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Modelling Lake Kivu water level variations over the last seven decades

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ABSTRACT

This study aimed at analysing the hydrological changes in the Lake Kivu Basin over the last seven decades with focus on the response of the lake water level to meteorological factors and hydropower dam construction. Historical precipitation and lake water levels were acquired from literature, local agencies and from global databases in order to compile a coherent dataset. The net lake inflow was modelled using a soil water balance model and the water levels were reconstructed using a parsimonious lake water balance model. The soil water balance shows that 370 mm yr^{-1} (25%) of the precipitation in the catchment contributes to the runoff and baseflow whereas 1100 mm yr^{-1} (75%) contributes to the evapotranspiration. A review of the lake water balance resulted in the following estimates of hydrological contributions: 55%, 25%, and 20% of the overall inputs from precipitation, surface inflows, and subaquatic groundwater discharge, respectively. The overall losses were 58% and 42% for lake surface evaporation and outflow discharge, respectively. The hydrological model used indicated a remarkable sensitivity of the lake water levels to hydrometeorological variability up to 1977, when the outflow bed was artificially widened.
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Introduction

The variations of water level of natural (unregulated) lakes are an indicator of changes in the hydrological budget of the lake catchment. Such changes may be caused by climatic variations (precipitation, evapotranspiration and other meteorological components) or by changes in the runoff characteristics (such as land-use changes) in the catchment (Vuglinskiy et al., 2009). Depending on the ratio of the catchment area per lake surface area, lake levels change within time scales ranging from hours to years (Mason et al., 1994). Also the sensitivity of lake water levels to rainfall evidently depends on the catchment-to-lake surface ratios (Vuglinskiy et al., 2009). For example, a significant relationship has been observed between rainfall variability and lake water level in the Lake Victoria Basin (Mistry and Conway, 2003).

The seasonal rainfall distribution in the East-African region is bimodal due to the twice-annual passage of the Intertropical Convergence Zone (Verschuren et al., 2009). A recent study suggests that long-term variations in East-African rainfall are mainly driven by sea surface temperatures in the Indian Ocean (Tierney et al., 2013). East-African lakes experienced a rise in their water levels, the so-called "*Centennial rising of River Congo and Nile water levels*" during the course of 1961–1964 due to an increase in rainfall (Lake Victoria: 2.25 m; Mistry and Conway, 2003; Lake Tanganyika: ~3 m; Kite, 1981; Bergonzini et al., 2002; Lake Kivu: 0.97 m, Pasche et al., 2010, 2012). Confusingly, for Lake Kivu, this period of higher rainfall coincided with the construction of a hydropower dam (1958/59) at the Ruzizi outflow, 3 km downstream of the lake (SINELAC, 1989) as well as with the beginning of increased human activities in the catchment (Muvundja et al., 2009). Unfortunately continuous hydrological data of this basin are lacking as the catchment remains

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ungauged except for the lake level. In addition, records from most rain gauge stations in the catchment are discontinuous.

For Lake Kivu, in addition subaquatic groundwater discharge (SGD) that enters the lake below 100 m is of high relevance. The SGD drives a slow upwards advective transport within the lake that is the main source of nutrients for primary production in the lake surface layer (Pasche et al., 2012; Schmid and Wüest, 2012). An increase in precipitation may be expected to also lead to an increase of the SGD and thus an increase in the availability of nutrients for primary production.

The hydrological modelling of the lake water levels has already been identified as a relevant information because the lake serves as the principal reservoir for the downstream hydropower dam cascade. In addition, lake level variability has an impact on fisheries, especially the littoral zone ecological functions such as fish breeding and feeding. In the case of Lake Kivu, the littoral zone plays an important role as it is the permanent habitat for 27 of the only 29 fish species of this lake (Snoeks et al., 2012 and references therein). The littoral zone is the breeding and growing area of *Limnothrissa miodon* on which the fisheries resource is largely based (Isumbisho et al., 2004; Masilya et al., 2011).

This study aimed to evaluate the lake level response to the hydrological variability in the catchment and to dam operation. The importance of Lake Kivu as a source of water resources, in the context of increasing demography and demand, is expected to increase in the forthcoming decades for further electricity production, irrigation as well as domestic and industrial uses. Thus, the assessment of the hydrological patterns and their effect on the water resource is crucial for monitoring and predicting the evolution of the water level of Lake Kivu and the discharge of the Ruzizi River (Vodacek et al., 2010). This analysis will contribute in providing the information needed to allow policy-making for an integrated water resource management in the lake catchment.

Study site

Lake Kivu is one of the equatorial East-African rift lakes (Fig. 1). The lake is situated at the feet of the volcanically active region of Nyiragongo between the Democratic Republic of the Congo and Rwanda. The lake surface is 2370 km^2 with a drainage basin of 4940 km^2 (excluding the lake, Ballatore, 2012). Most of the drainage basin consists of a river-active area (4255 km^2) dominated by Haplic Acrisols (clay-rich but nutrient- and mineral-deficient acidic soils) in the Northwest and Southeast, by Humic Ferralsols (lateritic soils rich in iron, low clay soils; IUSS Working Group WRB, 2007) in the Southwest and by Humic Acrisols in the East. A river-free area (685 km^2) is situated in the North of the lake and dominated by Mollic Andosols (Muvundja et al., 2009) which are black volcanic ash soils and consist of a mixture of volcanic ashes, stones and gases (Driessen et al., 2001). The SGD into the lake is most probably at least partially fed by infiltration in this river-free area. The land-use in the catchment is currently dominated by Dryland Cropland and Pasture (65%) whereas Evergreen Broadleaf Forest accounts for only 17%, Shrubland for 11% and other land-uses for 7% (Muvundja et al., 2009).

The climate is humid with a bimodal precipitation regime (~1400 mm yr^{-1} over the lake catchment; Muvundja et al., 2009). The rainy season spans from September to May and the dry season from June to August (Bultot, 1971; Fehr, 1984; Bergonzini, 1998). The evaporation over the lake surface was estimated to ~1530 mm yr^{-1} (CGIAR-CSI, http://www.cgiar-csi.org/data/global-aridity-and-pet-database). For comparison, Bultot (1971) estimated evaporation to ~1410 mm yr^{-1}, while estimates from other sources ranged from 800 to 1800 mm yr^{-1} (TRACTIONEL and Rhein-Ruhr-Ingenieur (RRI), 1980). The potential evapotranspiration in the catchment estimated by different authors ranges from 900 to 1500 mm yr^{-1} (Kilauli, 1976; Vangu, 1981; Bigororande, 1982; Kombi, 1982; CGIAR-CSI, http://www.cgiar-csi.org/data/global-aridity-and-pet-database). An increase in evaporation and evapotranspiration is expected in East African climatic zone as a response to global warming (Verburg et al., 2003; Taylor et al., 2006). The surface runoff coefficient for this region is ~0.3 according to Shahin (2002) which contributes to feed the more than 100 rivers and streams that flow into the lake (Muvundja et al., 2009; Schmid and Wüest, 2012).

In previous studies, the water balance of Lake Kivu was estimated to be composed of inputs of 3.3 $km^3\,yr^{-1}$ by precipitation, 2.0 $km^3\,yr^{-1}$ by river inflows, 1.3 $km^3\,yr^{-1}$ by SGD and outputs of 3.6 $km^3\,yr^{-1}$ by lake surface evaporation and 3.0 $km^3\,yr^{-1}$ by the Ruzizi River outflow (Muvundja et al., 2009; Schmid and Wüest, 2012). The SGD are permanent underground water springs with most of the discharge attributed to cool and fresh SGD that mainly drive the upwelling in the lake, and a smaller contribution of hydrothermal sources that maintain the permanent stratification of the lake (Degens et al., 1973; Schmid et al., 2005; Ross, 2014; Ross et al., 2014).

Regarding the outlet, it is important to consider the construction and the operation of the Ruzizi I Hydropower Dam since 1959, located 3 km downstream of the lake (TRACTIONEL and RRI, 1980, FICHTNER, 2008). In 1977, dredging and widening operations were conducted, and a by-pass was erected at the lake outlet to regulate the amount of water in the river channel (FITCHNER, 2008). However the by-pass did not work properly and was decommissioned shortly afterwards. All these operations may have induced some bias to the “natural” lake level versus discharge relationship (Bergonzini, 1998; TRACTIONEL and RRI, 1980; FICHTNER, 2008) and sometimes to an unknown extent.

Data

Rain data from 34 meteorological stations (1928–1993; Fig. 1 and Table 1) were compiled from the literature (Bultot, 1954, 1971; INEAC, 1960; Kilauli, 1976; Bitacibera and Gatsimbanyi, 1978; Vangu, 1981; Bigororande, 1982; Bikoba, 1984) and local meteorological services (Météo-Rwanda as well as Division Provinciale de Météorologie and Division Provinciale d'Agriculture, Pêche et Elevage in D.R. Congo; Fig. 1). Arithmetic means were used in rainfall data compilation as the variation between the individual stations was comparably small (coefficient of variation: 17.8%).

Furthermore, two global precipitation databases were used for the analysis: the Global Precipitation Climatology Centre database (GPCC; Rudolf and Schneider, 2005; Rudolf et al., 2010; http://gpcc.dwd.de) and the satellite-based Tropical Rainfall Measuring Mission 3B43 product (TRMM; Jiang et al., 2011 and references therein; http://trmm.gsfc.nasa.gov/) which combines estimates generated by the TRMM and other satellite products as well as available rain gauge data from various sources available at: http://disc.sci.gsfc.nasa.gov/precipitation/documentation/TRMM_README/TRMM_3B43_readme.shtml.

The monthly GPCC data were averaged for the three grid cells covering most of the catchment area of the lake and compared to the average of the rain gauge measurements for the years 1941–1993 (Fig. 2). The correlation between the two time series is excellent (R^2 = 0.94; Fig. 3), with the GPCC data being on average ~7% higher. After 1993, both the rain gauge and the GPCC data cannot be considered reliable due to the absence of a sufficiently dense local in situ measurement network. For the water balance calculations, the GPCC data were used until 1997, while for the years 1998–2012 the average values of the TRMM 3B43 products for the grid cells shown in Fig. 1 were used. However, these TRMM

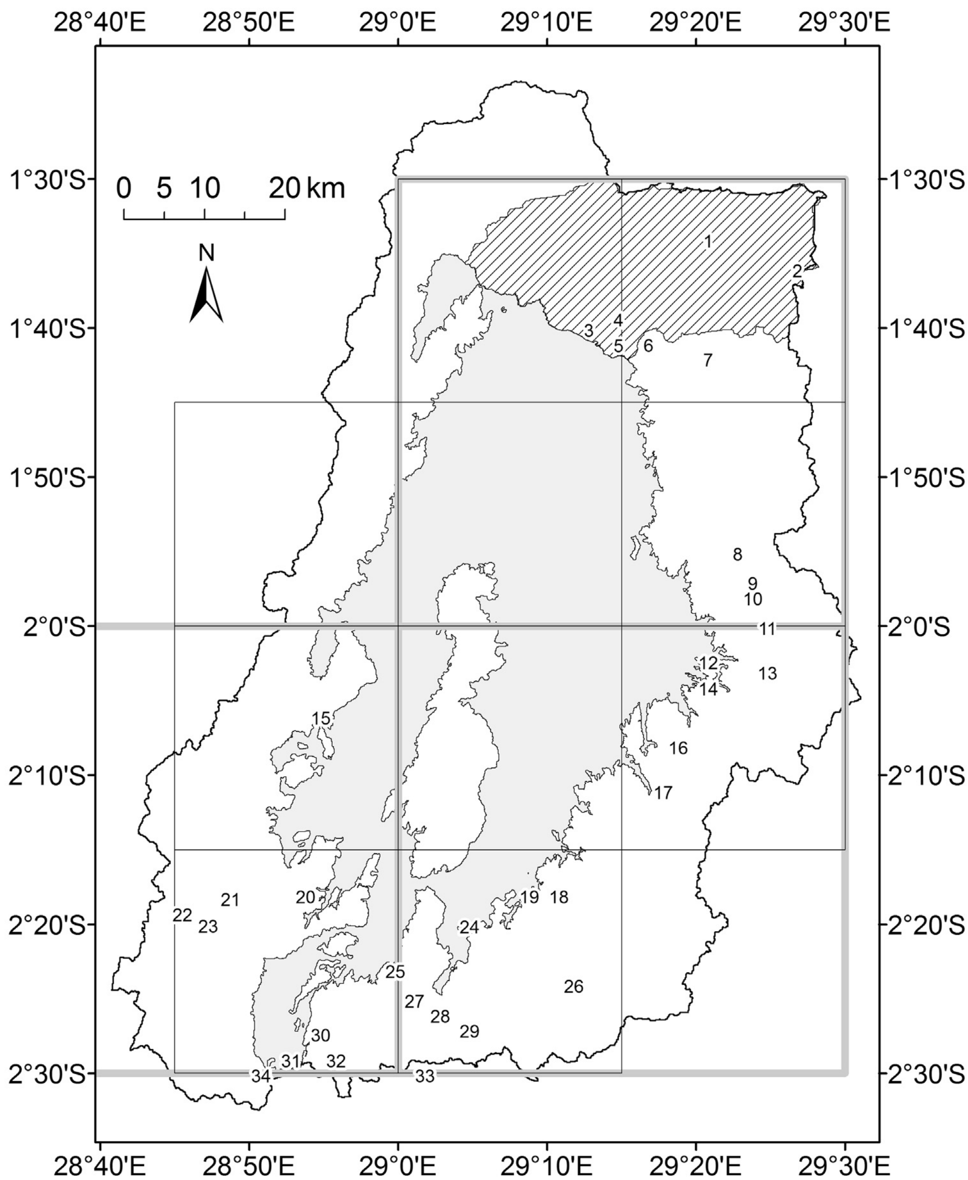

Fig. 1. Map of Lake Kivu and its catchment. The numbers indicate the locations of the meteorological stations used in this study as listed in Table 1. The hatched area represents the river-free catchment area to the North of the lake. The large grey squares and the small black squares indicate the grid cells of the GPCC and TRMM data, respectively, that were used to calculate average precipitation in the catchment.

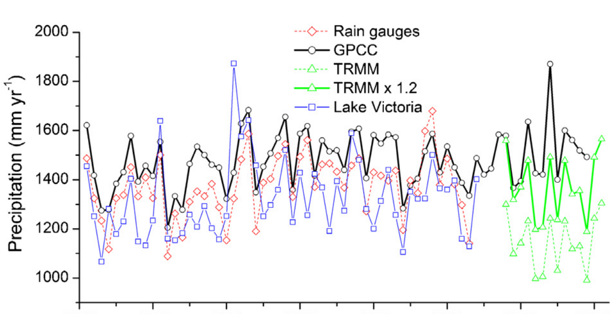

Fig. 2. Time series of annual precipitation for the basins of Lake Victoria (blue line; calculated back using lake surface precipitation data and relationship provided by Nicholson and Yin (2002)) and of Lake Kivu (different sources indicated by the other lines). For other data sources, see text. TRMM data are corrected by a factor of 1.2.

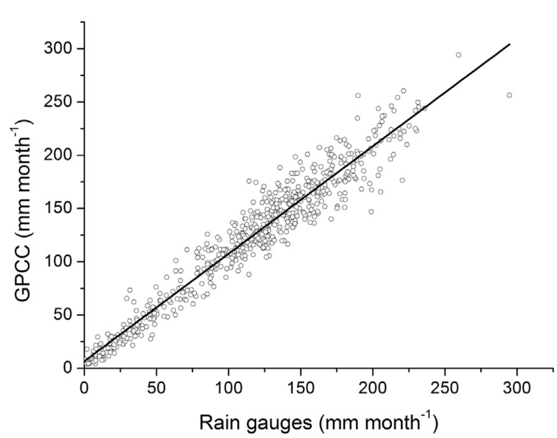

Fig. 3. Correlation between monthly rainfalls calculated from the rain gauge data (Table 1) and average rainfall in the GPCC dataset for the three grid cells marked in Fig. 1. The regression line is defined by the equation $P_{GPCC} = 1.01 \times P_{gauge} + 7\,\text{mm month}^{-1}$; $R^2 = 0.94$.

Table 1
Meteorological stations used in this study as located in Fig. 1.

Station no.	Station name	Altitude (m asl)	Rainfall ($mm\,yr^{-1}$)	# of years
1	Tamira	2300	1196	9
2	Kora	2500	1272	11
3	Goma	1493	1196	44
4	Gisenyi–Airport	1554	1164	23
5	Prefecture	1540	1185	67
6	Pfunda	1480	1326	21
7	Kanama	1900	1477	8
8	Murunda	1875	1348	49
9	Rutsiro	2300	1482	13
10	Crête Congo-Nil	2300	1231	3
11	Mushumbati	1800	1197	3
12	Kibuye	1470	1259	32
13	Rubengera	1700	1200	44
14	Nyamishaba	1470	1100	18
15	Kalehe	1500	1728	19
16	Mubuga	1650	1361	53
17	Mugonero	1600	1406	51
18	Gatare	1800	1511	7
19	Maseka	1465	1221	49
20	Mushweshwe	1700	1270	19
21	Nyamunyunye	1746	1548	32
22	Tshibinda	2070	1860	21
23	Mulungu	1715	1607	21
24	Nyamasheke	1500	1209	62
25	Shangi	1600	1418	27
26	Kamatsira	1500	1729	12
27	Bumazi	1600	1621	29
28	Mwaga	1850	1877	11
29	Gisakura	1946	2191	16
30	Kamembe- Airport	1591	1390	42
31	Cyangugu	1525	1411	49
32	Shagasha	1700	1612	14
33	Bugutu	2025	1846	31
34	Bukavu	1635	1317	50

data had to be multiplied by a constant factor of 1.2 to maintain the agreement with the mean lake levels. In fact, TRMM's performance and uncertainties for Africa (e.g., Nicholson et al., 2003; Dinku et al., 2011; Beighley et al., 2011; Liechti et al., 2012; Sylla et al., 2013) and elsewhere (Wolf et al., 2005; Franchito et al., 2009; Javanmard et al., 2010; Cheema and Bastiaanssen, 2012) have been widely discussed, and its uncertainties were estimated to reach up to 30% or in some cases even more. Topography has been found to be a major source of error for TRMM data which has been shown to moderately underestimate rainfall over highland regions compared to gauged data in East Africa and abroad (e.g., Ebert et al., 2007; Asadullah et al., 2008; Dinku et al., 2011; Ward et al., 2011). The reason given is the failure of the satellite to pick up the orographic enhancement of rainfall (Ebert et al., 2007). An underestimation of rainfall by TRMM in the mountainous region of Lake Kivu is in agreement with these findings. Nevertheless, the TRMM dataset is one of most reliable satellite products in the tropics, and even ground gauged meteorological data have similar uncertainties (of up to ~30%; WMO 2006).

Catchment potential evapotranspiration (PET) data as well as lake surface evaporation data were downloaded from the Consortium of Spatial Information (CGIAR-CSI) Database of the CGIAR-Global Research Partnership for a Food Secure Future (Zomer et al., 2008; http://www.cgiar-csi.org/data/global-aridity-and-pet-database). These data had been generated by Zomer et al. (2008) using the data available from the WorldClim Global Climate data (Hijmans et al., 2005) as input parameters. WorldClim is based on a high number of climate observations and the NASA Shuttle Radar Topography Mission which is a 90 m resolution digital elevation database and provides a major advance in the accessibility of high quality elevation data for tropical regions (FAO, 2004). Monthly potential evapotranspiration (PET) data have been characterized and tested for Africa and South America using different temperature-based methods applied to the WorldClim Global Climate data (available at http://worldclim.org; Zomer et al., 2008). The Hargreaves model (Hargreaves et al., 1985) yielded the best agreement and was applied (Zomer et al., 2008). The model was validated by these authors using PET measurements calculated from direct observations provided by the FAOCLIM 2 Climate station dataset (Allen et al., 1998) available on the FAO website. Many other studies have successfully used these global PET data (e.g., Trabucco et al., 2008; MacDonald et al., 2013; Metzger et al., 2013).

Historical records of lake water levels (1941–2011) and the outflow discharge calibration curves were collected from the Ruzizi I Hydropower Dam company in Bukavu-Mururu (Société Nationale d'Electricité, SNEL). Furthermore, lake levels determined by remote sensing measurements were retrieved from the global hydrological database HYDROWEB (Crétaux et al., 2011) and compared to ground measurements. Discharges of the Ruzizi outflow were calculated from the lake water level using the calibration curves provided by TRACTIONEL and RRI (1980) and by Bergonzini (1998) as summarized in Table 2.

Model description

Runoff model

The water balance of Lake Kivu and its catchment was calculated with a monthly time step Δt based on the meteorological data described above. Since only few actual discharge measurements from the tributaries of Lake Kivu were available (Bergonzini, 1998; Muvundja et al., 2009), we used a runoff model for estimating the monthly runoff from the catchment as an input to the lake water balance model.

Many authors have used hydrological models based on the Budyko framework (Budyko, 1958) in their studies for various purposes. For example, Zhang et al. (2008) applied the Budyko framework to develop and test a water balance model over variable time scales which allows predicting streamflow for ungauged catchments. Donohue et al. (2010) studied the importance of vegetation dynamics to improve Budyko's model. Chen et al. (2013) used modified Budyko-type equations to estimate the seasonal evaporation and annual water storage in catchments. Van der Velde et al. (2013) used Budyko's framework to identify regions with contrasting hydroclimatic change during the past 50 years in Sweden. In this study, we estimated the runoff of the Lake Kivu catchment by applying a monthly hydrological model based on the Budyko framework, the water partition and balance (WAPABA) model developed for diverse ungauged catchments by Wang et al. (2011).

The model comprises five steps summarized as below:

1. Rainfall, $P(t)$ ($mm\,month^{-1}$), is partitioned into the catchment water yield, $Y(t)$ ($mm\,month^{-1}$) and the catchment water consumption, $X(t)$ ($mm\,month^{-1}$):

$$Y(t) = P(t) - X(t) \tag{1}$$

$Y(t)$ comprises surface runoff, $Q_S(t)$ ($mm\,month^{-1}$) and groundwater recharge, $R(t)$ ($mm\,month^{-1}$) such as:

$$Q_S = Y(t) - R(t) \tag{2}$$

A supply–demand–consumption equation is applied to calculate $X(t)$ from rainfall:

$$X(t) = P(t)\left\{1 + \frac{X_0(t)}{P(t)} - \left[1 + \left(\frac{X_0(t)}{P(t)}\right)^{\alpha_1}\right]^{1/\alpha_1}\right\} \tag{3}$$

Table 2
Parameter values used for the runoff model and the lake water balance model.

Model parameter	Symbol	Value	Unit	Comment/reference
Lake surface area	A_L	2370	km^2	
Lake basin area	A_B	7310	km^2	Ballatore (2012)
Catchment area (without lake)	A_C (= $A_B - A_L$)	4940	km^2	
Volcanic area without rivers	A_V	685	km^2	Ballatore (2012)
River-active area	A_r (= $A_C - A_V$)	4255	km^2	
Subaquatic spring inflow	Q_{sp}	1.3	$km^3\ yr^{-1}$	Schmid et al. (2005)
Soil storage capacity	S_{max}	300	mm	Bultot (1971)
Coefficient 1 in runoff model	α_1	2.2		Model calibration
Coefficient 2 in runoff model	α_2	2.0		Wang et al. (2011)
groundwater storage parameter	β	0.6		Model calibration
groundwater residence time	k	5	months	Model calibration
Rating curve slope 1941–1976	a_1	78.9	$m^2\ s^{-1}$	SNEL (pers. comm.)
Rating curve intercept 1941–1976	b_1	124.6	$m^3\ s^{-1}$	SNEL (pers. comm.)
Rating curve slope 1977–2011	a_2	82.3	$m^2\ s^{-1}$	SNEL (pers. comm.)
Rating curve intercept 1977–2011	b_2	131.7	$m^3\ s^{-1}$	SNEL (pers. comm.)

Here, α_1 is the catchment consumption curve coefficient; $X_0(t)$ (mm month^{-1}) is the potential catchment water consumption or water demand limit given by:

$$X_0(t) = ET_0(t) + \frac{S_{\max} - S_{(t-1)}}{\Delta t} \tag{4}$$

where $ET_0(t)$ (mm month^{-1}) is the catchment potential evapotranspiration; S_{max} (mm) is the maximum water holding capacity of the soil in the catchment; $S_{(t-1)}$ is the amount of water held in the soil for the prior time step $t-1$; and $\Delta t = 1$ month is the simulation time step.

2. The amount of water available for evapotranspiration, $W(t)$ (mm month^{-1}), is then given by:

$$W(t) = \frac{S(t-1)}{\Delta t} + X(t) \tag{5}$$

The actual evapotranspiration is calculated from:

$$ET = W(t)\left\{1 + \frac{\left(ET_0(t) + (S_{\max}/\Delta t)\right)}{W(t)} - \left[1 + \left(\frac{\left(ET_0(t) + (S_{\max}/\Delta t)\right)}{W(t)}\right)^{\alpha_2}\right]^{1/\alpha_2}\right\} \tag{6}$$

where α_2 is the catchment evapotranspiration curve coefficient. The soil water storage at the end of the time t, $S(t)$ is:

$$S(t) = S(t-1) + [w(t) - ET(t)]\Delta t \tag{7}$$

3. The catchment water yield at time step t, $Y(t)$ is partitioned into $R(t)$ (mm month^{-1}) and $Q_s(t)$ (mm month^{-1}) by:

$$R(t) = \beta Y(t) \tag{8}$$

where β is the proportion of the water yield and the groundwater recharge rate, $R(t)$.

The rest of $Y(t)$ contributes to the surface runoff, $Q_s(t)$ given by:

$$Q_S = Y(t) \times (1 - \beta) \tag{9}$$

4. The groundwater storage is drained to generate a baseflow $Q_b(t)$ (mm month^{-1}) given by:

$$Q_b(t) = \frac{G(t)}{k} \tag{10}$$

where $G(t)$ (mm) is the groundwater storage and k (months) the groundwater residence time. The baseflow here indicates the amount of infiltrated groundwater which returns to the surface. Given the steepness of the basin topography, the residence time of the groundwater should be comparably short. However, we have no concrete observational evidence for the residence time. We therefore chose to estimate this parameter during the model calibration (see 'Model parameterization and calibration' section). Thus the remaining water in the groundwater storage at the end of time t is:

$$G(t) = G(t-1) + \Delta t\,(R(t) - Q_b(t)) \tag{11}$$

5. The sum of surface runoff and the baseflow results in the total flow, $Q(t)$, during the time step Δt and closes the hydrological cycle by:

$$Q(t) = Q_S(t) + Q_b(t) \tag{12}$$

The catchment runoff coefficient, k_r is calculated by:

$$k_r = \frac{Q(t)}{P(t)} \tag{13}$$

Finally, the inflow into the lake, $Q_r(t)$ (m^3 s^{-1}), is calculated from $Q(t)$ by

$$Q_r(t) = c \times Q(t) \times A_r \tag{14}$$

Here A_r (m^2) is the river-active area of the catchment, and c is a conversion factor to convert from mm month^{-1} to m s^{-1}. The procedures for estimating or calibrating the five model parameters α_1, α_2, β, k, and S are described in 'Model parameterization and calibration' section below and the values of the parameters are given in Table 2.

Lake water balance model

A parsimonious water balance model was used to reconstruct the lake level dynamics from the knowledge on lake hydrological and morphological parameters (Table 2). The calculations of the hydrological inputs to the model were made from January 1941 to December 2011.

The model used is based on the following equation:

$$\Delta Q(t) = A_L \times [P(t) - E(t)] + Q_r(t) + Q_{SGD}(t) - Q_{out}(t) \tag{15}$$

where ΔQ (m^3 s^{-1}) is the net water inflow to the lake; A_L is the lake surface area (m^2), $P(t)$ is the rainfall (m s^{-1}) on the lake surface at time t (s), and $E(t)$ is the evaporation rate (m s^{-1}) from the lake surface.

$Q_r(t)$ (m^3 s^{-1}) is the total catchment flow to the lake (except SGD) calculated from the sum of catchment runoff and baseflow as given by Eqs. (12) and (14).

The long-term mean total discharge of the SGD, $Q_{SGD}(t)$, is relatively well constrained by the salt balance of the lake (Schmid and Wüest 2012), but nothing is known about the residence time of the water before entering the lake or the temporal dynamics of the SGD. We therefore used two different approaches for estimating Q_{SGD}, either as constant:

$$Q_{SGD}(t) = \overline{Q_{SGD}} = 41.2\,\mathrm{m^3\,s^{-1}} (= 1.3\,\mathrm{km^3\,yr^{-1}}) \tag{16}$$

or as variable in time, and thus, as a function of the precipitation during the previous year:

$$Q_{SGD}(t) = \overline{Q_{SGD}} \times \gamma \left[1 + \frac{P_n - \bar{P}}{\bar{P}}\right] \tag{17}$$

where P_n is the mean precipitation during the past year, and, $\bar{P}$ is the average long-term precipitation; γ is a non-dimensional fit parameter describing the extent to which the SGD discharge varies with precipitation.

$Q_{out}(t)$ ($\mathrm{m^3\,s^{-1}}$) is the discharge of the outflow given by:

$$Q_{out}(t) = aH(t) + b \tag{18}$$

where $H(t)$ is the lake water level gauged at the outflow (m, above 1460 m asl); a ($\mathrm{m^2\,s^{-1}}$) and b ($\mathrm{m^3\,s^{-1}}$) are the slope and the intercept of the rating curve, respectively (Table 2). Two different rating curves were used for the periods before and after the year 1977 when the outflow was modified by dredging and widening.

The lake water level was then calculated from the net water inflow by:

$$H_i = H_{i-1} + \frac{(\Delta Q)_{i-1}}{A_L} \Delta t \tag{19}$$

Where H_i is the simulated water level for the month i; H_{i-1} is the simulated water level for the previous month $i-1$; $(\Delta Q)_{i-1}$ the net inflow of the previous month calculated using Eq. (14), Δt the time elapsed from the first day of the previous month to the first day of the month under consideration.

Model parameterization and calibration

The model parameters were defined or calibrated as follows: For the soil water holding capacity, S_{max}, a value of 300 mm was used, which is the value given for the region by Bultot (1971) and agrees with average values around Lake Kivu in the FAO Soil Map of the World. Of the two parameters α_1 and α_2 only one could be used for model calibration, as their effects on the total runoff from the catchment are qualitatively very similar. Therefore parameter α_2 was arbitrarily set to 2.0, a typical value observed in 331 test catchments by Wang et al. (2011). Then, α_1 was optimized to set the mean difference between observed and calculated lake levels for the entire time series to zero. This resulted in $\alpha_1 = 2.2$.

Finally, the parameters β and k were calibrated to reduce the difference between the observed and simulated seasonality of the lake level. Here, seasonality is defined as the difference between the monthly lake levels and their 12-months running mean, averaged for the period 1942–1997, i.e. not including the years for which the TRMM data were used. The best fit between observed and simulated seasonality was achieved with $\beta = 0.6$ and $k = 5$ months, meaning that 60% of the water yield is contributed by the baseflow, which resides on average 5 months in the catchment (the value of 5 months was chosen to optimize the model but we have no concrete observational evidence).

Model evaluation

The predictive power of the model was assessed using the Nash-Sutcliffe efficiency (NSE) index (Nash and Sutcliffe, 1970) as well as

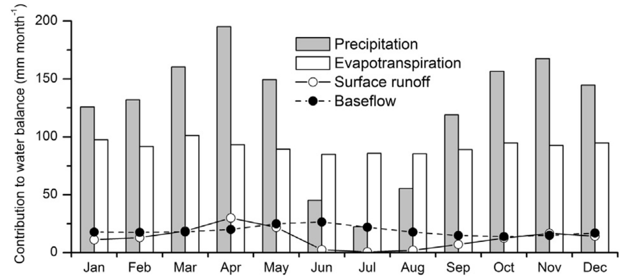

Fig. 4. Monthly components of the soil water balance (precipitation, evapotranspiration, surface runoff and baseflow) calculated with the runoff model for the catchment of Lake Kivu for the period 1941–1991 (the period with most reliable precipitation data).

the ratio of the root mean square error and the standard deviation of the observations (RSR) as described by Moriasi et al. (2007 and references therein).

Observations and results

Precipitation

The precipitation record for Lake Kivu shows a shift towards wetter conditions around 1961. Similar observations were made for the Lake Victoria Basin (Nicholson and Yin, 2002; Kizza et al., 2009; Fig. 2) indicating that rainfall in the catchment of Lake Kivu is driven by the same regional meteorological patters as for Lake Victoria. In order to support this, we give in the following the respective values for Lake Kivu (in italics) and Lake Victoria (in parentheses, data are from Nicholson and Yin, 2002). The annual mean precipitation (± standard deviation) in the rain gauge data for the period 1941–1960 was *1417 ± 112 mm yr⁻¹* for the Lake Kivu Basin (1244 ± 129 mm yr⁻¹). The minimum precipitation of *1090 mm yr⁻¹* (1070 mm yr⁻¹) was observed in 1952 (1943), the maximum of *1500 mm yr⁻¹* (1640 mm yr⁻¹) occurred in 1951 (Fig. 2). Subsequently, the mean rainfall rose to *1415 ± 118 mm yr⁻¹* (1367 ± 167 mm yr⁻¹), in the period 1961–1993, corresponding to an increase by *8%* (10%) compared to the average before 1961. The minimum values for this period were *1140 mm yr⁻¹* (1110 mm yr⁻¹) in 1993 (1984), whereas the maxima were *1590 mm yr⁻¹* in 1963 and *1680 mm yr⁻¹* in 1988 (1870 mm yr⁻¹ in 1961 and 1640 mm yr⁻¹ in 1963).

Based on the classification of Fehr (1984), the long-term series indicate that June to August are dry months with 46, 29 and 57 mm month⁻¹ respectively whereas the months from September to May are wet with precipitation ranging between 121 and 199 mm month⁻¹ (Fig. 4). Among the wet months, September and January are the least wet with 121 and 128 mm month⁻¹, respectively, while November and April are the wettest with 171 and 199 mm month⁻¹, respectively, according to a bimodal rainfall regime (Fig. 4).

Runoff

The runoff model indicated an annual mean land potential evapotranspiration rate of 1100 mm yr⁻¹ and mean baseflow of 220 mm yr⁻¹ (Table 3; Fig. 4). The surface runoff was 150 mm yr⁻¹ (Table 3; Fig. 4). Except for the baseflow, all soil water balance components showed lower values in the dry season (Fig. 4). The average runoff coefficient for the entire basin was estimated at $k_r = 0.25$ (Table 3). The runoff was estimated to have increased by 19% in the period 1961–1993 compared to 1941–1960.

Table 3
Soil water balance in the catchment of Lake Kivu for the years 1941–1991.

Soil water balance	$mm\,yr^{-1}$
Precipitation	1470
Evapotranspiration	1100
Surface runoff	150
Baseflow	220

Lake water levels

A comparison of lake levels observed in situ and with remote sensing confirmed that both time series are accurate within a few cm (Fig. 5). Remotely sensed lake levels for neighbouring Lakes Edward and Victoria show very similar temporal dynamics as for Lake Kivu, indicating that the lake level fluctuations are driven mainly by regional meteorological variations. This is also supported by a comparison of historical trends of lake levels and rainfall in the drainage area (Fig. 6). Periods of high annual precipitation matched with high lake water levels and vice versa both before and after the dam construction of 1959 (Fig. 6). Both curves indicate higher water levels for the period after 1960 with a maximum peak in 1963. The average lake levels increased from 1462.40 m asl for 1941–1960 to 1462.86 m for 1961–1993, and fell back to 1462.41 m in the years 1994–2011, albeit with a twice as large interannual variability than before.

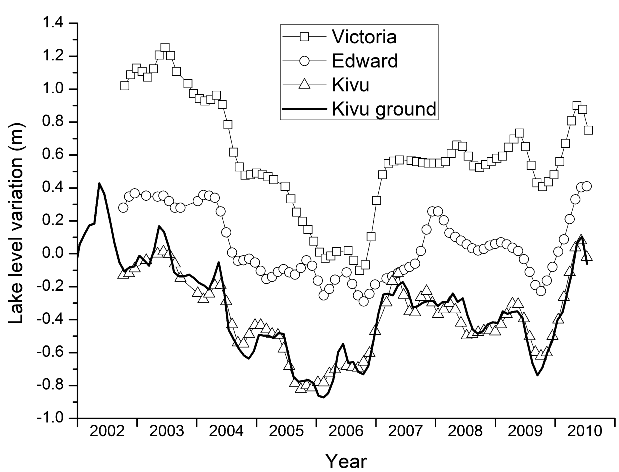

Fig. 5. Comparison of satellite (Crétaux et al. 2011) water level variation (relative to an arbitrary average level) of selected East-African great lakes with the levels observed in situ for Lake Kivu. "Kivu" indicates the satellite-based data and "Kivu ground" the in situ gauged data.

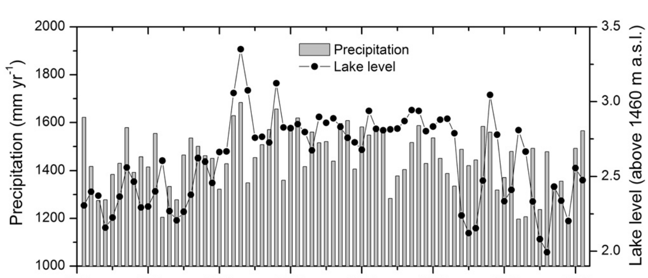

Fig. 6. Annual mean Lake Kivu water level (grey line with circles; data from SNEL) and precipitation (black bold line, data from GPCC until 1997 and TRMM multiplied with a factor 1.2 afterwards). The lake water levels are relative to a height of 1460 m asl. Note that the lower number of precipitation data (Fig. 7) affected the quality of the agreement after 1993.

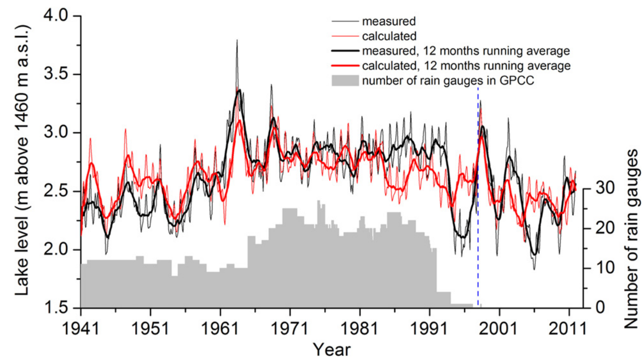

Fig. 7. Comparison between observed and simulated (model output) lake water levels generated by assuming a constant subaquatic groundwater discharge to the lake. The calculated and measured curves are compared with their 12 months running average curves (see legend). The shaded curve indicates the number of rain gauges used in this study.

Lake water balance

Observed and simulated lake levels are compared in Fig. 7. The mean absolute difference between observed and simulated monthly lake levels in the model with constant SGD inflow was 0.17 m. Adding a variable SGD inflow depending on the precipitation of the previous years (Eq. (17)), improved the agreement of extreme (maximum and minimum) lake levels between observations and simulations, but did not remarkably decrease the mean absolute differences or strongly modify the their relationship. We therefore do not see sufficient justification in the observed data to support or reject the hypothesis of a variable SGD inflow depending on precipitation. For the study analysis we used the results of the model with constant SGD inflow, but none of the conclusions would have been different using the model with variable SGD inflow.

The model evaluation suggested that its performance was satisfactory (NSE = 0.60 and RSR = 0.64) for 1941–1958 and good (NSE = 0.72 and RSR = 0.53) for 1959–1976. However for the period after 1977, the predictive power of the model was lower (NSE = 0.34 and RSR = 0.81) most likely due to turbine operating problems (TRACTIONEL and RRI, 1980; FICHTNER, 2008) which induced large uncertainties in the lake discharge.

The correlation between mean annual observed and simulated water levels was good before the outlet of the river was modified in 1977, for both periods before and after the dam construction (Fig. 8). The same was true for the correlations between observed and simulated lake level increase during the rainy season from October to May (Fig. 9). Correlations for the lake level decrease during the dry season were weaker, and the slope was only 0.42 before dam construction and 0.34 thereafter (Fig. 10). After the modification of the outlet, the predictive capability of the model for all three quantities (mean annual level, increase during the wet and decrease during the dry season) became consistently weaker, both for the period 1977–1991 when still sufficient precipitation data was available, and for the period after 1992 for which almost no rain gauge data was available (Figs. 9 and 10).

The observed and simulated lake levels show a consistent seasonality. Maximum lake levels are reached in May (0.16 m above annual average) and minimum lake levels in September (0.10 m below annual average; Fig. 11. Interestingly, the reproduction of the mean seasonal lake water level was equally good (with residuals generally lower than 0.02 m) for all periods, independent of dam construction or modification of the river outlet (Fig. 11). It is only somewhat worse for the period where TRMM data was used for driving the model, which might indicate a seasonal bias in the TRMM data.

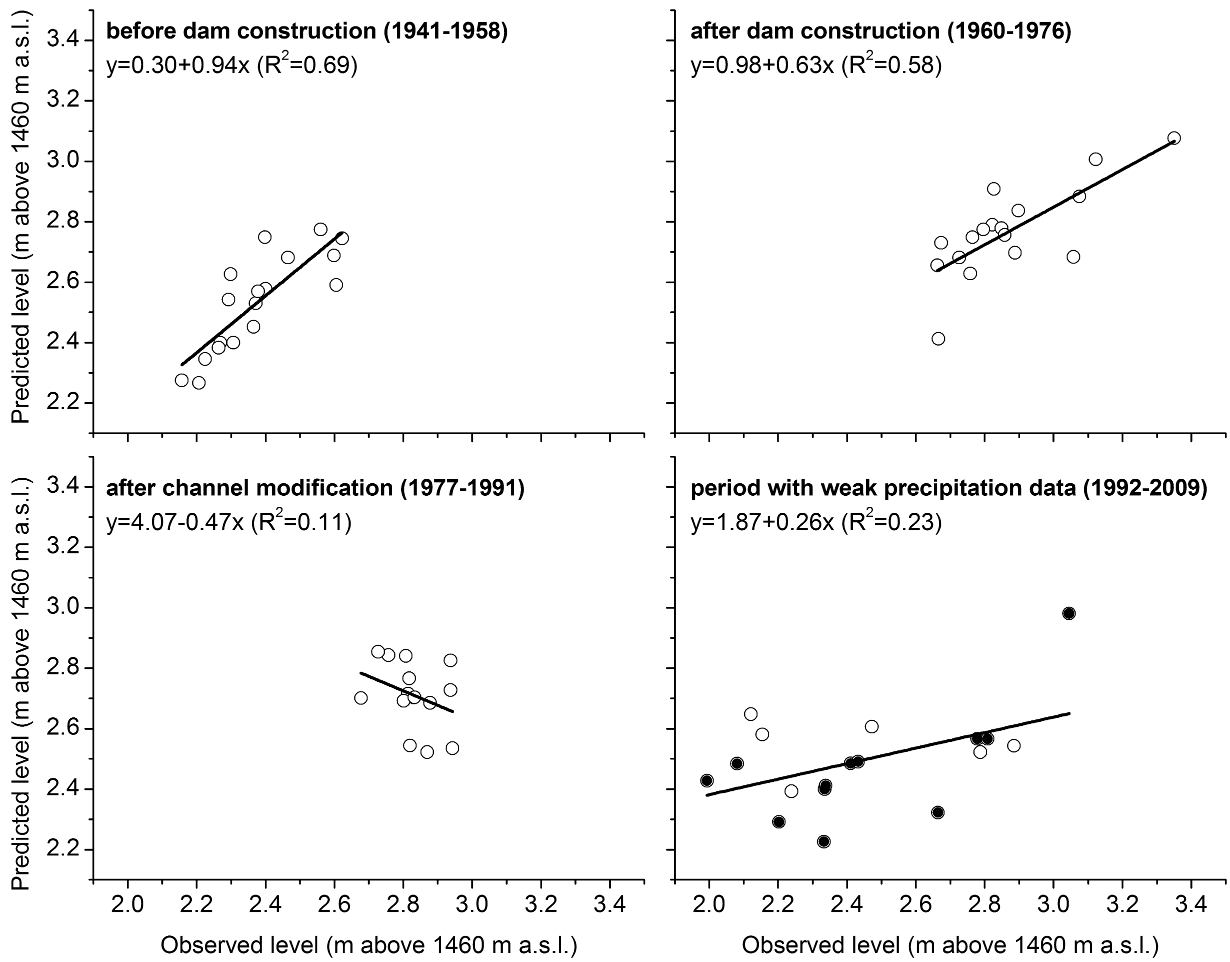

Fig. 8. Correlations between predicted and observed lake levels for different periods. The black dots indicate the years where the TRMM data was used.

The mean annual flows of the calculated lake water balance are summarized in Table 4 and their seasonal variability is shown in Fig. 12. Table 4 highlights the importance of direct precipitation on the lake surface and evaporation (3.5 and 3.6 $km^3\,yr^{-1}$, respectively), which contribute more than half to the total inputs and outputs. The estimated surface inflows (1.6 $km^3\,yr^{-1}$) are lower than the previous estimates of 2.4 $km^3\,yr^{-1}$ (Muvundja et al., 2009) and of 1.6 to 2.4 $km^3\,yr^{-1}$ (Schmid and Wüest, 2012), but similar to the 1.8 $km^3\,yr^{-1}$ proposed by Rinta (2009) from the application of the Soil and Water Assessment Tool (SWAT) model. However the SWAT estimates for evaporation (2.2 $km^3\,yr^{-1}$) and precipitation (2.8 $km^3\,yr^{-1}$) were lower than the estimates found in the literature (Bultot, 1971; Bergonzini, 1998; Muvundja et al., 2009) probably due to large uncertainties in the data sources and comparably low precipitation during the study period (1998–2008) of the SWAT model. Precipitation and its seasonal variability are the same as for the runoff model (Fig. 4), while the river inflows correspond to the sum of the surface runoff and the baseflow.

The SGD inflows were estimated in previous studies to close the salt balance of the lake (Schmid et al., 2005). They are assumed to be constant in the model, and their small apparent temporal variability in Fig. 12 is due to the different number of days per month. The seasonal variation of the water balance is mainly due to the variation in precipitation and the resulting seasonality. The total output is almost constant throughout the year, as the seasonal variation of the outflow that results from water level variations is almost exactly compensated by the seasonal variation of evaporation from the lake surface.

Discussion

The hydro-meteorological features of the Lake Kivu Basin are in accordance with the regional climate (Fig. 4) where the altitude-moderated equatorial climate is bimodal with rainy months (September to May) interrupted by dry months (June to August) because of the twice-annual passage of the Intertropical

Table 4
Lake Kivu water balance as calculated with the model for the years 1941–1991.

Lake water balance	$m^3\,s^{-1}$	$km^3\,yr^{-1}$	mm yr^{-1} [a]	Contribution (%)
Precipitation	111	3.5	1470	55
Inflows	50	1.6	670	25
Subaquatic springs	41	1.3	550	20
Evaporation	115	3.6	1530	57
Discharge	86	2.7	1150	43

[a] related to the lake surface area.

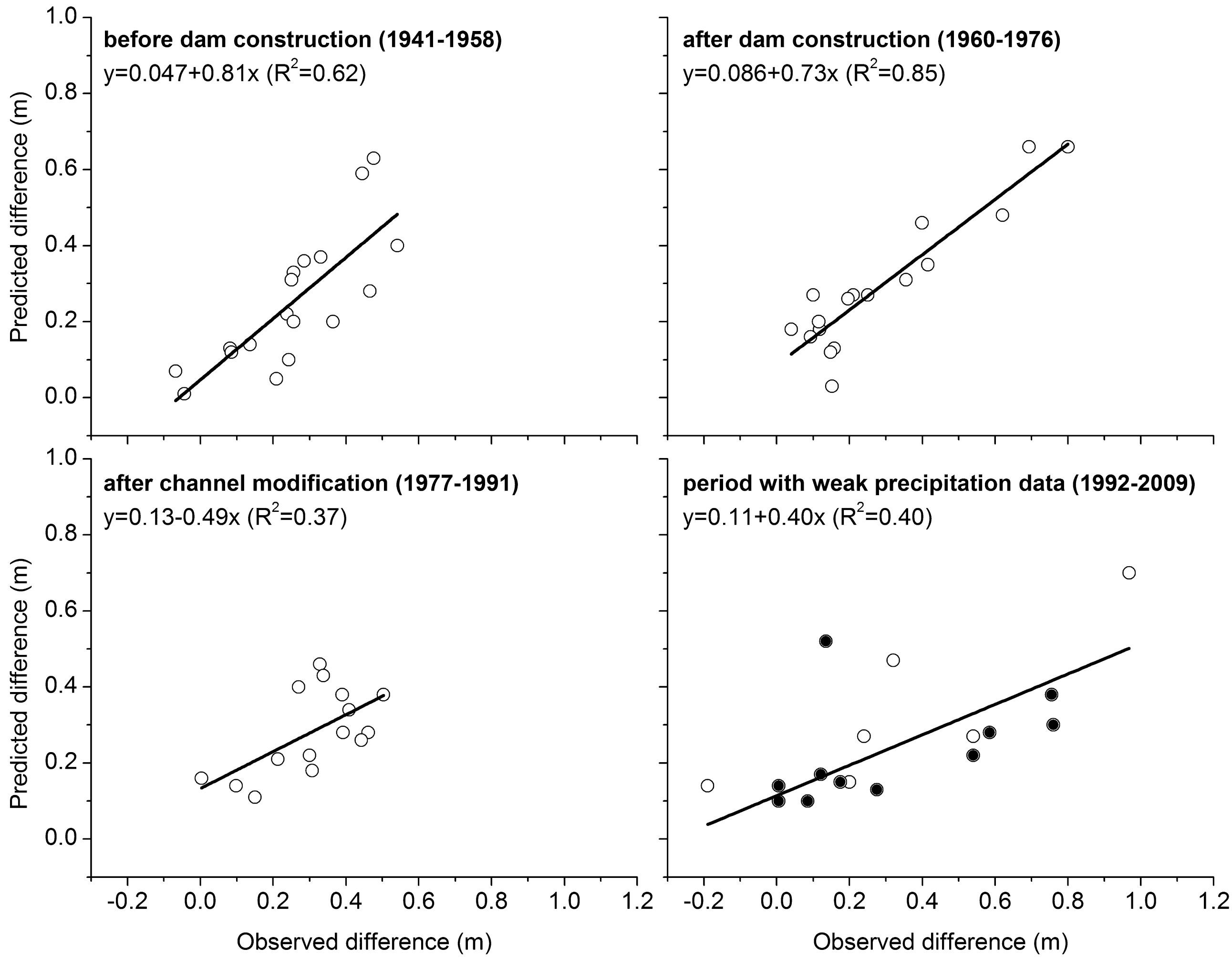

Fig. 9. Comparison of simulated and observed lake level differences between 1 October and 1 May next year (Wet Season).

Convergence Zone (Verschuren et al., 2009). Less seasonal variation is noticed in evaporation and potential evapotranspiration (Figs. 4 and 10) due mostly to low variation in air temperatures near the equator. Evaporation rates of East-African lakes are similar to the precipitation they receive: 1537 mm yr^{-1} for Lake Victoria (Nicholson and Yin, 2002,2004), and 1695 mm yr^{-1} for Lake Tanganyika (Bultot, 1962, 1971).

This study shows a strong similarity of the dynamics of precipitation and lake levels between the basins of Lakes Kivu and Victoria (Fig. 3). Results in Fig. 12 indicate that the Lake Kivu level takes about two months lag to react from precipitation inputs and one month from catchment runoff. The Lake Victoria Basin experienced drought conditions in the 1930s, 1950s, 1970s and 1980s (Nicholson and Yin, 2002; Mbungu et al., 2012). Corresponding low precipitation (Mbungu et al., 2012) was observed in the Lake Kivu Basin (Fig. 2) and led to lake water level low stands (Fig. 6). However the two basins underwent remarkable increasing and decreasing hydrological trends since the 1960s and the 1990s, respectively (Fig. 6), as also reported by Mbungu et al. (2012). The increase in rainfall for the period from 1961 (which was an extreme rainfall year for Lake Victoria; Conway, 2002 and references therein) until 1993 compared to 1941–1960 is very similar in both basins (Fig. 2). These observations are in agreement with those of Hulme et al. (2001) who estimated that there was a wetting trend over the East-African region, as a part of a more coherent zone of wetting across most of the equatorial Africa where some areas experienced increasing rainfall trends of up to 10% or more per century. Meanwhile, an increasing trend in natural hazards mostly due to hydro-meteorological events from the 1960s has recently been reported by Vandecasteele et al. (2010) for the African Great Lakes region (Kivu, Rwanda and Burundi). IPCC (2007) also forecasts a rainfall increase of ~10 to ~20% for East Africa for the next century, which has been confirmed by a more recent simulation project (Bony et al., 2013).

The low lake levels of East-African lakes during the period of 2005/2006 which were felt as an emergency case by the hydropower companies on Ruzizi River (SNEL and SINELAC, 2006), were related to the El-Niño Southern Oscillation cycle and a forcing by the 2006 Indian Ocean dipole (Becker et al., 2010). The response of Lake Kivu to these events was similar to those of Lakes Victoria and Edward (Fig. 5). Bergonzini et al. (2002) discussed the interannual variation of the water balance of Lake Tanganyika and found that its current status is related to precipitation variability. However he argued that the change in runoff conditions due to human activities might also have led to a change in the runoff coefficient relatively to the period before 1960.

The similarity of the agreement before and after dam construction indicates that the dam had no significant influence on the lake level (Figs. 7–10). The correlations for the rainy season are better than those for the dry season indicating that our predictions for runoff (which characterize the rainy season) are better than those for evaporation. This is probably caused by the lack of information on the interannual variation of lake surface evaporation as well as the overall uncertainties of this parameter on the basin scale.

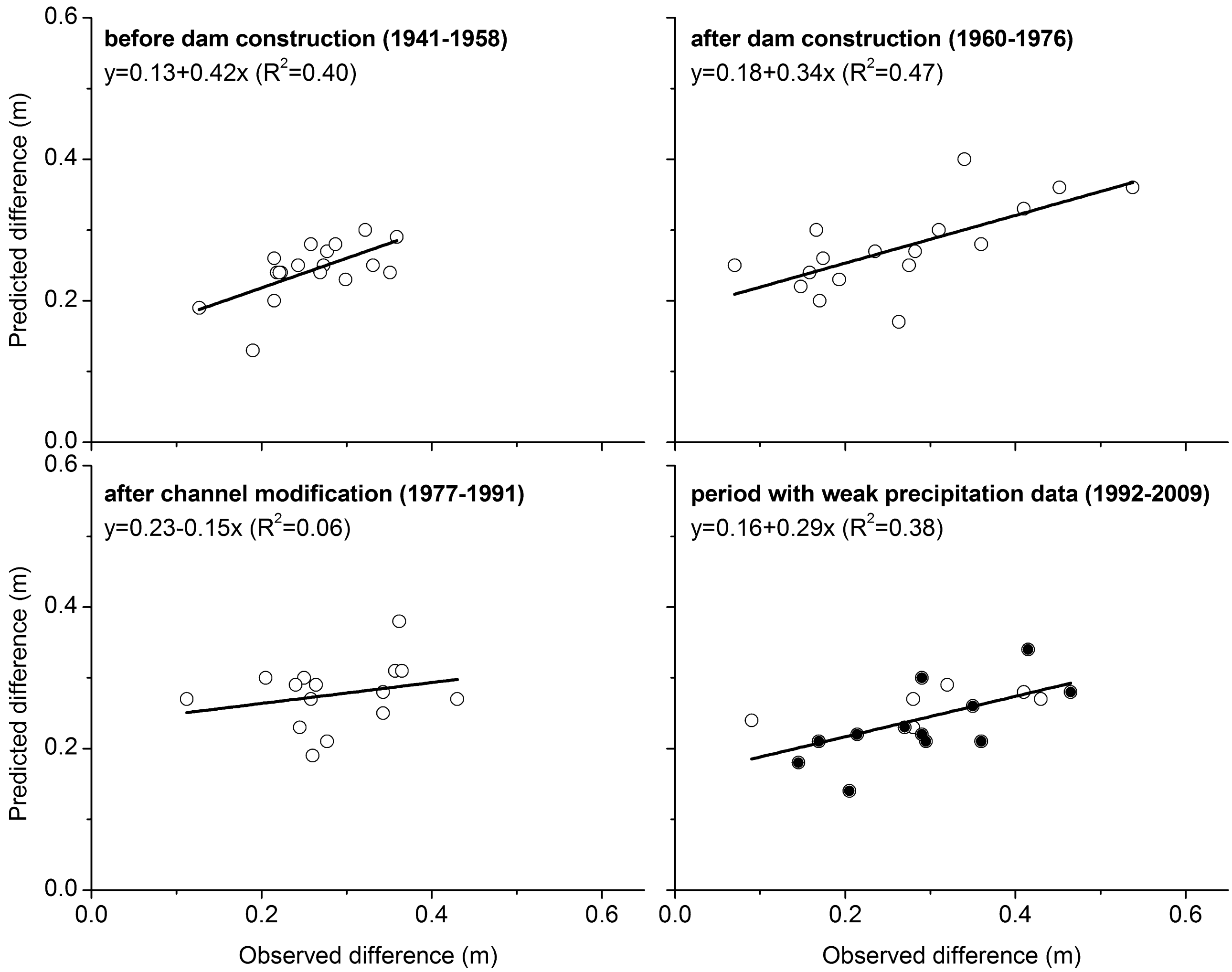

Fig. 10. Comparison of simulated and observed lake level differences between 1 June and 1 September (Dry Season).

Another major source of uncertainty in the lake level model might be the quality of the outflow rating curves.

After 1977, when the hydropower bypass was set up at the Ruzizi outlet together with the Ruzizi channel dredging and widening, the lake level regime seems to have been disturbed considerably as the model is much less successful in predicting the lake levels. TRACTIONEL and RRI (1980) reported that the dam has occasionally operated inadequately during this period causing a slowing down of the river flow. In contrast, the average seasonal variation of the lake level was still perfectly reproduced by the model. The average absolute residuals between the calculated and the observed seasonality were 0.01 m for all periods studied until 1998 (Fig. 11) and only increased to 0.03 m for the period where the TRMM data were used. This confirms that the modification on the Ruzizi outlet did not modify the seasonality of the outflow, but induced some interannual variability in the outlet rating curve. Possible causes might be that the outlet was further modified by changes in flow conditions after the construction work made in 1977, that the modification of the outlet allowed the dam operations to take some influence on the mean annual water level, e.g. in cases of malfunctioning of the turbines as reported above, or that the outflow of the lake was to some extent managed.

Despite of the uncertainties in the raw data and the model setup, the water balance devised in this study matches well with the ranges provided by previous studies (Schmid and Wüest, 2012). The long-term average precipitation estimate used in this study (1470 mm yr^{-1}) is very close to the estimate of 1497 mm yr^{-1} used by Bergonzini (1998), while he used 8% lower lake surface evaporation (1412 mm yr^{-1} from Bultot, 1971). However, previous evaporation estimates range from 1060 mm yr^{-1} (Verbeke, 1957) to 1690 mm yr^{-1} (UNESCO, 1978).

The model estimated average baseflow and surface runoff to 220 mm yr^{-1} and 150 mm yr^{-1}, respectively. Together they yield 370 mm yr^{-1}, which corresponds to a runoff coefficient of 0.25. Similar values have been predicted in several studies for this region (Shahin, 2002). The baseflow is estimated to be more important than surface runoff, which may be due to the volcanic soils which retain much water (Driessen et al., 2001; IUSS, 2007). The subaquatic groundwater discharge (SGD) is an important component of the lake water balance (Schmid et al. 2005; Schmid and Wüest, 2012). The inflow by SGD is assumed to be at least partially derived from infiltration in the volcanic soils on the river-free area of 685 km^2 in the North of the lake. However, the estimated SGD of 1.3 km^3 yr^{-1} would correspond to 1900 mm yr^{-1} relative to this sub-catchment area, which is higher than the precipitation received. Further investigations are therefore required to determine the origin of these water masses as well as their residence time. Recent findings revealed that groundwater resources in East Africa are dependent on extreme rainfall rather than average rains (Taylor et al., 2013).

Previous lake discharge estimates of 3.2 km^3 yr^{-1} (Degens et al., 1973) and 3.6 km^3 yr^{-1} (Muvundja et al., 2009) were rather

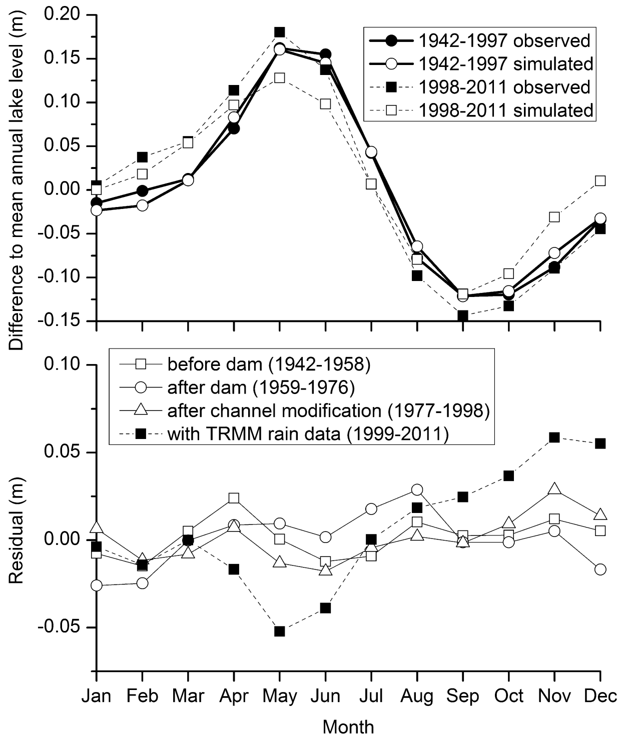

Fig. 11. Above: Monthly deviation from the annual mean of the observed and simulated lake levels, averaged for the periods where the GPCC (1942–1997) and the TRMM data (1998–2011) were used, respectively. Below: Monthly residuals (differences between calculated and observed lake levels) for different past periods.

applicable to a certain period of the time series or overestimates. However our estimate of 2.7 $km^3\,yr^{-1}$ is close to the value of 2.8 $km^3\,yr^{-1}$ suggested by Bergonzini (1998) despite of the difference in the method he used to establish the outflow data for the period of 1951–1973. Although Bergonzini (1998) accorded low confidence to the lake level records up to 1950, our compilation showed only a slight difference of +5% between the lake discharge (1.9 $km^3\,yr^{-1}$) for the period of 1941–1950 and that of 1951–1959 (2.0 $km^3\,yr^{-1}$). In addition, Bultot (1962) estimated the lake discharge to be 2.1 $km^3\,yr^{-1}$ for the period of 1951–1973, which is similar to our estimations. From the early 1960s, the lake level (Fig. 8) as well as the discharge significantly increased with the latter rising to 2.9 $km^3\,yr^{-1}$ for the period 1961–1993 due to an increase in rainfall. Recently, the mean lake level has fallen back to the level before 1961, but with a twice as high interannual variability than before (Fig. 7).

Precipitation and net inflow (runoff + SGD) represent 55% and 45% of the overall inputs (Table 4) in agreement with estimates (54 vs. 46%) of Bergonzini (1998). Evaporation and outflow represented

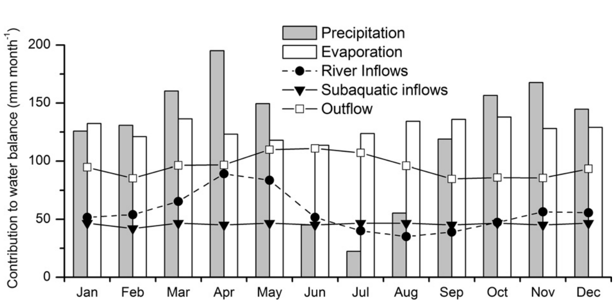

Fig. 12. Seasonal contribution of the different inputs and outputs to the lake water balance averaged for the period from 1941 to 1991. Precipitation and evaporation refer to the lake surface precipitation and evaporation, respectively, whereas subaquatic inflows represent the SGD and outflow indicates the lake discharge.

57 and 43% (Table 4) of the total water losses, respectively, indicating a high lake level sensitivity to hydro-meteorological changes (Russell and Johnson 2006). By reducing the precipitation values in the model input, we can roughly estimate at which average of long-term precipitation the lake would get closed, assuming that evaporation from the lake surface as well as the SGD remain unchanged. This would be the case if precipitation in the basin were reduced to ~60% of its current value or ~900 mm/yr.

The results of the present study and the discussion of the uncertainties involved highlight the necessity to better monitor the hydrology of Lake Kivu and its basin. Continuous time series of quality-assured data of precipitation and other meteorological observations on the lake and in the catchment, as well as of the discharge of selected tributaries to the lake would help to better constrain the water balance of the lake. This will be necessary in order to be able to observe and quantify potential effects of climate change on the water level and the hydrological balance of the lake in the future.

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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration: Guidelines for Computing Crop Requirements, Irrigation and Drainage Paper No. 56. FAO, Rome.

Asadullah, A., McIntyre, N., Kigobe, M., 2008. Evaluation of five satellite products for estimation of rainfall over Uganda. Hydrol. Sci. J. 53 (6), 1137–1150.

Ballatore, T., 2012. Lake Basins: Topography and Surface Water. Lake Basin Action Network. http://www.lakebasin.org/

Becker, M., Llovel, W., Cazenave, A., Güntner, A., Crétaux, J.-F., 2010. Recent hydrological behaviour of the East African great lakes region inferred from GRACE, satellite altimetry and rainfall observations. C. R. Geosci. 342, 223–233.

Beighley, R.E., Ray, R.L., He, Y., Lee, H., Schaller, L., Andreadis, K.M., Durand, M., Alsdorf, D.E., Shum, C.K., 2011. Comparing satellite derived precipitation datasets using the Hillslope River Routing (HRR) model in the Congo River Basin. Hydrol. Process. 25, 3216–3229.

Bergonzini, L., Richard, Y., Camberlin, P., 2002. Interannual variation of the water budget of Lake Tanganyika (1932–1995): changes in the precipitation-lake water excess relationship. Hydrol. Sci. J. 47 (5), 781–796.

Bergonzini, L., 1998. Bilans hydriques des de lacs du rift Est-Africain (lacs Kivu, Tanganyika, Rukwa et Nyassa). Série Sciences Géologiques, vol. 103. Musée Royal de l’Afrique Centrale, Tervuren (Belgique).

Bigororande, K., 1982. Bilans Hydriques Comparés de Deux Stations du Kivu: Mulungu et Tshibinda. Mémoire de Licence. Département de Géographie-Sciences Naturelles. ISP/Bukavu, Bukavu, R.D. Congo.

Bikoba, Z.C., 1984. Etude Pluviométrique de la Station de Nyamunyunye de 1952 à 1983. Mémoire de Licence. Département de Géographie-Sciences Naturelles, ISP/Bukavu, Bukavu, R.D. Congo.

Bitacibera, K., Gatsimbanyi, S., 1978. Essai D’analyse des Relevés Météorologiques au Kivu. Travail de Fin d’Etudes. Département de Géographie, ISP-Bukavu, UNAZA, Bukavu, R.D. Congo.

Bony, S., Bellon, G., Klocke, D., Sherwood, S., Fermepin, S., Denvil, S., 2013. Robust direct effect of carbon dioxide on tropical circulation and regional precipitation. Nat. Geosci. 6, 447–451.

Budyko, M.I., 1958. The Heat Balance of the Earth’s Surface. US Department of Commerce, Washington, DC.

Bultot, F., 1954. Saisons et Périodes Sèches et Pluvieuses au Congo Belge et au Ruanda-Urundi. INEAC, Bureau Climatologique, Communication. no. 9, Brussels.

Bultot, F., 1962. Sur la détermination des moyennes mensuelles et annuelles de l’évaporation réelle et de l’écoulement dans le bassin congolais. Bull. Acad. R. Sci. d’Outre-mer 8 (4), 816–838.

Bultot, F., 1971. Atlas Climatique du Bassin Congolais, vol. 2: Les Composantes du Bilan d'eau. Publications de l'Institut National pour l'Étude Agronomique du Congo, R.D. Congo.

Cheema, M.J.M., Bastiaanssen, W.G.M., 2012. Local calibration of remotely sensed rainfall from TRMM satellite for different periods and spatial scales in the Indus Basin. Int. J. Remote Sens. 33 (8), 2603–2627.

Chen, X., Alimohammadi, N., Wang, D., 2013. Modeling interannual variability of seasonal evaporation and storage change based on the extended Budyko framework. Water Resour. Res. 49, 6067–6078.

Conway, D., 2002. Extreme rainfall events and lake level changes in East Africa: recent events and historical precedents. In: Odada, E.O., Olago, D.O. (Eds.), The East African Great Lakes: Limnology, Palaeolimnology and Biodiversity. Kluwer Academic Publishers, Netherlands, pp. 62–92.

Crétaux, J.-F., Jelinski, W., Calmant, S., Kouraev, A., Vuglinskiy, V., Bergé-Nguyen, M., Gennero, M.-C., Nino, F., Abarca Del Rio, R., Cazenave, A., Maisongrande, P., 2011. SOLS: a lake database to monitor in near real time water level and storage variations from remote sensing data. J. Adv. Space Res. 47 (9), 1497–1507.

Degens, E.T., von Herzen, R.P., Wong, H.K., Deuser, W.G., Jannasch, H.W., 1973. Lake Kivu: structure, chemistry and biology of an East African Rift Lake. Geol. Rundsch. 62, 245–277.

Dinku, T., Ceccato, P., Connor, S.J., 2011. Challenges of satellite rainfall estimation over mountainous and arid parts of east Africa. Int. J. Remote Sens. 32 (21), 5965–5979.

Donohue, R.J., Roderick, M.L., Vicar, T.R., 2010. Can dynamic vegetation improve the accuracy of Budyko's hydrological model? J. Hydrol. 390, 23–34.

Driessen, P., Deckers, J., Nachtergaele, F., 2001. Lecture Notes on the Major Soils of the World. World Soil Reports 94, June 2001. FAO, Rome.

Ebert, E.E., Janowiak, J.E., Kidd, C., 2007. Comparison of near-real-time precipitation estimates from satellite observations and numerical models. Bull. Am. Met. Soc. 88, 47–64.

FAO, 2004. Global Map of Monthly Reference Evapotranspiration-10 arc minutes, Available at http://www.fao.org/geonetwork/srven/main.home

Fehr, S., 1984. Réflexions conceptuelles sur l'étude des régimes pluviométriques en milieux tropicaux et exposé d'une nouvelle approche de leur analyse. Cahiers du CERUKI 12, 107–124.

FICHTNER, Décembre 2008. Etudes préalables pour l'aménagement d'un site hydroélectrique communautaire Ruzizi III sur la Rivière Ruzizi et le Développement du volet Energie des activités de la Communauté Economique des Pays des Grands lacs (CEPGL). Lot 1 et Lot 2: Etude de faisabilité pour l'aménagement hydroélectrique de Ruzizi III, Etude de préfaisabilité du site SISI 5 sur la Ruzizi et du réaménagement de l'exutoire du lac Kivu à Cyangugu (Topographie), Rapport de Topographie 5761P21. Energie des Grands lacs (EGL)-Union Européenne (UE).

Franchito, S.H., Rao, V.B., Vasques, A.C., Santo, C.M.E., Conforte, J.C., 2009. Validation of TRMM precipitation radar monthly rainfall estimates over Brazil. J. Geophys. Res. 114, D02105.

Hargreaves, G.L., Hargreaves, G.H., Riley, J.P., 1985. Irrigation water requirements for Senegal River Basin. J. Irrig. Drain. Eng. ASCE 111 (3), 265–275.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978.

Hulme, M., Doherty, R., Ngara, T., New, M., Lister, D., 2001. African climate change: 1900–2100. Clim. Res. 17, 145–168.

INEAC, 1960. Bulletin climatologique annuel du Congo et du Ruanda-Urundi/Bureau Climatologique. Publications de l'Institut National pour l'Etude Agronomique du Congo. Communication/Bureau Climatologique [000962565], Bruxelles.

IPCC, 2007. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment, Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, p. 976.

Isumbisho, M., Kaningini, M., Descy, J.-P., Baras, E., 2004. Seasonal and diel variations in diet of the young stages of *Limnothrissa miodon* in Lake Kivu, Eastern Africa. J. Trop. Ecol. 20, 73–83.

IUSS Working Group WRB, 2007. World Reference Base for Soil Resources 2006. First Update 2007, World Soil Resources Reports No. 103. FAO, Rome.

Javanmard, S., Yatagai, A., Nodzu, M.I., Bodaghjamali, J., Kawamoto, H., 2010. Comparing high-resolution gridded precipitation data with satellite rainfall estimates of TRMM_3B42 over Iran. Adv. Geosci. 25.

Jiang, H., Liu, Ch, Zipser, E., 2011. A TRMM-based tropical cyclone cloud and precipitation feature database. J. Appl. Meteor. Climatol. 50, 1255–1274.

Kilauli, N., 1976. Bilan D'eau à la Station de Bukavu. Travail de Fin d'Etudes. Département de Géographie-Sciences Naturelles, ISP/Bukavu, Bukavu, R.D. Congo.

Kite, G.W., 1981. Recent changes in level of Lake Victoria. Hydrol. Sci. Bull. 26 (3), 233–243.

Kizza, M., Rodhe, A., Xu, C.-Y., Ntale, H.K., Halldin, S., 2009. Temporal rainfall variability in the Lake Victoria Basin in East Africa during the twentieth century. Theor. Appl. Climatol. 98, 119–135.

Kombi, M., 1982. Bilan Hydrique de la Station de Ndihira. Mémoire de Licence. Département de Géographie-Sciences Naturelles, ISP/Bukavu, Bukavu, R.D. Congo.

Liechti, T.C., Matos, J.P., Biollat, J.L., Schleiss, A.J., 2012. Comparison and evaluation of satellite derived precipitation products for hydrological modeling of the Zambezi River Basin. Hydrol. Earth Syst. Sci. 16, 489–500.

MacDonald, A., Taylor, R.G., Bonsor, H.C., 2013. Groundwater in Africa. Is there sufficient water to support the intensification of agriculture from land grabs? In: Allan, T., et al. (Eds.), Handbook of Land and Water Grabs in Africa. Rontledge, Abington-New York, pp. 376–383.

Masilya, M.P., Darchambeau, F., Isumbisho, M., Descy, J.-P., 2011. Diet overlap between the newly introduced *Lamprichtys tanganicanus* and the Tanganyika sardine in Lake Kivu, Eastern Africa. Hydrobiologia 675, 75–86.

Mason, I.M., Guzkowska, M.A.J., Rapley, C.G., 1994. The response of lake levels and areas to climatic change. Clim. Change 27, 161–197.

Mbungu, W., Ntegeka, V., Kahimba, F.C., Taye, M., Willems, P., 2012. Temporal and spatial variations in hydro-climatic extremes in the Lake Victoria basin. J. Phys. Chem. Earth 50–52, 24–33.

Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Sayre, R., Trabucco, A., Zomer, R., 2013. A high-resolution bioclimate map of the world: a unifying framework for global biodiversity research and monitoring. Global Ecol. Biogeogr. 22 (5), 630–638.

Mistry, V.V., Conway, D., 2003. Remote forcing of East African rainfall and relationships with fluctuations in levels of Lake Victoria. Int. J. Climatol. 23, 67–89.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 5 (3), 885–900.

Muvundja, F.A., Pasche, N., Bugenyi, F.W.B., Isumbisho, M., Müller, B., Namugize, J.-N., Rinta, P., Schmid, M., Stierli, R., Wüest, A., 2009. Balancing nutrient inputs to Lake Kivu. J. Great Lakes Res. 35, 406–418.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models: Part1. A discussion of principles. J. Hydrol. 10 (3), 282–290.

Nicholson, S.E., Some, B., McCollum, J., Nelkin, E., Klotter, D., Berte, Y., Diallo, B.M., Gaye, I., Kpabeba, G., Ndiaye, O., Noukpozounkou, J.N., Tanu, M.M., Thiam, A., Touré, A.A., 2003. Validation of TRMM and other rainfall estimates with a high-density gauge dataset for West Africa Part II: validation of the TRMM rainfall products. J. Appl. Meteorol. 42, 1355–1368.

Nicholson, S.E., Yin, X., 2004. Mesoscale patterns of rainfall, cloudiness and evaporation over the Great Lakes of East Africa. In: Odada, E.O., Olago, D.O. (Eds.), The East African Great Lakes: Limnology, Palaeolimnology and Biodiversity. Advances in Global Change Research 12(2), pp. 93–119.

Nicholson, S.E., Yin, X., 2002. Interpreting annual rainfall from the levels of Lake Victoria. J. Hydrometeorol. 3, 406–416.

Pasche, N., Muvundja, F.A., Schmid, M., Wüest, A., Müller, B., 2012. Nutrient cycling in Lake Kivu. In: Descy, J.-P., Darchambeau, F., Schmid, M. (Eds.), Lake Kivu: Limnology and biogeochemistry of a tropical great lake, Aquat. Ecol. Ser. 5, pp. 31–45.

Pasche, N., Wehrli, B., Alunga, G., Muvundja, F.A., Schurter, M., Schmid, M., 2010. Abrupt onset carbonate deposition in Lake Kivu during the 1960: response to environmental changes. J. Paleolimnol. 44, 931–946.

Rinta, P., Msc thesis 2009. Modelling nitrogen and phosphorus inputs to Lake Kivu, Central Africa. Department of Geography, Faculty of Mathematics and natural resources, University of Turku, Turku, Finland.

Ross, K.A., 2014. The effect of subaquatic volcanism on the structure of Lake Kivu in the Albertin Rift, East Africa. In: PhD thesis. ETH-Zürich, Zürich, Switzerland.

Ross, K.A., Smets, B., De Batist, M., Hilbe, M., Schmid, M., Anselmetti, F., 2014. Lake-level rise in the late Pleistocene and active subaquatic volcanism since the Holocene form the current state of Lake Kivu; East Africa Rift. Geomorphology (in press).

Rudolf, B., Becker, A., Schneider, U., Meyer-Christoffer, A., Ziese, M., 2010. The New GPCC Full Data Reanalysis Version 5 Providing High-quality Gridded Monthly Precipitation Data for the Global Land-surface is Public Available Since December 2010. GPCC Status Report December 2010. Global Precipitation Climatology Centre (GPCC).

Rudolf, B., Schneider, U., 2005. Calculation of gridded precipitation data for the global land-surface using in-situ gauge observations. In: Proceedings of the 2nd Workshop of the International Precipitation Working Group IPWG, Monterey, October 2004, EUMETSAT.

Russell, J.M., Johnson, T.C., 2006. The water balance and stable isotope hydrology of Lake Edward, Uganda-Congo. J. Great Lakes Res. 32, 77–90.

Schmid, M., Halbwachs, M., Wehrli, B., Wüest, A., 2005. Weak mixing in Lake Kivu: New insights indicate increasing risk of uncontrolled gas eruption. Geochem. Geophys. Geosyst. 6, Q07009.

Schmid, M., Wüest, A., 2012. Stratification, mixing and transport processes in Lake Kivu. In: Descy, J.-P., Darchambeau, F., Schmid, M. (Eds.), Lake Kivu: limnology and biogeochemistry of a tropical great lake.

Shahin, M., 2002. Hydrology and Water Resources of Africa. Kluwer, Dordrecht, pp. 688–689.

SINELAC, 1989. Aménagement hydroélectrique de la Ruzizi II par la Communauté Economique des Pays de Grands Lacs (CEPGL). Tractebel S.A. 07.1989, Bruxelles.

SNEL, SINELAC, 2006. Compte Rendu de la réunion sur l'évaluation du comportement du niveau du lac Kivu, Mururu (Rwanda), 08 Juin 2006.

Snoeks, J., Kaningini, M., Masilya, P., Nyinawamwiza, L., Guillard, J., 2012. Fishes in Lake Kivu: diversity and fisheries. In: Descy, J.-P., Darchambeau, F., Schmid, M. (Eds.), Lake Kivu: limnology and biogeochemistry of a tropical great lake.

Sylla, M.B., Giorgi, F., Coppola, E., Mariotti, L., 2013. Uncertainties in daily rainfall over Africa: assessment of gridded observation products and evaluation of a regional climate model simulation. Int. J. Climatol. 33, 1805–1817.

Taylor, R.G., Mileham, L., Tindimugaya, C., Majugu, A., Muwanga, A., Nakilez, B., 2006. Recent glacial recession in the Rwenzori mountains of East Africa due to rising air temperature. Geophys. Res. Lett. 33, L10402.

Taylor, R.G., Todd, M.C., Kongola, L., Maurice, L., Nahozya, E., Sanga, H., MacDonald, A.M., 2013. Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. Nat. Climate Change 3, 374–378.

Tierney, J.E., Smerdon, J.E., Anchukaitis, K.J., Seager, R., 2013. Multidecadal variability in East African hydroclimate controlled by the Indian Ocean. Nature 493, 389–392.
Trabucco, A., Zomer, R.J., Bossio, D.A., Van Straaten, O., Vercot, L.V., 2008. Climate change mitigation through afforestation/reforestation: a global analysis of hydrologic impacts with four case studies. Agric. Ecosyst. Environ. 126 (1–2), 81–97.
TRACTIONEL and RRI, 1980. Projet Définitif D'une Deuxième Centrale Hydroélectrique sur la Ruzizi, Hydrologie. Pièce Contractuelle No. 2A. A.S.B.L. pour l'Electrification de la Région des Grands Lacs “EGL-Bujumbura”, Bruxelles-Dortmund.
UNESCO, 1978. World water balance and water resources of the Earth. Stud. Rep. Hydrol. 25, 663.
Van der Velde, Y., Vercauteren, N., Jaramillo, F., Dekker, S.C., Destouni, G., Lyon, S.W., 2013. Exploring hydroclimatic change disparity via the Budyko framework. Hydrol. Process. (in press).
Vandecasteele, I., Moeyersons, J., Trefois, P., 2010. An assessment of the spatial and temporal distribution of natural hazards in Central Africa. In: Runge, J. (Ed.), African Palaeoenvironments and Geomorphic Landscape Evolution. Series ‘Palaeoecology of Africa’, vol. 30. CRC Press, Taylor & Francis Group, London, UK, pp. 279–300.
Vangu, L., 1981. Bilan hydrologique du bassin versant de la Ruzizi: Esquisse d'une étude hydrologique. Mémoire de Licence. Département de Géographie-Sciences Naturelles, ISP/Bukavu, Bukavu, R.D. Congo.
Verbeke, J., 1957. Recherches écologiques sur la faune des grands lacs de l'Est du Congo Belge. Exploration hydroécologique des lacs Kivu. Edouard et Albert (Bruxelles) 3 (1), 177.
Verburg, P., Hecky, R.E., Kling, H., 2003. Ecological consequences of a century of warming in Lake Tanganyika. Science 3001, 505–507.
Verschuren, D., Sinninghe-Damsté, J.S., Moernaut, J., Kristen, I., Blaauw, M., Fagaut, M., Haug, G.H., 2009. CHALLACEA project members Half-precessional dynamics of monsoon rainfall near the East African Equator. Nature 462 (7273), 637–641.
Vodacek, T., Ebinger, C., Hecky, R., Gasingirwa, M.-C., Hughes, M., Nyinawamwiza, L., Sebashongore, D., January 13–15, 2010. Tropical Rift Lake Systems: Integrated Volcanologic, Tectonic, and Biogeochemical, and Geohazard Assessment of Lake Kivu, White Paper of the Workshop. Gisenyi, Rwanda.
Vuglinskiy, V., Monteduro, M., Sessa, R., Gronskaya, T., Crétaux, J.-F., 2009. Water Level: Water Level in Lakes and Reservoirs, Water Storage. Assessment of the Status of the Development of Standards for the Terrestrial Essential Climate Variables. Global Terrestrial Observing System, FAO, Rome.
Wang, Q.J., Pagano, T.C., Zhou, S.L., Hapuarachchi, H.A.P., Zhang, L., Robertson, D.E., 2011. Monthly versus daily water balance models in simulating monthly runoff. J. Hydrol. 404, 166–175.
Ward, E., Buytaert, W., Peavert, L., Wheater, H., 2011. Evaluation of precipitation products over complex mountainous terrain: a water resources perspective. Adv. Water Resour. 34, 1222–1231.
WMO, 2006. Guide to Meteorological Instruments and Methods of Observation and Information Dissemination, 7th ed. World Meteorological Organization, Geneva, Switzerland.
Wolf, D.B., Marks, D.A., Amitai, E., Silberstein, D.S., Fisher, B.L., Tokay, A., Wang, J., Pippitt, J.L., 2005. Ground validation for the Tropical Rainfall Measuring Mission (TRMM). J. Atmos. Oceanic Technol. 22, 365–380.
Zhang, L., Potter, N., Hickel, K., Zhang, Y., Shao, Q., 2008. Water balance modelling over variable time scales based on the Budyko framework – model development and testing. J. Hydrol. 360 (1–4), 117–131.
Zomer, R.J., Trabucco, A., Bossio, D.A., van Straaten, O., Verchot, L.V., 2008. Climate change mitigation: a spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agric. Ecosyst. Environ. 126 (1-2), 67–80.