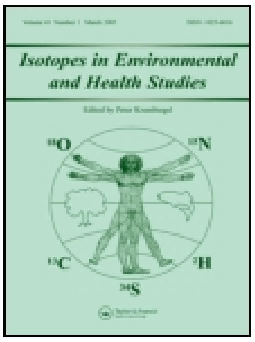

Isotopes in Environmental and Health Studies

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Use of isotopes to study floodplain wetland and river flow interaction in the White Volta River basin, Ghana

Benjamin Kofi Nyarko[a], David Kofi Essumang[b]*, Moses J. Eghan[c], Barbara Reichert[d], Nick van de Giesen[e] and Paul Vlek[a]

[a] *Center for Development Research, University of Bonn, 53113 Bonn, Germany;* [b] *Department of Chemistry, University of Cape Coast, Cape Coast, Ghana;* [c] *Department of Physics, University of Cape Coast, Cape Coast, Ghana;* [d] *Geological Institute, University of Bonn, Bonn, Germany;* [e] *Delft Technical University, 2600 AA Delft, The Netherlands*

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Floodplain wetlands influence the timing and magnitude of stream responses to rainfall. In managing and sustaining the level of water resource usage in any river catchment as well as when modelling hydrological processes, it is essential that the role of floodplain wetlands in stream flows is recognised and understood. Existing studies on hydrology within the Volta River basin have not adequately represented the variability of wetland hydrological processes and their contribution to the sustenance of river flow. In order to quantify the extent of floodwater storage within riparian wetlands and their contribution to subsequent river discharges, a series of complementary studies were conducted by utilising stable isotopes, physical monitoring of groundwater levels and numerical modelling. The water samples were collected near Pwalugu on the White Volta River and at three wetland sites adjacent to the river using the grab sampling technique. These were analysed for ^{18}O and ^{2}H. The analysis provided an estimate of the contribution of pre-event water to overall stream flow. In addition, the variation in the isotopic composition in the river and wetland water samples, respectively, revealed the pattern of flow and exchange of water between the wetlands and the main river system.

Keywords: Ghana; hydrogen-2; isotope ecology; oxygen-18; riparian wetlands; river; seasonal rainfall variations

1. Introduction

Subsurface water of the floodplain wetlands in the White Volta River basin plays a vital role in the economy of Ghana by acting as a major source of water for agricultural activities and for communities living within the basin. This area is characterised by mono-modal rainfall pattern, therefore making agricultural activities a risky business to undertake. The government of Ghana through the Ministry of Food and Agriculture is encouraging farmers in the Upper East Region to embark on dry season floodplain cultivation to make use of residual moisture and river water through pump irrigation. However, there is a growing importance of floodplain wetland

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*Corresponding author. Email: kofiessumang@yahoo.com

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agriculture and the ability to develop and sustainably manage the floodplain wetland system. An understanding and identification of floodplain wetland–river flow interaction is necessary for viable sustainable floodplain agriculture. The lack of continuous hydrological data makes it difficult to study floodplain wetlands and river flow interaction and also surface and subsurface interaction. The floodplain wetlands and subsurface water are highly seasonal variable [1]. The main aim of this research is to use stable isotopes to examine the hydrological processes going on within the White Volta River catchment basin. Specifically, it aims at the following:

- identification of sources of water into wetlands and the White Volta River;
- estimation of evaporation from wetlands;
- development of a water budget model for the wetlands; and
- identification of the interaction between the floodplain wetland and the White Volta River.

Water in the White Volta basin is distributed spatially in various reservoirs: groundwater, dams, atmosphere, wetlands and rivers. The hydrogen and oxygen isotopes of water vary among these reservoirs in time and space. The isotopic compositions of some of these reservoirs do change through the exchange of water either by equilibrium or by kinetic processes [2]. Isotope tracers have the potential of providing new insights into hydrologic processes within the White Volta basin [3], because they integrate small-scale variability to give an effective indication of catchment-scale processes. Isotope tracers like ^{18}O and D are integral parts of natural water molecules that fall as rain each year over the White Volta basin and thus they become ideal tracers of water sources and allow a wide-spread application of these natural tracers to study runoff generation on scales ranging from macropores through hill-slopes to various catchments. Stable isotopes of hydrogen and oxygen behave conservatively [4,5], as they move through the landscape, and interact with oxygen and hydrogen in the organic and geologic materials.

1.1. *Description of study site*

The climate of the study site (Pwalugu and Tindama, Figure 1) is characterised as semi-arid type, which is influenced by three air masses: Eastern continental (E), Tropical maritime (mT) and Tropical continental (cT). The interaction of these air masses depends on the oscillation of the inter-tropical convergence zone. The sole influence of mT or cT determines the characteristics of the weather at that particular point in time. The cT winds are dusty and dry, mostly experienced in the dry seasons from November to April. The temperature within these periods ranges from 20 to 34 °C. The mT is highly moisture laden and it is felt mostly in the wet season between March and October, exhibiting a high rate of humidity. Humidity is variable and ranges from 60 to 90% at 6.00 a.m. and from 77 to 78% at 3.00 a.m. In a semi-arid climate, the annual potential evaporation is estimated to exceed precipitation in six to nine months. The total annual rainfall is estimated to be 1100 mm, of this 301 mm is recorded within the months of August and September. The rainfall in this region begins in May and ends in October.

The catchment area is underlain by the Voltaian, Birimian and granitoids systems. The Voltaian system consists of quartzite, shale, sandstone, limestone, conglomerate and arkose. The Birimian system consists of metamorphosed lava, pyroclastic rock, schist, tuff and greywacke. Faulting in this system tends to follow the folds, and the joints in the rocks have different orientations but are mostly parallel to the folds. The granitoids are mostly of the Bongo and Cape Coast series. The Bongo granitoids consist of prophyritic hornblende and microcline granite, and the Cape Coast series has potash-rich muscovite–biotite granite. The Voltaian systems are well consolidated and are not inherently permeable except in a few areas. A borehole at a depth of 100 m in the northern region and Kete Krachi has an average yield ranging from 800 to 16,380 l/h. The soils found within the Volta River catchment are grouped as those derived from granites, sandstones, alluvial

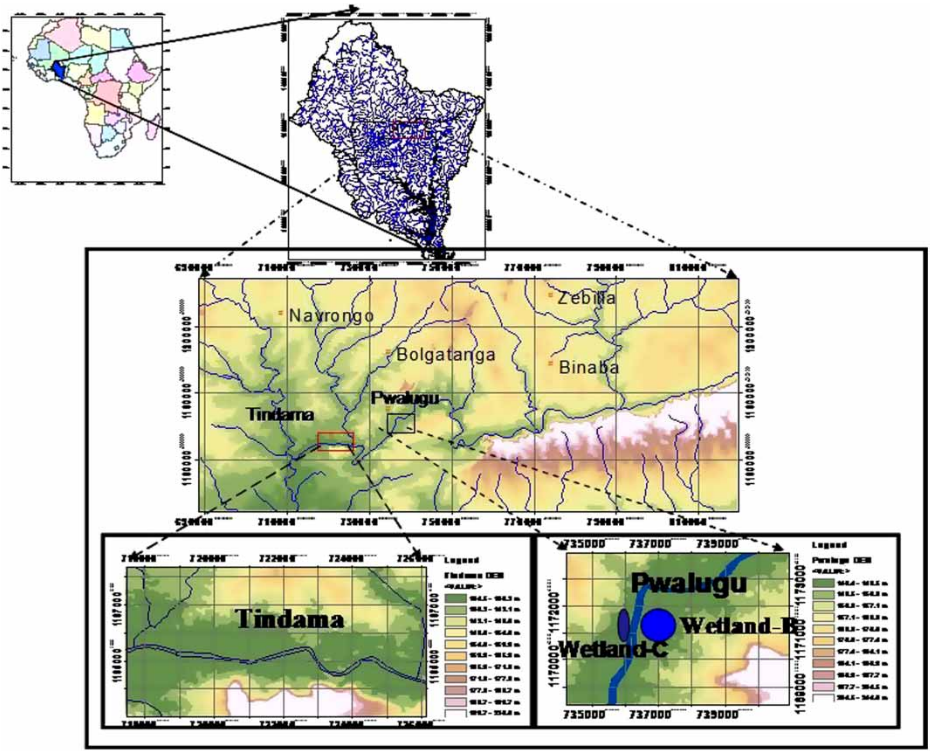


Figure 1. (Colour online). Sampling (study) site.

materials, greenstone, andesite, schist and amphibolites. Specifically, the soils are eutric fluvisol, gleyic lixisols, eutric gleysols and lithic leptosols. Ghana has two main vegetation patterns: tropical forest occupies the southern portion and savanna the northern and some parts of southeastern Ghana. Taxonomically, the two are very distinct and very few plant species occur naturally in both ecosystems. The few tree species which can be found in both vegetation zones are *Afzelia africana* and *Diospyros mespilliformis*. *Leptaspis cochleata* and *Olyra latifolia* are some of the grasses found in the high forest but not in the savanna. The vegetation in the study site is characterised by interior wooded savanna (mid-dry savanna and wet savanna) and Guinea savanna (dry savanna). The vegetation of the study area has changed over the years as a result of the human activities giving it a heterogeneous cover characteristic. This can be attributed to annual burning, cropping and grazing. Also during cultivation, trees and shrubs are cut down. The prolonged sequences of farming periods with shorter bush fallow have led to a considerable decrease in trees.

2. Methods and data analysis

The water samples were collected from three selected wetland sites, nine installed piezometers and the main White Volta River at Pwalugu gauging station. These points were sampled once every two weeks (twice in a month). In addition, two rainfall sample sites were located in Pwalugu and Tindama. For the rainfall, a monthly composite sampling procedure was adopted; all the samples

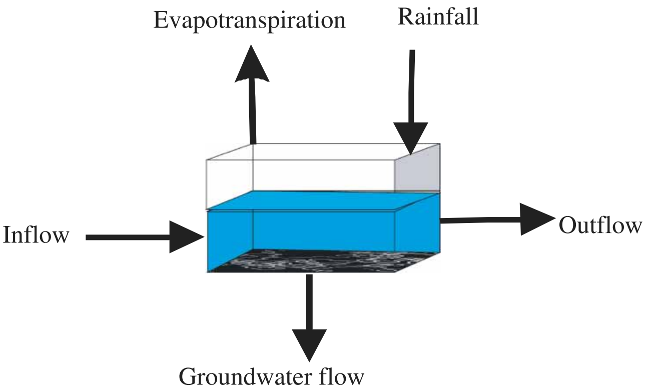


Figure 2. Conceptual model for the water balance.

were collected and stored in 50 ml brown glass bottles with poly-sealed lids. The samples were analysed in the International Atomic Energy Agency (IAEA) Isotope laboratory in Vienna.

Conceptually, the water balance is assumed to occur within a pixel with a dimension of $30 \times 30\,\mathrm{m}^2$ (Figure 2). For estimation, the surface inflow and outflow were not measured, groundwater flux was also not estimated and therefore the variables that contributed to the level of water changes in the wetlands are as a result of relating water input as from rainfall to an output due to evaporation. The rainfall data were obtained from the Ghana Meteorological Agency Station in Navrongo. The lack of instrumentation hindered the measurement of groundwater inflow and outflow of the study area. Using both Penman–Monteith potential evapotranspiration (PET) valves [6] and the evaporative fraction (EF) [1,5,7] of ^{18}O (EF–^{18}O), an estimated water budget was calculated for the wetland-B in Pwalugu.

The use of floodplain wetlands and their environs for any form of agricultural activities requires an assessment of how sustainable these wetlands' water will meet the required water supply per unit area put under cultivation is important for policy. An estimate of water budget for floodplain wetland B was calculated using the water budget equation for open lake [8]:

$$\frac{\mathrm{d}H}{\mathrm{d}t} = P(t) - E(t) + \left(\frac{R_{\mathrm{in}}(t) - R_{\mathrm{out}}(t) + G_{\mathrm{net}}(t)}{A(h)}\right) + \varepsilon_t, \tag{1}$$

where $\mathrm{d}H/\mathrm{d}t$ is the water level of the wetland (mm), $A(h)$ the depth-dependent surface area of the wetland (mm), $P(t)$ the rainfall over the wetland (mm/day), $E(t)$ evaporation (mm/day), t time (day), R_{in} and R_{out} the surface water inflow and outflow (mm/day), G_{net} the net groundwater flux (mm/day) and ε_t the error term.

Modelling water level changes within the wetland is constrained because of limited and lack of continuous hydrological data, making it difficult to study the hydrological processes in floodplain wetlands. Hence, the Equation (1) used by Kedebe *et al.* [8] was modified by eliminating the flow variables because the data were not readily available. Modified Equation (2) was used to calculate the changes in water level as per unit area (A):

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \frac{P(t) - E(t)}{A}. \tag{2}$$

Tindama wetland and Pwalugu wetland sites are the two wetlands (named wetlands B and C, respectively) that were studied.

3. Results and discussions

3.1. *Rainfall variation over the White Volta basin*

Rainfall is the major source of water to the streams, rivers, reservoirs, groundwater and wetlands in the White Volta River basin. In assessing the basin water balance, the rainfall amount relating to its temporal and spatial variation has to be accounted for. As water undergoes changes of state in the process of rainfall formation over the basin, the isotope molecules present in the water redistribute themselves between the phases such that the heavier molecules (with ^{2}H and ^{18}O) are concentrated in the condensed phase, while the lighter molecules (with ^{2}H and ^{16}O) are concentrated in the remaining phase, thereby making quantification of rainfall possible [2].

The interplay of several factors determines δ^{18}O and δ^{2}H in water vapour over the White Volta River basin. The surface of the Atlantic Ocean plays a role in evaporation and fractionation that occurs during the change of state from liquid to vapour [9]. The trajectory of the cT from the Sahara and maritime air masses (mT) from the Atlantic Ocean affects the isotopic composition of rainfall over the catchment [9,10]. In addition to the trajectories of cT and mT, rainfall formation through orographic or convectional processes within the White Volta basin accounts for differences in the isotopic composition in the Pwalugu and Tindama wetland sites (Figures 3 and 4).

The White Volta basin experiences seasonal variations in precipitation with peaks in June, July and September. The Navrongo synoptic weather station of the Ghana Meteorological Agency recorded a total amount of rainfall of 179 mm in June, 226.1 mm in July and 88.3 mm in September

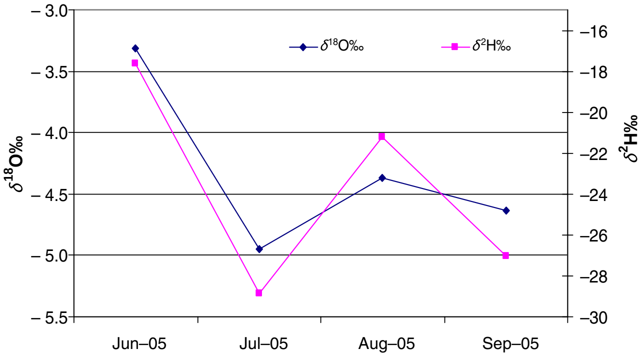


Figure 3. Monthly variation of δ^{18}O and δ^{2}H in rainfall in Pwalugu wetland site.

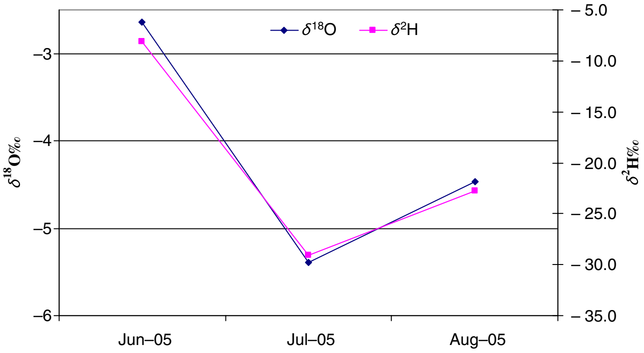


Figure 4. Monthly variation of δ^{18}O and δ^{2}H in rainfall in Tindama wetland site.

in 2005. As noted in the work of Mathieu and Bariac [11], the isotopic composition at the beginning and at the end of the rainy season is characterised by a low amount of rainfall with relatively enriched δ values. Hence, within the Pwalugu wetland catchment, δ^{18}O was measured as -3.3 ‰ and δ^{2}H as -17.6 ‰ (Figure 3) in June 2005; this is the beginning of the major rainy season. For July 2005, with a total monthly rainfall of 226.1 mm, the isotopic composition showed signs of depletion with values of -4.9 ‰ (δ^{18}O) and -28.8 ‰ (δ^{2}H).

The isotopic composition of rainfall becomes enriched in August 2005 as a result of erratic rainfall pattern. However, in September 2005, a reduced rainfall of 88.3 mm was recorded, δ^{18}O measured as -4.6 ‰ and δ^{2}H measured as -27 ‰. In the Tindama wetland site, δ^{18}O measured in June was -2.1 ‰ and δ^{2}H was -8.1 ‰ (Figure 4). Despite the unreliability of rainfall with isolated storm events in August 2005, at the Tindama wetland site a δ^{18}O value of -4.0 ‰ and δ^{2}H value of -22.7 ‰ were registered. A similar pattern of isotopic variation with a high depletion in the rainy season and enrichment in the dry season is reported by Martin [12] and Acheampong and Hess [13] in the northern and southern parts of the Volta basin. The observed temporal and spatial variations in the isotopic composition of the rainfall in the Pwalugu and Tindama wetland sites are complicated by the systematic of the hydrological cycle which includes evaporation, transpiration and mixing of air masses.

Kendall and Caldwell [2] noted that during the process of surface and atmospheric interaction, part of the rained-out moisture is returned to the atmosphere by evapotranspiration, and during this process, the simple Rayleigh law no longer applies. Therefore, the change in the isotopic composition along air–mass trajectory within the basin measures only the net loss of water from the air mass, rather than the integrated total rainout. On the other hand, during the evaporation process, vapour is usually depleted in the heavy isotopic species in order to be in equilibrium with the isotopic composition of atmospheric moisture. Hence, the mixing of moisture derived from evaporation of wetland back into the atmospheric moisture reservoir has a somewhat smaller effect than the addition of transpired water in restoring the isotopic composition of the original air mass [9,10].

3.2. *Meteoric water line*

Evaporation from surface water bodies and its return via rainfall and runoff is an annual process at the local and global scale inclined to achieve some dynamic equilibrium [14]. Periodically, there is a deviation from equilibrium, which may be due to a serious climatic shift caused by El Niño or other climatic phenomena that influence rainfall pattern, groundwater and surface water storage. Within the hydrological cycle and at each step, δ^{18}O and δ^{2}H have been noted to behave in a predictable manner [5], thereby a relationship can be defined at the global or local level when δ^{18}O and δ^{2}H are plotted against each other (Figure 5).

The isotopic composition of rainfall in the White Volta River basin tends to follow the rainfall pattern and so the isotopic depletion is measured in July when the total monthly rainfall is very high. However, due to topographic variation and distance (800 km) from the coast, there is a marked difference in rainfall storm events due to variation in humidity and temperature across the Volta basin [15]. In this situation, a local meteoric water line (LMWL) was computed for the Pwalugu and Tindama wetland sites by plotting δ^{18}O and δ^{2}H (Figure 5). For the Pwalugu wetland site, the LWML computation yielded a d-excess of 8.13 and a slope of 7.66 ($r = 0.93$), while a d-excess of 5.73 and a slope of 6.81 ($r = 94$) was computed for the Tindama wetland site. The general observation is that the δ^{2}H values in storm events differ between the Pwalugu and the Tindama wetland sites, but show a behaviour that is characteristic of a tropical region [16]. The slope and deuterium excess in the Pwalugu and Tindama sites indicate that the rainfall occurred when the atmospheric humidity was less than 100% [5]. In other words, storm events

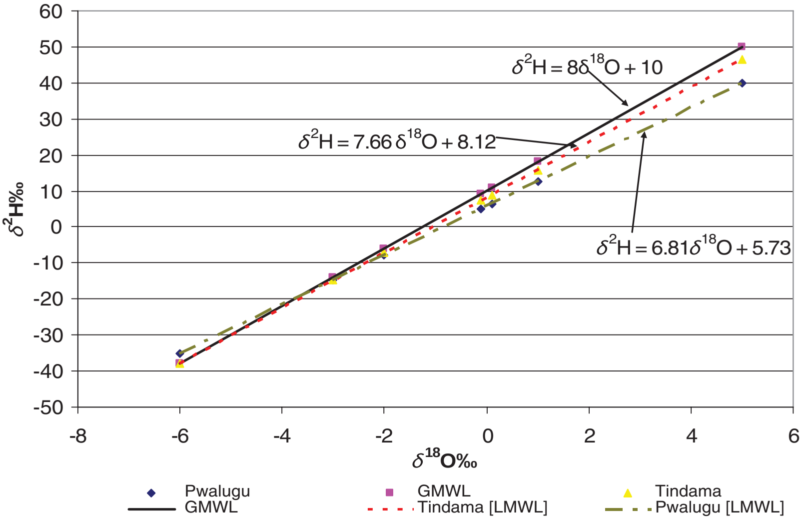


Figure 5. (Colour online). Global and LMWLs for Pwalugu and Tindama floodplain wetland sites.

and the associated isotope enrichment at these sites are highly dependent on the humidity and temperature conditions in the evaporation region. However, the rainout effect of the storms moving over the basin determines the isotopic distribution and enrichment at the different sites.

3.3. *Isotope variation in surface (river and wetlands) and subsurface (piezometer) water*

The Pwalugu wetland sites (wetlands B and C) derive their water from four main sources. These are direct rainfall, overland flow, occasional overbank flow of the White Volta River and groundwater upwelling [1,17]. For the Tindama wetland, the water source is limited to direct rainfall, overland flow and occasional overbank flow. There is no groundwater upwelling because the geological formation in which it occurs is a poor aquifer [1]. However, the isotopic composition of these wetlands follows the seasonal (rainy and dry season) pattern which gives information about their hydrodynamics (Figures 6–8).

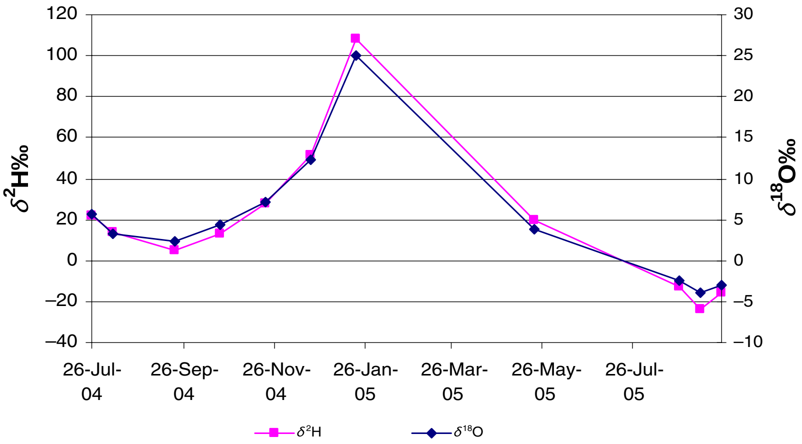


Figure 6. Seasonal variations of δ^{18}O and δ^{2}H in wetland B of the Pwalugu site.

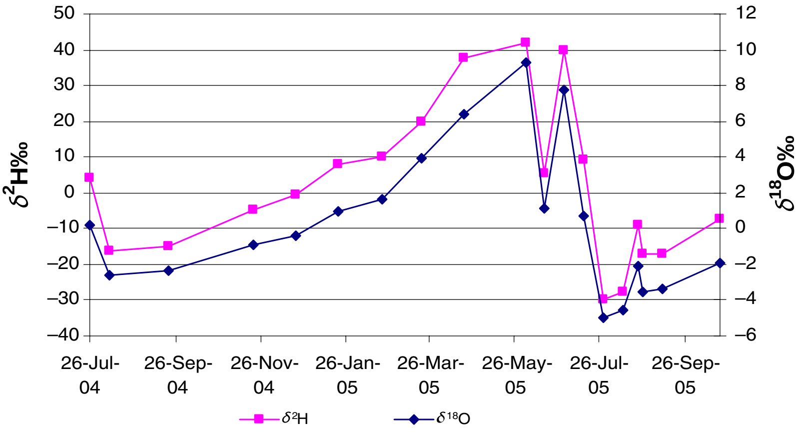


Figure 7. Seasonal variations of δ^{18}O and δ^2H in wetland C of the Pwalugu site.

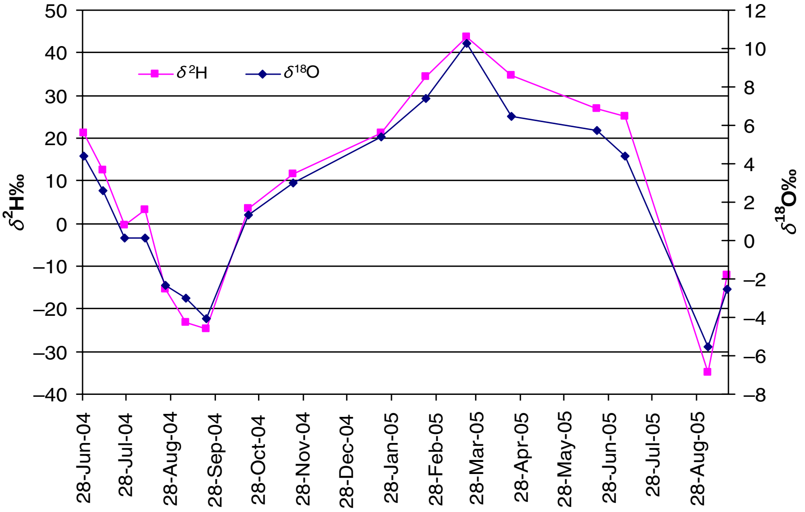


Figure 8. Seasonal variations of δ^{18}O and δ^2H in the Tindama wetland.

To elucidate wetland hydrodynamics, δ^{18}O and δ^2H values over the seasons in surface water and subsurface water enabled a classification of the pattern of recharge and flow within the floodplain wetland. Thus, the seasonal dynamics of the floodplain wetlands in Pwalugu (wetlands B and C) and Tindama can be explained to some extent by noting the enrichment and depletion in ^{18}O and ^{2}H over the seasons under different atmospheric (humidity, temperature and evaporation) conditions. For instance, during the dry season in January 2005, with a mean temperature of 33 °C, low humidity of 40% and average potential evaporation of 50 mm/month, in the Pwalugu wetland B site, a highly enriched isotopic composition ($\delta^{18}O = 25$ ‰ and $\delta^2H = 108.2$ ‰) was measured. The Tindama wetland also showed some form of enrichment ($\delta^{18}O = 5.4$ ‰ and $\delta^2H = 21.3$ ‰). During the rainy season with high rainfall, dilution is prominent and only a little evaporation occurs in the system. For the period between 26 July 2005 and 9 August 2005, the rainfall values were high thereby increasing the percentage of dilution in wetlands B and C given by δ^{18}O values of −16.11 and −18.80 ‰, respectively, from the mass spectrometer readings. During this period, temperatures ranged between 20 and 28 °C, the humidity was always above 72% and minimal evaporation was measured.

For the White Volta River, a high isotopic enrichment is mostly recorded between November and May during the dry season, while between June and October the isotope ratio shows signs of depletion (Figure 9). An exception is seen in the variation of isotopic concentration during the rainy season, for example, July 2005 ($\delta^{18}O = -5.1$ ‰ and $\delta^{2}H = -30.8$ ‰) and September 2005 ($\delta^{18}O = -3.4$ ‰ and $\delta^{2}H = -20.1$ ‰) showed a high depletion ratio.

However, isotopic composition showed fractionation at all sites with significant deviations from the LMWL (Figures 10 and 11). Hence, the values plot below the LMWL indicates the occurrence of evaporation. Using the Raleigh equation [5], an estimated EF of 9.62% was calculated for wetland B in August 2005 and 5.81% in September 2005. In wetland C, in August and September 2005, 5.9 and 8.24% were estimated, respectively. For the Tindama wetland, an estimated EF of 15.83% was calculated for August 2005 and 16.79% for September 2005. The difference in EF in the wetland sites might be due to the differences in soil moisture, geology and biophysical factors [5].

Noting from the isotopic composition measured in Pwalugu and Tindama, evaporation occurring within these sites shows some similarities with infinite-reservoir kinetic fractionation [18,19]. This

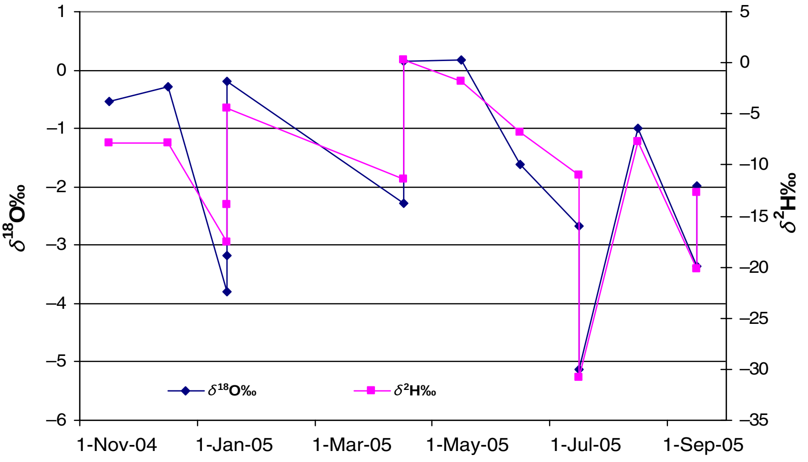


Figure 9. Seasonal variations of δ^{18}O and δ^{2}H in the White Volta River at Pwalugu gauging station.

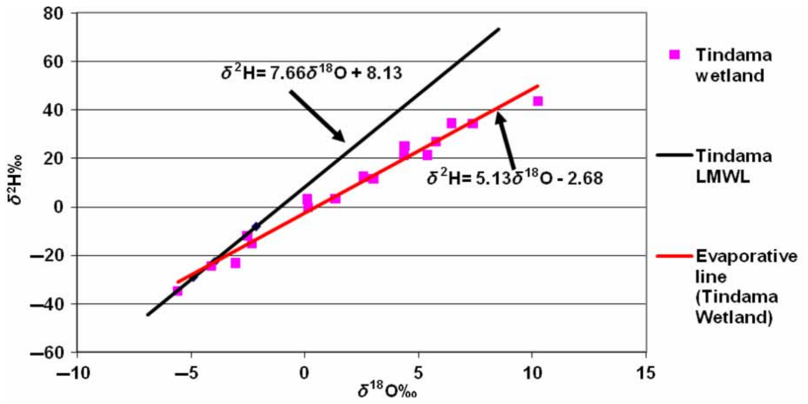


Figure 10. Isotopic composition of the sampled water from the Tindama wetland compared with the LMWL.

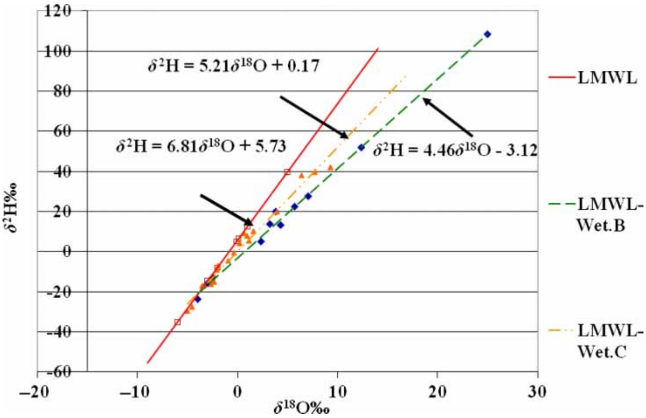


Figure 11. (Colour online). Isotopic composition of the sampled water from the Pwalugu sites (wetlands B and C) compared with the LMWL.

is because the isotopic composition of the samples falls below their respective LMWL. Within the study period from May to December 2005, using Rayleigh equation [5], the estimated fraction of water loss from the wetlands in the form of evaporation varied from 5.81 to 53.25% for wetland-B, from 1.04 to 16.01% for wetland C and from 9.53 to 28% for the Tindama wetland. In this situation, wetland B will be expected to dry up more rapidly than the other wetlands; the only source of water into wetland B is through overland flow and direct precipitation. Wetland C has other sources of water supply including high overbank flow, it also lies within a highly fractured granite zone with an appreciable yield of water to sustain its moisture content/water level [12].

3.4. *Water balance estimation*

The subsurface water of the floodplain wetlands in the basin plays a vital role as it acts as a major source of water for agricultural activities and for the communities there. However, there is a growing concern about the sustainable use and management of this resource. An understanding and identification of floodplain wetland–river flow interaction is necessary for viable sustainable floodplain agriculture. For any policy implication, it is important to assess how sustainable wetland water supply will be able to meet the demand of a unit area of floodplain under cultivation.

However, this is limited by the lack of continuous hydrological data, making it difficult to study the hydrological processes in floodplain wetlands. As an alternative means of providing hydrological data, a comparative analysis was made between the use of PET and isotope EF as input into the open-lake water budget model.

The wetland B site was used as an example for estimating the water balance. The modified water budget equation for open lake [8] was adopted (Equation (2)).

Conceptually, the water balance is estimated for a pixel with a dimension of $30 \times 30\,m^2$ and varying height that corresponds to the water level in the wetland (Figure 2). Groundwater flux, inflow and outflow were not measured. Therefore, these variables were constrained so that they did not contribute to the water level changes. As a result, the water level in the wetland, rainfall and potential evaporation were the three variables that were considered to have some influence on the water balance in the wetlands. Using both Penman–Monteith PET valve [6] and an evaporative fraction of $\delta^{18}O$ (EF–$\delta^{18}O$) [5], an estimated water budget (Table 1) was calculated for wetland B in the Pwalugu floodplain site.

The water budget mirrors changes in the rainfall in the wetland catchment (Table 1). The drastic change in evaporation (PET and EF) influences the variation in the water level in the wetland.

Table 1. Water budget for the wetland B (Pwalugu floodplain).

Date	Surface area (A, m^2)	Rainfall (mm)	Potential evapotranspiration (mm)	Evaporative fraction ($\delta^{18}O$)	ΔH_PET (mm/m^2)	$\Delta H–EF–\delta^{18}O$ (mm/m^2)
June 2005	200	179	100.10	0.00	0.63	1.13
July 2005	500	226.1	74.18	0.00	0.21	0.36
August 2005	1530	205.5	60.40	5.90	0.10	0.13
September 2005	1410	88.3	57.29	11.11	0.02	0.06
October 2005	1210	28.7	65.31	15.31	−0.03	0.01
November 2005	920	0	122.39	27.38	−0.13	−0.03
December 2005	530	0	136.13	53.25	−0.26	−0.10

Note: ΔH_PET, change in water level in wetland due to potential evapotranspiration; ΔH–EF–$\delta^{18}O$, change in water level in wetland due to the evaporative fraction of $\delta^{18}O$.

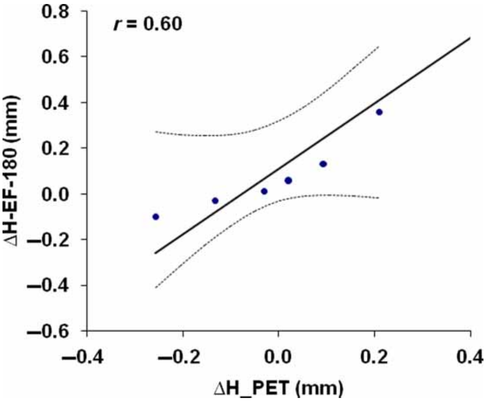


Figure 12. Relationships between potential evapotranspiration and EF–$\delta^{18}O$ evaporative fraction in wetland B, Pwalugu. The dotted lines indicate 95% confidence interval.

For a given unit pixel area of 900 m^2 (Figure 2) using an evaporative fraction of 5.9% for August 2005, an estimated potential of 0.13 mm of water is calculated as water added to the wetland, but from November to December, the evaporation increased from 0.03 to 0.1 mm. In using the PET, the loss of water from the wetland began in October with 0.03 mm and increased to 0.26 mm in December 2005. For the months of June and July, the wetland was not sampled, hence there is no data on the evaporative fraction of $\delta^{18}O$. The evaporative fraction (ΔH–EF–$\delta^{18}O$) values stated in Table 1 as 1.13 mm in June and 0.36 mm in July are simulated values. A comparison was made between the PET and the EF (Figure 12) using regression analysis at 95% confidence level, which yielded $r = 0.60$.

3.5. *Interaction between wetland and river flow*

The stable oxygen and hydrogen isotopic composition can be used to determine the contribution of old and new water to a stream (and to other hydrologic components of the catchment) during periods of high runoff because the rain (new water) that triggers the runoff is often isotopically different from the water already in the catchment (old water). The comparison of stable isotope data of surface (wetlands and river) and subsurface water samples (piezometers) in the wetlands plotted relative to their LMWL provides information on hydrological connections. Tables 2 and 3 show temporal variation between surface water (wetland B) and subsurface water (piezometers

Table 2. Temporal variation of δ^{18}O in subsurface water and surface water between August 2004 and September 2005.

	Subsurface water						Surface water	
Date	PZ1	PZ3	PZ5	PZ6	PZ8	PZ9	White Volta	Wetland B
31 August 2004	−3.30	−2.63	−1.37	−2.93	–	–	–	–
2 October 2004	−2.73	−2.46	−1.60	−2.82	–	–	–	–
12 May 2005	−2.8	−2.0	−0.4	–	–	–	–	–
20 May 2005	−2.7	–	–	–	–	–	–	3.8
26 May 2005	−2.8	−2.0	−0.4	–	–	–	–	–
9 June 2005	−2.8	−2.0	−0.3	–	–	–	–	–
23 June 2005	−2.8	−2.0	−0.3	–	−2.7	−2.7	−1.6	–
7 July 2005	−0.3	−1.9	−0.3	−3.6	–	−2.6	−2.7	–
21 July 2005	−4.8	−1.1	−1.0	−3.8	−3.5	−2.5	−5.1	–
4 August 2005	−3.4	−1.4	−3.7	−4.3	−3.5	−2.4	–	–
18 August 2005	−4.0	−3.1	−4.5	−2.2	−3.5	−2.3	−1.0	−2.5
1 September 2005	−2.4	−3.4	−3.4	−2.9	−3.4	−2.4	–	–
15 September 2005	−3.2	−3.5	−3.4	−3.2	−3.4	−2.3	−3.4	−4.0
29 September 2005	−2.4	–	−3.3	−2.0	–	−2.3	−2.0	−3.0

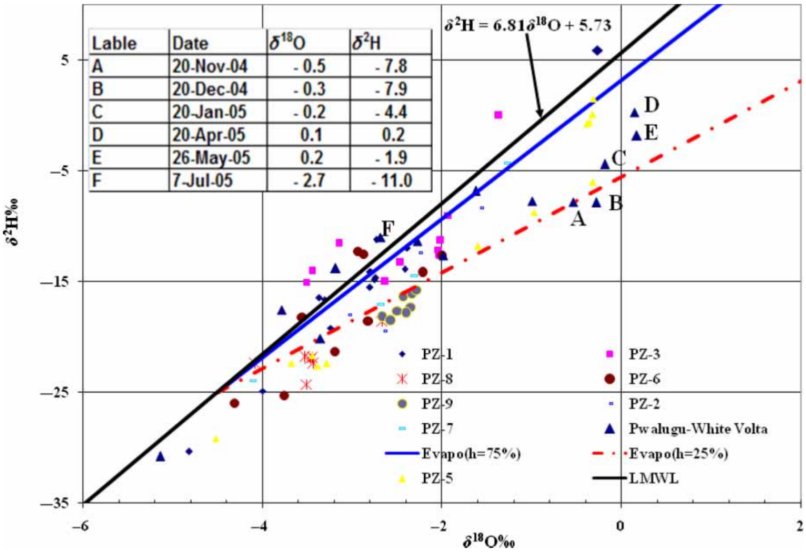
Table 3. Temporal variation of δ^{2}H in subsurface water and surface water between August 2004 and September 2005.

	Subsurface water						Surface water	
Date	PZ1	PZ3	PZ5	PZ6	PZ8	PZ9	White Volta	Wetland B
31 August 2004	−16.6	−15.0	28.0	−12.3	–	–	–	–
2 October 2004	−11.2	−13.3	−11.8	−18.6	–	–	–	–
12 May 2005	−14.1	−12.1	−0.8	–	–	–	–	–
20 May 2005	−14.7	–	–	–	–	–	–	19.8
26 May 2005	−15.5	−12.6	−0.6	–	–	–	–	–
9 June 2005	−14.8	−11.3	1.5	–	–	–	–	–
23 June 2005	−14.2	−12.6	0.1	–	−18.6	−18.2	−6.8	–
7 July 2005	5.9	−9.0	−6.1	−18.2	–	−18.6	−11.0	–
21 July 2005	−30.3	2.5	−8.8	−25.3	−21.9	−17.6	−30.8	–
4 August 2005	−16.5	0.0	−22.4	−26.0	−21.8	−16.4	–	–
18 August 2005	−24.9	−11.6	−29.2	−14.2	−24.3	−17.3	−7.7	−13.0
1 September 2005	−12.0	−14.1	−22.6	−12.5	−21.9	−17.8	–	–
15 September 2005	−19.2	−15.0	−21.7	−21.3	−22.4	−16.1	−20.1	−23.8
29 September 2005	−13.9	–	−22.4	−12.7	–	−15.7	−12.7	−15.9

PZ1, PZ3 and PZ4); however, the isotopic composition of subsurface water corresponds closely in July to September 2005.

In September 2005, piezometers PZ3, PZ5, PZ8 and the White Volta River (Table 2) had same δ^{18}O measurement of −3.4 ‰, but δ^{2}H composition differed. The piezometers and river samples differed in isotope content from October onwards when the water lever was low. During this period (between 31 August 2004 and September 2005), the isotopic composition of the White Volta was over the evaporative line (Figure 13) and estimated at a humidity level of 25 and 75%, thus reflecting an enrichment process. This indicates that, in the dry season, the river baseflow may not be sustained by subsurface seepage from the floodplain wetlands. The flow of the river in the dry season might be due to the constant discharge from the Bagre Dam in Burkina Faso.

The isotope ratios of wetland B and subsurface water (piezometers) during some periods are similar. It is difficult to isolate the water inflow associated with these two ratios, as in the rainy season (August 2005 to September 2005) they plot around the LMWL (Figure 14). Some subsurface points such as PZ9 and PZ5 show high levels of evaporation as they plot around the evaporation line with 25% atmospheric humidity. Additionally, there is an indication of discrete distinct isotopic signatures that characterise water inflow, giving an idea about origin and residence time



Lable	Date	$\delta^{18}O$	δ^2H
A	20-Nov-04	- 0.5	- 7.8
B	20-Dec-04	- 0.3	- 7.9
C	20-Jan-05	- 0.2	- 4.4
D	20-Apr-05	0.1	0.2
E	26-May-05	0.2	- 1.9
F	7-Jul-05	- 2.7	- 11.0

Figure 13. (Colour online). δ^{18}O and δ^2H of subsurface water and White Volta River water in Pwalugu site.

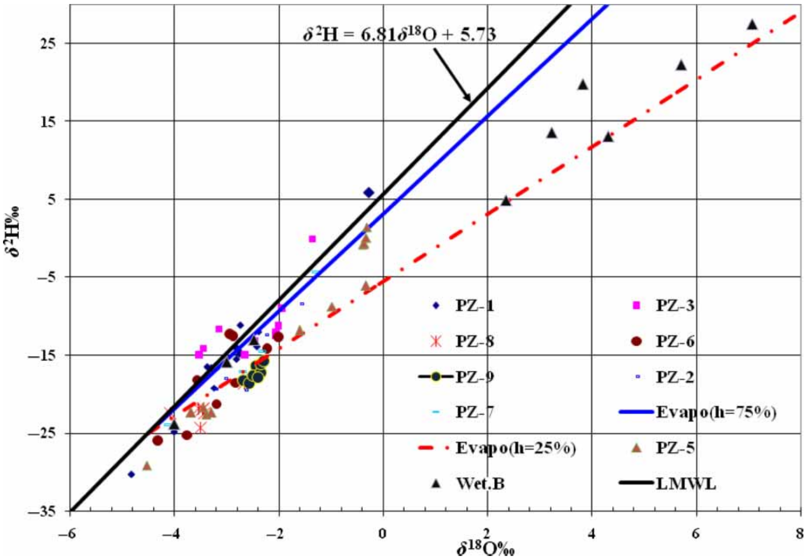


Figure 14. (Color online). δ^{18}O and δ^2H of subsurface (piezometers) and surface water in Pwalugu site.

of wetland water. Therefore, the stable isotopes in the subsurface water in wetland B show a relative response to the rainfall input as piezometers close to the main river are always subject to occasional water-table rises [1]. Moreover, the isotopic composition of subsurface water also follows a seasonal variation pattern, but shows less fractionation compared with surface water.

The White Volta River serves as a point where different water source flows converge. To ascertain any form of interaction, it is important to determine the various sources of water that flow into the river. The proportion of mixing of these sources is related to the position of the sample on the mixing line (Figure 15). Mixing endmembers to the White Volta River are isotopically distinct temporally. The linear mixing models have been used to estimate the proportion of two or three

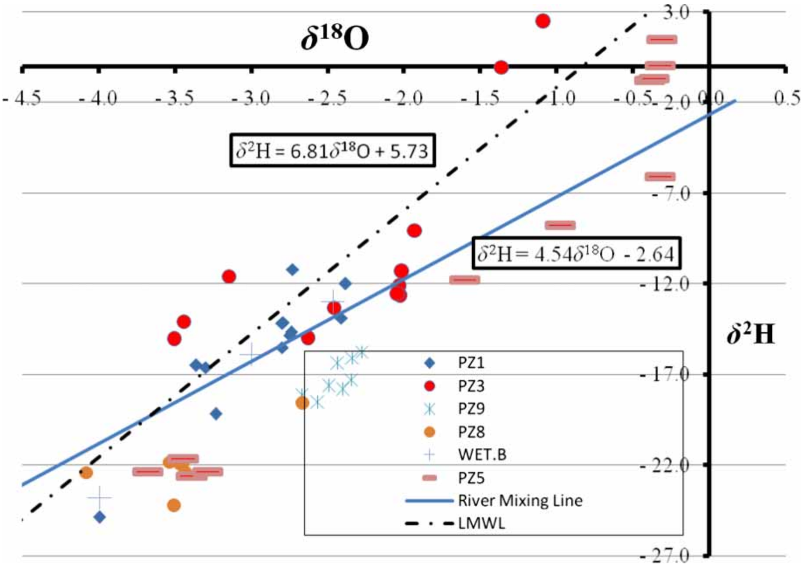


Figure 15. (Colour online). Plot of δ^{18}O and δ^2H for water around the White Volta River, indicating that greater proportion of the sources of water into the White Volta River is from PZ1, PZ3 and WET-B (Wetland B).

sources into the stream using isotopic signatures of [20,21]. A regression line plotted through points of the river samples resulted in a slope of 4.54; this shows the characteristics of open water body subjected to evaporation during certain periods of the year, especially in the dry season or prolong dry spells within the rainy season. Though mixing proportion for the samples was not calculated, water flowing into the river is a mixture of water from the groundwater and the wetland. A closer look at the regression line of the river, water from groundwater well PZ1, PZ3 and wetland B have a high proportion in contributing to the flow of the main river in the months of May, August and September. The proportion of contribution of PZ5, PZ8 and PZ9 is very low as they are further away from the mixing line.

4. Conclusion

Measurement of ^{18}O and ^{2}H provided new insights into hydrologic processes within the basin. The concentrations of ^{18}O and ^{2}H in water vapour over the White Volta River basin are influenced by the trajectory of the cT from the Sahara and maritime air masses (mT) from the Atlantic Ocean, thus resulting in observed differences in the isotopic composition of rainfall in the Pwalugu and Tindama wetland sites, respectively. Within Pwalugu wetland catchment in June 2005, during the onset of rainfall, δ^{18}O was measured as −3.3 ‰ and δD as −17.6 ‰. The isotopic concentrations of rainfall showed some depletion in the samples collected. For instance, in July 2005 with a total monthly rainfall value of 226.1 mm, δ^{18}O was measured as −4.9 and −28.8 ‰ for δ^2H. At the Tindama wetland site, δ^{18}O measured in June was −2.1 and −8.1 ‰ for δ^2H. For the Pwalugu wetland site, the LWML computed yielded a d-excess of 8.13 and a slope of 7.67, while a d-excess of 5.729 and a slope of 6.81 were computed for the Tindama wetland site.

To elucidate the seasonal dynamics in Pwalugu and Tindama wetlands, Pwalugu wetland B in January is highly enriched in ^{18}O and ^{2}H, for example, δ^{18}O and δ^2H are 25 and 108.2 ‰. Tindama showed a similar trend in January 2005 with 5.4 ‰ for δ^{18}O and 21.3 ‰ for δ^2H. During the rainy season with high rainfall input, dilution of surface water is prominent and there is little evaporation from the system. Isotopic compositions plotted on their respective LMWL deviated due to their low deuterium excesses. Using the Raleigh equation, an estimated evaporative fraction of 9.62% was estimated for wetland B in August 2005 and 5.81% in September 2005. In wetland C, the estimated evaporative fractions for August and September 2005 were 5.9 and 8.24%, respectively. For the Tindama wetland, in August 2004, the estimated evaporative fraction was 15.83%, while in September 2005, 16.79% was the estimated fraction. In August, little or no evaporation occurred and thereby the water input was more than the output. Therefore, the fraction of water loss from the wetlands as evaporation ranges from 5.81 to 53.25% for wetland B and from 1.04 to 16.01% for wetland C. In the Tindama wetland, not much evaporation was shown; it ranged from only 9.53 to 28%. Moreover, the results from the Penman–Monteith PET analysis and the evaporative fraction of ^{18}O (EF–^{18}O) suggest that the estimated water budget calculated for the wetland B in Pwalugu mirrors the changes in rainfall. A comparison was made between the PET and the EF using regression analysis. At 95% confidence level, the estimated equation had an R^2 of 0.94.

Regarding surface water and subsurface water interactions, some form of relationship on seasonal basis was detected based on the variation in their isotopic composition (δ^{18}O and δ^2H). The isotope data from the sites correspond closely between July and September on the LMWL indicating that most of the sources of water are from direct rainfall. The isotope ratio of wetland B water and subsurface water in the piezometers are similar and it is difficult to isolate the water inflow associated with these two due to the fact that in the rainy season, within August and September 2005, they plot around the LMWL. But a closer examination of the river mixing line, water from groundwater well PZ1, PZ3 and wetland B contribute significant amounts of water to the main river in the months of May, August and September. While the contribution from the wells such as PZ5, PZ8 and PZ9 is very low.

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