Vol. 37(1), pp. 72-88, June 2018
ISSN 1821-536X (print)
ISSN 2619-8789 (electronic)

Tanzania Journal of Engineering and Technology

Full Length Research Paper

Modelling Transport of Heavy Metals in Geita Wetland along Mamubi River

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ABSTRACT

The modelling of heavy metals in rivers is highly dependent on hydrodynamics, the transport of suspended particulate matter and the partition between dissolved and particulate phases. This paper presents the development of hydrodynamic model DUFLOW, which is a one dimensional flow and water quality simulation package, that describes the processes governing transformations and transport of heavy metals (Hg, Ni and Cu) along Mabubi River in the Geita wetland. Two monitoring stations were established along Mabubi River at the inlet (MBSP1) and outlet (MBSP2) of the wetland. A set of DUFLOW model inputs representative of the water conditions were collected from the established monitoring stations. The model was calibrated and validated for the prediction of flow and heavy metals (Hg, Ni, and Cu) transport, against a set of measured mean monthly monitoring data. Sensitive model parameters were adjusted within their feasible ranges during calibration to minimize model prediction errors. At the gauging station MBSP2, the calibration results showed the model predicted mean monthly flow within 17% of the measured mean monthly flow while the r^2 *coefficient and Nash-Sutcliffe (NSE) were 0.83 and 0.79 respectively. At the water quality monitoring station MBSP2, the calibration results showed the model predicted heavy metals (Hg, Ni and Cu) concentrations within 13% and 17% of their respective measured mean monthly concentrations. The mean monthly comparisons* r^2 *values for heavy metals ranged from 0.75 to 0.88 while the NSE values were between 0.70 and 0.82. The model results and field measurements demonstrated that about 40% of the annual heavy metals loadings which would otherwise reach the Lake Victoria are retained in the wetland. The Mabubi river model can therefore be used for prediction of heavy metals (Hg. Ni and Cu) transformation processes in the Geita wetland.*

Keywords: *Copper, DUFLOW, Geita wetland, Mabubi River, Mercury, Nickel.*

INTRODUCTION

A wetland is a land area that is saturated with water, either permanently or seasonally, such that it takes on the characteristics of a distinct ecosystem. The primary factor that distinguishes wetlands from other land forms or water bodies is the characteristic vegetation of aquatic plants (Muraza *et al.*, 2013). Wetlands are often used for domestic and municipal wastewater disposal and inappropriate and illegitimate solid waste disposal (Muraza, 2013; Kayima *et al.*, 2018). However, wetlands have capacities to remove pollutants, nutrients and toxins from water, thus to some extent filtering and purifying it (Kansiime, 2004; Mayo *et al.*, 2018). This function enables natural wetlands to act as *ecotones* acting as buffer zones, which helps to protect the quality of water in downstream fresh water bodies such as rivers and lakes (Terer *et al.*, 2005; Henry and Semili, 2005; Marwa, 2013).

Natural wetlands cover about 7% of Tanzania's total land surface area, and provide a wide variety of bio-physical and socio-economic functions (NEMC *et al.*, 1990).

However, the contamination of wetlands by heavy metals poses a serious environmental and health risk in regions where heavy metals are either mined or previously mined and subsequently abandoned (Marwa, 2013). Drainage from such heavy metals mine lands can result in contamination of surface water with heavy metals such as mercury, nickel and copper (Irwin, 2002; Ongore *et al.*, 2013). Heavy metals at or near the soil surface can be transformed to overland flow in solution form by the mixing of rainwater with soil solution, dissolution of the heavy metal partly present in solid form, de-sorption of an adsorbed or absorbed chemical from the soil and residues in place, and de-sorption of the chemical from eroded sediment. As many metals are highly associated with suspended solids, sedimentation and re-suspension processes play important role in the behaviour of these pollutants in water. Accumulation of the pollutants in the sediment is the main removal mechanism in wetlands (Mwanuzi and DeSmedt, 2003).

Geita wetland is one of the tributaries of Lake Victoria, the lake which is shared by three countries namely, Kenya, Tanzania and Uganda. The wetland plays big role of removing pollutants from surface runoff and small streams which would otherwise reach the Lake. Water pollution of Mabubi River in the Geita wetland is largely because of mining activities in the upstream. Small-scale artisanal gold mining, whereby mercury is used to collect the gold particles have resulted in the pollution of wetland with this heavy metal (LVEMP, 2003). Copper and nickel loading have been released into Mabubi River from the old tailing area, which served the previous gold processing. As mining continues to expand with timwe, a very large area of the wetland has been cleared out to give room for gold washing. The heavy metals (Hg, Cu and Ni) overloading together with loss of wetland are likely to significantly affect the overall buffering capacity of this wetland (Machiwa, 2002).

There have been several modeling efforts in the past to describe heavy metals transport processes over land surfaces (Rivlin and Wallach, 1995). Water quality models are often used to aid stakeholders in making critical decisions about how to improve water quality (Meixner *et al.*, 2005). While it is important to note that Mabubi River in the Geita wetland suffers heavy metals pollution loads as have been reported, very little is known on the fate and transport of these pollutants. There is no updated information on heavy metals (Hg, Ni and Cu) pollution levels in the River and no managerial tools have been developed for managing the pollution load to this River.

One of the potential models that can be used to model the transport of pollutants in the wetland is DUFLOW, which is a simulation package that describes hydrodynamic processes in the wetland, which defines processes and pollutant interactions. DUFLOW Modeling Studio (DMS) uses two components namely the DUFLOW water quantity and quality and RAM (precipitation runoff module), which calculates the supply of rainfall to the surface flow. It calculates the losses and delays that occur before the precipitation has reached the surface flow. DUFLOW program performs unsteady flow computations in networks of open watercourses. The program also simulates the transportation of substances in free surface flow and more complex water quality processes. Within its limits, DUFLOW generate results that can be applied in real life situations such as planning, decision-making, environmental conservation and wetlands management. The main objective of this research is therefore to use a hydrodynamic model DUFLOW (EDS, 1995; STOWA, 2000) for describing the processes governing transformations and transport of heavy metals (Hg, Ni and Cu) along Mabubi River in the Geita wetland.

METHODS AND MATERIALS

Description of the study area

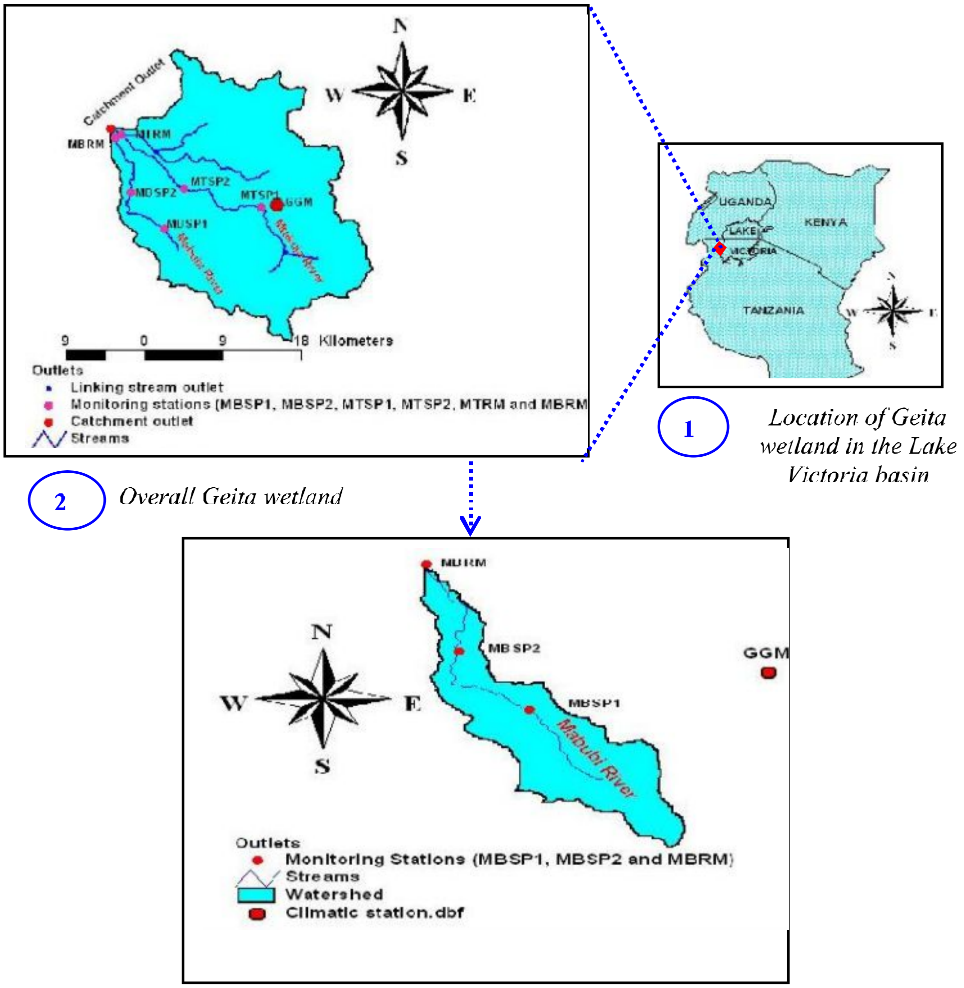
Mabubi River in the Geita wetland is located in the southwest of Lake Victoria in the north-western part of Tanzania and it is lies between longitudes of 32^0 00'E - $32^0$12'E and Latitudes $2^0$46'S – $2^0$54'S (Figure 1). The total wetland area which drains to the Mabubi River is estimated to be 90 km^2. Geita wetland is a seasonally flooded type of wetland with is a mixture of tree swamps in the middle and in the periphery is surrounded by forest reserves. It consists of two arms which join together close to Nungwe bay forming a permanent swamp of about 9 km^2. Mtakuja River flows through the right arm while Mabubi River flows through the left arm adjacent to hills and passing through the Geita forest reserve and discharges into the Nungwe bay. The wetland average slope is 4.8% and its elevation varies from 1138 m above mean sea level in the lowland areas to around 1631 m at the hilltops. The wetland has two distinct rain seasons, the short one runs from mid November to December and the long rains from mid February to May with the mean annual rainfall in the range between 996 mm and 1128 mm during three years of data collection. The mean annual evaporation ranges between 1256 mm and 1276 mm while the annual minimum and maximum temperatures were 14^0C and 32^0C, respectively. The most dominant plants in the wetland are *Cyperus papyrus* and mixed wooded grassland-paddy community. There are also patches of mixed sedge-*Miscanthus-Phragmites-Typha* community and mixed *Forest swamp–reed- papyrus* community.

Field survey of the study area

At the beginning of this study, a field survey was undertaken in the study area to evaluate mining activities, vegetation mapping and establishment of monitoring stations. Ground truthing of remote sensing images was also done, which were used to delineate watershed boundaries and the river network. During the survey, it was noted that at its upper part near Mugusu village there is an intensive small-scale gold mining where mercury is used to amalgamate gold. Other human activities in the area were largely paddy farming, but to a lesser extent maize and cotton were cultivated. Two monitoring stations namely MBSP1 (inlet) and MBSP2 (outlet) were established in the study area where flow measurement and water sampling were carried out (Figure 1). The sampling points were located on areas with minimum interference from human activities in order to get samples of good representation of the bulk water.

Field flow measurement and water quality sampling

The flow measurement and water sampling exercise in the established monitoring stations started in January, 2006. The measurement of water flow in the Mabubi River was carried out using velocity-area method, which comprises of measurement of the mean velocity and the sectional flow area and computing the discharge from the continuity equation. The sectional flow areas were computed from the measured water depth and section width. The water depth was measured using sounding rods of bamboo while the velocity was measured using current meter. The depth and velocity were measured at a number of points along the vertical to define subsections of the River cross section. The sub section flow area was obtained from the product of water depth and the sub-section width. The River cross sectional flow was then determined by summing flow in these sub-sections. For the case of River sampling, water samples were collected beneath the surface with the mouth directed towards the current.



① *Location of Geita wetland in the Lake Victoria basin*

② *Overall Geita wetland*

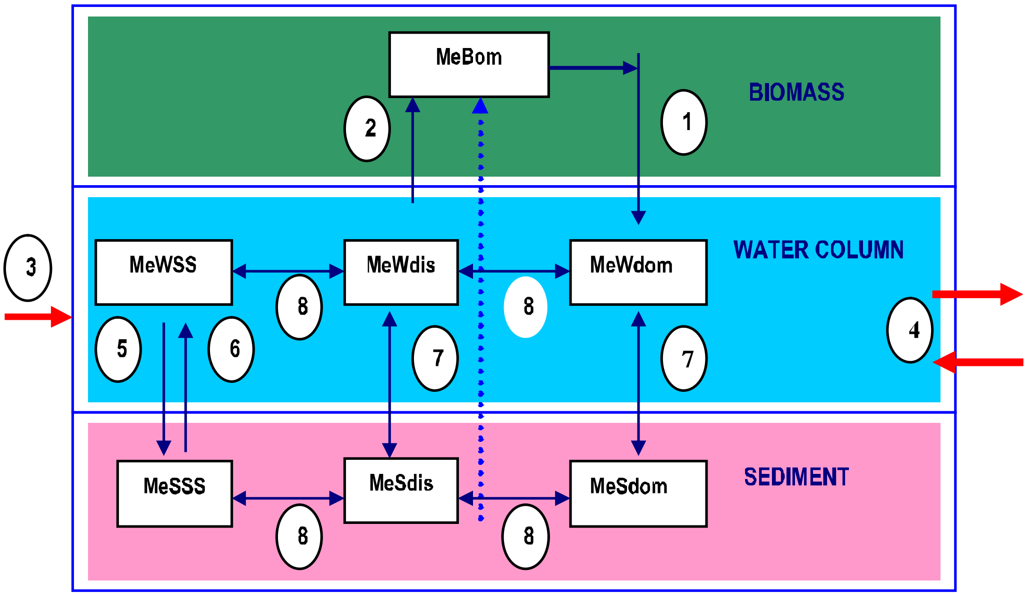
③ *Mabubi River study area in the Geita*

Figure 1: Map of study area

The sampling points were in the water layer of about 4 to 5 cm from the surface at the centre of the main flow. The buckets were rinsed with three separate bucketfuls of River water before collecting samples. Care was taken not to put hands into the water as this could contaminate samples. The sample bottles were also rinsed 3 times before filling. The bottles were filled almost full, leaving a very small headspace at the top of the bottle. The water samples from the monitoring stations were collected after every two weeks and were analyzed in the laboratory in accordance with standard methods for examination of water and wastewater samples (APHA *et al.*, 2012). Mercury was measured using cold-vapour atomic absorption method whereas the measurement of Copper (Cu) and Nickel (Ni) was carried out using Atomic Absorption spectrophotometer.

Heavy metals DUFLOW model

Figure 2 shows the processes in the heavy metals DUFLOW model. In the model, heavy metals are present as dissolved metals (MeDis), associated with dissolved organic matter (MeDom) and adsorbed to suspended solids (MeSS). As many metals are highly associated with suspended solids, sediment water exchange plays an important role in the behaviour of these pollutants in water. Therefore metals were both defined in the water column and in the sediments.



Key: **1** = Biomass Me release and die off   **2** = Biomass Me uptake   **3** = Input loading
4 – Output exchange with a pond   **5** – Sedimentation   **6** – Re-suspension
7 = Pore water exchange through diffusion   **8** = Adsorption

Figure 2: Processes in the heavy metals model (DUFLOW – Reference guide, 2000)

Equations Solved by DUFLOW

The basic equations used in DUFLOW for flow are defined by equations (1) and (2) and for quality are defined by equations (3) through (7). The flow package is based on the one-dimensional partial differential equations that describe non-stationery flow in open channels (Dronkers, 1964; Abbot, 1979). These equations, which are the mathematical translation of law of conservation of mass and momentum are described by equations (1) and (2), respectively.

$$\frac{\partial B}{\partial t}+\frac{\partial Q}{\partial x}=0 \quad \ldots\ldots(1)$$

$$\frac{\partial Q}{\partial t}+gA\frac{\partial H}{\partial x}+\frac{\partial(\alpha Qv)}{\partial x}+\frac{g|Q|Q}{C_d^{\,2}AR}=a\gamma w^2\cos(\Phi-\phi) \quad \ldots\ldots(2)$$

The relation $Q = Av$ holds here.

Where t is time (s), x is distance as measured along the channel axis (m), $H(x,t)$ is water level with respect to reference level (m), $v(x,t)$ is mean velocity (averaged over the cross-sectional area) m/s, *Q(x,t)* is the discharge at location *x* and at time *t* (m^3/s), *R(x,H)* is the hydraulic radius of cross-section (m), *A(x,H)* is cross-sectional flow area (m^2), *b(x,H)* is cross-sectional flow width (m), *B(x,H)* is cross-sectional storage width (m), *g* is acceleration due to gravity (m/s^2), $C_d(x,H)$ is coefficient of De Chezy, *w(t)* is wind speed (m/s), *Φ(t)* wind direction in degrees, $\phi(x)$ is direction of channel axis in degrees measured clockwise from the north, $\gamma(x)$ is wind conversion coefficient, *a(x, H)* cross-sectional flow width (m) and α is the correction factor for non-uniformity of the velocity distribution in the advection term.

Equation (1) states that if the water level changes at some locations, this will be the net results of local inflow minus outflow. Equation (2) expresses that the net change of momentum is the result of interior and exterior forces like fiction, wind and gravity. Equation (1) and (2) are discretized in space and time using the four point implicit pressman scheme, which is unconditionally stable and allows non equidistant grids. It computes discharges and elevations at the same point.

The quality part of the DUFLOW package is based upon the one dimensional transport equation. This partial differential equation describes the concentration of a constituent in a one dimensional system as function of time and place.

$$\frac{\partial(BC)}{\partial t} = \frac{\partial(QC)}{\partial x} + \frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right) + P \;..... (3)$$

Where *C* is constituent concentration (g/m^3), D is dispersion coefficient (m^2/s) and *P* is the production of constituent per unit length of the section (g/m.s). The production term of the equation include all physical, chemical and biological processes to which a specific constituent is subject to.

$$\frac{\partial S}{\partial x} + \frac{\partial(BC)}{\partial t} - P = 0 \;..........................(4)$$

in which *S* is the transport (quantity of the constituent passing a cross-section per unit of time:

$$S = QC - AD\frac{\partial C}{\partial x} \;................................ (5)$$

Equation (5) describes the transport by advection and dispersion. Equation (4) is the mathematical formulation of the mass conservation law, which states that the accumulation at a certain location *x* is equal to the net production rate minus the transport gradient.

The dispersion coefficient can be determined from the characteristics of the flow. The flow dependent part can be calculated from empirical equation in accordance with Fisher (1979). To prevent the dispersion coefficient to become 0 at low flow velocities, a constant term is added that reflects background dispersion. The flow independent part is in particular important in stagnant systems, where it represents the wind induced mixing. The following equation is used:

$$D(x,t) = \alpha_k \frac{u_s^2 W^2}{Z u_*} + D_0 \;...................... (6)$$

Where α_k is a proportionality constant (-), W is flow width (m), u_s is average flow over the cross-sectional area (m/s), Z is water depth (m), u_* is shear stress velocity (m/s) and D_0 is background dispersion coefficient (m^2/s). The shear stress u_* can be written as shown by equation (7).

$$u_* = u_s \frac{\sqrt{g}}{C} \;... (7)$$

As both D_0 and α_k are external variables, both can vary in time and space. For smooth river systems, the α_k values of 0.001 have been reported and for River Rhine stretches where the mixing is influenced by dead zones behind groynes, the found values of α_k are in the order of magnitude of 0.02 (Mazijk, 1996).

Equation (6) can be rewritten as:

Equations Describing Processes of Heavy Metals in DUFLOW Model

It is assumed that the three forms in which metals present are in equilibrium. This means that sorption is assumed to be fast compared to the time scales of interest. Sorption is used to describe the process by which a chemical moves from one phase and becomes accumulated in another, particularly where the second phase is a solid. Each time step the total metal (*Me*) concentration is distributed over the three forms using a linear partition coefficient.

For the water column the following equations hold:

$$MeWdis = \frac{MeWtot}{1 + KMeDOM \times DOMW + KMeSSw \times SSWtot} \quad (8)$$

$$MeWdom = \frac{MeWtot \times KMeDOM \times DOMW}{1 + KMeDOM \times DOMW + KMeSSw \times SSWtot} \quad (9)$$

$$MeWSS = \frac{MeWtot \times KMeSSw \times SSWtot}{1 + KMeDOM \times DOMW + KMeSSw \times SSWtot} \quad (10)$$

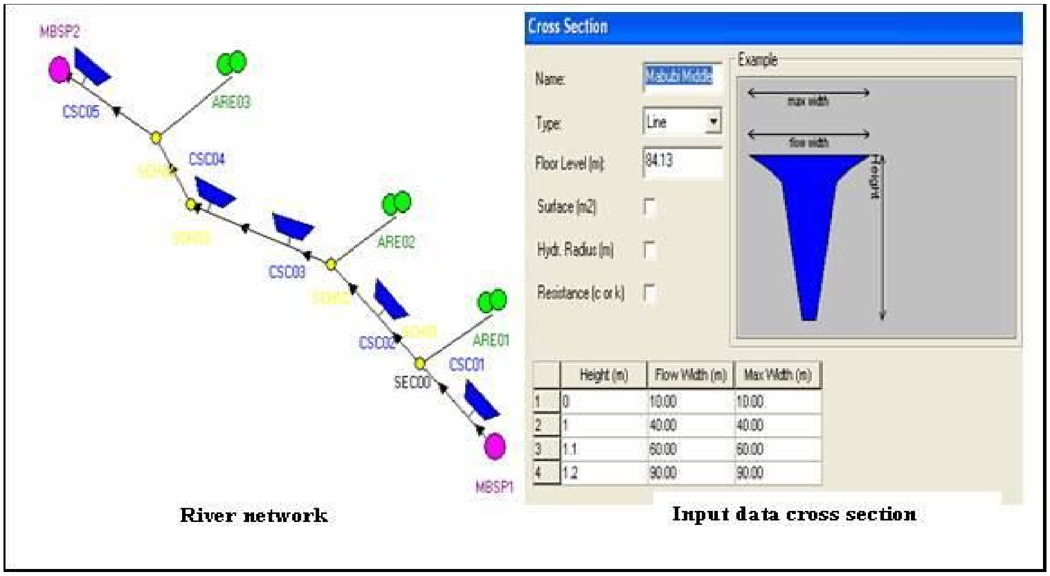
Where *MeWtot* is the total metal concentration in the water column ($g.m^{-3}$), *MeWdis* is the dissolved metal concentration in the water column ($g.m^{-3}$), *MeWdom* is the metal sorpted to dissolved organic matter ($g.m^{-3}$), *MeWSS* is the metal sorpted to suspended solids ($g.m^{-3}$), *KMeDOM* is the partition coefficient for dissolved organic matter ($m^3.g^{-1}$), *KMeSSw* is the partition coefficient for suspended solids in the water column ($m^3.g^{-1}$), *SSWtot* is the total suspended solid concentration in the water column [sum of organic and inorganic] ($g.m^{-3}$) and *DOMW* is the dissolved organic matter in the water column ($g.m^{-3}$).

Mabubi River DUFLOW model

DUFLOW model development first consisted of developing model inputs. Most input development focused on input information and data on pollution that was derived mainly from the monitoring stations in the study area. The model was calibrated for flows and pollution levels using data collected from the field between 2006 and 2007. Thereafter, the model was validated using data collected in the year 2008. The DUFLOW model requires detailed knowledge of the river geometry and channel characteristics at a discrete number of points along the river reach. At each point, the cross-sectional geometry, bed elevations and channel roughness data are determined. The program allows Manning or Chezy steady state flow formulas. In this study Chezy roughness coefficient (C_d) was adopted.

The Mabubi river network schematization was made based on geographical and morphological data obtained from the field survey. On schematization network, objects like nodes, sections and cross sections were defined. The sections represent river reaches and the shape of the waterways is represented by the cross sectional shape. The two established monitoring stations in the Mabubi River were defined in the network. The data collected at MBSP1 were used as model inputs while those collected at node MBSP2 were used for model calibration and validation. Figure 3 shows Mabubi River model schematization.

The climate inputs are utilized by RAM component for prediction of flow. The daily climate inputs data required for the model application were precipitation depths and evaporation. These inputs data were sourced from Geita Gold Mine (GGM) climatic station within the study area. Care was taken to ensure that the model climate inputs were the recorded ones instead of allowing the model to randomly generate them. The point source inputs in DUFLOW can vary daily, monthly or annually or be constant. Since the point sources measured flow and pollution concentrations were available on a monthly time scale, point source inputs in the model were defined monthly. The point source water quality parameters modeled in this study include mercury (Hg), nickel (Ni) and copper (Cu). Others data such as model parameters were sourced from reported values in literature and their values were identified by calibration of the model. Tables 1 and 2 give water quality variables and the state variables used in the DUFLOW model, respectively.



Name: Mabubi Midd

Type: Line

Floor Level (m): 84.13

Surface (m2) ☐

Hydr. Radius (m) ☐

Resistance (c or k) ☐

	Height (m)	Flow Width (m)	Max Width (m)
1	0	10.00	10.00
2	1	40.00	40.00
3	1.1	60.00	60.00
4	1.2	90.00	90.00

Figure 3: Mabubi River DUFLOW model schematization

Table 1: Water quality variables included in the Mabubi River DUFLOW model

Variable (Heavy metals)	Symbol used	Remarks
Mercury (Hg) Copper (Cu) Nickel (Ni)	HgTot CuTot NiTot	The key pollutants modelled

Table 2: The state variables in the Mabubi River DUFLOW model

Symbol used	Description
MeWtot ($g.m^{-3}$)	Total metal in the water column
MeWdis ($g.m^{-3}$)	Dissolved metal in the water column
MeWdom ($g.m^{-3}$)	Metal adsorbed to dissolved organic matter in the water column
MeWSS ($g.m^{-3}$)	Metal adsorbed to suspended solids in the water column

RESULTS AND DISCUSSION

Measured flow and water quality data

Figure 4 shows the mean monthly concentration levels of Mercury, Nickel and Copper from the water column sampled at station MBSP1 of Mabubi River. The mean monthly inlet levels of mercury varied between 0.00012 ppm and 0.0015 ppm. For Nickel, the mean monthly concentrations at the inlet varied between

0.0168 ppm and 0.112 ppm while concentration of copper ranged from 0.006 ppm to 0.0356 ppm.

On the other hand, the measured flow and water quality data from the downstream station (MBSP2) of the study area were used for model calibrations and validations. Figure 5 shows mean monthly River flow and water quality data collected at MBSP2 station. The high stream flows were recorded in the months of March, April, May and December, which were the months with high rainfall period in the area. The highest recorded Mabubi River stream flow at MBSP2 gauging station was 0.85 m^3/s. It was also observed that most of the mean monthly concentration levels of all the heavy metals from the samples taken at the downstream station (MBSP2) were lower than those collected from the upstream station (MBSP1). The mean monthly levels of mercury at station MBSP2 varied between 0.00004 ppm and 0.000559 ppm, while for nickel mean monthly concentration varied between 0.0186 ppm and 0.084 ppm and Copper levels ranged between 0.000751 ppm and 0.0145 ppm. The concentration levels of heavy metals is consistently decreasing towards the downstream station (MBSP2) of the River. The noted low concentration levels in the downstream end of the River are due to retention of pollutants in the wetland caused by existing plants and sediments. Plants have tendency to uptake pollutants in to their tissues whereas sediments tend to adsorb and sometimes release pollution in to the wetland.

Model Calibration

The objective of calibration is to determine the model parameters such that an acceptable match is obtained between the observed behaviors of the variable of interest, say discharge. For flow calibration, the most important parameters are the *Chezy roughness coefficient* and the allocation of the *total cross sectional width* over flow and *storage width*. The important parameters involved in the mass transport are the *dispersion coefficient*, which characterize the ability of the stream to disperse pollutants and *alfaK* (α_k). The calibration of flow and water quality was done by optimizing the parameter values starting from the chosen initial values until the simulated variables fits with the observations. The initial conditions reflect the state of the system at the starting time of the simulation. In this study the initial conditions for flow and the concentration of all state variables was done by making a few initial model runs and use the model results as an estimate for the next simulation run. Table 3 presents the initial values for flow and concentration state variables used in the study.

The calibration was assessed statistically using percentage difference (D_p), coefficient of determination (r^2 coefficient) and the Nash-Sutcliffe simulation efficiency (NSE) indices. The sensitivity analysis was executed to determine how the model calibration results are affected with different parameter values chosen. The most sensitive parameters used in the DUFLOW model are presented the Table 4.

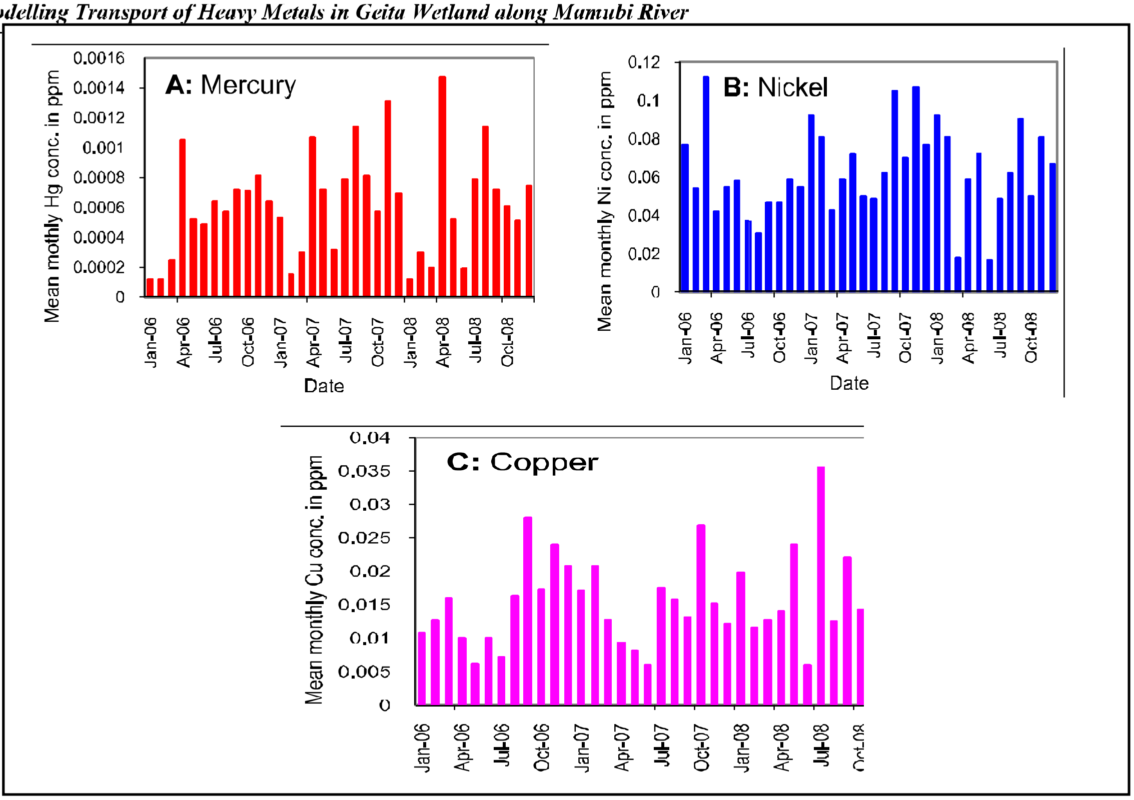


Figure 4: Measured mean monthly concentration levels of Hg, Ni and Cu at MBSP1 station.

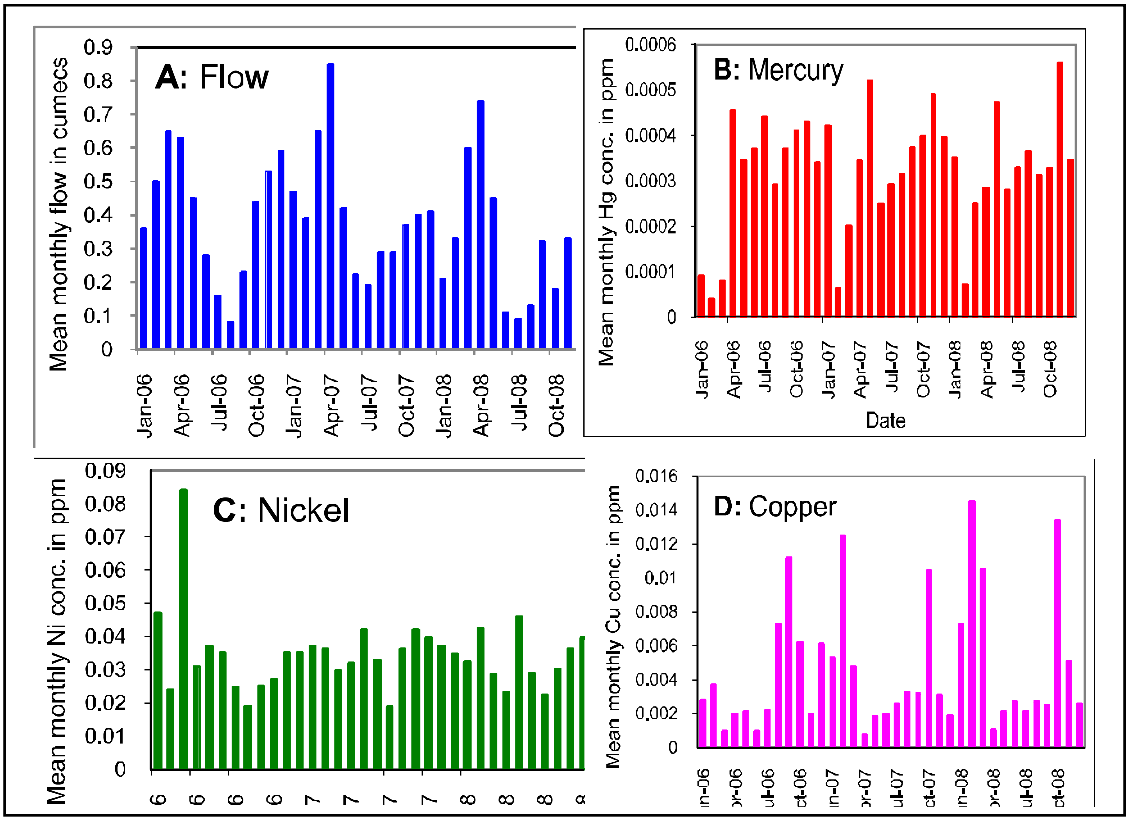


Figure 5: Measured mean monthly flow and water quality data at MBSP2 station

Table 3: The initial values in the Mabubi River DUFLOW model

Node	Discharge	HgWtot	NiWtot	CuWtot	SSWin	SSWorg	DomW
Inlet	0.13	0.00001	0.03	0.002	1	3	11
Outlet	0.58	0.00002	0.05	0.005	2	5	18

Table 4: Sensitive parameters in the Mabubi River DUFLOW model

Parameter	Description	Default value	Adopted value	Units
Chezy	Chezy roughness coefficient	20	40	$m^{0.5}/s$
D	Dispersion coefficient	6000	10000	-
α_k (Alfak)	Proportionality constant	0.002	0.001	-
kHgssw	Partition coefficient Hg for ssw	0.63	0.7	m^3/g
kCussw	Partition coefficient Cu for ssw	0.5	0.5	m^3/g
kNissw	Partition coefficient Ni for ssw	0.008	0.065	m^3/g

The Mabubi river DUFLOW model was calibrated against river flows and water quality monitoring data over a period of two years. The model was calibrated against flow and water quality data measured at MBSP2 station from 2006 to 2007 as shown in Figure 6. Generally, the calibration results show that the model calibration with respect to mean monthly flow predictions is good, with r^2 of 0.83 and NSE of 0.79. Examination of the entire calibration period shows that the DUFLOW model slightly over-predicts flow except on July 2006 and November 2007 where the flow is also slightly under-predicted.

Similarly, the comparison in heavy metals demonstrated that the model prediction of heavy metals (Hg, Ni and Cu) concentrations was good. The r^2 between calibrated values and observed values for Hg, Ni and Cu were 0.81, 0.88 and 085, respectively. On the other side the Nash-Sutcliffe (NSE) for Hg, Ni and Cu were 0.76, 0.82 and 080, respectively (Table 5). It was noted that heavy metals (Hg, Ni and Cu) concentrations were over-predicted by the model during calibration period with exception of April, August and November 2007 where the model slightly under-predict these concentrations. The seasonal variation in rainfall intensity has seen to influence the rate of flow as well as the concentration levels of the studied heavy metals. The high rainfall in the study area occur during months of February, March, April, May and September resulting into high measured and modeled flow.

The calibration results in Figure 6 show that during high flows the concentration levels of studied heavy metals are lower as compared to the concentration levels when the flows are higher. For example, on April, 2006 the simulated flow was 0.71 m^3/s and the simulated mercury concentration level during this month was 0.00055 ppm. The simulated Nickel and copper concentration levels during this month of April 2006 were 0.029 ppm and 0.007 ppm respectively. The simulated flow on July 2007 was 0.26 m^3/s and the simulated mercury concentration level during the same month was 0.00051 ppm. The simulated Nickel and copper concentration levels during this month of July 2007 were 0.03 ppm and 0.0081 ppm, respectively.

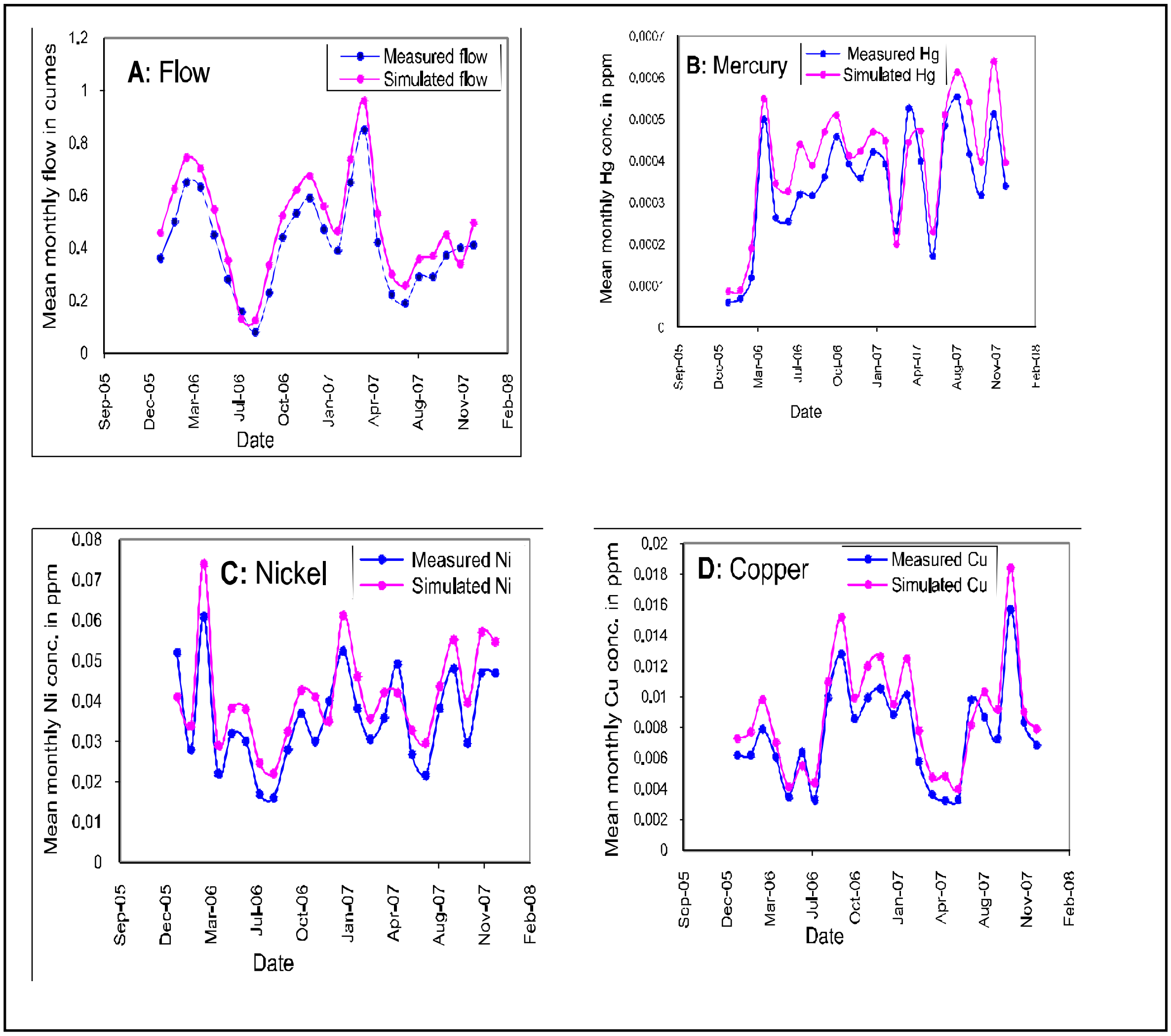


Figure 6: DUFLOW model calibration results

Table 5: Mabubi river DUFLOW model performance for the calibration period

Modeled parameter	% Difference, D_p	r^2	NSE
Mean monthly flow - Q	17	0.83	0.79
Mean monthly mercury - Hg	13	0.81	0.76
Mean monthly nickel - Ni	14	0.88	0.82
Mean monthly copper - Cu	16	0.85	0.80

Model Validation

Model validation is the process of testing model performance of the calibrated model parameter set against an independent set of measured data. The measured validation and calibration data sets cover different time periods. Figure 7 shows that the model performance with respect to mean monthly flows and heavy metals (Hg, Ni and Cu) concentrations prediction during validation is generally good with r^2 of 0.90, 0.85, 0.81 and 0.80, respectively.

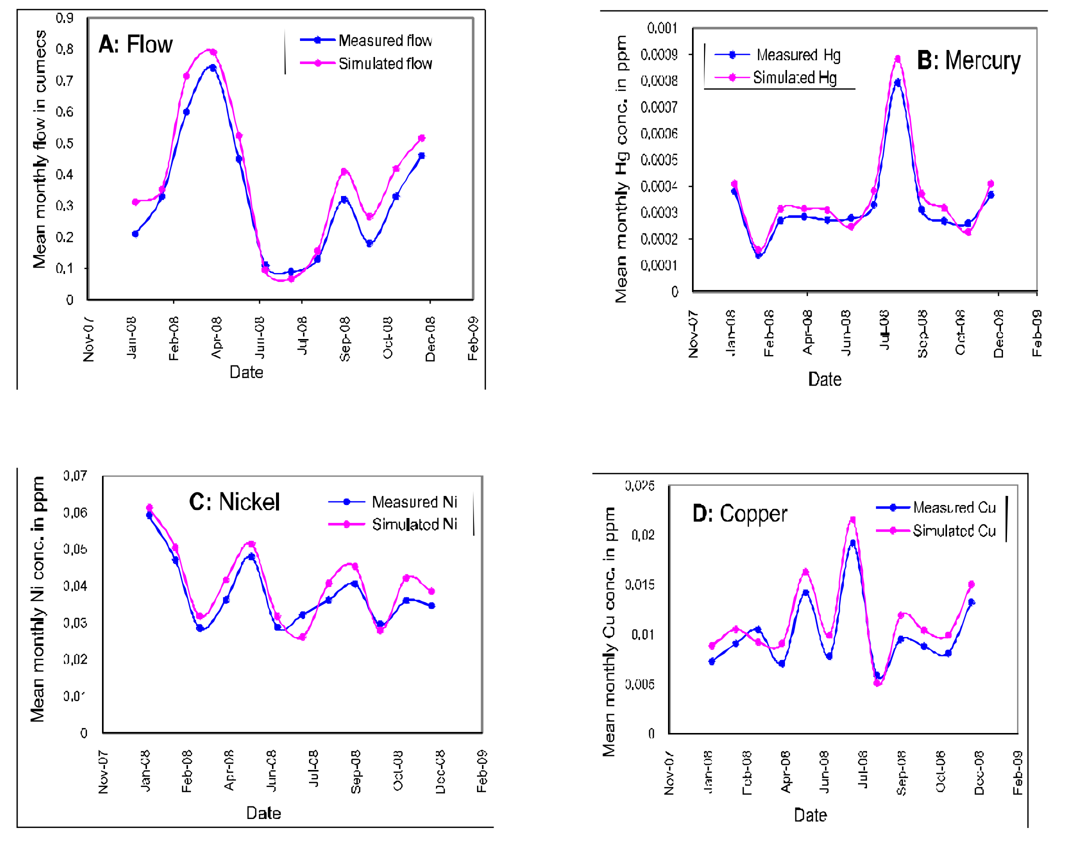


Figure 7: DUFLOW model validation results

The Nash-Sutcliffe (NSE) for flow, Hg, Ni and Cu were 0.85, 0.83 0.78 and 075, respectively (Table 6). The good validation results support the usefulness of the model to predict future conditions (i.e. heavy metals loading) under alternative management scenarios and future climates. The general examination of the entire validation period shows that the DUFLOW model slightly over-predicts the modeled parameters with exception of February, June, July and October 2008 where the parameters are under-predicted. At the gauging station MBSP2, the validation results shows the model predicted mean monthly flow within 16% of the measured mean monthly flow. On the other side, model validation results at station MBSP2 showed that the predicted concentrations of Hg, Ni and Cu were within 10%, 11% and 14% of the observed values, respectively (Table 6).

Table 6: Mabubi river DUFLOW model performance for the validation period

Modeled parameter	% Difference, D_p	r^2	NSE
Mean monthly flow - Q	16	0.9	0.85
Mean monthly mercury - Hg	10	0.85	0.83
Mean monthly nickel - Ni	11	0.81	0.78
Mean monthly copper - Cu	14	0.80	0.75

Retention capacity of Hg, Ni and Cu of Mabubi study area in Geita wetland

The mean monthly concentration levels of the heavy metals were converted to loads by multiplying with the respective measured flow rates. The measured mean monthly heavy metals (Hg, Ni and Cu) load discharged at the outlet station (MBSP2) suggested that certain amount of pollution load that entered at station MBSP1 has been retained in the wetland. Table 7 shows that mercury, nickel and copper were retained at an average rate of 37.0%, 29.3% and 32.0%, respectively (Table 7). The assessment show that during three years of study the mercury load retention ranged from 31% to 42% while nickel ranged from 28% to 31%. However, it was noted that copper load retention decreased from 34% to 29% in 2008. The capacity of wetland to retain pollution depends mainly on the existing plants and sediments. Plants have a tendency to uptake pollution in to their tissues whereas sediments tend to adsorb and sometimes release pollution in to the wetland. Therefore the study shows that there is a need to conserve this wetland as it acts as a buffer against pollution load entering the Lake Victoria. The calculated mean monthly heavy metals (Hg, Ni and Cu) loading in the upstream and downstream stations of the Mabubi River study area is shown on Figure 8, which indicates that Geita wetland has a buffering capacity for heavy metals.

Table 7: Summary of heavy metals retention capacity of Mabubi study area

	Annual retention of heavy metals (%)			
Parameter	**Year 2006**	**Year 2007**	**Year 2008**	**Mean**
Mercury - Hg	31	38	42	37.0
Nickel - Ni	28	29	31	29.3
Copper - Cu	34	33	29	32.0

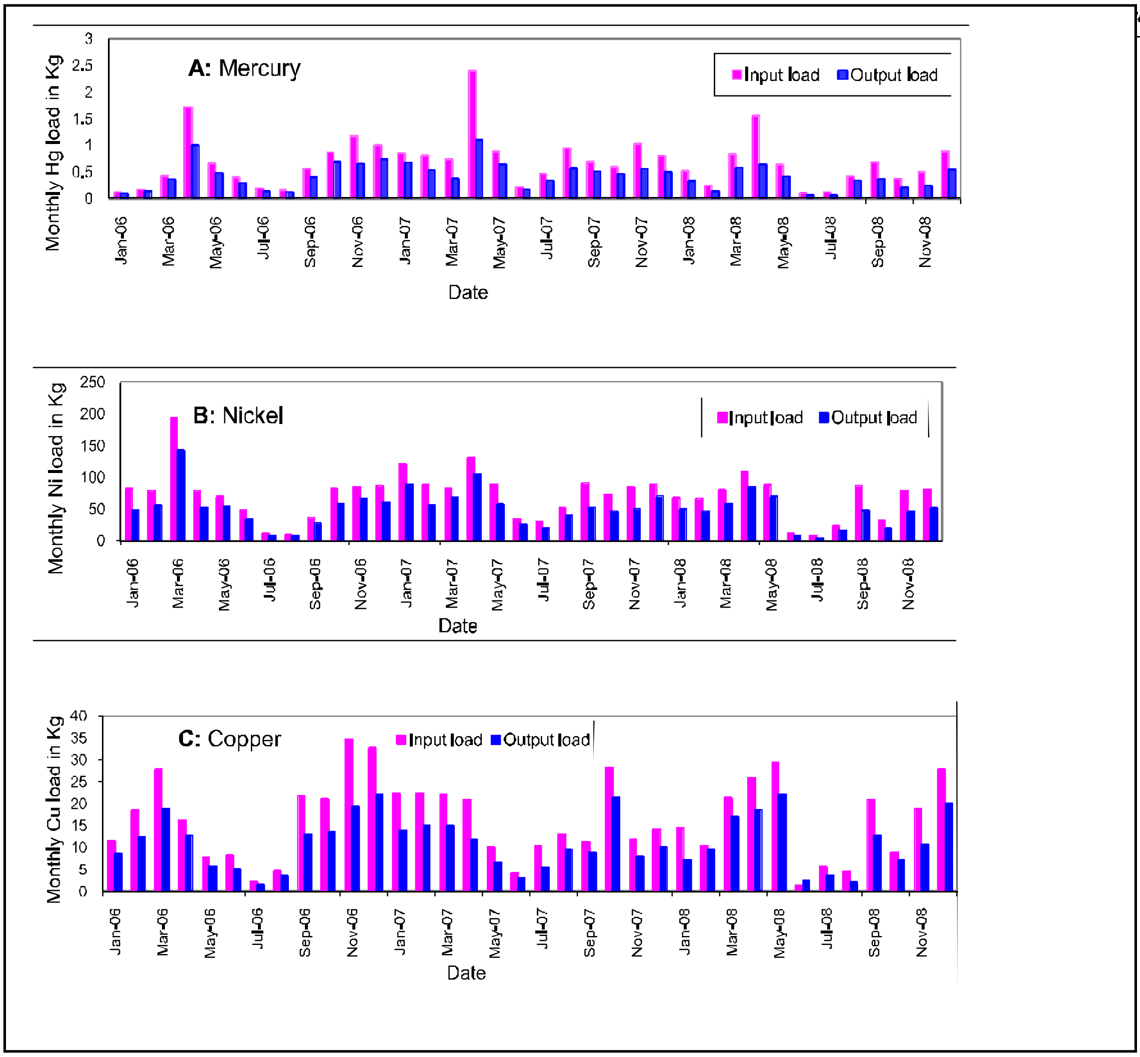


Figure 8: Mean monthly heavy metals (Hg, Ni and Cu) loading

CONCLUSIONS

The DUFLOW model has shown that it can reasonably predict the temporal nature of the measured flow and water quality data at the monitoring stations along Mabubi River in the Geita wetland. The measured water quality data and the model results document high levels of heavy metals concentrations in Mabubi River as a result of mining activities in the area. Examination of the entire calibration and validation periods show that, generally the DUFLOW model slightly over-predicts River flow and the modeled heavy metals (Hg, Ni and Cu) concentration levels with exception of some few months where the model under-predicted them. However, the model calibration efficiencies of 0.83, 0.81, 0.88 and 0.85 for flow, mercury, nickel and copper, respectively, were good. Therefore DUFLOW model can be employed to predict heavy metals (Hg. Ni and Cu) transformation processes in the Geita wetland. The assessment of buffering capacity of Geita wetland against heavy metals (Hg, Ni and Cu) loading during three years of study showed that mercury load retention ranged from 31% to 42% while nickel ranged from 28% to 31%. However, it was noted that copper load retention decreased from 34% in 2006 to 29% in 2008. Therefore the study shows that there is a need to conserve this wetland as it acts as a buffer against the studied heavy metals pollution load entering the Lake Victoria.

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