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Hydrology and Water Balance of Devils Lake Basin: Part 1 Hydrometeorological Analysis and Lake Surface Area Mapping*

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Abstract

The spatial distribution of stocks of water is useful in studying flood, water pollution and water supply problems. Flood prone and closed basin watersheds benefit from spatial water balance studies in understanding the hydrologic processes and deal with excess water problems. In this study, we present results of a study of the hydrology Devils Lake basin of the Red River of the North, northeastern North Dakota partitioned in to two parts. Part 1 addresses the hydrometeorological analysis and lake surface area mapping of the basin and Part 2 deals with spatial surface water balance modeling using Landsat images and geographic information system (GIS). Hydrometeorological analysis using 100-years of historical record for the Devils Lake basin was conducted to capture the historical variability of the flood. In addition, surface area of the lake was mapped using Landsat image from 1991 to 2003. The Hydrometeorological analysis of the historical data showed the runoff inflow from upstream watersheds driven by snowmelt and spring rain falling on wet soil is the dominant source of the lake rise. Results show an increase in lake surface area by 117% between 1993 and 2003. The analysis also showed a correlation and possible interactions between the lake and the Spritwood aquifer indicating potential contribution of the groundwater flux to the water budget.

(Key Terms: hydrometeorology, Devils Lake, remote sensing, GIS, runoff)

Introduction

Flooding, water supply concerns, and the assessment of non-point source pollution are important issues that are largely dependent on the spatial distribution of water. An improved understanding of the spatial water balance - the partitioning of precipitation between evapotranspiration, runoff, and groundwater recharge at different points in space will directly benefit those who wish to understand flood (Maidmentet al., 1996). Flood mitigation work requires hydrologic information of the basin and spatiotemporal variation of major hydrologic cycle components.

A basic approach for determining stocks and fluxes of water involves the calculation of water balance. A water balance applied to a particular control volume is an application of the law of conservation of mass. Achieving this will require the difference between its rates of inflow and outflow across the control surface to be equal (Maidment et al., 1996). Spatial water balance information provides the distribution of the different components of the hydrologic cycle on a spatial basis. Spatial representation of these components requires geographic information system (GIS).

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The use of GIS for spatial water balance study has been documented in various studies. Luijten (1999) used GIS data structure to develop the Spatial Water Budget Model (SWBM), a continuous, distributed parameter, watershed scale model that simulates water supply and demand over space and time on a daily basis. White et al. (1996) studied the water balance of the Missouri River after the 1993 flood utilizing GIS. The study area encompasses the entire Upper Mississippi River basin (north of Cairo, Illinois) and part of the eastern Missouri River basin. The study found that the grid GIS-based visualization of the components of the water budget was useful for flood management. (Maidment et al., 1996) studied the surface water balance of Texas using data from the United States Geological Survey (USGS) gauging stations. The study used a 500-m digital elevation model (DEM) to delineate the drainage areas for each gage. A 5-km grid of mean annual precipitation and mean annual runoff values compiled for each gage from 1961-1990 were used to derive a relationship between mean annual precipitation and the mean annual surface runoff. Hoogeveen (FAO, 2003) used GIS to determine the spatial water balance of the Aral Sea Basin as part of the Food and Agricultural Organization's effort for the development of Land and Water Information Systems. The study delineated sub-basins using a DEM and the water balance for each sub-basin was computed using the components of the surface water budget, including irrigation applications. The study also concluded the methodology would be useful for similar studies in other regions of the world. Wiche (1992) studied the water balance of Devils Lake using observed values. He considered only the lake area instead of the entire watershed. In addition, the study used point measurements to estimate the water balance and energy-budget and mass-transfer methods to compute evaporation from Devils Lake during the open-water periods of 1986-88. Vecchia (2002) used a monthly water balance model to compute the change in total volume of Devils Lake and a regression model to estimate monthly water-balance on the basis of limited recorded data. Estimated coefficients for the regression model indicated, fitted precipitation and lake evaporation to be higher and lower than measured values, respectively.

The objectives of this study presented in two parts are to (1) conduct hydrometeorological analysis of the basin to gain an improved understanding of stocks of water of the hydrologic cycle, (2) map lake surface area using Landsat images, (3) estimate the stocks of the water budget from remotely-sensed data and, (4) estimate the change in storage for selected years and compare estimated values to observed values. Part 1 of the study, reported in this paper, deals with the hydrometeorological analysis and lake surface area mapping of the Devils Lake, terminal lake and Part 2 addresses the grid-based spatial water balance mapping of the study area using GIS and remote sensing.

Study Area

The Devils Lake Basin has a 9,870 km^2 drainage area in the Red River of the North Basin located in northeastern North Dakota (Figure 1). About 8,600 km^2 of the total 9,870 km^2 drains into the Devils Lake. It contributes to the Red River of the North basin when the level of Devils Lake is greater than 444.7 m (1,459 ft) above mean sea level (amsl) (Wiche, 1998).

Devils Lake has a continental climate characterized by relatively warm, short summers and long cold winters. Precipitation averages about 432 mm annually, some 75% of which falls between April and September. The 25% of the annual precipitation that is received during the colder months contributes the most to spring runoff and the subsequent recharge of Devils Lake. The mean annual snowfall at

the City of Devils Lake is 91 cm. The maximum recorded temperature is 44 ^{o}C and the minimum is -43 ^{o}C. The growing season is short, averaging 131 days (Wiche and Vecchia, 1996).
Historically, the level of the lake has fluctuated. Since the basin is a closed drainage basin, the only outlet of water is evapotranspiration (Wiche, 1992). High volumes of precipitation and less evaporation caused the flooding of more than 20, 000 ha of land in 1993 (Williams-Sether et al., 1996). Devils Lake spills into Stump Lake at an elevation of 441 m amsl. In the summer of 2001, Devils Lake reached a peak flow of 0.8 to 1 m^3/s into Stump Lake. At its spill elevation, Devils Lake will cover more than 112,000 ha (1120 km^2) and the volume of water in Devils Lake has increased since the spring of 1993 with more than $450 million in damages as a result of flooding throughout the Devils Lake basin (Williams-Sether et al., 1996).

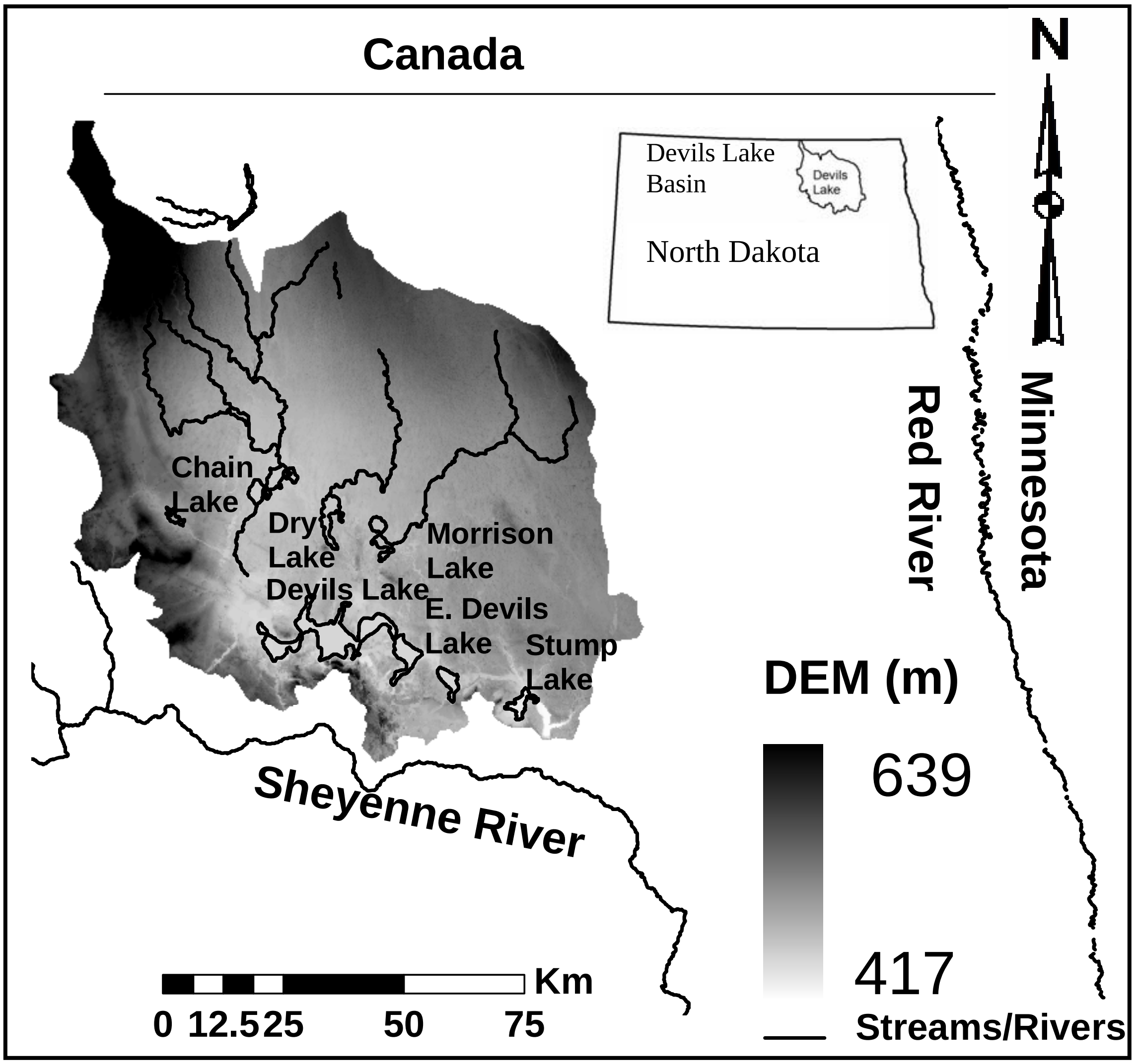

Figure 1 Location of Devils Lake Basin and 10-M Digital Elevation Model (DEM)

Natural spills due to the continuing rise of the lake would have significant impacts on the quantity and quality of water in the Sheyenne and Red Rivers. A study by the United States army Corps of Engineers (USACE) summarized the environmental and natural resources affected by the flood.

These include downstream water quality and quantity, downstream natural resources, downstream erosion and sedimentation, groundwater quality and quantity and aquatic resources of the Sheyenne and Red Rivers. Biota transfer issues which include the potential for the transfer of biota from Devils Lake to the Sheyenne and Red Rivers and the potential for the introduction of invasive species to the downstream rivers is another related problem (USACE, 2003).

Datasets and Methodology

Hydrometeorological analysis and spatial water balance modeling requires various types of data from different sources. Remotely-sensed data (Landsat images), topography (digital elevation model, DEM), meteorological (precipitation, and air temperature), hydrologic (lake stage) and GIS layers (soils and watershed boundary) were used to conduct the analysis and study the effect of these variables on the flooding process. Table 1 summarizes description of the types of data used in the study.

Table 1 Summary of Data Used in the Study.

Type	Data	Year	Format	Resolution	Source
Remote sensing	Landsat TM and ETM+	1991-2003	Raster	30 m and 60, 120 m (thermal)	USGS
Elevation	DEM		Raster	10m	USGS
Soils	HSG		Raster	1:250, 000	USDA-NRCS
Meteorological	Precipitation	1900-2003	vector	7 stations	NCDC, 2003
	Radiation	1991-2003	point data	7 stations	NDAWN, 2003
	Wind Speed	1991-2003	point data	7 stations	NDAWN, 2003
	Air temperature	1991-2003	point data	7 stations	NDAWN, 2003
Hydrological	Lake stage	1991-2003	point data		USGS
	Groundwater Recharge	1991-2003	point data		Wiche,1992
	Discharge	1991-2003	text		USGS

Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) images aboard the Landsat-5 and 7 satellites, respectively, for the years 1991- 2003 were used to derive Level 1 (Anderson et al., 1976) land cover classes, delineate flooding map, map lake surface area and also compute spatial evapotranspiration. A mosaic of three Landsat scenes (Path/Row: 31/27, 32/26, 32/27) was used to cover the entire study area.

A 10-m DEM (Figure 1) was obtained from the USGS and processed using grid GIS tools to derive hydrologic parameters (watersheds, flow accumulation and stream network) necessary for computing upstream runoff inflow into each cell. Since a 10-m DEM was not available for the southeastern portion of the basin, the 30-m DEM data was resampled to 10-m.

Precipitation data from seven North Dakota Agricultural Weather Network (NDAWN, 2003) rain gages (Figure 2) were used to produce thiessen polygon-based areal precipitation of the basin. Missing rain gages for 1991 and 1994 were extracted from the National Climatic Data Center database (NCDC, 2003). Precipitation maps were used to generate cell-based excess precipitation based on the United States Department of Agriculture-Natural Resources Conservation Service-Curve Number (USDA-

NRCS-CN) method (USDA, 1986) and also an input into the water balance model. Wind speed and air temperature data were also acquired from the weather stations and used in the evapotranspiration model to generate surface energy fluxes.

Groundwater recharge and outflows are important components of the spatial water balance. Since Devils Lake is a closed basin lake, groundwater outflows were negligible (Wiche, 1992). Previous studies estimated annual groundwater recharge to be 4 million m^3 (Wiche, 1992).

Based on the data collected, analysis of the hydrometeorological data was conducted to understand the main contributing variables to the flooding of Devils Lake. Lake surface area mapping using Landsat images were also conducted and comparisons were made. The relationship between lake surface area and lake stage was also studied.

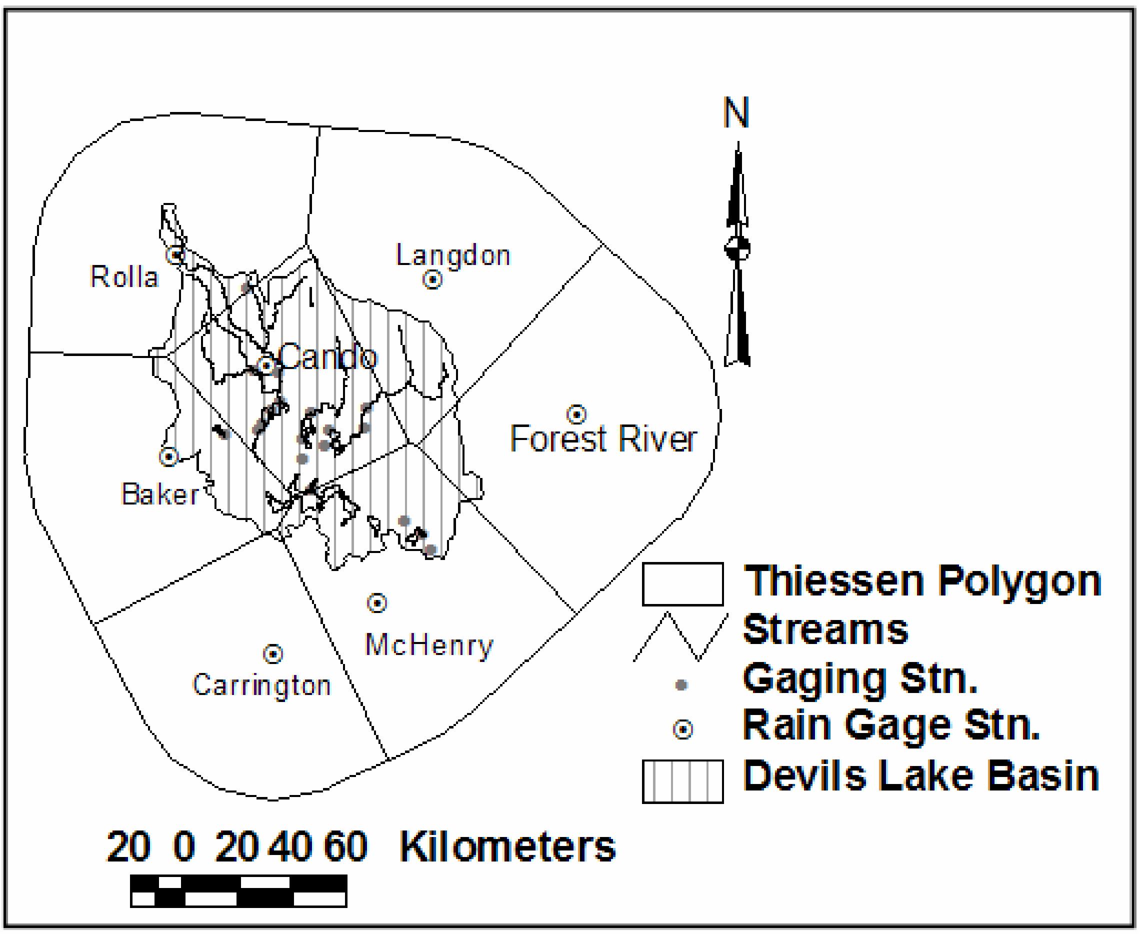

Figure 2 Thiessen Polygon and Network of Rain and Discharge Gaging Stations.

Results and Discussion

Hydrometeorological Analysis

Starting with the spring runoff from snowmelt and peaking in the summer when increasing evaporation and decreasing flows reach a balance (Figure 3) indicate the rising of Devils Lake is a slow process. Each succeeding year's flood potential is directly related to the antecedent lake level and hydrometeorological processes. Melesse and Wang (2006) indicated that prediction of lake level was achieved well with the inclusion of antecedent precipitation and lake level in an artificial neural network model applied to the Devils Lake basin. Figure 3 shows the 100-year average monthly values of air temperature, precipitation and Palmer Hydrologic Drought Index (PHDI) mapped with the Devils Lake stage. PHDI is an index closely tied to water storage showing the extent of dry and wet spills from a hydrological perspective. It more closely reflects soil moisture, stream flow, and lake levels than other indices, and is used to assess long-term moisture supply. Negative values denote periods of drought and similarly positive values reflect wet spills. From March to June, the lake rises mainly from snowmelt, rainfall and lower evapotranspiration. In June, the level of the lake begins to decease due to higher evapotranspiration and decreasing precipitation (Figure 3).

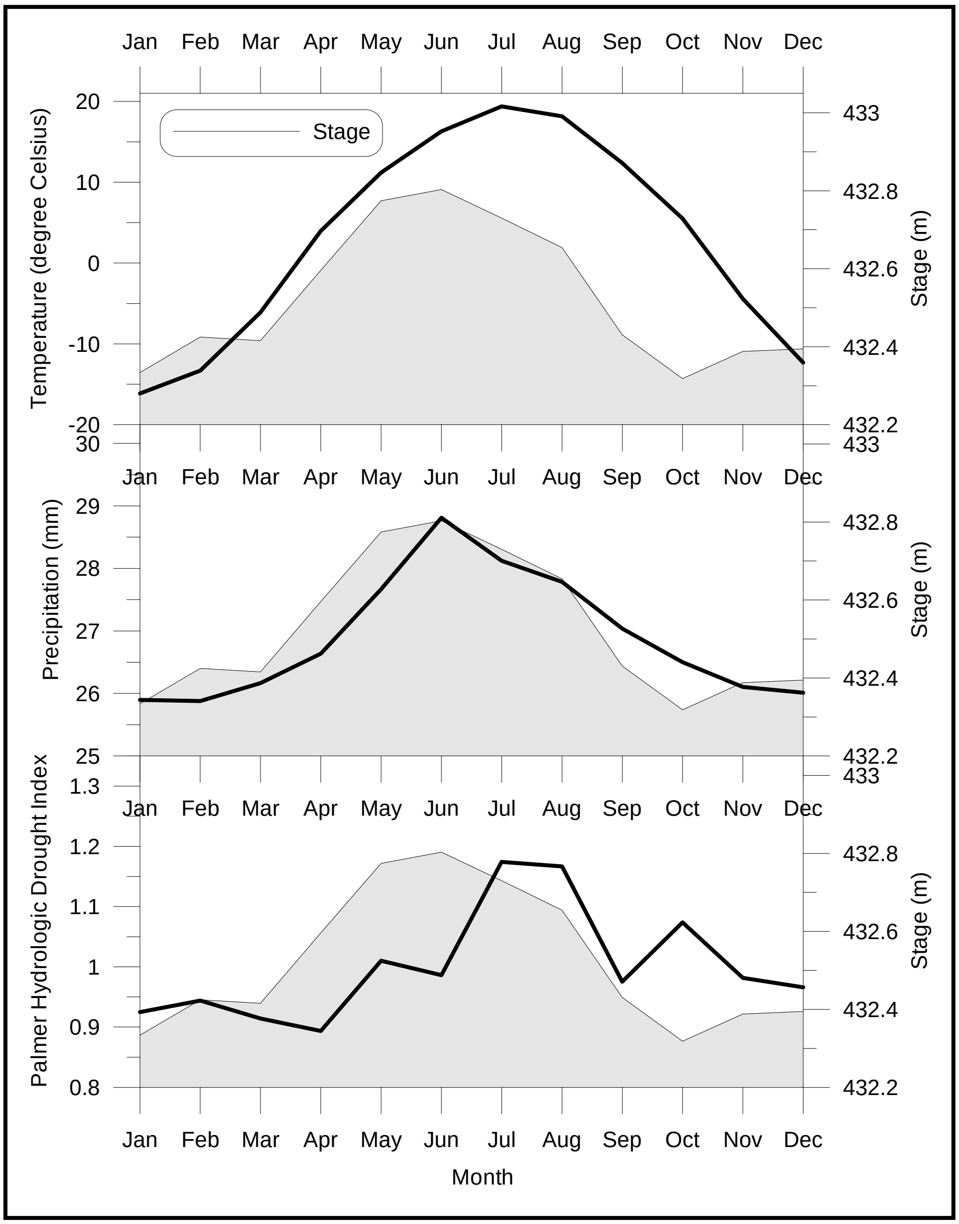

Figure 3 Mean Monthly Stage of Devils Lake (1931 – 2003).

The level of the lake from 1900-2003 (Figure 4) showed a great variation over the last century. This variation can be shown by dividing the time of record into three periods. From 1900 to 1940, the lake showed a decline in its volume followed by a variable lake stage between 1941 and 1993. Since 1993, the level of the lake rose over 6.8 m compared to 13.8 m from 1940 to 2003 indicating an increase in lake surface area and volume. The level of the lake responds to precipitation and air temperature changes. Analysis of the 100-year air temperature data indicates air temperature is increasing with a slope of 5% (Figure 4). The PHDI also shows a close correlation with the lake volume changes. Wet years (high PHDI) correspond to an increase in the lake volume. Similarly, dry years (low PHDI) exhibited a decline in lake volume.

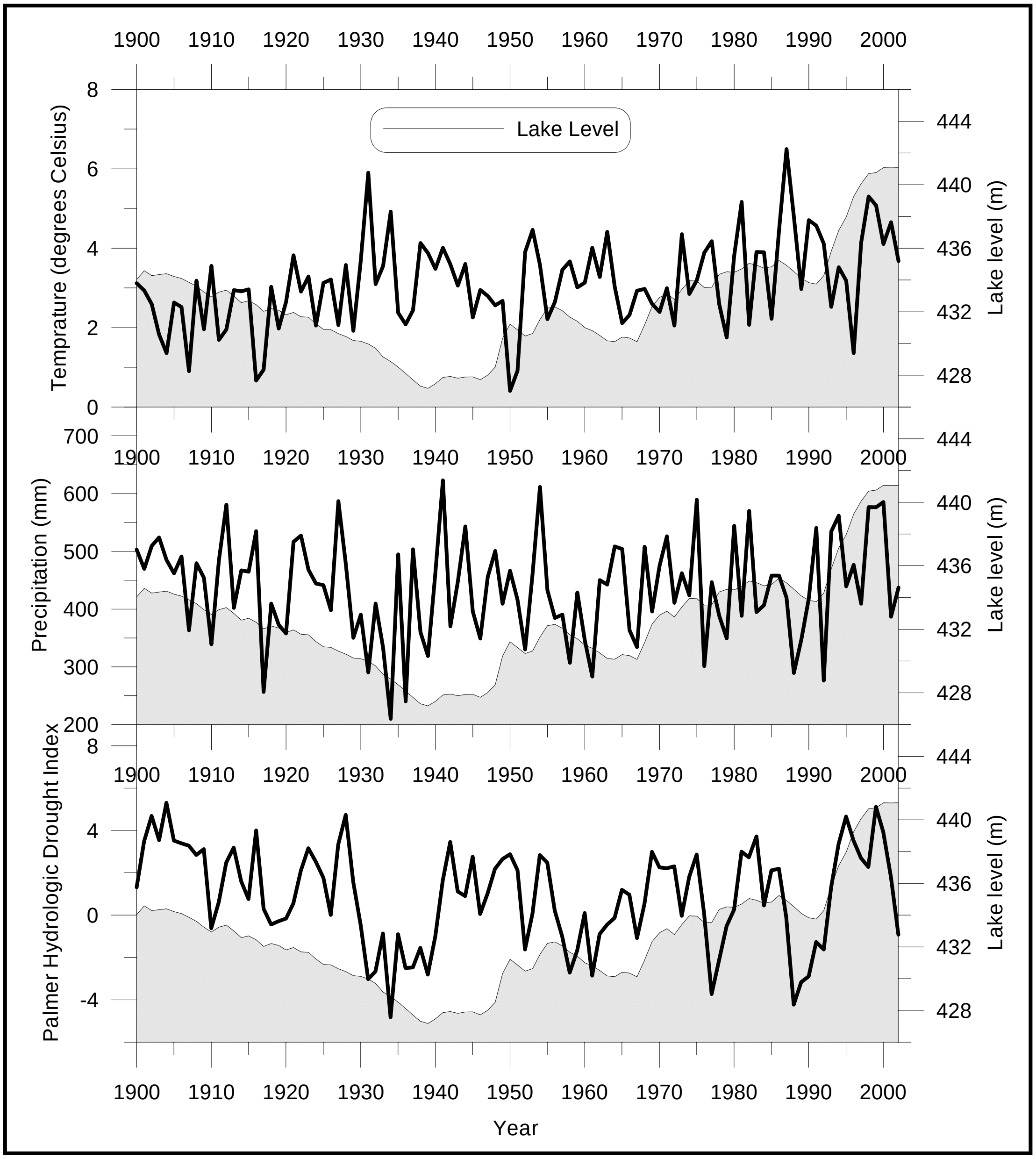

Figure 4 Annual Lake Stage, Air Temperature, Precipitation and Palmer Hydrologic Drought Index at Devils Lake (1900-2003).

Analysis of the precipitation data (1900–2003) shows 80% of the data from 1993 to 2002 were above the 102-year mean (436 mm) rainfall of the area (Figure 4). The precipitation data showed fluctuation from year to year as part of the regional climate dynamics. The lowest and highest historical precipitation occurs in 1934 and 1941 respectively.

Based on the records at the gauging station near the City of Devils Lake, the water budget of the devils lake from 1950-2000 is shown in Figure 5. From the results it is also shown that the inflow to the lake is the driving force to the lake's level rise and this clearly shown from 1993-2000. The evaporation from the lake did not exhibit large variations unlike that of the runoff. The precipitation has also shown an increase in the last 7 years of the record in Figure 5.

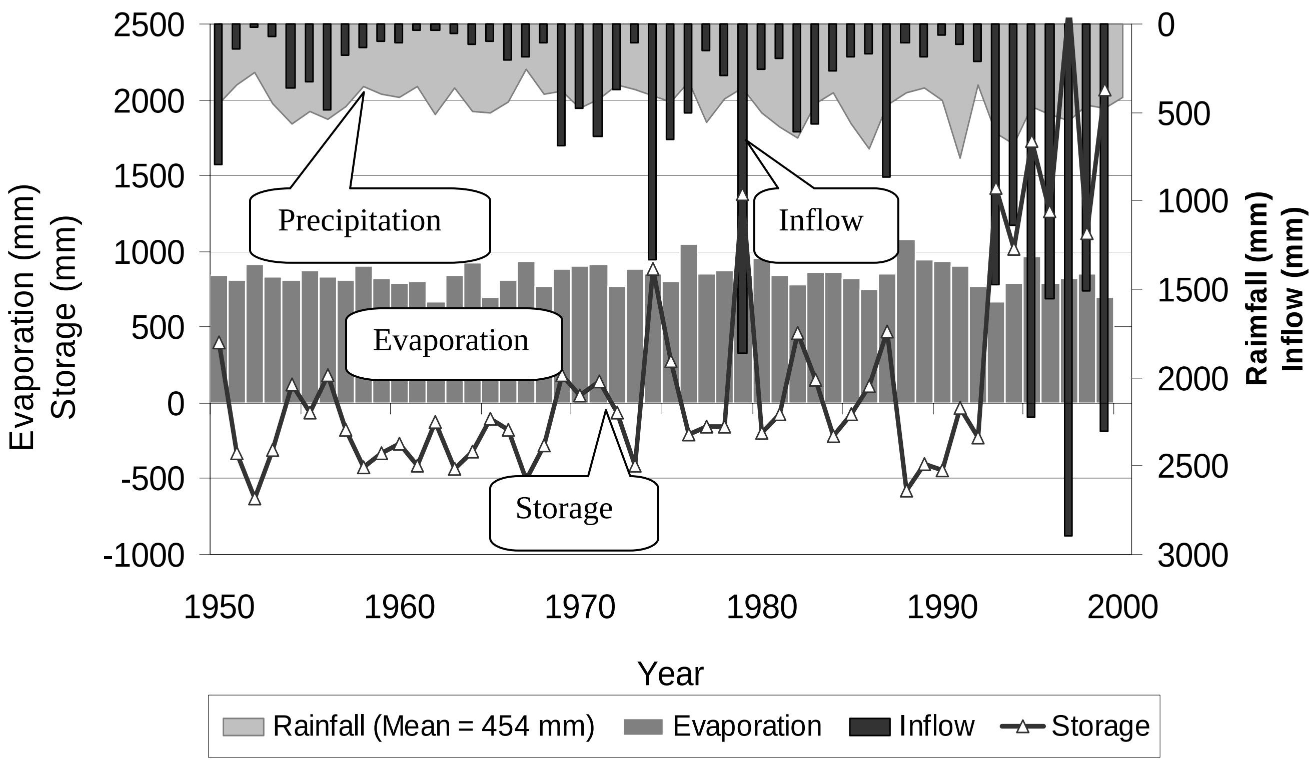

Figure 5. Annual water budget of Devils Lake.

Groundwater and Devils Lake interaction

Pusc (1993) has shown that Devils Lake closely interacts with the Spiritwood aquifer. Using the network of groundwater wells in the Spiritwood aquifer (Figure 6), groundwater and lake levels were mapped (Figure 7). Nine groundwater monitoring wells distributed throughout the basin were selected. As shown in Figure 6, Wells 3, 8 and 13 are located southeast of Devils Lake. These wells showed little interaction with the Devils Lake. Pusc (1993) has indicated the existence of a groundwater divide northwest of these wells. Wells 30 and 50 are located further north close to the main bay of Devils Lake. These well data showed a close interaction between groundwater and the lake. Wells 28 and 65 located on the south and southwestern portion of the lake, respectively, also showed a similar trend in the groundwater level rise as that of the lake. Well 75, which is located in the extreme northwestern portion of the basin showed little interaction with the lake.

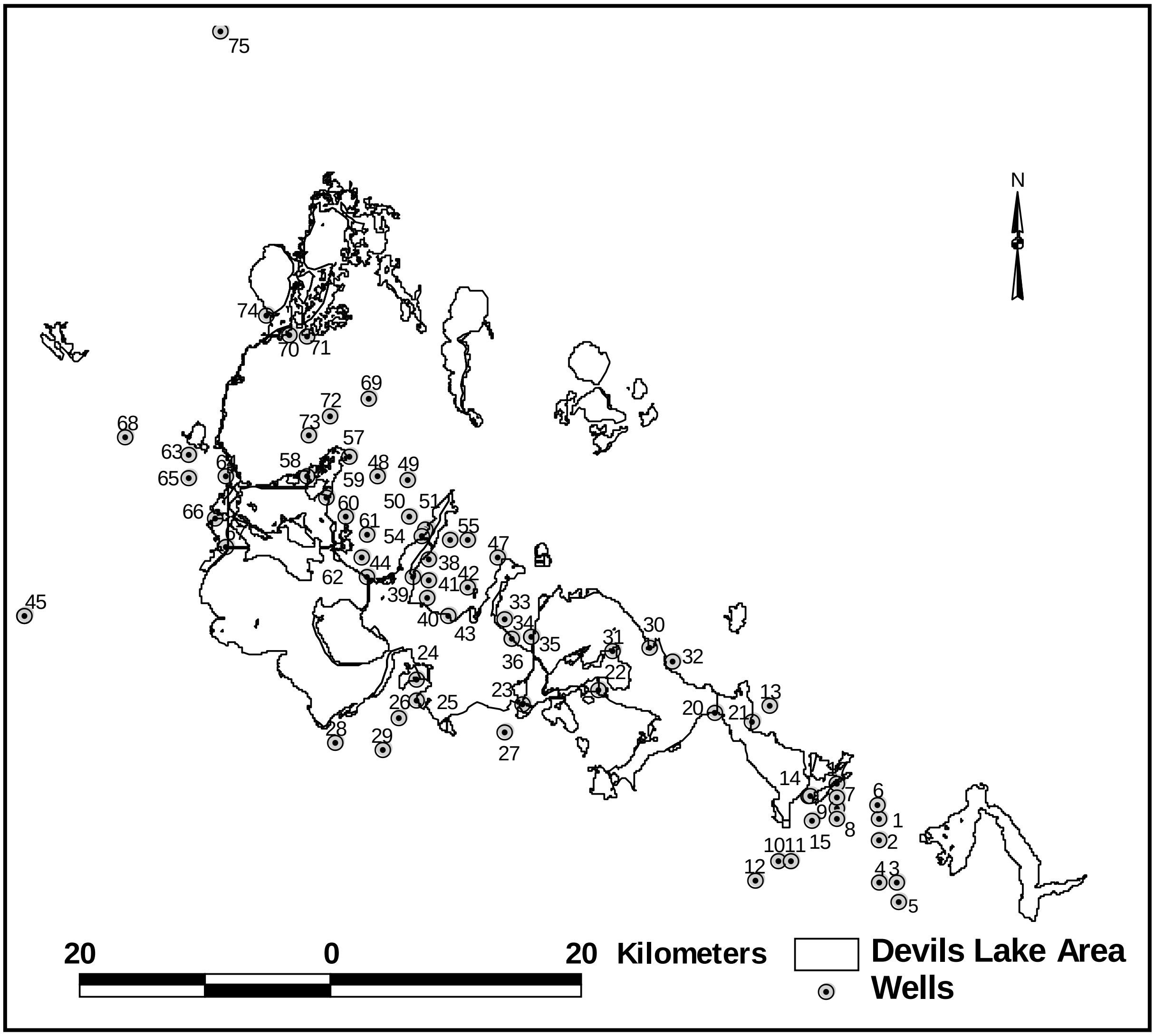

Figure 6 Groundwater Monitoring Wells for the Spritwood Aquifer.

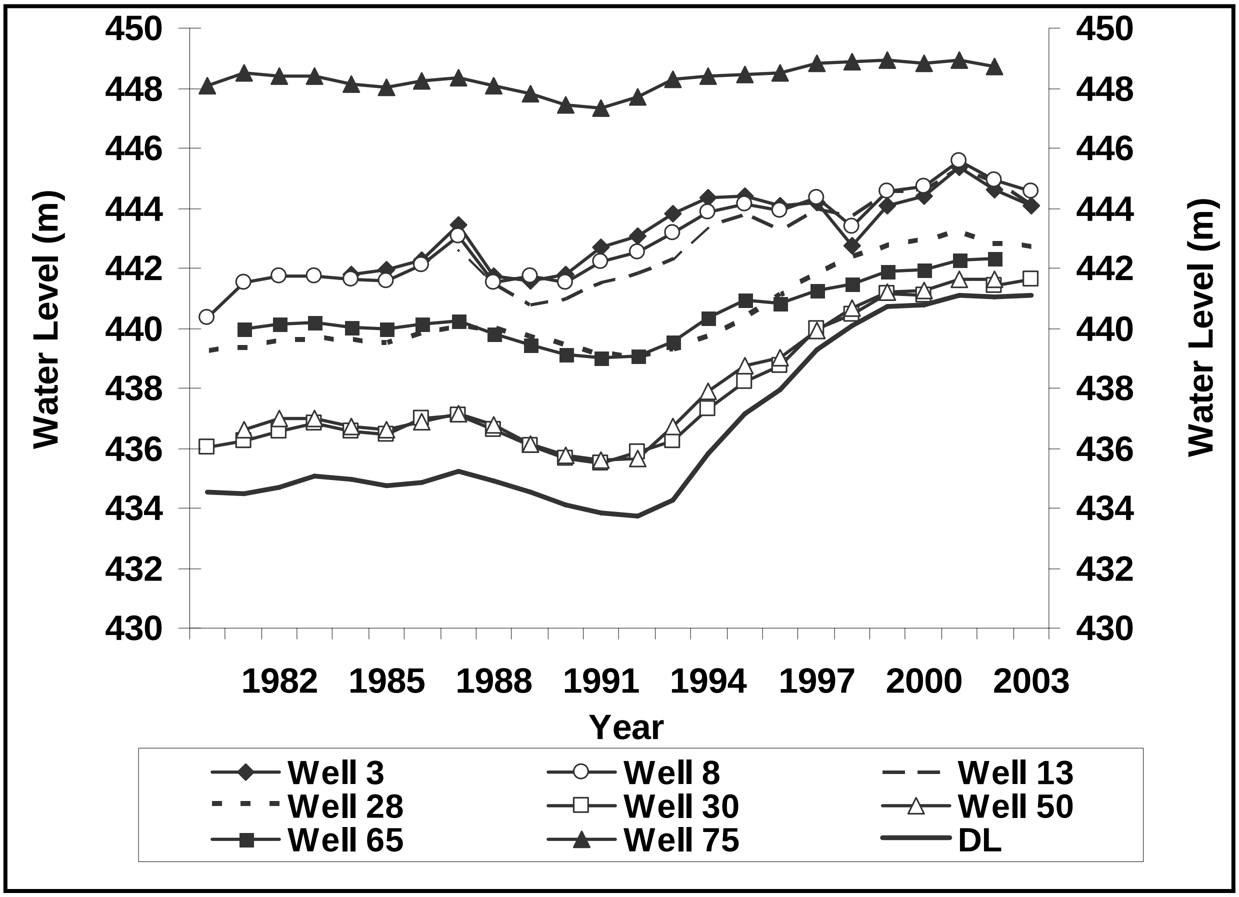

Figure 7 Groundwater and Lake Level for Selected Wells in the Study Area.

Lake surface area

The lake surface area of the chain of Devils Lakes excluding Stump Lake mapped from Landsat for 1993 and 2003 is indicated in Figure 8. Between 1993 and 2003, the surface area of the lake was lowest in 1993 and highest in 2003 (Figures 8 and 9).The lake surface area from Landsat images was classified and only lake areas were computed for each respective year. As depicted from the images, the areal increase of the lake is greater in recent years. The white line in Figure 8 marks the level of the lake in 1992. The corresponding surface areas for 1993 and 2003 are also shown in the figure indicating an increase in the flooded area by 117% between 1993 and 2003.

Figure 9, lake surface area by elevation and year (without Stump Lake) derived from Landsat images, shows that each meter rise of lake inundates a progressively greater area resulting in increased flood volume. It is shown that a 1.3 m increase between 1994 and 1995 at an elevation of 435.8 m adds about 39.5 km^2 to the lake's surface area, whereas a 1.3 m increase between 1996 and 1997at an elevation of 438 m adds nearly 49 km^2. This indicates the severity of the flooding problem at higher lake levels attributed partly due to the flat topography of the contributing watershed.

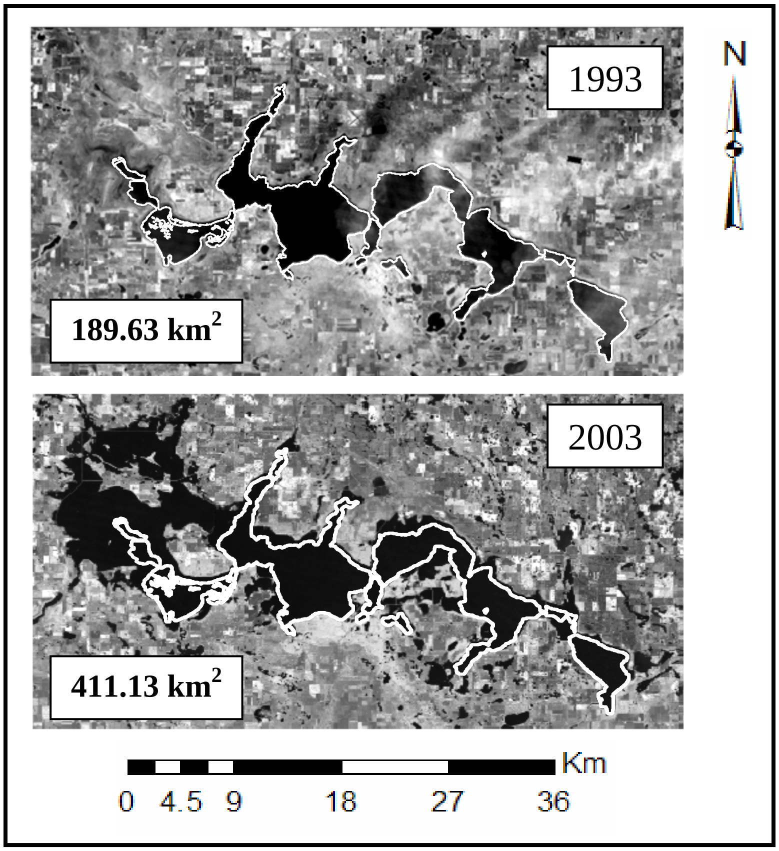

Figure 8 Areal Map of the Lake from Landsat Images (1993 and 2003). White Line Marks Lake Area in 1992.

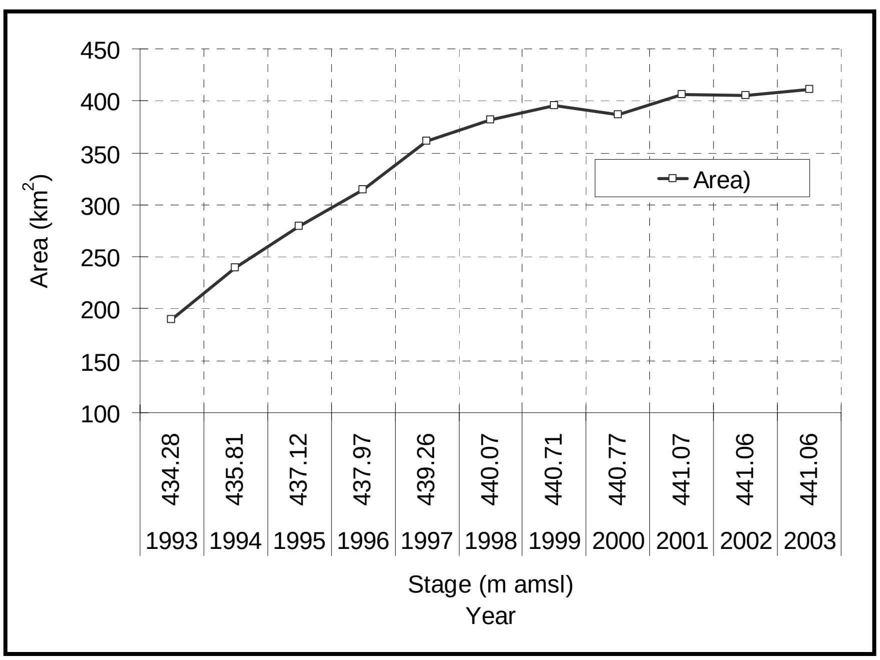

Figure 9 Lake Surface Area Computed from Landsat Images.

Conclusion

Hydrometeorological analysis of the historical data of the study area shows seasonal variability in the hydrologic response of the basin mainly driven by snowmelt and rain falling on wet soils. In order to capture this variability, it may be necessary to compute the water balance of the basin for spring and summer.

Remotely-sensed data from Landsat TM and ETM+ sensors were used to estimate the surface area of the Devils Lake. Landsat-based lake surface area of the lake showed an increase by 117% between 1993 and 2003 largely towards the northwest of the lake.

The groundwater level was highly correlated with Devils Lake except in the southeastern portion of the basin. Further study might be needed to estimate the level of interaction and groundwater recharge and discharge beyond the current assumption. Since the hydrologic response of the basin is complex, future flood management efforts would benefit from flood prediction and modeling using new statistical learning and modeling techniques.

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