

Environmental controls on stable isotope precipitation values over Mali and Niger, West Africa

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Abstract This study evaluated the effects of the environmental factors precipitation amount (P), temperature (T), and vapor pressure (V_p) on the stable isotope composition (δ) of precipitation and the excess-deuterium (d) parameter in Mali and Niger, West Africa. At both locations, δ values were greatly affected by seasonal climatic conditions and a statistically significant negative correlation was observed between δ and P . In Mali, a statistically significant negative correlation was also observed between δ and V_p . There was no statistically significant correlation between δ and T . Mean-weighting of δ values may be masking both dry-season and individual storm event precipitation phenomena, which are otherwise observed in arithmetically averaged δ values. Mean monthly d values for peak monsoonal months indicate that precipitation is first-fraction, gaining little recycled water on its journey inland from the Atlantic Ocean near the equator. Agreement between rainy-season precipitation and groundwater δ values, specifically peak monsoonal months, indicates that groundwater is being recharged by infiltration of current monsoonal rains and is not paleo-groundwater recharged under past climatic conditions. Similarity between rainy-season precipitation and groundwater d values provide another indication that monsoonal precipitation under current climatic conditions is the source of groundwater recharge. The knowledge that groundwater is

recently recharged monsoonal rains, rather than paleo-groundwater, is important for evaluating groundwater sustainability and the effects that climate change will have on water resources. Understanding and predicting changes in precipitation amounts and intensities, which ultimately affect timing and amount of groundwater recharge, is critical for water resource management.

Keywords Isotopes · Groundwater · Sustainability · West Africa

Introduction

The stable isotopes of hydrogen (δD) and oxygen ($\delta^{18}O$) of water are important tools used for understanding the effects of environmental factors within the hydrologic cycle. Relationships between stable isotope values (δ) in precipitation and environmental factors, such as temperature, latitude, precipitation amount, distance inland from an oceanic source, and altitude, have been described on global and local scales (Dansgaard 1961; Merlivat and Jouzel 1979; Yurtserver and Gat 1981; Rozanski et al. 1993; Zhang et al. 1995; Araguás-Araguás et al. 1998, 2000; Gat 2000; Taupin et al. 2002). While the effects of environmental factors on precipitation isotope composition has been described for some tropical and semi-tropical regions of the world (Zhang et al. 1995; Hoffmann and Heimann 1997; Yamanaka et al. 2004), relatively little research of this nature has taken place in semi-arid West Africa.

This study evaluated the effects of the environmental factors precipitation amount (P), temperature (T), and vapor pressure (V_p , via relative humidity) on precipitation δD and $\delta^{18}O$ values at Bamako, Mali (12°39'N, 8°0'W) and Niamey, Niger (13°31'N, 2°6'W) in West Africa (Fig. 1).

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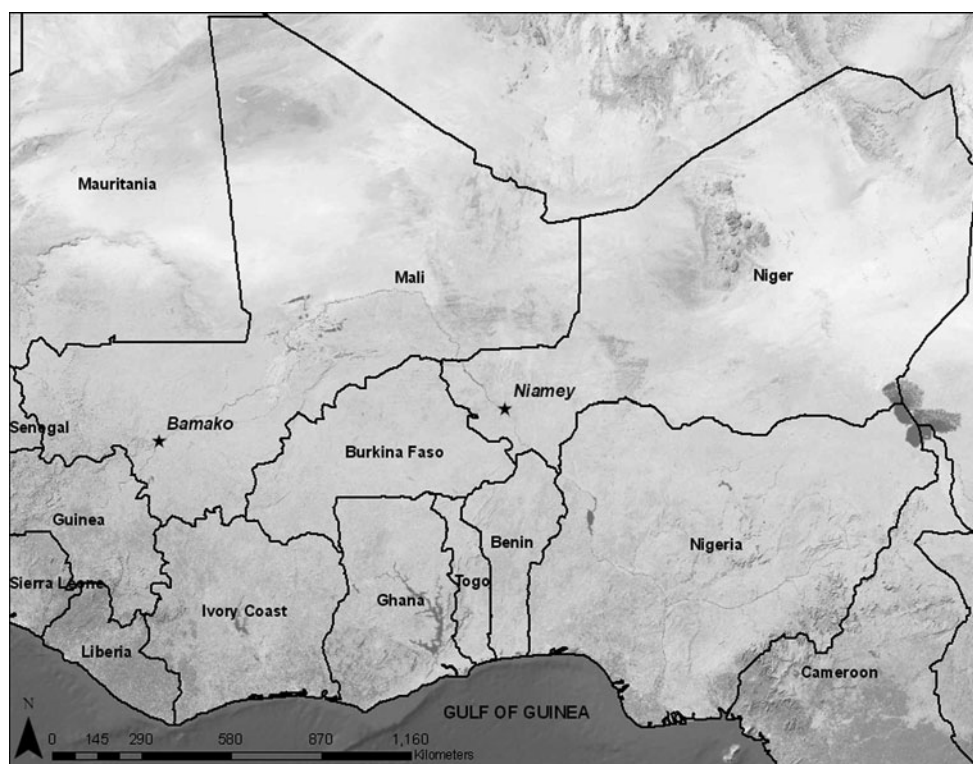
As an additional parameter, excess deuterium (d) was evaluated to provide insight into isotope fractionation both along the trajectory of the precipitation air mass and at the oceanic source area of precipitation, where d values are correlated with physical conditions, such as wind speed, relative humidity, air temperature, and sea surface temperature (Craig and Gordon 1965; Merlivat and Jouzel 1979; Gat 2000; Fröhlich et al. 2002).

Some environmental effects that are present in monsoonal isotopic precipitation data include the amount, humidity, temperature, and altitude effects. At low-latitude inland locations under the influence of monsoonal rains, such as at Bamako and Niamey, the “amount effect” describes the negative correlation between P and δ values as relatively heavy rainfall results in very negative δ values during rainy-season months and more positive δ values correspond to low-intensity dry-season precipitation (Dansgaard 1964; Zhang et al. 1995; Hoffmann and Heimann 1997; Araguás-Araguás et al. 1998, 2000). The “humidity effect” (relative humidity is a function of vapor pressure) describes the positive relationship between the dew-point deficit and δ values (Dansgaard 1964; Zhang et al. 2005). The “temperature effect”, which describes the positive relationship between T and δ values, may be observed, but may not be present at all when temperature remains consistently above 15°C (Hoffmann and Heimann 1997). Finally, the “altitude effect” describes the negative correlation between altitude and δ values. The topography

of Mali and Niger, which consists of plains undulating between approximately 200 and 450 masl, precludes the altitude effect described along transects at mountainous monsoonal locations.

In Bamako and Niamey, climate is marked by distinct wet and dry seasons, which are controlled by migration of the inter-tropical convergence zone (ITCZ). The ITCZ separates two sub-tropical air masses: wet maritime monsoonal air from the Gulf of Guinea (rainy season) and dry Sahara Desert air (dry season), which is locally known as the Harmattan, from the interior of northern Africa (Fig. 1). Temperatures are generally highest during the dry season (Fig. 2). During April at Bamako, mean monthly temperature is reported as 32°C (IAEA/WMO 2006). Minimum and maximum daily temperatures recorded during April are 27 and 39°C at Bamako, and 28 and 41°C at Niamey (National Center for Atmospheric Research) (NCAR 2006). Lower daily temperatures recorded during the cool dry season month of December are 18 and 34°C at Niamey, and 19 and 33°C at Bamako (NCAR 2006). Mean December temperature recorded at the Bamako GNIP station is 25°C (IAEA/WMO 2006). As temperature fluctuates with the seasons, so does relative humidity. Minimum and maximum mean monthly relative humidity ranges from 12 to 96% at Bamako and 4 to 88% at Niamey (NCAR 2006). Relative humidity values are lower during the dry season and higher during the rainy season.

Fig. 1 Location of Bamako, Mali and Niamey, Niger



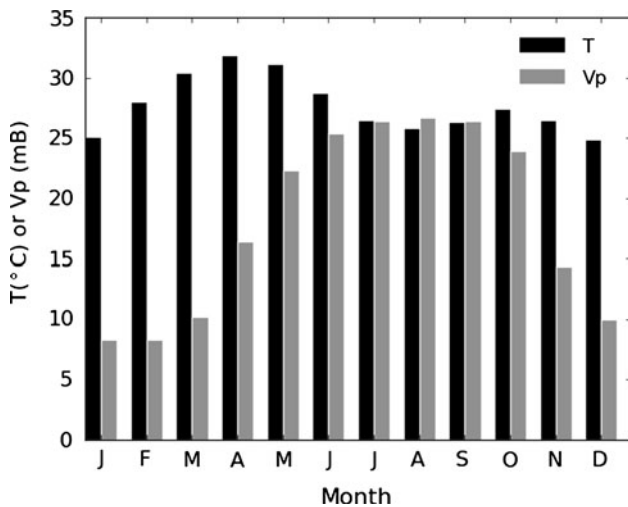


Fig. 2 Mean monthly temperature (*T*) and vapor pressure (*V_p*) recorded at the Bamako, Mali GNIP station (IAEA/WMO 2006)

At both Bamako and Niamey, the rainy season occurs from approximately May through October (Fig. 3), with most rainfall occurring as heavy downpours during July and August (N’Djim and Doumbia 1998; Leduc et al. 2000; Taupin et al. 2002). Generally, a south to north trend of decreasing rainfall is characterized for the larger geographical area of West Africa and rainfall is highly variable both spatially and temporally (van de Giesen et al. 2001). Mean annual rainfall, for years in which each month is reported, at the Bamako GNIP station is 948 mm, ranging from 508 to 1,499 mm (IAEA/WMO 2006). Mean annual rainfall, for years in which each month is reported, recorded at the Niamey GNIP station is 583 mm ranging from 407 to 957 mm (IAEA/WMO 2006).

Characterizing the dominant environmental factors that control temporal variation in precipitation supports

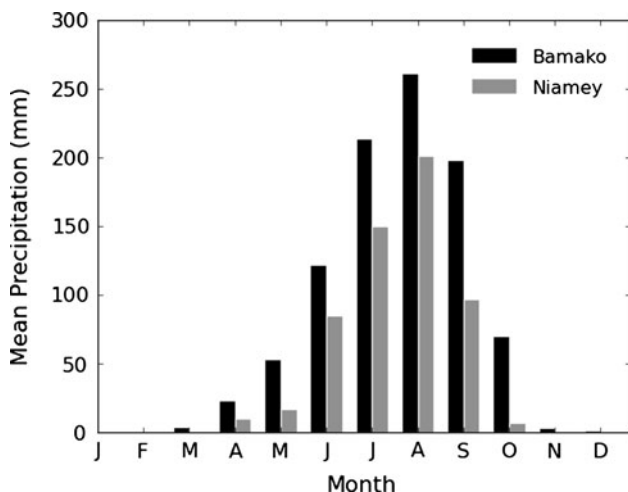


Fig. 3 Mean monthly precipitation (*P*) recorded at the Bamako, Mali and Niamey, Niger GNIP stations (IAEA/WMO 2006)

ongoing research on groundwater recharge and sustainability in both Mali and Niger (Lutz et al. 2009). Groundwater is increasingly relied upon as a source of potable water for rural populations in Mali and Niger, but the long-term sustainable yield of these resources is not usually known. When precipitation δ values are compared with groundwater δ values throughout the region, these data provide insight into groundwater recharge mechanisms, as well as the relative age and source of the groundwater (Edmunds et al. 2006). A better understanding of the source and age of groundwater is critical to managing this resource in a sustainable manner.

While evaluation of environmental factors and δ values is often done by visual inspection of plots (i.e., Araguás-Araguás et al. 1998, 2000; Taupin et al. 2000; Lebel et al. 2003), linear regression and correlation provide a more rigorous statistical tool for evaluation. In general, statistical criteria for evaluating environmental factors and δ values can be unclear. For example, some studies describe the strength of relationships in data sets with a correlation coefficient, but it is unclear if it is the coefficient of determination (from a linear regression) being used or another measure of correlation. Numerical criteria also can be unclear; there are no known set of numerical ranges for quantifying if the strength of a relationship is “good”, “moderate”, or “poor”. Additionally, the method used to calculate a mean can vary. Some studies analyze precipitation-weighted mean data, while others analyze arithmetically averaged data. Different methods of analysis may lead to different results and, in turn, different interpretations of a single data set. So as not to exclude any results and interpretations, this study used visual inspection of plots, linear regression, and correlation and then compared the results.

Methods

Though limited isotope precipitation data are available for other locations in West Africa, this study focused on the International Atomic Energy Agency/World Meteorological Organization (IAEA/WMO) Global Network of Isotopes in Precipitation (GNIP) (IAEA/WMO 2006) stations at Bamako and Niamey. These are the most complete data sets in this area of the Sahel and this information supports ongoing groundwater studies in the countries of Mali and Niger. Other stations are either too geographically distant to be considered within West Africa, recent records are not available, or the available records are related to event- or seasonal-scale studies. The station at Bamako has the longest historical record available for all of West Africa, spanning approximately three decades. At the Niamey station, relatively recent records are available for just over

a decade. Monthly data were available for the years 1962–1983 and 1991–1999 at Bamako and 1992–1999 at Niamey. Values of δD and $\delta^{18}O$ are available for monthly precipitation samples at both Bamako and Niamey. Monthly measurements of P , T , and V_p are available at Bamako, while only monthly measurements of P are available at Niamey.

Values of δ are reported as parts per thousand (‰), or per mille, deviation relative to the reference standard VSMOW (Clark and Fritz 1997). The values of δD and $\delta^{18}O$ are typically proportionate to one another and plot along the Global Meteoric Water Line (GMWL), which is defined as: $\delta D = 8 \times \delta^{18}O + 10$ (Craig 1961). Under non-equilibrium (kinetic) fractionation, relative amounts of δD and $\delta^{18}O$ are no longer proportionate to one another, causing deviations from the GMWL. For example, precipitation falling in dry environments may be subject to kinetic fractionation, which is a function of temperature, wind speed, and humidity (Clark and Fritz 1997). Deviation of isotope values from the GMWL are calculated using the equation: $d = \delta D - 8 \times \delta^{18}O$ (Dansgaard 1964; Fröhlich et al. 2002), where d is essentially the y -intercept for a line with equivalent slope to that of the GMWL. The analytic uncertainty for the d parameter is approximately 2‰, which is primarily dependent on the uncertainty of δD analysis (Fröhlich et al. 2002). More detailed explanations of isotope ratios, measurement techniques, and fractionation are addressed in other sources (Dansgaard 1964; Clark and Fritz 1997).

When environmental effects are being evaluated between environmental factors and precipitation δ values, data are assessed according to various temporal or spatial organizations. Dansgaard (1964) evaluated the amount effect by visual observation of the anti-phase variation (negative correlation) of the averaged (unweighted) monthly means of δD and $\delta^{18}O$ and P for two neighboring months. Since then, studies evaluating δD and $\delta^{18}O$ precipitation values have organized data according to categories such as month, season, year, distance inland, or storm event, using averages that are calculated arithmetically or weighted by precipitation amount (Zhang et al. 1995; Hoffmann and Heimann 1997; Araguás-Araguás et al. 1998; Taupin et al. 2000; Yamanaka et al. 2004).

West African monsoonal precipitation and climate are frequently described on a seasonal and/or monthly basis (N'Djim and Doumbia 1998; Lebel et al. 2003), so this study uses the designation of both seasons and months. All data are organized by month and season and a mean is calculated with respect to that temporal interval. Arithmetically averaged data are indicated by the subscript δ_a , while mean precipitation-weighted data are indicated by the subscript δ_w . Calculated values of the d parameter are not subject to weighting.

The relationships between environmental factors P , T , and V_p , and values of $\delta^{18}O_w$, δD_w , $\delta^{18}O_a$, and δD_a are statistically quantified using Minitab software (Minitab 2003). A simple linear regression model provides an equation that quantifies predictive capability of a response variable (δ value) based on the value of a predictor variable (environmental factor P , T , or V_p). At Bamako, the availability of data describing several environmental factors allows for stepwise regression of multiple linear regression models (MLRs). The coefficient of determination (R^2) is a measure of this predictability and is reported as a percent (%) value. Values closer to 100% indicate that δ values are better predicted by an environmental factor than values closer to 0%. It is important to note that using only an R^2 value as a measure of the goodness of fit of a statistical model can be unreliable, because values near 100% can be generated from poor regression models (Helsel and Hirsch 2002). Stepwise procedures with standard rules determining the final model were used in MLR. As for simple linear regression, normality of the residuals was checked for all multivariate models.

Since using only an R^2 value as a measure of a statistical model can be unreliable, this study also uses the correlation coefficient Pearson's ρ to measure the strength of the linear relationship between the X (isotope value) and Y (environmental factor) variables. If plotted values for the two variables lie exactly along a straight line with a positive slope, then Pearson's $\rho = 1$, whereas if data lie exactly along a straight line with a negative slope, then Pearson's $\rho = -1$. More detail on Pearson's ρ can be found in Helsel and Hirsch (2002).

Results and discussion

Long-term, seasonal, and monthly data

All pairs of $\delta^{18}O$ and δD values available from Bamako and Niamey were plotted to obtain the slope and intercept equations of the Local Meteoric Water Lines (LMWLs) (Fig. 4). The GMWL is displayed on Fig. 4 as a reference. Calculated LMWLs are given as follows:

$$\delta D_{\text{Bamako}} = 6.39\delta^{18}O + 0.89 \quad (R^2 = 0.95) \quad (n = 139) \quad (1)$$

$$\delta D_{\text{Niamey}} = 7.22\delta^{18}O + 2.60 \quad (R^2 = 0.92) \quad (n = 34) \quad (2)$$

Seasonal LMWLs for Bamako are given as follows:

$$\delta D_{\text{Rainy}} = 6.76\delta^{18}O + 2.50 \quad (R^2 = 0.93) \quad (n = 117) \quad (3)$$

$$\delta D_{\text{Dry}} = 5.72\delta^{18}O + 0.94 \quad (R^2 = 0.93) \quad (n = 22). \quad (4)$$

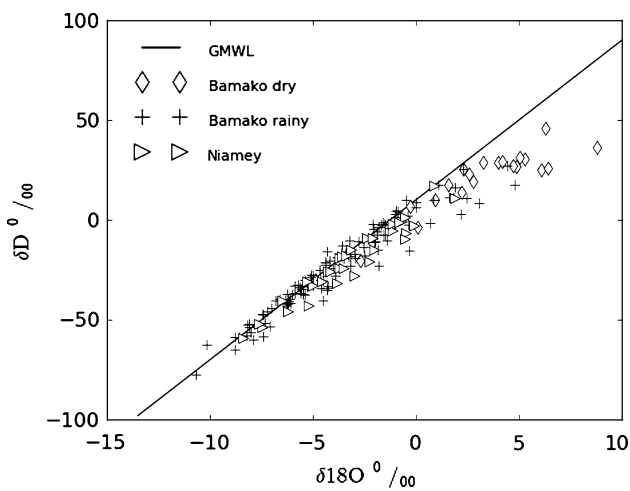


Fig. 4 Plot of all pairs of $\delta^{18}\text{O}$ and δD values from Bamako, Mali and Niamey, Niger (IAEA/WMO 2006). GMWL is the global meteoric water line and it is added as a reference for the data

Insufficient data precluded seasonal separation of LMWLs for Niamey. The slopes of all LMWLs were less than 8 (with the Bamako dry season slope having the lowest value), which indicates that precipitation is taking place in a semi-arid region and is subject to evaporation (Yurtserver and Gat 1981; Clark and Fritz 1997).

Mean annual and mean seasonal (rainy and dry seasons) values were calculated for δ , P , T , V_p , and d (Table 1). Seasonal variations were observed in both δ and the meteorological data. Since the ITCZ controls the movement of humid monsoonal air and dry desert air, it follows that vapor pressure and relative humidity vary seasonally, peaking during rainy months and lowest during the dry season. At Bamako, V_p increased more than twofold during the rainy season as compared to the dry season. Comparison of seasonally averaged precipitation values with annual average precipitation values indicates that relatively little

of the total mean annual precipitation occurs during the dry season (less than 5%) at either Bamako or Niamey. Although mean monthly temperature is highest during the dry season (Fig. 2), the mean seasonal temperatures show no discernable seasonal variation.

Mean annual precipitation isotope values are characterized by negative δ values (Table 1). At Bamako and Niamey, mean rainy season precipitation δ values are also negative, whereas mean dry season rains have positive δ values. Mean rainy season and mean dry season δ values varied by 6.99‰ for $\delta^{18}\text{O}_a$ and 43.1‰ for δD_a at Bamako and by 4.35‰ for $\delta^{18}\text{O}_a$ and 35.7‰ for δD_a at Niamey. Average annual δ values at Bamako and Niamey are similar, but at Niamey they are slightly more negative than for those at Bamako. This difference could indicate a slightly greater rainout effect for the precipitation at Niamey as compared with Bamako, but this difference is more likely the result of the small number of dry season samples (with more positive δ values) at Niamey (three $\delta^{18}\text{O}$ and two δD dry season samples) as compared to Bamako (25 $\delta^{18}\text{O}$ and 22 δD dry season samples) that are used in calculating the average annual δ values.

Mean annual d values at both locations are 5.0‰, which is less than the global value of 10‰ (Table 1). Values lower than the global average indicate some evaporation of rainfall in these dry climates. At Bamako, the low dry season d value of $-5.8‰$ indicates a significant degree of kinetic fractionation. This kinetic fractionation is most likely occurring as low-intensity rainfall evaporates as it falls through a dry sky characterized by low relative humidity (Gat 2000; Fröhlich et al. 2002). Niamey precipitation d values follow a similar pattern as those observed for Bamako.

A comparison of δ_a and δ_w values (Table 1) shows that precipitation-weighted δ values are more negative than arithmetic averaged values, except for the dry season precipitation $\delta^{18}\text{O}$ value at Niamey, which was similar to

Table 1 Summary data for mean annual and mean seasonal (rainy and dry seasons) values of $\delta^{18}\text{O}_w$, $\delta^{18}\text{O}_a$, δD_w , δD_a , d , P , V_p , and T at Bamako, Mali and Niamey, Niger

	Bamako						Niamey					
	Annual	<i>n</i>	Rainy	<i>n</i>	Dry	<i>n</i>	Annual	<i>n</i>	Rainy	<i>n</i>	Dry	<i>n</i>
$\delta^{18}\text{O}_w$ (‰)	-3.48	147	-3.63	122	0.82	25	-4.21	39	-4.31	36	0.93	3
$\delta^{18}\text{O}_a$ (‰)	-2.36	147	-3.55	122	3.44	25	-3.18	39	-3.52	36	0.83	3
δD_w (‰)	-22.0	139	-22.9	117	4.7	22	-25.7	34	-26.4	32	10.5	2
δD_a (‰)	-15.5	139	-22.3	117	20.8	22	-19.7	34	-21.8	32	13.9	2
d (‰)	5.0	139	7.0	117	-5.8	22	5.0	34	5.2	32	2.0	2
P (mm)	888	354	858	175	30	179	562	72	552	44	10	28
V_p (mbar)	18.1	285	25.2	141	11.3	144	NA	NA	NA	NA	NA	NA
T (°C)	27.7	354	27.7	175	27.8	179	NA	NA	NA	NA	NA	NA

NA data not available

rainy-season precipitation (0.93‰ as compared to 0.83‰). This general observation reflects the greater sub-cloud evaporation, and associated isotope enrichment (δ values become more positive), of rainfall during low-intensity storms. This evaporative enrichment is further observed at Bamako, where the greatest difference in values is observed during the dry season as compared to the rainy season. There was a dry-season difference of 2.62‰ between $\delta^{18}\text{O}_w$ and $\delta^{18}\text{O}_a$, while the rainy-season difference was only 0.08‰. A large difference was also observed for dry-season δD_w and δD_a values (16.1‰) as compared with rainy-season δD_w and δD_a values (0.6‰) at Bamako.

Mean monthly precipitation δ values (Fig. 5) for Bamako show an inverse relationship with P (Fig. 3) and V_p (Fig. 2). These negative correlations indicate the presence of both an amount and humidity effect on precipitation δ values. As both P and V_p increase during rainy months, a depression is observed for monthly δ values (Fig. 5). Values drop as low as -35.6‰ (δD_w) and -45.4‰ (δD_a) during rainy months and can be as high as 38.9‰ (δD_w) or 41.2‰ (δD_a) during the dry month of February. A similar pattern is observed for $\delta^{18}\text{O}$ values. In contrast, there is no apparent correlation between T and δ values (Figs. 2, 5). Consistently high T with little seasonal variation de-emphasizes the temperature effect at Bamako. Similar results are reported for GNIP stations in monsoonal areas where $\delta^{18}\text{O}$ appears to be negatively related to precipitation amount and temperature varies little (Yurtserver and Gat 1981).

Given the relatively larger differences between δ_a and δ_w during the months of March, April, November, and August than for other months at Bamako (Fig. 5) and the dissimilarities observed between annual and seasonal δ_a and δ_w values (Table 1), it is possible that mean-weighted data (weighted for precipitation amount) is masking extreme precipitation phenomenon such as rainfall events

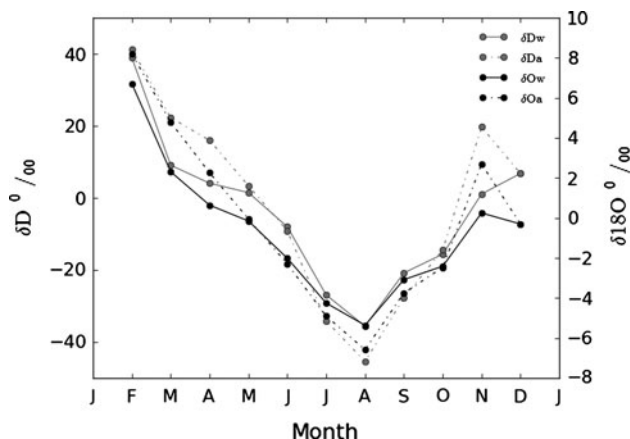


Fig. 5 Mean monthly values of δ_a (arithmetically averaged) and δ_w (mean-weighted for precipitation amount) at Bamako, Mali

of larger and smaller intensity. For example, August is the peak of the rainy season, with the highest mean rainfall and largest maximum relative humidity values recorded, while November, March, and April are characterized by scant rainfall and low relative humidity values. Thus, differences between δ_a and δ_w during these times suggest that δ_w may not be reflecting extreme precipitation phenomenon, which may have implications for interpretations of event-scale studies.

Monthly $\delta^{18}\text{O}_a$, δD_a , $\delta^{18}\text{O}_w$, and δD_w values at Niamey (Fig. 6) show negative correlations with P (Fig. 2). These relationships indicate the presence of the amount effect. A depression of monthly δ values, in particular δD_w and δD_a , is observed as P increases during the rainy months. Values decrease to -37.2‰ (δD_w) and -40.5‰ (δD_a) during rainy months and increase to 10.5‰ (δD_w) and 13.0‰ (δD_a) during the dry month of April. A similar relationship is observed for $\delta^{18}\text{O}$ (Figs. 2, 6).

The d values at Bamako approach the global value of 10‰ during the rainy season and decrease during the dry season (Fig. 7). At Bamako, d is most constant during the peak monsoonal months of June, July, and August. Values of d are approximately 9‰ during these 3 months, which is about the value of first-fraction precipitation d calculated for GNIP stations in the Atlantic Ocean near the equator (Fröhlich et al. 2002). The d values at Niamey follow a similar trend as the Bamako values, but they are generally lower (Fig. 7). These mean monthly d values at Bamako and Niamey suggest that monsoonal precipitation is first-fraction water originating from the Gulf of Guinea in the Atlantic Ocean near the equator and generally it does not contain a significant portion of recycled water from evaporation gained on its journey inland during this time.

As the monsoon begins to end, d values at Bamako vary between about 0 and 10‰ and then drop as low as -24‰ during February. The more negative dry-season d values, as

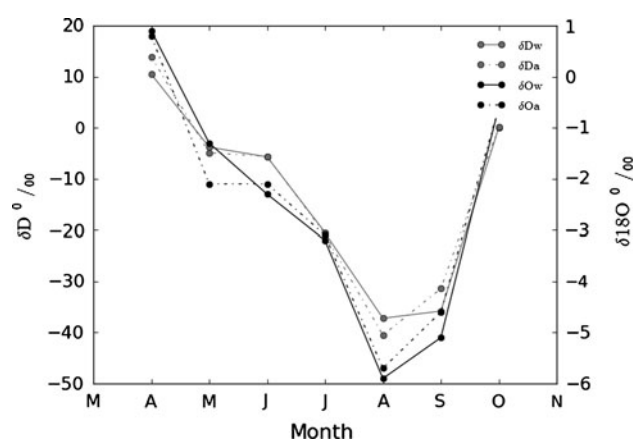


Fig. 6 Mean monthly values of δ_a (arithmetically averaged) and δ_w (mean-weighted for precipitation amount) at Niamey, Niger

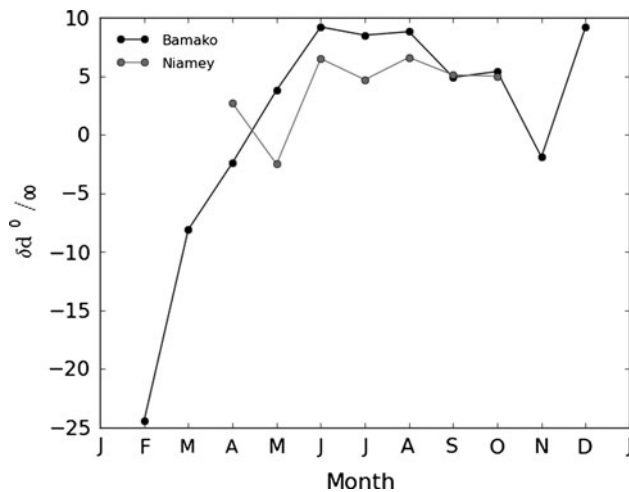


Fig. 7 Mean monthly values of excess deuterium (*d*) at Bamako, Mali and Niamey, Niger

compared to monsoon *d* values, are in agreement with the low slope of the Bamako dry-season LMWL, indicating that both δ and *d* values are strongly affected by high rates of sub-cloud evaporation during dry season climatic conditions (Gat 2000; Fröhlich et al. 2002). At Bamako, large seasonal variations of *d* (about 34‰) far exceed the analytical uncertainty of the parameter (about 2‰). The *d* values at Niamey do not vary as much as at Bamako (Fig. 7), but this is an artifact of the lack of data for the dry season at Niamey, except for the months of April and May which have a similar range in *d* values as is observed at Bamako.

Water recycling by evaporation from surface water bodies and small pools of water from previous rain events or by plant transpiration from soil moisture and groundwater into precipitation could be occurring as storms move from the Gulf of Guinea to Mali and Niger. A study by Gong and Eltahir (1996), using a water mass balance to develop a recycling model, indicates that 27% of precipitation in West Africa is from recycled water. This value is greater than an earlier estimate of 11% recycled water in West Africa precipitation (Budyko 1974). Using a Lagrangian method diagnosis, Nieto et al. (2006) reached the conclusion that recycling was the major source of moisture over the Sahel, except for the monsoonal summer months when the Gulf of Guinea is the main moisture source. Koster and Dirmeyerl (2004) compared the results of 12 atmospheric general circulation models and concluded that the impact of soil moisture recycling in the Sahel region of West Africa was significant, based primarily on where potential evapotranspiration (PET) is high and soil moisture is low. Thus, to evaluate the amount of recycling of inland surface waters into atmospheric moisture that then falls as rain, precipitation with *d* values

greater than 10‰ were evaluated (Yurtserver and Gat 1981, 2000; Taupin et al. 2000; Fröhlich et al. 2002; Yamanaka et al. 2004). Although such *d* values are often observed in eastern parts of West Africa, where evaporated water originates from Lake Chad and surface water behind the Kainji Dam in Nigeria (Taupin et al. 2000), in this study, mean monthly *d* values do not exceed 10‰. This lack of mean monthly *d* values >10‰ is likely due to the absence of large bodies of water, such as Lake Chad, located near Bamako or Niamey or along storm trajectories from the Gulf of Guinea in the Atlantic Ocean to these areas. Thus, most precipitation falling in Bamako and Niamey is first-fraction water evaporated from the Atlantic Ocean, or is water recycled to the atmosphere by plant transpiration (there would be no change in the *d* parameter since transpiration does not fractionation deuterium or oxygen-18), there is little evidence of evaporated surface water or soil moisture in precipitation at Bamako and Niamey.

Precipitation falling at Bamako and Niamey with a significant portion of recycled water from evaporation may be occurring sporadically, however, this would only taking place on an event-scale related to individual storms with a duration of several days between storms. Of samples collected at Bamako, 13% have *d* values greater than 10‰. At Niamey, 6% of samples have *d* values greater than 10‰. No distinct trend with respect to month is observed for *d* values greater than 10‰, although all samples were collected during rainy season months (May–October). Most observations with *d* values greater than 10‰ are recorded during the month of June, and the highest *d* value of 19‰ was recorded in August 1967. Water vapor could be forming by evaporation of soil moisture and small pools of water from previous rain events, but no known isotope surface water or vapor studies have been conducted that would have the isotope composition of these sources.

Any significant recycling of water likely originates from transpiration by plants along storm trajectories from the ocean to Bamako and Niamey, but this is difficult to ascertain, because *d* is not significantly modified in this process (Yurtserver and Gat 1981; Taupin et al. 2000). Taupin et al. (2000) used the criteria that precipitation originating from transpired water gives rainy-season $\delta^{18}\text{O}$ values between -5 and -3 ‰ and *d* values between 8 and 12‰. Applying this criteria to the data used in this study results in 7% of all samples at Bamako and 5% of all samples at Niamey having precipitation that contains a significant amount of recycled water from transpiration (analytical uncertainty of *d* is excluded). Similar to evaporation, cycling of precipitation due to transpiration occurs intermittently, probably on an event-scale and would be

related to individual storms and the length of time between storms.

Correlation and linear regression

Table 2 lists the summary data for Pearson’s ρ and p values of δ , P , T , V_p , and d . Values of δ and T are not listed, because no statistical significance is observed ($p > 0.050$). All other relationships are statistically significant ($p < 0.050$). Strong relationships were indicated between δ_a and P and V_p , and δ_w and P and V_p at Bamako, supporting the precipitation amount and humidity effects as environmental factors controlling δ values of precipitation. At Niamey, strong relationships were observed between δ_a and δ_w and P , supporting the amount effect as an environmental factor controlling the δ values of precipitation at this site. Increasing values of Pearson’s ρ between δ and environmental factors occurred in the order of weighted to arithmetic values. The strongest relationship overall (-0.93) was between P and δD_a at Bamako. This strong relationship indicates that masking of precipitation phenomenon by mean-weighted data may be occurring. The strongest relationship for d is with V_p (0.70), supporting the humidity effect at Bamako, which indicates that humidity strongly influences precipitation δ values. During peak monsoonal months, values of d increased as V_p and relative humidity increased, while during dry season months values of d decreased as rains experience increased sub-cloud evaporation.

Linear regression results for δ , P , T , V_p , and d are presented in Table 3. At Bamako, R^2 values greater than 50% indicate that P and V_p can predict the majority of variation observed for δ values, while predictive capability of T is low. At Niamey, R^2 values greater than 50% indicate that P can predict the majority of variation observed for δ values. Arithmetic R^2 values between δ , and P , T , and V_p

are all greater than weighted R^2 values, which also indicates the masking of precipitation phenomenon by mean-weighted data and supports the conclusion of Zhang et al. (1995), who noted the precipitation amount effect to be more significant in arithmetic rather than weighted data. The strongest predictive capability is between P and δD_a at Bamako ($R^2 = 86\%$), which is also the largest Pearson’s ρ value (-0.93). These analyses indicate that the amount effect has the greatest influence on δD values at Bamako. Vapor pressure has moderate predictive capability for d , while P and T have low predictive capability for d .

The stepwise addition of environmental factors into a MLR model does not necessarily improve predictive capability. With the exception of $\delta^{18}O_a$, stepwise addition yields reduced predictive capability and p values exceed the significance level of 0.050. In the model of $\delta^{18}O_a$, predictive capability increases from 75 to 84% as T is added to the linear regression equation after V_p . Addition of P decreases the predictive capability to 82% and the p value exceeds the significance level. The equation for the MLR model of $\delta^{18}O_a$, V_p , and T is given as:

$$\delta^{18}O_a = -0.50 V_p + 0.61T - 7.76 \quad (R^2 = 84\%). \quad (5)$$

Limited GNIP data for Niamey precludes creation of an MLR model. Results from MLR models of the relationship

Table 2 Summary data of Pearson’s ρ and p values for isotopic values and environmental factors

Variables	Weighted average			Arithmetic average		
	ρ	p	n	ρ	p	n
<i>Bamako</i>						
$\delta^{18}O$; P	-0.82	0.002	11	-0.86	0.001	11
$\delta^{18}O$; V_p	-0.86	0.001	11	-0.88	0.000	11
δD ; P	-0.86	0.001	11	-0.93	0.000	11
δD ; V_p	-0.87	0.001	11	-0.89	0.000	11
d ; V_p	- ^a	- ^a	- ^a	0.70	0.016	11
<i>Niamey</i>						
$\delta^{18}O$; P	-0.87	0.011	7	-0.85	0.015	7
δD ; P	-0.84	0.018	7	-0.87	0.010	7

^a d not subject to weighting

Table 3 Summary data of linear regression equations and R^2 values for isotopic values and environmental factors

Linear regression equation	n	R^2 (%)
<i>Bamako</i>		
$\delta^{18}O_w = 1.74 - 0.03 P$	11	64
$\delta^{18}O_w = 6.75 - 0.39 V_p$	11	71
$\delta^{18}O_w = -17.1 + 0.59 T$	11	7
$\delta D_w = 11.5 - 0.18 P$	11	71
$\delta D_w = 42.1 - 2.42 V_p$	11	73
$\delta D_w = -96.3 + 3.30 T$	11	4
$\delta^{18}O_a = 3.14 - 0.04 P$	11	71
$\delta^{18}O_a = 9.87 - 0.53 V_p$	11	75
$\delta^{18}O_a = -23.9 + 0.85 T$	11	11
$\delta D_a = 20.2 - 0.26 P$	11	86
$\delta D_a = 59.5 - 3.21 V_p$	11	77
$\delta D_a = -146 + 5.17 T$	11	11
$d_a = -3.92 + 0.06 P$	11	24
$d_a = -17.3 + 0.97 V_p$	11	43
$d_a = 42.8 - 1.49 T$	11	2
<i>Niamey</i>		
$\delta^{18}O_w = -0.21 - 0.03 P$	7	71
$\delta D_w = 3.38 - 0.21 P$	7	65
$\delta^{18}O_a = -0.45 - 0.03 P$	7	67
$\delta D_a = 5.13 - 0.22 P$	7	71
$d_a = 2.08 + 0.02 P$	7	19

between $\delta^{18}\text{O}$, T , and relative humidity (H_r) for another study at Niamey (Taupin et al. 2002) produced the following equations:

$$\delta^{18}\text{O} = 1.03T - 34.5 \quad (R^2 = 63\%) \quad (6)$$

$$\delta^{18}\text{O} = -0.16H_r + 7.24 \quad (R^2 = 68\%) \quad (7)$$

$$\delta^{18}\text{O} = -0.13H_r + 0.26T + 7.24 \quad (R^2 = 69\%). \quad (8)$$

No other statistical values are given by Taupin et al. (2002), and it is unclear if, or how, the data are averaged. Further comparisons are difficult to make, since GNIP does not provide T or relative humidity (or V_p) data for Niamey.

Groundwater

Near Bamako, reported groundwater $\delta^{18}\text{O}$ values range from -5.69 to -3.47‰ (Jusserand 1976); -6.89 to -5.08‰ (Dray et al. 1983); and -7.09 to -2.36‰ (Dinçer et al. 1984). Reported values of δD for groundwater range from -49.6 to -33.5‰ (Dray et al. 1983) and -48.9 to -17.7‰ (Dinçer et al. 1984). Near Niamey, reported groundwater $\delta^{18}\text{O}$ values range from -6.41 to -1.30‰ and δD values range from -45.9 to -15.2‰ (Leduc et al. 2000). Groundwater samples collected recently by the authors for groundwater studies near Niamey have $\delta^{18}\text{O}$ and δD values that range from -3.99 to -2.50 and -29.4 to -14.0‰ , respectively, and for groundwater samples about 250 km east of Bamako have $\delta^{18}\text{O}$ and δD values that range from -6.42 to -4.57 and -43.1 to -28.4‰ , respectively (Table 4).

Mean annual δ precipitation values for both Bamako and Niamey (Table 1) fall within the range of groundwater $\delta^{18}\text{O}$ and δD values, although limited samples collected by the authors (Table 4) are more negative for both $\delta^{18}\text{O}$ and δD than the arithmetic and precipitation-weighted δ values for rainy-season Bamako precipitation. However, these groundwater samples near Bamako are within the range of the average precipitation δ values for the peak monsoonal months of July, August, and September (Fig. 5). Agreement between groundwater δ values and annual precipitation δ values suggests that groundwater is being recharged on a continual basis under current climatic conditions, rather than a paleo-groundwater that was recharged under different climatic conditions. Examining seasonally separated data shows that groundwater δ values are dissimilar from dry season δ precipitation values, but resemble rainy season δ values. Agreement between rainy-season precipitation δ values, more specifically the peak monsoonal months of July, August, and September (Figs. 5, 6), and groundwater δ values indicates that groundwater is predominantly recharged by monsoonal rains. Additionally, these rains are experiencing little evaporation before recharging the groundwater system, because average

Table 4 Summary $\delta^{18}\text{O}$, δD , and d values for groundwater samples collected for this study

Location	Date	$\delta^{18}\text{O}$ (‰)	δD (‰)	d
<i>Mali</i>				
Well Id 0002	1-Dec-05	-5.24	-34.4	7.5
Well Id 0002	1-Dec-05	-5.50	-35.9	8.1
Well Id 0002	1-Jan-06	-5.59	-34.9	9.8
Well Id 0002	1-Jan-06	-5.50	-35.1	8.9
Well Id 0002	1-Apr-06	-5.60	-35.6	9.2
Well Id 0002	1-Apr-06	-5.69	-35.7	9.8
Well Id 0042	1-Dec-05	-5.85	-40.2	6.6
Well Id 0042	1-Dec-05	-5.60	-39.6	5.2
Well Id 0042	1-Apr-06	-5.51	-38.7	5.4
Well Id 0042	1-Apr-06	-5.90	-40.4	6.8
Well Id 0058	1-Dec-05	-5.07	-33.4	7.2
Well Id 0058	1-Dec-05	-5.12	-32.6	8.4
Well Id 0058	1-Apr-06	-4.95	-31.8	7.8
Well Id 0074	1-Dec-05	-6.38	-42.5	8.5
Well Id 0074	1-Dec-05	-6.42	-43.1	8.3
Well Id 0074	1-Apr-06	-6.41	-41.3	10.0
Well Id 0074	1-Apr-06	-6.40	-42.3	8.9
Well Id 0065	1-Dec-05	-4.78	-29.3	8.9
Well Id 0065	1-Dec-05	-4.57	-28.4	8.2
<i>Niger</i>				
Well ID 18982	29-Nov-04	-3.99	-29.4	2.5
Well ID 27648	1-Dec-04	-3.68	-27.5	1.9
Well ID 22320	29-Nov-04	-3.54	-26.3	2.0
Well ID 27785	29-Nov-04	-3.46	-23.6	4.1
Well ID 22213	1-Dec-04	-3.69	-21.4	8.1
Well ID 90679	1-Dec-04	-2.50	-14.0	6.0

values of d calculated from groundwater samples collected in Mali ($d = 8.1\text{‰}$) and Niger ($d = 6.7\text{‰}$) are within the 2‰ analytical range of uncertainty of rainy-season precipitation d values (Table 1). Thus, groundwater recharge from monsoonal rains must be fairly rapid because of the lack of significant evaporation.

Research described here forms the foundation for groundwater sustainability studies in both Mali and Niger. Evaluating environmental factors and precipitation δ values is necessary for predicting potential changes in groundwater availability and quality by understanding changes in precipitation amount and timing. Ultimately, alteration of the groundwater system (i.e., use exceeding the available sustainable yield of an aquifer) may lead to changes in surface water and ecosystem sustainability. The use of precipitation δ values to link rainfall patterns with effective recharge in warm semi-arid zones provides a basis for evaluating global climate change models and for assessing their potential for predicting the impact of climate change scenarios on groundwater sustainability. More

detailed examination of the precipitation record over time may indicate a rainfall intensity threshold (i.e., mm/month) that leads to effective recharge, below which groundwater recharge is greatly reduced. Understanding and predicting changes in precipitation amounts and intensities, which ultimately affect timing and amount of groundwater recharge, and quality and quantity of groundwater resources, is critical for water resource management.

Conclusions

This study evaluated the effects of the environmental factors precipitation amount (P), temperature (T), and vapor pressure (V_p) on precipitation δ values and excess d values at Bamako, Mali and Niamey, Niger in West Africa. Environmental factors and δ values were examined on an annual, seasonal, and monthly basis. Values of δ that were evaluated were: mean-weighted by precipitation (δ_w) and arithmetically averaged (δ_a). Relationships between environmental factors and δ values were evaluated by visual inspection of plots, linear regression, and correlation.

The slopes of LMWLs for both Mali (including the rainy season LMWL) and Niger are less than the slope of the GMWL, as expected for the arid environment of these countries. Mean annual and mean rainy-season P are characterized by negative δ values, whereas dry season rains had positive δ values. However, dry season rains represent less than 5% of total annual precipitation. The greatest differences were between annual and dry-season δ values.

At both Bamako and Niamey, d values approach the global d value of 10‰ during the peak monsoonal months of June, July, and August. Values of d indicate that precipitation at Bamako and Niamey during the rainy season are first-fraction, with little recycled water acquired on its journey inland from the Gulf of Guinea. This does not, however, exclude some recycling of water from surface water bodies or plant transpiration, which may be occurring on an event-scale, related to individual storms or the duration of days between storms.

The amount effect on δ precipitation values is observed at both Bamako and Niamey. There are statistically significant negative correlations between δ values and P . Strong correlations are indicated by Pearson's ρ values and good predictive capabilities are observed in the linear regressions between δ values and P . The strongest Pearson's ρ value and best predictive capability overall was between P and δD_a at Bamako, suggesting the amount effect to be more negatively correlated with δ_a values than δ_w values at that location.

The humidity effect on δ precipitation values is observed at Bamako. There is strong negative correlation

between δ values and V_p (V_p is a surrogate for humidity). Strong correlations are indicated by Pearson's ρ values and good predictive capabilities are observed in the linear regression between δ values and V_p . The temperature effect is not observed, as there is no statistically significant correlation between δ values and T . With the exception of $\delta^{18}O_a$, the stepwise addition of environmental factors into an MLR model generally did not improve predictive capability of precipitation δ values.

In this study, precipitation volume mean-weighting of δ values may be masking dry-season precipitation phenomena, such as very low relative humidity and very low volumes of precipitation, and individual storm event monsoonal phenomena, which are otherwise observed in arithmetically averaged data. Dissimilarities were evident between δ_a and δ_w values. Relatively larger dissimilarities were observed between δ_a and δ_w during March, April, November, and August than for other months at Bamako. In general, stronger correlations (Pearson's ρ) and better predictive capability were observed between environmental factors and δ_a values than environmental factors and δ_w values. The method of averaging (weighted or arithmetic) may have implications for interpretations of event-scale studies.

Characterizing the dominant environmental processes that control temporal variation in precipitation isotope values supports ongoing groundwater sustainability studies in both Mali and Niger. Agreement between rainy-season precipitation, specifically the peak monsoonal months of July, August, and September, and groundwater $\delta^{18}O$ and δD values indicates that groundwater is predominantly recharged monsoonal rains under current climatic conditions, rather than paleo-groundwater recharged under different climatic conditions. Groundwater values of d also are similar to rainy-season precipitation values providing another indication that monsoonal precipitation is the source of groundwater recharge and that monsoonal precipitation is not experiencing significant evaporation during the recharge process. Knowledge that groundwater is recharged monsoonal rains under current climatic conditions, rather than paleo-groundwater that was recharged thousands of years ago under different climatic conditions, is important for evaluating groundwater sustainability. A better understanding of the source and timing of groundwater recharge is critical to managing this resource in a sustainable manner.

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