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Paleolimnological investigations of anthropogenic change in Lake Tanganyika: VIII. Hydrological evaluation of two contrasting watersheds of the Lake Tanganyika catchment

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Abstract

This study was conducted to delineate the impact of human activities on stream flow and water chemistry as well as other factors that influence the chemical character of both surface and groundwater in two contrasting watersheds of the Lake Tanganyika catchment. The study sites the Mwamgongo and Mitumba streams along the northern Tanzanian coastline of the lake are representative of disturbed and undisturbed watersheds, respectively, but are quite similar in other characteristics of slope, bedrock geology and size. Separation of stream flow components was undertaken using classical hydrograph analysis along with chemical methods using both Cl and ^{18}O data. All the data show that groundwater accounts for the predominant source of total stream flow in both the Mwamgongo and Mitumba watersheds (65 and 70% respectively). The streams have an average $\delta^{18}O$ of about −3.0% and less than 10 mg/l for Cl. The basin recession constants of 9.4×10^{-3} d^{-1} and 9.6×10^{-3} d^{-1} for Mwamgongo and Mitumba, respectively, indicate existence of both fissured and fractured aquifer systems. The chemical data exhibit low values of all determined ions. This supported the hypothesis that natural processes influence the water chemical character of the study area. An Mg–HCO_3 type of water dominates in the two watersheds. Despite their similar size and bedrock character the Mwamgongo watershed has an order of magnitude in sediment transport than the Mitumba one. The data show that the disturbed watershed discharges less groundwater and more sediments, and has a poorer water quality than the forested Mitumba watershed, which lies within the Gombe National Park. The data show that soil erosion processes are more active at Mwamgongo, and that both the surface runoff component of the total stream flow and increased dissolved salt load is greater in the deforested Mwamgongo watershed than in the Mitumba watershed. The chloride and $\delta^{18}O$ data complemented each other in delineating the amounts of groundwater in the total stream flow as the results using both data differed insignificantly. It may be concluded that the undisturbed watershed has a higher retention of good quality water and traps more sediments than the disturbed one. In addition, the groundwater component plays a dominant role in the total annual stream flow at each watershed.

Introduction

This study was conducted in the context of a wider study (Cohen et al. 2005) to understand the major controls on hydrological processes in contrasting watersheds under different land use patterns around Lake Tanganyika. The broad goal of this work was to distinguish influences on hydrological processes linked to both physiographic processes and human activities. In this context three questions arise:

(1) To what extent do human activities, such as deforestation, poor agriculture practices, fire outbreaks, overgrazing, tree felling and charcoal making and water use affect stream flow components in small, mountainous, Afrotropical watersheds?
(2) How is water chemistry affected by these same types of human activity or natural processes in such streams?
(3) What is the role of groundwater discharge in these types of watersheds, how much groundwater is contributed to the total stream flow, and how is groundwater discharge linked to variations in human activity?

A common approach adopted by some hydrologists to answer such questions is to study paired watersheds of similar size, topography, geology, soils and climate, which differ only in extent of human disturbance (Branson and Owen 1970; Waterloo 1998). Stream flow hydrograph separations and Piper trilinear diagrams are commonly used methods of analysis for differentiating potential anthropogenic effects because they can easily demark various components of the total stream flow and the hydrologic framework under which groundwater flows is identified respectively. Stream flow separation using both classical techniques and chemical methods, as explained by Fetter (1994), and Chow (1964) can quantify the total stream flow into its major components of both base flow (groundwater) and surface runoff. The chloride ion as a conservative chemical tracer has been used to separate hydrographs along with graphical decomposition and $\delta^{18}O$ data (Ribolzi et al. 2000).

A mass balance approach for the two major components of the stream flow (surface runoff and groundwater flow) is used in the analysis of the data. Variability in $\delta^{18}O$ and chloride values in the types of watershed described here are meteorologically derived, and are subsequently affected by evaporation processes during infiltration of surface runoff controlled by among other factors the degree of land surface cover, which in turn is affected by anthropogenic activities. Disturbed watersheds often display compacted land surfaces that discourage maximum surface infiltration while promoting overland flow. Thus in disturbed watersheds, total stream water displays $\delta^{18}O$ values that are close to those of watershed rainfall since they are dominated by surface runoff especially immediately after storm events. However, this phenomenon is reversed in heavily forested watersheds where maximum infiltration takes place due to slowed surface flows by vegetation cover. Furthermore, in deforested areas where human activities occur, the lack of infiltration causes meteoric water signals (and therefore chloride) to increase as a proportion of the total stream flow's solute load. This compositional tracer can be used to separate the total stream flow components since Cl^- is a conserved ion that does not react with the environment and can easily trace the stream flow history of a given watershed. Thus changes in groundwater regime of a given watershed can easily be quantified using data from both chloride and $\delta^{18}O$.

The aim of this work was to study the surface and groundwater hydrology of two typical, small watersheds along the eastern shore of Lake Tanganyika, Africa, in the northern part of the Tanzanian coastline of that lake, one heavily wooded inside a national park and the other extensively deforested and heavily populated. I identified and quantified the stream flow components that contribute to the total stream flow by using graphical decomposition and chemical tracing methods. Also, I investigated factors influencing the chemistry of water in the two watersheds in an attempt to identify those components influenced by human activity.

Site description

The study area is about 20 km north of Kigoma town and can be reached by boat over Lake Tanganyika and by local footpaths northeast of the watersheds (Figure 1).

The studied watersheds are located adjacent to each other within the slopes of Mwamgongo hills and Gombe National Park escarpment close to the shores of Lake Tanganyika as shown in Figures 2 and 3. The Mitumba Stream watershed occupies an area of 5.75 km^2 whereas the Mwamgongo Stream watershed is slightly larger (7.7 km^2).

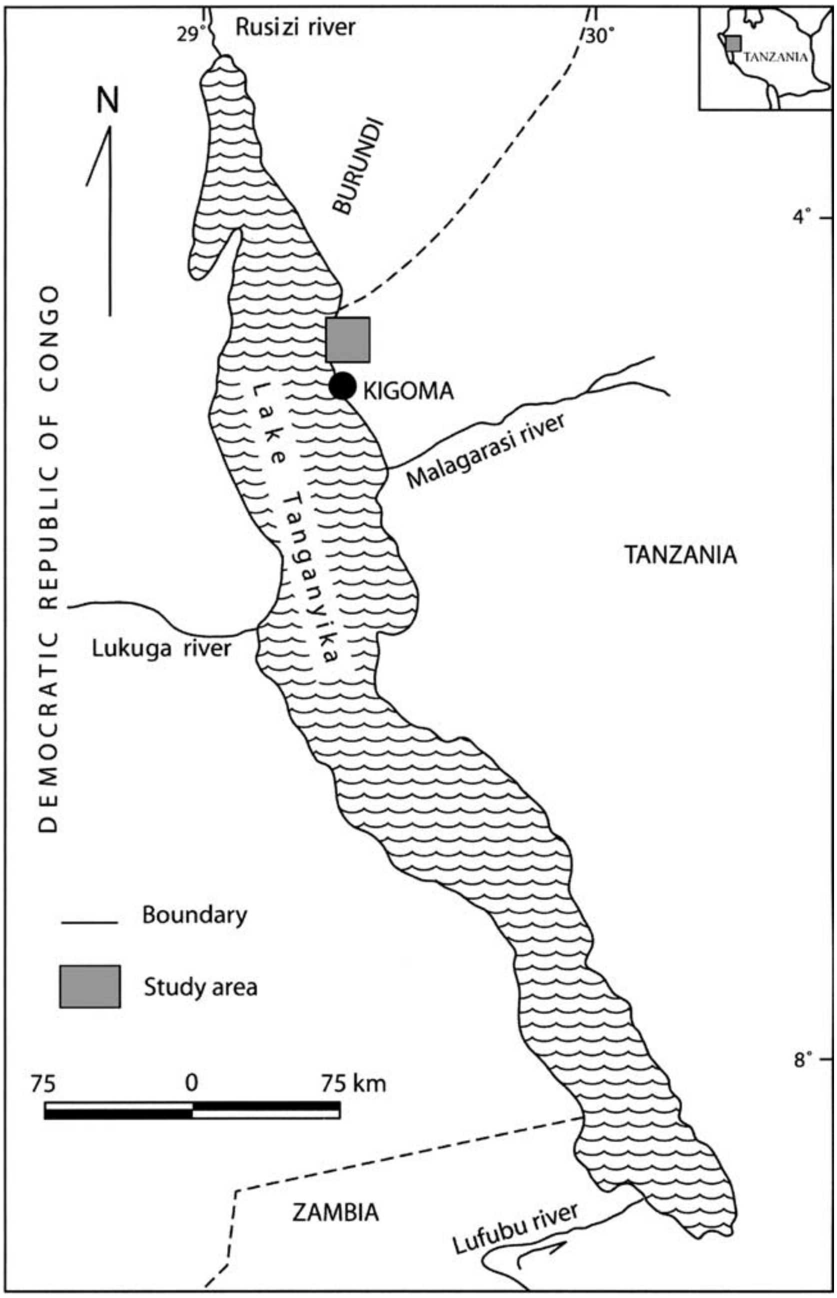

Figure 1. Location map of the study area (modified after Patterson 1996).

The headwaters of the two watersheds are at an elevation of about 1600 m above mean sea level. All the lower order streams draining the two watersheds flow in a westerly direction towards Lake Tanganyika whose mean surface elevation is 773 m above mean sea level.

Mwamgongo is an impacted (disturbed) watershed occupied by about 7000 inhabitants (900/ km^2) in which hill-slope subsistence agriculture is practised. The Mwamgongo watershed area is occupied primarily by cassava, banana, and oil palm cultivation, along with burned and grazed grasslands with minor shrubs in uncultivated areas. About 90% of the watershed is deforested. Mitumba is an undisturbed, densely forested watershed within the Gombe Stream National Park

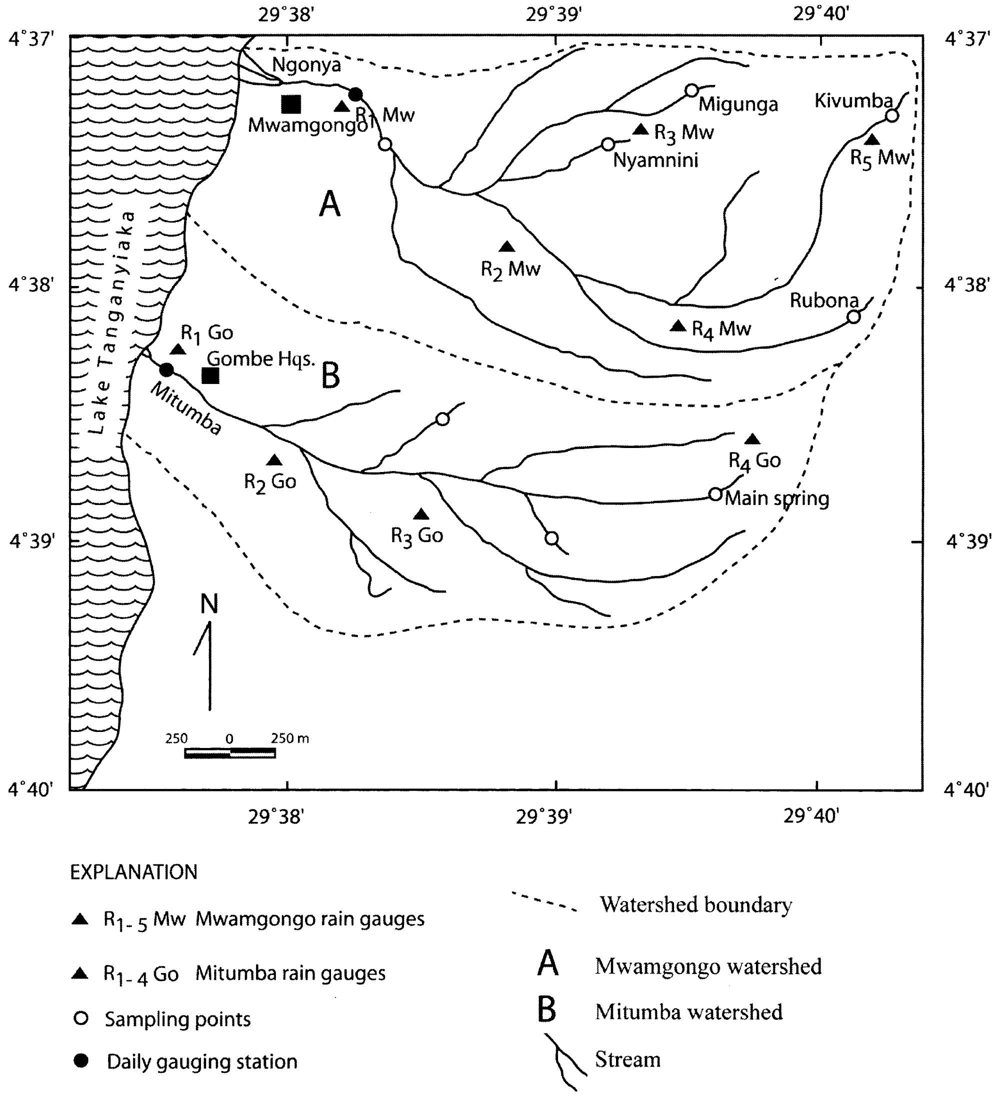

Figure 2. Map of the study area showing sampling locations.

with almost 99% of the watershed covered with predominantly native vegetation ranging from grasslands at higher elevations to miombo woodland on lower slopes and gallery forests along stream courses. The Park workers inhabit a small part of the watershed.

Climatically, the two watersheds are characterized by semi-humid tropical climate with alternating dry and wet seasons. Air mass movement along the escarpment produces frequent intense rainfall that falls in highly localized heavy thunderstorms. The average rainfall in this area lies between 800 and 1500 mm/year with mean annual of 1200 mm/year, while temperatures vary between 25 and 30 °C, averaging at 27 °C. The potential evaporation ranges between 1800 and 2000 mm/year (Norconsult 1982a). The Mwamgongo and Mitumba watersheds are known for intense localized heavy thunderstorms, which give rise to sudden and destructive flooding that often occurs with the return of heavy rainfall in the wet season. In addition to the material damage caused, such events are accompanied by flash floods, erosion of the land under cultivation and the stream banks. Lateral shifting of the stream channels (south to north sides and vice versa) is common especially in the Mwamgongo watershed.

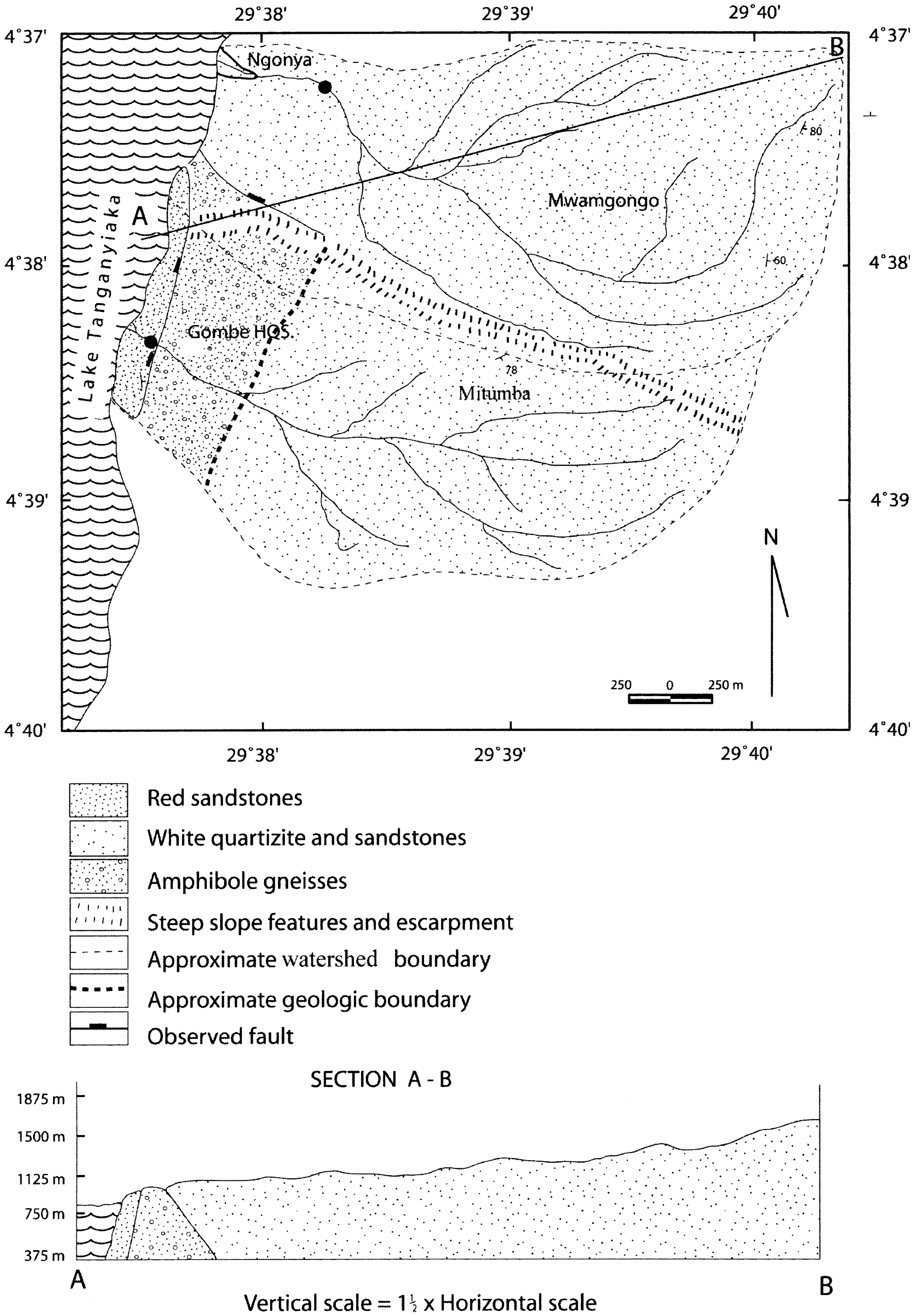

Figure 3. Geological map of the study area.

The amount of runoff is highly dependent on the amount and intensity of rainfall, and evapotranspiration which is influenced by both vegetative and soil cover. Computation of actual evapotranspiration using chloride data from the two streams resulted in about 1060 mm, which is about 80% of the mean annual precipitation of 1200 mm at the study area. However, computation of actual evaporation using ^{18}O data from the Lake Tanganyika resulted in a value of 1080 mm, which is about 90% of the mean annual precipitation of 1200 mm implying that evaporation is a major mechanism of water loss from the Lake Tanganyika. The differences in the computed values of actual evapotranspiration from the two systems may be attributed to the differences in the degree of exposure of the streams and the lake to wind and radiant energy.

The great variations in vegetation ranging from gallery forest to grassland and bare ground within the study areas are associated in different directions with the great variations in areal runoff. Both wind and rainfall are influenced by seasonal variations, but are also influenced by topography. For example, on the western slopes of the hills of the study area towards the Lake, the mean annual rainfall is about 1200 mm (Norconsult 1982a). This heavy rainfall is caused by orographic effects as moist air masses moving east over Lake Tanganyika rise and release precipitation as they go over the mountains in this area; resulting in heavy rainfall being observed at the shoreline and progressively decreasing towards the mountains.

Geological setting

The bedrock geology in the Mitumba/Mwamgongo watersheds is characterized by Ubendian-aged (2.1 Ga), high-grade metasediments and gneisses, which are unconformably overlain by much younger Precambrian low-grade metamorphic or unmetamorphosed sedimentary rocks. The Ubendian plagioclase (albite)-rich gneisses occur in the northwest part of the study area, and intermittently along the shores of Lake Tanganyika to the south (Halligan 1960; Norconsult 1982b). The late Precambrian Kigoma Quartzite unconformably overlies these metasediments (Figure 3). This thick formation consists almost entirely quartzite and sandstones, with occasional shale beds. Between 50 and 100 m thick of Late Precambrian Manyovu red beds also outcrop intermittently along the lakeshore within the study area (Halligan 1960).

Structures within the area show a regional North–South trend and generally they are more evident in the west and die out completely towards east. Foliation strikes vary between NW–SE and NE–SW to nearly vertical, and a swing towards an E–W direction has been observed in some places. The dip of the foliation is regular, mainly to SE and S generally with angles of 10–80° . The NE-strike and SE-dip of foliation are prominent in the Kigoma Quartzite, while the W-strike and S-dip are clearly observed in the Manyovu red beds close to the lakeshore. The Ubendian rocks are folded at close to the regional trend with clear vertical or near-vertical foliation dips. According to Halligan (1960), rift faults in the area have resulted in the production of narrow down faulted blocks of Manyovu red beds bordering the lakeshore, with throws of more than 1500 m equivalent to the escarpment and maximum watershed elevations in this area (Halligan 1960; Norconsult 1982b).

Hydrogeology and hydrology

Most of the groundwater in the study areas occurs in bedrock fractures, faults and fissures. The overburden of this area does not play an important role in groundwater storage, as it is very thin and compact. Shoreline deposits represent a narrow zone of extremely shallow aquifers (Norconsult 1982b). The groundwater potential of bedrock in the study area varies from virtually nil, to highly productive zones in well-drained parts through fracture systems. Though the rocks have undergone low-grade metamorphism in some parts, no matrix (intergranular) flows are observed, leaving fissure flows to dominate even in the coarse-grained Kigoma Quartzites.

The hydraulic conductivity of these rocks is predominantly associated with rift faulting thus resulting in the formation of a fractured aquifers system that apparently controls groundwater occurrence and flow in this area. Hence one can conclude that groundwater flow is tectonically controlled, flowing in the direction of the dips of the faults and fractures of this area.

Most of the tributary streams and springs in the Mwamgongo and Mitumba watersheds have their origin at the high altitudes with few of them being intermittent, which are normally very small streams and springs that essentially go dry during the peak of the dry season.

Methods

Hydrogeological studies

Basement mapping of the Mwamgongo and Mitumba watersheds has not been done in any detail prior to this study. However, Halligan (1960) and Norconsult (1982b) provided general information on some specific areas on the region. In order to determine if a relationship exists between bedrock lithology and hydrochemistry, I prepared a 1:50,000 geological map of both watersheds (Figure 3).

Stream flows, water sampling and analysis

Gauging stations were established on the Mwamgongo and Mitumba streams, about 100 m upstream from their outlets (Figure 2). Water flow velocity measurements and suspended sediment load sampling were carried out at these stations for a period of two years, from October 1997 until September 1999. Discharge measurements were computed using the velocity-area method and rating curves and hydrographs were established for the two streams. The volume of discharge of Mitumba and Mwamgongo streams were hydrologically analyzed under hydrograph separation into direct runoff and groundwater flow by using two methods, classical or graph decomposition and chemical methods. For simple and easy separation, the hydrographs were treated as simple hydrographs in order to avoid ambiguity (Linsley et al. 1988). Therefore, a method described by Pinder and Jones (1969); Linsley et al. (1988) and Ward and Robinson (1990) has been adopted and followed to separate the two hydrographs into direct runoff and groundwater flow components, respectively (Figures 4 and 5).

The hydrograph separation based on graphic decomposition identified two parts of the stream discharge, direct runoff and groundwater flow. The process of baseflow recession is spontaneous and obeys an exponential equation (Chow 1964; Pinder and Jones 1969; Freeze and Cherry 1979; Todd 1985):

$$Q_t = Q_o e^{-\alpha t} = Q_o K_r t \tag{1}$$

where Q_t is the flow or discharge rate at time t, Q_o is the flow or discharge at the start of the recession period ($t = 0$), the two quantities, Q_t and Q_o are measured in m^3/s while t is in seconds, α is the Horton recession constant for the studied catchment (expressed as $1/T$ or d^{-1}), K_r is Barnes recession constant, thus Equation (1) gives

$$\alpha = -1/t \ln Q_t/Q_o = \ln kr \tag{2}$$

Values for Q_o, Q_t and t are from the hydrographs (Figures 4 and 5). From the available data, α is calculated as 9.6×10^{-3} d^{-1} and 9.42×10^{-3} d^{-1} (Horton basin constants) for the Mitumba and Mwamgongo watersheds respectively.

Chemical methods

The concentration of ions in solution in total runoff consists of contributions from groundwater and direct runoff. Assuming that there is no chemical interaction when solutes from groundwater and direct runoff combine and that each component of runoff has a density of 1 g l^{-1}, the relationship between runoff components may be expressed in the form of mass-balance equation (Pinder and Jones 1969; Todd 1985).

$$C_{TR} Q_{TR} = C_{GW} Q_{GW} + C_{SR} \tag{3}$$

where C is ionic concentration, Q is stream flow, TR is total runoff, GW is groundwater contribution (baseflow), and SR is surface runoff. Solving for groundwater, this gives:

$$Q_{GW} = \%[(C_{TR} - C_{SR})/(C_{GW} - C_{SR})] Q_{TR} \tag{4}$$

where $Q_{TR} = Q_{GW} + Q_{SR}$.

Values of GW were measured during rainless periods, C_{SR} was measured from rainfall as direct runoff concentration during rainfall periods and C_{TR} was measured during the peak flow period in the main stream. From values of C_{TR}, Q_{GW} and C_{SR} using chloride and $\delta^{18}O$ data, the groundwater flow component of the total stream flow was calculated accordingly as shown in Figure 6a, b.

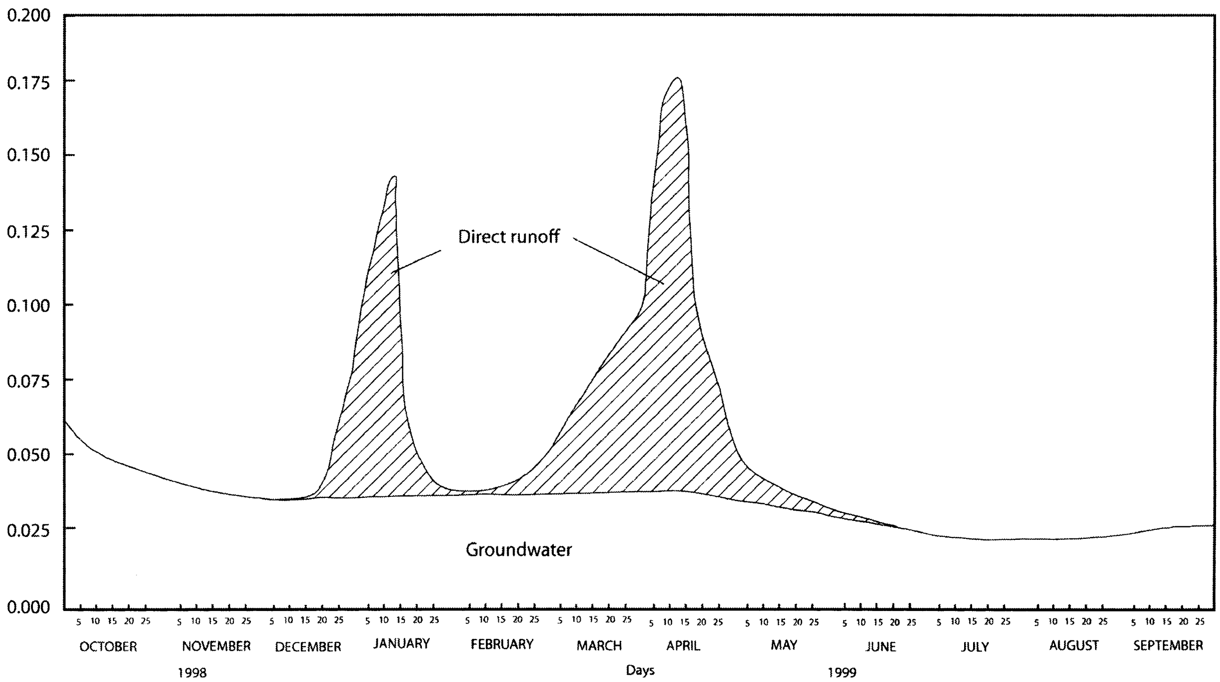

Figure 4. Stream flow hydrograph for Mitumba watershed.

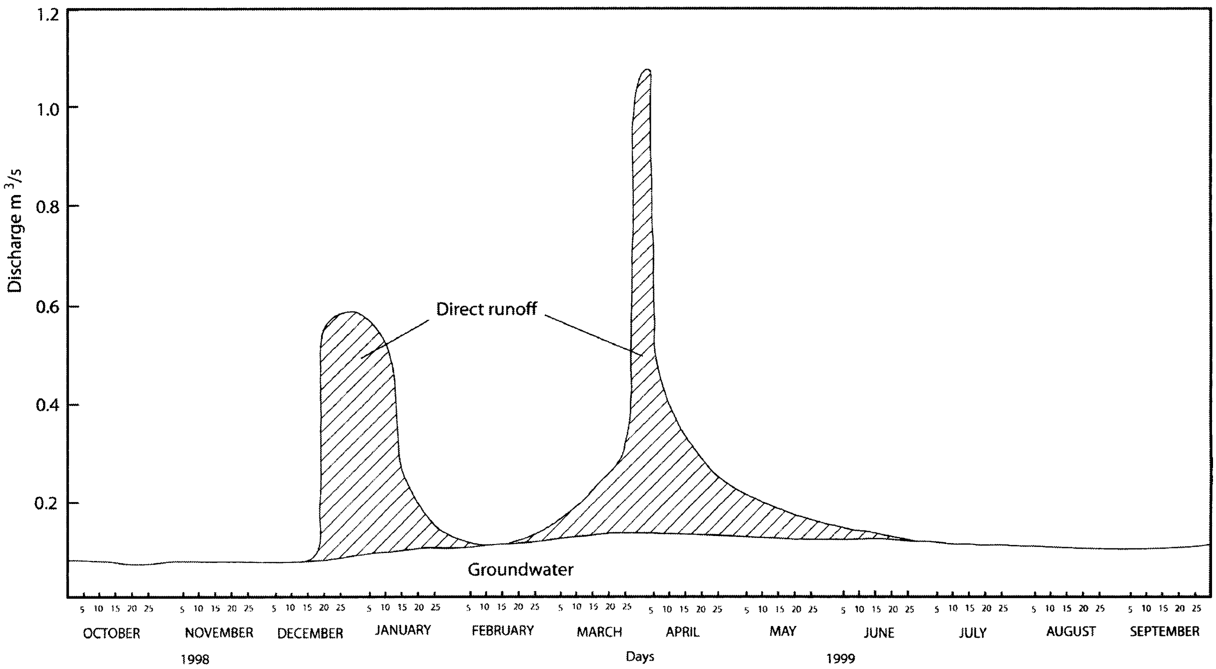

Figure 5. Stream flow hydrograph for Mwamgongo watershed.

Graphical decomposition and chloride ion methods along with ^{18}O data were used to separate stream flow hydrographs into base flow and surface runoff. Chemical analyses of the water samples for Cl^-, SO_4^{2-}, HCO_3^-, Na^+ K^+, Ca^{2+} and Mg^{2+} were performed by the chemical laboratory of Tanzania Bureau of Standards (TBS). Resulting chemical data were graphically analyzed using Piper diagrams as discussed by Back (1966), along with correlation analysis explained by Davis (1986). Stable isotope analyses were made at the stable isotope hydrology laboratory of the Department of Geosciences, University of Arizona, using a Delta S Finnegan Mass Spectrometer at a precision of about 0.005(‰). All water samples were collected in half litre plastic bottles then stored for three months in a cold room at 4 °C before being analyzed for both chemical and stable isotopes.

Results

Hydrograph separation for Mwamgongo and Mitumba streams hydrographs

From the hydrograph (the shaded and unshaded areas) I obtained total stream flow discharge including both direct runoff and groundwater flow (Figures 4 and 5). Equation (4) was used to perform the separation using chloride and δ^{18}O data whose results are shown in Figure 6a, b.The relationship between δ^{18}O and δ^{2} H for the rainfall in this area resulted in a Local Meteoric Water Line (LMWL) with an equation of δ^2 H = 7.35^{18}O + 17, r^2 = 0.91. A similar relationship for the shallow groundwater flow system as reflected by spring discharges resulted in an equation of δ^2 H = 6.93δ^{18}O + 12, r^2 = 0.86. The slopes of the two equations indicate a slight evaporation effect on rainfall and or surface runoff before infiltration, or a bit of mixing of various infiltrating water with variable δ^{18}O and δ^2 H values. The relationships of the δ^{18}O and δ^2 H from rainfall and springs have been determined from the data shown in Table 1. The mean δ^{18}O was calculated to be −3.01(‰) and −2.98(‰) for rainfall and springs, respectively, thus implying fast infiltration of precipitation through the macropores. A comparison of the δ^{18}O data for the two streams shows more depletion in the Mitumba stream than in the Mwamgongo one. This shows that there is more delayed infiltration at the disturbed watershed than at the pristine one, possibly a consequence of compaction of the surficial macropores by human and livestock trampling and other activities.

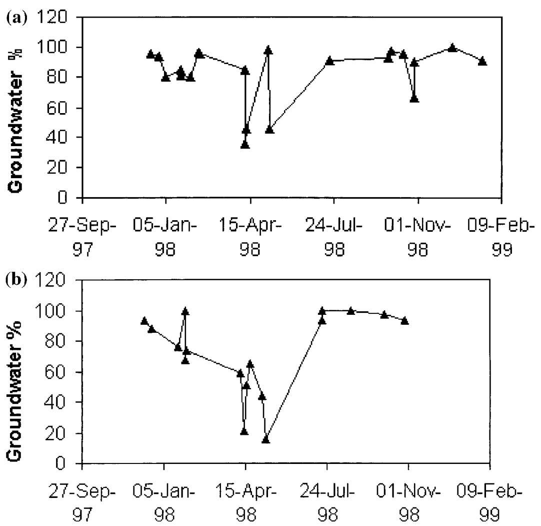

Figure 6. (a) Groundwater component of the Mitumba stream on selected dates. (b) Groundwater component of Mwamgongo stream on selected dates.

Groundwater contribution to the total stream flow

The groundwater component of stream discharge estimated from both the classical and chemical methods indicates that in the two respective watersheds groundwater forms a large part of stream flow. The classical analysis of the hydrographs and recession curves showed that the calculated groundwater component is 70% of total stream flow for Mwamgongo and 65% for Mitumba. However, the chloride and δ^{18}O chemical methods yielded groundwater component proportions of 65 and 70% for Mwamgongo and Mitumba, respectively, indicating a slightly greater proportion of groundwater contribution for the undisturbed site. Although the percentage difference of 5% in groundwater flow looks small between the two watersheds, in quantitative terms per year is a significant inflow to the lake, particularly when extrapolated to the entire Lake Tanganyika shoreline.

From the chemical mixing model developed by Pinder and Jones (1969) and that of Ribolzi et al. (2000) the results from the chemical techniques have been taken to be more representative than those of the classical analysis, the latter being considered more arbitrary or subjective. However, such chemical methods are approximate and sometimes difficult to apply (Ribolzi et al. 2000).

Table 1. Stable isotopes in spring water and rainfall from Mwamgongo and Mitumba watersheds.

No.	Sample source	δ^{18}O (‰)	δ^{2} H (‰)	Cl (mg/l)
1	Nyamnini	−3.61	−11.27	2.7
2	Mitumba Gauging Station	−3.51	−11.49	5.3
3	Mitumba main spring	−3.28	−8.32	5.3
4	Mgunga Spring	−4.97	−25.92	10.0
5	Mgunga Spring	−3.35	−11.60	8.0
6	Nyamunini Spring	−3.44	−12.15	6.7
7	Nyamnini Spring	−3.33	−8.80	8.0
8	Mitumba Spring A	−4.18	−17.81	5.3
9	Mwamgongo Gauging Station	−1.53	1.59	5.8
10	Mitumba Spring A	−3.59	−12.69	8.0
11	Mitumba Spring B	−3.60	−11.54	5.3
12	Mitumba Spring A	−3.32	−10.16	8.0
13	Nyamnini Spring	−3.33	−10.89	7.3
14	Rainfall (R_1MW)	−1.93	−2.70	5.2
15	Rainfall (R_2MW)	−2.11	−4.36	5.2
16	Rainfall (R_4MW)	−1.46	5.82	8.7
17	Rainfall (R_5MW)	−1.94	3.3	5.9
18	Nyamninini Spring	3.31	−12.24	6.7
19	Mitumba Spring A	−3.33	−8.8	5.2
20	Mitumba Spring B	−3.57	−10.76	5.3
21	Kivumba Spring	−3.51	−10.79	6.1
22	Nyamnini Spring	−3.49	−12.37	6.6
23	Rainfall (R_1MW)	−2.44	−1.78	8.7
24	Rainfall (R_5MW)		6.25	6.0
25	Rainfall (R_4MW)	−1.52	8.04	8.6
26	Rainfall (R_5MW)	−3.18	−9.70	8.7
27	Rainfall (R_3Go)	−0.62	12.05	5.3
28	Rainfall (R_5MW)	−2.61	0.06	5.2
29	Rainfall (R_4Go)		−6.69	6.0
30	Rainfall (R_2MW)	−0.09	14.73	5.9
31	Rainfall (R_4Go)	−2.32	−0.57	5.3
32	Rainfall (R_3MW)	−3.17	−9.26	8.7
33	Rainfall (R_1MW)	−3.10	−8.04	7.3
34	Rainfall (R_4MW)	−2.55	−6.72	7.3
35	Rainfall (R_3MW)	−3.15	−10.76	5.9
36	Rainfall (R_2MW)	−0.89	8.67	7.3
37	Rainfall (R_1(R_3MW))	−2.94	−7.65	5.3
38	Rainfall (R_2Go)	−0.43	12.67	5.2
39	Rainfall (R_1Go)	0.11	17.72	5.3
40	Rainfall (R_3Go)	−2.57	−3.07	5.9
41	Rainfall (R_5MW)	−2.84	−8.78	5.2
42	Rainfall (R_1Go)	−1.51	6.66	8.8
43	Rainfall (R_3MW)	−1.46	5.82	5.3
44	Rainfall (R_3MW)	−1.62	3.86	7.3
45	Rainfall (R_4MW)	−3.25	−9.69	6.0
46	Rainfall (R_5MW)	−2.40	−1.70	8.6
47	Rainfall (R_1MW)	−3.61	−15.41	
48	Rainfall (R_1MW)	−0.02	5.82	
49	Rainfall (R_1Go)	0.39	14.98	
50	Rainfall (R_1MW)	−2.19	−10.69	
51	Rainfall (R_1MW)	1.14	18.19	
52	Rainfall (R_1Go)	−3.69	−17.83	
53	Rainfall (R_2MW)	−3.62	−16.70	
54	Rainfall (R_2MW)	2.52	20.12	

Table 1. Continued

No.	Sample source	δ^{18}O (‰)	δ^{2} H (‰)	Cl (mg/l)
55	Rainfall (R_3MW)	0.55	17.39	
56	Rainfall (R_1Go)	−0.14	7.43	
57	Rainfall (R_2Go)	−5.63	−30.94	
58	Rainfall (R_3MW)	−2.01	−6.28	
59	Rainfall (R_1MW)	1.38	3.57	
60	Rainfall (R_3MW)	−3.80	−22.78	
61	Rainfall (R_1MW)	−1.23	4.18	
62	Rainfall (R_2Go)	−4.94	−28.51	
63	Rainfall (R_1Go)	−4.31	−23.93	
64	Rainfall (R_1Go)	−4.29	−16.97	
65	Rainfall (R_1MW)	−6.35	−35.72	
66	Rainfall (R_1MW)	−2.07	2.52	
67	Rainfall (R_3MW)	0.13	11.54	
68	Rainfall (R_1MW)	−0.08	9.84	
69	Rainfall (R_1Go)	−4.03	−19.81	
70	Rainfall (R_1MW)	2.66	18.88	
71	Rainfall (R_1Go)	−6.71	−40.12	
72	Rainfall (R_1Go)	−10.22	−65.66	
73	Rainfall (R_1MW)	−6.22	−36.52	
74	Rainfall (R_1MW)	−5.23	−26.45	
75	Rainfall (R_1MW)	−5.44	−32.04	
76	Rainfall (R_1MW)	−4.28	−15.04	
77	Rainfall (R_1MW)	−0.11	−27.97	
78	Rainfall (R_1MW)	−1.84	−3.32	
79	Rainfall (R_3MW)	−11.77	−75.05	
80	Rainfall (R_3MW)	−1.98	2.42	
81	Rainfall (R_3MW)	−5.16	−28.14	
82	Rainfall (R_1MW)	−3.79	−19.35	
83	Rainfall (R_1MW)	−4.45	−11.19	
84	Rainfall (R_1MW)	−3.38	−12.86	
85	Rainfall (R_1MW)	−0.25	11.41	
86	Rainfall (R_1Go)	−3.11	−8.6	
87	Rainfall (R_1MW)	−10.80	−72.99	
88	Rainfall (R_1MW)	−14.06	−103.35	

The chloride ion can be regarded as an inert element in the hydrologic cycle with its source from atmospheric deposition. It is ‘mobile’ (quasi-conservative), being neither added nor removed by water–rock interaction during percolation in the vast majority of environments as compared to other inorganic ions (Ohrui and Mitchell 1999). In addition it undergoes only insignificantly adsorption on to solids, and thus qualifies as being a tracer. Chloride always advects with water implying that it travels at more or less the same speed as the water through advection process (Ward and Robinson 1990; Nkotagu 1996; Richey et al. 1998).

The isotope ^{18}O is stable and forms part of the water molecule and therefore behaves as an ideal tracer. It is therefore very effective in the separation of stream flow into both direct runoff and groundwater components. The relative difference in groundwater flow contribution to total stream flow between Mwamgongo and Mitumba watersheds is probably due to the result of differences in evaporation and evapotranspiration rates between the two watersheds. The Mitumba watershed may be less affected by evaporation due to higher density vegetation cover although evapotranspiration may be very high. Mwamgongo watershed is less vegetated, having only sporadic grassland cover, which is frequently subjected to fires, leaving the watershed soils bare. As shown elsewhere (Ribolzi et al. 2000) this situation in the Mwamgongo watershed would accelerate surface runoff. In turn this would allow for little or reduced infiltration rates, and hence a reduced proportion of groundwater to total stream flow in comparison with the Mitumba watershed, where the data indicates higher infiltration rates.

However, the analysis of recession curves indicated that in the two watersheds the values of the recession constants do characterize the groundwater component. The calculated recession constants of $0.94\times10^{-3}\ d^{-1}$ for Mitumba and $0.96\times10^{-3}\ d^{-1}$ for Mwamgongo are typical values for groundwater component according to Hewlett (1961). This indicates good drainage rate of groundwater storage from the watersheds leading to sustained stream flow even in the driest seasons. The sustained groundwater or base flow in the two watersheds implies the presence of large and permeable aquifers. Otherwise, if the aquifers were small and of low permeability, the groundwater discharge to the surface would have decreased significantly, or even ceased.

Piper's chemical classification

The major chemical ions are plotted on Piper trilinear diagram in Figures 7 and 8. The plots indicate that the waters in both watersheds are dominated by alkaline earths characterized by an $MgHCO_3$ type of water, similar to that of the Lake Tanganyika. The type of water indicates that water–rock interaction determines the chemical character of water in both watersheds whose geology is the same pointing out that at the time of the study, domestic sources of pollution in both watersheds played an insignificant role in the overall chemical character of the stream flows. In addition, silica was determined to be the most dominant nutrient in comparison to phosphates and nitrates for both streams Figures 9b and 10b). These results further supports the view that anthropogenic factors have a limited effect on the major element and nutrient chemical character of the water in this area because silica is primarily a product of the reaction of silicate minerals with water.

Correlation analysis shows salinity as indicated through electrical conductivity values (EC values) of both surface and groundwater to be strongly and positively correlated with Na^+, K^+, and HCO_3^-, and to a lesser extent with Mg^{2+}, and Cl^- (Table 2). The correlation results further suggest that the chemical character of water in this area is caused primarily by water–rock interaction. The reaction of albite (a common mineral in the watersheds as determined during geological mapping) with meteoric water could generate the following chemical reaction:

$$\begin{aligned} &2.33\ NaAlSi_2O_8 + 8.64H_2O + 2CO_2 \\ &\quad \rightarrow Na_{0.33}Al_{2.33}SiO_{3.67}O_{10}(OH)_2 + 2Na^+ \\ &\qquad + 2HCO_3^- + 3.32H_2SiO_4 \end{aligned}$$

Silica was determined to be more abundant than either phosphates or nitrates supporting the water–rock interaction hypothesis process that determines the chemical character of the stream water in both watersheds because silica is primarily a product of the reaction of silicate minerals with water (Figures 9b and 10b). The concentration of the Na^+ and K^+ tends to be smaller than Mg^{2+}, which can be attributed to the cation exchange process that depletes the Na^+, and K^+ ions from solution in favor of the Mg^{2+} enrichment from the soil matrix.

Mean monthly variation in the chemical composition of stream water in the two watersheds

Mean monthly variations in the chemical composition of water in the Mitumba and Mwamgongo watersheds show the chemical composition to have similar trends in the two watersheds (Figures 9a and 10a). In general, total dissolved solids (TDS) are observed to decrease during the high rainfall

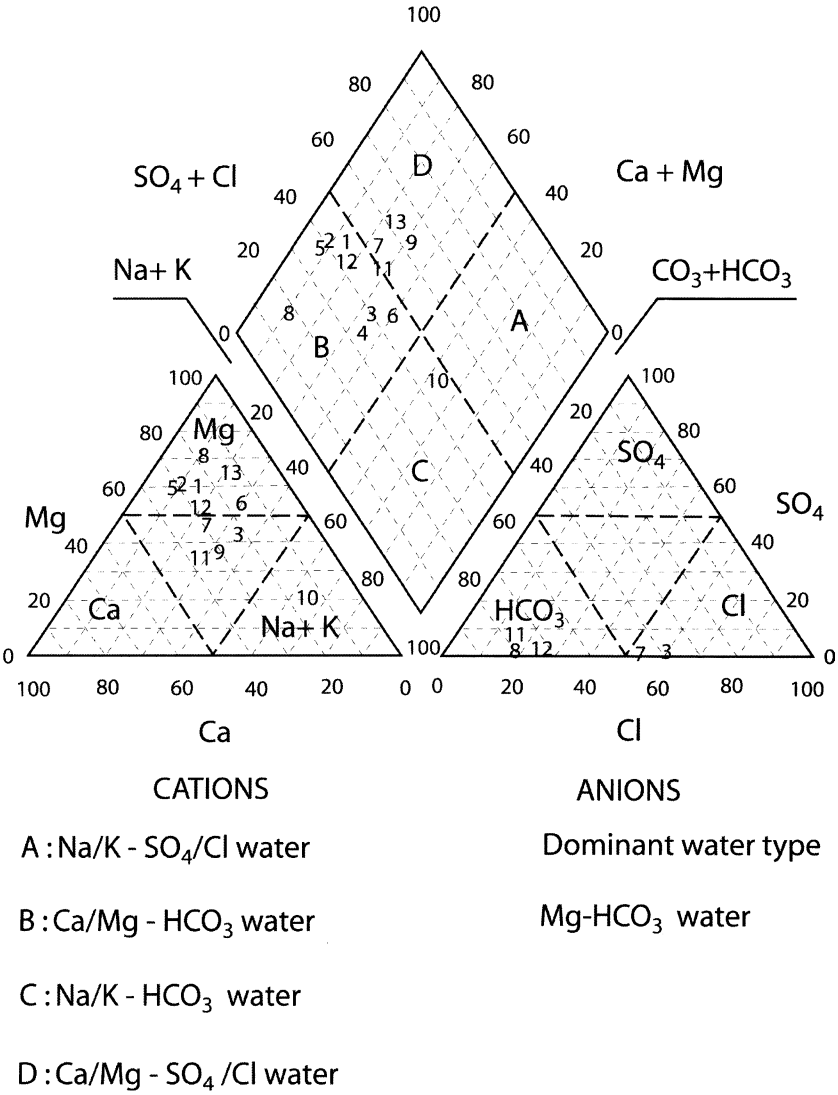

Figure 7. Piper trilinear diagram for Mitumba catchment.

months as a consequence of dilution effects when stream flow increases, specifically in the months of April and January. Rapidly flowing fluxes of surface runoff generated by high rainfall results in decreased water rock contact time. The increase of TDS in the period of decreased rainfall and runoff results from both the increase in contact time between the rock and the water thus enabling effective dissolution process to take place, as well as the increased evaporation effect to be significant.

Magnesium is observed to be the dominant cation and bicarbonate the dominant anion during the entire water year (Figures 9a and 10a). This implies that natural processes are responsible for the chemical character of the water in the two watersheds as there are no anthropogenic sources of Mg or HCO_3 in this area and the ions are naturally being introduced into the aquatic environment independent of seasonal variation. The major influence of natural processes to the general chemical character of the two streams is further supported by the dominance of silica (SiO^2) over other nutrients like phosphate (PO_4^-) and nitrates (NO_3^-) as shown in Figures 9b and 10b.

The data show an increase in dissolved salts going from rainfall to surface runoff then to

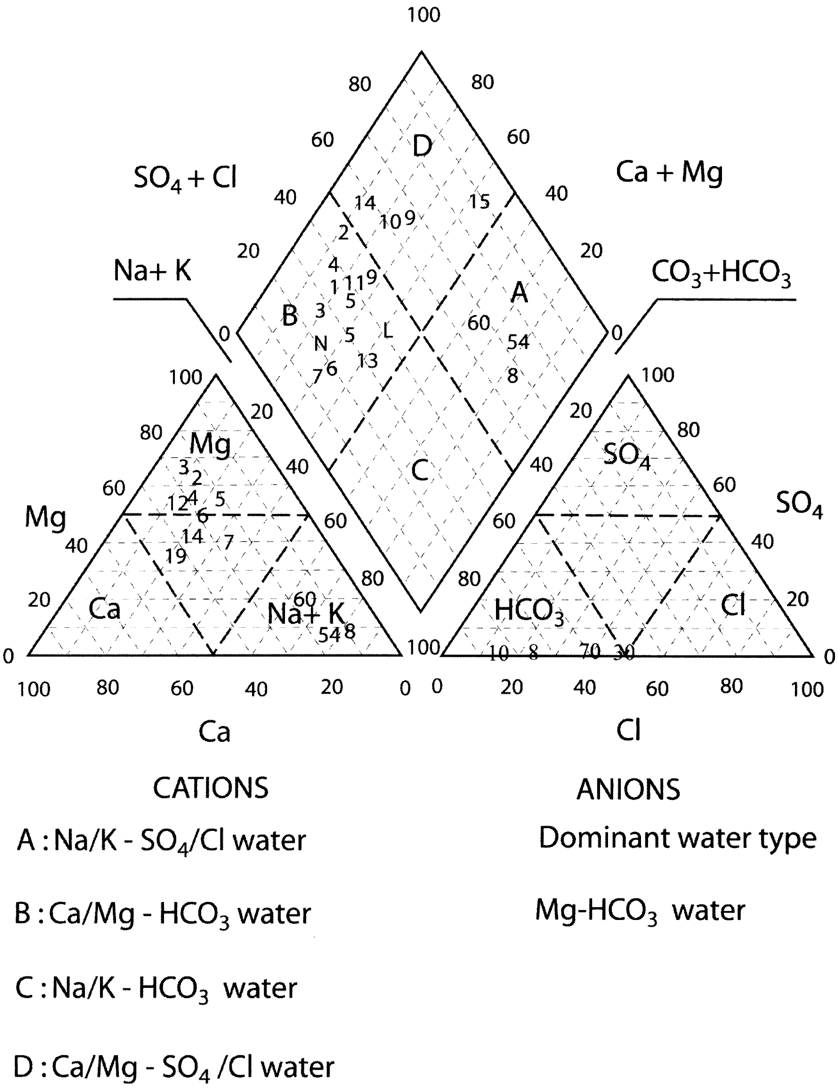

Figure 8. The Piper trilinear diagram for Mwamgongo watershed.

groundwater as indicated by stream base flow component at the end of the dry season in both watersheds. However, waters from the Mwamgongo watershed have higher total dissolved salt contents than waters from the Mitumba watershed. The difference in the total dissolved solids may be attributed to less permeability of aquifers in the Mwamgongo watershed than in the Mitumba one resulting in high residence time in the former than the later watershed as also supported by the calculated decreased groundwater flow in the Mwamgongo watershed as calculated from the chloride and stable isotope method. The ratio of the peak flow to lowest flow is higher in the Mwamgongo watershed than in the Mitumba watershed indicating that Mwamgongo watershed has higher retention time of groundwater than the Mitumba one in which groundwater is transmitted faster than in the Mwamgongo watershed. Alternatively the higher TDS in Mwamgongo watershed may be attributed to the presence of more exposed rocks by human activities at the watershed than in the Mitumba one which is densely forested, thus enabling wide surface area for water–rock interaction during infiltration hence resulting in high total dissolved salts at the Mwamgongo watershed.

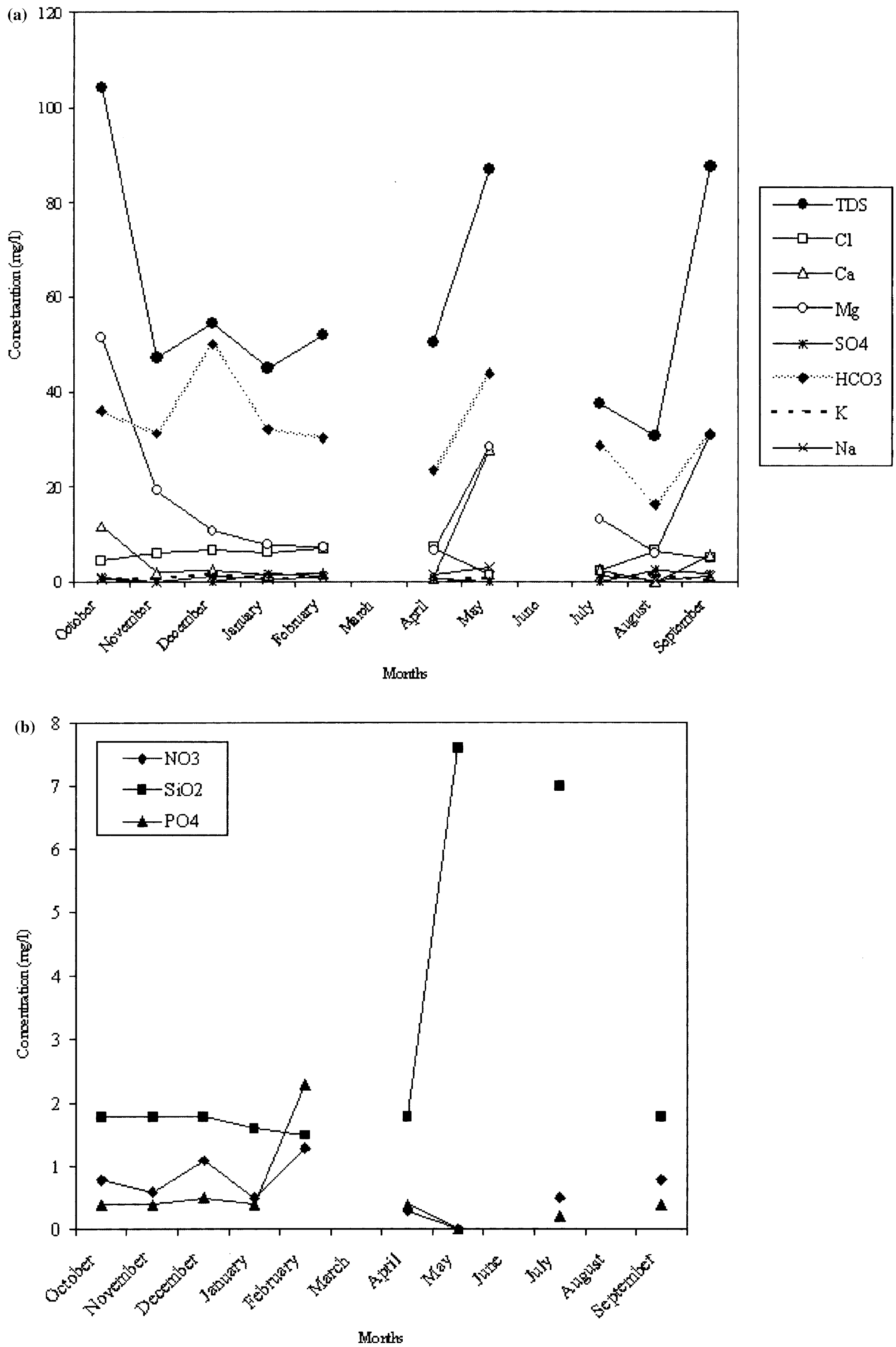

Figure 9. (a) Mean monthly variation of major ions of the Mitumba stream. (b) Mean monthly variation of nutrients for the Mitumba stream.

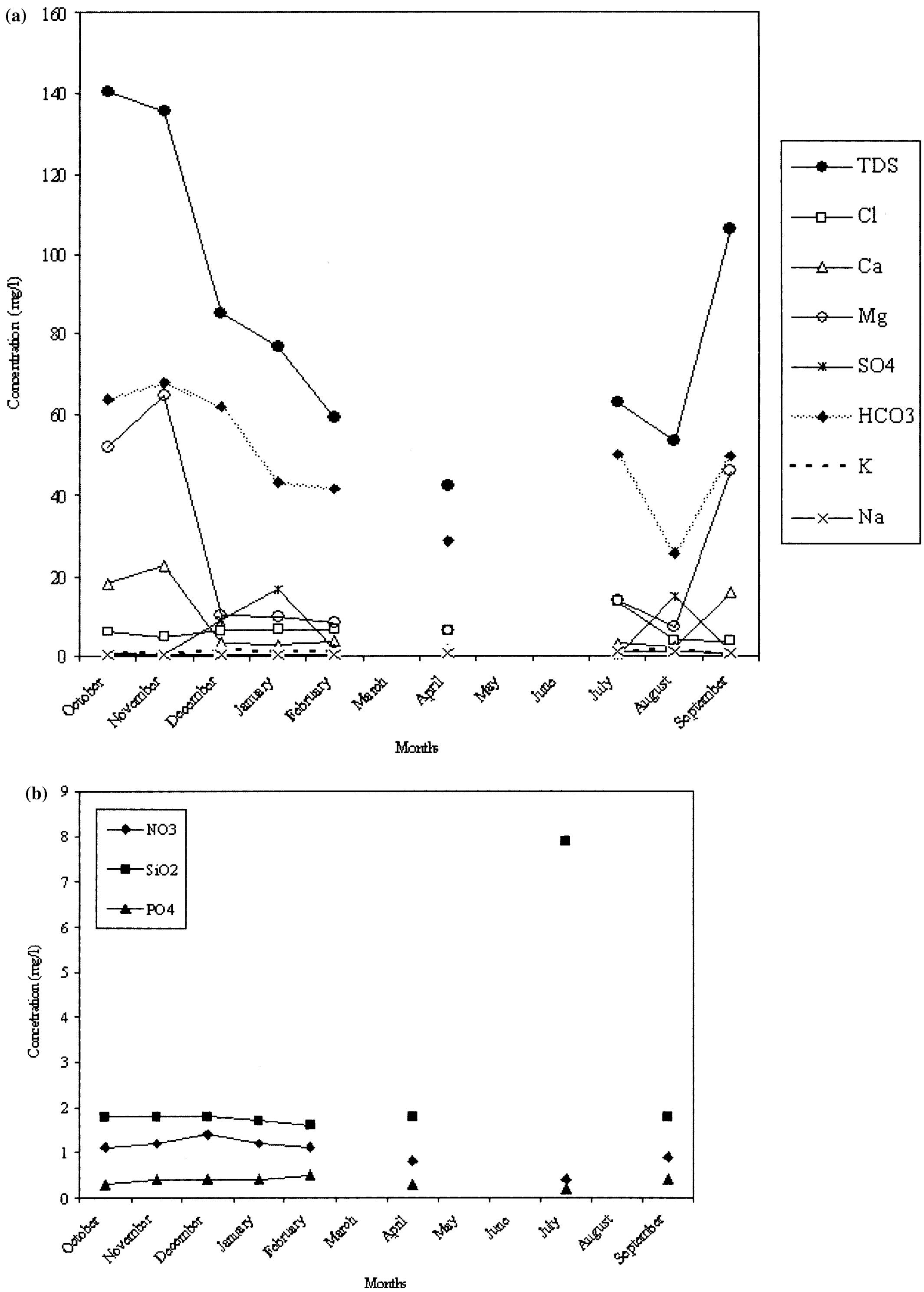

Figure 10. (a) Mean monthly variation of major ions for the Mwamgongo stream. (b) Mean monthly variation of nutrients for the Mwamgongo stream.

Table 2. Correlation matrix for chemical data.

Variable	Temp	pH	EC	Cl	Ca	Mg	SO_4	HCO_3	Fe	K	Na
Temp	–										
pH	0.12	–									
EC	0.11	0.76	–								
Cl	0.15	0.21	0.37	–							
Ca	0.13	0.31	0.26	0.19	–						
Mg	0.15	0.37	0.31	0.21	0.77	–					
SO_4	0.12	0.01	0.09	0.22	0.00	0.06	–				
HCO_3	0.13	0.77	0.95	0.27	0.29	0.37	0.00	–			
Fe	0.08	0.09	0.10	0.02	0.07	0.09	0.71	0.10	–		
K	0.11	0.75	0.94	0.26	0.20	0.30	0.01	0.95	0.06	–	
Na	0.10	0.75	0.94	0.42	0.25	0.33	0.01	0.92	0.10	0.93	–

Human activities at the Mwamgongo watershed could have resulted in compacted macropores at the surface and near surface soils. This would result in decreased infiltration rates, which in turn increases the residence time of groundwater. A resulting increase in water–rock interaction, especially in the unsaturated/vadose zone could explain the observed increased dissolved salts in the Mwamgongo watershed. The compaction effect is further supported by the more enrichment in the $\delta^{18}O$ and δ^{2} H values observed in the Mwamgongo stream than in the Mitumba one. This points towards increased evaporation effect prior to infiltration as a consequence of slowed infiltration rates.

Conclusions

The study provides support for the hypothesis that human activities influence the hydrological conditions of recharge and stream/ground water composition in the Lake Tanganyika catchment, as demonstrated by the study of two paired watersheds of the same size in the northern Tanzanian part of the lake area. The heavily disturbed and deforested Mwamgongo watershed displays a reduced groundwater component of the total stream flow and overall increased dissolved salts in comparison to the forested Mitumba watershed. However, in both watersheds groundwater forms a major part in the total stream flow, about 65 and 70% for the Mwamgongo and Mitumba watersheds, respectively. Human activities taking place in the Mwamgongo watershed also affect total stream flow, in that this stream experiences higher rates of surface runoff relative to groundwater contributions to total discharge in comparison with the Mitumba watershed. Most likely this is a consequence of deforestation activities in the Mwamgongo watershed, which has lead to lower rates of soil water infiltration than in the forested Mitumba watershed.

The stream water in both watersheds is dominated by alkaline earths (Mg^{2+}) and weak acids (HCO_3^-, CO_3^{2-}). However, the water chemistry is observed to be influenced by natural processes i.e., water–rock interaction.

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