The Effects of Groundwater and Surface Water Use on Total Water Availability and Implications for Water Management: The Case of Lake Naivasha, Kenya

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Abstract This study discusses the effects of water abstractions from two alternative sources on the available water volume around Lake Naivasha, Kenya: the lake itself and a connected aquifer. An estimation of the water abstraction pattern for the period 1999–2010 is made and its effect on the available water volume in Lake Naivasha and its connected aquifer is evaluated using a simple water balance modeling approach. This study shows that accurate estimates of annual volume changes of Lake Naivasha can be made using a simple monthly water balance approach that takes into account the exchange of water between the lake and its connected aquifer. The amount of water that is used for irrigation in the area around Lake Naivasha has a substantial adverse effect on the availability of water. Simulation results of our simple water balance model suggests that abstractions from groundwater affect the lake volume less than direct abstractions from the lake. Groundwater volumes, in contrast, are much more affected by groundwater abstractions and therefore lead to much lower groundwater levels. Moreover, when groundwater is used instead of surface water, evaporation losses from the lake are potentially higher due to a larger lake surface area. If that would be the case then the overall water availability in the area is more strongly affected by the abstraction of groundwater than by the abstraction of surface water. Therefore water managers should be cautious when using lake levels as the only indicator of water availability for restricting water abstractions.

Keywords Lake Naivasha · Water balance model · Water use · Irrigation · Groundwater

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1 Introduction

Water scarcity occurs when water demand exceeds water availability and varies in space and time due to a combination of natural processes and human actions. Socioeconomic developments depend on the stable availability of freshwater resources from local water systems. At the same time these socioeconomic developments could lead to reduced water availability through overexploitation. At the global scale, the impact of groundwater and surface water abstractions on water availability variations is largely unknown, partly due to a lack of data on the amounts of abstracted water for irrigation (Döll et al. 2012). For many semiarid basins in developing countries rapid population growth and related increases in water demand add to risks of water scarcity (Millennium Ecosystem Assessment 2005). A desire to commit to increasing water demands due to socioeconomic developments in many cases resulted in river basin closure (van Oel et al. 2011; Molle et al. 2010). For water systems facing increasing water demands the interconnectedness of the water cycle, aquatic ecosystems, and water users also increases. In case of temporal water deficiencies due to climatic variations aquifers could serve as a reliable source of freshwater. Currently, the use of groundwater (for irrigation) increases both in absolute terms and relative to surface water abstractions (Siebert et al. 2010). In literature on the impact of water use on water availability mostly no distinction is made regarding the source of water. This is not surprising since, at least for the global scale, no estimates are available that differentiate between withdrawals from groundwater and surface water (Döll et al. 2012). Because it is very difficult to determine the source of water use from the available statistics sometimes the assumption is made that all withdrawals are from surface water, such as for WaterGAP (Alcamo et al. 2003). In other cases no distinction is made at all, as is usually done in water footprint studies (e.g. Hoekstra et al. 2012; van Oel and Hoekstra 2012) that refer to the combined body of groundwater and surface water as 'blue water'.

It is known that local efforts aiming at increasing water-use efficiency could result in spatially and temporally 'redistributing' water availability rather than increasing basin level water-use efficiency (e.g. Venot 2009; van Oel et al. 2012). In order to enable decision-makers to make informed decisions on the types of water abstraction to promote or discourage, it is important to evaluate the net impact of water abstractions from different sources. Therefore, improved insight is required into the direct and long-term effects of the distinct contributions of groundwater and surface water abstractions on total water availability. Obviously this kind of knowledge is case specific. In this study the effects of groundwater abstractions and surface water abstractions on the water balance of the area around Lake Naivasha (Kenya) are explored.

1.1 The Lake Naivasha Basin

Like most African Rift Valley water systems, Lake Naivasha (Fig. 1) is an endorheic lake system vulnerable to outside perturbations such as the introduction of alien species, physical-chemical degradation and overexploitation of water resources for human use (e.g. Harper et al. 1990). The runoff generated in the Lake Naivasha basin feeds a connected aquifer and a lake ecosystem attracting worldwide attention because of its diversity in wildlife and Ramsar status (Ramsar 2012). Among the socio-economic developments in the area recent investments in the irrigated horticulture sector are notable. These developments have stimulated the local economy and have led to increased population growth in
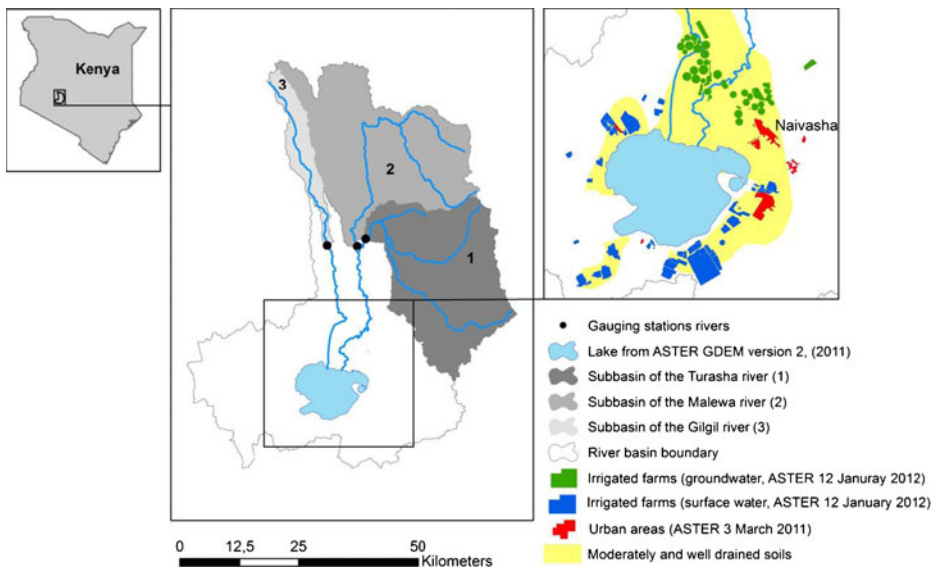
Fig. 1 Lake Naivasha basin and its main rivers and tributaries; three gauged subbasins used for estimating Q_{inflow}, and the locations of abstraction sites from the two alternative sources for water abstraction: the lake aquifer and the lake. Irrigated farms and urban areas are based on a land cover classification of ASTER images for 13 March 2011 and 12 January 2012

response to increasing employment opportunities. Population growth and investments in irrigation have substantially increased water demand. (e.g. Otiang'a-Owiti and Oswe 2007; Becht et al. 2005; Harper and Mavuti 2004).

Whereas it is well-known that for effective water management and governance at all levels of organization accurate data are a prerequisite (García 2008; McDonnell 2008) for the Lake Naivasha basin there is no effective collection and analysis of data to support the management process (Becht et al. 2005). The Water Resources Management Authority (WRMA) suffers from the unavailability of data on meteorological parameters, hydrological parameters and water abstractions. Even though, authorities apply abstraction restriction rules. The rules for both surface and groundwater are based on the well-monitored lake levels (WRMA 2010).

Among the literature on the present-day hydrology of the Lake Naivasha basin studies by McCann (1974) Gaudet and Melack (1981), Åse et al. (1986) and Becht and Harper (2002) are most comprehensive. These studies have focussed on the water-budget of the lake rather than on the entire Lake Naivasha basin (Table 1). There are both subsurface water flows directed towards the lake and away from the lake (McCann 1974; Ojiambo et al. 2001). Estimates of net annual groundwater outflow from the lake range between $18*10^6$ m^3 year^{-1} and $50*10^6$ m^3 year^{-1} (Åse et al. 1986; Clarke et al. 1990; Ojiambo and Lyons 1996; McCann 1974; Becht and Harper 2002).

Literature on the effect of water abstractions for irrigation on lake volumes and levels does exist (Becht and Harper 2002; Mekonnen et al. 2012). However, the exact magnitude of the effects is uncertain and no distinction has been made between the influence of water abstractions from groundwater and lake surface water. Obviously this omission of knowledge hampers the effective operational and long-term water resources management and governance. In this study the effects of groundwater and surface water (i.e. from the lake)

Table 1 Estimates of the 'natural' annual water budget for Lake Naivasha. This table shows estimates for the period before large-scale water abstractions commenced to impact

	McCann (1974)	Gaudet and Melack (1981)	Åse et al. (1986)	Becht and Harper (2002)	This study	
Hydrologic budget item	various sources and years	1973–1975 avg (including Oloiden)	1972–1974[a]	1978–1980	1932–1981	1965–1979
Total inflow (10^6 m^3 year^{-1})	**380**	**337**	**279**	**375**	**311**	**353**
Precipitation	132	103	106	135	94	123
River Discharge	248	234[b]	148	215	217	230
Total outflow (10^6 m^3 year^{-1})	**380**	**368**	**351**	**341**	**312**	**362**
Evaporation from lake, (including swamp)	346	312	284	288	256	328
Groundwater outflow (including abstractions)	34	56	67[c]	53[c]	56[c]	34
Assumptions						
Precipitation (mm year^{-1})	650	683	575	709	648	695
Evaporation (mm year^{-1})	1700	1989	1542	1504	1788	1788

[a] For this study the numbers from the water level changes (in mm) to actual volumes have been recalculated, using the height-area relation presented by Åse et al. (1986, Figure 2.7). Two errors made in summations by Åse et al. (1986), Table 4.3 have been corrected. These are the values for July 1973 and April 1974

[b] Including 'seepage in' from the northern section of the lake

[c] Derived from the difference between the observed lake volume changes and the calculated volume changes as reported by Åse et al. (1986) and Becht and Harper (2002) respectively

abstractions are quantified for the period 1999–2010 by using a simple water balance modeling approach.

2 Method

The method applied consists of four steps that are described below.

Step 1.   Estimation water abstraction for the period 1999–2010.

The estimates are based on population census data, livestock census data, irrigated area estimates and a water abstraction survey. Four editions of the Population and Housing Census (KNBS 1979, 1989, 1999, 2009) have been used to estimate the development of the population. Assuming that the census data represent the population in the month of January, monthly population estimates are based on linear interpolation. Estimations of livestock water abstraction are based on livestock numbers from the International Livestock Research Institute (ILRI 1998). It is assumed that these numbers follow a similar trend as those for the human population statistics. Estimates for the monthly abstraction for irrigation rates are based on the estimates of the area under irrigation and the average irrigation depth. The irrigated area is based on a visual classification of the following images: LANDSAT TM: 21 January 1995; ASTER: 8 March 2003, 19 January 2009 and 12 January 2012 and

the results of the abstraction survey carried out by WRMA in 2010 (De Jong 2011) and interpolated to a monthly time step. For irrigation depth measured actual evapotranspiration (Mpusia 2006) and data from local organizations (FBP 2012; LNGG 2005) have been used. Actual average evapotranspiration was determined to be 3.5 mm day^{-1} for the irrigation of flowers inside greenhouses and 5.4 mm day^{-1} for outdoor irrigation. When taking into account annual average rainfall (695 mm year^{-1}) the additional crop water requirement is around 3.5 mm day^{-1} (net) as well. The amount of 3.5 mm day^{-1} is well below the daily applied amount of irrigation of around 5.0 mm day^{-1} as reported in a report of monthly abstractions from the Lake Naivasha Growers Group (Musota 2008; LNGG 2005) and 4.9 mm day^{-1} as reported in a report of monthly abstractions from the Flower Business Park (FBP 2012). For this study it has been assumed that all of the excess irrigation depth (above 3.5 mm day^{-1}) is return flow to its source. Therefore the consumptive use assumed throughout this study is 3.5 mm day^{-1} for all types of irrigation. In Fig. 1 the locations of irrigated farms and urban areas are indicated. These locations are associated with water abstractions from groundwater and the surface water (the lake).

Step 2.   Model calibration for 'natural conditions' for the period 1965–1979

The water balance of the lake is determined on a monthly basis using a simple water balance equation including groundwater. Following Becht and Harper (2002) the model uses a monthly time step, and is expressed as follows:

$$\frac{\Delta V}{\Delta t} = P^t - E^t + Q^t_{inflow} - Q^t_{aq} - Q^t_{abs\_lake} \; [\mathrm{m^3 month^{-1}}] \qquad (1)$$

where P is rainfall on the lake surface, E is evaporation from the lake surface, Q_{inflow} is surface water inflow, Q_{aq} is outflow to a groundwater aquifer linked to the lake and Q_{abs_lake} is the water that is abstracted from the lake directly. Q_{inflow} is derived as follows:

$$Q^t_{inflow} = \sum_{i=1}^{n} inflow^t_i \; [\mathrm{m^3 month^{-1}}] \qquad (2)$$

where $inflow_i$ refers to the runoff from n subbasins i. Q_{aq} is derived as follows:

$$Q^t_{aq} = C \times \left(H^{t-1}_{lake} - H^{t-1}_{aq} \right) \; [\mathrm{m^3 month^{-1}}] \qquad (3)$$

where C is the hydraulic conductance of the aquifer (m^2 month^{-1}), H_{lake} is the lake water level (m) and H_{aq} is the aquifer water level. The water level in the aquifer is updated using the calculated in/outflow:

$$H^t_{aq} = H^{t-1}_{aq} + \left(\frac{Q^t_{aq} - Q_{outflow} - Q^t_{abs\_aq}}{A \times S_y} \right) \; [\mathrm{m}] \qquad (4)$$

where and $Q_{outflow}$ is a constant outflow to an external area and A is the surface area of the aquifer, S_y is the specific yield of the aquifer and Q_{abs_aq} is the water abstracted from the aquifer. Calibration is performed on the parameter for hydraulic conductance of the aquifer C. In this study it has been assumed that recharge of the aquifer from rainfall through deep percolation is constant. In our simple model this term is considered to be incorporated in our estimate of $Q_{outflow}$ which should therefore be regarded as net-outflow.

A lake-area-volume relationship is used for the water balance of the lake (Åse et al. 1986). This relationship is based on a bathymetric survey conducted in 1983 (Åse et al. 1986).

A series of discharge readings from the Water Resources Management Authority (WRMA) has been used to quantify the inflow into the lake. The sum of discharges derived from readings at three river gauging stations has been used to estimate the inflow into the lake. These three stations are located at the outlets of three subbasins: the Turasha (1), the Malewa (2), and the Gilgil (3) subbasins (Fig. 1). These three stations have reasonable data coverage:

- Turasha (1): 80 % coverage of daily readings for the period 1965–1979 and 91 % coverage for the period 1999–2010
- the Malewa (2): 33 % coverage of daily readings for the period 1965–1979 and 99 % coverage for the period 1999–2010
- the Gilgil (3): 89 % coverage of daily readings for the period 1965–1979 and 92 % coverage for the period 1999–2010.

For filling the gaps for these stations linear interpolation has been used for gaps of 6 days and shorter. For the larger data gaps a more sophisticated method (Hughes and Smakhtin 1996) has been applied taking into account stream flow data from other stations and the relationship between the occurrence of flows based on the flow duration curves of these stations. The flow duration curves of all stations taken into consideration have been based on all data available at these stations during the period 1960–2010. Rating curves used for translating the river water levels into discharges ($m^3 s^{-1}$) are based on discharge measurements performed by the Water Resources Management Authority (WRMA) and the Ministry of Water for the period 1958–2010.

Precipitation data is taken from a station at the Naivasha District Office (close to the Lake, code 9036002) close to the town of Naivasha (Fig. 1) obtained from the Water Resources Management Authority (WRMA) in 2012. For evaporation annual averages for monthly values from the Kenya Ministry of Water Development (MOWD 1982) have been used.

Constant groundwater outflow has been set at $2.8*10^6$ m^3 month^{-1} consistent with estimates from literature (Gaudet and Melack 1981; McCann 1974). In the 'natural' situation the groundwater level was estimated to be around 1 m below lake levels (interpreted from Gaudet and Melack (1981)). Using this information the Conductance C was set to $2.8*10^6$ m^2 month^{-1} to achieve an average aquifer level of around 1 m below lake level for the 'natural' period 1965–1979 using a Generalized Reduced Gradient algorithm (Fylstra et al. 1998). For this reason the initial groundwater level has been set 1 m below lake level for both the 'natural' and the recent period. Recent groundwater measurements in the Naivasha area indicate a serious decline in groundwater levels (Reta 2011). The area of the aquifer (A) was estimated at 100 km^2 and specific yield (Sy) was estimated at 0.2. Both estimates for A and Sy are based on the soil survey of Kenya (Sombroek and Braun 1982).

Step 3.   Model Validation

For the validation of the simple water balance model proposed in this study, predictions on both monthly and annual lake volume changes are compared to observed volume changes. Therefore a series of lake level data (LNRA 2012; MOWD 1982) was used in combination with a level-area-volume relationship from Åse et al. (1986). Comparison

between simulated and observed values is done using Nash-Sutcliffe Efficiency (1970). For the annual volume changes all monthly values have been taken into account using annual intervals (i.e. the interval between January of year t and January of year t+1, the interval between February of year t and February of year t+1, etc.).

Step 4.   Exploring the effect of water abstraction on water availability

Water abstractions from the lake are accounted for in Eq. 1 (Q_{abs_lake}) and water abstractions from the lake aquifer are accounted for through Eq. 4, where Q_{abs_aq} is the water abstracted from the aquifer. To analyze the effect of water abstraction on the availability of water resources alarm levels from the Water Resources Management Authority (WRMA 2010) are taken into account. Restrictions to water abstraction are imposed when lake levels drop below a level of 1885.30 m a.m.s.l. (lake volume according to Åse et al. (1986): $401*10^6$ m^3), corresponding to a situation of water stress. When the lake level drops below 1884.50 m a.m.s.l. (lake volume according to Åse et al. (1986): $312*10^6$ m^3), a situation of water scarcity occurs. In case of water scarcity 'severe abstraction restrictions' are to be imposed (WRMA 2010).

3 Results

3.1 Water Abstractions in the Period 1999–2010

Estimates for domestic consumption are based on Population and Housing Census data (KNBS 1979, 1989, 1999, 2009) on the administrative location level. Population growth around the lake shows an annual average increase that is higher than for the upstream locations over the entire period 1979–2009. The share of the river basin population living in the area directly around the lake increased from 29 % (in 1979) to 46 % (in 2009). The values for 1965 are estimated based on the trend during the period between the population census of 1979 and 1989. Per capita municipal water withdrawal in Kenya is estimated to be 12.5 m^3 $year^{-1}$ (~34 l day^{-1}) for the period 2003–2007 (AQUASTAT 2012). This value has been assumed to apply the for the entire study period.

Estimates for livestock numbers are derived from the International Livestock Research Institute (ILRI 1998). Livestock water use is 9.1 m^3 $year^{-1}$ for traditional breeds (King 1983) and up to ~25 m^3 $year^{-1}$ for dairy cattle (Chapagain and Hoekstra 2003). It is assumed that 15 m^3 $year^{-1}$ is used on average.

Results for the irrigation estimation are presented in Fig. 2. This figure also shows the results from the Water Abstraction Survey (WAS) conducted in 2010 (De Jong 2011). The WAS 2010 is most probably an underestimation and is subject to many uncertainties as recognized in the Water Allocation Plan (WRMA 2010). In the report on the Water Abstraction Survey 2010 (De Jong 2011) it is explained why the estimates of groundwater abstraction estimates are probably too high whereas the surface water abstraction estimates are probably too low. The survey was conducted during a time when lake levels were extremely low (2009) and many abstractors did not have access to the lake anymore. For the period 1999–2010 water abstraction for irrigation (94 %) dominates water abstraction for domestic (4 %) and livestock (2 %) purposes .
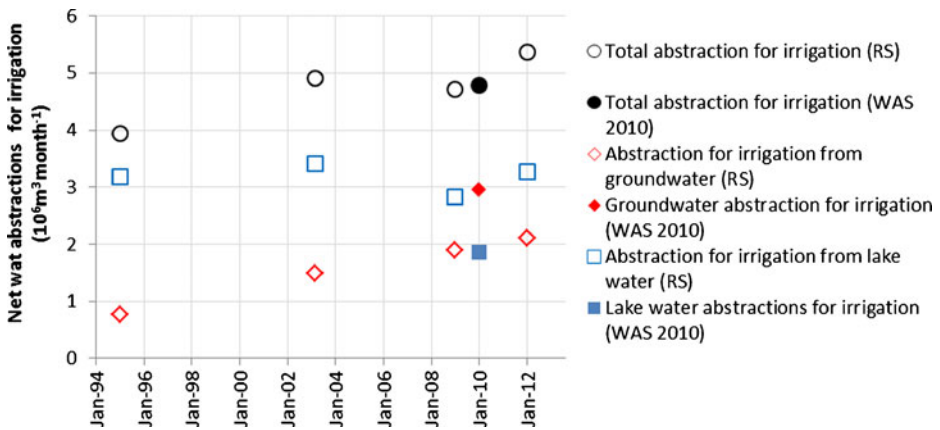
Fig. 2 Estimates of water abstraction for irrigation from visual interpreation of remotely sensed (RS) data. Images of the lake area for the following dates has been used: LANDSAT TM: 21 Jan 1995; ASTER: 8 March 2003, 19 Jan 2009 and 12 Jan 2012. In addition data from the Water Abstraction Survey 2010 (De Jong 2011) have been shown to indicate that the order of magnitude is very close to the estimates of that survey

3.2 Model Simulation Results

Model results for the natural period (January 1965—December 1979) and the recent period (January 1999—December 2010) are presented in Fig. 3. In this figure both observed and simulated lake levels are shown for the natural situation (S1) and the recent situation (S2). The simulated monthly lake levels over the two periods studied reasonably follow the observed lake levels. For the aquifer levels only simulated levels are shown since no reliable observations are available that represent the temporal fluctuations of the spatially varying profile over the entire aquifer. For the recent period (S2) the aquifer level is considerably lower than for the natural period (S1). This is explained by the groundwater abstractions that are accounted for in the recent period.

Model performance of the simple Lake Naivasha water balance model is measured based on volume changes (Fig. 4). Both monthly volume changes and annual volume changes have been analyzed. For the natural period (S1) the Nash-Sutcliffe Efficiencies (NSE) are 0.36 for monthly volume changes (156 observations) and 0.89 for annual volume changes (135 observations). For the recent period (S2) the Nash-Sutcliffe Efficiencies are 0.45 for monthly volume changes (141 observations) and 0.95 for annual volume changes (128 observations). The considerable difference between performance with regard to monthly volume changes and annual volume changes was not unexpected. As the model applies a monthly time-step, the difference in model performance is likely to be influenced by inaccuracies caused by in the temporal resolution of the input data-series used. Another factor that may influence the NSE is the fact that for annual intervals volume changes are generally larger.

3.3 The Influence of Water Abstractions from Surface Water and Groundwater on Lake Levels

The influence of abstraction on the water level of Lake Naivasha is substantial. In Fig. 5 the results of the simulation model with 'natural conditions' (S1, now for period January 1999—December 2010) and the simulation model including abstractions'(S2) are shown. It has been found
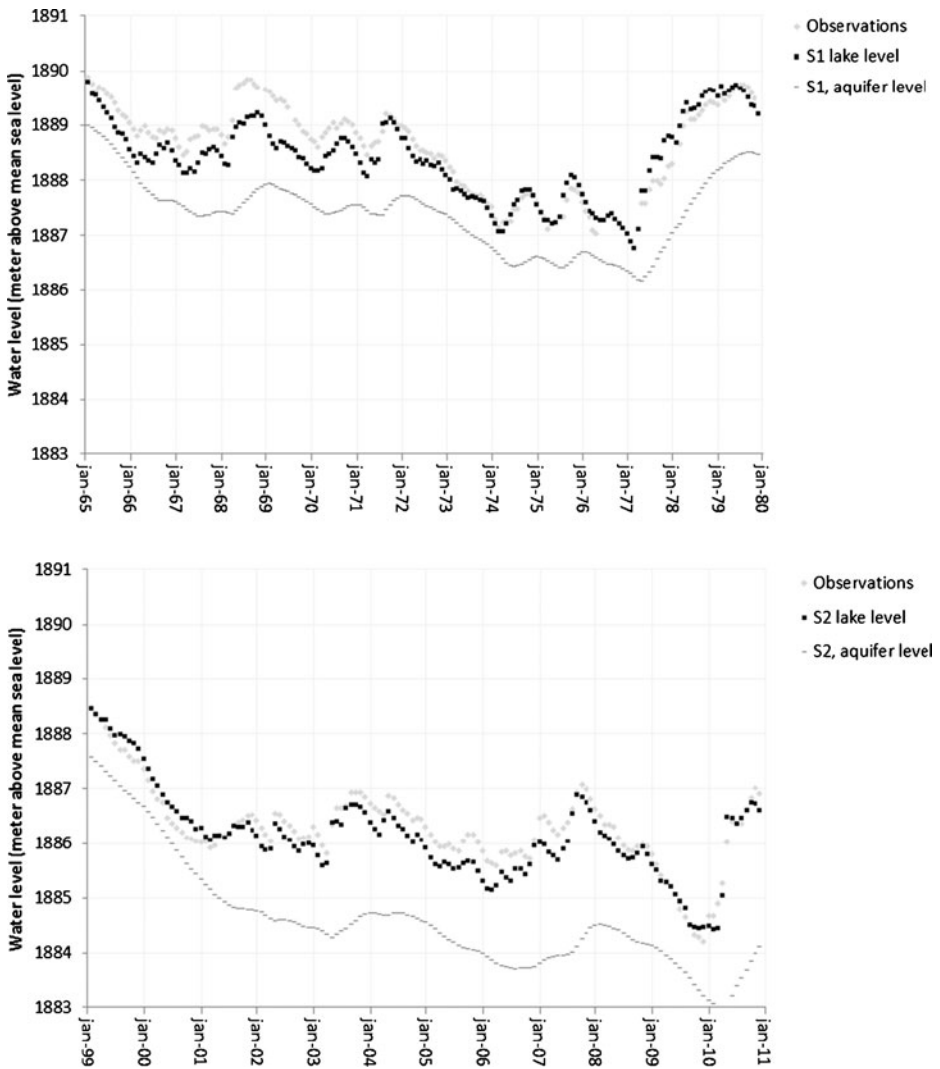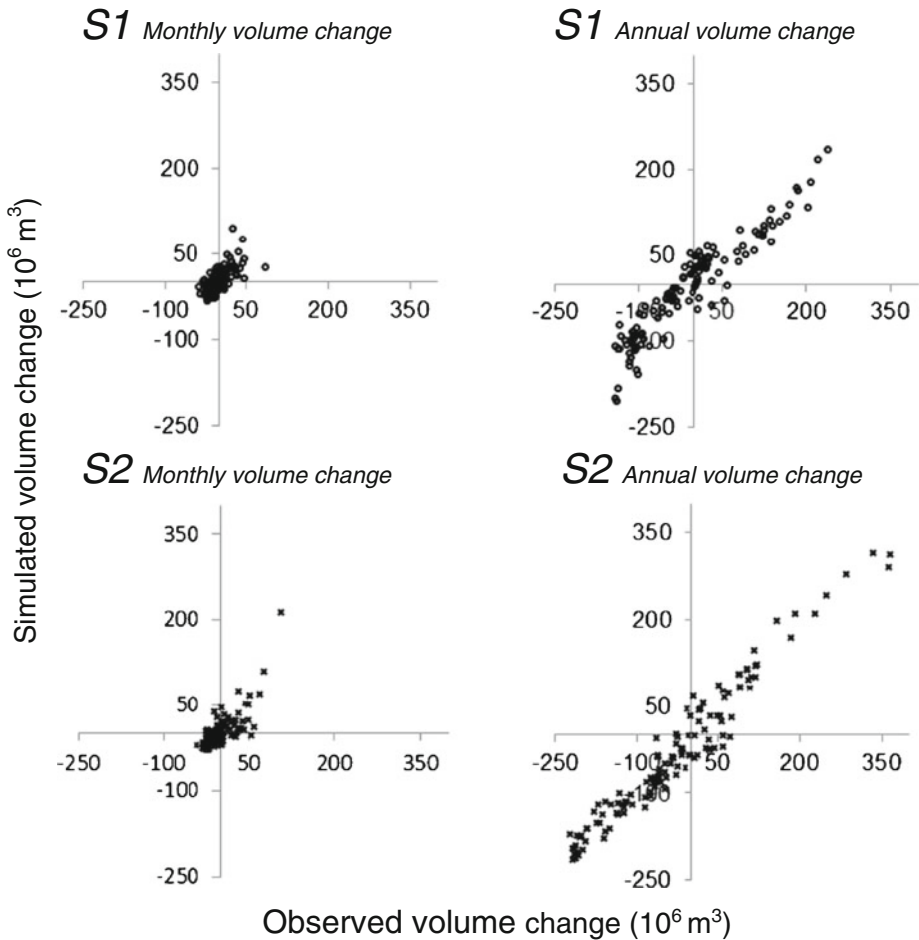
Fig. 3 *top*: Observed lake levels (MOWD 1982) and simulated (S1) lake and aquifer levels for the period January 1965—Dec 1979; *bottom*: Observed lake levels (LNRA 2012) and simulated (S2) lake and aquifer levels for the period January 1999—December 2010

that the difference between the two simulations amounts to more than 2 m in less than 10 years. In terms of volume available for abstraction the difference is even much more substantial. During a period in 2009, the lake levels (and corresponding volumes) dropped below the water stress alarm level and even below the water scarcity alarm level (Fig. 5, top). In case no abstractions would have been taken from January 1999 onwards (S1, period January 1999—December 2010) the lake volume in September 2009 would have been 2.2 times higher than it was in the situation with abstractions (S2).

In order to understand the individual contributions of water abstractions from ground-water and surface water the following situations have been analyzed:

Fig. 4 *top*: Comparison between observed lake volume changes based on lake level observations (MOWD 1982) and the lake-level-volume relationship from Åse et al. (1986) and simulated (S1) lake volume changes for the period January 1965—Dec 1979 for monthly intervals (*left*) and for annual intervals (*right*); *bottom*: Comparison between observed lake volume changes based on lake level observations (LNRA 2012) and the lake-level-volume relationship from Åse et al. (1986) and simulated (S1) lake volume changes for the period January 1999—Dec 2010 for monthly intervals (*left*) and for annual intervals (*right*)

- Only surface water abstractions, no groundwater abstractions (S3)
- Only groundwater abstractions, no surface water abstractions (S4)

The individual contributions of abstractions from groundwater and surface water are shown in Fig. 5 (bottom). Both contributions of groundwater abstractions and surface water abstractions are found to be substantial.

3.4 The Influence of Water Abstractions on Total Water Availability

In order to make a comparison between the effects of the use of groundwater and the use of surface water, two new situations are evaluated:
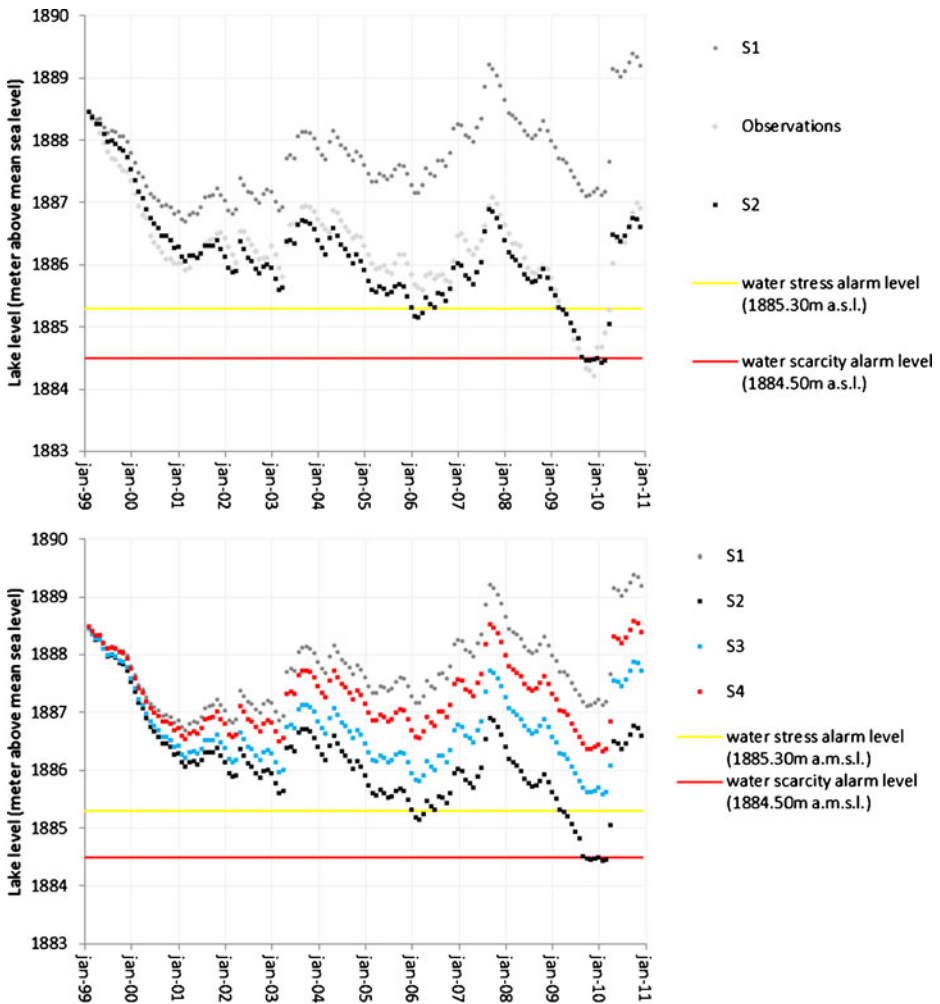
Fig. 5 *top*: Simulated lake and levels for the recent period with 'natural' conditions (S1) and 'including abstractions' (S2); *bottom*: Lake levels influenced by groundwater abstractions and surface water abstractions for four different situations: a natural situation (S1), a situation with all abstractions (S2), a situation with no groundwater abstractions (S3), a situation with no surface water abstractions (S4)

- Total estimated amount of water used abstracted from surface water (S5)
- Total estimated amount of water used abstracted from groundwater (S6)

When comparing situations S5 and S6, it is seen that lake levels (and volumes) remain slightly higher in the case of S6 (Fig. 6, top). However, looking at lake levels (and volumes) only offers limited insight into the water availability situation around Lake Naivasha. The water availability around Lake Naivasha consists of surface water (particularly the lake) and the groundwater aquifer. Figure 6, (top). shows how the average aquifer water level around the lake drops much more for situation S6.

Thus, for a meaningful comparison between the water availability situations including both surface water and groundwater we define water availability as the water volume in the lake reduced by the groundwater deficit in the aquifer. The groundwater deficit is the volumetric

difference between a situation without groundwater abstractions and a situation with groundwater deficit. In Fig. 6 (bottom) it is shown that the actual available water is consistently slightly lower for situation S6 if compared to S5.

4 Discussion

4.1 Implications for Water Resources Management in the Lake Naivasha Basin

Water managers should be cautious when using lake levels as an indicator of water availability for the purpose of abstraction restrictions. When large amounts of groundwater
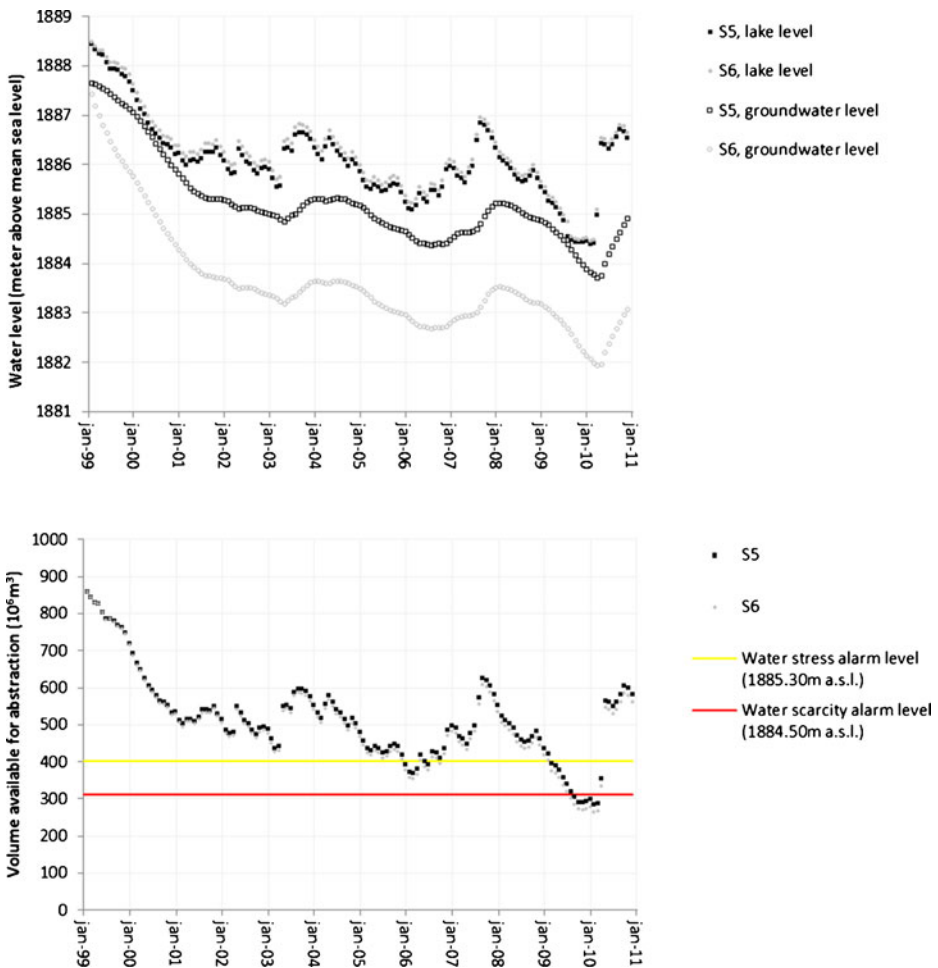
Fig. 6 *top*: Simulated lake levels and groundwater levels for the recent period (1999–2010) with all the abstracted water obtained from the lake directly (S5) and all the abstracted water obtained from the lake aquifer (S6); *bottom*: Water volumes for the period 1999–2010 done for different simulations: Lake volumes for a situation in which all abstractions are obtained from the lake directly (S5); Total available volume for a situation in which all abstractions are obtained from the aquifer (S6). For S6 water availability equals lake volume minus the difference between aquifer volumes for S5 and S6

are abstracted groundwater levels could be considerably lower than observed lake levels. Water managers should rather aim at monitoring both lake levels and groundwater levels separately when deciding on abstraction restrictions.

Decision-making with regard to the long-term development of irrigation could also benefit from a more comprehensive assessment of the different effects of groundwater abstractions and surface water abstractions on overall water availability.

When more groundwater is abstracted the relationship between the water availability situation and lake volume becomes less obvious. Whereas lake levels can be monitored using a set of simple gauging staffs at a single location at the lake shore, a much higher investment is required to monitor the availability of water in aquifers. For the aquifer around Lake Naivasha groundwater levels vary considerably. This is due to both natural factors like the overall hydrogeological setting and the influence of the lake levels on groundwater and drawdown caused by pumping from the aquifer. To estimate the volume of water pumped from the aquifer several observation wells need to be drilled in order to cover the cone of depression, the natural unstressed water levels need to be estimated and pumping tests with several nearby observation wells need to be carried out in order to obtain measured values for the specific yield of the aquifer.

Over abstraction of groundwater resources undermines its role as an ultimate resource in times of drought. Moreover, the lifting height from groundwater is generally higher than from surface water resulting in higher energy costs. During the period January 2009—May 2012 the average depth of one of the major wells in the Lake Naivasha area was around 58 m below the surface (FBP 2012).

This study suggests that overall water availability in the area is more affected by the abstraction of groundwater than by the abstraction of the same volume from surface water. Moreover, groundwater abstraction reduces groundwater levels, negatively affecting its accessibility. Despite the relatively high costs and generally more difficult task of monitoring groundwater resources the results of this study give reason for detailed monitoring of groundwater levels and an accurate assessment of the actual flows between groundwater and surface water resources.

4.2 Parameters of the Water Balance Model

In this study a simple water balance modeling approach has been applied. Although this approach did function well to illustrate the different effects of water abstractions from surface water and groundwater the assumptions made are not realistic with regard to the actual behavior of groundwater tables in particular. For the model it has been assumed that a groundwater aquifer that is connected to the lake has a specific water table that gradually moves up and down, whereas in reality the groundwater table is expected to vary in space and time. For the groundwater outflow ($Q_{outflow}$), conductance (C) and specific yield (S_y) parameters constant values are used whereas in reality these may vary considerably hence influencing the exchange of water between the aquifer and the lake and the actual groundwater level. The size of the artificial aquifer (A) used was set at 100 km^2. One could argue the actual size of the aquifer is likely to deviate from this number but more importantly the size (A) should not be associated with actual size at all because the boundary of the aquifer is unknown if it is anywhere near to the Lake Naivasha area at all. For the same reason the level of the aquifer H_{aq} is also not to be considered as a 'real value' but rather as a representative of the average level of the groundwater in the area. Moreover, in

reality levels at the actual locations of groundwater abstraction will be lower as cones of depressions are formed. Depending on where monitoring wells are located this further complicates the issue of alarm levels for groundwater abstraction. In this study the outflow from the groundwater has been assumed constant. It could of course be the case that varying groundwater levels affect the amount of outflow and therefore also affect the efficiency of groundwater use. Unfortunately no data are available to confirm this.

It is known that in cases where the dominant source of water abstraction for irrigation is surface water, net abstractions from groundwater could become negative as groundwater is recharged by irrigation (e.g. Döll et al. 2012). The opposite applies to cases in which groundwater is the dominant source for irrigation, i.e. net abstraction of surface water becomes negative because return flows recharges the surface water bodies. This effect was not accounted for in this study. Instead it has been assumed that recharge from irrigation only applies to the source from which water had been initially abstracted. If these effects would have been taken into account this would lead to even more pronounced differences between the 'all groundwater' and 'all surface water' simulations in this study (Fig. 6, bottom). Furthermore, no seasonal variations in the demand for irrigated water have been accounted for.

5 Conclusion

This study shows that accurate estimates of annual volume changes of Lake Naivasha can be made using a simple monthly water balance approach that takes into account the exchange of water between the lake and its connected aquifer.

The amount of water that is used for irrigation in the area around Lake Naivasha has a substantial adverse effect on the availability of water. In the recent period, the abstraction of water has led to a situation of water scarcity in which water management authorities had to impose 'severe water abstraction restrictions'.

Simulation results of our simple water balance model suggests that abstractions from groundwater affect the lake volume less than direct abstractions from the lake. Groundwater volumes, in contrast, are much more affected by groundwater abstractions and therefore lead to much lower groundwater levels. Moreover, when groundwater is used instead of surface water, evaporation losses from the lake are potentially higher due to a larger lake surface area. If that would be the case then the overall water availability in the area is more strongly affected by the abstraction of groundwater than by the abstraction of surface water. Therefore water managers should be cautious when using lake levels as the only indicator of water availability for restricting water abstractions.

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