Hydrologic Response of Surface Waters in the Prairie Pothole Region to Climate Variability

DISSERTATION

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Abstract

The 950,000 km$^2$ Prairie Pothole Region (PPR) of central North America contains millions of surface water bodies in the form of lakes, wetlands, and ponds. These water bodies provide irreplaceable services to maintain the stability and sustainability for the wildlife, ecosystems, water resources, agriculture, and the economy. Because most of them are hydrologically “closed”, the water bodies are extremely sensitive to climate variability and are highly dynamic in terms of their numbers, water levels, areas, and storage. The ultimate goal of this study is to provide a better understanding of the dynamic hydrologic response of the water bodies in the PPR to variability in climate. To achieve this goal, three individual studies have been conducted.

In the first study, a hydrologic model, capable of simulating surface water complexes comprised of tens-of-thousands or more individual closed-basin water bodies, was developed to simulate the hydrologic response of water bodies to climatic variability over a 105-year period (1901-2005) in an area of the PPR in North Dakota. Simulation results over the last century showed that the area-frequency power laws for water bodies changed intra-annually and interannually as a function of climate. Major droughts and deluges were shown to produce marked variability in the power-law functions. Analyses also revealed the frequency of occurrence of small potholes and puddles did not follow
pure power-law behavior with the departure from linear behavior closely related to the climatic conditions.

Next, a space-for-time (SFT) substitution approach was developed for the hydrologic study of the PPR water bodies. Evidence from a suite of surface-water complexes along a climate gradient in the PPR was used to validate the SFT substitution. Comparison of spatial and temporal trends in water-body population dynamics revealed a common response to climate variability in space and time. Findings on the validity of SFT substitution in hydrologic systems not only answered an important science question in its own right, but improved my understanding of climate-forcing and hydrologic-response mechanisms. This study also has important regional-scale implications, for the first time, providing a complete picture of the heterogeneous spatial and temporal water-body distribution across the entire PPR and revealing how these distribution patterns vary with changing climate.

Third, a new concept on integrated climatic forcing was developed and applied to elucidate the controlling factors on lake/wetland hydrologic dynamics. Currently, the existing paradigm is that lakes/wetlands can accurately track climate variations. Data on several closed-basin lakes and wetlands, however, implied that disparities in timing and magnitude exist between lake/wetland and climate records. It was found that what is important in determining the hydrologic behavior of lakes or wetlands is not the present climate signal but the cumulative history, with a memory that fades following exponential-decay trajectory at scale-dependent rates as time passes. Findings from this study provide a better understanding of mechanisms on how lakes/wetlands respond as a
function of climate and, therefore, hold considerable promise for improving the quality of climate reconstruction.
To my family
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Chapter 1: Introduction

The Prairie Pothole Region (PPR) of central North America is a “unique and extraordinary biome\(^1\)”. Before widespread agricultural development, “it was part of one of largest grassland ecosystems on earth\(^1\)”\(^{1}\). This 950,000 km\(^2\) region extends from southern Canada, including Alberta, Saskatchewan, and Manitoba to the United States including Montana, North Dakota, South Dakota, Minnesota, and Iowa. The PPR is the brooding area for more than half of North America’s migratory ducks, making it “one of the most ecologically valuable freshwater resources of the Nation” [Guntenspergen et al., 2006].

Numerous water bodies in the form of pothole lakes, wetlands, and ponds, are scattered across this region. They commonly occur in small closed basins or potholes formed by the uneven deposition of glacial till [Euliss et al., 1999]. The exact numbers of the water bodies in the PPR are unknown but could easily be several million [Larson, 1995] with densities in some areas >100 per km\(^2\) [Last and Ginn, 2005]. These water bodies are important for agriculture, recreation, and groundwater recharge, and play important roles in water purification, flood control, carbon sequestration, as well as preservation of local water quality [Kantrud et al., 1989; Euliss et al., 2006]. Recent

research also suggests that such surface waters can influence precipitation patterns both locally and regionally [Taylor, 2010].

The climate of the PPR is continental - subhumid to semiarid with short hot summers, long cold winters, low levels of precipitation, high evaporation, and interannual variation between wet and dry periods. Mean annual temperature ranges from approximately 1°C in the north to nearly 10°C in the south, while mean annual precipitation ranges from 30 cm/yr in the northwest (Alberta) to nearly 90 cm/yr in the southeast (Iowa) [Millett et al., 2009]. The prairie lakes, wetlands, and ponds in the PPR are mostly isolated from stream networks. Major inflows of water come from snow melt and summer precipitation, whereas the greatest loss of water is due to evaporation [Winter et al., 2001]. Owing to these hydrologic features, the natural ecosystems of the PPR are extremely sensitive to seasonal and interannual climate variability and will likely be impacted by projected changes in climate [e.g., Fritz, 1990; LaBaugh et al., 1996; Winter and Rosenberry, 1998; Johnson et al., 2005; Millett et al., 2009]. For example, Sorenson et al. [1998] suggested that global warming could reduce the number of ponds available for breeding ducks from 1.6 million to 0.6 million in the north-central United States. Larson [1995] determined that climate-change impacts on potholes in the northerly parkland ecoregion of Canada will be even more severe than those projected for the United States. These potential impacts give rise to an important set of science questions in their own right. Yet, before these can be adequately addressed, there is a need to better understand how these water bodies respond to climate.
To date, most studies of lakes and wetlands in the PPR have relied on careful observations or simulations of individual or a few clusters of pothole lakes and wetlands [e.g., Crowe and Schwartz, 1981a, 1981b; Poiani et al., 1996; Winter and Rosenberry, 1998; Su et al., 2000; Johnson et al., 2005, 2010]. An emerging grand challenge for hydrologists is describing and understanding the complex processes at work in large surface water systems with serious impacts from climate and human activities. As the community begins to understand the dimensions of these problems, there is a realization that conventional investigative approaches are inadequate, because of constraints imposed by conventional observational and modeling approaches.

Our focus is on the surface water complexes of the PPR, comprising tens-of-thousands of water bodies ranging in size from a few square meters to several tens of square kilometers and encompassing a range of climates from arid southern Saskatchewan to much moister central Minnesota. The overall goals of this study are (1) to better understand the dynamic hydrologic response of the surface water complex to variability in climate, (2) to elucidate the behavior of water bodies of different sizes as well as the importance of smaller lakes (less than 0.01 km$^2$ in area) in the regional hydrologic cycle, and (3) to apply the knowledge to explain the hydrologic conditions of the Dust Bowl Drought in the 1930s and the implications for future droughts.

To accomplish these goals, the study will rely on the integrated application of newly developed observational and theoretical approaches for the investigation of hydrologic systems at large scales. The integrated usage of various approaches and theories in this study, including mathematical modeling, remote sensing and GIS, space-
for-time substitution, power law, and evolutionary optimization, has great potential to open up new areas of inquiry and has tremendous potential for filling in important historical data and information gaps. For example, the retrospective examination of the Dust Bowl drought has the potential to redefine knowledge of the severity and duration of this important drought period, and to provide a basis for assessing the impact of a sustained drought on the pothole lakes and wetlands. In addition, the outcome of this study highlighting the complex interrelationships between space/time variability in climate and surface water behavior will appeal to a broad cross-section of interested researchers.

The dissertation is organized as a series of papers, one of which has been published. Chapter 2, titled “An integrated observational and model-based analysis of the hydrologic response of prairie pothole systems to variability in climate”, describes a newly developed pothole complex hydrologic model that is capable of simulating the hydrologic behavior of a complex comprised of tens-of-thousands or more water bodies. The chapter also demonstrates the application and efficacy of such a model coupled with observations from space in elucidating the behavior of a large complex of potholes along the Missouri Coteau in North Dakota through the 20th Century. This part of the study particularly focuses on power-law approaches as a basis for organizing the study of complex surface-water systems and for presenting results in a straightforward manner.

Chapter 3 is titled: “When prairie potholes go dry: evaluation of climate impacts with space-for-time substitution”. Generally, this study tries to answer the question as to whether space-for-time substitution, a widely used approach in ecology and
geomorphology, can be applied to solve problems in hydrology. Specifically, this chapter tests the validity of the space-for-time substitution, and examines how space-for-time substitution can elucidate long-term hydrological responses of closed-basin, wetland/pothole systems through time.

With a title of “Time lags in the adjustment of closed-basin water bodies to climate fluctuations”, the study described in Chapter 4 will examine controlling factors of lake/wetland hydrologic dynamics. Overall, it is designed to understanding of the relationships between the responses of lakes/wetlands and climatic forcings. One of the unique features of this study is that it aims to provide a new concept, i.e., integrated climatic forcing, to quantitatively examine the influences of climate on water-body hydrology (in terms of water level), while revealing the depth of memory integrating the proceeding climatic conditions.
Chapter 2: An Integrated Observational and Model-based Analysis of the Hydrologic Response of Prairie Pothole Systems to Variability in Climate

2.1 Introduction

There has been an emphasis recently on developing a quantitative description of the numbers and size-distribution of lakes around the world. What is emerging is a rather robust scaling theory based on power laws [e.g., Birkett and Mason, 1995; Meybeck, 1995; Lehner and Doll, 2004; Downing et al., 2006; Zhang et al., 2009a] that provides an ability to examine the function of such lakes in a new and different way. Moreover, power-law concepts have proven to be extremely useful in describing the behavior of water bodies in the PPR [Zhang et al., 2009a]. That work, based on Landsat observations, showed how water bodies in the Waubay Lakes area of South Dakota follow well-defined power laws that change intra-annually and interannually as a function of climate. These observation-based approaches are a useful complement to more traditional, field-based characterizations on clusters of pothole lakes and wetlands [e.g., Winter and Rosenberry, 1998]. Yet, there are limitations with satellite observations given the relatively short observational record, limited resolution, and need for cloud-free images. More generally, satellite-based monitoring approaches, like those of Zhang et al. [2009a, 2009b], cannot quantitatively describe water transfers and emphasize the need for more quantitative approaches.
An overlooked area in the study of water-body populations is the large numbers of small ponds and puddles that likely contain a small, but significant fraction of stored surface waters. These small water bodies are an enigma, however, because their size and numbers defy direct counting, and because they are commonly dry during some parts of a year. It could be expected then that power laws will have a lower limit of validity imposed by the behavior of these smaller water bodies that fluctuate on an intra-annual and interannual basis. Knowledge concerning the existence and behavior of such limits is tremendously important in providing a complete quantitative understanding of the volumes of water stored in surface waters.

Mathematical models have traditionally provided a powerful approach in the analysis of hydrologic systems. They facilitate quantitative explorations of the behavior of systems in terms of underlying processes and parameters, and provide a framework for extrapolating system behavior to evaluate future stresses [e.g., Crowe, 1993; Johnson et al., 2005]. Various lumped-element models have been remarkably successful in modeling the hydrologic response of lakes and wetlands [e.g., Crowe and Schwartz, 1981a, 1981b, 1985; Su et al., 2000], and hydrologic responses coupled with vegetation dynamics [e.g., Poiani et al., 1996]. Lake/wetland systems can also be simulated using more physically rigorous, distributed hydrologic models [e.g., Yu and Schwartz, 1995, 1998; Panday and Huyakorn, 2004; Sudicky et al., 2005]. These approaches are based on coupled solutions of surface/subsurface flow equations with a physically realistic description of processes. However, their use has been constrained by overall complexity of use, difficulties in calibration, extensive data requirements, and an often rigid geometry imposed by grid
blocks. An important next step with modeling potholes is in simulating problems involving tens-of-thousands or more water bodies, i.e., complexes of wetlands, which are characterized by huge observational data bases.

This chapter aims to develop an improved understanding of the dynamic hydrologic response of a pothole complex to variability in climate, and to elucidate the behavior and the importance of smaller water bodies (less than 0.01 km$^2$ in area) in the regional hydrologic cycle. It particularly focuses on power-law approaches as a basis for organizing the study of complex surface-water systems and for presenting results in a straightforward manner. The first objective of this chapter is to describe a pothole complex hydrologic model (PCHM) that is capable of simulating the hydrologic behavior of a complex comprised of tens-of-thousands or more water bodies. The second objective is to demonstrate the application and efficacy of such a model in elucidating the behavior of a large complex of potholes along the Missouri Coteau of the PPR in North Dakota (Figure 2.1) through the 20$^{th}$ Century. The third objective is to investigate power-law behavior especially considering small potholes and puddles. The study results presented here should contribute to a better understanding of the linkages between climate and the prairie pothole complex, fill in important historical data and information gaps, especially concerning the Dust Bowl drought, and provide an opportunity to raise awareness about the role and importance of small water bodies in water-resource inventories.
2.2 Methodology

This study makes use of the newly developed PCHM to simulate hydrologic response of a complex of pothole water bodies with water areas ranging over more than five orders of magnitude from lakes to puddles. Here, I classify potholes into two groups based on the size of their water area: large potholes and small potholes. Large potholes are the water bodies with area $> 1 \times 10^4 \text{ m}^2$. Pothole lakes are included in this group as bodies with areas $\geq 1 \times 10^5 \text{ m}^2$ and depths $> 2 \text{ m}$ [Sloan, 1972]. Small potholes are the water bodies with area $\leq 1 \times 10^4 \text{ m}^2$. Puddles are distinguished by water areas of $< 250 \text{ m}^2$ and short lifetimes (e.g., one or two months).
2.2.1 Pothole Complex Hydrologic Model

PCHM is derived from a lumped element, lake-watershed model \cite{Crowe1981a, Crowe1981b, Crowe1985}, capable of simulating the hydrologic responses of a lake-watershed system as a function of precipitation \(P\), temperature, evapotranspiration \(ET\), and the physical setting. The model simulates the routing of water through an idealized watershed to a closed-basin lake. As demonstrated in Figure 2.2, it incorporates key hydrologic processes, evapotranspiration, runoff, infiltration, and groundwater flow to provide a monthly accounting of inflows to, and outflows from a single water body. Knowing the geometry of the lake/wetland basin, these fluxes can be interpreted in terms of monthly water area and stage. In the system, water is assumed to be stored in ‘units’, which correspond to components of the hydrologic system, such as the soil zone or groundwater zone.

Precipitation is assumed to occur as rain or snow, depending upon temperature, with snow accumulated during the winter and melted in spring. A small fraction of the rain or snowmelt is able to runoff directly into the surface-water body. The model distributes precipitation excess \((P - ET)\) among storage, recharge, and surface runoff. Water can be stored in the upper and lower soil zones (Figure 2.2), which are parameterized in terms of maximum storage capacities. Excess water from the soil zone is available for recharge to groundwater storage. Routing equations, described by \textit{Crowe and Schwartz} [1981a], determine inflows to the lake/wetland and outflows from the watershed. Groundwater outflow from the water body is simply estimated based on a
seepage rate and a seepage area. Surface runoff is developed when the quantity of water available for infiltration exceeds the total amount of water retained in the soil zone and the maximum allowable recharge to the groundwater zone. The code calculates the monthly fluxes of water through the system and changes in storage. The water volume in the surface water body changes in response to the changes in inflows and outflows. Water depth and area are determined by a geometric model that relates volume to water depth and area.

Figure 2.2 Simplified flowchart of the PCHM model showing the hydrologic processes.
PCHM represents a major extension of the earlier model. Rather than simulating a single pothole basin, the enhanced PCHM code simulates a complex of basins, comprising numerous individual depressions of different sizes. As an initial condition for the simulation, a complex of potholes is created that properly accounts for the tendency for smallest basins (containing small potholes or puddles) to be more numerous than the largest (containing large potholes or lakes). This proportionation is based on abundances of water bodies, determined as a power-law description for the wettest condition observed. Effectively, this approach provides a starting pothole complex comprised of some maximum number of water bodies collectively having the maximum individual water areas. As a practical matter, simulation results are not particularly sensitive to this initial assumption because a relatively long model spin-up time eliminates the overall sensitivity to the initial conditions.

2.2.2 Pothole Geometry

It is well known that pothole bathymetry plays an important role in interpreting the results of surface-water mass balances. Mathematical functions are commonly used to convert changes in water volume to changes in the water area, and the depth of water [e.g., Crowe and Schwartz, 1981a; Hayashi and van der Kamp, 2000; Carroll et al., 2005]. For example, Hayashi and van der Kamp [2000] described a power function with two parameters, which provides area-depth and volume-depth relations for 27 wetlands and ephemeral ponds.
PCHM incorporates a general, self-similar geometric model of a pothole watershed. All potholes in the complex are assumed to share the same symmetric sinusoidal bathymetry, formed by rotating the cross-section around the central $z$-axis (Figure 2.3a). Such an assumption is not unusual [e.g., Johnson et al., 2005]. Mathematically my bathymetric function is defined as:

$$h = \frac{H}{2} - \frac{H}{2} \cos\left(\frac{2\pi r}{L}\right)$$

(2.1)

where $H$ is relief across the watershed, $L$ is watershed diameter, and $r$ is the water body radius of depth $h$. Based on equation (2.1), relations of area-depth ($A-h$) and volume-depth ($V-h$) are developed as:

$$A = \pi r^2 = \pi \left\{ \frac{L}{2\pi} \arccos\left(1 - \frac{2h}{H}\right) \right\}^2$$

(2.2)

$$V = f(h) = \int_0^h A dh' = \int_0^h \pi \left\{ \frac{L}{2\pi} \arccos\left(1 - \frac{2h'}{H}\right) \right\}^2 dh'$$

(2.3).

Operationally, water volume is calculated directly in PCHM at each time step, and equation (2.3) is used to calculate the depth inversely - given the known value of $V$, $h = f'(V)$.

Potholes represented in the model share a similar general shape but different scaled, geometric parameters. Each watershed is assumed to contain a single water body.
and the watershed diameter \((L)\) is known. A limitation with this simple model is that it cannot produce water bodies that disaggregate during dry periods or coalesce during wet periods. The total relief, \(H\), in each watershed is calculated as \(\gamma L\), where the \(\gamma\) is shape ratio. The value of \(\gamma\) was chosen to provide a \(V-A\) relation for my geometry model that is

Figure 2.3 Pothole-basin geometry model for the PCHM. (a) Sinusoidal shape is a schematic representation of a pothole-basin profile and the dimension is not scaled. (b) Comparison of the predicted water volume-area relationships for potholes in the Missouri Coteau using the PCHM geometry model and Gleason’s model [Gleason et al., 2008].
comparable to a function from *Gleason et al.* [2008]. Gleason’s function was developed from a survey for 186 pothole lakes and wetlands on the Missouri Coteau. Figure 2.3b shows that, with a $\gamma$ value of 0.0118, pothole geometries generated by the model satisfactorily reproduced Gleason’s $V-A$ results. I assume a small uncertainty in the value of $\gamma$ with a range from 0.009 to 0.014, and consider $\gamma$ as a parameter for calibration (Table 2.1).

### Table 2.1 Model parameters for the genetic-algorithm based calibration.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Ranges lower</th>
<th>Ranges upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCTIMP1</td>
<td>Impervious/direct runoff fraction during growing season (April - September)</td>
<td>[-]</td>
<td>0.001</td>
<td>0.10</td>
</tr>
<tr>
<td>PCTIMP2</td>
<td>Impervious/direct runoff fraction during dormant season (October - March)</td>
<td>[-]</td>
<td>0.001</td>
<td>0.10</td>
</tr>
<tr>
<td>USZMAX</td>
<td>Maximum allowable moisture storage in the upper soil zone</td>
<td>[m]</td>
<td>0.001</td>
<td>0.30</td>
</tr>
<tr>
<td>LSZMAX</td>
<td>Maximum allowable moisture storage in the lower soil zone</td>
<td>[m]</td>
<td>0.001</td>
<td>0.30</td>
</tr>
<tr>
<td>GWOLK</td>
<td>Lake discharge to groundwater</td>
<td>[m/month]</td>
<td>0.001</td>
<td>0.30</td>
</tr>
<tr>
<td>RGWMAX</td>
<td>Maximum allowable groundwater recharge</td>
<td>[m]</td>
<td>0.001</td>
<td>0.30</td>
</tr>
<tr>
<td>DT</td>
<td>Storage delay time of a groundwater element</td>
<td>[month]</td>
<td>0.5</td>
<td>24</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Shape ratio</td>
<td>[-]</td>
<td>0.009</td>
<td>0.014</td>
</tr>
<tr>
<td>SWOL</td>
<td>Fraction of maximum water depth to the watershed relief</td>
<td>[-]</td>
<td>0.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*Refer to *Crowe and Schwartz* [1981a] for the descriptions of other parameters and variables.

#### 2.2.3 Characterization – Missouri Coteau Study Area

PCHM was applied to simulate pothole systems in a 5396 km$^2$ study area in central North Dakota along the Missouri Coteau (Figure 2.1). This area was chosen in part to take advantage of the long-term observational record of water levels in wetlands at the Cottonwood Lake area operated by the USGS [*LaBaugh et al.*, 1996; *Winter and*
Rosenberry, 1998; Swanson et al., 2003]. Glacial retreat and uneven deposition of glacial till created tens-of-thousands of depressional lakes and wetlands [Euliss et al., 1999]. Major inflows of water to potholes come from snowmelt and summer rainstorms, whereas the greatest loss of water is due to evaporation [Winter and Rosenberry, 1998]. Groundwater inflows and outflows are smaller but still important components of the water budgets. Given the high rates of evaporation in summer and variable precipitation from year to year, the areas, stages, and volumes of pothole systems are sensitive to changes in climate and exhibit significant variability [e.g., Poiani et al., 1996].

The climatic input variables to PCHM include monthly precipitation, temperature, and potential evapotranspiration (PE). Long-term monthly precipitation and temperature data for a climate division, ND05, and two weather stations (Woodworth and Jamestown, North Dakota) were obtained from the National Climatic Data Center (NCDC). Division ND05 coincides almost exactly with the study area (Figure 2.1). Summary data, compiled for this division, were mainly used to simulate the collective behaviors (area-frequency distributions) of the widely distributed pothole complex. The Woodworth and Jamestown stations are located close to the Cottonwood Lake area, and precipitation data from there were applied to the simulation of the six individual wetlands.

Monthly averages in ND05 were calculated with equal weight given to stations reporting both temperature and precipitation within that division. From 1901 to 2005, the average annual precipitation was 543 mm, with about 16% of the total precipitation falling as snow in winter. Mean monthly mean temperatures ranged from -14.7 °C in January to 20.6 °C in July.
Monthly PE was calculated with the FAO Penman-Monteith method [Allen et al., 1998] based on monthly maximum and minimum air temperatures, solar radiation, wind speed, and air humidity. Solar radiation data from 1961 to 2005 were obtained by distance weighting values from nearby stations at Jamestown, Devils Lake, Bismarck, Fargo, and Minot. For years without complete solar radiation data, I calculated the PE in three steps: 1) estimating the correlation coefficient between the PE calculation procedures using missing data and complete data, 2) estimating the monthly PE for those missing-data years by using procedures suggested by Allen et al. [1998], and 3) converting the PE obtained from step 2) to the “real” model input PE for missing-data years based on the correlated coefficient. The average annual PE of the study area was estimated to be 950 mm, which was nearly two times higher than the precipitation. The annual moisture deficit (precipitation minus evapotranspiration) was more than 400 mm, and comparable to results from other studies [e.g., Laird et al., 1996; Grimm, 2001].

2.3 PCHM Calibration and Performance Evaluation

2.3.1 Calibration Method

Simulation of a lake/wetland complex requires values of parameters relating to climate, soil, land cover, groundwater, and hydrologic processes. Among them, several parameters controlling water/land-surface interactions, soil-water storage, groundwater inflows and outflows, and lake-basin bathymetry are typically uncertain and require calibration. Table 2.1 defines parameters whose values were determined by calibration and their initial ranges. To ensure that a globally optimal set of parameters, those with
large uncertainties are given broader initial ranges. Detailed descriptions of parameters and their sensitivities were given by Crowe and Schwartz [1981a].

Calibration requires one or several appropriate objective functions, which are consistent with the anticipated application of the model. PCHM is developed mainly to simulate water area-frequency relationships. However, as is the case with this study area, measured data on water depths for individual potholes are also available. Therefore, objective functions are defined for both area-frequency and water depths relationships as:

\[
\text{Minimize: } F(x) = (f_1(x_1, x_2, \ldots, x_p), f_2(x_1, x_2, \ldots, x_p))
\]

subject to \( x_i^l \leq x_i \leq x_i^u \) \((i=1,2,\ldots, p)\)

where

\[
f_1 = \sum_{t=T_0}^{T} \left\{ w_t \cdot \sum_{i=1}^{m} [w_i \cdot \text{abs}(N_{it} - N_{it}')] \right\}
\]

\[
f_2 = \sum_{t=T_0'}^{T'} \left\{ w_t' \cdot \sum_{k=1}^{m'} \text{abs}(L_{kt} - L_{kt}') \right\}
\]

\(x_1, x_2, \ldots, x_p\) are \(p\) decision variables (parameters); \(x_i^l\) and \(x_i^u\) are the lower bound and upper bound on parameter \(x_i\), respectively; \(w_t\) is the weight factor for data at time \(t\); \(w_i\) is the weight factor for the data at bin size \(i\); \(N_{it}\) and \(N_{it}'\) are the observed and simulated numbers of water bodies falling in area bin \(i\) from a Landsat image at some time \(t\), respectively; and \(L_{kt}\) and \(L_{kt}'\) are the observed and simulated water levels of wetland \(k\) at some time \(t\), respectively.
Equation (2.4) provides the objective-oriented fitness function, aiming to provide the best set of model parameters \((x_1, x_2, \ldots x_p)_{\text{optimum}}\) that minimizes differences between the simulated results and the observational data. Nine parameter values (i.e., \(p=9\)) need to be determined (Table 2.1). The value (fitness) of equation (2.4) is defined as the sum of two objectives, \(f_1\) and \(f_2\), to capture data on both area-frequency distributions and water depths. \(f_1\) is set to minimize the errors between simulated and observed numbers of water bodies from eight sets of power laws. \(f_2\) is set to minimize the errors between simulated and observed water depths of six \((m'=6)\) individual wetlands. In each of the \(f_1\) or \(f_2\) functions, weights were assigned to data points to offset the data bias \([\text{Sorooshian et al., 1983; Freedman et al., 1998}]\), which are caused by the uneven nature of power-law binning and uneven data coverage for average and extreme climatic conditions.

With numerous data points (water areas, depths, and counts of all individual potholes in the complex) and complicated relationships among model inputs, parameters, and the outputs, model calibration is only feasible with an automated scheme. Here, a genetic algorithm (GA) approach was implemented. It involves finding global optimum by searching wide solution space \([\text{Holland, 1975}]\). The securGA implementation \([\text{Carroll, 2001}]\) used here features a powerful “small-elitist-creeping-uniform-restart” algorithm \([\text{Yang et al., 1998}]\).

2.3.2 Observational Data

One set of calibration data was comprised of eight different water area-frequency relationships, essentially snapshots of the lake/wetland complex from 1986 to 1997,
provided by Landsat TM images [Zhang et al., 2009a] with zero cloud coverage. Four other similar datasets of 1998 and 2003 were used for validation (Figure 2.4). Images were selected to be representative of different climatic conditions. Power laws thus provide a simple way to summarize the observational data and to compare these results with comparable monthly frequency distribution on water areas calculated by the model.

    A second set of calibration data comprised sets of conventional water-depth measurements [Winter and Rosenberry, 1998] for three permanent and three seasonal wetlands from the Cottonwood Lake area (Figure 2.5). The 27-year record from 1979 to 2005 included a significant drought from 1988 to 1992 and a significant deluge from 1993 to 2001.
Figure 2.4 Comparison of observed and simulated area-frequency distributions. The number of water bodies in each bin was counted with a bin width of 900 m$^2$. 
Figure 2.5 Comparison of observed and simulated water depths of six individual wetlands in the USGS Cottonwood Lake area.
2.3.3 Parameter Estimation

GA-based calibration involved searching the global optimum with multiple searching points by improving the fitness of the equation (2.4). Calibration began by randomly generating five chromosomes or individuals (an individual represents a solution combining the values of nine parameters), and continued with the application of a set of evolution operators (e.g., selection, crossover and mutation) to the individuals in the population in order to generate new individuals. In every generation, each of the five individuals was evaluated to determine its suitability (fitness) based on equation (2.4). The individuals evolved from generation to generation until the parameters converged to constant values.

The history of parameter changes through the GA optimization are illustrated in Figure 2.6 with the x-axis representing the GA generations and the y-axis representing the value of fitness (Panel a) or parameters (Panels b-j). The parameter values, searched in each generation, were plotted as gray points. The wide scatter of points for each parameter (Panels b-j) indicates that the GA sampled across the search space to find best set of parameters. The best fitness and the best set of parameters found by GA in each generation were linked by the solid lines in Figure 2.6. The line in Panel (a) shows that the fitness value improved markedly after the first 200 generations and clearly had converged. Panels (b-j) also show that all nine parameters converged to constant values after a few hundred generations. The calibration was stopped after 1820 generations with total 9100 estimates of equation (2.4) accomplished (1820 generations \( \times \) 5 estimates per generation). Clearly, an optimal set of parameters was obtained.
Figure 2.6 Plots of the GA-based optimization process: (a) fitness and (b-j) model parameters. In each GA generation, five parameter sets (gray points) are searched simultaneously with the best set in each generation connected by solid lines.
2.3.4 Evaluation of PCHM Performance

Figure 2.4 provides a visual comparison of the water area-frequency power laws derived from Landsat data (solid squares) and comparable results from the model (open circles). PCHM was successful in simulating the population dynamics of large and small water bodies during average (1986), dry (1988 and 1991), and wet periods (1997). The validation tests for spring and summer/fall of 1998 and 2003 (lower four panels in Figure 2.4) yielded good agreement between observations and simulations. A slight tendency to overestimate the small water-body numbers was evident in the results for October 1986 and April 1991 (Figure 2.4).

The performance of the model in simulating dynamic changes in water areas was also evaluated quantitatively using the coefficient of determination ($R^2$). The mean $R^2$ value for all eight pairs of observed and simulated power laws used in calibration is 0.881 (Table 2.2). Values of $R^2$ range from 0.841 for dry years, to 0.905 for wet years, to 0.936 for average years. Although the dry-year coefficient is somewhat lower, the correlation is good, indicating strong model performance. The mean $R^2$ value for the validation is 0.884. I attribute this somewhat lower correlation for dry conditions to the inherent nonuniformity in the calibration data (regional lake numbers versus actual lake depths). Dry-time calibrations are probably being influenced more by Cottonwood Lake data, where drought conditions are prominently represented in record. Drought conditions in the satellite record are underweighted in the calibration, and less likely to influence the global calibration. Work is in progress to examine factors affecting calibration with nonuniform data and the overall uncertain that this might create in calibration.
Nevertheless, the calibrated parameter set in PCHM successfully simulated observed water area frequency relations.

Table 2.2 Quantitative evaluation of PCHM calibration.

<table>
<thead>
<tr>
<th>Area-frequency distribution**</th>
<th>$R^2$</th>
<th>$NSE^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration Landsat images</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 May 1986</td>
<td>0.939</td>
<td></td>
</tr>
<tr>
<td>20 October 1986</td>
<td>0.933</td>
<td></td>
</tr>
<tr>
<td>19 June 1988</td>
<td>0.906</td>
<td></td>
</tr>
<tr>
<td>23 September 1988</td>
<td>0.847</td>
<td></td>
</tr>
<tr>
<td>25 April 1991</td>
<td>0.841</td>
<td></td>
</tr>
<tr>
<td>31 August 1991</td>
<td>0.769</td>
<td></td>
</tr>
<tr>
<td>14 July 1997</td>
<td>0.916</td>
<td></td>
</tr>
<tr>
<td>02 October 1997</td>
<td>0.894</td>
<td></td>
</tr>
<tr>
<td>Overall calibration</td>
<td>0.881</td>
<td></td>
</tr>
<tr>
<td>Validation Landsat images</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28 April 1998</td>
<td>0.875</td>
<td></td>
</tr>
<tr>
<td>21 October 1998</td>
<td>0.889</td>
<td></td>
</tr>
<tr>
<td>12 May 2003</td>
<td>0.889</td>
<td></td>
</tr>
<tr>
<td>16 August 2003</td>
<td>0.884</td>
<td></td>
</tr>
<tr>
<td>Overall validation</td>
<td>0.884</td>
<td></td>
</tr>
<tr>
<td>Water depths</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semipermanent wetlands P1, P2, P6</td>
<td>0.953</td>
<td>0.943</td>
</tr>
<tr>
<td>Seasonal wetlands T5, T6, T8</td>
<td>0.705</td>
<td>0.691</td>
</tr>
<tr>
<td>Overall</td>
<td>0.937</td>
<td>0.927</td>
</tr>
</tbody>
</table>

\[
R^2 = \frac{\sum_{i=1}^{n}(o_i - \bar{u})(s_i - \bar{u})}{\sum_{i=1}^{n}(o_i - \bar{u})^2 \sum_{i=1}^{n}(s_i - \bar{u})^2} \quad \text{and} \quad NSE = 1.0 - \frac{\sum_{i=1}^{n}(o_i - s_i)^2}{\sum_{i=1}^{n}(o_i - \bar{u})^2}
\]

where $o$ indicates observed value, $s$ indicates simulated value, over-bar indicates mean, $R^2$ is coefficient of determination, and $NSE$ is Nash-Sutcliffe efficiency index. Performance ratings [Moriasi et al., 2007] are as follows:

$NSE \leq 0.50$, unsatisfactory; \hspace{1em} $0.50 < NSE \leq 0.65$, satisfactory;

$0.65 < NSE \leq 0.75$, good; \hspace{1em} $0.75 < NSE \leq 1.00$, very good.

**Mean $R^2$ is 0.936 for an average year (1986), 0.841 for two dry years (1988 and 1981), and 0.905 for a wet year (1997).
Simulating water depths was not a primary goal of this study. However, the exceptional record of water depth measurements at the Cottonwood Lake area provided an important opportunity in calibration/validation. Figure 2.5 compares the water depths, calculated by PCHM with calibrated parameters, to the observed water depths in the six individual wetlands. The model performed well in simulating water depths in the semipermanent wetlands, P1, P2 and P6 (upper three panels in Figure 2.5). These semipermanent wetlands mostly dried out during the severe drought from 1988 to 1992. Water depths increased markedly after 1993 and reached a maximum around 1999. PCHM clearly was able to simulate the significant transition from drought to deluge in 1993.

The model also successfully captured the behavior of small seasonal wetlands, T5, T6, and T8 (lower three panels, Figure 2.5). Their behavior featured a transition from water depth of less than one meter in spring to dryness during the hot summer months. Although the measured and predicted water depths matched much of the time, the model underestimated the water depths for seasonal wetlands in 1981 and 1987. One possible explanation is that for these smaller water bodies, single point-in-time measurements on occasion may not be directly equivalent to monthly averages from the model. Another possibility is that the quite idealized model for the pothole geometry does not appropriately capture the actual character of these small water bodies.

The overall $R^2$, comparing observed and simulated water depths for all six wetlands is 0.937, with a value of 0.953 for the semipermanent wetlands and 0.705 for the seasonal wetlands. The Nash-Sutcliffe Efficiency Index (NSE) [Nash and Sutcliffe,
1970], a commonly used criterion for model performance, was also applied to provide a quick overview of PCHM's accuracy. The NSE has a range of $-\infty$ to 1, with 1 indicating perfect match between the measured and simulated data. The NSE is 0.943 for three semipermanent wetlands and is considered to be very good [Moriasi et al., 2007]. The NSE value for the seasonal wetlands is 0.691 and is considered good, according to the ratings (described in Table 2.2). Thus, the model was able to capture the wide variety of hydrologic responses in wetlands at the Cottonwood Lake area.

2.4 Results and Discussion

2.4.1 Climate-driven Variability of Pothole Systems

The modeling approach was used to examine the behavior of pothole water bodies through the 20th Century. Of particular interest were the climatic extremes, two of which are noteworthy: the Dust Bowl drought of the 1930s and the deluge from 1993 to 2001. The simulations covered the period from 1901 to 2005 with a monthly time step. This analysis tracked the hydrologic behavior of a pothole complex consisting of 22,770 various sized potholes with an initial distribution representative of the North Dakota setting. Thirty years of average climatic conditions were used to spin-up the model so that the actual simulation could begin in 1901 with a plausible set of initial conditions rather than poor guesses.

Intra-annual Analysis

In nearby South Dakota, Zhang et al. [2009a] found quite marked changes in water areas in any given year as the pothole complex transitioned from wet spring to
hotter and drier conditions in summer. I applied the PCHM model to the study area in North Dakota to re-examine this intra-annual variability more systematically through the 20th Century.

Figure 2.7 describes the simulated seasonal shift in the size structure of the pothole complex in 1985, a year with average precipitation. A linear power law was maintained from month to month. However, the slopes of the lines for April, June, and August decreased as conditions shifted from wet to drier conditions. This behavior in power-law slopes indicated a preferential impact on the frequency distributions of the potholes.

Figure 2.7 Simulated area-frequency distributions for April, June, and August 1985 depict the behaviors of potholes in response to the intra-annual climatic variability. Regression lines show that the water areas follow a pure power-law distribution.
potholes with small water areas ($< 1 \times 10^4$ m$^2$). Generally, with the increased evaporation from spring to summer, the areas of smaller water bodies declined to a much greater extent than the larger potholes. The sensitivity of the small potholes was also related to water depth in relation to the particular shape of the pothole basin [Zhang et al., 2009a]. Effectively, then, these changes were manifested by a reduction in the numbers of small potholes of a given size. However, as Figure 2.7 shows, the numbers of large water bodies approaching the size of lakes ($\sim 1 \times 10^5$ m$^2$), remained constant. The decline in the numbers of small potholes and the stability in the number of large potholes produced the observed slope decline in power-law lines in the spring-to-summer transition.

**Interannual Analysis**

The climate often deviates from average conditions for several or more years at a time with evident periods of drought and deluge. Figure 2.8a shows the variation in the Palmer Hydrological Drought Index (PHDI) for ND05 over the 20th Century. PHDI, like the familiar Palmer Drought Severity Index (PDSI) takes into account precipitation, evapotranspiration, and soil moisture, but better reflects the hydrological impacts of drought. A value $> 0$ is indicative of conditions wetter than average, while a value $< 0$ is indicative of conditions drier than average. The Dust Bowl drought from 1930 to 1940 is shown clearly, along with a number of preceding wet years. The deluge beginning in 1993 also stands out (Figure 2.8a). Such climatic extremes in the PPR are known to produce extraordinary impacts on the water-area systematics for pothole systems. In South Dakota, Zhang et al. [2009a] found that these same periods of drought and deluge
provided the lower and upper limits for fluctuations in the power-law lines over the 20th Century.

My simulation results from 1901 to 2005 provide a basis for describing these effects in more detail. Shown in Figure 2.8b and 2.8c are power-law lines that illustrate how water-area relationships changed for periods preceding and through these two extreme events. In order to minimize the impact of intra-annual variability to some extent, results are presented for August of each year. Through the 1930s, persistent and intense drought conditions dramatically reduced water areas and decreased the number of pothole water bodies of a given size. Power-law lines (Figure 2.8b) declined year after year, reaching the lower limit in August 1940. However, the drought’s hydrologic impact was variable. By August, 1930, a large number of water bodies had already disappeared with a marked reduction in the numbers of small potholes (\( < 1 \times 10^4 \text{ m}^2 \)) as seen by comparing the lines of August 1928 and August 1930. The flattening of slopes of power-law lines through the early 1930s indicates a rapid decline in the population of smaller water bodies. As the drought intensified in 1934 and in 1936 (Figure 2.8a), the numbers of large potholes of a given size declined markedly with the reduction in their water areas. During the latter years of the drought, declines were evident but less marked (Figure 2.8b).

The deluge from 1993 to 2001 began with several rainstorms in July 1993 that produced nearly 30 cm of rainfall and broke the drought of 1988-1992. With the smaller potholes (\( < 1 \times 10^4 \text{ m}^2 \)), the power-law lines flipped nearly instantaneously from a condition indicative of drought to one of deluge (Figure 2.8c). For the larger water bodies
(> 1 × 10^4 m^2), there was a lag time of three or four years (Figure 2.8c) when they increased their size and stage according to the wetter conditions.

Simulation data for various months of August were used to create power-law envelope that is bounded by lines from the driest of the Dust Bowl times to the wettest times in the deluge of 1993 to 2001 (Figure 2.8d). There is a surprising range in the numbers of water bodies reflected by this envelope. The bounding power-law lines for these two extreme events are separated by an order of magnitude, and even more for small water bodies (Figure 2.8d).

The results of the simulations confirmed basic ideas presented in Zhang et al. [2009a] that the frequency distributions of water areas of large prairie potholes are usually well described by a pure power law (Figures 2.7 and 2.8). The numbers exhibited a consistent size structure interannually and intra-annually as a function of climate. The impacts of climatic fluctuations on water bodies were remarkable with a tendency for slopes of power-law lines to flatten under drier conditions and for intercepts to be lower under drought conditions. Large and small pothole water bodies, however, showed different rates of response to the climate variations. The numbers of smaller water bodies were more sensitive and fluctuated more rapidly than larger water bodies.
Figure 2.8 Simulated water area-frequency distributions for August through the two dominant climatic extremes indicated by (a) PHDI time series over 1901-2005: (b) the 1930-1940 Dust Bowl drought (1\textsuperscript{st} drought) and (c) the 1993-2001 deluge (1\textsuperscript{st} deluge). The envelope of power-law lines (d) shows an order of magnitude or more variability in the numbers of water bodies due to the extreme climatic variations. (*PHDI data source: http://www.ncdc.noaa.gov oa/ncdc.html*)
2.4.2 On the Behavior of Small Water Bodies

**Significant Volume Fluctuations**

There are hints in Figures 2.7 and 2.8 that the flattening of power-law lines indicates a preferential impact of drought on small water bodies (e.g., $< 1 \times 10^4 \text{ m}^2$). In this section, I examine the behavior of small water bodies in more detail. Figure 2.9a shows how the volume of water in surface-water bodies, averaged over the 20th Century, varies from spring through summer. Small water bodies ($900 \text{ m}^2$ to $1 \times 10^4 \text{ m}^2$) contained about 9-14% of the surface water. However, about 33% of the total loss in surface water from April to August came from these small bodies (Figure 2.9b). Through the Dust Bowl drought, I estimated an 89% loss in total surface water volume from pre-drought 78.9 million cubic meters in 1928 to 8.5 million cubic meters the end of the drought in 1940. The loss attributed to the small water bodies was 15%, the largest among all different sizes of surface water bodies (Figure 2.9c). These remarkable fluctuations in water storage of the small water bodies are thus quite significant in accounting for the transfer of water through the hydrologic cycle.
Figure 2.9 Simulation results that show (a) the water volume stored in water bodies decreased as the water area increased. Small water bodies ($< 1 \times 10^4$ m$^2$) exhibited larger variability in stored water volumes and contributed much more to the total storage loss than large bodies through both (b) intra-annual drying from April to August over the 20th Century and (c) interannual drying from July 1928 to July 1940.
Deviation from Pure Power-law Behavior

Generally, not much is known about the frequency distribution on water areas for the small pothole water bodies. They are difficult to observe remotely because of their small size, and because they are often dry during hot summer months. The smallest of these water bodies are essentially puddles (< 250 m$^2$) and dry most of the time. The model, however, is sufficiently general that it can simulate the changes in water stored in these small water bodies, including completely dry conditions. Here, I examine how the intra-annual and interannual variability in climate especially influences small potholes and puddles.

PCHM was applied to simulate the behavior of a hypothetical pothole/puddle complex consisting of 55.7 million water bodies. The complex was generated and water bodies counted with a greater resolution in bin size (10 m$^2$). With this resolution, the behaviors of water bodies as small as several square meters could be examined.

The strategy for this analysis was to examine both intra-annual and interannual behaviors. From spring through summer in a single dry year, the greatest number of these smallest water bodies should be associated with the spring snow-melt period or large rainfalls when there is an excess of water. Panels a, b, and c in Figure 2.10 illustrate the simulated behavior of the pothole/puddle complex from spring to summer for an average year 1985, a dry year 1992, and a wet year 1998, respectively. Although the details are different, the general patterns of behavior are similar. Pure power-law behavior that is evident with the larger potholes broke down when the smaller water bodies (< 1000 m$^2$) were included. The power-law curves have several important features. First, the point of
departure from pure power-law behavior changes depending upon the wetness or dryness, which is generally related to the time of the year. For example, because spring was wetter than summer, the departure points for April in 1985 and 1992 were associated with much smaller water areas than the following months. In the wet year 1998, several rainy months (i.e., June and August) exhibited pure power-law behavior, while other drier months (i.e., July and September) exhibited more complex, non-linear behaviors. The pure power-law behavior had the greatest range in spring or wet months, usually extending to water bodies as small as puddles (< 250 m²). By summer, the pure power-law behavior only held for the somewhat larger pothole bodies (> 1000 m²).

Second, these non-linear curves are characterized by some maximum number (with outliers excluded) of water bodies in one or several bins. For example, in Figure 2.10a, the maximum number of water bodies was about 400 thousand in April; the May maximum was about 70 thousand water bodies; and the July maximum was about 3 thousand water bodies. Clearly, the maximum number of water bodies fluctuated markedly from month to month, depending upon the moisture excesses or deficiencies.
Another feature of these functions is the tendency for the water-area frequency curve to simply terminate as the number of water bodies abruptly drops to zero or sharply increases. The numbers of the smallest water bodies (i.e., puddles) generally decreased in a non-linear manner as water areas declined. However, there were occasional conditions when the numbers of puddles actually began to increase again. This departure from the general trend has an unsystematic character, e.g., the data point in the 10 m$^2$ bin in May.
1985 and the 20 m$^2$ bin in July 1985 (Figure 2.10a). Thus, puddles can behave unsystematically in a single month. With these small water bodies, individual storms in a month can influence their numbers without appreciably influencing larger bodies, producing quite interesting and complex behavior.

The interannual variability in the behavior of the small water bodies was also examined. Figure 2.10d compares the small pothole and puddle behaviors in August, the same month, for an average year (1986) and for years characterized by the extreme events (1938, 1992, and 1997: dry, dry, and wet years, respectively). As expected, pure power-law behavior extended to water bodies of smaller sizes during wetter times than was the case with droughts. The water-area limit for pure power-law behavior was about 3000 m$^2$ for August 1938, 1000 m$^2$ for August 1992, 400 m$^2$ for August 1986, and as small as 200 m$^2$ for August 1997. The simulated water areas in the midst of the deluge from 1993 to 2001 exhibited linear behavior down to quite small bodies. During the two major droughts, a nonlinear power law developed.

The maximum number of water bodies associated with each of the curves is also highly dependent on conditions of drought and deluge (Figure 2.10d). The maximum number of water bodies (peak value, with outliers excluded) decreased steadily from a deluge value of 48,170 in August 1997 to about 620 during the Dust Bowl drought in August 1938. Effectively during droughts, the point of termination of the water-area function was associated with larger and larger water bodies.

2.4.3 Conceptual Models on the Response of Pothole Complex to Climate
Pure power laws provide a convenient and simple graphical approach for describing the behavior of a pothole water body complex. They are limited to the extent that they are weakly coupled to the dynamic character of the water bodies, because no history of behaviors is incorporated there. Moreover, linear power-law relationships only hold for the somewhat larger water bodies observable on Landsat or aerial photographs. Similar deviations from pure power-law behavior have also been observed, for example, with document sizes on the web [Crovella and Bestavros, 1997], webpage link distribution [Pennock et al., 2002], and actor collaboration [Barabási and Albert, 1999].

The area-frequency distribution for pothole/puddle systems should be describable with a general functional form that effectively combines linear (e.g., Figures 2.7 and 2.8) and curvilinear components (e.g., Figure 2.10). Several functions were examined to determine their applicability including lognormal, Discrete Gaussian Exponential (DGX) distribution [Bi et al., 2001], polynomial, power, etc. The most satisfactory function applied to potholes and puddles was a modification of a function described by Pennock et al. [2002]:

$$N(A) = k \cdot [2m(1 - \alpha)]^{\frac{1}{\alpha}} \cdot A \cdot [\alpha A + 2m(1 - \alpha)]^{-(1 + \frac{1}{\alpha})}$$

(2.5)

where $N$ is the total number of water bodies in the bin, whose mean size value is $A$. The parameters governing the shape of the function ($k$, $\alpha$, and $m$) were explained in detail by Pennock et al. [2002]. This function consists of unimodal body and linear power-law tail. The parameter $k$ essentially scales the function, controlling the maximum value of the
unimodal body, which occurs at $A = 2m(1-\alpha)$, and the parameter $\alpha$ controls the slope of the linear portion of the function.

As the water area varied with climate, so did the shape of the function. The function in equation (2.5) was fitted to the ensemble of results for the large water bodies (e.g., data shown in Figure 2.8) and the small water bodies (e.g., data shown in Figure 2.10). A genetic algorithm was used to fit the function by optimizing $k$, $\alpha$, and $m$. Figure 2.11 demonstrates the fitting results for intra-annual pattern (Panel a) and interannual pattern (Panel b). Clearly, all simulated distributions (points) were fitted extremely well. The fitted function could be examined to determine the slope of the linear portion and the maximum number of water bodies in a bin. The point of termination was empirically determined as the last bin that the number of water bodies dropped to zero or there was a significant deviation from this function. To finally confirm validity of these functional relationships suggested by the model will require observational data that captures this small pothole behavior.

To help in understanding behaviors of the water bodies, two conceptual models have been developed. They encompass the intra-annual (Figure 2.11c) and interannual (Figure 2.11d) behaviors of water bodies varying in size from small puddles and large potholes. For illustrative purposes, a single line (solid) with circles is shown and considered to represent some average condition. Over a few months only the puddles and small potholes respond to the seasonal variability in precipitation and evaporation (Figure 2.11c). Excess water from snowmelt in spring maximizes the extent of the linear power law, the number of water bodies, and the overall range of systematic behavior.
Evaporation through the hot summer months shifts the function, reducing the linear portion of the power law, the maximum number of water bodies, and the range in systematic behavior (Figure 2.11c). Large potholes (> $1 \times 10^4$ m$^2$) are relatively unaffected by short-term climatic variations. The conceptual model for interannual variations (Figure 2.11d), while similar to Figure 2.11c, differs in the pattern of behavior of the large potholes. With a significant drought and deluge, not only does the position of the function change at the small water-body end, but at the large end as well (Figure 2.11d).

The conceptual model separates the water area-frequency distribution into two parts: a systematic part and an unsystematic or random part. The term systematic implies a behavior characterized by regular functional form. The unsystematic part on the one hand is associated with the small puddles. At some lower threshold, the numbers of small puddles would become erratic, fluctuating from no puddles to many puddles on a monthly basis. This behavior was likely driven by small irregular variability in monthly rainfall. On the other hand, large potholes or lakes exhibited unsystematic behavior due to the relatively limited number of lakes (also bins with no lakes) in certain large-size classes in my study area.

The boundaries between the systematic and unsystematic parts and division between linear and non-linear segments of the power law are not fixed. The peak in the numbers of water bodies is directly proportional to the parameter $k$ and the location of the peak was directly proportion to parameter $m$. Values of $k$, $m$, as well as $\alpha$, are highly
correlated to the climatic conditions. Testing of these correlations is one of my future study topics.

Figure 2.11 Two sets of simulated area-frequency distributions were fitted well by equation (2.5). Panels (a) and (b) display intra-annual and interannual relations, respectively. The dotted lines show boundaries between the linear and non-linear segments of the distribution. The dashed dotted lines mark the end of the systematic behavior of the function. Panels (c) and (d) present conceptual models built to visualize how the water bodies of different sizes respond to different climatic variation scenarios.
2.5 Conclusions

There are three key conclusions. First, it is feasible to simulate the behavior of a pothole complex using the PCHM described in this chapter. The calibrated model was successful in simulating the hydrologic response of a pothole complex to the broad range of climatic variability in North Dakota. Second, climate driven variability in the numbers of large potholes ($> 1 \times 10^4 \text{ m}^2$) as a function of water area can be described well by a pure power law. Major droughts and deluges create marked variability in the power-law function. The time required for surface waters to adjust to drier or wetter conditions is proportional to the size of the water body. Thus, increased evaporation in late spring and summer in a given year mostly would affect the small potholes in the complex. Changes to large potholes would be associated with droughts and deluges that span a number of years.

Third, deviation from pure power-law behavior should be expected for small potholes and puddles. As a group, these water bodies exhibited tremendous variability in terms of water volume and area. A significant fraction of the gains or losses in total surface water storage is associated with these water bodies. For this reason, understanding the behavior of the small water bodies is critical to quantitatively describing the evaporative fluxes. Empirical results and theoretical mathematical results suggest that much of the behavior across much of the spectrum of water bodies can be described by a general equation that includes the parameters $k$, $m$, and $\alpha$ controlling the shape of the unimodal body and power-law tail. At some points the functions would
terminate when water bodies became dry under the particular climatic conditions, or in a few cases, behaved in an unsystematic manner.

This study provides a better understanding of the linkages between climate and wetland/lake systems in the PPR. Such knowledge is important for policy development, water resources management, and wetland restoration and wildlife conservation. My findings continue to show the potential for space-based monitoring that ultimately might lead to regular monitoring of the behavior of millions of water bodies across the PPR. Such capabilities are essential to a better assessing global climate change impacts here. My modeling approach for the first time provides a way to fully account for the spatial and temporal distribution of surface waters. Such knowledge is essential for developing a more realistic understanding of the feedbacks between climate and hydrologic systems, and elucidating the role of coupled processes like precipitation recycling. Moreover, understanding the behavior of wetlands as nodes in a complex wetland habitat network is critical for defining critical habitats and establishing the role of habitat fragmentation as drivers for species biodiversity in the PPR [Wright, 2010].

The next step is applying these approaches to the PPR more broadly. Although this study primarily focused on pothole-basin geometries appropriate for the Missouri Coteau, the PCHM is sufficiently general that it should be applicable to pothole lakes and wetlands in other regions of the PPR, such as Southern Saskatchewan, Minnesota, and the Prairie Coteau of South Dakota. Such a comprehensive spatial and temporal investigation on the scale of the PPR opens the possibilities for closing the water cycle over this
important region and better understanding its implications on regional problems like
droughts and deluges and waterfowl populations.
3.1 Introduction

There has been a long history in ecology and geomorphology of using the variations of parameters in space to extrapolate forward or backwards in time [e.g., Welch, 1970; Fukami and Wardle, 2005]. The point of such analyses is usually to understand the dynamic response of slowly-changing systems over long times. In practice, different aspects of this idea are represented, for example, in concepts of gradient analysis [Vitousek and Matson, 1991; Fukami and Wardle, 2005], space-for-time (SFT) substitution [Picket, 1989], chronosequences [Engstrom et al., 2000; Wardle et al., 2004], or natural experiments [Diamond, 1986].

This chapter examines the general question of how SFT substitution can elucidate long-term hydrological responses of closed-basin, wetland/pothole systems through time. More specifically, I set out to examine how the part of the larger Prairie Pothole Region (PPR), e.g., Missouri Coteau (Figure 3.1) responded to the Dust Bowl drought of the 1930s. While considered unremarkable in comparison to more severe droughts over the last two millenniums [Laird et al., 1996], the Dust Bowl is the most severe drought of record in the written history of the United States.
Figure 3.1 Shaded relief map of the Prairie Pothole Region in central North America. The map was prepared from Shuttle Radar Topography Mission (SRTM) DEM data. Water bodies in blue were detected from Landsat images collected in 1997.
My approach here depends on gradient analysis, which describes how the dynamics of hydrologic processes change along gradients of some underlying parameter. The parameter in this case is climate, represented in terms of regional variation in effective moisture ($\varepsilon$), defined as precipitation minus potential evaporation (i.e., $\varepsilon = P - E$). Gradient analyses provide a basis for extrapolating backwards or forward in time by SFT substitution. By itself, such substitution yields little information on the rate of change in the underlying process, except if time is the gradient parameter (e.g., examination of a number of sites of different ages), or the gradient parameter is a function of time, which is the case in this study. I use a collection of spatial data-sets, some associated with droughts and deluge (i.e., spatial snapshots), to examine the climatic gradient over much of its natural range.

Many different, apparently successful, applications of SFT substitution point to the power of this approach. Yet, few studies have validated the approach and examined its limitations from a quantitative point of view. This chapter examines how well this approach works in hydrologic applications. I describe a model-based approach to creating a time record capable of validating the quality of a backwards in time substitution.

3.2 Methodology

3.2.1 Lakes and Wetlands in the Prairie Pothole Region

This approach to SFT substitution is applied in a regional study of the hydrology of water bodies in the PPR (Figure 3.1). Millions of pothole lakes and wetlands are scattered across this 950,000 km$^2$ region. They commonly occur in small closed basins or
potholes formed by the uneven deposition of glacial till [Euliss et al., 1999]. The distribution of surface waters is strongly influenced by the physiography. Pothole lakes and wetlands are associated with till-covered bedrock uplands (e.g., western Manitoba and eastern South Dakota, Figure 3.1), and hummocky glacial moraines, like the Missouri Coteau, that extends from South Dakota along the Missouri River northwest into southern Saskatchewan and Alberta (Figures 3.1 and 3.2).

Water bodies range in size from puddles to lakes of several square kilometers, and are usually < 1 m deep. They reflect a delicate balance between periodic charging from snow melt and summer precipitation and loses due to evaporation [Winter et al., 2001]. With the large evaporation in summer months and year-to-year variability in precipitation, the numbers of water bodies and water areas vary both intra-annually and interannually. Details of the unique hydrology of the water bodies have been presented by Winter [1989] and, more recently, by Liu and Schwartz [2011].

3.2.2 Data and Methods

Climate data, i.e., monthly precipitation and monthly temperature (including monthly mean, maximum, and minimum temperature), were assembled for 121 selected nodes (69 in the U.S. and 52 in Canada, Figure 3.2) providing spatial and temporal climate patterns for the Prairie Pothole Region. Climate data of each U.S. node were obtained by averaging records of all NCDC (National Climate Data Center, http://www.ncdc.noaa.gov/) weather stations within a radius of ~40 km. Climate data for Canada were collected from stations of the National Climate Data and Information
Archive of the Environment Canada (http://climate.weatheroffice.gc.ca/). Due to relatively fewer number of weather stations located in Canada, data from the nearest stations were preferentially collected to complete the records for each of the nodes. Climate records for nearly 600 weather stations were accessed. After processing, all 121 nodes have complete records from 1981 to 2000, with 27 of them along the Missouri Coteau (centers of green blocks, Figure 3.2) having records from 1931 through 2005.

Figure 3.2 Locations of the 27 measurement blocks (green, 40 km × 40 km) along Missouri Coteau and its extension. The grid network consists of 1520 cells (light gray, 25 km × 25 km) and define sub-areas for statistical analyses on water-body numbers and water area coverage.
Effective moisture or P - E was selected as the major climatic variable for two reasons. First, earlier studies [e.g., Winter and Rosenberry, 1998; Winter et al., 2001] showed that P and E dominate the water balance. Second, effective moisture was also shown to be a highly significant explanatory variable describing the dynamic behavior of pothole water bodies [Zhang et al., 2009a]. Monthly potential E was calculated with Penman-Monteith method [Allen et al., 1998; Liu and Schwartz, 2011].

The spatial variability in the numbers of water bodies in the PPR was determined with three different snapshots (an average year, 1987, a dry year, 1992, and a wet year, 1997) using Landsat TM data. Each snapshot is a virtually cloudless mosaic that was constructed from 85 Landsat scenes (Table 3.1). To lessen effects of intra-annual

Table 3.1 List of the PATH and ROW numbers for the Landsat TM data (Worldwide Reference System-2) covering the Prairie Pothole Region.

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variability images from June, July, August, and September were preferentially selected. In a few cases, it was necessary to use using Landsat data from neighboring months or years because no suitable cloud-free imagery was available.

Pixels indicating water (one pixel = 900 m²) were detected automatically using image processing and classification methods described by Zhang et al. [2009b]. The numbers of water bodies (with area ≥ 900 m²) and percentages of water coverage were counted or calculated for each of the spatial snapshot on a grid of 1520 cells (Figure 3.2). The grid size (25 km × 25 km) was selected both to resolve local elements of physiographic settings and to provide a sufficient number of water bodies in most cells for statistical analyses.

The gradient analysis describes how the numbers of water bodies and water areas at a suite of sites changed as a function of the effective moisture. Along the Missouri Coteau and its extension, total of 27 measurement blocks (green, 40 km × 40 km, Figure 3.2) were defined for this purpose. The numbers of water bodies in each block (one pixel or larger) was measured at three times (1987, 1992, and 1997) to provide a total of 81 observations. A corresponding set of 81 effective moisture values were also determined for each block.

Each observation \( i \) \((i = 1, 2, 3, \ldots 81)\) on the number of water bodies, \( N_i \) is associated with a time \( (t_i) \) at which the observation was made. For each \( N_i \), I determine the value for average equivalent moisture, \( \bar{\varepsilon}_i \) that best reflects the climate history giving rise to \( N_i \). Experience has shown \( \bar{\varepsilon}_i \) to be a weighted average of preceding effective moisture values. My approach is to find the single averaging function that can transform
the sets of monthly effective moisture values \((e_{i,t}, e_{i,t-1}, e_{i,t-2}, e_{i,t-3}, \ldots e_{i,t-n})\), associated with each observation to the desired averaged value, \(\bar{\epsilon}_i\). A global optimization tool, genetic algorithm [Holland, 1975; Yang et al., 1998; Carroll, 2001; Liu and Schwartz, 2011], is used to find the optimum averaging scheme that maximizes the correlation between \(\{ \bar{\epsilon}_1, \bar{\epsilon}_2, \bar{\epsilon}_3, \ldots \bar{\epsilon}_{81} \} = C\) and \(\{ N_1, N_2, N_3, \ldots N_{81} \} = N\).

Specifically, for example, for any measurement \(i (i = 1, 2, \ldots 81)\) taken at time \(t\), my working hypothesis was that the measured water-body population, \(N_i\), is related to the so-called average equivalent moisture, \(\bar{\epsilon}_i\), which was defined to capture the preceding \(\epsilon\) information, i.e., \(\{\epsilon_{ij}\} (j = t, t-1, t-2, \ldots)\) in the following way

\[
\bar{\epsilon}_i = \frac{\sum_{k=1}^{5} (w_k \cdot \bar{\epsilon}_{ik})}{\sum_{k=1}^{5} w_k} \tag{3.1}
\]

Here, \(\bar{\epsilon}_i\) is set to be the overall average of the weighted \(\bar{\epsilon}_{ik}\) \((k = 1, 2, \ldots 5)\) over five periods of time in the past (present month \(t\) included), with \(\bar{\epsilon}_{ik}\) representing the average \(\epsilon\) and \(w_k\) representing the corresponding weight of the \(k^{th}\) period. Starting from \(t\), each period spans \(n_k\) months backwards in time in sequence with no overlap. Thus, \(\bar{\epsilon}_{ik}\) could be computed by

\[
\bar{\epsilon}_{ik} = \frac{\sum_{j=t-n_k+1}^{t-n_k-1} e_{i,j}}{n_k} \tag{3.2}
\]

54
In a special case when $l = 1$, $n_{l,j}$ (i.e., $n_0$) is equal to 0. A genetic algorithm was implemented to find the optimum values of $\{w_k\}$ and $\{n_k\}$ ($k = 1, 2, \ldots, 5$) which provided the best correlation ($R = 0.89$) between $\{\bar{e}_i\}$ and $\{N_i\}$. The results of the optimization were summarized in Table 3.2 while the progress of the optimization to the best fit was plotted in Figure 3.3. Inserting the optimum set of parameter values, $\bar{e}_i$ could be calculated easily through the re-written equation (3.1):

$$
\bar{e}_i = \frac{\sum_{j=t-n_1-1}^{t-1} E_{ij} w_1}{n_1} + \frac{\sum_{j=t-n_1-n_2-1}^{t-n_1-1} E_{ij} w_2}{n_2} + \frac{\sum_{j=t-n_1-n_2-n_3-1}^{t-n_1-n_2-1} E_{ij} w_3}{n_3} + \frac{\sum_{j=t-n_1-n_2-n_3-n_4-1}^{t-n_1-n_2-n_3-1} E_{ij} w_4}{n_4} + \frac{\sum_{j=t-n_1-n_2-n_3-n_4-1}^{t-n_1-n_2-n_3-n_4} E_{ij} w_5}{n_5}
$$

$$
= \frac{w_1 + w_2 + w_3 + w_4 + w_5}{w_1 + w_2 + w_3 + w_4 + w_5}
$$

(3.3).

Table 3.2 List of optimized parameter values used to calculate the average equivalent moistures with equation (3.3).

<table>
<thead>
<tr>
<th>$k$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w_k$</td>
<td>1.000</td>
<td>0.999</td>
<td>0.998</td>
<td>0.997</td>
<td>0.996</td>
</tr>
<tr>
<td>$n_k$</td>
<td>10</td>
<td>15</td>
<td>14</td>
<td>11</td>
<td>9</td>
</tr>
</tbody>
</table>
Figure 3.3 Plots of parameter convergence during the genetic algorithm based optimization process. Solid lines show how the values of fitness ($R$) and ten parameters evolve through generations. Note that the value of $w_1$ was set to be fixed at 1.0.
The validity of the SFT substitution is tested by taking the $N_i = f_s(x_i)$ function derived from the spatial observations at the measurement blocks and comparing it to a temporal function, developed for a single site. The calibrated hydrologic model (PCHM) \cite{Liu and Schwartz, 2011} was applied to Site 7 (shown in red, Figure 3.2) to provide simulated monthly water-body numbers from 1901-2005, $N_j (j = 1, 2, 3, \ldots 1260)$ given monthly weather data. The collection of climate data also provided a basis for calculating 1260 $\bar{e}_j$ values. The range in effective moisture at Site 7 is large because of the Dust Bowl drought of 1930s and the severe deluge of 1990s. If the SFT substitution is valid the independently-determined $N_j = f_t(x_j)$ function in time should be statistically similar to the $N_i = f_s(x_i)$ function in space.

3.3 Results

3.3.1 Gradient in Effective Moisture

The average of annual values of effective moisture values from 1981-2000 was contoured using data at 121 nodes (Figure 3.2). The map shows a gradient in effective moisture that ranges from about 0.02 m in the southeast (Iowa, Minnesota) to -0.60 m in the northwest (Palliser Triangle of Alberta and Saskatchewan) (Figure 3.4a). Thus, across much of the PPR evaporation exceeds precipitation (mean -0.33 m).

The range in variation in effective moisture is examined with five-year average $\varepsilon$ or P - E maps for periods of drought and deluge. During the drought of 1988-1992, effective moisture (Figure 3.4b) was lower than the 20-year average (Figure 3.4a). Across the central PPR, the -0.40 m front moved from southeastern Saskatchewan to eastern
North and South Dakotas. During the deluge that began in the summer of 1993 (Figure 3.4c), the -0.10 m zone moved northwestward from Minnesota to the central Dakotas with a reduction in size of driest area ($\varepsilon < -0.50$ m) in the Palliser Triangle (in red, Figure 3.4c) and wetter-than-average conditions everywhere in the PPR.

Figure 3.4d depicts the change in effective moisture from drought to deluge. In general, the PPR exhibited $\varepsilon$ variability greater than 0.10 m. Locally, in central North Dakota, the range in $\varepsilon$ changes was about 0.30 m (in red, Figure 3.4d). This part of the PPR was impacted by both the 1988-1992 drought and the 1990s deluge. The fluctuations of effective moisture in Canada during these periods were less extreme with a variation of less than 0.10 m. In southern Alberta, the variability was as low as 0.03 m (Figure 3.4d).

The results presented in Figure 3.4 show that a gradient in effective moisture is evident across the PPR. Droughts during the period of interest 1981-2000 effectively pushed the typically dry conditions of Alberta and Saskatchewan southeastward into North and South Dakota. Deluge conditions did just the opposite, producing wetter conditions in the Dakotas.
Figure 3.4 Average annual precipitation minus potential evaporation (i.e., P - E) maps for (a) 1981-2000, (b) 1988-1992 (drought) and (c) 1993-1997 (deluge). They illustrate the marked gradient in effective moisture gradient across the Prairie Pothole Region. Panel (d) shows the magnitude of the P - E changes from drought to deluge.
3.3.2 The Distribution of Surface Water

The distribution of water on the landscape under different climatic conditions is shown in Figure 3.5 in terms of both water coverage (% of area covered by water, Figures 3.5a-3.5d) and water-body density (counts per 10 km$^2$, Figures 3.5e-3.5h). It is evident that water bodies were distributed heterogeneously in space across the PPR. Regions with relatively large water coverage (> 15% of the land surface) occur in (i) western Minnesota, (ii) northeastern South Dakota, (iii) central North and South Dakota, and (iv) the northern edge of PPR in central Alberta and Saskatchewan. Comparisons with topography (Figure 3.1) and effective moisture (Figure 3.4) show that the areas with larger water-body coverages were associated with hummocky glacial terrains in wetter portions of the PPR. Examples include the flat-iron shaped upland or Prairie Coteau of eastern South Dakota (Region ii), the Missouri Coteau (Region iii). Occasional blocks indicating large-percentage coverages (> 25%) coincided with large lakes, such as Devils Lake in North Dakota and Quill Lakes in Saskatchewan. Relatively low coverages (< 1% of the land surface) occurred in the dry southern Canada and northern Montana, as well as in the flat plains and valleys, such as drift plains to the east of the Missouri Coteau and the Red River Valley.

Water-body densities generally followed a similar pattern of association as water coverages. Thus, high densities (> 20 water bodies per 10 km$^2$) were evident along the Missouri Coteau, Devils Lake area, Prairie Coteau, western Minnesota, and the glaciated, bedrock highlands of eastern Saskatchewan. Low densities water bodies (< 1.0 counts/10
km$^2$) were mainly observed in regions that are dry (e.g., Palliser Triangle) or flat (e.g., Red River Valley).

The distribution varied greatly in time as well. When comparing the water coverage and density patterns among 1987 (normal year, Figures 3.5a and 3.5e), 1992 (a year at the end of drought, Figures 3.5b and 3.5f), and 1997 (a year during the biggest deluge of the century, Figures 3.5c and 3.5g), dramatic changes were found in water-body distribution through time as the climate fluctuated (Figures 3.5d and 3.5h). The histogram summary in Figure 3.5i shows that drought resulted in a substantial decline in water area to 1.45% and in the total numbers of water bodies to 0.21 million, mostly through the Dakotas. Elsewhere, declines were much less evident. The deluge resulted in increases in water coverages to 3.14% and in total water body numbers to 0.92 million. The averages tend to hide some huge local changes in water occurrence through the transition from drought and deluge. Between 1992 and 1997, water coverages increased by 10% and densities increased by 30 counts/10 km$^2$ in the following areas Devils Lake, the glaciated bedrock highlands of southeastern and western Manitoba, and the Missouri Coteau.

These patterns in water coverages imply that the data from the 27 measurement blocks along the Missouri Coteau capture broad variability in the distribution of water bodies. Moreover, the additional snapshots, following periods of droughts and deluges, magnify the range in variability.
Validation of Space-for-time Substitution for Hydrologic Systems

One important goal of this chapter is to examine whether SFT substitution provides a way to utilize the present-day store of satellite observations to elucidate hydrologic conditions during times of much more limited observation. A necessary first step is to validate the approach. Figure 3.6a shows how the numbers of water bodies ($N_i$)
varies as a function of the optimized average equivalent moistures ($\bar{\varepsilon}_i$) considering the 81 spatial observations (i.e., $i = 1, 2, 3, \ldots 81$). The scatters, though derived from 27 different sites, follow the same prevailing trend: smaller water-body numbers are associated with lower $\bar{\varepsilon}$ values while larger water-body numbers are associated with higher $\bar{\varepsilon}$ values. The pattern can be quantified by fitting an S-shaped (sigmoidal) logistic model (i.e., Boltzmann’s function), which in the four-parameter form is:

$$N = A_2 + \frac{(A_1 - A_2)}{\bar{\varepsilon} - \bar{\varepsilon}_0} \frac{\bar{\varepsilon} - \bar{\varepsilon}_0}{1 + e^{\frac{\bar{\varepsilon} - \bar{\varepsilon}_0}{\Delta \bar{\varepsilon}}}}$$

(3.4)

with first derivative given as:

$$\frac{dN}{d\bar{\varepsilon}} = \frac{A_2 - A_1}{\Delta \bar{\varepsilon}} \frac{e^{\frac{\bar{\varepsilon} - \bar{\varepsilon}_0}{\Delta \bar{\varepsilon}}}}{(1 + e^{\frac{\bar{\varepsilon} - \bar{\varepsilon}_0}{\Delta \bar{\varepsilon}}})^2}$$

(3.5)

where $A_1$ is the lower asymptote (limit), $A_2$ is the upper asymptote (limit), $\bar{\varepsilon}_0$ is a fitting parameter representing $\bar{\varepsilon}$ value of the center point or point of inflection, and $\Delta \bar{\varepsilon}$ is another fitting parameter serving as the shape parameter that controls the slope in the vicinity of the inflection point, that is, the change in $\bar{\varepsilon}$ corresponding to the greatest change in $N$ values. As shown in Figure 3.6a, the data are fitted well by this function.
(solid line) with $R^2 = 0.81$. Parameter values fitted for this spatial trend are summarized in Table 3.3.

Figure 3.6b displays simulated values of $N$ at Site 7 as a function of $\bar{\varepsilon}$ determined using the same optimal weighting. A subset of simulated data over 105 years (i.e., 1901-2005) are plotted that includes the sixth year of each decade (e.g., 1916, 1926, 1936, etc) and years associated with extreme events (e.g., 1939, 1992, 1997, etc). The strong correlation ($R^2 = 0.91$) in temporal data fitted by Boltzmann model (solid line, Figure 3.6b) shows clearly that water-body numbers for the block, Site 7, are correlated to effective moisture, suggesting that the P - E in terms of $\bar{\varepsilon}$ is able to explain most of the temporal dynamics. The parameters of this distribution (Figure 3.6b) compare favorably with those of in Figure 3.6a (Table 3.3).

Figure 3.6c displays both the regression curves (solid lines) and their 95% prediction intervals (dashed lines). The curves describing the spatial and temporal results are almost identical, validating the SFT substitution along the Missouri Coteau.

<table>
<thead>
<tr>
<th></th>
<th>$A_1^*$</th>
<th>$A_2^*$</th>
<th>$\bar{\varepsilon}_0$</th>
<th>$\Delta \bar{\varepsilon}$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial</td>
<td>0</td>
<td>5900</td>
<td>-0.0259</td>
<td>0.0073</td>
<td>0.81</td>
</tr>
<tr>
<td>Temporal</td>
<td>0</td>
<td>6181</td>
<td>-0.0247</td>
<td>0.0079</td>
<td>0.91</td>
</tr>
</tbody>
</table>

* Values were preset to secure reasonable predictions. For example, values of $A_1$ were set to 0 so that the number of water bodies will never go below zero.
Figure 3.6 Validation of the space-for-time substitution in hydrologic systems. Panels (a) and (d) display spatial and temporal patterns of numbers of water bodies ($N$) versus average equivalent moistures ($\bar{\epsilon}$), respectively. Panel (c) compares the regression curves (solid lines) together with the 95% prediction intervals (dashed lines) between the spatial and temporal data. Panel (d) shows a conceptual model (logistic growth model) for hydrologic interpretations possible from space-for-time substitution. The conceptual model (solid line) describes how the water-body population changes as a function of climate while its first derivative (dashed line) represents the changing rate.
3.4 Discussion

3.4.1 Gradients in Effective Moisture: Observations and Implications

The results show that climate in the PPR exhibits considerable spatial and
temporal variability (Figure 3.4). There was a strong annual $\varepsilon$ or P - E gradient ranging
from several centimeters in the southeast to lower than -60 cm in the lower northwest.
The gradient, however, was not static, but varied greatly over time as the region
experienced deluges or droughts. Such variability in climate has been attributed to the
interactions among air masses influencing the PPR or the larger northern Great Plains
region. These air masses, including the cold, dry Continental Polar, the warm, wet
Maritime Tropical, and the cool, moist Maritime Polar [Bryson and Hare, 1974], each
have their own spatially and temporally varying impacts on the region [Woodhouse and
Overpeck, 1998] and their complex interactions create “one of the most extreme and
dynamic climates on Earth” [Millet et al., 2009].

Hydrologically “closed” water bodies are extremely sensitive to climate
variability and are highly dynamic in terms of their abundance, water levels, areas, and
storage [e.g., Winter and Rosenberry, 1998; Johnson et al., 2005; Zhang et al., 2009a; Liu
and Schwartz, 2011]. The results of my study confirm this tremendous variability at a
broad scale. Moreover, it demonstrates that water bodies were distributed
heterogeneously in both space and time across the whole PPR over the last two decades
of the past century (Figure 3.5).

The uneven spatial and temporal distributions are mainly attributed to the
combination of the physiographic setting and the climate. The spatial patterns in climate
(Figure 3.4) and water-body distribution (Figure 3.5) show that small water coverages and small water-body densities were associated with the dry areas (e.g., the Palliser Triangle). Large water coverages and densities were associated with relatively wet areas (e.g., South Dakota, North Dakota, and Minnesota). These differences in the spatial distribution of water distribution can also be magnified by climate variability. For example, large differences in the water-body distributions between North Dakota and southern Saskatchewan existed in 1987 (Figure 3.5a). The deluge that started in 1993 by 1997 had enhanced the differences (Figure 3.5c). As other examples, the Missouri Coteau and Devils Lake areas in central North Dakota were unique in that, they exhibited the greatest variability in P - E over the 20-year period (red areas, Figure 3.4d) of any place in the PPR. Not surprisingly then, these areas were associated with the greatest changes in water-body area and density (Figures 3.5d and 3.5h).

3.4.2 Validity in the Space-for-Time Substitution

SFT substitution has been applied extensively and a commonly used method in ecology. SFT substitution makes it possible to infer the temporal dynamics of long-term process (e.g., ecological succession and landscape evolution) from modern observations on multiple sites with gradient in some variable. Often, this approach offers the only alternative to long-term observations. Commonly, SFT substitutions assume implicitly that some independent systems respond to changes driving forces in the same way over space and time [Pickett, 1989; Dunne et al., 2004]. This underlying assumption, however, has little empirical support. Thus, its validation continues to remain as a significant
challenge, mainly because of the paucity of data over long times as well as its inherent limitations.

In one of the few attempts at validation, La Sorte et al. [2009] found disparities between the spatial and temporal trends of climate-change impacts on winter bird assemblages. Their results suggest that care must be taken in the use of the approach. Ecologists point out that SFT substitutions are least suitable for studying species-rich and highly disturbed systems, and are most suitable for those systems having “low biodiversity, rapid species turnover and low frequency and severity of disturbance” [Walker et al., 2010].

With these limitations in mind, I am cautious in the use of the SFT substitution method to select regions that are homogeneous except for the gradient in some parameter. I have tested this method using data collected along the Missouri Coteau that provides a single physiographic setting and mixed-prairie ecosystem modified by farming and grazing. Essentially, this strategy reduces the number of factors controlling the system behavior to one, effective moisture (ε or P - E). The results in Figure 3.6c clearly show that spatial and temporal trends follow a common trajectory suggesting that the water-complex along the Missouri Coteau responds to varying climate over space in the same way as over time. Three factors are believed to be important to the successes of SFT substitution in this case. First, the relatively homogenous physiographic and prairie settings led to similar behaviors among the hydrologic systems. In other words, the systems at different sites tracked variability in the controlling factor similarly. Second, the gradient in the controlling factor in the space has comparable range to that in the time,
allowing direct comparisons without extrapolation. Third, relative to ecological processes
that usually are slow and prone to disturbances and diverge, hydrologic processes are
relatively fast with less possibilities of diverging naturally, if there is no substantial
anthropogenic disturbance.

3.4.3 Surface-water Dynamics Inferred from the Curve Fitting

The results of the validation lead naturally toward a generalized conceptual
model, describing how surface water complex responds as a function of climate (solid
line, Figure 3.6d). The model suggests that the status of some watershed system,
represented, for example, in terms number of water bodies or population, $N$, is primarily a
function of average effective moisture or $\bar{e}$. Note that each $\bar{e}$ value is a weighted
function of the past history in effective moisture as described in section 3.2.2.

The conceptual model also carries dynamic information on how the system status
varies with the forcing factor. Although the pathway for change is unique due to climate
forcing (solid line, Figure 3.6d), it is also complex. For example slope of the curve
(dashed line, Figure 3.6d), varies from bottom to top, with the smallest values at both
ends and the largest value in the middle (dot on the solid line, Figure 3.6d). A small slope
represents a situation where the hydrologic character of the system is not particularly
sensitive to the driving force. Regions with steeper slope suggest hydrologic
characteristics are much more sensitive to changes in the climatic forcings (dashed line,
Figure 3.6d). Taking wetting for example, the water-body complex would start as a small
population ($N = N_{min}$); as climate gets wetter, that population would grow with an
increasing growth rate up to the midpoint of the function, where the growth continues with an decreasing growth rate until hitting the maximum ($N = N_{\text{max}}$).

3.4.4 Application of SFT Substitution for Understanding Extreme Climate Impacts

Integrating both spatial and temporal information, the most important implication of the SFT-based model is that, given climate condition, it allows the status of hydrologic systems to be predicted at any location and at any time, both backward and forward in time. As a demonstration, here I applied the functional relationship to reconstruct the status of water complexes across the MC from 1936 through 2005 accounting for spatial and temporal variability in climate. Of particular interest are the impacts of climatic extremes, e.g., the Dust Bowl drought of the 1930s and the deluge of the 1990s.

Figure 3.7 displays the spatiotemporal patterns in the water-body population for the water complexes at Sites 1 thru 19, 21, and 24 ($y$-axis) along the MC from 1936 to 2005 ($x$-axis). The spatial and temporal variability in climate produces heterogeneity in the population distributions, indicating that the dynamic status of the lake/watershed complex varies from site to site and through time. Among all 21 sites examined, the population of water bodies at North Dakota sites (Sites 4-13, Figure 3.7a) had the greatest variability with time, a pattern that was evident in climate (Figure 3.4d). In this region, the population of water bodies has varied from less than a hundred to over 5000, through the swing from dry to wet climate conditions. In Alberta and part of Saskatchewan (Sites 19, 21, and 24), the driest area of Palliser Triangle, the numbers of water bodies were found to be consistently low ($< 1000$) from 1936 to 2005.
During the 70-year period, the wettest period was from the mid 1990s to early this century, with water-body populations greater than 4000 (Figure 3.7b). The effects of this deluge as well as other wetter conditions (e.g., the 1950s and 1970s) impacted only the U.S. portion of the MC. The Dust Bowl Drought of the 1930s was the drought of record of the 20th Century. The prolong drying associated with this drought produced a marked decline in water-body populations (< 1000) along the MC from Site 1 in South Dakota to Site 24 in Alberta (Figure 3.7c). Other noticeable dry periods occurred in the early 1960s and 1988-1992. These droughts, although not as serious as the 1930s’ Dust Bowl, significantly impacted water bodies at local or intermediate scales.

It is worthwhile noting that the population estimates based on SFT substitution are independent of space or time, implying the system status impacted by the climate variability can also be transformed in space and time. For examples, I estimated water-body population to be 498 at Site 7 (North Dakota) in 1940 and 480 at Site 24 (Alberta) in 1982. The approximately equivalent population suggests that the system in Alberta (by-nature arid system) would be representative of and be able to predict system status in central North Dakota during the 1930s’ Dust Bowl drought. This implication is valuable as it takes advantage of the essence of the SFT substitution – forecasting/exploring long-term system dynamics in time from modern observations in space.
3.5 Conclusions

The results of this study, for the first time, provide an explicit and comprehensive picture of the water-body distribution across PPR and how the distribution changes with climate variability in space and time. The availability of this a complete picture should play an important role in future water resources management, wetland restoration, and wildlife conservation. Given the projected climate change, my results may also have
important implication as to how to set up space-based monitoring on the behavior of millions of water bodies across the PPR.

My comparison of the spatial and temporal trends of the water-body population dynamics revealed a common response function for prairie water bodies to climatic fluctuations in space and time. The existence of such a function provides support for the SFT substitution assumption and led to a SFT-based conceptual model. It provides a unique approach to better understand the impacts of historic extreme climate events.

My finding of the validity of the SFT substitution in the hydrologic systems not only contributes to solving an important science question in its own right, but has important implications. Clearly my study implies that applying the SFT substitution may provide an additional dimension in hydrologic study: temporal information can be extended through the judicious use of spatial information, and vice versa. Trading time for space makes it possible to apply investigation results from known sites to those remote or inaccessible sites where the direct measurements or observations are not possible. Trading space for time, also holds promise (for some case may be the only way) for understanding long-term system dynamics, which further lets us reconstruct the historic status and predict potential impacts of future climate change.

Like any other tool or approach, the SFT substitution has its own limitations and sometimes may be misused. Concerns on its limitations, however, did not prevent the SFT substitution becoming the most frequently used approach for measuring temporal dynamics in ecology, as it offers invaluable insights that cannot be achieved in any other way [Walker et al., 2010]. Through this study, I have demonstrated the great potential of
the SFT substitution for improving understanding of hydrologic dynamics. I hope this study of the SFT will receive attention from the hydrology community and, therefore, expect growing applications in the field of hydrology.
4.1 Introduction

Researchers have made significant progress in statistical or mathematical modeling of the dynamics of lakes or wetlands [e.g., Crowe and Schwartz, 1981a, 1981b; Crowe, 1993; Poiani et al., 1996; Winter and Rosenberry, 1998; Su et al., 2000; Johnson et al., 2005, 2010]. Implicitly, such modeling has captured quantitatively the linkages between stage response and climatic fluctuations.

Closed-basin lakes have also long been long-recognized as sensitive indicators of climate changes and lake sedimentary archives widely used for reconstructing the history of climate changes [Fritz et al., 1991, 2000; Laird et al., 1996, 2003; Baker et al., 2001; Battarbee et al., 2002; Schwalb and Dean, 2002; Blass et al., 2007; Giralt et al., 2011]. Such climate reconstructions implicitly assume that the lakes are in fact sensitive recorders, preserving information on climate variations. However, is this really the case? A study by Mason et al. [1994] showed that lakes can respond differently to climate in terms of a so-called “equilibrium response time”. The implication then is that lakes can vary in their capabilities in capturing the history of past climates. Such indications, in turn have raised several questions; for example how differently do lakes respond to climate, or conversely how do climate impacts differentiate among lakes, how well can
lakes record climate, and are climate reconstructions inferred from lacustrine sediments reliable. The answers to these questions remain elusive and will require a better understanding of the coupling between lakes/wetlands and climate.

The purposes of this chapter, therefore, are to elucidate controlling factors of lake/wetland hydrologic dynamics and to enhance the understanding of the relationships between the responses of lakes/wetlands and climatic forcings. Here I hypothesize that water bodies (i.e., lakes and wetlands) may not record climate signals as simply or directly as usually expected, and furthermore that there must be some ambiguity between the climate signals and the record preserved in the lake/wetland sediments. To test this hypothesis, I first present and analyze observational data that relate lake/wetland water level response to the corresponding climatic history. Next, a series of numerical experiments are used to explore direct links between stage behavior and climatic fluctuations. Finally, I elucidate the mechanism of how climate impacts lake/wetland systems, or how such systems respond to the climatic forcings.

One of the unique features of this study is that it aims to provide a new approach to quantitatively examine the influences of climate on stage, while revealing the depth of memory integrating the proceeding climatic conditions. The study results will contribute to a better understanding of the how climate influences stage behaviors and provide a simple but effective way to predict future water-body responses to a changing future climate. The results should also lead to new approaches to evaluate the accuracy of climate reconstructions from sedimentary archives and to suggest ways of improving the accuracy of reconstruction.
4.2 Data and Methods

Water-level/stage data were tabulated for four water bodies of quite different sizes. Devils Lake is a large, closed-basin lake with a watershed area of 9,867 km$^2$ in northern North Dakota (ND). It has been investigated extensively in various hydrologic studies, including climatic reconstructions [e.g. Fritz et al., 1991, 1994]. Water levels of Devils Lake have been monitored back into the 19th Century [Wiche, 1998]. Waubay Lake, with watershed area of 793 km$^2$, is located in northeastern South Dakota. Water levels records date back to the 1950s with sporadic records from the 1930s [Niehus et al., 1999]. The last two water bodies are smaller semi-permanent wetland, P1 (~ 0.1 km$^2$) and a tiny seasonal wetland, T8 (~ 0.01 km$^2$) are located at the USGS Cottonwood Lake area in central ND and monitored since the 1970s [LaBaugh et al., 1996; Winter and Rosenberry, 1998]. Figure 4.1 shows the geographical locations of the four lake and wetlands.

The investigation also uses the recently developed Pothole Complex Hydrologic Model (PCHM) [Liu and Schwartz, 2011] to implement examination of a series of hypothetical lake/wetland systems of varying basin sizes. This model is capable of simulating the hydrologic responses of a complex of lake-watersheds as a function of climate and physical settings. The climatic input variables to PCHM include monthly precipitation, temperature, and potential evapotranspiration (PE). Long-term monthly precipitation and temperature data over 1901-2005 were obtained from two weather stations (Woodworth and Jamestown, ND) of the National Climatic Data Center
(NCDC). Monthly PE was calculated with the FAO Penman-Monteith method [Allen et al., 1998].

To explore the direct links between hydrologic responses and climate, correlation coefficients between the water levels and the climate (in terms of Palmer Drought Severity Index, PDSI) [Palmer, 1965; Cook et al., 2004] were calculated. There was a hint in recent studies that water-body behavior could be integrating climatic conditions [Zhang et al., 2009a]. Thus, different from previous studies targeting month-to-month

Figure 4.1 Locations of the four selected lakes/wetlands in South Dakota and North Dakota of the United States.
comparison of PDSI and lake/wetland dynamics [e.g., Sorenson et al., 1998; Winter and Rosenberry, 1998], my approach here examine controlling mechanisms in terms of cumulative influences of climate. My working hypothesis is that stage at any given time is some function of the present climate but also conditions in the past. I defined the integrated forcing of climate on a water body for a target year \( t \) (\( CuIMP_t \)) as the summation of the climatic conditions over \( m \) preceding and target years (\( IMP_n, n = t, t-1, t-2, \ldots t-m+1 \)):

\[
CuIMP_t = \sum_{n = t-m+1}^{n = t} IMP_n = \sum_{n = t-m+1}^{n = t} CLM_n \cdot WT_{n-t}
\]  

(4.1)

where \( CLM_n \) refers to the PDSI of year \( n \), and \( IMP_n \), the effective climatic forcing for year \( n \), is a product of the \( CLM_n \) and the corresponding weight, \( WT_{n-t} \). \( m \) represents some number of years backwards in time such that the influence of any year earlier than \( t-m+1 \) is assumed to be negligible. The PDSI for year \( n \) was calculated by averaging monthly PDSIs, which were obtained from NCDC (if available) or computed using a self-calibrating PDSI program [Wells et al., 2004]. For example, the integrated climatic forcing on a lake in year 2011 equals to the effective climatic forcings from years 2011, 2010, 2009, \ldots until a year is reached at which time influence is negligible.

To calculate the \( CuIMP_t \), the values of the weights, \( WT_i (i = 0, 1, 2, \ldots) \), need to be determined in the range from 0 to 1 for \( m \) years. Here \( i \) (or \( n - t \) in equation 4.1) is an index representing the distance (i.e., how many years) between the year \( n \) of the climate
that is considered and the target year $t$, with $i = 0$ (i.e., $n = t$) representing the target or present year. For example, to investigate the integrated climatic forcing on the stage of a water body in 2011, i.e., $CuIMP_{2011}$, I assigned $WT_0$ to the $CLM_{2011}$ (i.e., PDSI value of year 2011), $WT_1$ to the $CLM_{2010}$, $WT_2$ to the $CLM_{2009}$, etc, and $CuIMP_{2011}$ is calculated as

$$CuIMP_{2011} = CLM_{2011} \cdot WT_0 + CLM_{2010} \cdot WT_1 + CLM_{2009} \cdot WT_2 + \ldots$$

A FORTRAN program of correlation-coefficient calculator coupled with a genetic-algorithm [Holland, 1975; Carroll, 2001] optimization technique (CC-GA) has been developed to automatically identify the optimum set of weights ($WT_i^{opt}$, $i = 0, 1, 2, \ldots$). Starting from multiple random points, the CC-GA searches for the global optima within the space through successive generations until the some optimum set of weights are found that provide the best correlation coefficient between the integrated climate forcings and stages.

4.3 Results and Discussion

4.3.1 Disagreement Between Water-body Hydrology and Climate Signals

Figure 4.2 compares time series of water levels and PDSI values for four lakes/wetlands. Generally, the stage behavior of all four lakes/wetlands (black scatters, Figure 4.2) was found to be somewhat correlated with PDSI values (gray bars, Figure 4.2). Thus, relatively high water levels were observed in wetter periods and low water levels in dryer periods. For example, Devils Lake declined to century-low water elevation of 427.1 m in 1940 after being impacted by the 1930s Dust Bowl drought, and rose to the highest stage ever recorded, 442.6 m in 2010 after a series of wet years starting in
summer 1993 (Figure 4.2a). Waubay Lake exhibited a similar pattern of responses with persistent high water levels since the deluge in 1993 (Figure 4.2b). The water level in Wetland P1 coincided with the bottom of the wetland during the 1988-1992 drought and

![Graph showing water levels and PDSI for four lakes/wetlands](image)

Figure 4.2 Comparisons between climate (Palmer Drought Severity Index, PDSI) and water levels of four lakes or wetlands: (a) Devils Lake, (b) Waubay Lake, (c) semi-permanent Wetland P1, and (d) seasonal Wetland T8. Note that the corresponding watershed size decreases from (a) Devils Lake through (d) T8. PDSIs of Devils Lake and Waubay Lake were obtained from NCDC climate divisions of ND03 (northeast) and SD03 (northeast), respectively. PDSIs of P1 and T8 were obtained through calculation described in section 4.2.
rose dramatically during the 1993-2001 deluge (Figure 4.2c). As a seasonal wetland, T8 usually contained water in wet spring, whereas dried up in the hot and dry midsummer (Figure 4.2d).

Clearly Figure 4.2 shows that the some of the time series are not well correlated with annual PDSI, as a measure of wetness and dryness. The water-level time series usually are smoother than PDSI series. This effect is more evident with the larger lakes (Figures 4.2a and 4.2b) than in smaller wetlands (Figures 4.2c and 4.2d), suggesting larger lakes are less sensitive to and, in turn, exhibit less responsiveness to short-term or seasonal climate variations. Besides magnitude, timing disparities were also observed between the two types of signals. It is quite evident that the peaks of PDSI, i.e., the wettest conditions, occurred around early or middle of 1990s; however, the highest water levels did not emerge until the end of the decade (e.g., Waubay Lake and Wetland P1) or even the next decade (e.g., Devils Lake). Such lag effects in water-body responses will be discussed further in the following sections.

Lake/wetland watersheds are complex systems consisting of various hydrologic components and processes. They often function in a manner that buffers the effects of environmental or climate forcings [Weltzin et al., 2003]. Examination of Figure 4.2 reveals that, rather than being perfectly linked to the present climate and its short-term fluctuations, water-body systems tend to buffer climate fluctuations, effectively acting as climate filters with characteristics that vary from water body to water body. Generally, large water bodies (e.g., large lakes) act as low-pass "filters", passing low-frequency climatic signals (i.e., interannual or long-term climate trends or fluctuations, such as the
multi-year drought of 1930s or the deluge of 1993-2001) but attenuating high-frequency climate signals (i.e., seasonal or short-term climate fluctuations). Small water bodies (e.g., small lakes or wetlands) in contrast act as high-pass "filters", passing high-frequency seasonal or short-term climate signals with limited ability to reproduce or display long-term trend of climate signals.

4.3.2 Scale-dependent Responses of Water Bodies

The data in Figure 4.2 show that stages of water bodies respond to long-term climatic fluctuations in a scale-dependent manner. To further explore such scale effects, I carried out a theoretical, numerical investigation of four hypothetical closed-basin watersheds with areas ranging from $1 \times 10^4$ m$^2$ to $1 \times 10^7$ m$^2$. Isolated from other effects such geomorphology, here the four watersheds were assigned a uniform but scaled topography, which has been shown to work well in representing water bodies and watersheds of various sizes [Liu and Schwartz, 2011]. The PCHM was applied to simulate the responses of four water bodies to an identical, idealized 1000-year climate signal. The climate, in terms of precipitation minus evaporation (i.e., $P - E$), is assumed uniform except for a single 10-year perturbation away from the background or undisturbed condition (Figure 4.3a). Such settings of the watersheds and climate allowed me to discriminate how differently the water bodies varying in size respond to the climate perturbation (Figures 4.3b-4.3e).

Before the perturbation, (simulation time: yr 0 to yr 500), the hydrographs for all four water bodies were essentially horizontal lines, suggesting that the water bodies were
in equilibrium with the background climate. Once disturbed by the climate fluctuation (yr 501 to yr 510), however, differences in the shape of response curves could be observed. The most notable difference lies in tail length, implying different period of time for water bodies to return the pre-disturbance status: approximately 7 years, 30 years, 100 years, and over 250 years for Water Body 1 (with watershed size of $1\times10^4$ m$^2$), Water Body 2 (size: $1\times10^5$ m$^2$), Water Body 3 (size: $1\times10^6$ m$^2$), and Water Body 4 (size: $1\times10^7$ m$^2$), respectively. It seems that a small water body is able to fully recover to its equilibrium almost instantaneously, whereas a large water body may spend a long period of time.

Figure 4.3 Scale-dependent responses of water bodies to simple variations in climate. (a) shows an idealized climate (precipitation minus evaporation, P - E) signal with 10-year perturbation; and (b) - (e) show the hydrologic responses, in terms of annual water depths, for four hypothetical water bodies with various watershed sizes: (b) Water Body 1 ($1\times10^4$ m$^2$), (c) Water Body 2 ($1\times10^5$ m$^2$), (d) Water Body 3 ($1\times10^6$ m$^2$), and (e) Water Body 4 ($1\times10^7$ m$^2$). WB: Water Body.
I attribute the scale-dependent response variability among small and large water bodies to differences in their hydrologic stability. Stability is a key characteristic of a system as it determines system’s ability to continue functioning under varying conditions [Orwin and Wardle, 2004]. Adopted from ecology, the stability or response of water body to a climate can be analyzed using two components: resistance (the degree of response or change in a water-body system caused by a climate disturbance) and resilience (the speed of a water-body system recovering to its pre-disturbance or equilibrium status after the disturbance) [Pimm, 1984; Orwin and Wardle, 2004]. In terms of a rising water-level stage, the slope of the response curves (rising limb, Figures 4.3b-4.3e) becomes flatter with increasing lag time as water-body sizes increases, suggesting any climate disturbance has an instantaneous impact on small water bodies and slow effects on large water bodies. It is implied that small bodies are highly sensitive to the climate variations with low resistance, while large bodies are less sensitive with high resistance. In the recessional stage, similarly, as water-body size increases the response curves (falling limb, Figures 4.3b-4.3e) become flatter and the tails longer, indicating smaller water bodies have faster rates of recovery and higher resilience than larger water bodies. Such findings were also supported by the comparisons of the calculated resistance and resilience indices (Table 4.1).
Table 4.1 Summary of characteristics of four hypothetical watersheds.

<table>
<thead>
<tr>
<th></th>
<th>Water Body 1</th>
<th>Water Body 2</th>
<th>Water Body 3</th>
<th>Water Body 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watershed size (× 10⁴ m²)</td>
<td>1.0</td>
<td>10.0</td>
<td>100.0</td>
<td>1000.0</td>
</tr>
<tr>
<td>Resistance*</td>
<td>-0.70</td>
<td>-0.63</td>
<td>-0.56</td>
<td>-0.28</td>
</tr>
<tr>
<td>Resilience*</td>
<td>1</td>
<td>0.37</td>
<td>0.11</td>
<td>0.05</td>
</tr>
<tr>
<td>Model</td>
<td>WT (t) = e⁻ᵗ/τ, t = 0, 1, 2, ...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Correlation**</td>
<td>0.944</td>
<td>0.964</td>
<td>0.975</td>
<td>0.983</td>
</tr>
<tr>
<td>Optimized τ (years)</td>
<td>1.297</td>
<td>4.010</td>
<td>7.296</td>
<td>15.416</td>
</tr>
<tr>
<td>²τ = 3τ (years)</td>
<td>3.891</td>
<td>12.030</td>
<td>21.888</td>
<td>46.248</td>
</tr>
</tbody>
</table>

*Resistance and resilience indices, ranging from -1 to 1, were calculated based on Orwin and Wardle’s method [2004]. A value of 1 in either case indicates maximal resistance (disturbance has no effect on system) or maximal resilience (full recovery). A lower value of resistance indicates stronger effect (less resistance); and a lower values of resilience indicates a slower rate of recovery (less resilience).

**Correlation: optimized correlation coefficient by CC-GA between water levels and integrated climatic forcings. The latter were calculated by using equation (4.1), with weights (WT) derived from the model and τ listed.

4.3.3 Climatic-forcing and Water-body-response Mechanisms

The long recovery time for relatively large water bodies implies lag effects [Weltzin et al., 2003] in the water-body responses. The patterns of climate fluctuations, measured as PDSIs or P - E, could involve multi-year or decadal time scales. Examples include the extreme PDSIs related to the 1930s Dust Bowl drought and the 1993-2001 deluge (Figure 4.2) or these same extremes measured in terms of P - E (Figure 4.3).

Moreover, the effects of these changes may persist for perhaps several decades or over a century and, by which time new fluctuations in the climate might be evident. Such lag
effects undoubtedly enhance the complexity of the relationship between water-body response and climate.

A new concept (i.e., integrated climatic forcing, equation 4.1) has been developed to capture information about the integration of climatic forcings and the sensitivity of the response variables to those variables. Using Wetland P1 as an example, I employed CC-GA to examine the correlation between the PDSI data and the extended water-level records (1951-2005) provided by the PCHM. After hundreds of GA generations, a significant correlation coefficient ($R = 0.976$, Figure 4.4a) and high agreement between the time series of integrated forcings ($CuIMP_t$, solid line, Figure 4.4a) and water levels (dashed line, Figure 4.4a) were obtained. Such a strong quantitative correlation, indicating a close correspondence between the time series proves my hypothesis that water bodies respond as a function of climate in a complex way, and the present character of a water body is a result of integrated climate forcing. The results also suggest that my concept or model of integrated climatic forcing (equation 4.1) is sufficient to explain the timing and magnitude of the water-body hydrologic dynamics.

Figure 4.4b shows the optimum set of weights ($WT_{i}^{opt}$) defined in equation (4.1). As expected, the weight decreased moving backwards in time year by year from the present. The weights can be understood in two different ways. From the point of view of a reference year, $t$, the PDSI of year $t$ has a weighting of 1.0 contributing to the water-body stage at $t$. However, as time moves forward, $t+1$, $t+2$, and $t+3$, the weights for year $t$ decline, 0.75, 0.50, and 0.26, respectively. Using stage at time $t$, alternatively, the integrated climatic forcing on water-body status at year $t$ consists of contributions from
the climate of present and proceeding years, with present year \( t \)'s climate weighing 1.0, previous year \( t-1 \)'s climate weighing 0.75, year \( t-2 \)'s climate weighing 0.5, etc. The declining trend of weights clearly indicates that, as time passes, the impact/influence of the climate for a particular past year on water-body stage becomes weaker and weaker. The pattern of the declining weights is an exponential function. Result of a nonlinear regression analysis (\( R^2 = 0.913 \)) confirmed that the weights decay through time following well-defined first order exponential function:

\[
WT(t) = e^{-t/\tau}
\]  

The constant \( \tau \) represents the basic lag time which is the inverse of the decay rate, \( \lambda \) (i.e., \( \tau = 1/\lambda \)) in a general decay function, or the equilibrium response time described by \textit{Mason et al.} [1994]. Here in equation (4.2), \( \tau \) is considered as a characteristic of water bodies, describing the time in years required for the weight for a particular year to drop to 36.8\% \( (e^{1}) \) of its original value. A smaller \( \tau \) value of a water body means that the time lag before the stage readjusts following a climatic excursion is small, or in other words, the water body readjusts rapidly. For a lake/wetland then at some year of interest, \( t \), the weights for years backwards in time can easily be derived from equation (4.2), once \( \tau \) is determined. It is a simple matter to determine the integrated climate for year \( t \) with equation (4.1), knowing the weights and PDSI values back in time. This simple but accurate approach quantitatively describes the climate impacts on lake/wetland
Figure 4.4 Validation of integrated-climatic-forcing concept. (a) demonstrates significant correlation \((R = 0.976)\) and high agreement between the time series of integrated climatic forcings (gray line) and water levels (black line or open squares) of Wetland P1; and (b) plots scatters of the optimized weights of equation (4.1) with nonlinear regression model (i.e., equation 4.2: \(WT(t) = exp(-t/\tau)\), when \(\tau = 3.421\)).
hydrologic systems. Moreover, my findings reveal a new concept of how climate impacts lake/wetland systems, or how lake/wetland systems respond to climate changes.

4.3.4 Climate Memory and Adjustment Time Lags

Results from section 4.3.3 suggest that the concept of integrated climatic forcing can be used to explain the present hydrologic condition of a water body. The adjustment time lag (i.e., $\tau$ in equation 4.2) is obviously scale-dependent, proportional to the size of the water body and its watershed. To further explore the links between $\tau$ and watershed size, I will reexamine the behavior of the four hypothetical water bodies. Now, the behaviors of the four hypothetical water bodies are examined in simulations using actual climate records from 1901 to 2005 described in section 4.2. As before, the simulations are conducted using CC-GA approach to determine the optimum $\tau$ of each watershed. Figure 4.5a compares the times series of optimized integrated climatic forcings and the simulated water levels of the four water bodies, with the optimum correlation coefficient values and the corresponding $\tau$ values listed in Table 4.1. Figure 4.5b plots the weights derived from the value of $\tau$ of each water body.

Several features of the results need to be noted. First, the strong correlations as indicated by $R > 0.94$ for the four water bodies (Table 4.1), confirming that my concept of integrated climatic forcing is applicable for different-size lake/wetland watersheds. Second, it is clearly demonstrated that the a water body’s memory of climate declines backwards in time, and the time lag $\tau$ (inverse of declining rate) is proportional to the size of watershed. The climate memory of smaller water bodies (with lower $\tau$) is much shorter
Figure 4.5 Application of integrated-climatic-forcing concept to four hypothetical water bodies. (a) Visual and statistical comparisons of integrated climatic forcings (bold gray lines) and water depths (black lines) of four water bodies indicate that the concept can sufficiently explain the timing and magnitude of the responses of various-size water bodies. (b) shows that the impact of climate (in terms of weights) on water-body hydrology declines as time passes at a rate determined by \( \tau \), which varies with the size of watershed in a linear way (c). WB: Water Body.

than with larger water bodies (with higher \( \tau \)). As compared in Figure 4.5b, for example, the basic time lag or the time to recover 63.2% of some original perturbation in water
depth is only 1.3 yrs on a small water body (Water Body 1), but 15.4 yrs on a large water body (Water Body 4). To reach $3\tau$ (95% recovery), similarly, it takes 4 yrs on Water Body 1 and about 46 yrs on Water Body 4.

In Figure 4.5c, these values of $\tau$ are plotted versus the respective sizes of watersheds on a log-log scale (Figure 4.5c). The linear relationship that is obtained, provides a start at predicting values of $\tau$ for any given lake/wetland watershed. Finally, an interesting application of these results would be to quantitatively examine the impacts of the historic extreme events, such as the 1930s Dust Bowl drought, on the lake/wetland systems. Figure 4.6 shows how the hydrologic memory of the ten-year drought (highlighted in red) for the four hypothetical water-body systems faded as time passed. A zero value on y-axis indicates no effects and negative values represent negative effects on

![Figure 4.6](image.png)

Figure 4.6 Comparisons of the impacts of the 1930s Dust Bowl drought on water-body systems of different sizes. WB: Water Body.
water balance. The influences of the Dust Bowl drought lingered only a few years with small water bodies such as Water Body 1. The impacts on the large water bodies, e.g., Water Body 4, persisted for many decades. If there were no offsets from the climate afterwards, Water Body 4 might still be noticeably influenced by the 1930s’ drought up to the year 2000 (blue line, Figure 4.6). One can speculate that a water body larger than Water Body 4 could have even a larger hydrologic memory.

An important implication of my results is that the hydrologic character of lakes or wetlands, represented, for example, by water levels or the associated sedimentary records, may not simply represent the operative present climate, but integrated historical climate. This concept challenges the traditional views that there is not necessarily a tight coupling between the present character of a water body and the operative climate. Essentially, past climates have the potential to influence present behavior. Small water bodies, owing to their high sensitivity, low resistance, and high resilience to climate, have relatively short and simple memory. For example, Wetland T8 and Water Body 1 exhibit remarkable seasonal hydrologic variability in response to intra-annual climate fluctuations. Such bodies exhibiting a small $\tau$ or a small time lag accurately track the short-term variability in weather. Large water bodies, on the contrary, due to their large time lags, respond in a more complicated manner because they are integrating the historical climate. These water bodies (e.g., Devils Lake and Water Body 4), on one hand, might be influenced by unusual climate events that took place decades or even hundreds of years ago; on the other hand, they may “forget” or filter out those normal events even just happened.
The discovery of a water-body’s size-dependent memory has important implications for climate reconstructions. My findings suggest that, depending on the purpose and requirements of the reconstruction, water body of an appropriate size should be selected. Generally, small water bodies respond to climate variability with a short time lag. Thus, they would be most useful for studying short-term climate fluctuations at high temporal resolution. However, small water bodies may not be appropriate for recording extreme events because once a small water body is dry it no longer is discriminating in intensity. For example, Wetland T8 was dry almost every summer; and given some sediment record for T8, it would be a challenge to differentiate extremely dry summers from normally dry summers. It is also worth noting that small water bodies may only record a narrow range of climate fluctuations, because of their relatively limited water storage capacities. Moreover, the settings of small water bodies (e.g., bottom bathymetry) are usually susceptible to natural or anthropogenic disturbances, which can possibly prevent them providing consistent records through time.

Large water bodies in contrast are insufficiently sensitive to record local or short-term climate disturbances. They are effectively integrators of climate changes over many years or decades and, thus, are appropriate for broad climate reconstructions at decadal or centurial scales. Moreover, compared with small water bodies, large water bodies can usually provide longer and more self-consistent records, and this might be the reason why previous climate reconstructions from water-body proxies favored the water bodies of this type [e.g., Fritz et al., 1994]. To better reconstruct the historic climate, here I suggest that integrated sediment archives from both large and small water bodies should be
extracted and analyzed. I believe that accessing memories of various-size water bodies will permit the acquisition of more valuable and complete information on climatic changes in the past.

My findings also have great potential to improve the interpretation of historic lake or other water-body archives. Direct translation of lake records to climate fluctuations may produce a misleading interpretation. Inverse application of the integrated-climatic-forcing and water-body-memory concepts provides a unique opportunity to correct the timing mismatch between climate changes and water-body responses and, in turn, promote the reconstruction reliability.

4.4 Conclusions

My work led to several important results. First, my comparison of lake/wetland and climate time series revealed that differences with respect to timing and signal amplitude may exist between proxy records of climate and actual climate measurements. Further investigations through numerical simulations reveal scale-dependent responses of water bodies to climatic variations. Small wetlands/lakes generally are characterized by high sensitivity, low resistance, and high resilience to climate disturbances, and act as high-pass filters. Large lakes/wetlands manifest high buffering capacity, high resistance, and low resilience to climate fluctuations, and behave as low-pass filters. Second, despite differences in timing and signal amplitudes, the responses of stages of both small and large water bodies can be explained by my newly developed concept of integrated climatic forcing. Most important some present water-body stage may not simply be
indicative of the prevailing climate, as traditionally assumed. More likely it is the result of climate integration over a lengthy period of time. Finally, by applying the concept, it is apparent that the record for small water bodies is high-resolution but often exhibiting time gaps. Large water bodies cannot preserve short-term climate fluctuations, but instead record long-term climate changes or interannual extreme climate events (i.e., multi-year deluges or droughts) which might take place long time ago.

My findings of water bodies’ memory and scale-dependent responses have tremendous potential for improving the climate constructions. Recently, researchers have been seeking for new methods or models to improve the quality of climate inference from lake sediments [e.g., Ryves et al., 2009]; my study suggests that better attention needs to be paid in selecting appropriate water bodies of appropriate sizes. Moreover, my concept of the climate integration provides a better understanding of mechanisms by which water bodies respond to the controlling factor, climate. Not only can this improved understanding potentially benefit the translation of the climate proxy information from water-body (e.g., lake) archives to actual climates, but it also holds considerable promise for offering a novel but simple way to quantitatively predict water-body status under the projected climate changes.
Chapter 5: Summary and Conclusions

As the title of the dissertation implies, the purpose of this study was to provide a better understanding of the dynamic hydrologic response of surface water bodies in the Prairie Pothole Region to variability in climate. This dissertation has resulted in the development of new computational and observational approaches as well as important new results.

Chapter 2 describes a new hydrologic model capable of simulating surface water complexes comprised of tens-of-thousands or more individual closed-basin water bodies. It was applied to simulate the hydrologic response of a prairie pothole complex to climatic variability over a 105-year period (1901-2005) in an area of the Prairie Pothole Region in North Dakota. The model was calibrated and validated with a genetic algorithm by comparing the simulated results with observed power-law relationships on water area-frequency derived from Landsat images, and a 27-year record of water depths from six wetlands in the Cottonwood Lake area. The simulated behavior in water area and water-body frequency showed good agreement with the observations under average, dry, and wet conditions. Analysis of simulation results over the last century showed that the power laws changed intra-annually and interannually as a function of climate. Major droughts and deluges can produce marked variability in the power-law function (e.g., up
to one and a half orders of magnitude variability in intercept from the extreme Dust Bowl
drought to the extreme 1993-2001 deluge). Analyses also revealed the frequency of
occurrence of small potholes and puddles did not follow pure power-law behavior and
that details of the departure from linear behavior were closely related to the climatic
conditions. A general equation, which encompasses both the linear power-law segment
for large potholes and nonlinear unimodal body for small potholes and puddles, was used
to build conceptual models to describe how the numbers of water bodies as a function of
water area respond to fluctuations in climate. A general equation, which encompasses
both the linear power-law segment for large potholes and nonlinear unimodal body for
small potholes and puddles, was used to build conceptual models to describe how the
numbers of water bodies as a function of water area respond to fluctuations in climate.

Space-for-time substitution approach, which is used commonly in ecological and
geomorphological studies, was examined in Chapter 3 for possible applications to
hydrological studies. There, I examined the behavior of water-body populations in a
collection of smaller sub-areas aligned along a climate gradient in the Prairie Pothole
Region. The analysis of these data provided the basis for validating the space-for-time
substitution. Comparison of the spatial and temporal trends of water-body population
dynamics revealed a common response function to the climate variability in space and
time. My findings of the validity of space-for-time substitution in hydrologic systems not
only answered an important science question in its own right, but improved
understanding of climate-forcing and hydrologic-response mechanisms. For example, a
conceptual model based on SFT substitution helped to better understand the impacts of
historic extreme climate events. Clearly, the SFT substitution was able to provide a valuable new dimension in the analysis of hydrologic systems. Along the way, this chapter has produced important regional-scale implications including, for the first time, a complete picture of the heterogeneous spatial and temporal water-body distribution across the entire Prairie Pothole Region and understanding of how the patterns vary with changing climate.

Chapter 4 examined questions related to the suitability of lakes as measuring devices. It is well known that lakes sediment records are likely the most important, if not the best sensors for climate reconstruction. The implicit assumption is that at any time lakes are in equilibrium with respect to climatic drivers and thus, related proxies are capable of accurately track climatic variations. The data I collected on several closed-basin lakes and wetlands, however, implied that mismatches in timing and magnitude exist between how a lake responds and the actual climatic conditions I found that what is important in determining the hydrologic behavior of lakes or wetlands not the present climate signal but some cumulative history, with a memory that fades following exponential-decay trajectory at scale-dependent rates as time passes. My new concept of integrated climatic forcing, capable of capturing scale-dependent water-body responses, was able to explain the disparities and showed that the present hydrologic setting is conditioned by the past history of climate. Results of this study provide a better understanding of the mechanisms of how water bodies respond as a function of climate which, in turn, offers a novel but simple way to quantitatively predict lake/wetland status with different scenarios of future climate changes. In addition, findings from this study
hold considerable promise for improving the quality of climate reconstruction. These new ideas will benefit the translation of the climate proxy information from lake archives to actual climates. Moreover, they call attention to the need for selecting water bodies of appropriate sizes.

With the integrated usage of various approaches and theories, this study has successfully opened up new areas of inquiry and filled in important gaps in historical data and information. The newly developed PCHM has made it possible to investigate the dynamics of water-body complexes and enabled me to reveal the area-frequency characteristics of small water bodies, i.e., deviating from the linear power laws. The introduction of SFT substitution has added a new dimension to hydrologic studies, and has been shown to be an attractive alternative to model-based approach evaluating the impacts of historical climate events such as the 1930s Dust Bowl drought and future scenarios as well. The new concept of integrated climatic forcing has offered a unique way interpreting the discrepancy between climate and water-body hydrology and led to important implications for climate reconstruction. In addition, the study has provided a complete picture of the water distribution in the Prairie Pothole Region and how it would change through time with varying climate.

Overall, the study has contributed an expanded/improved understanding of the linkages between climate and wetland/lake systems, in respect of both water-body complexes (Chapters 2 and 3) and individual water bodies (Chapter 4). Such knowledge will be very helpful to water resources managers, policy makers, and people involved in wetland restoration and wildlife conservation. The outcome of this study and the new
methods developed or introduced will also appeal to a broad cross-section of interested researchers.
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