PROCEEDINGS OF THE TWENTY-SIXTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2013
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SEEPAGE CONDITIONS AND WATER BUDGET ANALYSIS OF DUCK LAKE IN MILTON, WISCONSIN

CAROLINE LABRIOLA, Colgate University
Research Advisor: Jeni McDermott

INTRODUCTION

Seepage lakes can provide valuable insight into the response of groundwater systems to climate conditions and the susceptibility of a region to groundwater flooding. Groundwater flooding occurs when the water table rises above the land surface of a region and can cause either local flooding around springs or flooding downstream when drainage systems are not sufficient (Macdonald et al., 2008). Without the outflow from streams in seepage lakes, such groundwater flooding in seepage lakes would take longer than surrounding lakes to drain.

In 2007 and early 2008 southern Wisconsin received twice the average precipitation. Extensive flooding took place along several rivers and lakes in June of 2008, including the overflow of the Lake Delton reservoir (Fitzpatrick et al., 2008). A series of seepage lakes in southern Wisconsin responded differently than other kettle lakes and rivers in the region: Grass, Clear, Duck, and Mud Lake showed little response to the high rainfall in 2007 and 2008 and did not flood until July 2009 when water table levels rose by as much as 2.4 meters. Several houses, wells and septic systems were flooded and remained at flood conditions until fall 2011. Following the prolonged high stage, lake levels experienced a dramatic fall starting in fall 2011. The lagged response from the record precipitation events suggest that groundwater flooding caused the sustained flooding and abrupt fall in lake levels, a unique response of these lakes (Joachim et al., 2011).

This project focuses on the hydraulic components of Duck Lake for the period from October 2008 to September 2012. Due to Duck Lake's unique response to the 2007-2008 flooding, the project aims to understand better how the groundwater system reacts to climate conditions through analysis of the lake budget. The project examines the precipitation, evapotranspiration, groundwater inflow rates, groundwater outflow rates, and lake storage of Duck Lake to assess the flow systems reaction to the record precipitation. This analysis seeks to determine the factor of the water budget that can explain the sustained flooding and recent fall in lake stage.

FIELD SITE

Duck Lake is located about three and one-half miles from the nearest town of Milton in southeastern Wisconsin. It has an approximate surface area of 50,700 m^2. The land cover in the region in dominated by agriculture, but on a smaller scale includes some wetlands, open water, urban developments, and forestation (Juckem, 2009). The entire region is comprised of hummocky topography due to glaciation. The field area is underlain by glacial material or till stratigraphy overlying east-sloping sedimentary bedrock with Precambrian crystalline bedrock at approximately 1,000 feet. The glacial material was deposited during the Wisconsin Glaciation, the last major glaciation event about 10,000-25,000 years ago (Juckem, 2009). The Michigan and Green Bay Lobes during the Wisconsin Glaciation formed the famous Kettle Moraine just east of the field site that is comprised of stacked terraces and glacial outwash. The field site is located in an area once covered by the Green Bay Lobe that produced the Johnstown and Milton Moraines during the Lobe's outer most advance. The retreat from this outmost advance left the hummocky topography and several kettle lakes in its wake (Holt et al., 1970). Kettles form from a block of ice left behind by the receding glacier that melts and creates a negative feature in the landscape. These lakes are usually round and fairly uniform in lake sediment compositions. Duck Lake exemplifies such a lake created by the retreat of the Green Bay Lobe. Duck Lake is situated in offshore lake sediments between the Johnstown and Milton Moraines. The outwash in the region exhibits high permeability compared to other regions within the Rock River Basin (Holt et al., 1970). The surrounding region receives an annual average of 86.4 centimeters of precipitation with temperatures that range from -12°C to 30°C on average annually (Juckem, 2009).

METHODS

This study utilizes the fieldwork performed from early 2008 to summer 2012. The majority of the fieldwork collected for Duck Lake occurred in summer 2012. The measured stage levels of neighboring Clear Lake from 2008 to 2012 were correlated to the lake stages of Duck Lake to allow for analysis of the conditions at Duck Lake prior to, during, and following the current recession from the 2009 flooding stage. Data collected in the field were mapped and analyzed in ArcGIS in order to examine the seepage patterns and calculate Duck Lake's water budget.

CALCULATION OF WATER BUDGET

The regional groundwater system flows north toward Lake Koshkonong and the Rock River. Due to the topography, the surface runoff aspect of the water budget in Duck Lake is insignificant, therefore precipitation and groundwater inflow comprise the inputs, while the evapotranspiration and groundwater outflow comprise the outputs. The precipitation measurements are from the closest weather station Fort Atkinson, Wisconsin. The evapotranspiration measurements are national averages from the U.S. Department of Commerce and the Weather Bureau (Mueller and Reichelderfer, 1959). The groundwater components of the lake budget were measured in the field. The lake storage was calculated in ArcGIS using the bathymetry data collected in the field. The water budget was calculated using:

$$\Delta S = P - E + G_{in} - G_{out} \text{ or } G_{in} - G_{out} = \Delta S - P + E$$

where ΔS is the change in storage at a given water year, P is the precipitation per water year, ET is the evapotranspiration per water year, G_{in} is the groundwater inflow per water year, and G_{out} is the groundwater outflow per water year (Eqn. 1). The combined groundwater inflow and outflow was calculated for all three water years using the water budget equation. Since groundwater inflow and groundwater outflow data were measured directly during water year three, this allowed a check on combined groundwater inflow and outflow for this water year.

GROUNDWATER INFLOW AND OUTFLOW

The groundwater component of Duck Lake was measured using seepage meters and mini-piezometers. A total of 18 seepage meters were installed in Duck Lake. The seepage meters were made of plastic buckets that were pushed into the lake bottom on their open side (Fig. 1). A bag with a known volume of water was attached to the bucket, and after several hours, the change in volume was measured to determine the inflow or outflow around Duck Lake (Sanders, 1998). The seepage data were put into ArcGIS to visualize the flow patterns of the lake and to use in the calculation of the water budget for water year three. Two mini-piezometers were installed also in Duck Lake. The mini-piezometers were made of plastic tubing with bridal veil attached to the bottom to prevent sediments from clogging the tube. The tubing was pushed into the sediment with the aid of metal pipes and left over night. The change in head in the tubing between the groundwater and the lake was measured to determine the direction of the gradient. The location and magnitude of the seepage data, and the patterns of groundwater inflow versus groundwater outflow were mapped in ArcGIS.

Figure 1. Photograph example of seepage meters used in the field to measure groundwater inflow and groundwater outflow.

STORAGE

Lake bathymetry was measured using a Trimble 6000 series GeoExplorer within and on the shore of the lake. Within the lake, measurements were taken approximately every 30 meters. The shoreline measurements were collected in rows of three points, one at the edge of the lake, one at the break in slope and the last above the break in slope. This process was repeated approximately every 10 meters. The shore measurements were collected to determine where the level of high stage reached on the shore during the sustained flooding events. The highest stage was assumed to occur at the break in slope.

The bathymetry data from the field were hand contoured and then digitized into ArcGIS. (Fig. 2) In addition to the bathymetric map of Duck Lake, the bathymetry data were used to calculate the volume and surface area of the lake at certain lake stages since 2008 using a combination of the Cut and Fill and the Surface Volume tools in ArcGIS. The surface area used in calculating the water budget during each water year was determined by the average of the minimum and maximum stages in each year. Precipitation values used in each year's water budget were the sum of total precipitation over each water year and applied to the respective year's surface area. Evaporation data used a similar process, except the same value was used for all three water years (76 cm/year) due to the available evaporation resources. The groundwater components of the year three water budget were known from the seepage data collected only for water year three.

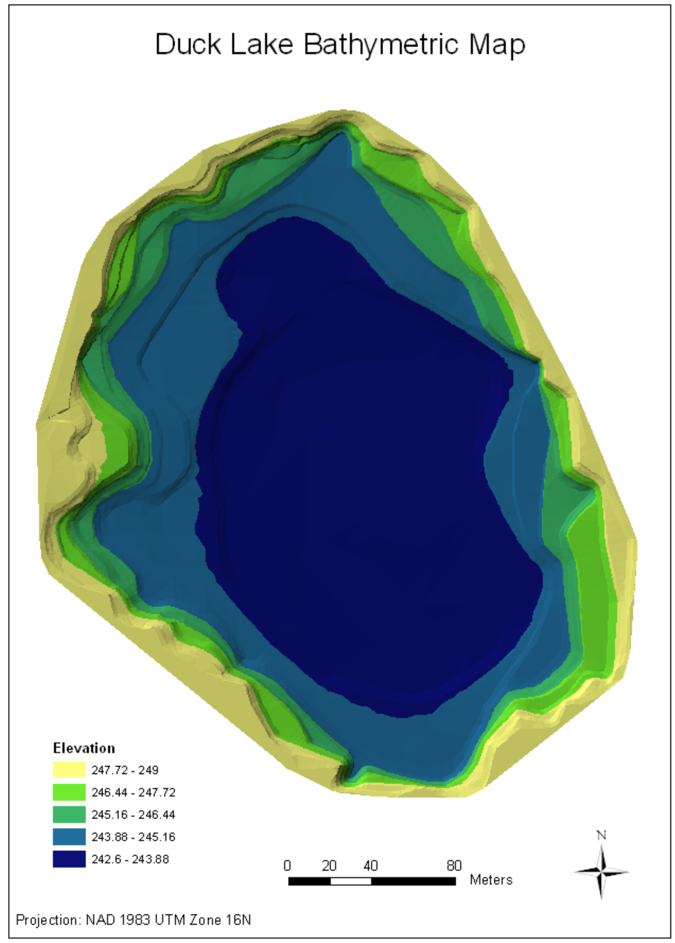

Figure 2. Bathymetric Map of Duck Lake made in ArcGIS.

RESULTS

The data used in this study were broken up into three water years that contain the phases of Duck Lake's response to the change in climate conditions. Water year one (October 2008 to September 2009) represents the period of flooding. Water year two (October 2009 to September 2010) consists of the period of sustained flooding at the highest stage. Water year three (October 2011 to September 2012) comprises the period of falling stage. Most of the field data collected for Duck Lake occurred during water year three and shows the current decline in lake stage towards pre-flood conditions (Tab. 1).

Water Year	One (10/08 to 9/09)			
	Stage (m)	Surface Area (m^2)	Volume (m^3)	Δ Storage (m^3)
Start Stage	245.18	71272.4	45063.2	133303.4
End Stage	247.74	204575.8	57949.0	
Average Stage	246.47	51932.7	134522.9	
Water Year	Two (10/09 to 9/10)			
	Stage (m)	Surface Area (m^2)	Volume (m^3)	Δ Storage (m^3)
Start Stage	247.65	199383.4	57433.6	-6286.7
End Stage	247.54	193096.7	56954.8	
Average Stage	53091.3	145533.1		
Water Year	Three (10/11 to 9/12)			
	Stage (m)	Surface Area (m^2)	Volume (m^3)	Δ Storage (m^3)
Start Stage	246.85	154663.4	54228.9	-56009.8
End Stage	245.76	98653.6	49015.5	
Average Stage	246.19	50700.8	120153.9	

Table 1. Comparison of the average stages (m), surface area (m^2), volume (m^3), and change in storage (m^3) in each water year.

As groundwater flow values are only measured for water year three, the water budget for water year three provides the opportunity to test the accuracy of our water budget approach. As no field data for groundwater flow patterns exist for water year one and two, only the total change in groundwater can be calculated. Positive groundwater volumes suggest more inflow than outflow and negative groundwater volumes indicate greater outflow than inflow into the lake. As demonstrated in Table 2, the value for groundwater flow was positive in water year one, thus there was more inflow. Although the value was negative, the relative small magnitude of groundwater flow in water year two might be expected for groundwater inputs and outputs during the sustained flooding within expected errors of calculation.
The negative value calculated for water year three corresponds to greater outflow during this year as the lake level fell.

Water Year	1	2	3
	Volume (m^3)	Volume (m^3)	Volume (m^3)
Precipitation	$4.64x10^4$	$5.93x10^4$	$3.47x10^4$
Evaporation	$4.00x10^4$	$4.04x10^4$	$3.86x10^4$
Total Groundwater Flow	$1.27x10^5$	$-2.51x10^4$	$-5.21x10^4$
ΔS (m^3)	$1.33x10^5$	$-6.29x10^3$	$-5.60x10^4$

Table 2. Comparison of the components of the water budget for each water year.

Testing the values and method for water year three brought unexpected results. The seepage data suggests that groundwater flows out of the lake on the western half of the lake, while groundwater flows into the lake on the eastern side. The mini-piezometer data support this trend of gaining in the east and losing in the west. Duke Lake is only separated from the neighboring Clear Lake by about 80 meters on the northeatersn side. Here there were small amounts of outflow thought to be horizontal flow between the lakes. Using the simplest seepage pattern of half of the lake inflow and the other half outflow to calculate the volumes, the volume of groundwater calculated from the water budget differs from the volumes calculated from the groundwater rates measured in the field by about 135,000 m^3. This large difference led to further investigations into the groundwater component of water year three. Two additional groundwater flow patterns were created and tested in ArcGIS. The first of the two removed the area of close to horizontal flow from the groundwater inputs and outputs. The second pattern tested included the region previously identified horizontal into the groundwater outflow because the values were negative, even if only slightly. The resulting volumes still produced a large difference between the volume of groundwater calculated through the water budget and the volume of groundwater measured in the field by close to 80,000 m^3.

DISCUSSION & CONCLUSION

The results of this study have supported previous hypotheses about the response of Duck Lake attributed to changes in groundwater flow. The magnitude of groundwater inflow in water year one supports the lag in flooding compared to other lakes and rivers that demonstrated a direct response to the record precipitation in June 2008. Little change in the flux of groundwater during water year two explained the sustained flooding. The greater outflow of groundwater flow calculated for water year three explains the drop in lake stage over this time period. However, the seepage measurements for water year three informed the study of the complexity of the system and possible questions to investigate for future studies.

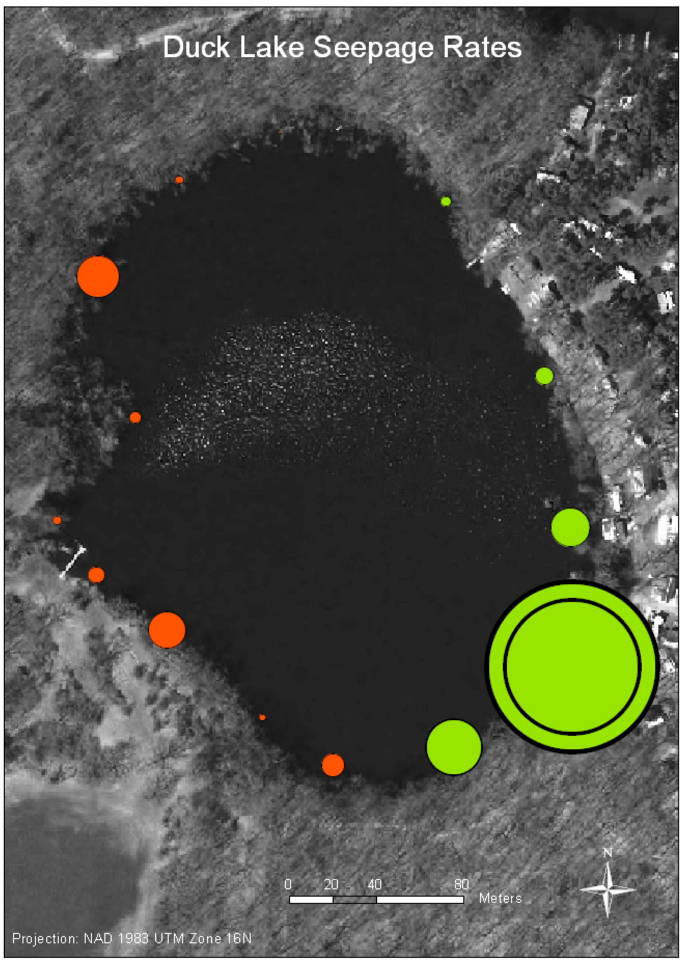

Figure 3. Duck Lake's seepage rates and comparison of groundwater inflow (green) and groundwater outflow (red).

The water year three groundwater volume results differ from the predicted volumes and indicate that seepage patterns within Duck Lake are more complicated than previously thought. A seepage meter on the southeastern side of the lake has inflow values double the rest of the inflow seepage data (Fig. 3). Based on this difference, the area could be a subaqueous spring. A subaqueous spring could form from variations in the lakebed geology, such as, highly permeable and conductive sand or gravel beds within finer grained material like clay and silt (Winter, 1998). When these data were removed from the groundwater inflow measurements and applied to the different seepage pattern models, the values were about five times smaller than previously calculated, and there was a difference between groundwater flow rates calculated from the water budget of approximately 47,000 m^3. Future studies would benefit from uncovering more about the lakebed geology of the southeastern area of Duck Lake and if a spring is present. The differences in rates around the lake suggest that the lakebed is comprised of poorly sorted heterogeneous material.

Increased precipitation or surface water inputs can cause groundwater flow reversals within a system (Winter, 1999). The record precipitation event could have stimulated such a reversal. The lag in response of Duck Lake could be explained through long residence times of the regional system and the possibility of low permeability material slowing the groundwater recharge.

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