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ORIGINAL ARTICLE

Modeling vadose zone hydrological processes in naturally occurring piezometric depressions: the Chari-Baguirmi region, southeastern of the Lake Chad Basin, Republic of Chad

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Abstract
The Chari-Baguirmi region, southeastern of the Lake Chad (Africa), has a wide naturally occurring piezometric depression with values deeper than the expected regional groundwater level. To date, the most widely accepted hypotheses to explain its origin and dynamics are based on lack of rainwater infiltration and exfiltration processes. The code HYDRUS-1D is applied to numerically simulate the hydrological flow processes along the unsaturated zone in two soil profiles located in the central part and on the boundary of this piezometric depression under bare and vegetated soil coverage. The simulated time period is 2004–2015 with 715 mm annual rainfall average. The computed recharge with respect to total precipitation accounts for 21% on the boundary and 12% in the central part, which is limited by thick silty low permeability layer on the top surface. Considering modelling uncertainty and limitations under the simulated climatic conditions, the rainfall effect is observed only at upper soil layers, which leads to low aquifer recharge, while the upward water flux causing water table evaporation is very low. Past climate conditions, capable of developing a drying front to reach the water table after thousands of years of drying and geological structural constraints, may explain the current depressed area.

Keywords Hydrus 1D · Vadose zone · Piezometric depression · Chari Baguirmi

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Introduction

Large closed piezometric depressions, manifested by closed curves and depths attaining tens of meters lower than the regional groundwater level, also known as “hollow aquifers”, are naturally occurring phenomena in some area of the Sub-Saharan Africa aquifers, i.e., Senegal (Dieng et al. 1990), Niger (Favreau et al. 2002), Cameroon (Ngounou Ngatcha and Reynault 2007), Chad (Durand 1982; Schneider 1989; Leblanc 2002; Boronina and Ramilien 2008; Abderamane et al. 2016) and Mauritania (Lacroix and Semega 2005).

Different hypotheses about hydrological mechanisms have been proposed to give an explanation on the origins of these depressions: aquifer overexploitation, land subsidence, deep drainage conditioned by geological structures, seawater level changes and/or high evapotranspiration rates (e.g., Durand 1982; Dieng, et al. 1990). Aranyossy and Ndiaye (1993) suggested that Sahel piezometric depressions occur in areas characterized by low natural recharge due to the outcropping of impervious geological materials, where evapotranspiration is not compensated by other water inputs.

In arid and semi-arid areas similar to the study area, a number of methodologies are currently applied to estimate both recharge and soil–water balance and reviews on aquifer recharge quantification have been conducted in the past (Scanlon et al. 2002). Among them, modelling upward and downward transport of tritium with the code SOLVEG was applied in southeastern Spain for natural recharge estimation (Jiménez-Martínez et al. 2012), based on data from vadose zone monitoring. Quantification of diffuse recharge in the Chari-Baguirmi area has been carried out by Salehi Siavashani et al. (2021) from a soil–plant–atmosphere model (VisualBALAN) based on the water balance and with ground and satellite-based meteorological input data sets. At Lake Chad basin level, based on Meteosat thermal findings and numerical modelling Leblanc et al. (2003) conclude that depressions present low rainwater infiltration, as very little precipitation is available for aquifer recharge. Exfiltration or other processes capable of extracting groundwater from the aquifer media founded on isotope data, are a process that has been previously assumed in the area by some authors (Eberschweiler 1993; Coudrain-Ribstein et al. 1998; Gaultier 2004; Ngounou Ngatcha and Reynault 2007). To date, no comprehensive model for the development of the piezometric depression does exist, and the most accepted approach considers negligible recharge (from natural infiltration) due to the scarce presence of permeability materials, along with considerable evapotranspiration rates.

Within the endorheic Lake Chad Basin area, according to Maley (2010) and Armitage et al. (2015) millennial and centennial rainfall dynamics have been documented for more than 11.5 kyr (thousand years ago). During the Holocene, the existence of a Mega Chad, with more than 350,000 km^2, and a level rising to 325 m.a.s.l., have been identified by Schuster et al. (2005), among other researchers, to evidence the changes in lake extension over time. Since the last African Humid Period (6000 AD, Kröpelin et al. 2008), which has led to important groundwater recharge, a significant reduction in rainfall has occurred, which has resulted in the current Lake reduction.

In the Quaternary aquifer of the Chad Formation Aquifer System—CFA, extending along all the Basin area (FAO 1973), naturally occurring wide piezometric depressions are found in Cameroon (Yaéré), Chad (Bahr El Ghazal, Chari-Baguirmi), Niger (Kadzell) and Nigeria (Bornu). In the Chari-Baguirmi region of Chad Republic, the wide piezometric depression in the eastern part of the Lake Chad Basin presents a groundwater level that is between 40 and 60 m deeper than expected. Despite its importance, its genesis is not yet known and several hypotheses have been proposed. One is the importance of the evapotranspiration phenomenon in the region, where only a scanty amount of rainwater constitutes aquifer recharge, which is underlined by isotopic data, piezometric studies and mathematical modeling (Eberschweiler 1993; Schneider 1989; Leblanc et al. 2003). Deep groundwater flow drainage (Arad and Kafri 1975; Abderamane 2012; Vaquero et al. 2021) is another proposed hydrological mechanism, because the flow direction is expected toward the North discharging to the basin’s lowest elevation point (the Lowlands, Bodelé, northern Chad, S1) and apparently, regional groundwater levels have decrease with time (Leblanc 2002). According to Abderamane et al. (2016), the structural geology of the underlying basement characterized by horsts and grabens may have controlled the genesis of the depressions, which is favored by the presence of a top thick silt layer with a high clay minerals content and low permeability, that impairs high evaporation rates from the groundwater level.

The objective of this research is to investigate the different hydrological processes that take place in the vadose zone of the piezometric depression area based on numerical simulations with HYDRUS-1D, a variable-saturated vadose-zone numerical flow model. Simulation was carried out for the 2005–2014 period in two different areas of the Chari-Baguirmi depression: Bokoro (boundary of the depression) and Amdedoua (center of the depression).

Study area

The Chari-Baguirmi region, a broad plain, located in Chad (Africa), on the boundary of the paleo-Chadian basin of the Lake Chad Basin (Fig. 1), extends over an area of 45,000 km^2. Its population is around 621,785 inhabitants. The surface height varies from 200 to 400 m above sea level.

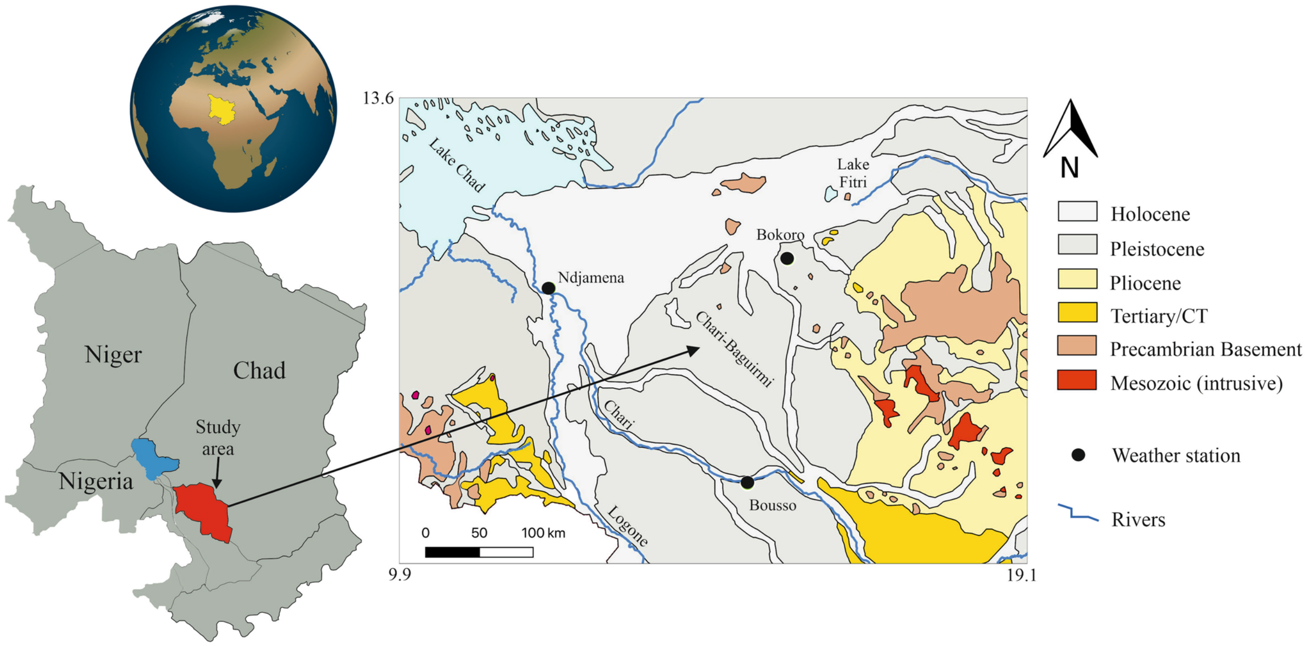

Fig. 1 **a** Chari-Baguirmi area (Chad Republic, Africa). **b** Geographic location and geological map of the area (modified from Schneider 1989). Meteorological stations from the Trans-African Hydro-Meteorological Observatory—TAHMO platform (Van de Giesen et al. 2014)

Several kinds of rubber, vine and rice are common vegetal species. Acacia, the doum palm, and *Ziziphus* (spiny shrubs and small trees) species (Mallon et al. 2015) dominate the sparse woody community. *Acacia tortilis* (umbrella thorn) is a small–medium-sized evergreen tree or shrub with high tolerance to strong salinity and seasonal waterlogging and drought-resistant. Acacias generally grow in open dry forests that consist exclusively of acacias (pure acacias stand), or is mixed with other species. This plant develops long lateral roots and a deep taproot system that enable the limited soil moisture existing in arid areas to be obtained (Heuzé and Tran 2015). During the dry season (winter in Chad) the woody vegetation loses its leaves, and grasses dry up and may burn.

The region lies in the Sudano-Sahelian climatic zone. The hottest months are May and April, and the coldest month is January. The mean annual temperature is 29.5 °C, with a maximum between 34 and 43 °C, and a minimum between 17 and 23 °C. Three ground-based weather stations, Ndjamena, Bokoro, and Bousso, presenting the fewest gaps in climatic data and the most closest to the simulated boreholes, were selected (Fig. 1). For the 2005–2014 period the average annual rainfall was 700 mm/year (715 mm/year in Bokoro, 890 mm/year in Bousso and 648 mm/year in N'Djamena) (Fig. 2). The air humidity at Bokoro ranges from 12% to 75%. Most rain falls in the summer months from May to September, followed by a 6–8-month dry season; extreme events occur during the rainy season. The Harmattan hot dry wind blows from the north, and often bring dust and sand from the Sahara Desert.

According to the literature, different geological materials (Fig. 1) make up the sedimentary basin and its basement (Genik 1992; Schneider and Wolf 1992; Moussa 2010): to the Northeast and Northwest, the crystalline basement (granite) outcrops (Kusnir 1995); in the central part, the Pliocene deposits of the paleo-Chadian sedimentary basin cover almost the entire area. The geological composition corresponds to detrital series with sandy clay intercalations and a thick layer of lake sediments with sandy and gypsiferous clays with diatomites intercalations. The overlying Quaternary deposits are composed of sandy–clayey sediments of fluvial, lacustrine, deltaic and eolian origin. They present frequent lateral and vertical changes of facies (Abderamane et al. 2016). Soils are composed mainly of sandy- and clay-rich materials.

The surface hydrology is composed by a channel network of the two main rivers, Chari and Logone, flowing into the lake.

At the basin level, the aquifer system known as the Chad Formation Aquifer System—CFA (FAO 1973) is the main source of freshwater. From the hydraulic point of view, an upper unconfined aquifer of Quaternary age and a deeper confined–unconfined aquifer of the Lower Pliocene and the Continental Terminal are defined (Supplementary material). The connection between the upper and lower multilayer aquifers in almost the whole area is conditioned by the impervious clay layers of the Upper Pliocene. However,

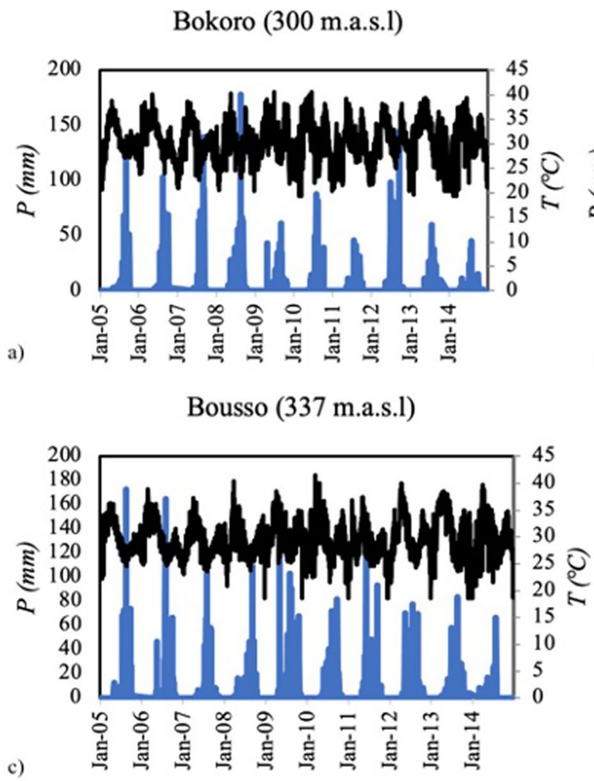

Fig. 2 Precipitation (blue bars) and temperature (black line) from the **a** Bokoro, **b** N'Djamena and **c** Bousso weather stations for the 2005–2014 period

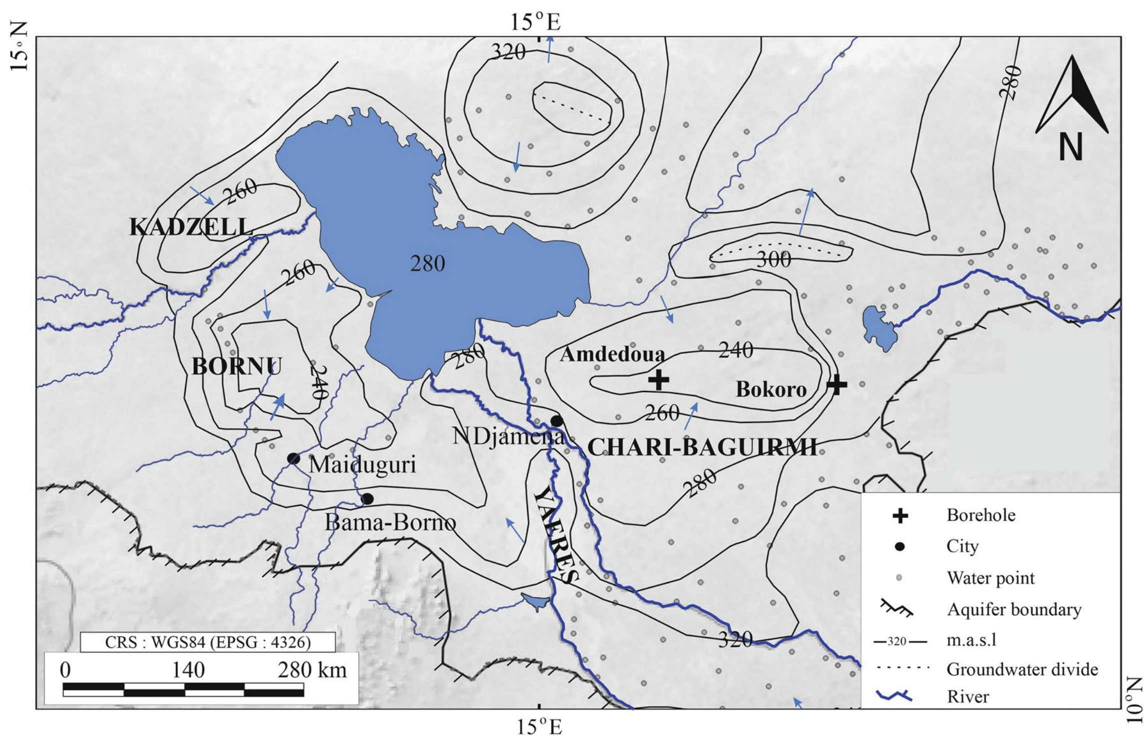

Fig. 3 Piezometric map (2008–2011) of the Chad Formation upper aquifer showing the Chari-Baguirmi depression and other existing depressions (after Vaquero et al. 2021)

they are hydraulically connected in the basin's southern area, where the deeper aquifer outcrops. According to Maley (2010) and Abderamane (2012) the current groundwater level of the upper aquifer (Quaternary) is the consequence of a groundwater level drop from the aquifer replenishment time during the last pluvial period of the Holocene (around 6000 years ago).

In the Chari-Baguirmi region, the upper aquifer groundwater level is characterized by a wide piezometric depression of 17,761 km^2, which extends from the border of the Lake to Bokoro (see Fig. 3). The groundwater depth ranges from a few meters in the lowland area close to the Lake Chad to around 50 m in the central part of the depression (Abderamane et al. 2016; Leblanc 2002). From a hydrochemical point of view, groundwater presents stratification: it has a calcium bicarbonate type at a shallow level, but in deeper groundwater, it is sodium carbonate-type water. According to Abderramane et al. (2013), the origin of the different groundwater salinities, with chloride concentration between 0.2 and 9 meq/L, is related to lithology, and also to the mixing of waters from the recharge areas near the Lake and from the basement area of the Massif de Guera to the east. In the piezometric depression, the δO^{18} isotopic composition is − 8‰ and − 0.12‰, with the lowest values in the central part. This process has led to a mixture of water recharged near the lake and in the eastern part, with different isotopic signatures flowing through the aquifer to the central part of the depression (Abderramane et al. 2013).

Materials and methods

For the selected period (2005–2014), two sites with existing lithological logs were considered for the simulation (Figs. 3, 4b). One is located in the central part of the depression (Amdedoua) and one on the eastern boundary of the aquifer and depression (Bokoro). Sedimentary lithology of Bokoro and Amdedoua corresponds to the distal zone and central zone of the Chari-baguirmi sedimentary basin. They represent two different geologic areas with regard to geological composition, texture, structure and hydrological characteristics.

To simulate the hydrologic processes taking place in the entire unsaturated zone, the HYDRUS-1D (Simunek et al. 2015) code was applied for the 2005–2014 time period (3651 days). Simulation of the water balance components for both sites included running the numerical model for bare soil conditions, as well as for *A. tortilis* land cover to assess changes driven by plants.

To obtain a better knowledge of the soil water fluxes process, a last run with no precipitation and bare soil was included by considering the existing setup to provide further information. To estimate the hydrological processes along the soil profile, several control points were set up at different depths of both the available geological logs (Bokoro and Amdedoua, Fig. 4) following code capabilities.

To identify the parameters that have or do not have a significant impact on the model simulation of real-world observations, and to assess the relevance of the uncertainty parameters on recharge (Jiménez-Martínez et al. 2010), a sensitivity analysis was performed.

Modeling the unsaturated zone. Numerical model

For the simulation of the one-dimensional water flow through the vadose zone, the HYDRUS-1D was selected; as presence of desiccation cracks has not been documented double porosity/permeability system was not considered. This well-known numerical model implemented in many different regions allows for water flow, heat and solute calculations in variably saturated porous media. The principles, main features and detailed presentation of the model are given in Simunek et al. (2015).

In the current code, water flow, vapor flow, heat transport and root water absorption are simulated under saturated and unsaturated conditions in a water–soil–plant system based on a gridded soil profile distribution. HYDRUS-1D input includes: geometric data, climatic data (precipitation, potential evapotranspiration), soil hydraulic properties, geological profile (layers setting) and vegetation parameters. The model also allows for up to six observation nodes definition along depth for which the values of the pressure head, water content, temperature and carbon dioxide are calculated and saved at each running time level. Outputs are evapotranspiration from soil and plants, the water flux along the top and bottom boundaries, and the soil water content and soil pressure head in the profile for each time step.

Governing equations

The Darcy–Richards equation is the governing equation for water flow. The Richards equation (Richards 1931) in the one-dimensional mode is

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)\left(\frac{\partial h}{\partial x} + \cos\beta\right)\right] - S \tag{1}$$

where θ is the volumetric soil water content, h is the soil matrix pressure head (L), S is the water uptake by roots (L^3 L^{-3} T^{-1}), $K(\theta)$ is the unsaturated hydraulic conductivity (L T^{-1}) as function of θ, β is the angle between the flow direction and the vertical axis, x is distance (L) and t is time (T). The relationships between saturated and unsaturated hydraulic conductivity are defined by

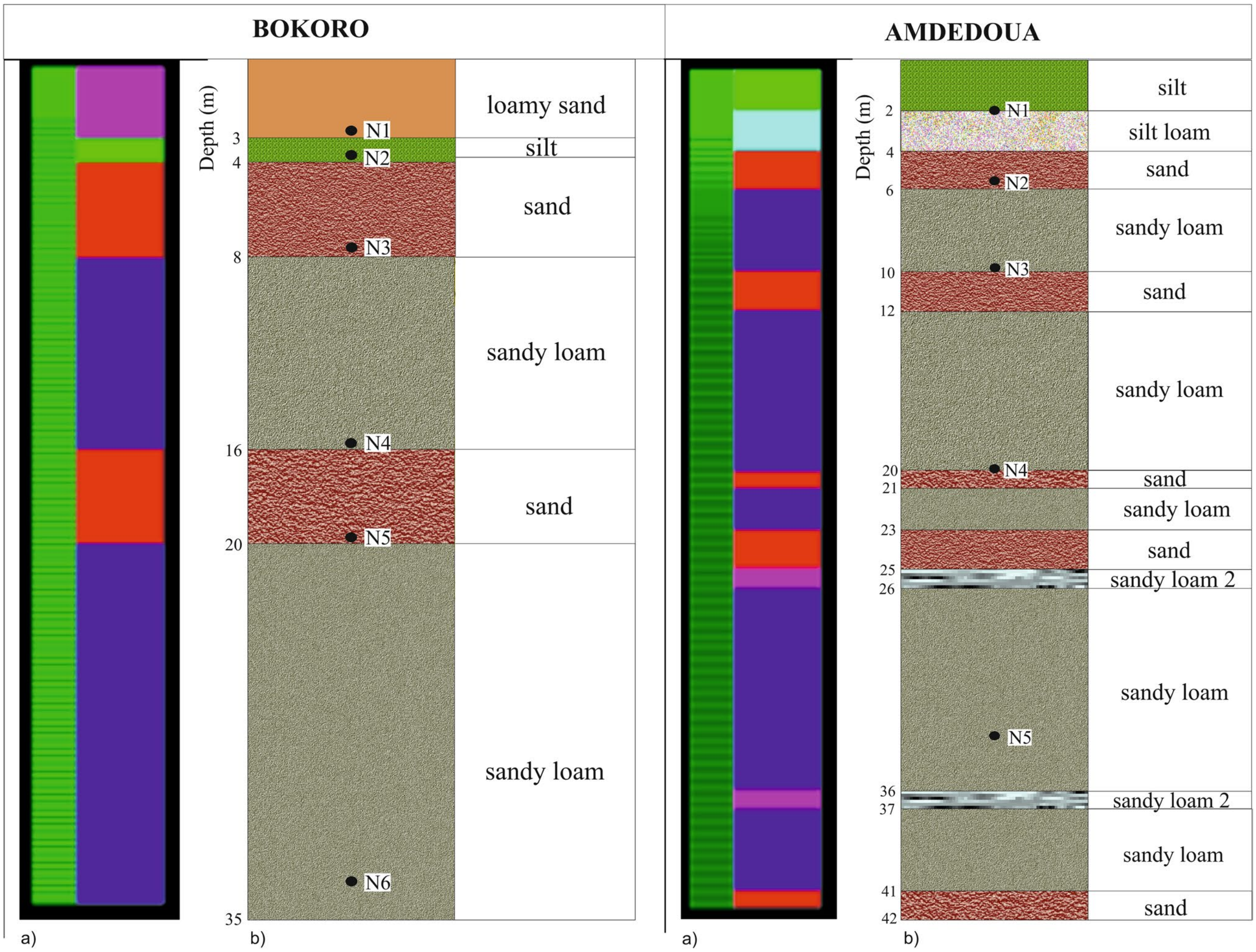

Fig. 4 **a** HYDRUS-1D input. **b** Bokoro and Amdedoua distribution of geologic materials and control points along depth (N1–N5 or N6). The adopted discretization of the geological logs and materials (red, blue, purple, green and turquoise) for HYDRUS-1D input is jointly shown on the left side of the Bokoro and Amdedoua geological logs description. Green column shows the defined nodes and depth used in HYDRUS-1D to discretize soil profile

$$K(h,x) = K_s(x) \bullet K_r(h,x) \tag{2}$$

where K_r is the relative hydraulic conductivity (dimensionless) and K_s is the saturated hydraulic conductivity (L T^{-1}). HYDRUS-1D solves the equation using a linear finite-element pattern.

The equation for unsaturated hydraulic conductivity, based on soil–water retention parameters, is obtained from the soil–hydraulic functions of van Genuchten (1980) and the statistical pore-size distribution model of Mualem (1976):

$$\theta(h) = \left\{ \begin{array}{ll} \theta_r + \frac{\theta_s - \theta_r}{[l+|\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{array} \right\} \tag{3}$$

$$K(h) = K_s S_e^l \left[1 - (1 - S_e^{1/m})^m\right]^2 \tag{4}$$

where

$$m = 1 - \frac{1}{n} \tag{5}$$

and

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{6}$$

where α is the inverse of the air-entry value (or bubbling pressure) (L^{-1}), n is pore-size distribution index of soil (dimensionless), l is pore-connectivity parameter (dimensionless), S_e is effective saturation (dimensionless), and θ_r and θ_s are residual and saturated water content, respectively (dimensionless). Parameters α, n and l are empirical coefficients describing the shape of hydraulic functions.

Climatic data

For the 2005–2014 considered period, daily data of precipitation, wind direction and velocity, relative air humidity, and air minimum and maximum temperature from the existing meteorological stations in the area, were downloaded from the Trans-African Hydro-Meteorological Observatory—TAHMO (Van de Giesen et al. 2014). The existing climatic records from Bokoro ground-based station are used in all the simulations, their accuracy and considering that observations are representative for the simulations in both boreholes.

Evapotranspiration estimation

Daily potential evapotranspiration (PET) is estimated based on the Hargreaves method (Hargraves and Samani 1985), which requires average, minimum, and maximum air temperatures and radiation. Selection was based on its applicability in arid and semi-arid regions and at non-irrigated sites. For vegetated soil with acacias crop plants, the potential evapotranspiration (ET_c) and crop-specific coefficient (K_c) values were independently estimated according to Ringersma and Sikking (2001), Ghebremicael (2003), Descheemaeker et al. (2011), Allen et al. (1998) and Allen and Pereira (2009). Calculation is based on crop coefficients defined for this vegetation type and geographical area (plant development, canopy, leaf area index, surface area cover). For the bare soil scenarios, only actual evaporation estimates are computed, while for vegetated soil with acacias, HYDRUS-1D allows independent estimation of actual evaporation and actual transpiration by plants; calculations are based on water availability in the soil profile.

To assess the effect of plants on the evapotranspiration component along depth for two different climatic conditions (dry, wet), simulations of water processes in the Amdedoua site for a dry and wet representative day of Bokoro meteorological data series were performed. The comparison of the potential water demand by plant and water uptake is done by HYDRUS-1D for computational day 1340, with 23 °C as the maximum temperature during the 2008–2009 wet period, and for computational day 3564 with the maximum temperature of 35.5 °C during the 2013–2014 dry period.

Geological data

The soil profiles and geohydrologic parameters from the geological logs in Bokoro and Amdedoua, gathered from Abderramane (2012), were used to infer all the water processes (flow, vapor) in simulations. According to soil texture and composition, and as shown in Fig. 4b, soil materials consist of loamy sand, sand and silty loam. Soil profile discretization was made according to the distribution of soil layers. The soil profile definition includes definition of observation nodes for Bokoro and Amdedoua at six and five depths, respectively, as depicted in Fig. 4. Selected location corresponds to depth of existing boundaries between permeable and low permeability materials.

Groundwater depth (LCBC–BGR 2010; Abderramane 2012) is around 40 m beneath land surface in the eastern part of the depression (Bokoro), and can be as high as 60 m in the central part of the depression (Amdedoua).

Soil hydraulic parameters and root water uptake

The initial input for the five independent parameters used in the simulation, θ_r, θ_s, α, K_s and n, according to defined types of geological materials at Bokoro and Amdedoua (Fig. 4), were obtained from the textural analysis of the geological samples from the study of Abderramane (2012). The adopted average pore connection parameter l in the hydraulic conductivity function, 0.5, is according to literature a value applied for most soils (Mualem 1976). The selected van Genuchten parameters are found in Table 1.

For root water uptake (RWU), the Feddes model (Feddes et al. 1978) was adopted. This approach is macroscopic and considers the whole root system as a diffuse sink that removes water from soil at each depth layer and at varying rates.

Table 1 Soil hydraulic parameters adopted for different soil textures

Soil type	θ_r	θ_s	α (1/cm)	n	K_s (cm/day)
Sandy loam[a]	0.034/0.065	0.41/0.47	0.0183/0.075	1.266/1.89	60/106
Sand[a]	0.04/0.67	0.41/0.46	0.01246/0.145	1.227/2.68	712.8
Silt	0.034	0.46	0.016	1.37	6
Silt loam	0.067	0.45	0.02	1.41	10.8

θ_s saturated water content, θ_r residual water content, K_s saturated hydraulic conductivity, α inverse of the air entry value, n pore size distribution index

[a]For sandy loam and sand, the two values represent the maximum and minimum values finally adopted in the simulation. K_s value is the average for the Bokoro and Amdedoua sand layer

Table 2 Range of K_s used for the sensitivity analysis

Layers	K_s (cm/day)	+ 10%	− 10%
Sandy loam[a]	60/106.1	66/116.7	54/95.5
Sand[b]	712.8	784.08	641.52
Silt	6	6.6	5.4
Silt loam	10.8	11.88	9.72

[a]As data correspond to both boreholes, two values are provided (Bokoro/Amdedoua)

[b]Average values from both logs

Table 3 Range of n used for the sensitivity analysis

Layers	*n*	+ 10%	− 10%
Sandy loam[a]	1.266/1.89	1.38/2.08	1.13/1.7
Sand[b]	2.68	2.94	2.41
Silt	1,37	1.5	1.23
Silt loam	1.41	1.55	1.26

[a]As data correspond to both boreholes, two values are provided (Bokoro/Amdedoua)

[b]Average values from both logs

The actual root water uptake term, $S(h)$, is expressed as

$$S(h) = \gamma(h)S_p$$

where S_p is the potential root uptake rate ($L^3\ L^{-3}\ T^{-1}$) and γ (h) (dimensionless) is a function of the soil water pressure head ($0 \le \gamma(h) \le 1$). RWU is zero when soil is near to saturation and lower than the wilting point (P3) for pressure head values; this RWU decline is due to a reduction of oxygen availability and unsaturated hydraulic conductivity, respectively. Water uptake is optimal between the pressure heads in which roots extract water (*P*opt) and cannot extract water (P2) at the maximum possible rate. To allow P2 to act as a function of potential transpiration rate, the model uses two additional parameters for the limiting pressure head value (P2H and P2L), which vary according to potential transpiration rates (R2H and R2L).

The *A. tortilis* parameters definition corresponds to a 79-year-old tree, 25 m high, with a distributed root density along a 25-m depth, 25 mm × 1 mm leaf dimension, a leaf area index of 0.5 and a crop specific coefficient (K_c) of 0.95. The adopted parameters are average values from the studies by Canadell et al. (1996), De Boever (2015), and Do et al. (2007): P0 = 0 cm, P3 = − 16,000 cm, Popt = − 400 cm, P2H = − 4000 cm, P2L = − 4000 cm, R2H = 0.5 cm/day, and R2L = 0.1 cm/day.

Initial and boundary conditions

Precipitation, runoff and potential evapotranspiration fluxes constitute the upper boundary condition. A free drainage condition is considered at the bottom of the model domain by considering that groundwater level is deep enough to not interfere with recharge processes in the simulated domain. To achieve the steady-state condition, a 10-year warm-up run was performed; the resulting profile of soil pressure head at the end of the warm-up run is the model initial condition. With this approach, possible impacts on model results by assumed boundary conditions are lessened.

Sensitivity analysis

Computing the effect of parameter uncertainties on recharge and evapotranspiration outputs is obtained by running HYDRUS-1D. For this purpose, simulations are run considering individual model parameters. The analysis is performed by perturbing the original value of hydraulic conductivity (K_s) and the pore size distribution (n) parameters up to ± 10% (Tables 2 and 3). The model is run several times with each changed factor to see how the input parameter affects the estimations. The impact of perturbation on the baseline calculation (simulation with the original values) in the recharge and the actual evapotranspiration is analyzed.

Table 4 Water balance results from 2005 to 2014 (10-year simulated period)

Parameters	Amdedoua bare soil	Amdedoua acacias	Bokoro bare soil	Bokoro acacias
Precipitation (*P*) (mm × 10)	715	715	715	715
Recharge (*I*), (mm × 10)	86	83	152	149
Runoff (*R*), (mm × 10)	78	86	0.08	0.08
Transpiration (*T*), (mm × 10)	0	66	0	107
Evaporation (Ev), (mm × 10)	556	484	644	552
HYDRUS-1D relative water balance error (%)	0.001	0.2	0.002	0.1

Results and discussion

For the simulated 2005–2014 period (10 years), the water budget for the two sites under bare soil and acacias land cover is shown in Table 4, which summarizes the unsaturated zone hydrological system components (precipitation, recharge, runoff, evapotranspiration) and interactions. According to the results, the relative error (%) of water balance for the entire flow domain accounts for values that are much lower than the recommended threshold value (5%, Anderson and Woessner 1992; Giambastiani et al. 2012) for Amdedoua (0.5–0.6%) but is higher for Bokoro located in the distal part of the depression (11–13%).

For the 715 × 10 mm precipitation (corresponding to a mean of 715 mm/year), deep recharge (*I*) occurs at both sites, and is lower at Amdedoua (86 × 10 mm and 83 × 10 mm for bare soil and acacias, respectively) as a result of a thick silty loam layer present at a 2-m depth of the soil surface, which favors runoff (Fig. 4). Bokoro site, at the depression area boundary, presents higher recharge values (152 × 10 mm and 149 × 10 mm for bare and acacias coverage, respectively) than Amdedoua. The infiltration values account for 12% and 21% of the total precipitation for Amdedoua and Bokoro, respectively. For the local hydrological cycle, the influence of Acacia cover on the final recharge values is not significant compared to the bare soil results, as also stated for other regions (Leduc et al. 2001). According to the model with Acacia vegetation, plant roots obtain the infiltrated water at upper layers due to the reduced evaporative demand and the increase of water content in the upper layers of soil. The infiltration rate and changes along time are conditioned by the initial water content, and on the soil texture, structure and layering order of soil profile. Obtained values of recharge (Table 5) are consistent with the recharge results estimated in the MODFLOW modeling of the Quaternary aquifer (WB 2020) ranging between 0 and 4 mm/year for the central and distal zone, respectively, and by Bouchez et al, (2019) based on isotopes with values of 16 ± 27 mm/year for the central part of the depression and 78 ± 7 mm/year for the boundaries of depression.

Table 5 Sensitivity analysis results (Amdedoua bare soil)

	Recharge (cm)	Runoff (cm)	Evaporation (cm)
Baseline	86	78	556
10% increase in K_s	92	70	562
10% decrease in K_s	79	87	552
10% increase in n	65	70	583
10% decrease in n	17	98	598

The runoff calculated by HYDRUS-1D is higher at Amdedoua (70–77 × 10 mm) than at Bokoro (0.08 cm). The very low runoff values at Bokoro versus Amdedoua can be explained by the existence of a slightly permeable layer (3 m of loamy sand) on the topmost soil surface profile, followed by low permeability materials (silt, 1 m) in depth (Fig. 4). When a high precipitation event takes place, water initially infiltrates through the upper permeable layer, remains held in the interface with the beneath less permeable layers until it slowly infiltrates deeper, leading to a temporal perched aquifer.

Potential evapotranspiration (PET), estimated by the Hargreaves method, accounts for 2214 cm for the 10-year study period. This method is recommended by the FAO (Allen et al 1998) instead of Penman–Monteith when insufficient meteorological data are available and for its good performance in arid and semi-arid regions. According to Allen and Stott (2003), however, uncertainty of daily estimates may occur because of changes in temperature, wind speed or cloud cover. Regarding the evapotranspiration results obtained at both sites, potential demands are much higher than total precipitation, which reveals clear plant water stress. Evaporative demand is slightly higher for bare soil and dominates over the transpiration effect by plants in vegetated soil, which is a particular feature of warm areas with sparse vegetation. This can be explained by the fact that reduction of insolation and thus evaporation due to the presence of vegetation has a stronger impact on the hydrological system than the additional transpiration rate of the Acacia woodland. According to Dong et al. (2022), plant transpiration generally takes place for air temperatures above 10 °C, depending on the growing conditions. The obtained actual transpiration of 66/107 mm/year are comparable with results from similar climatic areas such as, e.g., Northern Senegal (Do et al. 2007), e.g., Botswana (Chavarro-Rincon 2009) range from 7 mm/year to about 60 mm/year, following seasonal fluctuations, which are consistent with our obtained values. According to the results, plant water stress is significant, because rainfall is only capable of meeting 25% of the water demand, which will undoubtedly affect vegetation development.

The results of the actual (ETa) and potential (PET) transpiration for a dry and humid days along depth for Amdedoua (center of the depression) are plotted in Fig. 5a, b. Water uptake by *A. tortilis* follows its double root system distribution and root length density, and in this model is limited to a maximum root depth of 25 m. During both seasons, transpiration takes place preferentially at the upper most soil depth (0–5 m), where the root density is highest. For the humid and colder period, transpiration accounts for 4.9 mm (day 1340 of the 2008–2009 period). According to the model results, during the 'dry period' (day 3583 of the 2013–2014 period) values are higher, and total ETa amounts to 24 mm. During

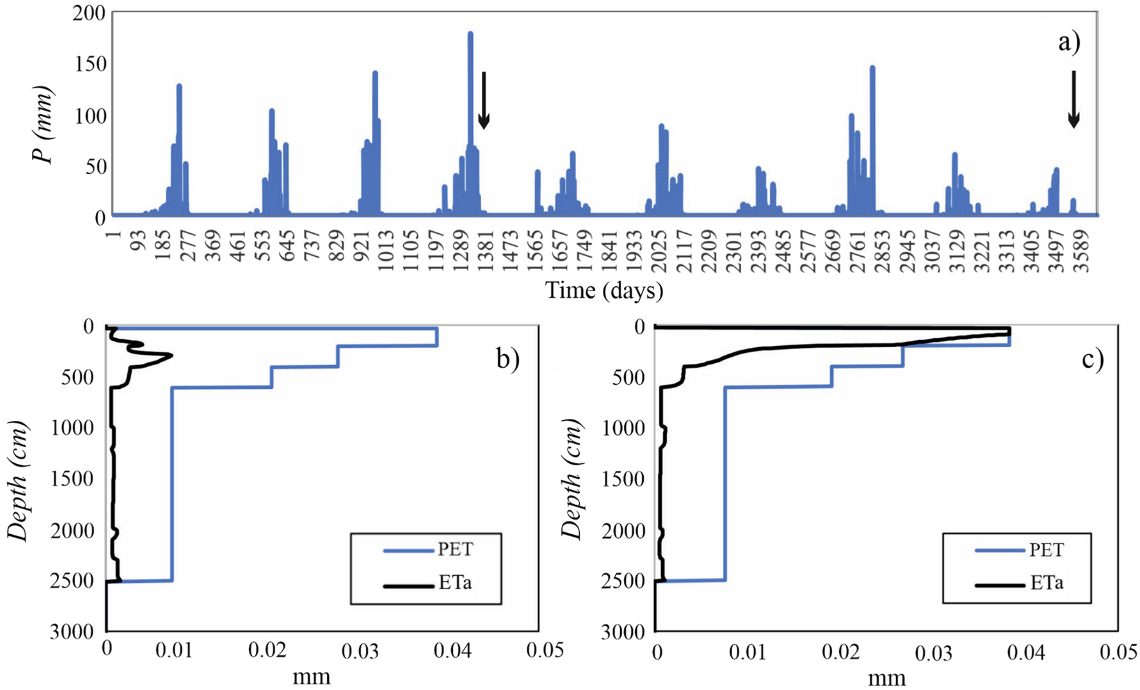

Fig. 5 Amdedoua site. **a** Precipitation *P*; simulation of PET and ETa along depth for **b** day 1340 humid season, total ETa 0.49 mm and **c** day 3583 dry season, total ETa 2.40 mm

the humid season, plant water needs are completely met at some depths, but water stress remains.

Water uptake and hydraulic lift, a wet to dry soil layers water movement through plant roots, generally occurs at nighttime (Richards and Caldwell 1987; Caldwell et al. 1998). Acacia trees can lift up a meaningful volume of water to at least 10 m from the tree base. For *A. tortilis* water uptake by tree roots can happen at depth when the matric potential equals or is higher than − 1.6 MPa (Do et al 2007). Data suggest that when the soil water potential drops below − 5.0 MPa, the hydraulic lift no longer operates (Ludwig et al. 2003). During the dry period, deep taproots (up to 25 m deep, considered selected root length) supply most of the plant water. During the wet period, lateral roots obtain water mainly from the recent precipitation stored in the upper soil layers.

For the prevailing simulated conditions (steady-state) and parameters at Bokoro bare soil, the consequence of a lack of precipitation (simulations not shown here) is an evaporation reduction (upward flux) to about 1–2 mm/year from the upper soil profile. This outcome illustrates the limited effect of evaporative demand on controlling the present groundwater level in the depression. In addition, vapor flux estimation and its contribution to water balance calculations is not significant and does not lead to changes in the final balance. Moreover, according to HYDRUS-1D modeling, the system seems to incorporate atmospheric air humidity amounts in the water balance due to the low soil pressure head. Air humidity is controlled by temperature in HYDRUS simulations.

Figures 6 and 7 plot HYDRUS-1D simulations of water content and downward water flux over time in the bare and vegetated soil at the control points distributed along the soil depth profile for Bokoro and Amdedoua, respectively (left bare, right acacias). At both sites, the flux rates are generally her for vegetated soil, while similar patterns are observed for water flux and water content along depth.

The recharge from the precipitation at Bokoro mainly takes place during intense rainfall periods at the three shallowest layers of the soil profile (Fig. 6, N1–N3), For the deepest layers, from 15 m deep to the lower boundary, the effect of main infiltration pulses is barely observed as high downward water fluxes are buffered by intermediate layers. For Amdedoua (Fig. 7), soil water content changes and the recharge flux occur mainly in the shallowest layers of the soil profile at 2 m from the soil surface. At the N2 monitoring point (Fig. 7, 5.59 m), changes only occur during years with exceptional rainfall events, generally years with a high precipitation. However, no recharge effect is observed from N4 (Fig. 7, 19.5 m) by both simulations. For the deepest layers (N3, N4), the maximum water recharge value is less than 0.1 mm/day (average 0.2 mm/day) response period in N3. However, it is important to note that these results may lie within error limits. The existence of low to moderate hydraulic conductivity layers, interbedded in soil profile and

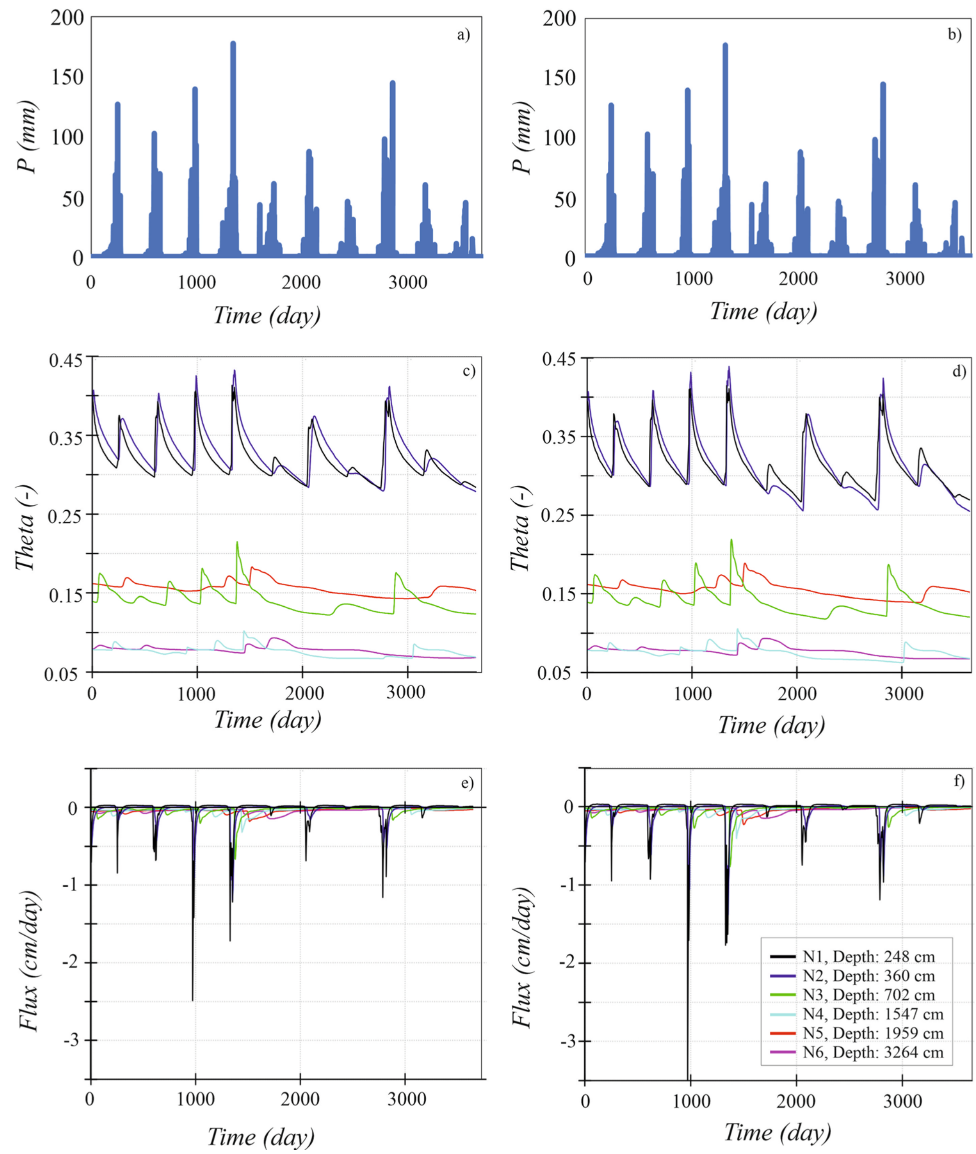

Fig. 6 **a**, **b** Precipitation *P*. Results of water content (**c**, **d**) and downward water flux (**e**, **f**) for the control points at Bokoro (left bare, right acacias); HYDRUS-1D outputs

defined observation points, is the main reason to explain the low recharge rates.

The regional groundwater level is around 40 m below ground surface at Bokoro and more than 50 m deep at Amdedoua, far below the root zone to enable evapotranspiration. Recharge to aquifer from rainfall (12% of precipitation, 83 mm/year, at Amdedoua, Table 4) appears to be very limited according to the results obtained for the water that reaches deep layers. Under the present climatic conditions and the estimated recharge rates, no major changes in groundwater levels of the piezometric depression are anticipated.

Simulation shows that the response to precipitation mainly affects the shallow upper soil layers. Limited aquifer recharge and evaporation from groundwater level in the depression has also been proposed by Abderamane (2012) from groundwater isotopic data and sedimentological research. Low rainfall recharge is also suggested by Leblanc et al. (2003) based on qualitative information from Meteosat thermal data. Similar results were obtained at different arids (Chihuahuan Desert, Texas; Amargosa Desert, Nevada) and semi-arid (High Plains, Texas) sites have been obtained by modeling Cl^- and water potential profiles in the unsaturated zone with HYDRUS-1D by Scanlon et al. (2003). According to Scanlon et al. (2003), infiltration is restricted to the 0.3–3 m depth of soil profile and recharge is lower than 0.1 mm/year. Further simulations of these sites from the pluvial Pleistocene to the dry Holocene past climate conditions (changes from mesic to xeric vegetation) indicate the importance of the upper water flux reduction to create a drying front (and an upward water flux) that propagates more deeply into the profile and reaches the water table after several kyr of drying.

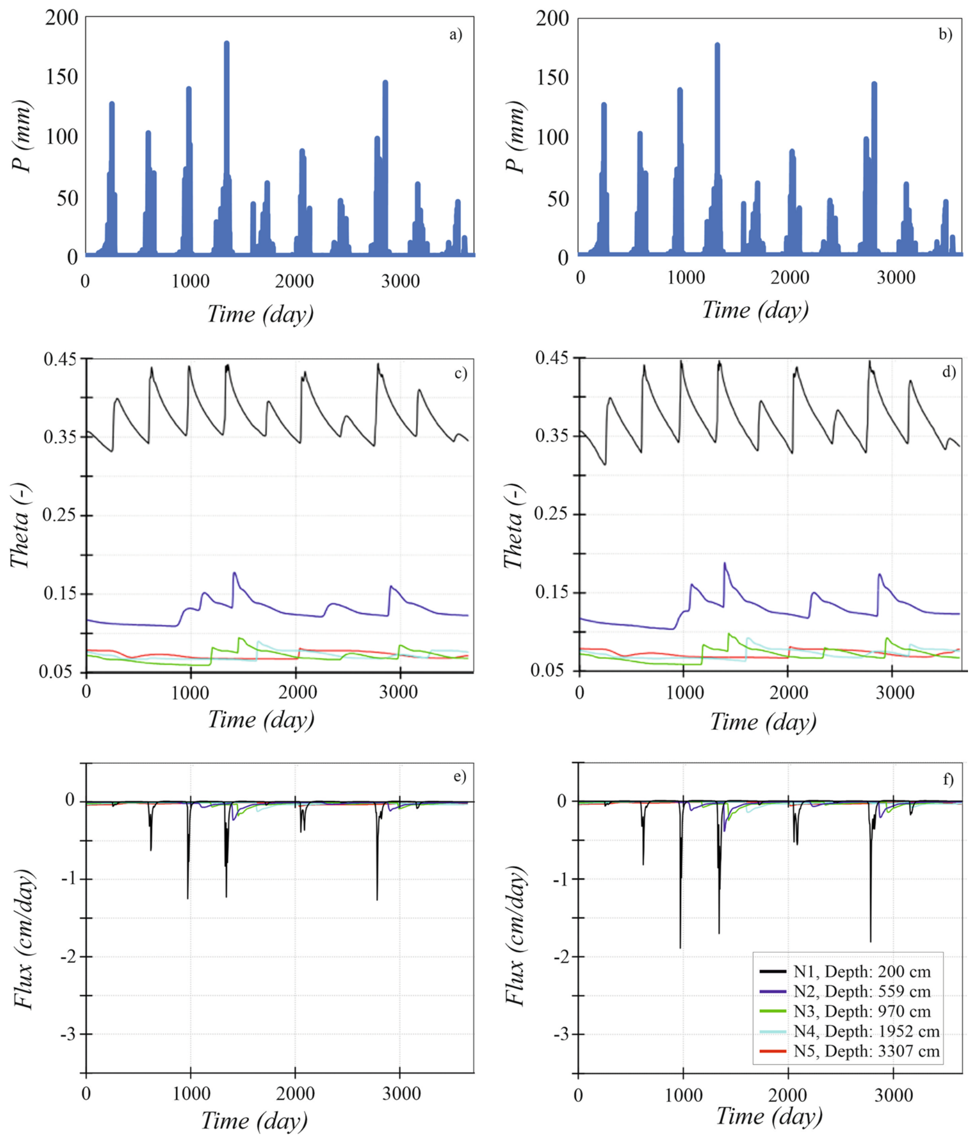

Fig. 7 **a**, **b** Precipitation *P*. Results of water content (**c**, **d**) and downward water flux (**e**, **f**) for the control points at Amdedoua (left bare, right acacias); HYDRUS-1D output

The results are considered satisfactory and consistent with the low natural recharge and unlikelyhood of exfiltration process from the saturated zone that can be expected for this zone. However, as sources of uncertainty from model conceptualization, model parametrization, hydrological components (climate, runoff) and input parameters (hydraulic parameters), exist and besides, external piezometric data are lacking for model calibration and validation, the predicted hydrologic values should only be considered as an indication of current hydrologic process taking place in the area.

Sensitivity analysis results

The sensitivity analysis of the fluxes to a 10% change in the soil hydraulic parameters for both sites (Amdedoua and Bokoro) were carried out; only for Amdedoua bare soil is presented in Table 5 and Fig. 8. For the hydraulic conductivity parameter K_s and n, analysis shows that for the cumulative surface flux (the actual amount of water that infiltrates into the soil or is lost from the soil surface due to evaporation or runoff.) the least sensitivity is linked with K_s, and the greatest sensitivity corresponds to n (porosity). Under unsaturated

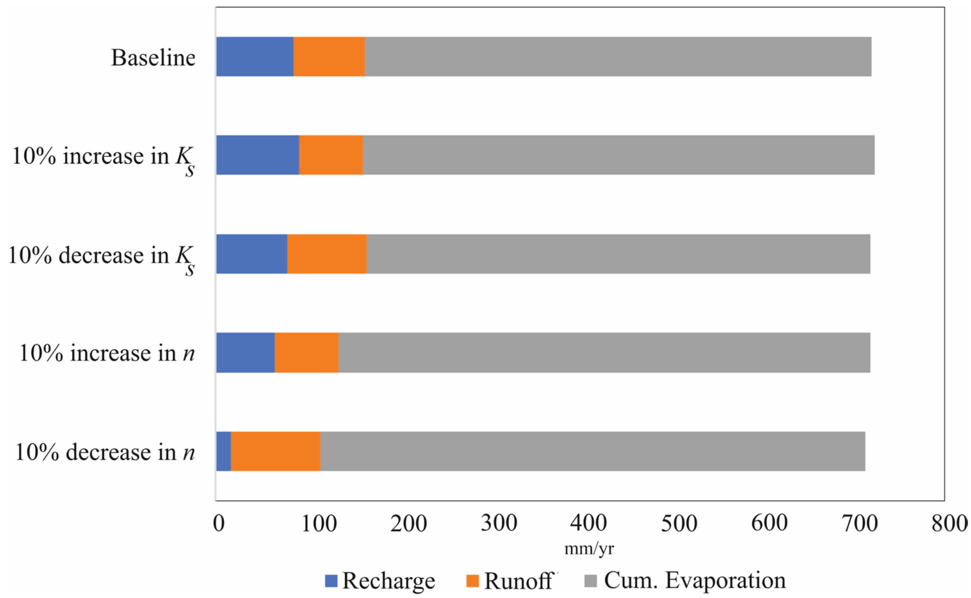

Fig. 8 Sensitivity analysis results of changes in K_s and n in recharge, runoff and evapotranspiration (mm/year). Amdedoua bare soil

conditions, the K_s (saturated soil water permeability) importance for controlling groundwater recharge process (or generally, porous water) is very limited. This is a basic concept from the soil water flow theory in variable-saturated porous media. When unsaturated conditions prevail, the main leading parameters controlling the water flow are related to the soil water retention curve, and hence, the n and α shape parameters, according to the van-Genuchten model to describe the soil, water-head and water-content relationships. These results indicate that the evaporation is the most sensitive to parameter changes (Table 5).

The analysis shows that climatic parameters (mainly precipitation, temperature and evapotranspiration) is the main driving force of soil water fluxes, and soil hydraulic properties are less sensitive. The most sensitive parameter is n. A reduction in n in relation to fine-grained sediments leads to a major decrease in the total water volume held by soil.

Conclusions

Under natural conditions, large piezometric depressions in regard to the regional groundwater level exist in the Lake Chad Basin, including the Chari-Baguirmi in the Chad Formation Aquifer.

Presently, the most accepted explanations for the origin and dynamics of such singularities are high evapotranspiration (exfiltration) combined with low natural recharge. Nevertheless, exfiltration processes or other approaches able to extract groundwater from the system (i.e., evapotranspiration from the saturated zone) are not completely able to naturally explain the current process at Chari Baguirmi when the water level is at more than 40 m below ground surface. Our results show that the given water table depths of 40 m at Bokoro and 50 m at Amdedoua and absolute dry climate (0 mm of precipitation), the evaporation rates are very low (1–2 mm/year from the upper 2 m of soil profile). This implies a negligible contribution to the groundwater depression process. For saturated porous media and bare soil, when groundwater level is greater than 10 m deep generally, the water table is not under direct evapotranspiration (Leblanc 2002). In this research for the area covered by acacia trees and given the water table level, this depth is controlled by a maximum acacia root depth of up to 25 m. The recharge process is very sensitive to parameter n (pore size distribution).

From the present model outcomes, no upward water flux (positive outputs) is observed under the present climate conditions, which highlights the existence of previous climatic setups when the groundwater depression process should have appeared. The soil profile results supports previous hypothesis (Abderamane 2012; Leblanc et al. 2003) by indicating that above the depression at Amdedoua, the rainfall effect is only observed at the upper soil layers, rainfall may accumulate on the soil surface and does not infiltrate deeply into the ground, resulting in a generally low aquifer recharge. From the numerical modeling in the semiarid areas, performed to evaluate the system's response to paleoclimatic fluctuations under transient flow conditions, the effect of the past drying climate over millennia could create an upward flux regime throughout the unsaturated zone that could reach the groundwater level (Scanlon et al. 2003). For the Chad Basin, the timescales of climate dynamics are probably shorter than the necessary time (thousands of years) to reach the steady state, which would condition the subsurface flow and the actual depression pattern. The study of Cl^- concentration profile in soil, supported by spatially distributed experimental research plots for vadose zone monitoring, would provide very useful information to validate the climate change hypothesis and its effect on soil water fluxes.

Finally, although the results suggest the governing role of recharge and evaporation in the depressed area, the development of the current depression is also conditioned by structural constraints according to the sediment deposition sequence. Maintaining the groundwater regional equilibrium also implies that the horizontal flow is very small. Although simulations provide information on the current hydrologic process, the model's outcomes and quantitative values should be carefully considered, because a calibration of the simulated domain is lacking. Quantitative results need to be considered as estimations of simulated hydrologic process; lack of observations, computing issues or intrinsic uncertainties in model development are generally translated to final results.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12665-023-11100-0.

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Author contributions Nafiseh Salehi Siavashani : Data preparation, Investigation Writing – original draft, Preparation. Javier Valdés-Abellán: Data modelling, Writing. Fréderic Do: Conceptualization, Modelling, Joaquín Jiménez-Martínez: Data modelling, Review & editing. F. Javier Elorza: Conceptualization, Modelling, Writing – review & editing. Lucila Candela: Supervision, Conceptualization, Writing – review & editing. Aleix Serrat-Capdevila: Conceptualization, Funding.

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Data availability Not applicable.

Declarations

Conflict of interest Lucila Candela reports financial support was provided by World Bank Group. Aleix Serrat-Capdevila reports a relationship with World Bank Group that includes: employment.

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