

Hydrology of a rainforest headwater swamp from natural chemical tracing (Nsimi, Cameroon)

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Abstract

The hydrological role of a headwater swamp in a tropical rainforest is studied using chloride mass balance and End-Member Mixing Analysis. The first method characterizes the interaction of the swamp with hillsides and stream at yearly time scale. The second method identifies the origin of water during two storms at hourly basis.

The main contribution to streamflow is from the hillside bedrock aquifer which represents 64 % of total stream flow. The second contribution is from overland flow on the swamp surface during storm events which contributes for about 25 % of the stream flow. The groundwater flow from the swamp aquifer contributes for only about 11% of streamflow.

Before rainfall events of October, the pre-event water is a mixing of bedrock aquifer water for 80 % and 20 % of swamp aquifer. During the storm, the relative contribution of overland flow increases according to the rainfall intensity and the initial saturation rate of the pre-event water reservoirs.

Relationships between the swamp and the stream fluctuate with space and time. While the swamp is drained by the stream most of the time, at the end of the long dry season, indirect recharge occurs from the stream to the swamp with a hydraulic gradient inversion in the swamp aquifer after the first rains.

Evapotranspiration is higher on the hillside than in the swamp. Nevertheless, depletion of water stored within the swamp is dominated by evaporation rather than by contribution to stream flow.

If the average contribution to the streamflow of bedrock aquifer flow is higher than swamp aquifer flow, the solute content (Na and Si) in the stream dominantly (55-60 %) originates from the swamp. The export of solutes through swamp groundwater flow below the weir is low (< 7 %). Nevertheless, the swamp is the most active area of weathering in the watershed.

Keywords: chloride mass balance, EMMA, wetland, evapotranspiration, streamflow, low flow, groundwater recharge

Introduction

The total area of African wetlands is estimated at 340 000 km². Their extensive distribution in headwater regions make them very important in the hydrological cycle (Bullock, 1992b). In addition, wetlands located in the upper part of African watersheds represent hydrological and hydrochemical systems which are not well understood. Their relationship with hillsides and streams are debated in several papers (Bullock and Acreman, 2003). Swamp supposed function of a headwater “sponge” capable of absorbing water during rainy season and releasing it slowly during the dry season (Balek, 2003; Balek and Perry, 1973) has been challenged (Bullock, 1992b; McCartney, 2000).

The relative contributions of swamp and hillside groundwater to stream in low flow conditions is a question of interest for stream management in low flow conditions during the dry season. Recently, it has been shown that the sustained middle to late dry season streamflow from a wetland can be through discharge of a deeper aquifer within the underlying regolith or bedrock (von der Heyden and New, 2003). Other authors came to an opposite conclusion (McCartney and Neal, 1999). Role of swamps during storms is also not well defined: do they really contribute to flood flow attenuation and retardation or not? The debate is also open with examples of such effects on storms (Balek and Perry, 1973) and counterexamples (Bullock, 1992a; von der Heyden and New, 2003).

A Cameroon headwater swamp has been studied using natural tracer analysis. Two different approaches have been used in order to characterize the hydrology of this forested swamp at various time scales: the chloride mass balance is computed on a yearly basis while the contributions of various source waters to two short storm events of a few hours duration are determined by end-member mixing analysis.

The combination of these methods of analysis allows characterizing the hydrology of the swamp: (i) the swamp / hillside contributions to stream flow during dry season (ii) the origin of water in the swamp (iii) the interaction of the swamp with the stream (iv) the evapotranspiration from the swamp and the watershed (v) the role of swamp in solutes output fluxes and weathering process.

Site description

The 60 ha Nsimi watershed (3°10'N-11°51'E) belongs to the Nyong river basin and is located 300 km from the Atlantic Ocean. The Nyong basin is located in the tropical rainforest between the latitude 2°48'N and 4°32'N (Figure 1), primarily on the South Cameroon Plateau. The basement of the Nyong basin is composed of highly faulted silicate rocks (schists, gneissic granites, and migmatites) belonging to either the North Congo Shield (Ntem complex) boundary or to the Pan-African belt (Vicat, 1998). The landform, now at a mean elevation of 700 m, namely “Interior Erosion Surface” (Tardy and Roquin, 1998), is composed of convexo-concave relief separated by flat swamps of variable size.

The current regional humid tropical climate is marked by two dry and two wet seasons of unequal length and intensities. Going inland, the rainfall decreases in the entire Nyong basin due to the steep elevation increase from sea level to 700 m (Figure 1). An automatic wet-only precipitation collector was operated at the station from 1996 to 2000. The rainfall regime, associated with eastward advection of moist and cool monsoon air masses, amounts to an average of 1700 mm/year. Ion Chromatography determined chlorine content of precipitation in 234 rainfall events, representing a total 4583 mm of rainfall from an overall of 7100 mm.

Semideciduous rainforest (Sterculiaceae-Ulmaceae) covers 60% of the rounded hills, and cultivated food crops, including tubers, manioc, peanuts, palm trees, and plantain, cover the remaining 40%. Semiaquatic plants of the Araceae family and tree populations of

Gilbertiodendron deweverei (Caesalpinaceae) and *Raffia monbuttorum* (raffia palm trees) comprise most of the swamp vegetation. The clearing of the forest, done before 1993, was the most important disturbance of the watershed hillside; but the whole swamp zone is still well preserved. The initial farming method consisted of slashing and burning the pre-existing vegetation followed by annual or biannual cultivation. Then the farmers left the fields fallow for a period of two to four years.

The swamp covers 20% of the watershed (Figure 1). All water-year long, the swamp is flooded and constitutes a seepage zone, the extent of which depends on the seasonal distribution of the rain. In the driest months, the extent is only 75% of the whole swamp area. Some small local ponds, however, continue to persist in the poorly drained zone, even during the dry seasons.

During the period 1994-1998, 378 mm/yr flowed at the weir located at the outlet (Figure 1) during which the mean annual rainfall was 1658 mm/yr.

One fractured aquifer is located in the regolith-bedrock complex below the hillside and the swamp. A part of this water emerges at specific seepage points and springs and is conveyed to the stream. The mean discharge rate of the main spring (spring MEN1, Figure 1) has been measured at 0.87 l/s, which corresponds to 46 mm/yr related to the watershed surface area.

Pits and observation wells have been drilled in order to measure water levels and chemical compositions (Figure 1). Sampling and analysis methods have been described in (Braun et al., 2005).

Figure 1 : Nsimi head watershed into the Nyong river basin, modified from (Braun et al., 2005)

Methodology

Chloride mass balance in a double hydrological system

Except few examples (McCartney and Neal, 1999), application of chloride mass balance method to swamp hydrology is very rare. Here, the classical chloride balance has been adapted to the specific case of a headwater swamp watershed constituted by two interacting hydrological systems: the swamp and the hillside systems (

Figure 2a). The bedrock aquifer of hillside is drained by several springs and seepages located in the transition zone at the bottom of the hills. The swamp aquifer flows parallel to the stream.

Figure 2 : (a) cross-section of Nsimi headwater catchment with a swamp, representation of flows exchange between swamp and hillside hydrological systems (b) isolated systems with their respective chloride balance and water budget equations

Assuming a steady state, the amount of Cl incoming from the atmosphere should balance the amount of Cl leaving the watershed (Figure 2b):

$$P [Cl]_p = Q_{st} [Cl]_{st} + Q_{swp} [Cl]_{swp} \quad (1)$$

With P the precipitation rate (mm/yr), Q_{st} the stream flow rate at the outlet (mm/yr), Q_{swp} the groundwater flow rate through the swamp below the weir (mm/yr), $[Cl]_p$ the weighted average of chloride content in rainfall, $[Cl]_{st}$ the weighted average of chloride content in the stream water and $[Cl]_{swp}$ the chloride content of swamp water. In all the equations, except when mentioned, the flow intensities are related to the total watershed area A .

The bedrock aquifer is recharged by infiltration of water on the hillsides (Figure 2c). A part of this water flows to the springs and seepages (Q_{hill}) while the other part flows to the swamp (Q_{base}). According to observation made on the watershed during rainfall events, we assume that the overland flow can be neglected on the forested hillside. Therefore, the chloride mass balance of hillside can be computed as:

$$P [Cl]_p A_{hill} = (Q_{hill} [Cl]_{hill} + Q_{base} [Cl]_{hill}) A \quad (2)$$

With Q_{hill} the total flow rate of springs and seepage at the bottom of hillside (mm/yr), Q_{base} the groundwater flow exchange between the bedrock aquifer and the swamp (mm/yr), $[Cl]_{hill}$ the chloride content of hillside/bedrock groundwater, A_{hill} (m²) the surface area of hillside and A (m²) the total surface area of the watershed.

The water budget of hillside/bedrock aquifer system (Figure 2c) is

$$R_{hill} = Q_{hill} + Q_{base} \quad (3)$$

with R_{hill} the recharge rate on the hillside.

In the swamp aquifer system (Figure 2d), inflows are recharge on the swamp ground surface and baseflow from the bedrock aquifer while outflows are groundwater flow below the weir at the outlet and exchange with the stream. The groundwater budget of the swamp is:

$$Q_{base} + R_{swp} = Q_{swp} + Q_{swp/st} \quad (4)$$

with R_{swp} the recharge rate to the swamp aquifer and $Q_{swp/st}$ the exchange flow rate between the swamp and the stream.

The corresponding chloride mass balance of swamp aquifer system (Figure 2d) is

$$Q_{base} [Cl]_{hill} + R_{swp} [Cl]_{Rswp} = Q_{swp} [Cl]_{swp} + Q_{swp/st} [Cl]_{swp/st} \quad (5)$$

with $[Cl]_{Rswp}$ the chloride content of recharge flow to the swamp and $[Cl]_{swp/st}$ the chloride content of exchanged flow between swamp and stream.

The total streamflow at the outlet of Nsimi watershed (Figure 2b) is the sum of the contributions of the bedrock aquifer, the exchange flow between the swamp and the stream and the overland flow on the swamp surface:

$$Q_{st} = Q_{hill} + Q_{swp/st} + OF_{swp} \quad (6)$$

with OF_{swp} the overland flow on the surface of the swamp.

The chloride mass balance of the swamp surface (Figure 2d) is

$$P[Cl]_p A_{swp} = (OF_{swp} [Cl]_{OFswp} + R_{swp} [Cl]_{Rswp}) A \quad (7)$$

with $[Cl]_{OFswp}$ the chloride content of overland flow on the swamp.

In considering the overland flow component, equation (7) becomes an extended version of the equation commonly used in the literature for recharge estimation (Bazuhaire and Wood, 1996; Wood and Sanford, 1995).

These seven equations describe the chloride mass balance and the water budget on both subsystems of the watershed and the whole watershed itself (see

Figure 2b to d for identification of subsystems concerned by each equation). These equations can be used in transient conditions provided a regular and long (several years) monitoring of chloride is conducted on rainfall, surface and groundwater. The weight average chloride in precipitation and runoff are calculated using same equations than (Wood and Sanford, 1995). A simple average is calculated for chloride in groundwater using waters regularly sampled in observation wells.

Some recent studies have shown that chloride can be temporarily retained in the soils due to interaction with organic matter (Öberg and Sandén, 2005). This may also be the case on the Nsimi watershed (Viers et al., 2001). However, as the Cl mass balance is equilibrated at Nsimi over the whole-year, Cl should be adsorbed and released at a seasonal scale (Viers et al., 2001). Generally, it appears that the delays of the involved processes are at most a few months. This is not significant for long-term flows and fluxes estimation using several years data (Alcalá and Custodio, 2008; Scanlon et al., 2006) and these equations can be used for average flows estimation on a yearly time-scale. In the Nsimi watershed, the substratum is free of evaporates and very poor in chlorine bearing minerals. Moreover, during the time of the study, care was taken to preserve the watershed from burning and clearing. In addition, farmers practiced cultivation without external chemicals. Then, it may be reasonably considered that chloride comes from atmospheric deposition only and that the CMB technique method can be applied with accuracy.

End-Member Mixing Analysis (EMMA)

End-member mixing analysis (EMMA) was used to determine proportions of end-members contributing to streamflow, following the procedures described by (Christophersen and Hooper, 1992). Streamflow samples and end-members were standardized for all conservative tracers using the mean and standard deviation of streamflow following the procedure of (Burns et al., 2001):

- (1) A dataset consists in the concentrations of n solutes in N samples of stream water at the outlet of the watershed,
- (2) The data were standardized into a correlation matrix such that solutes with greater variation would not exert more influence on the model than those with lesser variation (SO_4 for example),
- (3) A principal-components analysis (PCA) was performed on the correlation matrix using the n solutes,
- (4) the concentrations of the end-members were standardized and projected into the U space defined by the stream PCA by multiplying the standardized values by the matrix of eigenvectors,

(5) the extent to which the end-members bounded the stream-water observations for the studied rainstorms was examined in the U space;

(6) The goodness-of-fit of solute concentrations predicted by the EMMA were compared with the concentrations measured during the storms through least-squares linear regression.

The EMMA model was then used to calculate the proportion of stream water derived from each of the three end-members for each sample collected during storms by solving the following mass-balance expressions:

$$1 = f_1 + f_2 + f_3 \quad (8)$$

$$U1_{st} = U1_1 f_1 + U1_2 f_2 + U1_3 f_3 \quad (9)$$

$$U2_{st} = U2_1 f_1 + U2_2 f_2 + U2_3 f_3 \quad (10)$$

where f_i is the proportion of end-member i in streamflow, and $U1$ and $U2$ are the first and second principal components of the PCA; the subscript “st” signifies stream and 1, 2, and 3 three contributing sources respectively.

The uncertainty in EMMA model results for the percentage of streamflow contributed by each end-member during each storm was calculated through an adaptation of a method described by Genereux (1998) and Burns et al. (2001). An uncertainty value was calculated for each of the two principal components used in the model through the incorporation of analytical uncertainty in each of the chemical constituents (Huntington et al., 1993) as follows:

$$W_{ui} = \sqrt{[(V_{ia} W_a)^2 + (V_{ib} W_b)^2 + \dots]} \quad (11)$$

Where W_{ui} is the uncertainty value for principal component i , $V_{ia}V_{ib}$ are the eigenvectors for constituents a and b on principal component i , and W_a and W_b are the analytical uncertainties in the values of constituents a and b .

For end-members characterized by a set of multiple analyzes (characterizing spatial or temporal variability), the uncertainty is supposed equal to the standard error of the set in the $U1, U2$ space.

According to Burns et al. (2001), the uncertainty value for each principal component was then successively added and subtracted from the values of $U1$ and $U2$ for each end-member and for each stream sample collected during the storms to create two new sets of values for $U1$ and $U2$. These new values of $U1$ and $U2$ were then used in Equations (8)–(10) to calculate an uncertainty range W_{fi} on end-member contributions (f_i) for each stream sample collected during the storms.

The error on computed solute concentrations has been estimated using the following equation modified from (Genereux, 1998):

$$W_y = \sqrt{(Y_1 W_{f1})^2 + (Y_2 W_{f2})^2 + (Y_3 W_{f3})^2} \quad (12)$$

with W_y is the uncertainty on computed solute Y concentration in stream, $Y_{j=1 \text{ to } 3}$ is the solute Y concentration in j^{th} end-member and W_{fj} is the uncertainty on proportion of end-member j .

Results

Hydrology

The water table fluctuations of the upper part of the swamp aquifer (observation well L6-540) are presented in Figure 3 on a yearly basis. On this graph, all the measurements between 1996 and 2000 have been gathered according to their Julian day of the year. Median daily rainfall on the same period is also presented. The water table is lower during the long dry season between December and March. The first rains of the short wet season during March to June almost saturate the swamp. The short dry season of July-August has not much effect on water levels. Later, the first rains of the long wet season contribute to fully saturate the swamp until November. The amplitude of water table fluctuations is less than 30 cm, as compared with more than 6 meters in the bedrock aquifer at PZ1-L6 for example. This is a typical hydrological behaviour for a swamp aquifer compared to bedrock aquifer below a hillside (Bullock, 1992a).

Figure 3 : annual water table fluctuation in the swamp aquifer at observation well L6-540

Water table fluctuations during 1997 and 1998 in the swamp along the Layon L3 are represented on Figure 4: they contribute to understand the relationship between the swamp and the stream. Left and right banks of the stream show various types of hydrologic responses: that is why they are separately treated on Figure 4.

On the left bank of the stream (Figure 4a), the water table fluctuations are lower than one meter. The water table remains constant at a high level during most of the year. Water levels only decrease during the long dry period (December to March) with an accelerated depletion as soon as the stream is almost dry (flow rate less than 0.3 l/s from 26/01/98). After this date, the drainage of the swamp is faster at a rate of about 0.5 m / month. From the North to the South, the water levels gently decrease towards the stream with minimum water elevation close to the stream at observation well L3-540. The stream drains the swamp. The North-South hydraulic gradient is $i_{NS} = 0.05$. This gradient remains constant during the whole year.

On the right bank of the stream (Figure 4c), water table fluctuations are also smaller than one meter, except at L3-640 which is very close to the hillslope boundary and is therefore more influenced by hillside water table fluctuations. The south-north hydraulic gradient perpendicular to the stream $i_{SN} = 0.017$ is lower than on the left stream bank.

With the first rainfalls and the flow reappearance in the stream, the water levels sharply increase. This recharge process is uniform on the left stream bank but more heterogeneous on the right bank. There, the water levels increase first near the stream (L3-540 and L3-560) and later further away (L3-580, L3-610 and L3-640). This corresponds to a hydraulic inversion into the swamp due to water infiltration through the stream bed.

Figure 4 : water level fluctuations in the swamp along the layon L3 (period 1997-1998) on the left (a) and right (c) banks of the stream. Discharge rate at the outlet (b).

Solute content

The chemical composition of rainfall, throughfall, hillside groundwater, swamp groundwater and of the two stream storms are presented in Figure 5 as box plots with median and quartiles. All data except the 2002 storm were taken from Braun et al. (2005). Rainfall is particularly diluted with on average $2 \mu\text{mol.L}^{-1}$ of Na, $4 \mu\text{mol.L}^{-1}$ of K and $2 \mu\text{mol.L}^{-1}$ of Cl. The influence of atmospheric gases and particles sources on the precipitation chemical content and

the associated deposition of chemical species was determined by Sigha et al (2003). Chloride concentrations have been also measured in atmospheric aerosols collected in Zoétélé from 1999 to 2004. They were very low and range from 0.01 to 0.04 $\mu\text{g}/\text{m}^3$ leading to an atmospheric dry deposition of chloride of 4 to 6 $\text{ng}/\text{ha}/\text{yr}$. Chloride concentrations in rain dominate the atmospheric deposition budget of chloride.

The throughfalls display the highest concentrations in K, 47 $\mu\text{mol}\cdot\text{L}^{-1}$, as compared to Na, 6 $\mu\text{mol}\cdot\text{L}^{-1}$, or Cl, 9 $\mu\text{mol}\cdot\text{L}^{-1}$. The hillside groundwater, the spring and the groundwater from transition zone have quite similar composition and contain around 100 $\mu\text{mol}\cdot\text{L}^{-1}$ of Si, 20-50 $\mu\text{mol}/\text{L}$ of Na, <20 $\mu\text{mol}\cdot\text{L}^{-1}$ of Ca, Mg and K. Swamp groundwater is characterized by the highest concentrations in Si, 300-400 $\mu\text{mol}\cdot\text{L}^{-1}$, Na, 120-170 $\mu\text{mol}\cdot\text{L}^{-1}$, Ca and Mg, 46-90 $\mu\text{mol}\cdot\text{L}^{-1}$. It is remarkable that all these possible contributors to the stream display specific chemical composition, which should help in determining their respective contributions to the stream. Waters of the two stream storms are diluted with for instance 8-16 $\mu\text{mol}\cdot\text{L}^{-1}$ of K, 33-53 $\mu\text{mol}\cdot\text{L}^{-1}$ of Na, 124-132 $\mu\text{mol}\cdot\text{L}^{-1}$ of Si. Such concentrations are typical from rivers draining shields in tropical humid conditions (Gaillardet et al., 1995).

Figure 5 : Box plots with median and quartiles (25% and 75% and 5% and 95%) for selected solute concentration in streamflow of October 1997 storm (St Oct 97) and October 2002 (St Oct 02), spring MEN1 (Spring), groundwater from hillside (PIT1L6 and PIT8L6), groundwater from transition zone at 1 m depth (HSB1) and 2 m depth (HSB2), groundwater from the swamp at 1 m depth (Swamp1) and 2 m depth (Swamp 2), throughfall and rainfall.

Chloride mass balance

The chloride mass balance and water budget equations (1) to (7) have been solved on the 1994-1998 period.

Knowing all the factors of equation (1) except the groundwater flow through the swamp, this equation has been solved in order to compute this unknown flow rate $Q_{swp} = 13 \text{ mm}/\text{yr}$ according to Table 1.

Another way to compute the groundwater flow in the swamp is to use the classical Darcy law for flow through a porous media:

$$\frac{Q_{swp}}{A} = q_{swp} = k i_{WE} S \quad (13)$$

with q_{swp} the groundwater flow rate out of the swamp (m^3/s), k the hydraulic conductivity in the swamp (m/s), i_{WE} the West-East component of hydraulic gradient parallel to the stream (-) and S the flowing section (m^2).

Slug tests have been conducted in the downstream part of the swamp. The obtained hydraulic conductivity at three different locations is $1.5 \times 10^{-5} \text{ m}/\text{s}$, $2.1 \times 10^{-5} \text{ m}/\text{s}$ and $3.3 \times 10^{-5} \text{ m}/\text{s}$. Geophysical electrical investigations conducted in the swamp provided information about the thickness of more conductive rocks. The section of terrains with low electrical resistivity is estimated to $S = 3750 \text{ m}^2$. Assuming a swamp fully saturated throughout the whole year, the hydraulic gradient can be approximated by the surface slope: $i_{WE} = 0.005$. Therefore, using equation (13), the obtained groundwater flow ranges from 15 to 32 mm/yr according to the considered hydraulic conductivity. Both results are similar, within the same order of magnitude, i.e. 10 – 30 mm/yr (Table 1), which is very low compared to the other components of the hydrological cycle.

The spring MEN1 is the main outlet of bedrock aquifer in the Nsimi watershed. In this highly recharged system, the water table constitutes a subdued replica of the topography (Haitjema and Mitchell-Bruker, 2005). Its catchment can be adjusted to the head of the surface watershed (Figure 1), with a surface area of about $A_{MEN1} = 90\,000 \text{ m}^2$. Assuming that the rest

of the bedrock aquifer located below the hillside is equally drained by other springs and seepage points, we obtain:

$$\frac{Q_{MEN1}}{Q_{hill}} = \frac{A_{MEN1}}{A_{hill}} \quad (14)$$

with A_{hill} (m^2) the surface area of hill slope and Q_{MEN1} the discharge rate at the spring MEN1 (mm/yr). This equation allows calculating the yearly contribution of bedrock aquifer to the streamflow, $Q_{hill} = 244$ mm/yr (Table 2).

Assuming that the chloride content in bedrock aquifer is equal to spring MEN1 chloride content, equation (2) leads to $Q_{base} = 21$ mm/yr (Table 2). Then eq (3) is solved to determine $R_{hill} = 265$ mm/yr (Table 2).

Solving of equations (4-7) of chloride mass balance necessitated an assumption on chloride content of overland flow on the swamp. The chloride content has been optimized in decreasing the difference between computed and measured fluxes of sodium and silica in the streamflow.

From EMMA analysis of storms (see below paragraph), it is obvious that contribution of overland flow (from throughfall) to sodium and silica in the stream flow is negligible. Therefore the flux of element E (Na or Si) in the stream is:

$$[E]_{st} Q_{st} = [E]_{hill} Q_{hill} + [E]_{swp/st} Q_{swp/st} \quad (15)$$

with $[E]_{st}$ the concentration of solute E (Na or Si) in stream water, $[E]_{hill}$ the concentration of solute E (Na or Si) in bedrock aquifer and $[E]_{swp/st}$ the concentration of solute E (Na or Si) in swamp water exchanged with the stream.

The optimized chloride content in overland flow is $[Cl]_{OFswp} = 4.3 \mu\text{mol.L}^{-1}$, which is logically between chloride content in rainfall $[Cl]_p = 2.3 \mu\text{mol.L}^{-1}$ and chloride content at the surface of the swamp $[Cl]_{swp0} = 9 \mu\text{mol.L}^{-1}$ (Braun et al., 2005). The optimization leads to a good balance of Si and Na (Table 3). The difference between measured flux in the stream and computed flux adding flow rates computed using chloride mass balance is very low ($< 5\%$).

The origin of fluxes in Na and Si are compared at Table 3. It indicates that 61 % of Na and 54 % of Si come from the bedrock aquifer of hillside system while the rest comes from the swamp.

The equations (4-7) constitute one system of four equations with four unknown variables. The chloride content of exchanged water between swamp and stream has been taken at one meter depth. The flow rates calculated at Table 4 are discussed later.

Mixing model of storms

The study focuses on two storm events which occurred during the long wet season. The flow peak of Oct 97 storm was 25.5 l/s about 2.3 hours after a rain of 7 mm. The second storm (Oct 02) is constituted by a double rainfall event. Each event resulted in the rise of stream flow.

Total precipitation prior to the storm events over 7 days (API_7) and 14 days (API_{14}) were higher for the Oct 97 storm event compared to the Oct 02 event. As a consequence, the initial flow (Q_{min}) was four times higher before the Oct 97 storm. Hydrological conditions of both storms can be compared on Figure 6 with the stream flow rate fluctuations during 1997 and 2002 years. Oct 97 event happened after two months of large flow rate at the outlet due to the long wet season. At the opposite, Oct 02 storm event happened at the beginning of the wet season at a time when the flow rate is still low before the impact of large rainfalls.

Figure 6 : stream flow rate at the Nsimi outlet and rainfall during 1997 and 2002 years, both storm events are located

The end-member mixing analysis has been used to evaluate the contribution of runoff components to the flow at the outlet of the watershed during both storms. For both storms, the solutes contents used for the EMMA are: EC, SO₄, Na, K, Mg, Ca and SiO₂. The principal component analysis indicated that 83 % and 90 % respectively of the chemical variability in stream water during the two storms could be explained by two principal components. This indicates that chemical variation in stream water can be accounted for by three end-members. Tracer compositions of streamflow samples were plotted along with potential end-members in U space (Figure 7a and b). Except for the first and the two last samples of Oct 97 and for the first sample of Oct 02 which lie outside the domain, the stream water during the storms can be bounded by the following three end-members: spring, throughfall and swamp (at 1 meter depth) water (Figure 7a and b). The outliers have been corrected forcing the resulting fraction to zero and resolving other fractions by the geometrical approach described in (Liu et al., 2004).

The end-member compositions have been measured and not estimated or optimized. For Oct 97, the compositions of end-members are: average on 8 samples of the spring MEN1 taken during the storm, one sample taken at the same season (on 07 October 1995) at one meter depth for the swamp and average on 15 samples of throughfall taken in 1995 and 1996. For Oct 02, the throughfall end-member remains the same, the swamp is characterized by the average on 8 samples between 1994 and 1996 and the spring is characterized by the average on 11 samples taken during the storm. For each end-member, the uncertainty is supposed equal to the standard error of the set of samples in the U_1 , U_2 space.

In U space (Figure 7a), the Oct 97 storm points are concentrated between spring and swamp end-members, far away from the throughfall end-member. The path of Oct 02 storm in U space constitutes a double loop (Figure 7b). The contribution of throughfall increases during the rising limb of the hydrograph and decreases during the falling limb. This happened twice – for each event - leading to the double loop.

Figure 7 : Mixing diagram showing stream water evolution and end-member composition in U space. (a) Oct 97 storm (27/10/1997) and (b) Oct 02 storm (10/10/2002)

The relative contributions are very different for each storm (Figure 8a and b). During Oct 97 storm, the throughfall contributes during the peak of the storm in relatively low proportion (maximum 7 % of the stream flow). Relative contributions of hillside spring and swamp vary a little: they constitute the main absolute contributions to the stream flow with respectively 19 and 4.5 l/s at the flow peak (25 l/s), the remaining 1.5 l/s being supplied by throughfall. At the end of the storm, the contributions come back to the initial conditions with hillside spring dominating swamp contribution (Figure 8a).

During Oct 02 storm (Figure 8b), the rise of discharge is due to throughfall contribution that increases from zero up to 42 % and 52 % during respectively the first and the second events. The relative contribution of hillside spring to stream runoff simultaneously decreases with the throughfall contribution increase. The contribution of the swamp varies less than other end-member contributions. Its contribution increases from 14 to 30 % with a delay of about 2 – 3 hours. The second event of this double storm is characterized by the same behaviour. The absolute contributions at the first peak (33.5 l/s) are: 13.5 l/s from the hillside spring, 12.5 l/s from the throughfall and 7.5 l/s from the swamp. At the second peak (35 l/s), the contribution of throughfall has increased up to 18 l/s while the swamp contributes for 9 l/s and the spring for 8 l/s. The higher absolute contribution of the throughfall to the second event peak could be due to the saturation of the forest canopy and the swamp during the first event. At the end of the second storm, the initial contributions are restored: nil contribution of throughfall and a dominant contribution of hillside (~80 %) compared to the swamp (~20 %).

Figure 8 : End-member derived contributions during (a) Oct 97 storm event and (b) Oct 02 storm event

The EMMA model has been validated by calculating squared Pearson correlation coefficient (R^2) between predicted solute concentrations and measured concentrations (Table 6). For Oct 97 storm event, R^2 ranges between 0.76 and 0.93, the EMMA model being a strong ($R^2 > 0.75$) predictor of all the solutes. Comparison of predicted and observed mean shows a little underestimation of Ca and an overestimation of EC. For Oct 02 event, R^2 ranges between 0.62 and 0.96, the EMMA model being a strong predictor of all solutes except Si and Na (moderate predictor with $R^2 > 0.50$). Little overestimation of K and underestimation of Ca are observed.

Discussion

Recharge rate on the hillside system

On the hillside system, the recharge rate related to the surface area of the hills is 332 mm/yr (Table 2) out of which about 90 % flows to the springs and 10 % flows to the swamp as baseflow. This recharge rate represents 20 % of rainfall.

This result is obtained by solving equation (2) for hillside system with the assumption of negligible overland flow on the hillside. It is necessary to test the effect of such assumption on the results. For that purpose, the chloride mass balance including overland flow is separately applied to the MEN1 spring catchment:

$$P[Cl]_P = (R_{MEN1}[Cl]_{MEN1} + OF_{hill}[Cl]_{OF_{hill}}) \quad (16)$$

With R_{MEN1} the recharge rate on the spring MEN1 catchment, $[Cl]_{MEN1}$ the chloride content of the recharge water assumed equal to the chloride content at the spring, OF_{hill} the overland flow on the hillside and $[Cl]_{OF_{hill}}$ the chloride content of overland flow.

The recharge rate on the spring catchment can be related to its surface area A_{MEN1} according to:

$$R_{MEN1}A_{MEN1} = Q_{MEN1}A_{MEN1} + Q_{base}A_{MEN1} \quad (17)$$

With $Q_{MEN1} = 305$ mm/yr, the measured discharge rate at the spring MEN1 (related to A_{MEN1}). Introducing (16) in equation (17), we obtain a relationship between A_{MEN1} and OF as illustrated at Figure 9.

Figure 9 : relationship between overland flow on the hillside catchment of spring MEN1 and the size of corresponding surface area of the spring catchment according to chloride balance and water budget of the spring

On this figure, it is observed that the choice of a non negligible overland flow (> 100 mm/yr) induces a higher catchment size for spring MEN1 which is not possible given that it already occupies most of the watershed head (Figure 1). This confirms the observations of no overland flow on the hillside during rainy events due to high infiltration capacity of the soils. The generally permeable nature of granitic regolith would suggest that surface runoff on interfluvies is an infrequent and minor pathway (Bullock, 1992a).

Evapotranspiration and yield

Actual evapotranspiration (AET) is a major component of the water cycle which is hardly measurable specially in forested watershed. In case other components of water cycle are known, actual evapotranspiration can be estimated as the residual of the catchment water balance (Bosch and Hewlett, 1982):

$$AET = P - R - Q - \Delta S \quad (18)$$

where AET is actual evapotranspiration, P is precipitation, Q is surface runoff measured as stream flow, R is recharge to groundwater and ΔS is the change in soil water storage.

Usually, this technique for evapotranspiration estimate faces a lack of information on the recharge component. Using the recharges here above estimated and neglecting the soil water storage yearly fluctuations at the watershed scale, Eq. (18) is used to estimate the annual actual evapotranspiration in the Nsimi watershed (Table 7).

At the watershed scale, as a part of the recharge on the hillside flows into the stream (and is therefore already accounted in the water budget), this component is reduced to the part that is not accounted (flowing under the weir), i.e. the groundwater swamp flow Q_{swp} . The total

actual evapotranspiration $AET = 1269$ mm/yr is close to the potential evapotranspiration $PET = 1212$ m/yr measured 40 km south of the watershed. This reveals the high sucking capacity of the forest cover as already observed in tropical conditions (Maréchal et al., 2009).

These results show also that the evapotranspiration is higher in forested hillside than in the swamp. This result is very close to Oyebande and Balek (1989) who reported annual evaporation from the Luano swamps in northern Zambia to be 1075 mm compared with 1320 mm from non-swamp portions of the catchments. This result is not the first time that an African swamp is supposed to decrease the evapotranspiration rate as already mentioned by Balek (1977). It has been found also in a Zambian watershed that the swamp evaporates 10 % less than the hillside (von der Heyden and New, 2003). Each of these studies illustrated a lower water use by swamps than by woodland, to the positive benefit of river flows in catchments with higher swamp densities. It could be due to the shorter vegetation present in the swamp compared to woodland with deep roots present on the hillside. It suggests that the presence of the swamp contributes to increase the yield of the watershed.

Swamp aquifer water budget

At the top of the swamp, the precipitation (1658 mm/yr) is divided into three components: 62 % is lost by evapotranspiration (1036 mm/yr), 22 % constitutes the recharge rate to the swamp aquifer (360 mm/yr) and 16 % flows as overland flow (262 mm/yr). The latest appears as soon as the swamp is fully saturated.

The swamp aquifer water budget is given at Table 8. It shows that the recharge rate through the swamp ground surface represents 77 % of inflows, the rest (23 %) coming from the hillside as groundwater baseflow. Balek and Perry (1973) also identified direct precipitation onto the swamp as the dominant contribution to its hydrological cycle. The water budget of a small Zimbabwean catchment containing a single swamp has shown also that rainfall dominates, and inflow from the surrounding catchment comprises only a small percentage (ca. 12%) of the total water input to the swamp (McCartney, 2000).

The baseflow from hillside should be most probably constant throughout the year. Most of the recharge from top soil happens during the short rainy season and contributes to fill the swamp as suggested by water table rise during March-April (Figure 3 and Figure 4).

The outflow repartition is as follows: 87 % through exchanges between the swamp and the stream and 13 % as swamp groundwater flow below the weir. This is explained by the hydraulic gradient component perpendicular to the stream ($i_{SN-NS} = 0.017 - 0.05$) being much higher than its component parallel to the stream ($i_{WE} = 0.005$).

Origin of water in the stream

The chloride mass balance and water budget show that out of 378 mm/yr of the streamflow at the outlet, 64 % (244 mm/yr) comes from bedrock aquifer below hillslope, 11 % (41 mm/yr) from the swamp aquifer and 25 % (93 mm/yr) from overland flow on the swamp surface during storm events. These contributions are average on a several years period. Authors found that pre-event water formed 80-90% of the stream hydrograph volume for six of the seven storms analyzed in a Canadian headwater swamp (Hill and Waddington, 1993).

Amongst pre-event water (bedrock and swamp aquifers), the relative contributions of hillside and swamp to the streamflow are respectively 72 and 28 %. This can be compared to the results of the EMMA analysis of October storms where we obtained about 80 % of hillside contribution and 20 % of the swamp before and after the event.

Figure 10 : Profile of the swamp saturation with water table during high flood (in blue), during very low flow (red) and rising water table (in green), see Figure 1 for piezometers location on Layon L3

The profile of swamp saturation along Layon L3 (location on Figure 1) is given at Figure 10. During the rainy season (31/10/97), the swamp is fully saturated on the northern side of the stream and almost saturated on the other side. The hydraulic gradient is higher at the northern side, with for both sides groundwater flows from the hillside to the stream. During very low flow conditions, at the end of the very long dry period of January to March 1998 (64 mm of rainfall in 104 days between 28/11/97 and 12/03/98), the water table is depleted of about 90 cm. This depletion is quite regular on the entire profile and the same hydraulic gradients are observed with still groundwater flows occurring from the hillside to the stream. After this long dry period, the first rainfall events induce storms in the stream. Consequently, an inversion of hydraulic gradient is observed at the southern side of the stream. This indicates the infiltration of water from the stream bed into the swamp. This explains the sharp increase of water table in all the observation wells at the end of March 1998, the increase being sharper when closer to the stream. This phenomenon happens only during the first rainy days after a very long dry period. The rest of the time, the swamp is drained by the stream.

This observation shows that the interactions between stream and swamp change and are reversed with time. This suggests that exchange flow rate between swamp and stream calculated above constitutes the net exchange, i.e. the difference between flow from swamp to stream minus flow from stream to swamp.

The EMMA analysis has shown that the chemistry of the storm events was not compatible with highly diluted rainfall contribution. This is particularly due to the increase in K concentration during the flow peaks. The rainfall water is chemically modified by its percolation through the high density canopy cover especially on the swamp. The event-water contribution to storm events is then constituted by overland flow of throughfall water on the swamp.

During storm events, the relative contribution of overland flow fluctuates a lot according to storm conditions as illustrated by the EMMA analysis. During the October 1997 storm, the throughfall contribution is only 5 % of the total flow at the outlet as the rainfall was low (7 mm). The pre-event water dominates (76 % from the bedrock aquifer and 19 % from the swamp) as the swamp and bedrock aquifer were fully saturated before the storm. The low Q_{max}/Q_{min} ratio (= 2.5) is typical of a low contribution from event water with a low concentration time. During the October 2002 storm, for events of double intensity, the contribution of throughfall to the storm increases up to 34 % of the total flow at the outlet. The pre-event water moderately dominates with 40 % from the bedrock and 26 % from the swamp. This storm happened at a time when both pre-event water reservoirs were not fully saturated. The higher Q_{max}/Q_{min} ratio (= 12.5) indicates that event water had quickly reached the outlet.

Contribution of swamp to solute fluxes

The output fluxes of solutes out of this small watershed have been estimated in a previous study (Braun et al., 2005) assuming that groundwater flows below the weir are negligible. The determination of groundwater flow through the swamp using two techniques allows verifying afterwards that hypothesis.

Output fluxes of main solutes are computed at Table 9 using average solute contents in swamp and groundwater flows $Q_{swp} = 12$ mm/yr. They are compared to the output flux through the streamflow. While swamp groundwater flow represents 3% of total outflows, it appears that the output flux of solutes through the swamp below the weir is about 6-7 % for

all the solutes which is within the uncertainties range linked to water flows estimate and concentration measurements. This confirms the rightness of the hypothesis done.

The chloride mass balance determined above allows us going into details in the origin of weathering fluxes and then helps determining which parts of the watershed are active or not from the weathering point of view. Weathering fluxes from hillside system and swamp are obtained by correcting the chemical fluxes from the atmospheric inputs, assuming that all Cl comes from the atmosphere and that the rain is characterized by marine ratios (Braun et al. 2005). The specific weathering fluxes, expressed in mol/ha/yr are presented in Table 10. The swamp is by far the most active area of weathering in the watershed with relative efficiency compared to the hillside ranging from 5 for K and Si to nearly 9 for Na. Such variations according to solutes mean that the nature of weathered minerals varies according to the context. The high efficiency of Na export in the swamp would correspond to the weathering of primary minerals such as plagioclases: this reveals a deepening of the weathering front below the swamp. In the hillside, the export is slightly more important compared to cations. The weathering of hillside would mostly affect silica and/or secondary minerals, which means that solutes originate from the regolith above the weathering front.

Conclusion

The hydrology of a rainforest headwater swamp has been characterized using natural tracer analysis.

The main contribution to streamflow is through the hillside bedrock aquifer which represents 64 % of total stream flow. The groundwater that emerges at specific seepage points and springs is conveyed over the ground with little interaction with the swamp. The second contribution is from overland flow on the swamp surface during storm events which contributes for about 25 % of the stream flow. The groundwater flow from the swamp aquifer contributes for only about 11% of streamflow.

Before rainfall events of October, the pre-event water is a mixing of bedrock aquifer water for 80 % and 20 % of swamp aquifer. During the storm, the relative contribution of overland flow increases according to the rainfall intensity and the initial saturation rate of the pre-event water reservoirs. The overland flow on the swamp chemically corresponds to the throughfall end-member as rainfall water content is modified by its percolation through the forest canopy. It appears that the relationships between the swamp and the stream fluctuate with space and time. While the swamp is drained by the stream most of the time, it happens at the end of the long dry season, that indirect recharge occurs from the stream to the swamp with a hydraulic gradient inversion in the swamp aquifer after the first rains.

Evapotranspiration is higher on the hillside than in the swamp. Nevertheless, depletion of water stored within the swamp is dominated by evaporation rather than by contribution to stream flow.

If the average contribution to the streamflow of bedrock aquifer flow is higher than swamp aquifer flow, the solute content (Na and Si) in the stream dominantly (55-60 %) originates from the swamp. The export of solutes through swamp groundwater flow below the weir is low (< 7 %). The swamp is the most active area of weathering in the watershed.

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	Parameter	Value	Unit
Stream runoff at the outlet	Q_{st}	378	mm.yr ⁻¹
Precipitation	P	1658	mm.yr ⁻¹
Chloride content in precipitation ($n = 80$)	$[Cl]_p$	2.3*	μmol.L ⁻¹
Chloride content in streamflow ($n = 44$)	$[Cl]_{st}$	9.7 [#]	μmol.L ⁻¹
Chloride content in swamp water ($n = 21$)	$[Cl]_{swp}$	12.5 ^μ	μmol.L ⁻¹
Groundwater flow through the swamp	Q_{swp}	13 [Ⓞ]	mm.yr ⁻¹
	Q_{swp}	15 – 32 [Ⓢ]	mm.yr ⁻¹

Table 1 : flow rates and chemical contents used in equation (1) for the computation of the groundwater flow through the swamp, averages on 1994-1998 period. n is the number of samples * data from (Viers et al., 2001) [#] data from (Braun et al., 2005) ^μ average value of surface, swamp at 1 m and swam at 2 m depth (Braun et al., 2005) [Ⓞ]calculated using chloride mass balance method - equation (1) [Ⓢ] calculated using Darcy law method – equation (13)

	Parameter	Value	Unit
Discharge flow rate of spring MEN1	Q_{MEN1}	46	mm.yr ⁻¹
Surface area of MEN1 spring basin	A_{MEN1}	90 000	m ²
Surface area of the hillside system	A_{hill}	480 000	m ²
Hillside groundwater outflow from Eq (14)	Q_{hill}	244 (305)	mm.yr ⁻¹
Chloride content in bedrock aquifer ($n = 90$)	$[Cl]_{hill}$	11.5	μmol.L ⁻¹
Baseflow from the hillside, from Eq (2)	Q_{base}	21 (27)	mm.yr ⁻¹
Recharge rate on the hillside from Eq (3)	R_{hill}	265 (332)	mm.yr ⁻¹

Table 2 : variables used in equations (14), (2) and (3) to calculate respectively bedrock aquifer flows below hillside Q_{hill} , Q_{base} and R_{hill} . Flow rates in brackets are related to the hillside surface area A_{hill} .

	Na (mol/ha/yr)	Si (mol/ha/yr)
Solute flux from hills ($[E]_{hill} Q_{hill}$)	73	215
Solute flux from swamp ($[E]_{swp/st} Q_{swp/st}$)	107	253
Computed solute flux in stream from eq (17)	180	468
Measured solute flux in stream ($[E]_{st} Q_{st}$)	176	488
Difference	+ 4 (+ 3 %)	- 20 (- 4 %)

Table 3 : origin of sodium and silica fluxes in the streamflow, comparison between computed and measured fluxes

Variable	Parameter	Value	Unit
Chloride content of swamp at one meter depth ($n = 8$)	$[Cl]_{swp/st}$	15.9	$\mu\text{mol.L}^{-1}$
Chloride content of overland flow on the swamp ($n = 0$)	$[Cl]_{OFswp}$	4.3	$\mu\text{mol.L}^{-1}$
Exchange flow rate between swamp and stream	$Q_{swp/st}$	82 (409)	mm.yr^{-1}
Overland flow on swamp surface	OF_{swp}	52 (262)	mm.yr^{-1}
Recharge rate on the swamp	R_{swp}	72 (360)	mm.yr^{-1}
Chloride content of swamp recharge	$[Cl]_{Rswp}$	16.7	$\mu\text{mol.L}^{-1}$

Table 4 : variables used in equations (4-7) to compute swamp flows $Q_{swp/st}$, OF_{swp} , R_{swp} and $[Cl]_{Rswp}$ chloride content. Flow rates in brackets are related to the swamp surface area A_{swp} .

Storm	Date	API ₇ mm	API ₁₄ mm	Duration h	Rainfall mm	Qmin	Qmax	Qmax/Qmin	Volume m^3	Volume mm
Oct 97	27/10/1997	29	100	16	7	10.4	25.5	2.5	940	1.6
Oct 02	10/10/2002	14	60	36	28 (16 + 12)	2.8	35	12.5	2100	3.5

Table 5 : characteristics of studied storms

	EC	SO ₄ ²⁻	Si	Na ⁺	K ⁺	Mg ²⁺	Ca ²⁺
October 1997 storm event ($n = 19$)							
Observed Mean	13.8	0.5	132.2	33.1	7.8	17.5	24.5
Predicted Mean	16.3	0.4	124.1	35.5	7.1	18	20
Pearson Coefficient	0.76	0.86	0.79	0.78	0.93	0.87	0.85
October 2002 storm event ($n = 32$)							
Observed Mean	18.8	2.3	123.9	52.9	16.1	25.0	28.1
Predicted Mean	20.9	1.4	129.3	50.8	19.1	25.4	23.9
Pearson Coefficient	0.90	0.87	0.62	0.72	0.96	0.91	0.96

Table 6 : Comparison of observed and predicted tracer concentrations using the EMMA results for April and October storms

System	Precipitation	Recharge/under weir flow	Runoff/OF	Evapotranspiration
Hillside system		$R_{hill} = 332$	$OF_{hill} = 0$	$AET_{hill} = 1327$
Swamp system	$P = 1658$	$R_{swp} = 360$	$OF_{swp} = 262$	$AET_{swp} = 1036$
Watershed		$Q_{swp} = 12$	$Q_{st} = 378$	$AET = 1269$

Table 7 : Values of the components of the water balance of both hydrological systems and watershed, AET is calculated using Eq. (18) Rates are related to the respective surface areas (A_{hill} , A_{swp} and A)

In/outflow	Flow type	Value	
Inflow	Recharge on the swamp	360	mm.yr ⁻¹
	Baseflow from bedrock aquifer (hillside)	107	mm.yr ⁻¹
Outflow	Exchange flow between swamp and stream	409	mm.yr ⁻¹
	Swamp groundwater flow	59	mm.yr ⁻¹

Table 8 : in/outflow rates into the swamp, rates are related to the swamp surface area A_{swp}

Concentrations		Na	Si	K	Ca	Mg
Swamp surface ¹	$\mu\text{mol.L}^{-1}$	41	150	10.4	32	20
Swamp 1m depth ¹	$\mu\text{mol.L}^{-1}$	131	309	13	57	46
Swamp 2m depth ¹	$\mu\text{mol.L}^{-1}$	179	398	18	96	91
Average	$\mu\text{mol.L}^{-1}$	117	286	14	62	53
Output flux through the swamp	mol/yr	824	2011	98	433	371
Output flux through the swamp	mol/ha/yr	14	34	1.6	7.2	6.2
Output flux through the stream ¹	mol/ha/yr	171	478	28	122	91
Contribution of swamp to total flux	%	7	7	6	6	6

Table 9 : solute contents in swamp water and export solute fluxes through the swamp below the weir, ¹ data from Braun et al. (2005)

	Na*	Si*	K*	Ca*	Mg*
Swamp (mol/ha/yr)	543	1431	60	266	213
Hillside (mol/ha/yr)	61	268	12	35	39
Swamp/Hillside ratio	8.8	5.3	4.8	7.6	5.5

Table 10 : specific weathering fluxes from swamp and hillside systems. Fluxes are corrected from atmospheric inputs with marine ratios. Swamp flux includes flux below the weir and swamp/stream interaction.