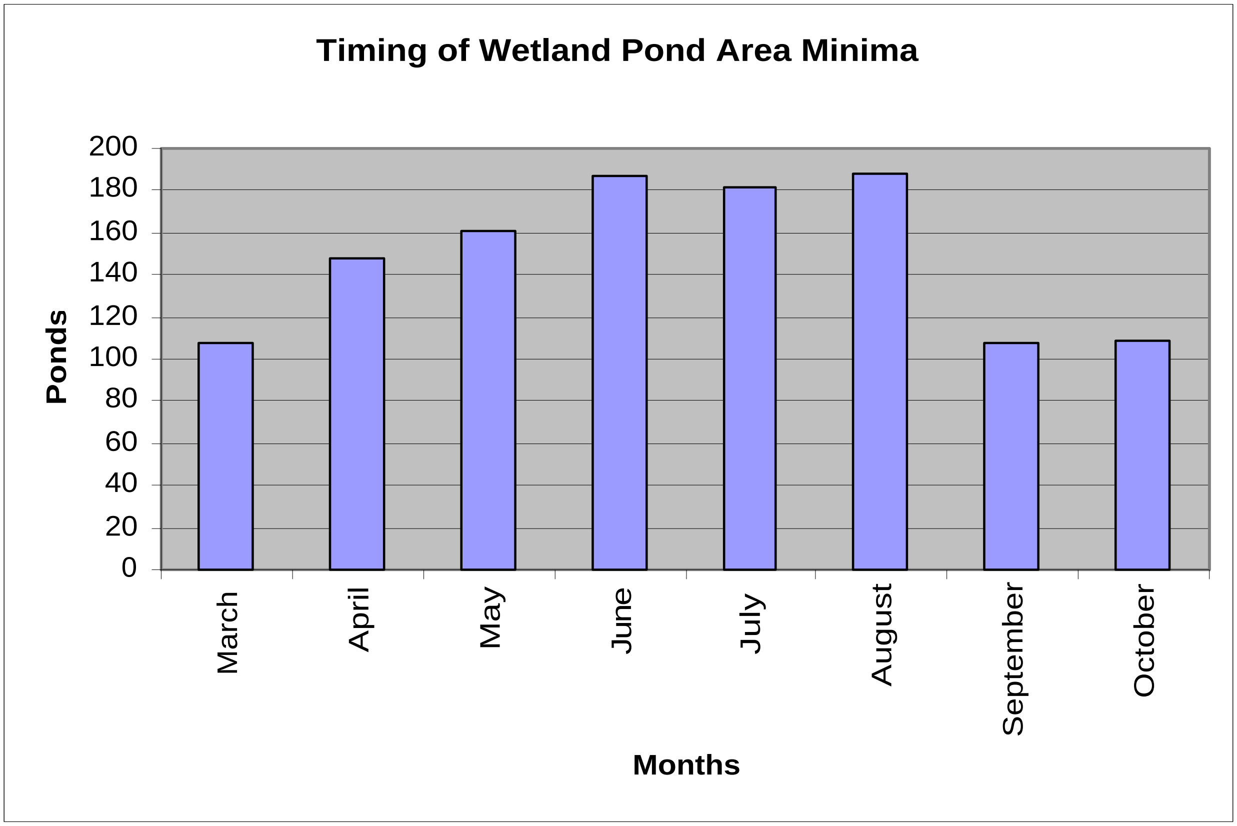


Figure 9. Cumulative maximum pond area stratified by end moraine surface type.

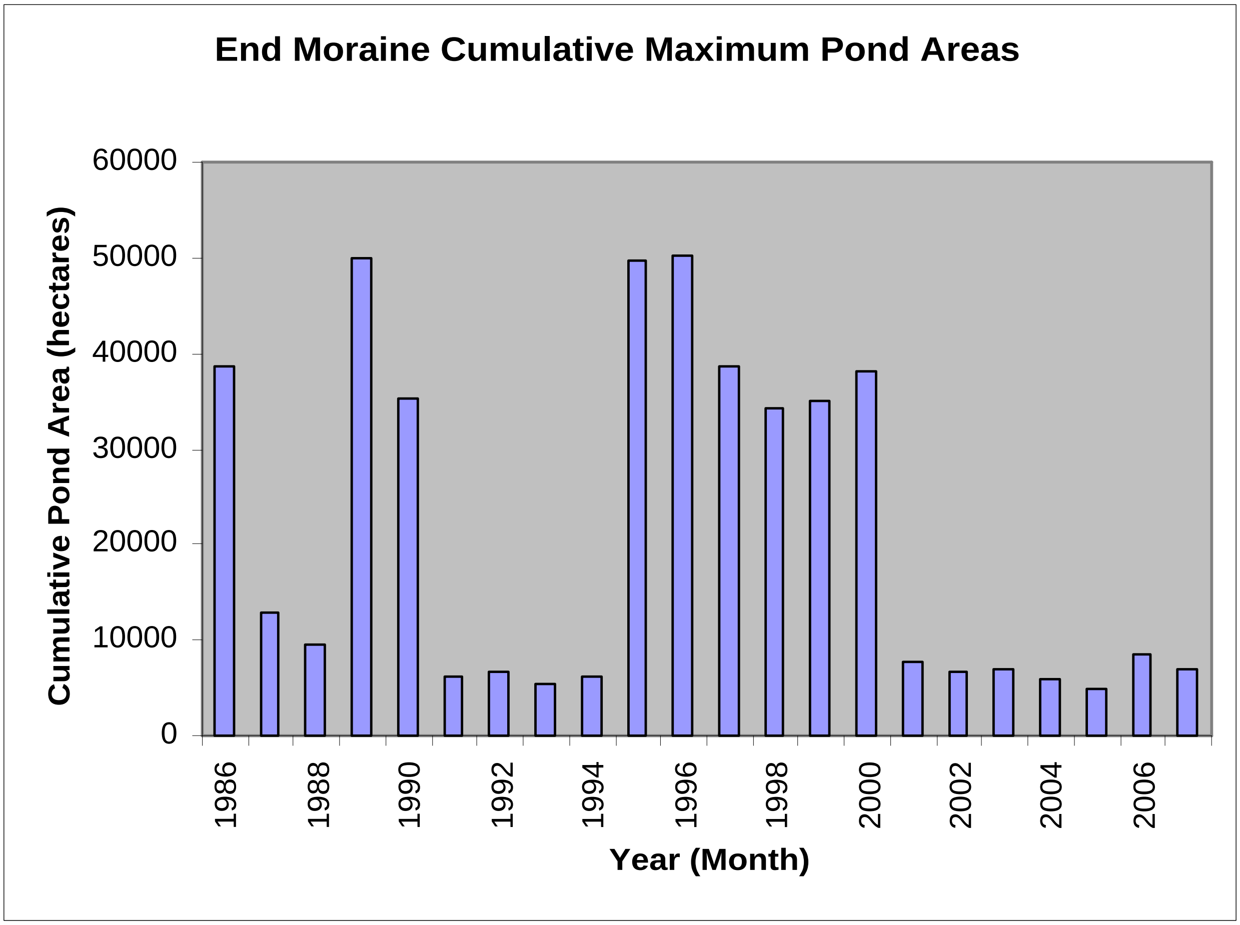


Figure 10. Cumulative maximum pond area stratified by ground moraine surface type.

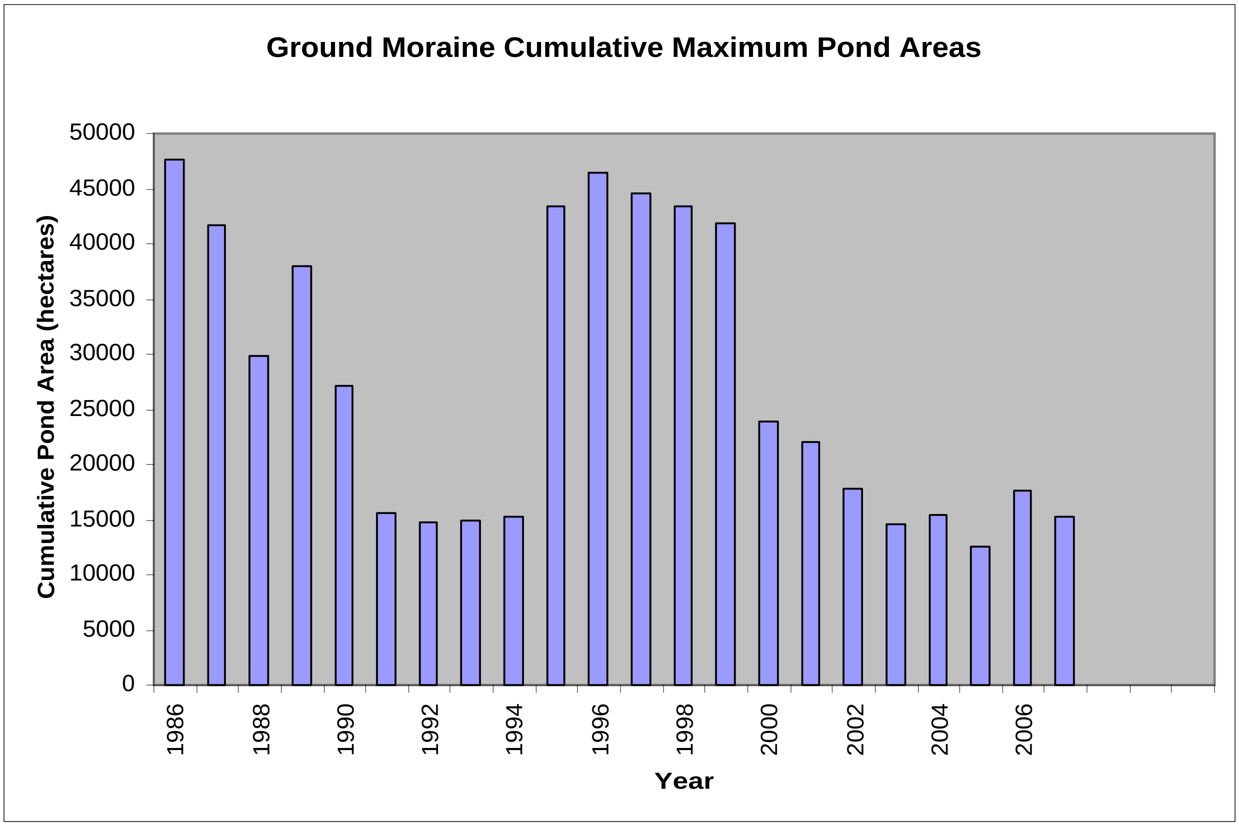


Figure 11. Cumulative maximum pond area stratified by scabland surface type.

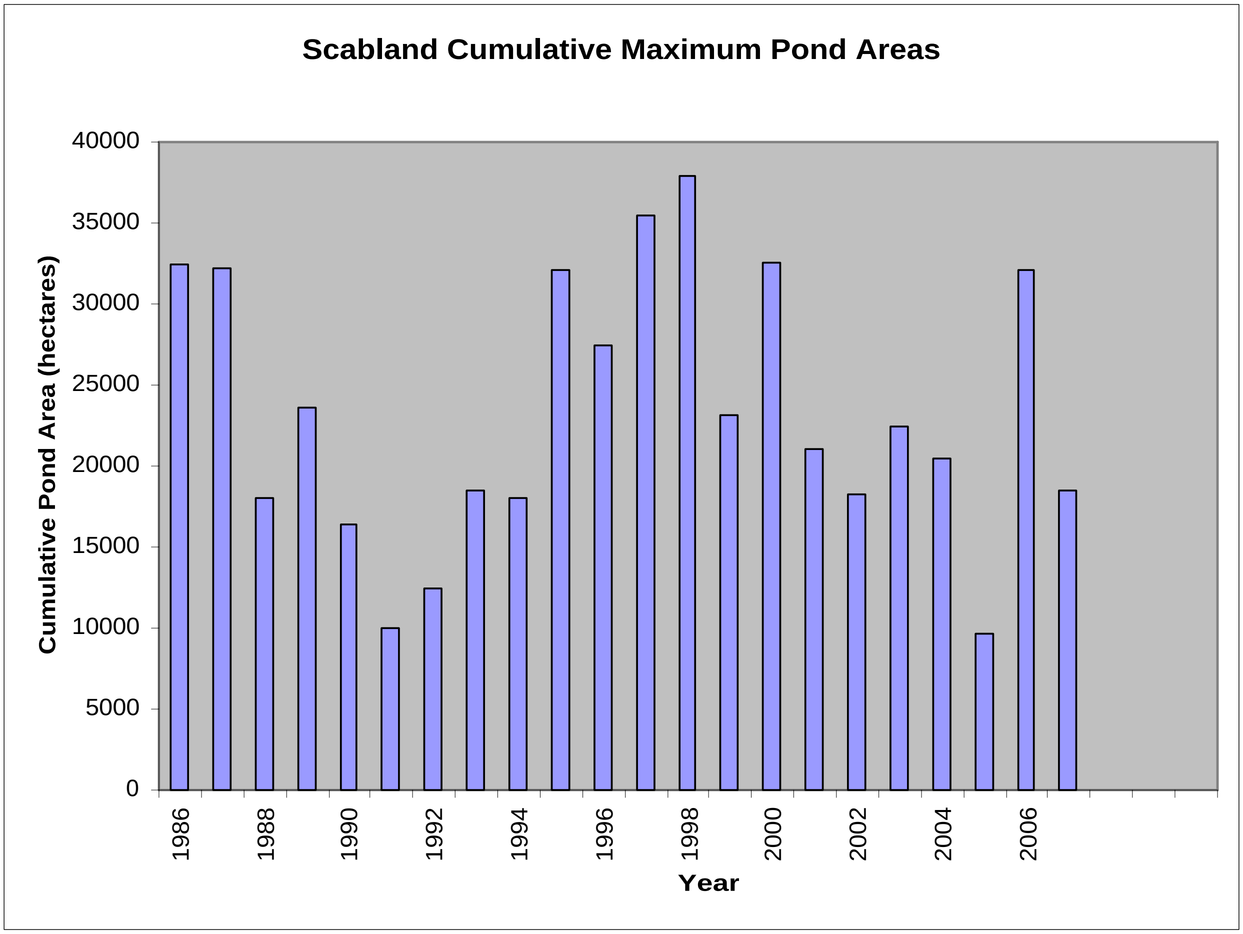


Table 5. Spearman rank correlations and associated significance (P) values of cumulative

	EM[1] Max Pond Area	GM[2] Max Pond Area	SL[3] Max Pond Area	Precip	Snowfall	EM[1] Wheat	GM[2] Wheat
GM[2] Max Pond Area	0.8634						
P-value	0.0000						
SL[3] Max Pond Area	0.6781	0.6917					
P-value	0.0007	0.0005					
Precip	0.4142	0.3001	0.4352				
P-value	0.0560	0.1732	0.0435				
Snowfall	0.2468	0.3868	0.5517	0.5194			
P-value	0.2648	0.0754	0.0086	0.0143			
EM[1] Wheat	0.0018	0.0453	0.1925	0.0332	0.1092		
P-value	0.9920	0.8404	0.3861	0.8799	0.6246		
GM[2] Wheat	-0.0018	0.0453	0.1925	-0.0332	-0.1092	-1.0000	
P-value	0.9960	0.8404	0.3889	0.8839	0.6282	0.0000	
SL[3] Wheat	0.0018	0.0453	0.1925	0.0332	0.1092	1.0000	-1.0000
P-value	0.9920	0.8404	0.3861	0.8799	0.6246	0.0000	0.0000

Figure 12. Average maximum temperatures over study period.

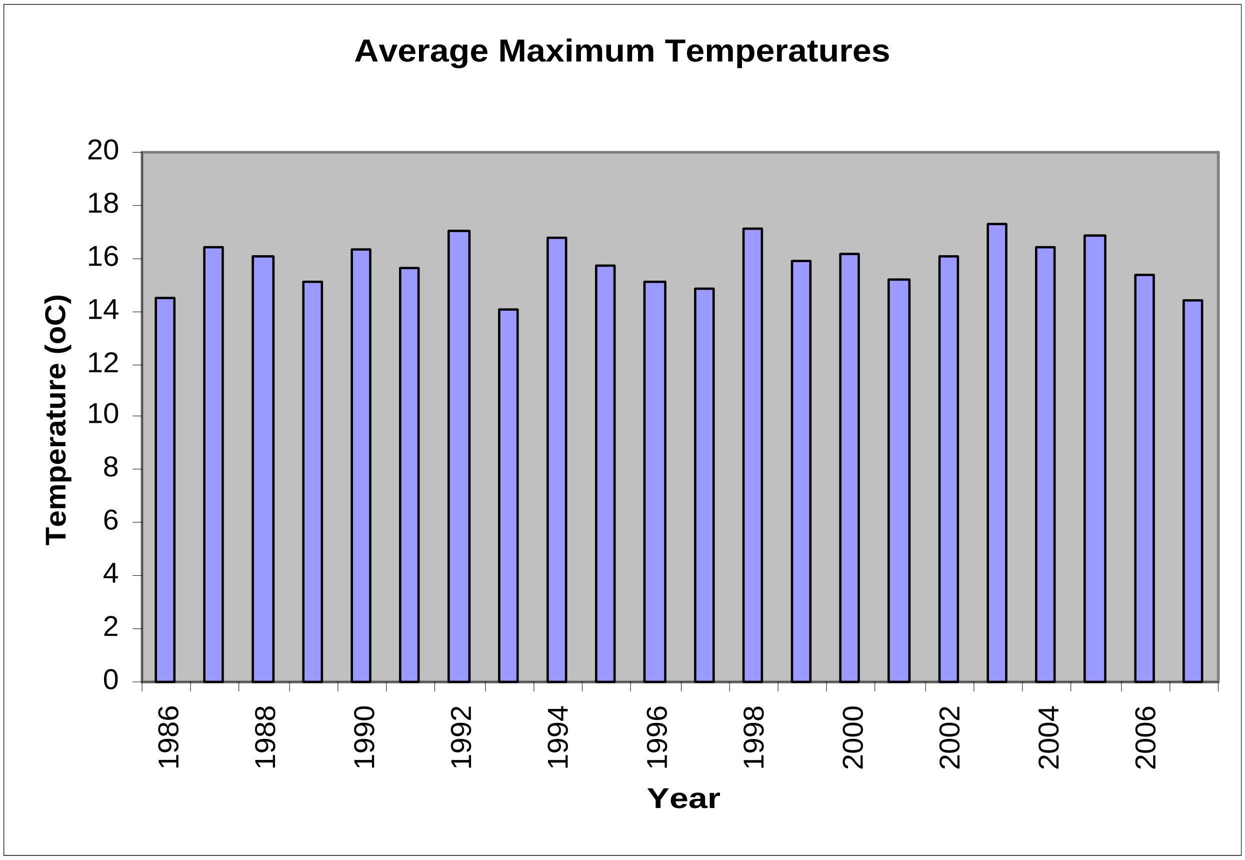


Figure 13. Average minimum temperatures over study period.

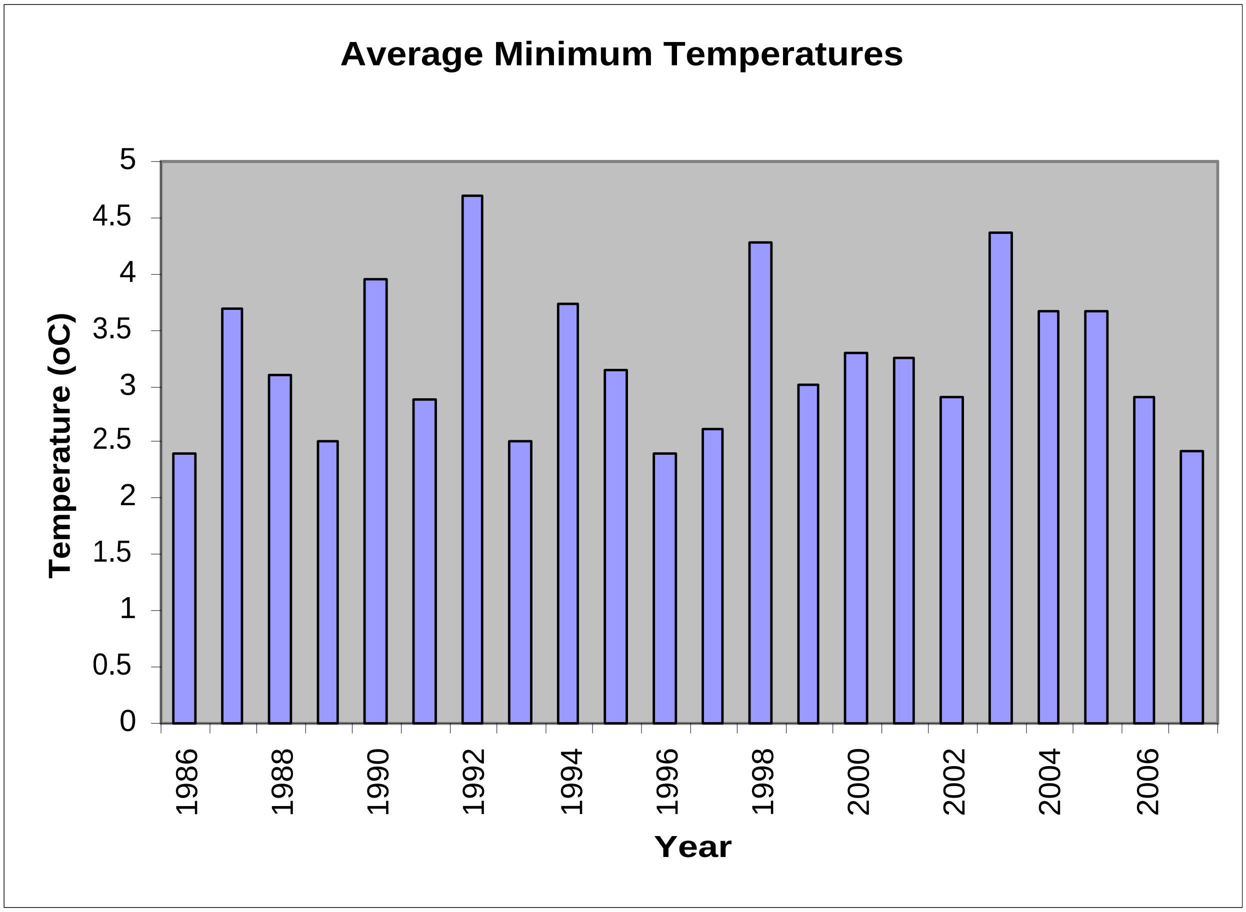


Figure 14. Total annual precipitation over study period.

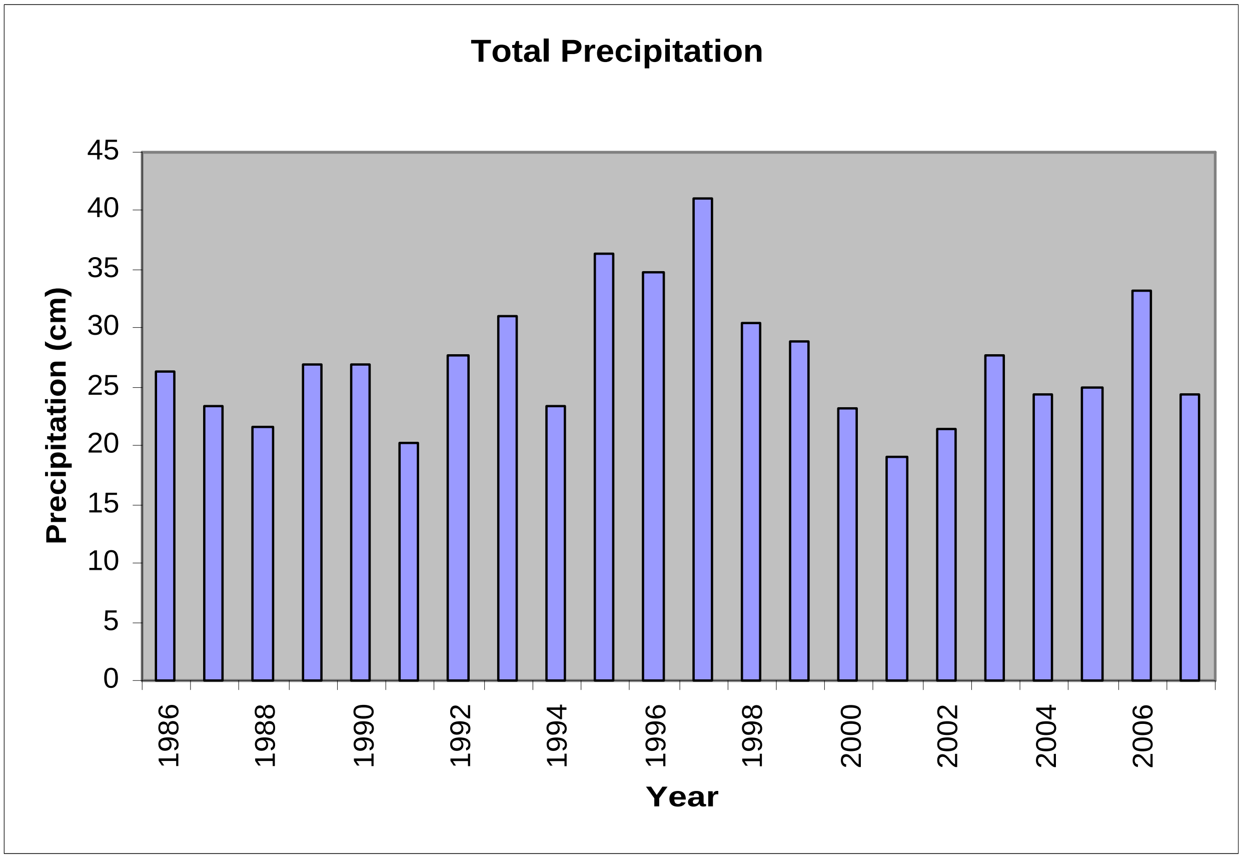


Figure 15. Total annual snowfall at Waterville, Washington over the study period.

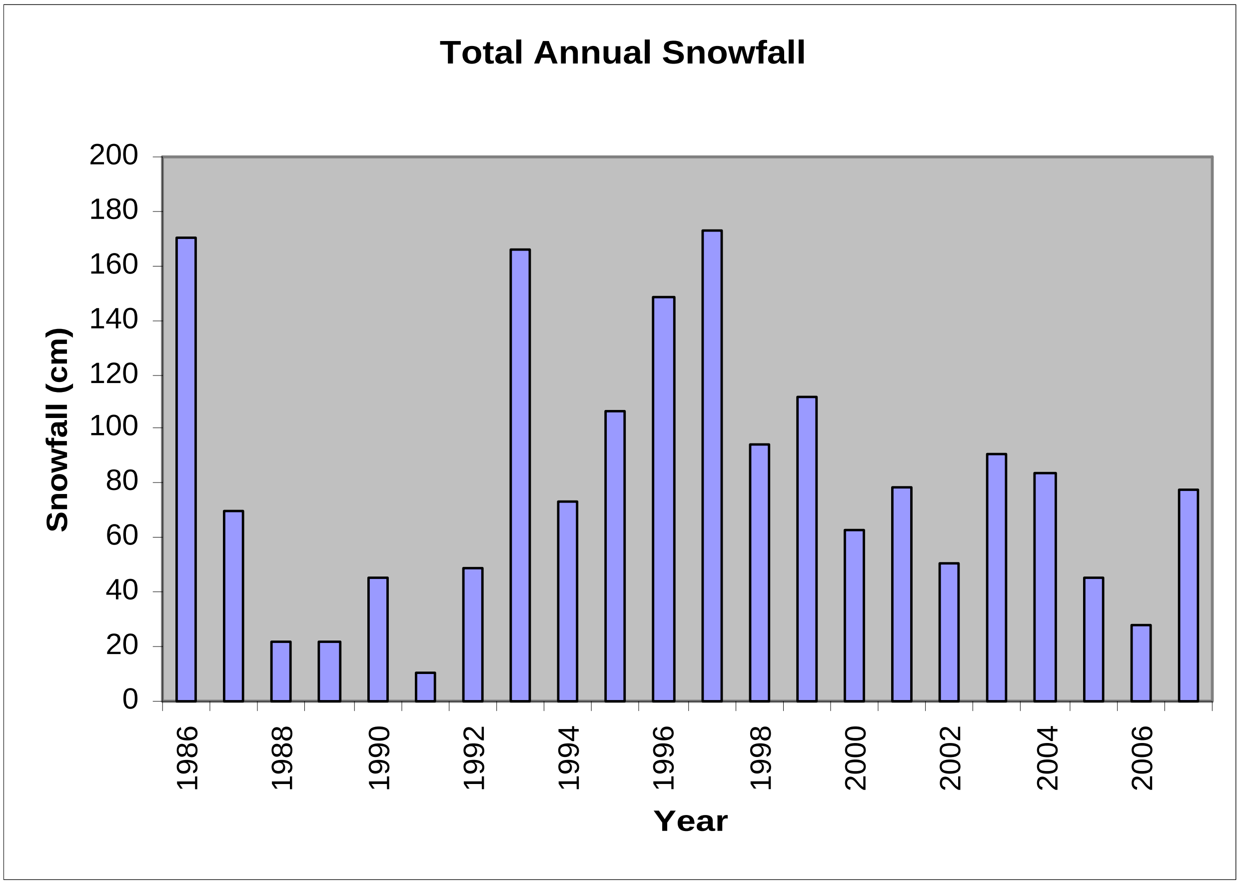


Figure 16. Percentage of farmland in end moraine watersheds over study period.

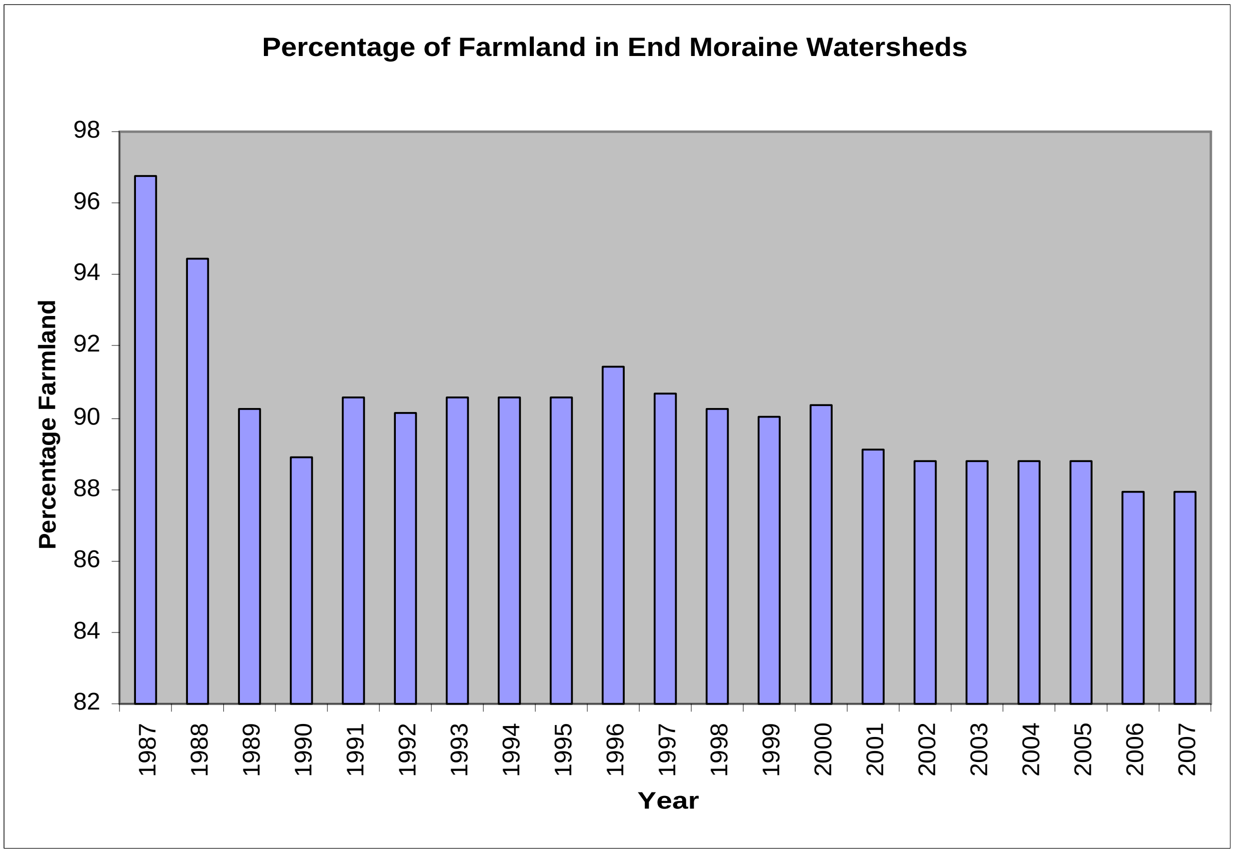
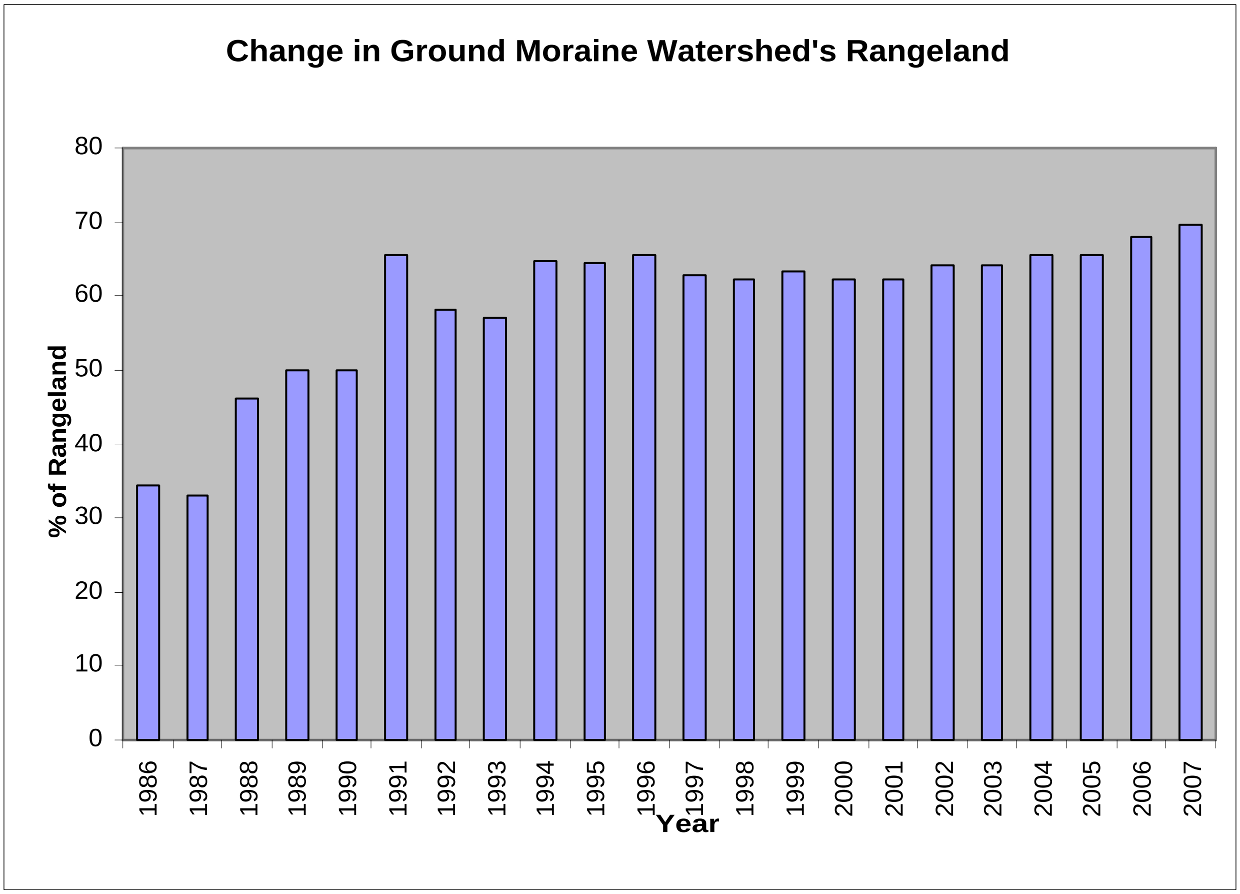


Figure 17. Percentage of farmland in ground moraine watersheds over study period.



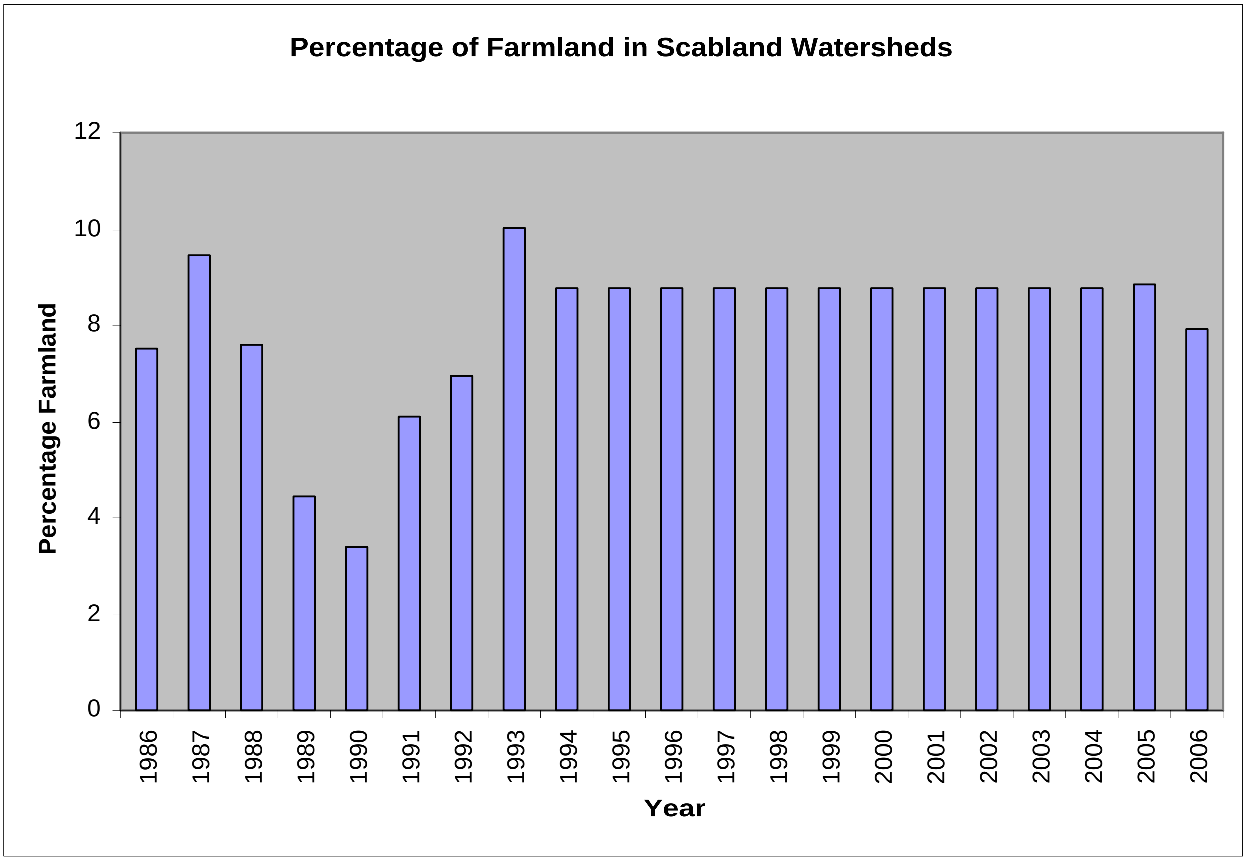


Figure 18. Percentage of farmland in scabland watersheds over study period.