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Hydrological analysis as a technical tool to support strategic and economic development: A case study of Lake Navaisha, Kenya

Yohannes Yihdego[1,2], Gebrehiwet Reta[2,3] & Robert Becht[2]

[1]Snowy Mountains Engineering Corporation (SMEC), Sydney, New South Wales 2060, Australia; [2]Geo-Information Science and Earth Observation (ITC), University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands; and [3]Bureau of Faculty of Water resources, Department of Water Resources, PO Box 520, Mekelle, Tigray, Ethiopia

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Correspondence
Yohannes Yihdego, Snowy Mountains Engineering Corporation (SMEC), Sydney, New South Wales 2060, Australia.
Email: yohannesyihdego@gmail.com

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Abstract

Effective integrated water resources management requires reliable estimation of an overall basin water budget and of hydrologic fluctuations between groundwater and surface-water resources. Seasonal variability of groundwater-surface water exchange fluxes impacts on the water balance. The long term lake water balance was calculated by Modflow using the stage-volume rating curve of Lake Package LAK3. The long term average storage volume change is 8.4×10^8 m^3/month. The lake water balances suggests that the lake is not in equilibrium with the inflow and outflow terms. Using field abstraction data analysis and model simulation, the combined volume of lake-groundwater used for industrial abstraction since the last three decades was estimated. This requires an average abstraction amount of 7.0×10^6 m^3/month with a long term trend of abstraction ratio 30% (groundwater) and 70% (lake water) since 1980. The amount resulted in a lake which might have been 4.8 m higher than was observed in the last stress period (2010).

A long term regional groundwater budget is calculated reflecting all water flow in to and out of the regional aquifer. The model water balance suggests that lake Navaisha basin is in equilibrium with a net outflow about 1% greater than the inflow over the calibrated period of time (1932–2010). The regional model is best used for broad-scale predictions and can be used to provide a general sense of groundwater to surface water and groundwater to groundwater impacts in the basin. A basin wide water resource management strategy can be designed by integrating the lake/wetland within the regional groundwater model to increase the level of sustainable production and good stewardship in Lake Navaisha. Such hydrological analysis is crucial in making the model serve as simulator of the response of lake stage to hydraulic stresses applied to the aquifer and variation in climatic condition.

Introduction

Lake Navaisha (Fig. 1) is considered as a highly significant national fresh water resource in Kenya. Its water is not only being utilized for domestic water supply and recreation but also sustains important economic activities such as flower and vegetable growing, tourism and fishing. Rapid industrial development and an increase in agricultural production like Lake Navaisha, have led to freshwater shortages in many parts of the world. Continued or increased withdrawals from Lake Navaisha and the surrounding aquifers have the potential to affect water levels in these aquifers. In view of increasing demand of water for agricultural, industrial and domestic consumptions, a greater emphasis on sustainability and optimal utilization of water, is required.

Lake Navaisha is the only freshwater resources among many saline lakes in the Kenyan rift valley. At this time the ever increasing demand of lake and groundwater water usage for irrigation and other activities is reflected by water

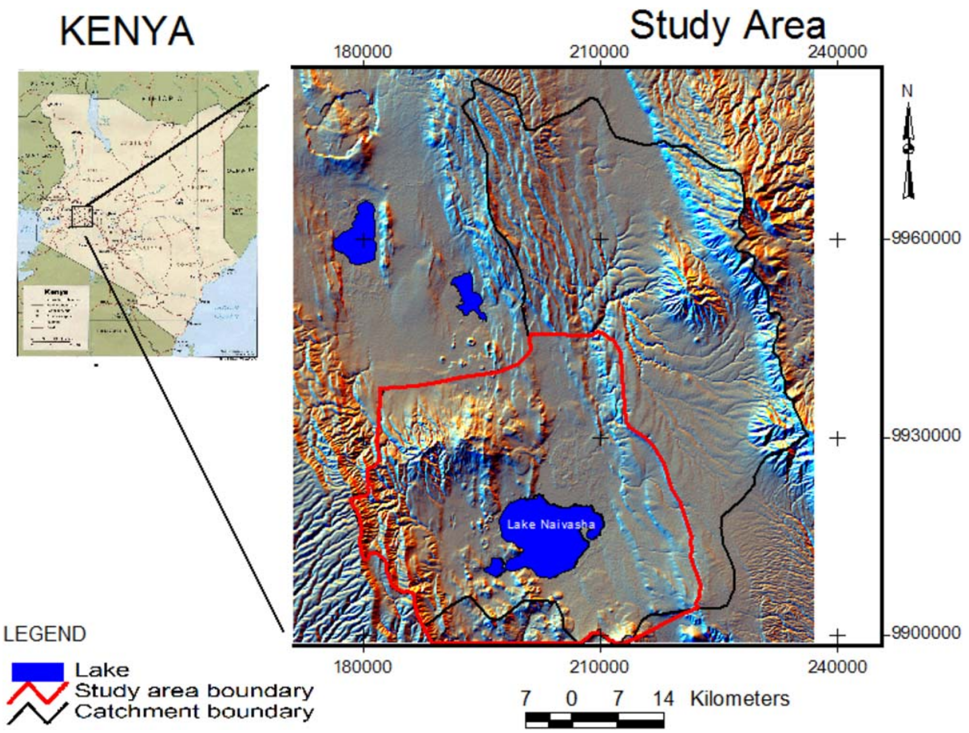

Fig. 1. Location map of the study area.

level decline and water quality deterioration in the study area (Odongo *et al*. 2015; van Oel *et al*. 2013). Most of the previous study attempts were to characterize the lake and the groundwater bodies as separate systems in the study area. The degree of interaction is less investigated; the surrounding aquifer and the lake Navaisha are believed to be in dynamic interaction (Odongo *et al*. 2015).

Sustainable development of water resources needs quantitative estimation of the available water resources (El-Kadi *et al*. 2014). Quantitative estimation is necessary to maintain the groundwater reservoir in a state of dynamic equilibrium over a period of time (Yihdego *et al*. 2016). Water balance studies have been extensively implemented to make quantitative estimates of water resources. Water balance also helps to evaluate quantitatively the contribution of individual sources of water in the system in time and space and studies the degree of variation in water regime because of changes in components of the system. Previous studies (e.g. Yustres *et al*. 2013) have addressed the extent to which a model's parameters should be adjusted in order to allow it to replicate past system behaviour as a precursor to its being used in management of future system behaviour and how complex it needs to be when used in this capacity. In this context, a model's purpose is to predict the behaviour of a system under a management regime (Yihdego *et al*. 2015b). Selection of an appropriate level of model complexity is most difficult where predictions required of a model are only partially constrained by historical data (Doherty & Simmons 2013; Turner *et al*. 2015).

The aim of this paper is to compute the long-term groundwater and lake water balance and to simulate of the lake-aquifer abstraction from the basin that could be utilized to evaluate the effects of changes in system flux, provide a technical basis for decisions on the quantity of water available and economic development activities on the area and provide insight for the high value Lake Navaisha management.

Site description

The study area is located in the Kenyan, Nakuru District, at about 100 km Northwest of Nairobi. It is located in the central rift valley of Kenya and covers an area of about 3500 km^2. Lake Navaisha dominates the central part of the Navaisha basin. It has a mean surface area of 145 km^2 at an average altitude of 1887 m (Yihdego & Becht 2013). There is an annual potential evaporation estimated at about 1700 mm (Ayenew & Becht 2008), monthly averaged potential evaporation on the floor of the basin exceeds rainfall by a factor of 2–8 for every month except April when the potential evaporation still exceeds rainfall for the wettest years.

The Lake is shallow with an average depth of 5 m. It has very flat bottom with major decrease in depth only close to the shores.

Geological and hydrogeological setting

The geology of the area is generally made of volcanic rocks and unconsolidated lacustrine deposits. In the basin are complex geological structures, which have been subjected

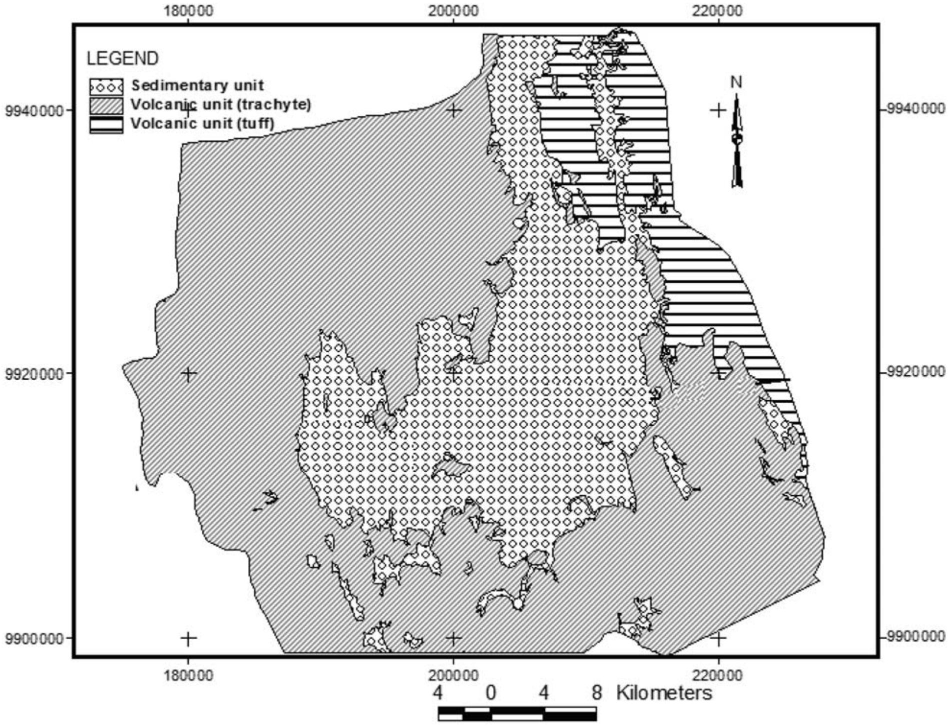

Fig. 2. Geological map of the study area (study area boundary is shown in Figure 1).

to several tectonic processes leading to varying structural features (Fig. 2). The volcanic rocks consist of a trachyte unit and a tuff unit (Yihdego & Becht 2013).

The Lake Navaisha catchment is hydrogeologically complex because of the rift valley geometry and tectonics (Becht & Harper 2002; Ayenew & Becht 2008; Yihdego & Becht 2013). The main aquifer is found in sediments covering parts of the rift floor. Groundwater is encountered at depths of 3–35 m below ground level in the sediment aquifer. Groundwater in the area is variable in quality both spatially and temporally, for reasons that are still unclear (Becht *et al*. 2006).

Groundwater level and flow system

Groundwater flow system pattern and direction was analysed on the basis of the available heads. The natural groundwater flow of the area was inferred from Piezometer heads measured before the abstraction stress on the local aquifer happened (roughly around 1980's). As indicated in Fig. 3 and Fig. 5, the groundwater flow has two flow patterns: lateral flow pattern and axial flow pattern. The Olkaria geothermal field (Fig. 3) is a high temperature geothermal resource which has been used for electric power generation since 1981.

The potentiometric surface has an uninterrupted fall from Lake Navaisha around the east side of Eburru towards Lake Elementeita, indicating flow in this direction (Fig. 3). The high hydraulic gradient accounts for the outflow of groundwater from the lake to the south as well as towards the north (Yihdego & Becht 2013).

Methodology

A Digital Elevation Model (DEM) was used to simulate the lake-aquifer abstraction. In Fig. 4, the DEM is directly compared with the measured elevation values and the correlation value was 0.89. Through successive calibration on the DEM and on the measured values, the final result with a correlation of 0.98. Fig. 4 was used as the surface elevation map for the model input. The lake bathymetry is an input parameter for the lake package in order to calculate the lake water balance of the model is shown in Fig. 4.

Model set up

The lake-groundwater interaction was modelled in three-dimension using GMS-MODFLOW 2000 (Harbaugh *et al*. 2000). The Groundwater Modelling System (GMS) is a complete graphical user environment for performing groundwater simulations. The entire GMS system consists of a graphical user interface (the GMS program) and a number of analysis codes like Modflow. GMS version 7 incorporates the lake package LAK3 which was utilized to estimate the water budget of the lake Navaisha. The modelled domain covers an area of 1817 km^2. The boundary conditions are simulated using the general head boundary package. The

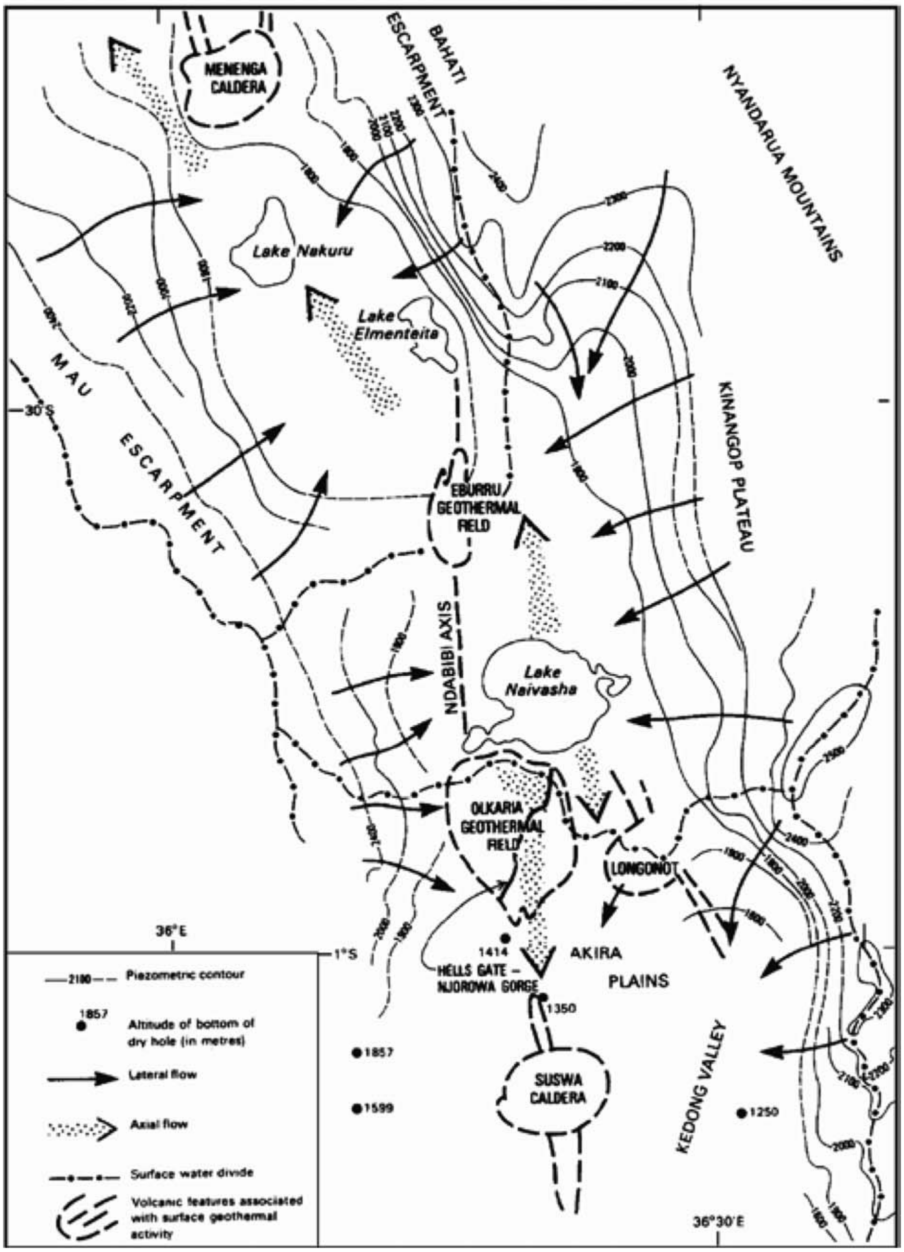

Fig. 3. Potentiometric map of Lake Navaisha and vicinities (after Yihdego & Becht 2013).

basic conceptual model assumes two non-coinciding aquifer systems. The upper aquifer is in hydraulic link with the lake. The lower aquifer is characterized by homogenous vertical and horizontal aquifer properties. The lower aquifer is also in hydraulic connection to the upper aquifer through a leakage terms (Yihdego & Becht 2013).

Representation of the lake

The current surface area of the lake is approximately 110–120 km^2. However the initial (historical lake surface area was about 181 km^2 (from historical data at the year 1932). Therefore, for model conceptualization purpose the lake surface area was set to the initial coverage as surveyed in 1957 by the Ministry of water Works (Kenya).

Modflow lake package (LAK3)

In the Lake Package described in this study, the lake is represented as a volume of space within the model grid which consists of inactive cells extending downward from the upper surface of the grid.

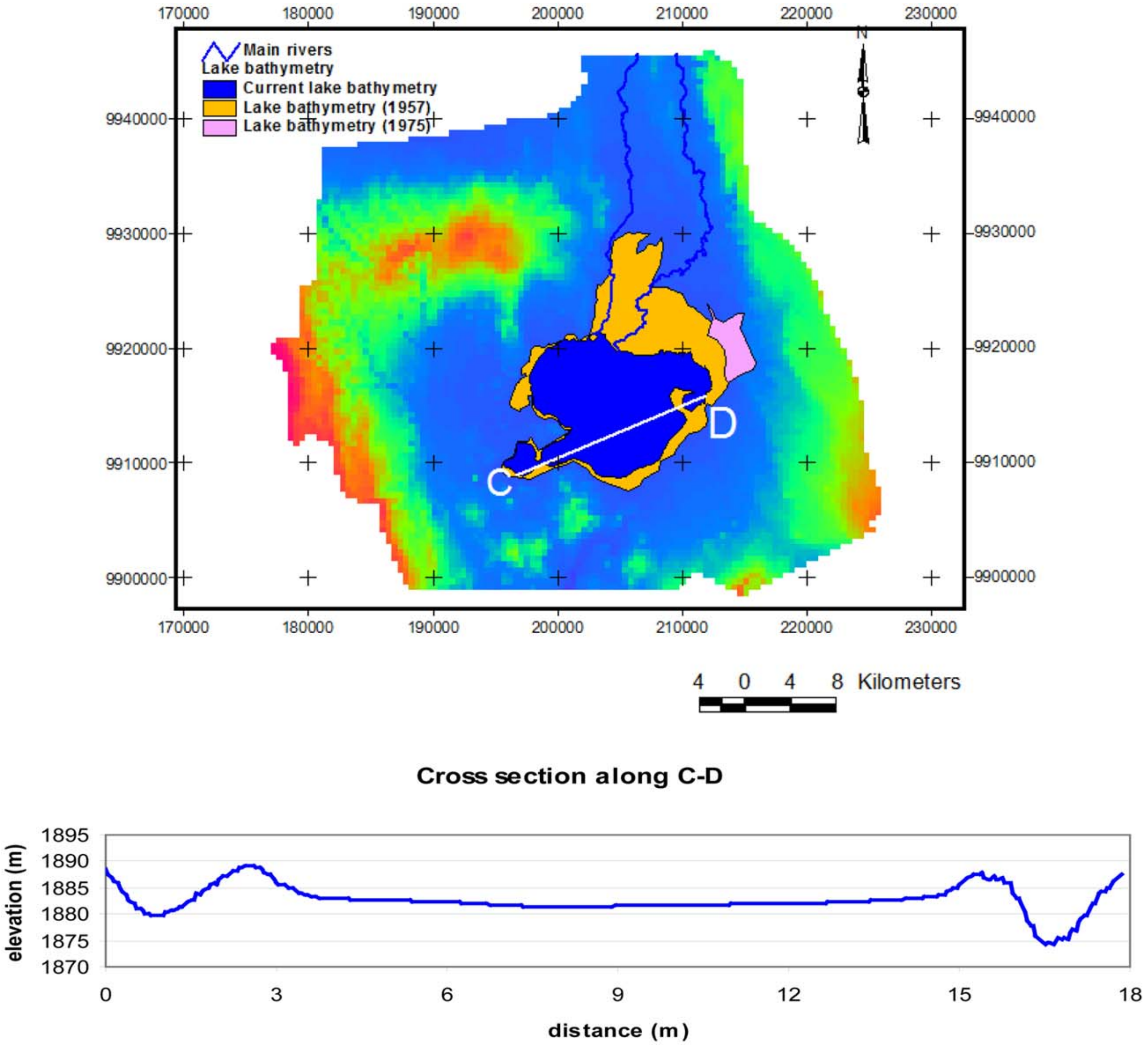

Fig. 4. Profile of Lake Navaisha WRAP (1998).

Seepage between lake and aquifer

The direction and magnitude of seepage between a lake and the adjacent aquifer system depends on the relation between the lake stage and the hydraulic head in the ground-water system, both of which can vary substantially in time and space (Fig. 5). Quantification of the rate of seepage between the lake and the aquifer is made by an application of Darcy's Law.

Lake water budget

The interaction between the lake and the surficial aquifer is represented in this Lake Package by updating at the end of each time step a water budget for the lake that is independent of the ground-water budget represented by the solution for heads in the aquifer.

Results and discussion

Long term lake storage

The lake storage was calculated by Modflow using the stage-volume rating curve of Lake Package LAK3. The stage-volume rating curve was generated using the DTM-derived Lake bathymetry within the limitations of the DTM. The lake storage volume imitates the temporal lake level fluctuations (Fig. 6), in which the abstraction of groundwater from the

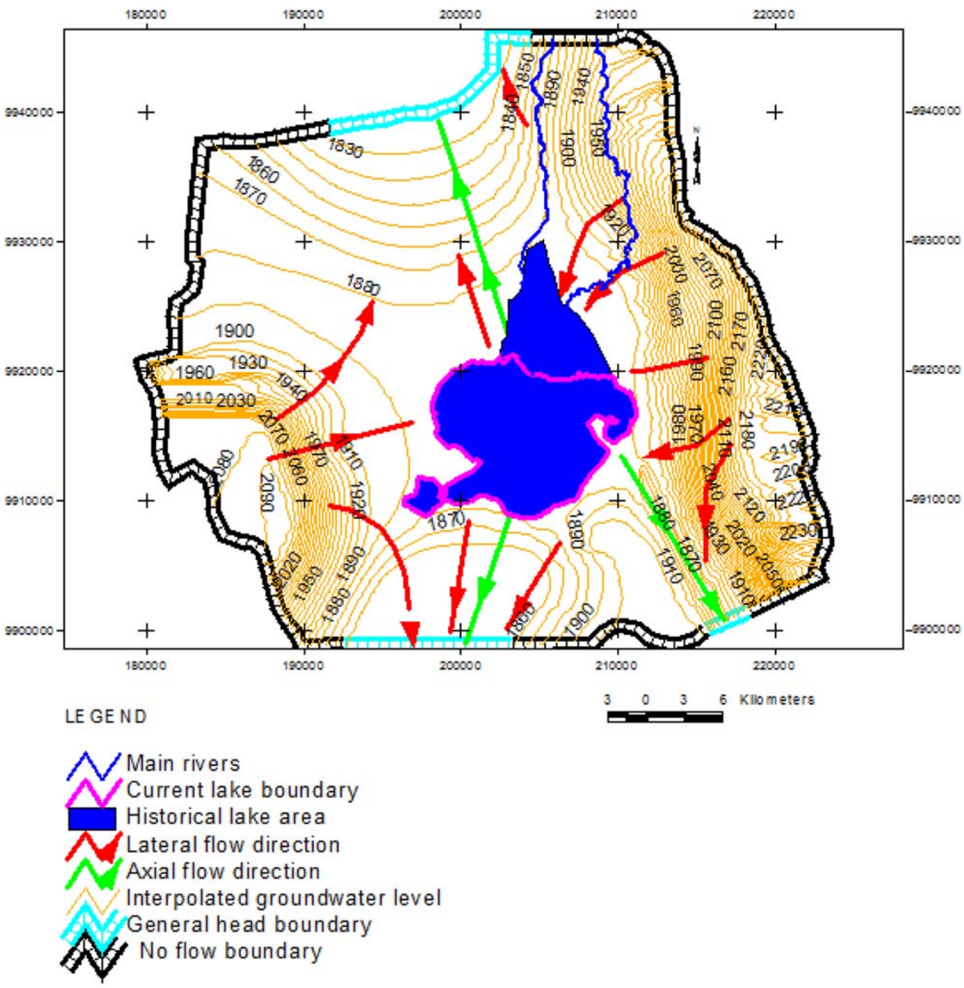

Fig. 5. Representations of boundary conditions and the lake surface area.

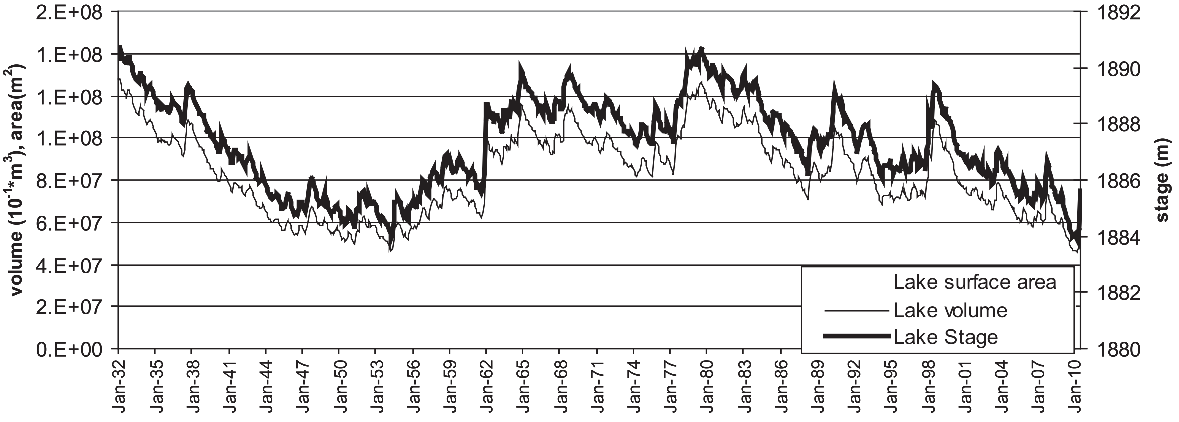

Fig. 6. Simulated lake storage volume-stage-surface area relationship (Reta 2011).

basin has likely caused the base line change. The average transient storage volume calculated is 8.4×10^8 m^3/month.

Long term aquifer-lake interaction

There is a temporal fluctuation of the total amount of water seeping in to and from the lake to the aquifer (Fig. 7). The long term lake seepage out (groundwater outflow from the lake) was calculated as 5.56×10^6 m^3/month equivalent to 66.7×10^6 m^3/year.

The lake levels are sustained during those periods when the total inflow (stream inflow, runoff and rainfall) exceeds the total outflow (lake seepage abstraction and

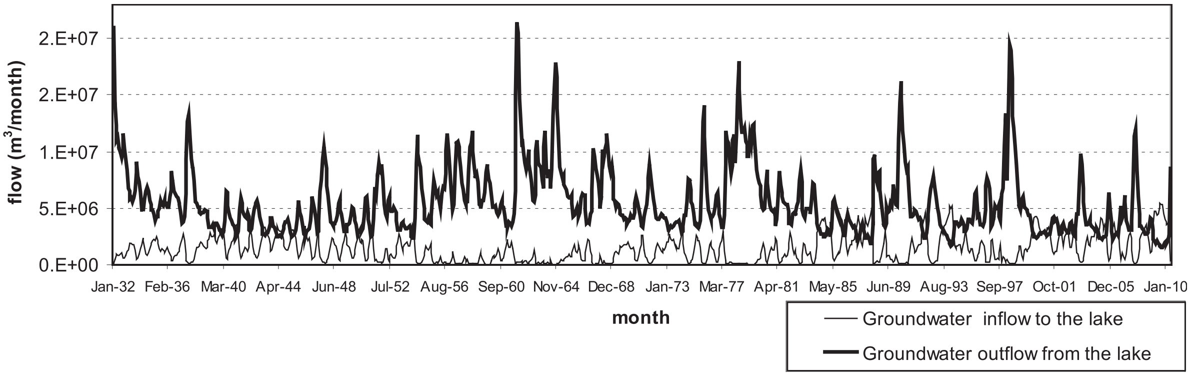

Fig. 7. Graph showing long term ground inflow and outflow from the lake (Reta 2011).

evapotranspiration). These periods are linked to consistent inflows into the lake possibly during the high rains after the dry spells. Similarly the long term lake seepage in (groundwater inflow in to the lake) was calculated as 1.1 × 10^6 m^3/month equivalent to 13 × 10^6 m^3/year.

The result is quite comparable to the result obtained by previous researchers (e.g. Becht & Harper 2002; Yihdego & Becht 2013). The relative increase in the current estimation indicates the increase of lake water outflow as a result of intense abstraction in the study area.

The long term lake water budget

The long-term (1932–2010) lake water balances obtained from the transient model is shown in the Table 1 below. The result indicates that the lake is in equilibrium with a long term average precipitation 7.72 × 10^6 m^3/month, evaporation 21.41 × 10^6 m^3/month, surface water inflow 19.36 × 10^6 m^3/month, lake water abstraction 1.92 × 10^6 m^3/month equivalent to 5.02 × 10^6 m^3/month, Lake seepage outflow 5.56 × 10^6 m^3/month and Lake seepage inflow 1.1 × 10^6 m^3/month. At the end of the simulation period the final status of the lake (stage, volume, and surface area) is calculated as stage 1885.5 m, volume 6 × 10^8 m^3 and surface area 1.04 × 10^2 km^2.

The long term groundwater and lake water budget

In geologically complex (Nelson & Mayo 2014; Yihdego & Webb 2015) and areas with permeable faulted zones (Ran *et al*. 2014; Yihdego *et al*. 2015a) areas, like the case of the Lake Navaisha, the assessment benefit from line of evidences as presented in this paper. Also, the results and recommendations about the groundwater-lake water interaction computation/analysis of water balance modelling (Becht *et al*. 2006; Ayenew & Becht 2008; Yihdego & Becht 2013) are incorporated in this study.

Table 1 Water budget for the Lake over the period 1932–2010

Flow components	Inflow (Mm^3/month)	Outflow (Mm^3/month)
Precipitation	7.722	0.000
Evaporation	0.000	21.414
Surface inflow	19.366	0.000
Lake water withdrawal	0.000	1.921
Groundwater inflow (Lake seepage in)	1.137	0.000
Groundwater outflow (Lake seepage out)	0.000	5.563
Total	28.225	28.898
In-Out		−0.673

Table 2 Groundwater budget for the entire model over the period (1932–2010)

Flow components	Inflow (Mm^3/month)	Outflow (Mm^3/month)
Storage	1.295	1.359
Head dependent boundaries	0.000	6.770
Wells	0.000	0.755
River leakage	0.141	0.020
Recharge	2.803	0.000
Lake seepage	5.563	1.137
Total	9.802	10.040
In-Out		−0.238
Percent of discrepancy		−0.013

A long term groundwater budget is prepared reflecting all water flow in to and out of the regional aquifer. Table 2 show the overall water budget of the study area. The inflow components include recharge 2.8 × 10^6 m^3/month, river leakage-in 1.4 × 10^5 m^3/month and Lake Seepage-in (groundwater outflow from the lake) 5.56 × 10^6 m^3/month. The outflow components include well abstraction 7.5 × 10^5 m^3/month (equivalent to 2 × 10^6 m^3/month over the past 30 years), river leakage-out 2 × 10^4 m^3/month, Lake Seepage-out (groundwater inflow in to the lake) 1.1 × 10^6 m^3/month and groundwater outflow through the head dependent boundaries 6.7 × 10^6 m^3/month.

The long term average river water inflow in to the groundwater is 1.4×10^5 m^3/month. The river water balance shows that the river water inflow in to the groundwater is 75% greater than groundwater inflow in to the river. This result indicates that the major rivers are dominantly loosing rivers and are recharging zones for the groundwater

Groundwater moves out of the model through the head dependent boundaries with a long term average rate 6.7×10^6 m^3/month.

The total long term average inflow in to the model is calculated as 9.8×10^6 m^3/month. Similarly, the total long term average outflow from the model is calculated as 1.0×10^7 m^3/month. The model water balance suggests that Lake Navaisha basin is in equilibrium with outflows about 1% greater than the inflows over the calibrated period of time (1932–2010). The discrepancy could be attributed partly to errors in the data measurement and estimation.

Discussion and conclusions

The interaction between the lake and the surficial aquifer in Modflow is represented in the Lake Package LAK3. By updating at the end of each time step, a water budget is calculated for the lake that is independent of the ground-water budget. The long term lake water balance was calculated by Modflow using the stage-volume rating curve of Lake Package LAK3. The long term average storage volume is 8.4×10^8 m^3/month. The long term average fluxes in to the lake are precipitation 7.72×10^6 m^3/month, surface inflow 19.36×10^6 m^3/month and groundwater inflow (Lake seepage in) 1.1×10^6 m^3/month. The long term average fluxes out of the lake: are evaporation 21.41×10^6 m^3/month, lake water abstraction 1.92×10^6 m^3/month and groundwater outflow (Lake seepage out) 5.5×10^6 m^3/month. The lake water balances suggests that the lake is not in equilibrium with the inflow and outflow terms.

There is a temporal lake-aquifer interaction in the study area. The long term lake seepage-out (groundwater outflow from the lake) was calculated as $5.5*10^6$ m^3/month and the long term lake seepage-in (groundwater inflow in to the lake) was calculated as $1.1*10^6$ m^3/month.

A long term groundwater budget is calculated reflecting all water flow in to and out of the regional aquifer. The inflow components include recharge 2.8×10^6 m^3/month, river leakage-in 1.4×10^5 m^3/month and Lake Seepage-in (groundwater outflow from the lake) 5.56×10^6 m^3/month. The outflow components include well abstraction 7.5×10^5 m^3/month (equivalent to 2×10^6 m^3/month over the past 30 years), river leakage-out 2×10^4 m^3/month, lake seepage-out (groundwater inflow in to the lake) 1.1×10^6 m^3/month and groundwater outflow through the head dependent boundaries 6.7×10^6 m^3/month. The regional model water balance suggests that Lake Navaisha basin is in equilibrium with a net outflow about 1% greater than the inflow over the calibrated period of time (1932–2010). The regional model is best used for broad-scale predictions and can be used to provide a general sense of groundwater to surface water and surface-water to groundwater impacts in the basin. Also, the model is best used for prediction of impacts to groundwater abstraction at a regional scale because of the uprising groundwater lake water usage in the basin.

A spreadsheet lake water balance model (Becht & Harper 2002; Yihdego & Webb 2012) was used for comparison of the lake water balance. The model water balance suggests that the basin is in equilibrium, with outflows greater than inflows over the simulated period (1932–2010). Comparison was made between the Modflow lake-package water balance result and a spreadsheet water balance model result. The spreadsheet water balance model cannot simulate abstraction stress directly applied on the aquifer. Apart from the abstraction information, there was no significant differences in the way the two models evaluate the stages from the given time step.

A basin wide water resource management strategy can be designed by integrating the regional groundwater model with other water evaluating software to increase level of sustainable production and good stewardship in Lake Navaisha.

Hydrological analysis is crucial to provide a technical basis for decisions on the quantity of water available and economic development activities on the Lake Navaisha area which is currently as the centre of industrial development, in order to quantify the linkages between the surface water and groundwater regime. This study presents a case study in enabling the hydrological analysis to address response of lake stage to hydraulic stresses applied to the aquifer and variation in climatic condition, desired by resources managers, specifically to high value RAMSAR wetlands (world class environmental assets), like Lake Navaisha, which supports economic activities including power generation, agriculture and tourism.

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References

Ayenew, T. and Becht, R. (2008) Comparative Assessment of the Water Balance and Hydrology of Selected Ethiopian and Kenyan rift lakes. *Lakes Reservoirs Res. Manage.*, **13** (1), 81–196.

Becht, R. and Harper, D. (2002) Towards an Understanding of Human Impact upon the Hydrology of Lake Naviasha, Kenya. *Hydrobiologia*, **488** (1/3), 1–12.

Becht, R. Mwango, F. and Muno, F.A. (2006) Groundwater Links Between Kenyan Rift Valley Lakes. *In*: Odada, E.O. et.al. (eds). *Proceedings of the 11th World Lakes Conference*, 31 October - 4 November 2005, Vol. II, pp. 7–14. Nairobi: Ministry of Water and Irrigation; International Lake Environment Committee (ILEC), Nairobi, Kenya.

Doherty, J. and Simmons, T.C. (2013) Conceptual Modelling in Decision Support; Reflections on a Unified Conceptual Framework. *Hydrogeol. J.*, **21**, 1531–1537.

El-Kadi, A.I., Tillery, S., Whittier, R.B., Hagedorn, B., Mair, A., Ha, K. and Koh, G. (2014) Assessing Sustainability of Groundwater Resources on Jeju Island, South Korea, Under Climate Change, Drought, and Increased Usage. *Hydrogeol. J.*, **22**(3): 625–642.

Harbaugh, A.W., Banta, E.R., Hill, M.C. and McDonald, M.G. (2000) *MODFLOW-2000, the U.S. geological survey modular ground-water model – User guide to modularization concepts and the ground-water flow process*. U.S. Geological Survey Open-File Report 00-92, p. 121.

Nelson, S.T. and Mayo, A.L. (2014) The Role of Interbasin Groundwater Transfers in Geologically Complex Terranes, Demonstrated by the Great Basin in the Western United States. *Hydrogeol. J.*, **22**, 807–828.

Odongo, V.O., Mulatu, D.W., Muthoni, F.K., van Oel, P.R., Meins, F.M., van der Tol, C., Skidmore, A.K., Groen, T.A., Becht, R., Onyando, J.O., van der Veen, A. (2014) Coupling Socio - Economic Factors and Eco - Hydrological Processes Using a Cascade - Modeling Approach. *J. hydrol.*, **518**, 49–59.

Odongo, V.O., van der Tol, C., van Oel, P.R., Meins, F.M., Becht, R., Onyando, J.O., Su, Z. (2015) Characterisation of Hydroclimatological Trends and Variability in the Lake Naivasha Basin, Kenya. *Hydrol. Processes*, **29**, 3276–3293.

Ran, G., Eyal, S., Yoseph, Y., Amir, S. and Noam, W. (2014) The Permeability of Fault Zones: A Case Study of the Dead Sea Rift (Middle East). *Hydrogeol. J.*, **22**, 425–440.

Reta, G.L. (2011) Groundwater and Lake Water Balance of Lake Naviasha Using 3-D Transient Groundwater Model. Unpublished MSc thesis, ITC, University of Twente, Enschede, The Netherlands.

Turner, R.J., Mansour, M.M., Dearden, R., Ó Dochartaigh, B.É. and Hughes, A.G. (2015) Improved Understanding of Groundwater Flow in Complex Superficial Deposits Using Three-Dimensional Geological-Framework and Groundwater Models: An Example From Glasgow, Scotland (UK). *Hydrogeol. J.*, **23**, 493–506.

van Oel, P.R., Mulatu, D.W., Odongo, V.O., Meins, F.M., Hogeboom, R.J., Becht, R., Stein, A., Onyando, J.O. and van der Veen, A. (2013) The Effects of Groundwater and Surface Water Use on Total Water Availability and Implications for Water Management: The Case of Lake Naviasha, Kenya. *Water Resourc. Manage.*, **27**, 3477–3492.

Yihdego, Y. and Becht, R. (2013) Simulation of Lake–Aquifer Interaction at Lake Naviasha, Kenya Using a Three-Dimensional Flow Model With the High Conductivity Technique and a DEM With Bathymetry. *J Hydrol.* **503**, 111–122.

Yihdego, Y., Webb, J.A. (2012) Modelling of Seasonal and Long-Term Trends in Lake Salinity in South-western Victoria, Australia. *J Environ Manage.*, **112**, 149–159.

Yihdego, Y. and Webb, J.A. (2015) Use of a Conceptual Hydrogeological Model and a Time Variant Water Budget Analysis to Determine Controls on Salinity in Lake Burrumbeet in Southeast Australia. *Environ. Earth Sci. J.*, **73** (4), 1587–1600.

Yihdego, Y., Webb, J.A. and Leahy, P. (2016) Modelling of Lake Level and Salinity for Lake Purrumbete in Western Victoria, Australia. *Hydrol. Sci. J.*, **6** (1), 186–199. http://dx.doi.org/10.1080/02626667.2014.975132

Yihdego, Y., Danis. C. and Paffard, A. (2015a) 3-D Numerical Groundwater Flow Simulation for Geological Discontinuities in the Unkheltseg Basin, Mongolia. *Environ. Earth Sci. J.* **73** (8), 4119–4133.

Yihdego, Y., Webb, J.A. and Leahy, P. (2015b) Modelling of Lake Level Under Climate Change Conditions: Lake Purrumbete in South Eastern Australia. *Environ. Earth Sci. J.*, **73**, 3855–3872.

Yustres, A., Navarro, V., Asensio, L., Candel, M. and García, B. (2013) Groundwater Resources in the Upper Guadiana (Spain): A Regional Modelling Analysis. *Hydrogeol. J.* **21**, 1129–1146.