Hydro-meteorological processes driving solute transport in Lake Victoria

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**ABSTRACT**
This study explores by a vertically integrated tracer transport model, hydro-meteorological event characteristics and their influence on solute transport. Changes in hydro-meteorological processes and increasing frequency of extreme weather events are responsible for changing the lake water balance, influencing streamflow variations, and lake tracer transport. We compare historical data over a long time with model data from a vertically integrated model in COMSOL Multiphysics. We consider water balance, sources of data uncertainty, correlations, extreme rain and inflow years, and seasonal variations. The lake transport model has estimated soluble loading and transportation. The results showed there are strong correlations between tributary inflows and precipitation, and between lake outflow and water level. It was found that “events” influence lake level fluctuations. The solute transport was shown to vary more in wet periods. Modeled transportations were higher in Kenya and Uganda lake zones than in Tanzanian zones. The major inflow, from the Kagera river, appears to strongly influence lake solute transportation, so the composition of this river must be considered.

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**Introduction**
Lake Victoria is the second largest freshwater lake in the world (Christopher, Paul, & Hamadi, 2014; Hasan & Jin, 2014; Kundu et al., 2017), lying within three East African countries: Uganda (43%), Kenya (6%), and Tanzania (51%) (Christopher et al., 2014; Hasan & Jin, 2014; Kundu et al., 2017). The lake is the major freshwater reservoir and source of water for domestic, agriculture, industrial, fishery, and transport purposes in the surrounding region (Kundu et al., 2017; LVFO, 2015). Its resources, support livelihoods, and ecosystem services for over 40 million people (Kundu et al., 2017). In three major cities in East Africa (Mwanza, Kampala, and Kismu) and several major towns and urban centers, nearly 5 million people receive their water supply directly from the lake, while many rural villages also get their water supply from the lake or from rivers within the basin (LVBC, 2006).

Lake Victoria lies on the equator and has a long shoreline with numerous gulfs and bays, many of which are recipients of river discharge and municipal and industrial effluents (Cornelissen, Silsbe, Verreth, Van Donk, & Negelkerke, 2014; Gikuma-Njuru & Hecky, 2005; MacIntyre, Romero, Silsbe, & Emery, 2014). The flow dynamics in lakeshore areas are complex due to variations in geomorphology that affect water, sediments, concentrations of chemicals, and ecological diversity in the lake (Gikuma-Njuru, Hecky, MacIntyre, & Guildford, 2018; Luyiga et al., 2015).

The lake water level is important for people living in the lake basin and their socioeconomic activities that depend on the lake. Knowledge of hydrological systems is necessary for understanding the lake water balance. Lake Victoria water balance was first studied by Hurst and Phillips (1933), followed by Hurst (1952), Merelieu (1961), de Baulny and Baker (1970), and the WMO (1974). Historical water-level variations have been reported (Awange et al., 2008; Hasan & Jin, 2014; Kite, 1981; Piper, Plinston, & Sutcliffe, 1986; Sene & Plinston, 1994; Swenson & Wahr, 2009; Tate, Sutcliffe, Conway, & Farquharson, 2004; Yin & Nicholson, 1998). The water level is determined by hydro-meteorological parameters and events, creating surface and sub-surface runoff, which contribute to pollution and sedimentation to the lake (Okungu et al., 2014). In recent decades, some of the rivers and streams serving the lake and its near-shore areas have become particularly polluted by partially treated municipal waste, industrial effluents, urban surface contaminated runoff, and raw sanitary effluent from settlements (LVEMP, 2005).

In Kenya, most lake nutrients originate from organic and inorganic waste for intensive agricultural activities, municipality sewage, and livestock (Kyomuhendo, 2003). Some rivers carry industrial discharges directly draining along the lake shoreline and shallow Winam Gulf, near Kisumu (Kundu et al., 2017; Kyomuhendo, 2003; Longgen, Zhongjie, Ping, & Leyi, 2009). Malfunctioning sewage plants discharge...
inadequately treated sewage into rivers and rivers is discharged into the lake (Christopher et al., 2014). The agricultural and chemical industries discharge pollutants directly into the lake (Christopher et al., 2014). In Tanzania, small-scale gold mining activities have increased potential sources of heavy metals (LVEMP, 2005), while pesticide and nutrient-rich effluents are also discharged into Lake Victoria (Shayo & Limbu, 2018). In Uganda, heavy metals originating from major cities and remote inland areas (Ljung, 2002), a major food processing, textile, leather, paper production, and metallurgy industries in Jinja (Oguttu, Bugenyi, Leuenberger, Wolf, & Bachofen, 2008), and pollution from Murchison Bay affect the near shore areas (Kabenge, Wang, & Li, 2016). There is much research into lake water balance, water pollution, and eco-system services separately, but definitive work of assessing hydro-meteorological processes and its characteristics that are influencing solute transportation are still missing.

To resolve the problem, it is necessary to understand lake hydro-meteorological character and its influence. In this study, historical data were applied in a shallow water model with an advection-dispersion process for tracer dispersion. Advection-dispersion process model and velocities were determined from the lake hydrodynamic model to determine the spread of pollutant substances, similar to (Hans, Peter, & Lars, 1992). The pollution load in the lake is dependent on the discharges into the lake from the catchments and atmospheric deposition on the lake and its outflow to the river Nile.

The Lake Victoria Basin Commission (LVBC) has recommended that the following studies be carried out (Mwanuzi, Abouda, Muyodi, & Hecky, 2005): i) Monitor the hydro-meteorological processes in the lake basin and use simulation models to assess whether possible interventions in the lake will affect lake circulation; ii) conduct studies on lake pollution near the lake shore, and iii) check the status of the Kagera river, which is one of the largest tributaries of Lake Victoria, and monitor events in its catchment that can influence the northern shores of Lake Victoria.

The main objectives of the present study were therefore to:

- Analyze how hydro-meteorological processes affect the water balance in Lake Victoria.
- Analyze how the recipient inflows, lake water circulation, and seasonal variations influence the lake water composition.
- Develop a hydrometeorology-driven simulation model that can describe the lake water balance and circulation effect.

The historical data were analyzed to gain an understanding of annual and seasonal stream flow variations, and particular months were compared for seasonal fluctuations in specific streams. Correlations between the time series were also analyzed. Monthly variations in precipitation were integrated with lake inflow data to identify important sources of variation and sources of uncertainty that contributed most to the variation in estimated water level. The numerical tracer transport model shows how water from the main tributaries spreads into the lake.

**Study area and data**

Lake Victoria has a surface area of approximately 68,800 km² and its shoreline is very irregular, with a total shoreline length of 30,000 km. The northeastern part of the lake catchment is relatively steep and forested, while the southeastern part is drier and flatter (Lipzig & Thlery, 2017). The average depth of the lake is 40 m and the maximum depth is 80 m, i.e., the lake is very shallow (Kayombo & Jorgensen, 2005; Paul et al., 2019). The surrounding areas contain different environments and 23 influential rivers (see Figure 1). The largest contributing river, the Kagera, originates from the southwestern part of the mountains of Rwanda and Burundi. The Victoria Nile, the source of the White Nile, is the only outflow from Lake Victoria. It is situated in the city of Jinja in Uganda and the flow at the outlet is controlled by the Nalubaale Dam complex (Lipzig & Thlery, 2017). The outflow has been regulated since 1954 (Sene & Plinston, 1994) presumably by an agreed curve related to the mean water level. However, the dam also produces hydropower and requirements for power may also influence the regulation (Kull, 2006).

The Water Resources Management Authority (WRMA) and LVBC supplied the hydro-meteorological data for the study. WRMA and LVBC both provided daily average data on lake inflow, evaporation, precipitation, and lake outflow for 1950 to 2006. LVBC also provided average monthly data on these parameters for 1950 to 2006 and data on the lake water level for 1899 to 2006, while WRMA provided mean monthly outflow data (WRMA, 2014). The LVBC and WRMA data differed slightly from each other, by 0% for lake outflow, 3% for lake inflow and evaporation, and 9% of precipitation.

**Uncertainty in data sources**

In this study, Lake Victoria hydro-meteorological process analyses were done in the context of water level fluctuations. The water level fluctuation has changed (Yin & Nicholson, 1998) and the major sources of uncertainty in different parameters of water level were studied (Kite, 1981; Piper et al., 1986; Sene & Plinston, 1994; Smith & Semazzi, 2014; Swenson & Wahr, 2009; Tate et al., 2004; Yin & Nicholson, 1998). The water
level is determined by tributary inflow, lake outflow, regulated by the Nalubaale dam, rain over the lake and evaporation from the lake (Vanderkelen, van Lipzig, & Thiery, 2018). Regular monitoring of lake water level is crucial for the basin’s population because the water level has influence on local community access to water, food via fishing, and transport (Semazzi, 2011). Decreased outflow may have major consequences for downstream areas (Taye, Ntegeka, Ogiramoii, & Willems, 2011). The major contributor to water level variability is heavy rainfall. The East African rainfall is dominated by the El Nino-Southern Oscillation (ENSO) and annual rainfall is distributed over the lake by the movement of the Inter-Tropical Convergence Zone (ITCZ) (Kite, 1982; Smith & Semazzi, 2014). Lake outflow and water level are easily measured, but lake inflow, precipitation, and evaporation are difficult to measure or estimate (Sene, Tych, & Beven, 2018). The onshore rain measured precipitation data were enhanced compared to the surrounding land by the presence of the lake itself (Sene et al., 2018; Thiery et al., 2015). Evaporation is very sensitive to air humidity on the lake and near-shore surface (Kite, 1981; Piper et al., 1986; Sene & Plinston, 1994; Smith & Semazzi, 2014; Tate et al., 2004), whereas the air temperature in the tropics are nearly constant and well measured.

**Methods**

The St. Venant SWEs were implemented in COMSOL Multiphysics (CM) to model Lake Victoria hydrology (Paul et al., 2019). This equation-based modeling approach makes it easy to include the transport of various types of dispersed material, including chemical and biological activity, velocity gradient, etc.

**Hydrological and meteorological variables**

The hydrological variables analyzed in lake tributaries where water volume, peak flow magnitude, correlation with hydrological and meteorological variables and their events, and seasonal variation in high peak flows. Whole-year series of data were used, with the only high peak in influential rivers being assessed on a seasonal basis, because many streams on the Lake Victoria have zero or low flow in the winter season. The precipitation data used to analyses annual rainfall and events. The seasonal events have consisted of the sum of the daily rainfall data, maximum rainfall events happen in wet and long rain periods. Whole-year data on a daily basis were available for all rivers, rainfall, outflow, and evaporation. The seasonal and annual computational calculation has been made by Excel, Matlab, and in COMSOL.

**St. Venant shallow water equations (SWEs)**

The depth-averages two-dimensional St. Venant SWEs model has been developed by Paul et al. (2019). The flow model was used to check the water level variation as well as provide transportation velocities for solutes (see section 3.4).
Lake level variations

The lake water balance equation summarizes the hydro-meteorological processes that are responsible for changes in lake water level, \( \frac{dz}{dt} \) (Melesse, McClain, Abira, & Mutayoba, 2008). The variability in river flows plays a significant role in hydro-meteorological modeling. The finite element model conserves a consistent approximation to the total water volume exactly only if all equations are solved exactly. Exact solution is not possible for non-linear models and a check on the overall water balance is necessary to verify the model simulations, and the lake flow is determined by the initial and boundary conditions.

This is not possible for non-linear models and a check of the overall lake water balance (LWB) is necessary to verify the model simulations, and the lake flow is determined by the initial and boundary conditions. Assuming that the shoreline \( L \) is fixed, the SWEs integrated over the lake area (\( A \)) give:

\[
[A] \frac{d\zeta}{dt} + \int_L h(U_n x + V n_x) ds = \int_A (P - E)dA \tag{1}
\]

for the mean water level:

\[
\zeta(t) = \frac{1}{|A|} \int_A \zeta(x, y, t)dA \tag{2}
\]

where \((U, V)\) is the velocity field, are unit shoreline normal components, \( 'A' \) is the total lake areas \( h \), is the water depth, \( P \) is the precipitation \( E \) and is the evaporation, and celerity \( \zeta \) are arbitrarily set to zero at \( t = 0 \). The shoreline integral vanishes except at river inflows and outflows. The inflows and outflow are measured, probably quite reliably, so the uncertainty in their values should be much smaller than that in precipitation and evaporation values. Precipitation was extrapolated by LVBC and WRMA, using methods unknown to us, from meteorological stations on land. Evaporation was modeled from temperature, wind, etc., also using data from land-based meteorological stations. The data were almost constant over 20 years (see Figure 2) which indicates that measurements were missing and/or were estimated from a ‘typical’ year. Smith and Semazzi (2014) and Kite (1982) also comment on the near-constancy of lake evaporation values. The result of Eq. (1) was compared to the COMSOL simulation (Eq. 2) for the 57-year period 1950–2006. To avoid excessively small time steps, the daily data were low-pass filtered by a monthly moving average.

Transport of dilute solution

Advection is the process by which a contaminant moves with a fluid. Dispersion is the combination of two processes, molecular diffusion and mixing by turbulent motion. Transport of dilute species was modeled by the advection-dispersion equation:

\[
\frac{\partial c}{\partial t} + U \cdot \frac{\partial c}{\partial x} + V \cdot \frac{\partial c}{\partial y} = -Q \frac{c}{h} + \text{div}((D + D_{art}) \nabla c) \tag{3}
\]

with vertically averaged velocity field \((U, V)\), the mean concentration \( c(x, y, t) \), \( D = 1 \cdot 10^{-3} m^2/s \) is the dispersion coefficient modeling the turbulent mixing, \( D_{art} \) is the artificial dissipation coefficient \( 2 \times 2 \), a tensor of minimal magnitude for numerical stability, and \( Q \) is the net source of water volume, precipitation minus evaporation.

Results and discussion

Lake water balance

The Lake Victoria has 23 inflows from Uganda, Kenya, and Tanzania, and the main river discharging into the lake is the Kagera (–33% of the total discharges). We have compared our daily data from the WRMA and LVBC with (Kayombo & Jorgensen, 2005), UNEP report, mean river discharges and outflow data. This report recorded 51 years’ historical yearly average data; so, we considered 51 years data of WRMA and

![Figure 2. Lake Victoria water balance: water level, monthly inflow, outflow, rainfall, and evaporation data for the period 1950–2000.](image-url)
LVBC for comparison. The WRMA and LVBC 51 years (1950–2000) data differ about 8% from (Kayombo & Jorgensen, 2005), the largest difference appearing for the Jinja outflow. Direct precipitation and evaporation dominates the lake water balance. The uncertainty of river in- and outflow is dwarfed by the uncertainties in precipitation and, above all, evaporation. The data are from reliable sources, but, as described in (Sewagudde, 2009), the raw data need significant manipulation to fill gaps and extrapolate geographically. We look at the expected correlation between rain and river inflows, and outflow and water level (for details, see section 4.2). Measured water level is compared with the computed water level (See Figure 5a, Eq. 1).

Table 1 shows the percentage contribution of the main contributors to lake inflow and outflow according to the WRMA/LVBC for 1950–2000 time span, the Sewagudde data (2009) for 1950–2004 time span, and data reported by Vanderkelen et al. (2018) for 1993–2014 time span (referring to a later period in the lake’s history). The WRMA/LVBC and Sewagudde data differed significantly in terms of outflow fraction, but this is really a difference in evaporation, since outflow is reliably measured.

The percentage of contributions to LWB have changed significantly in the past two decades. From 2001 to 2003, the frequency and intensity of flows from surrounding areas of the lake increased, but from late 2003 to 2006 level dropped because of drought and excessive outflow (Kull, 2006). All estimated inflows to and outflows from the lake shown in Table 1 are susceptible to error (Sewagudde, 2009), and in that work, these were corrected by balancing all the flows and comparing the results with the modeled lake water level. As can be seen, the percentages reported by Sewagudde (2009) were very different from those based on the WRMA/LVBC data, despite referring to almost the same period and using data from the same source, the Lake Victoria Environment Management Project (LVEMP). However, Sewagudde (2009) used different methods for data averaging. The differences in percentage input and output resulted in differences in lake water level, and even a small bias in one of these terms could lead to large variations in the LWB. The components of the water balance and the measured water level in Lake Victoria 1950–2000 are shown in Figure 2.

As can be seen from the diagram, precipitation, and evaporation dominate the water balance. Based on reference water balance variable data for 1956/57 to 1977/78 (Gibb & Partners, 1984), it is estimated that annual rainfall directly into the lake is increasing. The rainfall pattern and lake water level changed over the period 1950 to 1980 (Kite, 1981, 1982; Sene & Plinston, 1994) and in the period 1995 to 2007 (Vanderkelen et al., 2018). In particular, in the period January 1960 to June 1964, mean annual rainfall increased by 33% and lake water level rose by around 2.5 m (Kite, 1982; Sene & Plinston, 1994). Our result shows the water level rose by 2.8 m (Figure 2). Piper et al. (1986) recorded a water level rise in late 1961 and early 1962 (Figure 2), caused by increased rainfall and tributary inflows. In 1978 and early 1979, water level and rainfall increased in almost the same way as in 1964 (Kite, 1982) (Figure 2). As expected, there was a strong correlation between annual precipitation and total river inflow, while lake outflow was strongly correlated to the lake water level (Figure 2).

**Correlations**

Table 2 shows the WRMA/LVBC data over the 1950–2000 periods and the Hurst and Phillips (1938) data.

In the period 1950–2000, compared to (1938) the outflow increased by 55%, 0% for inflow, over-lake precipitation by 47%, and lake evaporation by 37%. More recent satellite-derived estimates for precipitation over the lake are available (Hasan & Jin, 2014; Swenson & Wahr, 2009), but there is still some uncertainty in evaporation and inflow estimation (Vanderkelen et al., 2018). The time-series monthly variation of precipitation is much larger than the monthly variation of evaporation. Figure 3 shows 1950–2006 averages each month for inflow, outflow, and precipitation is (m³/s) and water level is (m). To conclude, the seasonal pattern of

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**Table 1. Contribution of different sources (%) to the water balance in Lake Victoria.**

| Data source          | Data period | Precipitation, % | Inflow, % | Evaporation, % | Outflow, % |
|----------------------|-------------|------------------|-----------|----------------|------------|
| Vanderkelen et al.   | 1993–2014   | 76               | 24        | 77             | 23         |
| Sewagudde            | 1950–2004   | 82               | 18        | 76             | 24         |
| WRMA/LVBC            | 1950–2000   | 86               | 14        | 85             | 15         |

**Table 2. Mean annual contributions to lake water balance in Lake Victoria, estimated based on data from WRMA/LVBC and in Hurst and Phillips (1938).**

| Data source          | Inflow, mm/y | Outflow, mm/y | Precipitation, mm/y | Evaporation, mm/y |
|----------------------|--------------|---------------|---------------------|-------------------|
| Hurst and Phillips (1938) | 276          | 311           | 1151                | 1116              |
| WRMA/LVBC (1950–2000)   | 276          | 482           | 1697                | 1526              |
precipitation is similar to that of the inflow, as expected. Water level variation across an averaged year is minuscule; the averaging hides all long-term changes.

Studies of lake trends and hydrology are limited by the lack of analysis of hydrological variables and failure to consider hydro-meteorological events (Ogiramoi, Willems, & Katashaya, 2013). Precipitation trends in the Lake Victoria region follow an annual cycle, with a high peak in the long rainy season (Mar–Jul) and again in the short rainy season (Oct–Dec). In addition, Ogiramoi et al. (2013) and Yang, Seager, Cane, and Lyon (2015) indicate a trend of extreme rainfall events, which occur around every 32 years. Monthly averages of outflow do not vary widely, because of the flow regulation at the Nalubaale Dam. Peak flow and peak lake levels occur in April–May and in November–December.

**Precipitation with total inflows**

Historical rainfall and inflow data for the whole lake basin were collected and analyzed in the present study, to determine the seasonal and annual variability. Daily rainfall and river discharge time span data for the lake from 1950–2006 were obtained from LVBC. According to the computed water balance, on-lake precipitation input is much larger than river discharge to the lake, but river discharge varies much more than on-lake precipitation. Therefore, in a hydro-meteorological survey, we made a detailed analysis of all of the tributaries and precipitation over the lake.

Most of the region is classified as arid and semi-arid. The lake has an annual diurnal circulation system that increases with intense on-lake rainfall. Most rainfall events occur at night and are associated with thunderstorms and easterly winds (Yin & Nicholson, 1998). The important factor in hydrological modeling is precipitation, and its actual measurement on a specific temporal and spatial scale is crucial for analyzing land surface hydrological processes and making accurate predictions of future climate events. The largest tributary river, the Kagera, lies in the southwestern part of the lake Basin, and rainfall and runoff from the Kagera river catchment is relatively high. The catchments of the tributaries discharging to the most northeast parts of the lake, such as the Nzoia, Yala, and Soudo, have relatively fast runoff and highly intensive and prolonged rainfall. The southeastern tributary Mara has greater inflow variability, caused by lower rainfall (Sutcliffe & Perks, 1999; Tate et al., 2004). Tributary inflow increased by 50% during the study period (1950–2006). A more detailed explanation of inconsistencies in tributary river inflows is provided in section 4.3.

In hydro-meteorological surveys by the World Meteorological Organization (WMO, 1974, 1982), the rain gauged area was estimated to have increased from 1969 to 1978 to about 80% of the total basin area, with measurement of many more parameters in countries surrounding the lake. Following significant manipulation, imputation, and extrapolation, in the present study those data were compared with the Sewagudde data reported by Sewagudde (2009).

The rainfall in the catchment area of tributaries could likewise be estimated from existing data, so it would be strongly correlated to rainfall on the lake. The correlation between the time series Infl(t_i) and precip(t_i) for the 684 months observed in the 57-year study period is shown in Figure 4. Runoff in the catchment areas introduces lag and capacity, so the inflow time series is smoother than the precipitation data series. It is tempting to fit the model:

![Figure 3. Mean (1950–2006) averages of (a) inflow, (b) outflow, (c) rainfall, and (d) water level.](image-url)
\[
\frac{d\text{Infl}}{dt} = -\text{Infl} + \frac{A_{\text{catch}}}{A_{\text{lake}}} \cdot \text{Precip}
\]  

(4)

with lag (or time scale) \(\tau\) and catchment area to lake area ratio as parameters. For \(\tau = 0\), the correlation coefficient between \(\text{Infl}\) and \(\text{Precip}\) is 0.75, \(\frac{A_{\text{catch}}}{A_{\text{lake}}} = 0.21\). The optimal \(\tau = 0.3\) month with \(\frac{A_{\text{catch}}}{A_{\text{lake}}} = 0.21\) and correlation improved to 0.91.

As can be seen from Figure 4a, the variation in a single river is much greater than that of the sum. In fact, a few extreme peaks dominate the picture (Figure 4a). Figure 4b, which shows the model fit...
from Eq. (4), heavy rainfall and intensive runoff occur frequently in the lake basin and the surrounding areas. However, the model captured enough of the dynamics with yearly smoothing instead of monthly. The peaks in precipitation coincide with peaks in inflow, inflow variability is smaller than precipitation variability because inflow on average is only 0.21 of rainfall, and massive precipitation events (1961 to 1964, Figure 4a, b) are reflected in the water level rise. Figure 4c shows the correlation, 75% between instantaneous monthly precipitations and inflow without optimal delay ($\tau = 0$) while Figure 4d shows the correlation, 91% with optimal lag ($\tau = 0.31$) month. The latter correlation between instantaneous precipitation and inflow is statistically significant linear relationship.

**Water level with lake outflow**

Water level fluctuations and variability show abrupt chaotic hydrological behavior, which affect lake outflow through the Nile. The Nile outflow and water level variations and fluctuations are dependent on water resource use in the surrounding countries, atmospheric variations, and geo-topographical patterns. Before the construction of the Nalubaale Dam at Owen Falls in 1954, the lake outflow was controlled by the Ripon Falls on the Victoria Nile at Jinja. The dam is used to meet hydropower demand rather than to stabilize the lake water level. Analysis of correlations between lake water level and Nile outflow using 107 years time span (1899–2006) of data revealed that the water level rises in March–May and in November–December (seasonal change). Historical data show that water level increased in 1878, dropped again in 1880–1890, rose slightly in 1892–1895, fell again in 1896 and continued at that level until 1902 (Sene & Plinston, 1994). The reported water level in Lake Victoria is given in reference to the Jinja gauge, which is at 1122.86 m above mean sea level (mamsl) (Kull, 2006).

Figure 5a shows the monthly average computed (line) and measured (dash) time step water level in Lake Victoria for the time span period 1950–2000. The difference between 1953–1962 and 1990–1998 was almost 1.0 m, while in 1963–1989 the level showed less discrepancy. The low-pass filter method applied to the data is not responsible for this discrepancy; Sewagudde (2009) achieved better agreement essentially by processing rainfall and inflow data to match measured water levels.

As shown in Figure 5b, the outflow data match the water level precisely. Overall, the water level has changed significantly over the last 107 years’ time span (1899–2006), in regimes that have greatly puzzled researchers (Kite, 1982). As Figure 5b shows, there was a temporary water level rise in 1904–1908, a decline in 1909–1916, and a slight rise in 1917–1919. From the historical evidence for 1903–1959, the water level was low to medium (Piper et al., 1986). The water level in 1900–1961 differed from that in 1961–2000. The mean water level increased rapidly in 1961–1964. During the period 1961–2007, the level showed rises to 1961–1964, 1967–1968, 1977–1989, 1998–1999, and 1998–1998. The water level in Lake Victoria mostly depends on precipitation over the lake, inflow, and outflow. Since late 2003–2005, lake water level has decreased sharply, by approximately 1.1 m, and precipitation has decreased by 10% compared with previous years (Kull, 2006), although outflow discharge has not changed (which would otherwise have a negative impact on downstream reservoirs). Therefore, we can conclude that the cyclic (extreme events) and periodic (yearly event) precipitation events are changing lake inflows and are responsible for increases and decreases in lake water level.

Figure 5c shows, periods’ 1899–2006 (time span), the dam at Owen Falls regulates Nile discharge and water level variations. Outflow (= Jinja discharge) has a much smoother variation than precipitation, to be expected since the outflow is regulated by the water level. The regulation law is that lake discharge very close to linear of the Jinja water level (Figure 5c). However, the regulation of lake discharge has closely followed the agreed curve. The outflow curve has a correlation coefficient $R^2 = 0.89$ to the optimal linear model a very significant correlation between Nile outflow and lake water level.

**Inconsistencies in river discharge**

Three rivers of the 23 rivers discharging onto Lake Victoria come from Uganda, nine from Kenya, and 11 from Tanzania. These all of tributaries do not affect lake water level fluctuations, but the inflows from some affect lake water circulation and its nature. In East Africa, there are three distinguishable seasons and two rainy seasons with peak river flows in regions around Lake Victoria. These are: Dec.–March (dry period), April–July (wet season), and August–November (moderate rains), long-term rain (March–July) and short-term rain (Oct.–Dec) (Aguko, Nyaanga, & Onyando, 2014; Chamberlain et al., 2014; Yang et al., 2015). Table 3 shows seasonal variations in river discharge into Lake Victoria and the impact on the lake water level.

Flow in most rivers is extremely high in May (1952, 1961, 1962, 1963, 1964, 1968, 1978, 1979, 1990, 1994, and 1998). The main tributary is Kagera, with delayed inflow by river streamflow storage in wetlands and an inner lake. The other most influential tributaries are Nzoia, East-shore stream, Yala, Mara, Guicha-Migori, and Sondu,
a) Measured (dots) and computed (line) water level in Lake Victoria, 1950-2000

![Image](image1.png)

b) Water level [m] and lake outflow [m$^3$/s], yearly averages

![Image](image2.png)

c) Correlation between water level and lake outflow

![Image](image3.png)

Figure 5. (a) Measured and computed water level, (b) mean monthly water level and outflow, and (c) correlation between outflow and water level.

Situated off the northern and north-eastern lake shore in Kenya in areas with high rainfall and a more prolonged wet season. Magogo-moame, Simiyu, and South-shore stream, southern tributaries in areas with lower rainfall and runoff, are the next most important tributaries. The other tributaries contribute only small amounts of discharge.

River discharge, rather than precipitation, is an important indicator for climate change analysis, because changes in rainfall are usually amplified in runoff (Awange et al., 2008). A graphical depiction of estimated high peak inflows for Kagera, Nzoia, Mara, and Gucha-Migori is presented in Figure 6.

During the wet period, river inflows to Lake Victoria increase, and most of the water comes from the Kagera, Mara, Nzoia, Gucha-Migori, Sondu, South-shore stream, and Yala rivers. All these rivers showed high peak flows from 1961 to 1964 (all seasons), but discharge volume was greatest from Kagera (Figure 6). Kagera river flow increased from 1000 to 2400 m$^3$/s in 1961–64 and again in 1968 and 1998. The flow in the river on these occasions was almost tenfold the mean (Figure 4a). Interestingly, over the years Lake Victoria river inflows have increased not only in wet and moderate rainy periods, but also in dry periods (Aguko et al., 2014). This could be
a manifestation of climate change, as most rivers have very low flow in dry periods that accompany seasonal droughts.

**Seasonal variations and their impact**

Water problems in Lake Victoria have long been increasing, with more frequent droughts and growing water demand in different sectors in recent years. In this analysis, we compared seasonal flows from the different sub-basins in the lake, to determine the potential impact of hydrological extremes and water management actions (Melesse et al., 2008).

Four major river inflows affect the water level in Lake Victoria. These are: Kagera (33%), Mara (5%), Noiza (15%), and Gucha-Migori and/or Yala (5%) (FDMT, 2018). Thus, a total of 58% of all inflow comes from these four rivers, while the remaining 42% comes from the other 19 lake tributaries. The Kagera river is affected by two seasonal rainfall periods, the southeasterly monsoon (February to May) and the northeasterly monsoon (September to November). These cause a high peak runoff response in May and a lower response in November. The western part of the Kagera river catchment is covered by forest, peak season water level has risen above 2500 mm to 4500 mm and mean annual rainfall is 1800 mm, resulting in erosion and high sediment load. Annual runoff doubled after 1961 as rainfall intensity increased (Sutcliffe & Perks, 1999). The Mara river flows 395 km into Mara Bay in Lake Victoria and it has five major contributing tributaries. Mean annual rainfall in its basin is 1400 mm, and land use change in the basin can lead to long-term impacts on the hydrology and sustainability of other resources (Melesse et al., 2008). The Noiza is one of the major contributing sub-basins of Lake Victoria. Increasing seasonal runoff has resulted in huge increases in solute concentrations in the lake. The catchment of the Gucha-Migori river, located in the southwestern corner of Lake Victoria basin in western Kenya, consists of two river systems, i.e., Gucha and Migori, and rainfall is 2000 mm/year. Seasonal and flash flooding occurs following heavy rainfall, leading to high surface runoff and high sediment deposition in shallow lake areas (WRMA & JICA, 2014).

During the study period, these four major rivers, Kagera, Noiza, Mara, and Gucha-Migori, showed highly fluctuating inflows in the years 1952, 1963, 1968, 1988, 1990, and 1998. The seasonal variability is higher in these rivers than in other rivers, and is even greater when based on daily discharge data (Figure 6). The impact factor of the Kagera and

| Year          | Contributing rivers                                                                 | Time of high flow     |
|---------------|-------------------------------------------------------------------------------------|-----------------------|
| 1951 November – 1952 December | Gucha-Migori, East-shore stream, Kagera, Magogo moame, Mara, Nzoia, South-shore stream | December to May       |
| 1961 January – 1964 December    | Gucha-Migori, Magogo moame, Mara, Nyando, Nzoia, South-shore stream, Soundu, Yala   | October to May (every year) |
| 1967 October – 1968 December    | Gucha-Migori, Kagera, Magogo moame, Nzoia, South-shore stream, Simiyu              | December to May       |
| 1977 October – 1979 April       | Gucha-Migori, Mara, Nzoia, Yala                                                   | December to May       |
| 1989 October – 1990 September   | Gucha-Migori, Mara, Nzoia, Simiyu, Sondu                                           | December to May       |
| 1997 August – 1998 December     | Gucha-Migori, Kagera, Magogo Moame, Mara, Nzoia, Simiyu                           | December to May       |

**Table 3.** Years in the study period with high peak inflows to Lake Victoria, the contributing rivers, and time of high flow.

![Figure 6](image.png)

Figure 6. Seasonal variations in inflow from the major tributaries Kagera, Nzoia, Mara, and Gucha-Migori in the wet, moderate rain, and dry periods.
Gucha-Migori is much higher than that of the other rivers, especially in the dry period, at which time the contribution from all rivers is low and some make no contribution to Lake Victoria. The impact factor of these four rivers is also much higher in the wet and dry season than in the moderate rain season, because long and short rain events occur during these periods.

**Numerical tracer transport model for different rivers**

In this study, the depth averages 2D SWEs model combined with an advective-dispersive model to assess tracer transport patterns. The water from Kagera, Nzoia, Mara, and Yala was traced from 1950 to 2006 in the numerical model.

In the model, the tracer source \( c \) was considered to have an initial concentration of \( 1 \text{m}^3/\text{m}^3 \) for all tributaries. Tracer transport shows how water from different rivers spreads out in the lake (Figure 7a). The water from rivers is colored (red) according to the tracer concentration, set arbitrarily at \( 1 \text{mol}/\text{m}^3 \)in the river inflows and originally at \( 0 \text{mol}/\text{m}^3 \) in the lake. The concentration is diluted somewhat by net rainfall, but, since rainfall and evaporation almost balance, that effect is not visible. The chosen horizontal dispersion coefficient was also small, to show the effects of advection. The mean velocities are low (1cm/s) everywhere except at the outflow (Figure 7b).

Figure 7c shows the wet period model results for the four most influential rivers, when dispersion was much larger than in other periods. Figure 7d shows the results for the Kagera river with an added extra 0.25m$^2$/s as the dispersive coefficient term in the transportation model. Dispersion with the added term (Figure 7d) was much higher than in other models (Figure 7a, c, h). Figure 7e–h shows water from the four rivers in 1960, 1975, 1990, and 2006.

Tracing all inflows for the 57-year study period (Figure 7a) showed that most of the initial lake water was replaced by river water (red) in the period. The tracer transport model covered the lake, the surrounding shoreline, and island lake water. Kagera water takes 50 years (Figure 7a, c, d, h) to reach Jinja, traveling in a deep part of the lake. The Kagera water travels along most of the Ugandan shore and then enters the center of the lake (Figure 7a, c, d, h). The Kagera water moves slowly (Figure 7a, c, d, e, f, g, h), with low mean velocity. This slow movement causes high lake concentrations of pollutants from different sources that will affect Ugandan ecosystem services in the lake. Eleven years of concentration (1950–60; see Figure 7e) did not affect lake zone areas in Tanzania severely, but Kenyan lake areas were seriously affected. Water from the Kenyan rivers, travels much faster, due to the shallowness of Lake Victoria along the Kenyan shore (Figure 7c). Along the Kenya lakeshore, which is shallower than other parts of the lake, there are many factories and industries acting as pollutant sources.

**Conclusions**

In this hydrological-meteorological analysis, we included all inflows to and outflows from Lake Victoria and determined the water balance. A low-pass filter was applied to daily averages to give monthly and yearly averages. Lake precipitation involves a long- and short seasonal rain event, as well as periodic and cyclic events. The computed and measured lake water level agreement was good, although there were some differences in some years. Correlation analysis revealed a strong correlation between instantaneous precipitation and inflow, and lake outflow and water level. Indeed, there is an “agreed” curve for regulating outflow from the lake water level.

Most tributary inflows show seasonal variation, with an extremely high peak in May. In the wet and moderate rain periods, water level rises in all rivers. In the wet and dry periods, river inflow from the Kagera, Mara, Nzoia, Gucha-Migori, South-shore stream and Yala rivers fluctuates much more than that from other rivers. In the water balance, the precipitation input is much larger than river inflow, but inflow shows higher seasonal variability, with impacts on lake level fluctuations and dilution of solute concentrations in the lake. The transport model showed that river water disperses slowly near the shorelines and in shallower basin areas in Kenya, Uganda, and Tanzania, as the flow velocity is low.

It can be concluded that cyclic and periodic precipitation events are changing lake inflows and are responsible for increases and decreases in the water level in Lake Victoria. There is evidently a net contribution to the lake in relatively wet periods and the long and short rainy periods, and a net loss in drier periods. The complexities of the hydrology mean that all data on upstream tributary inflow and mean annual inflow have a certain degree of uncertainty. Cyclic and extreme precipitation events are the greatest source of water level rises and these events increase river discharges and associated transport to the lake. These fluxes are likely to increase with increased frequency of future flood events. A hydropower dam currently regulates lake water level and outflow, but increased temperature and
Drought events can lower the water level (as seen in late 2003–2006). Therefore, numerical hydrometeorological process analysis is very important not only for determining lake water level variability, seasonal effects, and its extreme events, but also for water quality assessments.

Figure 7. (a) Tracer concentrations in surface water in Lake Victoria 1950–2006 from all 23 tributaries, (b) flow velocity toward the Jinja outflow, (c) wet period tracer concentration from the major four main tributaries, (d) tracer concentration in Kagera water with increased turbulent diffusion, (e–h) tracer concentration in inflow from the four main tributaries in 1960, 1975, 1990, and 2006.
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Conflicts of Interest

The authors declare that no conflict of interest exists regarding publication of the paper.

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