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

April 2013
Pomona College, Claremont, CA

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Keck Geology Consortium: Projects 2012-2013
Short Contributions— Clear Lake, Wisconsin Project

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LAKE BUDGET ANALYSIS TO UNDERSTAND GROUNDWATER FLOODING OF A SEEPAGE LAKE NEAR MILTON, WI

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INTRODUCTION

Months following record high precipitation occurring in southern Wisconsin, Clear Lake and neighboring kettle lakes experienced severe flooding with sustained high lake stages persisting through summer 2011. Recently, the lake stage has dropped, coinciding with severe drought conditions in summer 2012 (Figure 1). This project seeks to identify the causes of changing Clear Lake storage between 2008 and 2012 and to develop a conceptual model of local groundwater flow surrounding the lake. A strengthened understanding of local flow systems connected to Clear Lake will lead to better anticipation for how the lake may respond to intensified precipitation extremes projected for the Midwest this century (Vavrus & Van Dorn, 2010).

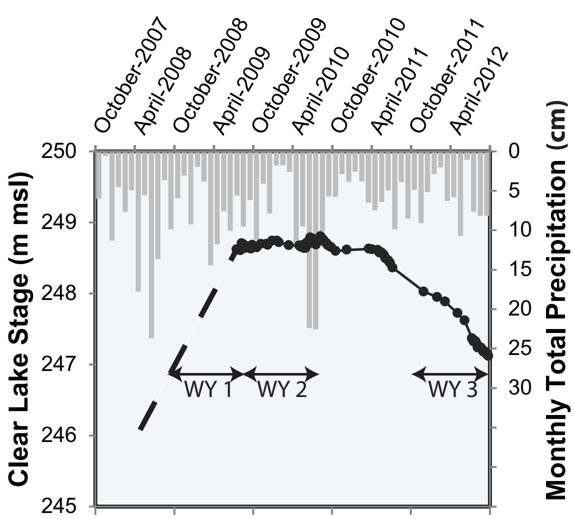

Figure 1. Clear Lake hydrograph showing stage trends between 2008 and 2012 and precipitation records for corresponding years (NCDC, 2012).

To identify causes for Clear Lake stage changes over the presented timeframe, lake budgets were balanced and analyzed for three water years. Selected years correspond to periods of stage rise, maintained high stage, and stage fall (Fig. 1). The water budget for Clear Lake is expressed as:

$$Gw_{in} + P - Gw_{out} - E = \Delta S$$

where Gw_{in} and Gw_{out} are groundwater inflow and outflow, P is precipitation, E is evaporation, and ΔS is the change in lake storage over one water year. Surface inflow and outflow are not substantial contributors to Clear Lake storage, so they are not included in the budget.

Clear Lake is a seepage lake hydrologically connected to the surrounding shallow aquifer system. Regional models of Rock County groundwater flow display a general northward flow beneath Milton, toward the Rock River valley (Gaffield et al., 2002). If Clear Lake were mostly influenced by regional groundwater flow, similar flooding would have occurred at other lakes connected to the regional system; however, no regional scale groundwater flooding was experienced. The unique flooding response of Clear Lake and neighboring kettle lakes therefore suggests that these lakes are mostly influenced by local flow systems, which act in isolation from regional systems. Beyond basic familiarity with the regional setting of the lake, a more detailed, localized model for groundwater flow through and around Clear Lake needs to be investigated to better understand lake stage response.

Aquifer length-to-depth ratio, heterogeneity, and surface topography all influence the development of local flow systems (Winter, 1976). Whereas regional flow systems operate along relatively uninterrupted, deep expanses of the aquifer, local flow is generally limited to relatively shallow subsurface depths and short flowpath distances (Toth, 1963). This implies that the shallow sand and gravel aquifer is most important in Clear Lake – groundwater interactions. The hummocky topography, heterogeneous composition, and the large length-to-depth ratio of the sand and gravel aquifer are factors that act together to support a local flow system at this study site.

The water-table configuration is the most dynamic factor that affects groundwater flow near lakes (Winter, 1991). While recharge to the deep Cambrian and Ordovician aquifers occurs elsewhere in the region at defined zones, recharge influencing Clear Lake occurs relatively close to the lake**.** This means that precipitation entering the local system may have a strong influence on lake behavior. Different amounts of precipitation will support different water table elevations, and a dynamic water table will correlate with a dynamic lake stage due to changing seepage distribution (Winter, 1981).

The three water years discussed here received varying precipitation amounts from 2009 to 2012 (Fig. 1). Therefore, it is hypothesized that while lake stage in Clear Lake is predominantly influenced by groundwater flow, precipitation indirectly controls the stage by influencing the surrounding water table configuration.

METHODS

This study measured values of the water budget for Clear Lake during three water years. Lake volumes were calculated for the start and end dates of each water year and were used to quantify change in lake storage. Volume calculations combined lake bathymetry with the start and end lake stage elevations of each year. To create a bathymetric map, lakebed elevation was measured at approximately 100m intervals around the lake from the side of a canoe (Figure 2). An extended staff gage was plunged into the water to measure lake depth. An anchored rope was used to measure depths greater than four meters. A Trimble GPS unit recorded position and elevation from which depth measurements were read, and the actual elevation of the bed of Clear Lake was determined by subtracting depth from the Trimble elevation. Surface elevations of Clear Lake shorelines were also measured to account for Clear Lake high stage. GPS positions of bathymetry measurements were imported, hand contoured, and digitized. The digitized contour map was converted into a triangulated irregular network (TIN), then into a raster format using ArcGIS.

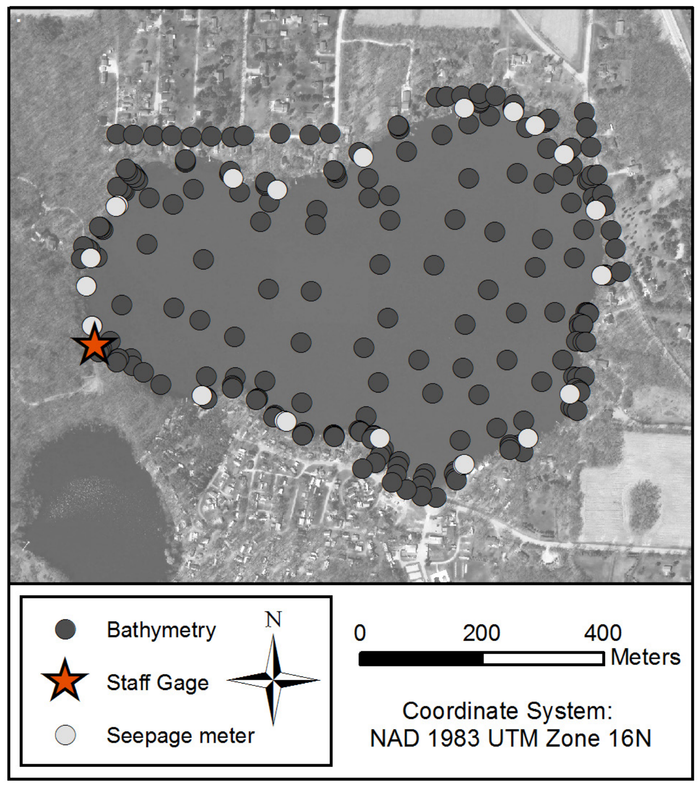

Figure 2. Positions of lake bed and shoreline elevation measured, staff gage, and seepage meters. (Image Source: Rock County Planning, Economic, and Community Development Agency.)

Lake stage elevations were recorded by a staff gage that was installed on the west side of Clear Lake in summer 2009, after the lake flooded. Stage measurements were recorded by the Rock County Health Department through 2012, and were checked almost daily during the three-week field study of this project in July 2012. Trees bordering Clear Lake were drowned by the 2009 flood, and the elevation of this tree line was used to determine the starting lake stage of water year 1.

Six lake stages corresponding to the beginning and the ending water year dates (Fig. 1) were digitized as polygon features, then converted to a raster format. To determine the lake volume at different stages, the bathymetric raster file was cut by each stage elevation raster using the ArcGIS 3D Analyst Cut Fill tool. The difference between end and start volumes for each water year were used to calculate the change in storage in the water budget analyses.

The average stage height of each water year was used to calculate average lake surface area, which in turn was used to develop the evaporation and precipitation balance for each water year. Over each defined year, maximum and minimum recorded lake stages were identified and averaged. Average lake surface areas were calculated using the bathymetry raster and ArcGIS 3D Analyst Cut Fill tool with each average stage.

Precipitation and evaporation values were obtained from Fort Atkinson monthly records (NCDC, 2012) and Department of Agriculture regional annual estimates (Weather Bureau, 1959), respectively. To calculate precipitation inputs (P), monthly precipitation amounts were summed and multiplied by the average lake surface area for each water year. Regional annual estimates of evaporation (76 cm/year) were similarly multiplied by the average lake surface area for each water year to calculate an evaporation output (E). Estimates of P and E were then used to determine the net groundwater contribution for each water year and investigate the relative role of groundwater in Clear Lake flooding using the following equation:

$$Gw_{in} - Gw_{out} = \Delta S - P + E$$

where a positive Gw_{in}-Gw_{out} value corresponds with a net groundwater inflow and a negative Gw_{in}-Gw_{out} value corresponds with a net groundwater outflow for a water year.

To estimate the actual distribution of groundwater inflow and outflow for water year 3, seepage meters were installed at 19 locations around the Clear Lake perimeter (Fig. 2). Seepage meters were used to determine inflow and outflow rates at discrete points around the lake. In order to apply these rates to Clear Lake budget calculations, they need to represent lake areas. As an initial estimate, this analysis used Theissen polygons to interpolate between points. By multiplying seepage rates over their representative surface areas, volumetric amounts of groundwater inflow and outflow were calculated. The seepage groundwater volumes provide a check on Gw_{in}-Gw_{out} for water year 3 budget calculations.

RESULTS

The bathymetric raster map of Clear Lake indicates that the deepest portion of the lake is located on the east side (Figure 3). Clear Lake had a positive change in storage during water year 1, a slightly negative change in storage during water year 2, and a significantly larger negative change in storage during water year 3 (Table 1).

The average lake surface areas for water years 1 and 3 were both lower than the average surface area for water year 2 (Table 1). Relative surface areas are especially important in evaporation output calculations, because the evaporation rate did not vary between years. Evaporation was 2.8×10^5 m^3, 3.0×10^5 m^3, and 2.9×10^5 m^3 during water years 1, 2, and 3, respectively. Direct precipitation onto Clear Lake was 3.3×10^5 m^3, $4.4\ 10^5$ m^3, and 2.7×10^5 m^3 during water years 1, 2, and 3, respectively.

Clear Lake budgets indicate a significant groundwater influence on lake levels. During water year 1, the net flow of groundwater to Clear Lake was 9.0×10^5 m^3. In the case of water year 2, there was a net outflow of groundwater (-1.6×10^5 m^3). Water year 3 had a large net outflow of groundwater (-3.9×10^5 m^3).

Seepage measurements indicate where inflow and outflow occurred around the lake perimeter for water year 3. Figure 3 shows most outflow occurring at the northwest, northeast, and east sides of the lake, and inflow occurring in the zones between. The highest rate of measured inflow occurred on the southeast side of Clear Lake.

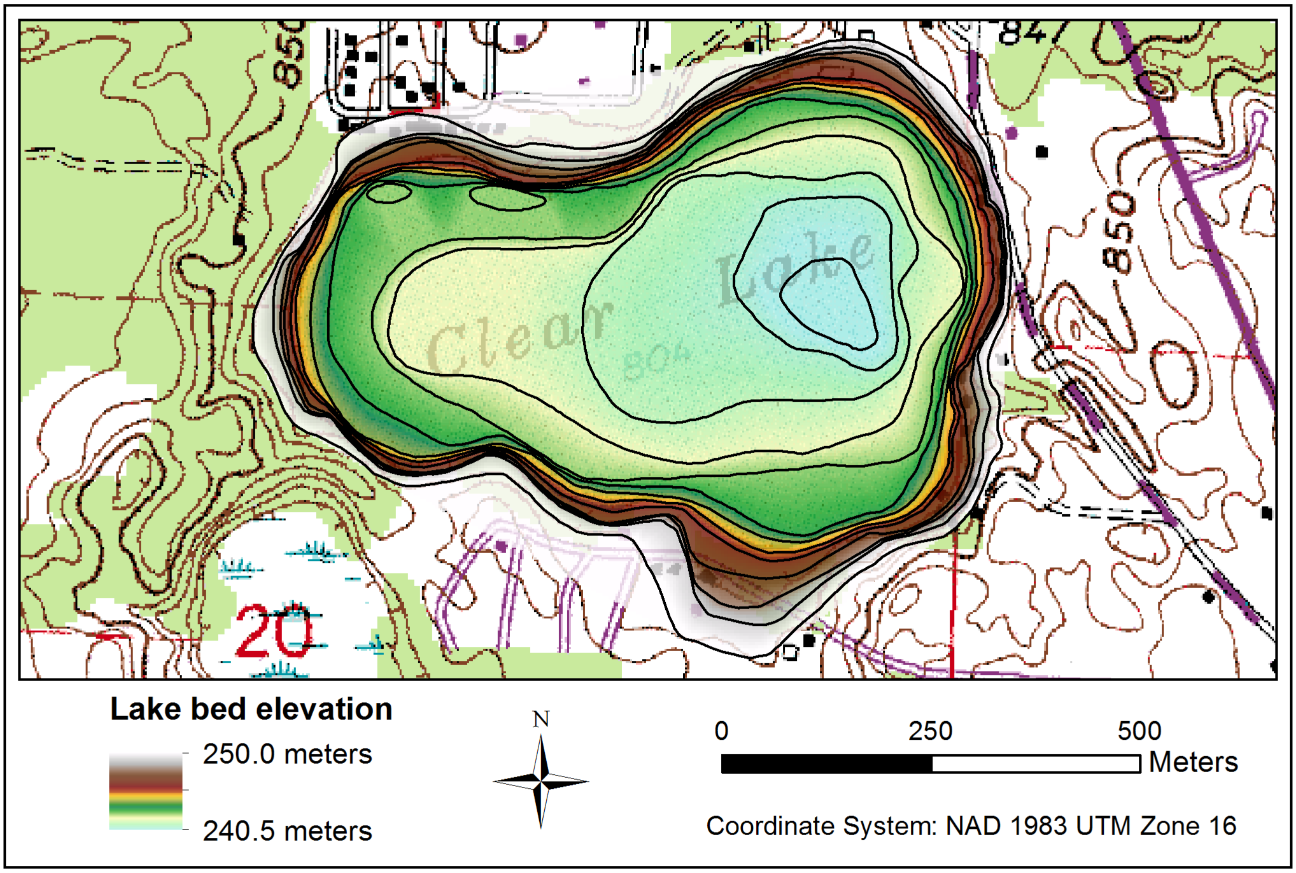

Figure 3. Bathymetric map of Clear Lake with the Milton, WI 7.5 minute topographic quadrangle (feet).

Water Year	Start Stage (m)	End Stage (m)	Average Stage (m)	Average SA (m^2)	ΔS (m^3)
1	246.11	248.67	247.40	372,258	9.5×10^5
2	248.67	248.63	248.72	392,793	-1.6×10^4
3	248.19	247.10	247.62	375,763	-4.1×10^5

Table 1. Stage, surface area (SA), and change in lake storage results.

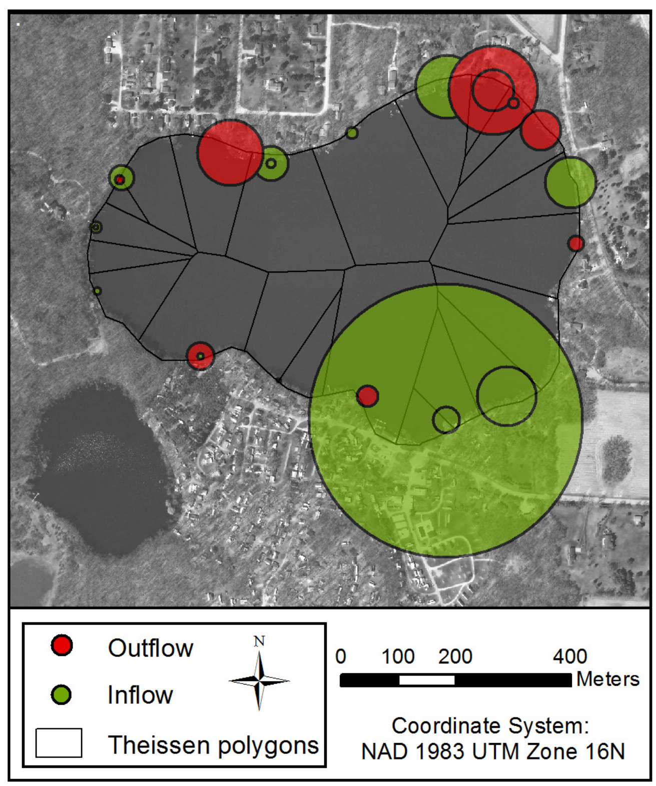

Figure 4. Clear Lake seepage distribution representing magnitude of flow rate with size of circle. (Image Source: Rock County Planning, Economic, and Community Development Agency.)

DISCUSSION

The purpose of this study was to characterize the causes of Clear Lake stage trends between 2008 and 2012. Balanced water budget calculations were used to solve for the difference between groundwater inflow and groundwater outflow for each water year. Results reveal a parallel relationship between change in storage and net groundwater contribution. During water year 1, Clear Lake demonstrated a large positive change in storage, which corresponds with a large net inflow of groundwater. Relatively small negative change in lake storage for water year 2 corresponds with a relatively small net outflow of groundwater. Water year 3 demonstrated a significant decrease in lake storage, which corresponds with a large net outflow of groundwater. These trends make sense because Clear Lake is dominated by groundwater flow. Over the study years, groundwater interactions largely outweigh precipitation inputs and evaporation outputs for Clear Lake. All water year stage trends are thus a result of changing groundwater flow patterns.

To understand why groundwater flow underwent a dramatic change in net distribution over the last several years, the local flow system surrounding Clear Lake needs to be considered. Precipitation that becomes groundwater recharge influences the water table configuration surrounding Clear Lake. Because a higher water table supports a different configuration of inflow and outflow than a lower water table, precipitation indirectly controls Clear Lake stage.

At the Clear Lake study site, a high water table within the surrounding hills developed after high amounts of precipitation in 2008. This recharge created a higher water table and a higher volume of inflow into the lake during water year 1. High stage was relatively constant during water year 2, and is attributed to high precipitation in 2010 (Fig. 1). High recharge into the local watershed would have helped maintain a relatively high water table. Thus, only a small shift in seepage distribution would have occurred between water year 1 and 2. Drought conditions during 2011-2012 correspond with a rapid Clear Lake stage drop during water year 3. Reduced recharge into the local system results in less inflow into the lake and substantially increased groundwater outflow.

A number of potential uncertainties exist within these data. The Theissen polygons have limited utility when attempting to reconstruct the distribution of groundwater inflow and outflow for water year 3. Inflow and outflow patterns across the center of Clear Lake are especially uncertain because seepage measurements were not possible in water deeper than about 1 m. Seepage data do, however, confirm that groundwater flow patterns in Clear Lake are complicated. The trading of inflow and outflow around Clear Lake confirm that groundwater flow is more complicated than a basic flow-through system, at least for water year 3, and thus is influenced by a unique local flow system that behaves much differently than the deeper regional systems of groundwater flow.

CONCLUSIONS

The lag in Clear Lake flooding following peak precipitation in 2008 is characteristic of seepage lakes due to the slow speed of water infiltration and the time required for groundwater inflow to occur. If Clear Lake were dominated by surface water inflow and outflow, the stage response would have been different; there would have been less of a time lag associated with initial flooding and subsequent recovery of lake water levels. Groundwater moves slowly compared to surface water, even within local systems. This explains the delayed response following precipitation, and also the slow lake draining. For Clear Lake stage height to change, the connected local water configuration must change. Flooding of Clear Lake therefore has prolonged impact for lake residents. The complicated distribution of seepage for water year 3 suggests the presence of local heterogeneous material in the shallow sand and gravel aquifer. However, further research is required to better characterize this system.

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