The influence of groundwater on lake-water management: the Naivasha Case.

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Abstract

Lake Naivasha, a lake in the Kenyan Rift Valley, is surrounded by shallow aquifers intimately linked to the lake. The analysis of the groundwater levels north of the lake show the development of a large depression cone caused by to large-scale abstractions for irrigation and drinking water supply. The natural flow in this area has reversed and water is now flowing from the lake towards the well field. Three distinct groundwater zones can be distinguished with different water use efficiencies and pollution hazard. A simple water balance model with a lumped aquifer reservoir clearly shows the influence of groundwater describing the system: if the groundwater node is de-activated the simulation of the lake levels overshoots 1 meter after periods of recovery or recession. A special version of USGS ground water model code Modflow, with a lake module, is used to simulate the long-term effects of groundwater abstraction. The simulation shows that it takes 10 of years to establish a new equilibrium state and an equal long period to recover from the exploitation. The slow response of the lake-groundwater system requires a long planning horizon from water managers.

Keywords: groundwater, modeling, water management

Introduction.

Ground water is critical for understanding most lake systems because it influences a lake's water budget and nutrient budget. Several studies report on the use of a simple mass balance approach to simulate lake levels from hydrological and meteorological data (Becht *et al* 2002, R. N. Jones *et al* 2001 and Almendinger 1990). Groundwater is not considered at all or simplified by lumping the aquifer system as one reservoir. A lake water balance model linked to a groundwater model is required to study the behavior of the system in more detail. Efforts to simulate ground water-lake interaction include the LAK1 (Cheng and Anderson 1993) and LAK2 (Council 1998) add-on "packages" to the widely used U.S. Geological Survey modular finite-difference flow model (MODFLOW). Most studies relate to research-basins and very few address the implications of a lake-groundwater system on the water management of the basin.

Physical description of the study area

Lake Naivasha is a shallow, endorheic, freshwater lake situated in warm and semi-arid conditions in the Rift Valley of Kenya. The lake is situated approximately 80 km North-West of Nairobi. The lake receives an average rainfall of 600 mm $year^{-1}$. lake transpiration is approximately 1700 mm $year^{-1}$. Lake Naivasha is fed by two perennial rivers, the Malewa and the GilGil, receiving their water from the highlands bordering the rift valley. During heavy rains the lake also receives water from direct runoff into the lake and some ephemeral streams. The natural variation of lake level was 12 meters over the last century. Around the lake a vibrant horticultural economy is fully dependent on the available water resources.

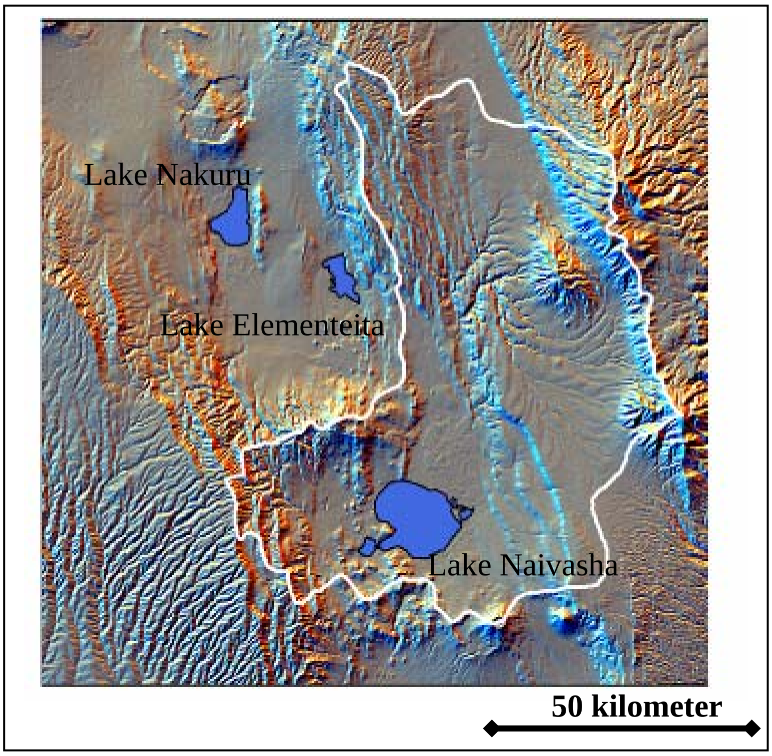

Figure 1: The Lake Naivasha basin

Hydrogeology

It has long been known that a substantial part of the surface inflow recharges the surrounding shallow and deep aquifer systems. This recharge that flushes the lake is the reason that the lake remains fresh. The lake and its surrounding aquifers form one tightly linked system. The shallow aquifers are composed of a complex mixture of water and air laid pyroclastic material, and lacustrine deposits. The intercalated layers of pumice lapili play an important role because of the very high transmissivity. Values of more than 10,000 m^2/day have been derived from pumping tests. The specific yield of the aquifers has an average value of 0.15. Due to the high transmissivity of the shallow aquifer the gradients of the water table low, and the lake surface extends almost horizontally into the aquifer. This water of the shallow aquifer recharges the deeper regional aquifer system. This system is partly geothermal and discharges to the lakes in the North and in the South (Clarke 1990), (Becht *et al* 2005). The groundwater levels in the vicinity of the lake closely follow the water level variations of the lake. Therefore a substantial portion of the available water resources and the changes in storage driven the variations of precipitation occurs in the groundwater reservoir. Based on accurate measurements of the water table, isotope analysis and flow system analysis the general direction of groundwater flow has been determined. The direct groundwater recharge to the aquifer is low and does not play an important role in the groundwater balance.

Exploitation of water resources for irrigation

Lake Naivasha being a fresh lake has been exploited for irrigation since the 1940s. In these days the water was pumped directly from the lake and in the lower Malewa a weir raised the water to allow gravity irrigation. In 1972 a large cattle farm on the Northern side of the lake sunk 12 wells used for the irrigation of fodder, mainly grass and alfalfa. Several of these wells are still in use. In the mid 1970’s 3 boreholes were sunk North of the lake for the drinking water supply of Naivasha town. Since the early 1980’s the flower industry around the lake has changed the rules of the game. The first farm started in 1980 at the South-Western side of the lake. The success of the flower production has caused a booming of this industry and at present a large part of the Southern shores is occupied with flower farms all using lake water for irrigation. Until 1999 the groundwater North of the lake was exploited for the water supply of Naivasha town and for fodder production. Than groundwater based horticultural industry started also North of Lake Naivasha and rapidly a large area was put under cultivation.

The inflow into the lake through the Rivers Gilgil and Malewa is also reduced. In 1992 a pipeline became operational pumping 20,000 $m^3 day^{-1}$ from the Malewa basin to GilGil and Nakuru town. Recently horticultural farm have started operations in the upper catchment taking water from the river.

At present the total irrigated area is approximately 40 km^2. During the large 20 years the irrigation technology has seen a shift from overhead sprinkler to more sophisticated systems as central pivots and drip irrigation. Also many farmers have moved from outdoor cultivation to greenhouses. The latest trend is hydroponics culture in greenhouses. The changes in irrigation practices definitely help to conserve water.

Shallow groundwater around Lake Naivasha

Figure 2 shows a satellite image of the lake with the known wells and the direction of groundwater flow.

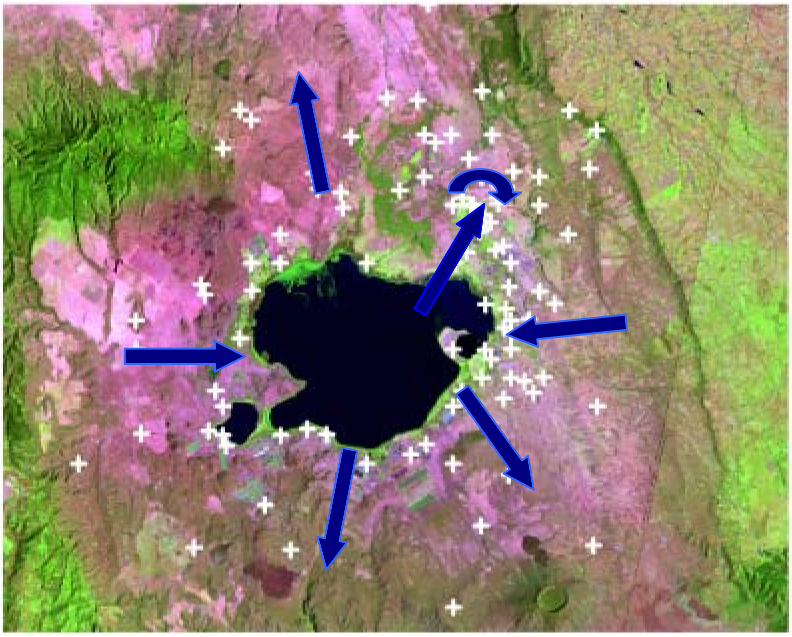

Figure 2: Lake Naivasha with wells (+) and general direction groundwater flow

The major flows are the outflow to the North and South draining the lake. Some ground water inflow occurs from the flanks of the Rift Valley towards the lake. North of the lake, in the area with important groundwater exploitation, the natural gradient is inversed and a groundwater depression has been formed. The water pumped from this area comes indirectly from the lake. The rather complicated flow pattern has implications for the management of the lake. The southern zone is an outflow zone with much lake water based irrigation. Over-irrigation in this zone will cause a net water loss since the excess water drains towards the shallow aquifer. Eventually, this water will re-appear in Lake Magadi after 10,000s of years. Agrochemical pollutants carried by the water will have the same fate. In outflow zones careful irrigation management preventing over irrigation is important, the risk that pollutants are carried to the lake by groundwater is small. Exactly the opposite is true for the inflow zones. In case of over irrigation the access water will find its way to the lake and can be reused. Of course the same holds true for pollutants, constituting a danger for the ecological quality of the lake. In the groundwater depression North of the lake water is re-circulated. All irrigation in this zone is based on groundwater. Irrigation return flow from over-irrigation will recharge the aquifer and the concentration of salts and pollutants is likely to increase.

The temporal evolution of the cone of depression caused by the pumping North of the lake is shown in figure 3. The transect runs from the lake shore over the irrigated area to the Malewa river.

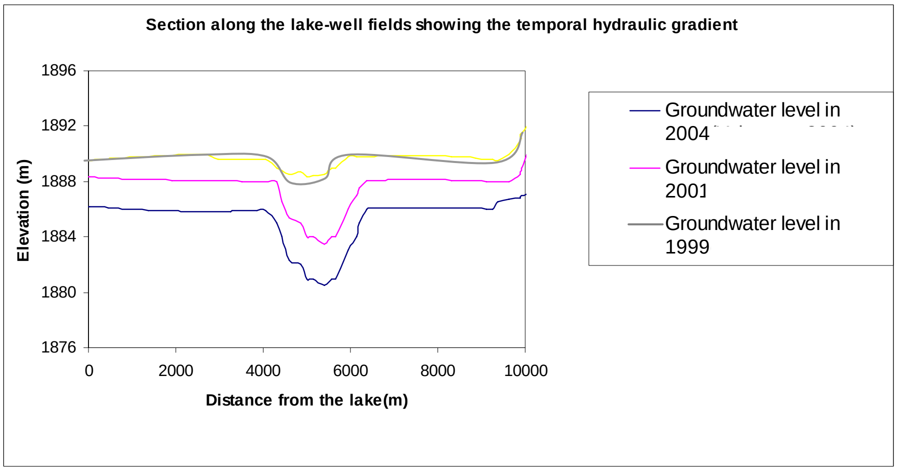

Figure 3: Transect of groundwater levels North of Lake naivasha

The cone of depression has reached a depth of more than six meters as compared to the natural water table. The natural flow in this area was directed towards the lake but has inversed. Water is now flowing from the lake towards the pumped zone.

The groundwater has an important effect on the water balance of the lake. If the lake levels rise the lake will recharge the surrounding aquifers. If the lake recedes the aquifers will discharge into the lake. This interaction causes inertia to the lake-groundwater system causing delayed reactions to external (meteorological) stresses. The groundwater acts as an extra reservoir absorbing water wet periods and releasing water during droughts.

This phenomenon can be shown using the Lake Water Balance Model (Becht, *et al* 2002). The model schematizes the aquifer as one reservoir hydraulically linked to the lake.

In figure 5 the effect of the groundwater on the lake levels is indicated by the arrows

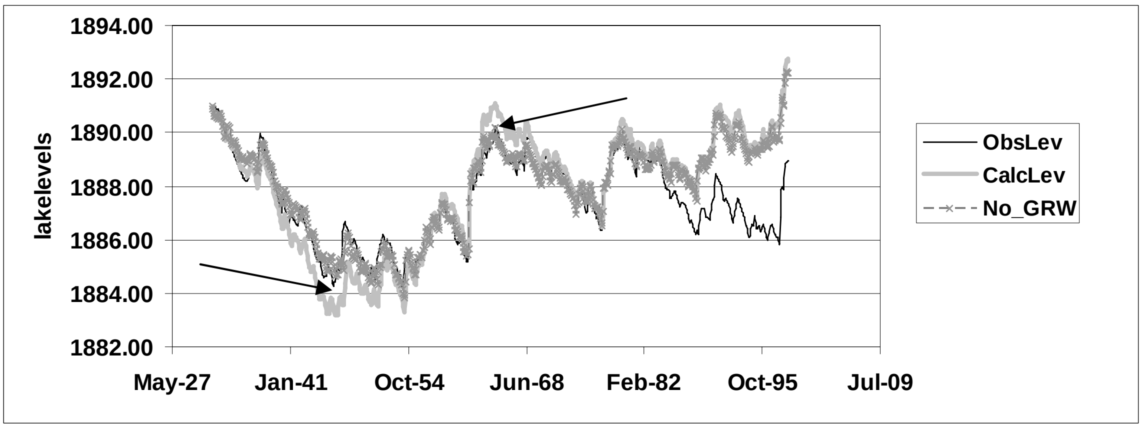

Figure 4: Observed and simulated water levels

At the end of the long drought periods between 1930 and 1950 the lake levels are simulated one meter lower than the observed levels due to the lack of groundwater inflow. The opposite is true during the period of rising lake levels in the 1960's where a one-meter overshoot of the simulated levels takes place. This can be explained by the absence of a flow recharging the aquifer. The model with a groundwater component accurately follows the observed levels, whereas the same model with no groundwater component overshoots after periods of rise or recession. The deviation starting 1982 between observed and modeled levels is due to the abstraction for irrigation from the basin (Becht *et al* 2002)

The groundwater regime around Lake Naivasha is complicated. Groundwater models with increasing complexity have been constructed by Owor (1999), Kibona (1999) and Nabide (2002) and Yohanis (2005). All models are based on Modflow, the groundwater modeling code of the United States Geological Survey (USGS) with the lake pachkage.
These models fully link the lake and the groundwater and enable a more reliable and sophisticated analysis of the role of groundwater than the simple water balance model presented earlier.

To illustrate the importance of groundwater in the management of Lake Naivasha the following scenario has been simulated using the models. The lake groundwater resources North of the lake are exploited at a rate equal to the actual abstraction. (55 m^3 $year^{-1}$) starting in 1932. The full abstraction is taken from groundwater, none from surface water.
The results are shown in figure 6.

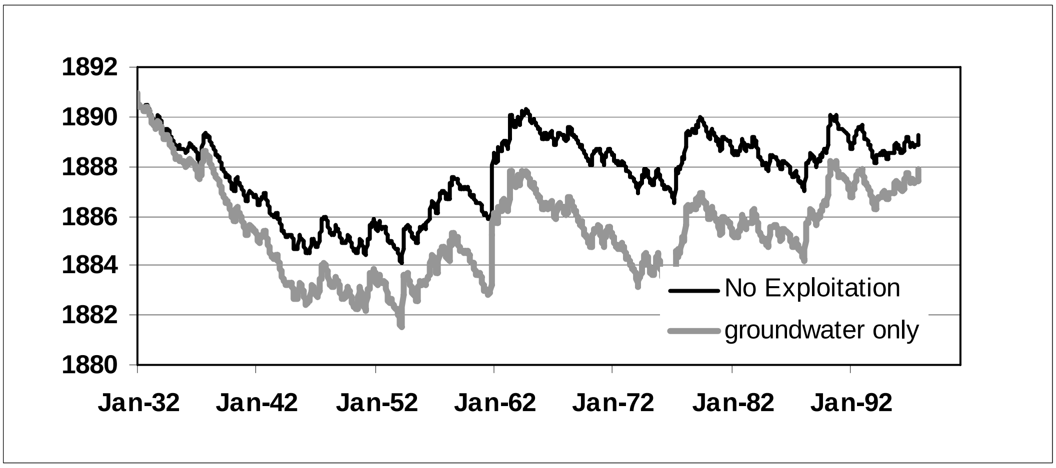

Figure 5: Simulated lake levels with an abstraction of 55 m^3 $year^{-1}$ from 1932 to 1970

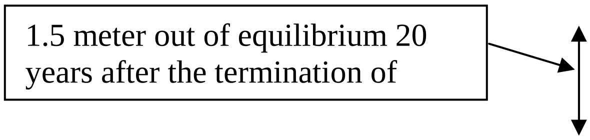

Figure 6: Difference between levels in figure 6

The equilibrium drawdown of the lake level can be calculated from the long-term water balance and is 3.5 meter. Figure 7 shows that this level is reached after a period of 35 years. Even after the moment the exploitation of the aquifer has stopped in 1970 it takes 6 years before the lake level reacts and starts to rise. At the end of the simulation period in 1997 the difference between the lake levels of an exploited lake and un-exploited lake is 1.5 meter. This means that 25 years after the termination of the exploitation the lake has only recovered 50% towards its natural equilibrium state.

Water management

The very slow reaction time of the lake groundwater system demonstrated by the simulations has important repercussions for the management of Lake Naivasha.

The drawdown effect of groundwater abstraction on the lake level takes decades and the recovery of the lake takes a period of similar length. This effect should be considered for the management of the lake. The groundwater abstractions taking now place in the area North of lake Naivasha will affect the lake levels for the coming years even if groundwater exploitation would be fully banned right now.

At the other hand the presence of good aquifer around the lake constitutes a large source of water and could be used for optimized water management. Especially after a wet period with a rise of the lake levels the water stored in the lake could be used to artificially recharge the aquifers. The techniques, also know as Managed Aquifer Recharge Systems (MARS) could play an important role in the rational use of water. Water that would naturally discharge into the lake like runoff from greenhouses, runoff from the perennial and ephemeral rivers or even water from the lake could be injected in the aquifer to be used in periods of water shortage.

Conclusions

The analysis of the flow direction around Lake Naivasha shows that 3 different groundwater zones can be distinguished: (1) a zone where over irrigation leads to a waste of water, (2) a zone where over-irrigation leads to pollution of the lake and (3) a zone where water is recycled and the water and solute balance of the lake is not affected.

With the lake water balance model including a lumped groundwater node the effect of groundwater can be clearly shown. If the groundwater node is disabled the simulation is less accurate especially after a periods of recovery or recession. A more realistic simulation using Modflow with the lake Module shows that the response and recovery time of the system after exploitation of the aquifer is tens of years.

The presence of good aquifers around the lake pose a problem since the water management is more complex; at the other hand they constitute an important opportunity as a buffer of water allowing a more rational management of the available resources.

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