Global Livestock CRSP

Sustaining Lake Levels in Lake Nakuru, Kenya: Development of a Water Balance Model for Decision Making

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Fluctuations in Lake Nakuru's water level, particularly since the mid-1980s have been a source of significant concern for the sustainability of the lake's unique ecosystem. To improve collective understanding of lake level fluctuation and drying, and to explore impacts of regional population growth, increasing water extraction, and land use changes, a preliminary water balance model of the lake was developed and initial analyses undertaken. Direct rainfall is the largest inflow to the lake, followed by tributary discharges and groundwater seepage. The lake's hydrologic balance appears to have changed substantially since the 1970's, with the proportion of water entering the lake rapidly as surface water - rather than perennially as groundwater - having increased, causing lake level and salinity to fluctuate more rapidly. This change is linked to an apparent increase since the 1970's in surface water runoff at the expense of groundwater recharge in the lake's River Njoro and other upstream watersheds. A declining groundwater table has the greatest negative impact on the sustainability of lake levels. The present situation calls for major efforts to improve hydro-meteorological monitoring and data management for the greater Lake Nakuru area with a priority on groundwater monitoring and institutionalization of these activities as essential governance rather than as piecemeal, short-lived projects.

Background

Lake Nakuru, located in Lake Nakuru National Park, at 1,759 meters elevation in the Eastern Rift Valley in Kenya is a broad, shallow, endorheic (no surface outlets) saline lake formed at the bottom of its closed catchment. Its unique ecosystem is internationally recognized for the diversity and density of its wetland birds, including the lesser flamingo, and large mammal wildlife that inhabit the surrounding Lake Nakuru National Park managed by the Kenya Wildlife Service (KWS). A prolonged lake drying period and falling water levels from the mid-1980's through 1996, and associated increases in water salinity, culminated with the lake completely drying in 1995 and 1996. Most bird life disappeared and tourism greatly diminished. Lake levels rebounded following extreme El Niño-driven flooding in 1997 and 1998; flamingos returned in 2000 but fewer than before. Such negative effects on the lake's unique birdlife cause concern for KWS and biologists and directly translate into economic losses from reduced tourism.

Of the three perennial rivers in the lake's catchment, the River Njoro drains the highest and wettest western side that rises to the Eastern Mau Escarpment, providing an important source of year-round surface inflow to the lake and recharge to the regional groundwater basin. The Njoro watershed, like much of the catchment, continues to experience the regional pressures of population growth, land use change, increasing rates of surface and groundwater extraction, and upland deforestation that has accelerated in recent decades (Baldyga et al. 2007).

Water balance modeling is commonly used as the first scientific step to understand the hydrological behavior of systems and impacts of water resource, climatic, and regional development changes. Water inputs consist of direct rainfall over the lake's surface, and surface water and groundwater inflows, while outputs consist of evaporation from the lake's surface and groundwater outflows.

Major surface water discharges into Lake Nakuru include several rivers, a perennial spring, and a sewage plant effluent. The lake has no surface outflow. An important portion of the rain falling over Lake Nakuru's catchment infiltrates to groundwater over the land or from its rivers before it reaches the lake (McCall 1957). Groundwater acts as a reservoir from which water seeps into (or out of) Lake Nakuru through the lake's bed sediments, in response to the difference in elevation head between the lake's surface level and the surrounding groundwater table.

Deforestation since the 1970's, along with increased surface and groundwater extraction, pollution, and land sub-division for small scale agriculture and population growth, continues to impact the Lake Nakuru region. Ongoing deforestation in the Njoro watershed is increasing surface water runoff at the expense of groundwater recharge, thereby increasing the proportion of rainfall water moving rapidly through the hydrologic cycle as runoff. Increased flash flooding and reduced groundwater replenishment result. Increased water extractions compound these effects, reducing already diminished stream flow during dry seasons and lowering groundwater levels further. Little is known, however, about the magnitude of water table declines or how regional trends are impacting the regional groundwater system. In constructing a preliminary water balance model of Lake Nakuru to gain insight into the sustainability of lake levels, several important questions emerge and are addressed in the following section.

Preliminary Findings

What long-term historic monitoring data are available for developing a water balance model of Lake Nakuru? An exhaustive inventory and assessment of available historic monitoring records and lake-related data was undertaken. Climate data at the lake were more abundant and extensive than hydrologic data, but both contained significant quality problems. Evaluation of flow data for the seven surface and sub-surface inflow gauging stations to Lake Nakuru found that monitoring for most was initiated and pursued in the 1990's for relatively short periods only and that a significant portion of the recorded values are missing (11% to 60%), while station records of the two rivers with the largest contributing drainage to Lake Nakuru could not be found at all. The only long-term station record is for the Ngosur River mouth (1948-2000; 89% complete). Groundwater in the area has never been monitored and the lake's sediment hydraulic properties have never been reported. Less reliable reports of the water table around the lake on three past occasions were obtained. Lake geometry is available for 1960s conditions, at which time a depth-salinity relationship was also developed (Vareschi 1982). Lake level monitoring data from 1956 though 2002 were obtained with some limitations: missing and unreliable values appear for the period 1977-1994 and 2000-present while several anomalous values appear elsewhere; the gauge datum has not been measured since the early 1970's and is likely to have been affected by lake sedimentation.

While there is no historical period for which a complete set of time-series observations for water balance modeling of the lake's hydrologic system was found, two periods of data were identified for which a preliminary water balance model could be constructed and initial calibration and validation undertaken (McCord 2007).

What are the relative contributions of each hydrologic component to Lake Nakuru's water balance and water levels, particularly that of River Njoro surface inflows? A monthly water balance model of the lake was constructed and simulated using the best available rainfall, evaporation, surface inflow, and groundwater level data as input. Monthly inputs of surface water, groundwater, and rainfall, and monthly evaporation losses were developed. The water balance model was calibrated to the period January 1958 – September 1976 by minimizing the error between simulated (model estimated) and observed lake levels.

Results indicate that direct rainfall is by far the largest source of water to the lake, followed by tributary inflows and then groundwater seepage. Groundwater, however, can be the dominant source in dry periods and has served historically to stabilize lake levels in those periods. The flashiness of several rivers that discharge into the lake was inadequately characterized in this preliminary effort, but appears important for explaining the more rapid rates of lake rising and drying behavior observed in the historic record than predicted by the model over the calibration period (Figure 1).

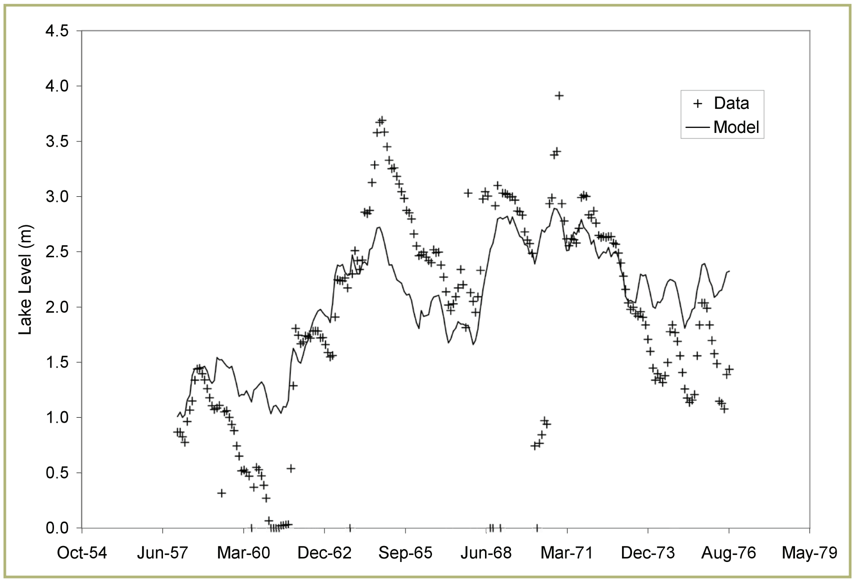
A validation test, where model performance is evaluated on an independent data set, was run for the period January 1994 – December 1999. This test revealed that significant changes in the lake's hydrology have occurred since the calibration period. To explore changes since the 1970s, model sensitivity and lake level response time analyses were undertaken.

What role does the surrounding groundwater basin play in sustaining Lake Nakuru water levels? Despite its small volume, the contribution of groundwater seepage to the lake's water balance is unique and appears particularly important historically for dampening the effects of extreme rainfall fluctuations on lake levels. Water moves into or out of the lake from and to the surrounding local groundwater basin depending on which level is higher. When high rainfall and runoff cause a rapid rise in lake level, the rate of groundwater seepage diminishes and may even reverse, causing water losses to increase. Lake levels tend to stabilize again at close to the long-term surrounding local groundwater table, as long it remains above the lake bottom.

An analysis of how quickly lake levels respond to changes in net rainfall (direct rainfall – evaporation over the lake surface) was undertaken. Response time in the relatively dry 1972-1976 period was compared to the relatively wet 1994-1998 period. In the earlier period, lake levels fluctuated less and more slowly with about a one-month lag in response to net rainfall changes. In the more recent period, lake levels responded directly to net rainfall with no apparent lag time. Furthermore, levels remained relatively steady in the 1970s despite low net rainfall but remained generally low in the 1990s period despite high net rainfall.

A long-term lowering of groundwater levels, starting in the 1970s and accelerating, is suspected. Increasing numbers of new boreholes installed starting in the 1960's provides some evidence to support this hypothesis. Sensitivity analysis explored potential effects: a lower groundwater level (three meters below the 1957 fixed groundwater level

Figure 1. Lake Nakuru water balance model calibration results comparing observed lake levels to model predicted levels over the January 1958 to September 1976 calibration period.

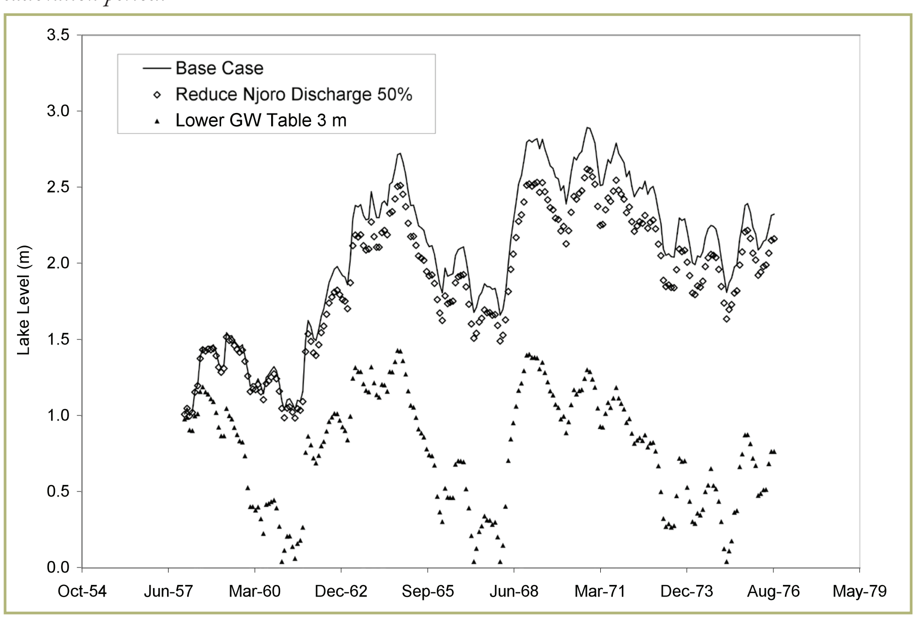


of 1,762 meters assumed in the calibration run) caused lake drying and the predicted mean lake depth over the calibration period to drop by 62%, or more than a meter (Figure 2).

What effects do population growth and land use changes in the Njoro watershed have on the sustainability of water levels in Lake Nakuru? Runoff from the Njoro watershed makes a disproportionately larger contribution to the lake than its drainage area would suggest because it drains the wettest portion of the lake's catchment. Lake level sensitivity to halving the volume of River Njoro discharge into the lake, holding all other assumptions constant, shows levels would drop by about 17 centimeters over the calibration period, much smaller than the drop predicted from a reduction in the groundwater table (Figure 2). The historic flashiness and complex stream-aquifer interactions of the lower River Njoro could not be characterized due to lack of systematic station recording. Recent changes in the River Njoro's hydrologic regime from deforestation, land use change, and increasing water abstractions affect the monthly distribution pattern of runoff and groundwater replenishment processes. These changes are likely to negatively impact lake levels, even if the total annual discharge volume remains the same.

What gaps and limitations in hydro-meteorological monitoring data, and other critical data need to be addressed in order to improve the scientific understanding of Lake Nakuru's water balance and water level fluctuations? Lack of long-term monitoring data and uncertainty in the quality of very limited records on surface discharges constrained the ability to match the historic record of lake levels in this initial effort. Major gaps and important limitations in the existence and quality of monitoring data were identified: 1) very short and sporadic stream gauging records for the major streams and rivers flowing into the lake largely do not overlap with lake level data; 2) the groundwater table around the lake has not been recorded; 3) monitoring and record keeping since 1970 have been highly problematic; 4) stream gauge data collection has been irregular and erratic since 2000; 5) a high degree of inaccuracy and unreliability of available records for a number of the climatic and streamflow stations; and 6) lack of lake geometry and sediment hydraulic properties and changes over time in light of increasing upstream sediment erosion to the lake (McCord 2007).

Figure 2. Predicted sensitivity of Lake Nakuru levels to a modeled reduction in a) the groundwater table, and b) the River Njoro discharge volume, over the January 1958 to September 1976 model calibration period.



Practical Implications

This preliminary modeling work identified the critical role of groundwater in sustaining and stabilizing lake levels, storing water when surface water discharges to the lake are high, and seeping back to the lake in drier periods. Groundwater functions to support long-term lake levels in this way as long as the local water table remains sufficiently high (above the lake bed bottom). Investment in a comprehensive regional and near-lake groundwater-monitoring program, accompanied by field and modeling studies to develop a greater scientific understanding of groundwater behavior in the Nakuru region and greater Rift Valley (where other lakes are likely to be similarly affected by groundwater levels) should be a government priority. Such investment is justified not only for the sustainability of ecosystems like Lake Nakuru's, but also for the long-term sustainability of local water supplies, a majority of which have and continue to draw from groundwater. As part of a groundwater-monitoring program, the Government of Kenya's Water Resources Management Authority (WRMA) needs to enforce the legal requirement of air lines in well construction permits. Some recently installed regional wells have not included air lines, precluding the ability to measure groundwater levels. The 2002 Water Act imposes a volumetric tax on groundwater extractions which is collected by WRMA. These funds would seem a viable source of investment for sustaining a regional, long-term, seasonal groundwater monitoring program.

Collecting and managing high quality, continuous, long-term hydrological and meteorological monitoring data for common use is imperative for a water budget analysis. This research highlighted countless significant cases where better data would have saved time and increased confidence in the data. Recommendations for improving hydrologic and climatologic monitoring to improve understanding of the lake's water balance and development of the water balance model include: 1) Investigate river gauging stations and records to assess and revise preliminary discharge factors used to represent ungauged inflows in the model; 2) Rehabilitate, upgrade and re-calibrate stream flow stage gauges on major inflows; 3) Monitor and record sewage discharges to address pollutant concerns and estimate local aquifer seepage; 4) Generate a detailed depth map of Lake Nakuru, compare to the 1960s map and measure sediment bed properties; and 5) Invest in long-term station gauge maintenance, calibration, and regular data quality assessment and archival record management systems (McCord 2007).

Further Reading

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The GL-CRSP Sustainable Management of Rural Watersheds (SUMAWA) project was established in 2003 and is a multi-disciplinary research effort focusing on biophysical and human-related factors governing health in the River Njoro watershed in Kenya. The research conducted for this brief is part of the NJORO WATER (Water and Sanitation in the Njoro Watershed) project, which supplements SUMAWA with scientific analysis and modeling of SUMAWA data sets. Dr. Marion Jenkins serves as Principal Investigator for NJORO WATER. Email: mwjenkins@ucdavis.edu.

The Global Livestock CRSP is comprised of multidisciplinary, collaborative projects focused on human nutrition, economic growth, environment and policy related to animal agriculture and linked by a global theme of risk in a changing environment. The program is active in East and West Africa, Central Asia and Latin America.

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