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Characterization of groundwater –surface water interactions using high resolution integrated 3D hydrological model in semiarid urban watershed of Niamey, Niger.

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Highlights:

- A methodological framework for integrated hydrological model calibration in a data scarce watershed is described
- The Niger river acts as a natural groundwater discharge zone
- Intense rainfall has significant impact on river aquifer exchange fluxes
- Plant transpiration dominates the water balance.

Keywords: Groundwater –Surface water interactions, calibration, integrated hydrological model, semi arid.

Abstract

This study investigates groundwater-surface water interactions using an equivalent porous medium approach in a data scarce and semi-arid hydrogeological watershed located south-west Niger. A large scale fully-integrated hydrologic model was built and calibrated using HydroGeoSphere with a sequential approach of increasing levels of temporal resolution: 1) steady state average conditions; 2) dynamic equilibrium with repeating monthly normal forcing data; and 3) fully transient conditions. This approach provided a useful and straightforward method for reducing the calibration effort of the large-scale fully-integrated hydrologic model. River-aquifer exchange flux dynamics, water balance components for different land use classes, as well as basin average groundwater recharge were computed from the model. Simulation results show that exchange flux between groundwater and surface water are important processes in the basin, with the Niger River acting primarily as a gaining stream, with local losing zones. Ephemeral streams constitute important focused groundwater recharge areas, while ponds exhibit either groundwater discharge behavior, or a recharge zone profile depending on local topography. The basin average water balance highlights the importance of plant transpiration (58 % of total rainfall) over surface evaporation (8%), with groundwater recharge of up to 5% of total rainfall. Overland flow and infiltration account for 11% and 16 % of the total annual rainfall respectively, and groundwater discharge to the river is 2% of the total rainfall

Introduction

The Niger River watershed covers approximately 7% of the surface area of Africa and is the major source of agriculture related socio-economic activities for more than 100 million people across nine countries (Benin, Burkina Faso, Cameroon, Chad, Côte d'Ivoire, Guinea, Mali, Niger and Nigeria). The Niamey watershed considered in this study has an area of approximately 1900 km² and is centrally located within the Niger River basin (Figure 1a and Figures 1b). Furthermore, the Niger River is of crucial importance in the Niamey watershed, as it constitutes the only permanent source of agricultural and domestic water needs.

It has been extensively reported that agro-pastoral production in the region is heavily affected by the interannual variability of rainfall over different spatio-temporal scales (Tarhule and Lamb 2003; Lebel et al., 1997; Lebel and Ali2009; Dai et al., 2004; Mahé et al., 2009). The natural variability associated with several rainfall indices between 1940 and 2010 reflect a high level of population vulnerability with 85% of activities linked to rain fed agriculture. This vulnerability is enhanced by rapid population growth resulting in increasing water demand.

To date studies have focused on rainfall variability, the Niger River flows rainfall characteristics and climate change, groundwater recharge and quality(Anderson et al., 2017; Leduc et al., 2001; Favreau et al., 2009; Girard, 1993; Williams, 1993, Ibrahim et al., 2014;Hassane et al., 2017; Mascaro et al., 2015).However, presently no studies exist for the Niger River Basin (or sub-basins) which explicitly consider the dynamics of groundwater and surface water interaction in a fully-integrated manner.

Sustainable river basin management is one of the most prudent adaptation strategies to climate variability and change, and to respond to increasing demand for agricultural and resource development water in the Niger River basin. Providing scientifically-based management policy to water resources managers requires properly addressing the hydrological risks from natural and anthropogenic stresses on water resources and should rely on integrated management at watershed scale (Berg and Sudicky, 2019). Therefore, delivering information on hydrologic system responses to increasing extreme events (floods, drought) frequency in the watershed requires the understanding of integrated hydrological processes at the large watershed scale. The challenges of scarce data, complex surface-subsurface interactions, as well as the high computational demand associated with integrated models is probably one reason why relatively few publications on the application of fully integrated models at the large scale exist in the literature (Barthel and Banzhaf ,2016). Although, it is widely acknowledged that integrated surface-subsurface models are useful for water resources managers, the application of these models would also be useful in order to support resources development and sustainable water management in the Niger River basin. In the Niamey watershed, most of the water for Niamey city and surrounding villages is supplied by treated water from the Niger River, which is the only permanent river in the basin. The main tributaries of the Niger River in Niamey are ephemeral streams, called koris. The groundwater in the Continental Terminal sandstone formation, and the fractured aquifers of the Precambrian basement, cover the remaining water demand of the watershed. Studies carried out in the watershed have shown that groundwater recharge in the Continental Terminal aquifer is predominantly governed by depression focused recharge (Desconnets et al.,1997; Favreau et al., 2012,) through ponds, with less contribution from diffuse recharge (Ibrahim et al.,2014) depending on land use types. Girard et al, (1997) has shown that the main recharge process in fractured aquifers is controlled by the fracture system. The aforementioned existing studies either investigated recharge using traditional water level fluctuation methods combined with hydrochemicals and isotopes approaches, or groundwater models with loosely coupled or simple representation of surface water, and vice versa.

Because the application of fully integrated hydrological models to large scale watersheds is a growing area of the literature, only a few manuscripts have been published that provide methodologies or guidance on the application of large scale integrated groundwater surface water models (i.e., Erler et al., 2019; Bartheland Banzhaf , 2016, Hwanget al.,2018; Hwang et al.,2015; Chen et al.). Additionally, to the author's knowledge, fully coupled surface-subsurface models have not yet been applied for the whole of the Niger River basin or its sub-basins. Moreover, none of the previous studies quantified directly the relation between Niger River and the underlying aquifer systems.

Therefore, for resilient water resources management in the context of increasing demand (irrigation and livestock, demography), along with variability and climate change, characterization of the interactions between the Niger River drainage system, and underlying aquifers is necessary. Furthermore, understanding and quantifying the interactions between the river drainage system and aquifers is very important for alleviating the impact of recurrent extreme events as it can provide valuable guidance for water resources management policies in the watershed. For instance, determining flux exchange direction and magnitude between the river and underlying aquifers can help support minimum environmental flows of the river or buffer flood events (loosing river). The groundwater table may also act as a flood amplifier in case the river or part of its reach is gaining. Understanding the groundwater surface water interaction will also provide useful information for groundwater management purposes. Characterization of this type of groundwater surface water interactions is very complex in general, and particularly challenging in data scarce and semi-arid watersheds.

The first objective of this paper is to provide methodological guidance in the development of watershed scale integrated surface-subsurface models in data scarce and semi-arid environments. The second objective is to determine the magnitude and direction of the exchange of water between the surface water system and complex groundwater aquifer systems. The third objective is to provide practical information to water managers on the water balance components considering different land use types, groundwater systems, as well as surface water bodies.

2. Data and Methods

2.1Study area

The study area corresponds to the Niamey watershed located south west of Niger (Figure 1b) and the hydrogeological watershed considered in this study covers 1900 km². It is a semi urban watershed with a population of 1.3 million. The rainfall patterns are characteristic of the semi-arid climate with a dry season from October to May, and a rainy season from June to September. Precipitation is dominated by heavy rainfall events with low frequency, typical of the West African summer monsoon rainfall. The mean annual rainfallfrom1947 to 2007 is 560 mm, and the mean annual Penman Monteith potential evapotranspiration is 2500 mm with an average temperature of 29°C.

Recent land use maps (CILSS, 2016) indicate that agricultural land covers 11 % of the watershed, natural vegetation of Sahelian savanna and steppe cover 32% and bare and sandy soil cover 45% of the watershed. The main city and surrounding village occupy approximately 8 %, and water bodies cover the remaining are 4 %.

2.1.1. Geology and Hydrology of Niamey watershed

According to its geographical position, the Niamey watershed is located on the western edge of the Paleoproterozoic basement of the Liptako, and on the southeastern part of the

Iullemmeden sedimentary basin. The Niamey watershed terrains consist of two main geological units, including:

- The Paleoproterozoic basement (2300-2000 Ma ((Soumaila et Konaté, 2005), which outcrops to the west of the study area at the vicinity of the Niger River. It includes granitoid plutons alternating with Greenstone belts. Granitoids consist of diorite intrusions, quartz diorite to tonalite, monzonite, granodiorite and granite or syenite locally. These intrusive bodies are either syn-tectonic or post-tectonic (Machens, 1973; Soumaila et Konaté, 2005: Perotti et al., 2016). The greenstone beltsconsist of sandstones-pelitic rocks more or less metamorphosed (shales, sericite schists, micaceous schists, quartzitic schists) and low to medium metamorphic greenstone (amphibolite, chloritoschists, metabasalts, metagabbros) (Machens, 1973; Soumaila et Konaté, 2005; Perotti et al., 2016).
- The sedimentary deposits overlie unconformably thePaleoproterozoic basement. The lowermost depositsare represented by an older unit essentially consisting of Upper Precambrian sediments (Niamey sandstone) (Machens, 1973) and the uppermost deposits consist of the clayish to silty sandstones of the Oligocene Continental Terminal 3 formation (CT3) (Chardon et al., 2018) and quaternary to recent deposits that infill the ephemeral streams and the Niger River.

The hydrogeology of the watershed is characterized by the geological conditions, with two types of aquifers. The fractured aquifers of the Liptako basement formations are found in both the granitic and Greenstone belts formations, and the Continental Terminal, CT3 aquifer (Figure 2a). Depth to groundwater table varies from 5 m in the fractured aquifers, to 50 m in the CT3 aquifer.

The hydrological conditions of the watershed are quite complex. The only permanent freshwater source is the Niger River, and its flow is generated from the upper Niger basin in the Fouta Djallon Massif in Guinea. In the study area, the Niger River flow has two peaks, one peak due to the contribution of the local rainy season in September and the other in December due to the inflow from upstream (Andersenet al., 2005). The others hydrological features are the endorheic ephemeral stream, called koris that are hydrologically active during the rainy season, and surface runoff discharge into a mosaic of permanent and semi permanents ponds where groundwater recharge is shown to occur (Massuel et al. 2011). The strong spatial variability of the ephemeral stream and the ponds drainage area is critical to the determination of watershed area, due to the general endorheic configuration of the landscape .Therefore, to summarize the complex hydrological setting, the Niger River flow is driven by the inflow coming from upstream, and the local precipitation that drives ephemeral stream and ponds.

2.2. Data set

2.2.1 Geological data

A 3D geological model of the watershed is built (Figure 2b) using Machens' (1973) geological map and more than 120 borehole logs documented by Bernertet al.(1985) and Dehays et al.(1986). The construction of the 3D geological model of the study area involves the lithological interpretation of the individual 120 borehole logs to create 2D surface maps of model layers. The interpolation was performed using the inverse distance weighting method. Based on different lithological elevations of the boreholes, a grid model and contour map of geological layers were built. Then, from the grid model and contour map of the different geological layers, a 3D geological model was constructed, as defined in the HGS grok command file.

The inverse-distance method represents one of the more common gridding methods. In this method, the value assigned to a grid node (cell value) is a weighted average of either all of the data points or a number of directionally distributed neighbors. In this case, the cell values represent the absolute elevation of the interfaces between lithological formations, which have been derived from the boreholes.

The fractured aquifer is characterized by three different units: The granitic formations are intrusive into the birrimian greenstone belt formation. However, this geological configuration was simplified in the 3D geological model by considering the granitic aquifer at the bottom of the model and the greenstones belts formations aquifer at the top of the granitic layer. The third aquifer is composed of weathered formations, consisting up to the undifferentiated weathering horizons of both granite and schist formations.

Six geological units are included in the geological model; from bottom (oldest) to top (youngest): the granitic formation of the Precambrian basement, the birrimian Greenstone belts formations, the undifferentiated weathering zone of basement formations, and the

Continental Terminal CT3 formations. The CT3 formation is subdivided in its three geological facies of clay, clayish sandstones, and silty sand. Hydraulic conductivities and specific storage values for each geological unit are derived from literature. Initial estimates of hydraulic conductivities for the fractured aquifers are taken from Domenico and Schwartz (1990), while CT3 hydraulic conductivity was from (Favreau 2000). Manual parameter estimation is performed during the calibration process and this is the first estimation of hydraulic conductivities and Van Genuchten parameters of the fractured aquifer at regional scale (Table 2).

2.2.2. Soil and Land Use data

Soil data used in this study are derived from Graef et al., (1998), who used soil types, geomorphologic and hydrological criteria to extensively map the soil and terrain in south west Niger, and provide a complete Soil and Terrain Digital Database(SOTER). The study area is discretized in 41 soil zones derived from the SOTER database. Unsaturated soil zone *K* values, porosity and Van Genuchten (1980) soil hydraulics parameters for the 41 SORTER based soil zones are estimated by grain-size derived estimates using the ROSETTA neural network prediction method (Schaap et al. 2001). Pressure saturation curves for the 41 soil zones were derived from the Van Genuchten soil hydraulic parameters.

2013 land use map (CILSS, 2016) at 2km resolution was reclassified at 30m resolution into six different classes consisting of Sahelian short grass savanna, steppe, agriculture, water bodies, rocky and sandy land, and settlements. Leaf Area Index for the agriculture land use class was determined from Levy and Jarvis (1999), and for the natural vegetation from Iio and Ito (2014).

2.2.3 Hydroclimate forcing data

Hourly climate data for rainfall, maximum and minimum temperatures (Tmax, Tmin), wind speed, relative humidity and solar radiation from 2011 to 2017 were obtained from an automatic weather station installed at the Agriculture Hydrologie et Meteorologie (AGRHYMET) Regional Center. Daily Penman-Monteith potential evapotranspiration was computed using aggregated hourly data from the above weather station.

Stream flow gauging stations of Kandadji and Niamey were used in the model along the Niger River part of the modeled watershed. Kandadji gauge represents the closest upstream gauging location and is used to define inflow to the upstream end of the model domain. The gauging station (Fig 1b) located in the middle of the watershed is used to calibrate the integrated hydrological model. Daily time series for both gauging locations were obtained from the Niger Basin Authority (NBA) database.

A total of 24 observation wells were selected to calibrate the models for hydraulic heads based on the availability and aquifer types screened. 8 observation wells out of the 24 are piezometers equipped with automatic pressure recorder and are installed in the fractured aquifer and groundwater heads were recorded hourly from 2014 to 2017. The rest of observation wells are open wells with large diameter (1m), and/or boreholes pumped mostly to supply water for domestic use, whose pumping rate is as small as $1m^3$/day (Hassane, 2016). Hydraulic head data for all the observation wells was provided by the Direction Régional de l'Hydraulique et de l'Assainissement de Niamey and the NBA.

2.3. Hydrological Model

A 3D fully-integrated surface and subsurface hydrologic model, HydroGeoSphere (HGS) (Aquanty Inc, 2017) was used to calculate overland flow, variably-saturated groundwater flow, flux exchange between the Niger river, ephemeral stream, ponds and the aquifer system (i.e., CT3 and the fractured aquifer). Also water balance components such as groundwater infiltration/exfiltration and evapotranspiration for various land use types were computed. HGS uses control-volume finite element/difference method to implicitly solve a modified form of Richards' equation for 3D variably-saturated subsurface flow and a depth-integrated Saint Venant diffusion wave equation for 2D surface water flow in a parallelized manner (Hwang et al., 2014) as described in Equation (1).

$$\nabla \cdot (k_r \mathbf{K} \nabla h) \pm Q + \Gamma = \frac{\partial}{\partial t}(\theta_s S_w) \qquad (1)$$

where k_r is the relative permeability, representing the water saturation function S_w or the pressure head ψ, $\mathbf{K}$ is the hydraulic conductivity tensor, h corresponds to the total head provided by ψ+z where z is the elevation, θ_s is the saturated water content. Q corresponds to the volumetric flow rate per unit volume representing a source or sink, and Γ is the exchange flux between the surface and subsurface domains.

The depth-integrated surface flow equation adopted in HGS involves the 2D diffusion-wave approximation:

$$\nabla \cdot (d_o \mathbf{K}_o \nabla h_o) \pm Q_o + \Gamma_o = \frac{\partial h_o}{\partial t} \qquad (2)$$

where d_o is the depth of flow, h_o is the water surface elevation ($= d_0 + z$), and $\mathbf{K_o}$ is the surface conductances that is function of the friction slope of the surface and is determined by the Manning's equation in the x- and y- directions as

$$K_{ox} = \frac{d_o^{2/3}}{n_x}\frac{1}{[\partial h_o/\partial s]^{1/2}};\ K_{oy} = \frac{d_o^{2/3}}{n_y}\frac{1}{[\partial h_o/\partial s]^{1/2}} \quad (3)$$

where n_x and n_y are the Manning's roughness coefficients and s is the direction of maximum surface-water slope. The surface conductances K_{ox} and K_{oy} are complex functions of the dependent variables d_0 or h_0 ($= d_0 + z$), and the relationships make Equation (2) nonlinear.

The surface and subsurface flow equations are coupled with a third type flux equation as follows:

2.3.1 Flux exchange and Evapotranspiration equations

The individual surface and subsurface flow equations can be coupled by assuming that the two flow regimes are separated by a thin boundary layer. Thus, Γ_o represents a first-order exchange flux between the subsurface and surface domains as follows:

$$\Gamma_o = (k_r)_{exch} K_{exch} (h - h_o)/l_{exch} \quad (4)$$

where $(k_r)_{exch}$ is the relative permeability for fluid exchange, K_{exch} is the surface/subsurface conductance, and l_{exch} is the thickness of the interface layer between surface and subsurface domains. In Equation (4), a positive Γ_0 indicates water mass movement from the subsurface to the surface domain and vice versa for negative fluxes.

In this study, the actual evapotranspiration (AET) is computed following the approach suggested by Kristensen and Jensen(1975). Detailed information on the approach can be found in the HGS documentation (Aquanty Inc, 2017).

2.3.2 Groundwater recharge

The definition of groundwater recharge considered is the same approach followed by Erler et al.(2018); wherein groundwater recharge is derived from the HGS output of exchange flux between surface and subsurface domains as described in equations 5 and 6.

Equation 5 describes the groundwater recharge for a terrestrial landscape where there is no standing surface water (i.e., ponds, river, and spring).

$$R = \Gamma_o - (Ss_e + Ss_t) \qquad (5)$$

Where R is the groundwater recharge, Γ_o corresponds to the HGS exchange flux between surface and subsurface, and Ss_e and Ss_t are respectively the subsurface evaporation and subsurface transpiration.

With standing surface water such as river or ponds, groundwater recharge corresponds to the HGS exchange flux term (Equation 6).

$$R = \Gamma_o \quad (6)$$

Since the exchange flux term is calculated after surface evaporation, and when standing water is present, no subsurface evapotranspiration occurs, groundwater recharge equals exchange flux where standing water (i.e., ponds) are present.

2.4 Conceptual Model and Discretization

The modelled study area covers both the sandstone CT3 aquifer, and the fractured Precambrian basement aquifers. An equivalent porous medium (EPM) approach is considered to represent the fractured aquifer unit in the integrated model. The first motivation in applying an EPM approach is the complexity of the fractured distribution in the study area. The data required to simulate flow in the fractured aquifer (vertical fracture distribution, spacing, and aperture) are not available, and even with these data; the spatial heterogeneity is variable and may not be well represented at the watershed scale. Since this study only focuses on water quantity, we believe that an effective representation of the fracture aquifer unit with the EPM approach is appropriate.

The second reason for applying an EPM approach is that, while HGS is able to simulate flow in discrete fractures, it solves the Brooks-Corey (1964) equation for both porous medium and discrete fractures in the unsaturated flow domain. The conceptual geological model (Figure2a) is composed of four hydrogeological units. The CT3 unit is represented at the top of the conceptual model and considered to be in hydraulic connection with the alluvial aquifer. As stated in section 2.2, the CT3 is conceptually represented by three different geological facies of clay, clayish sandstones, and silty sand. The fractured aquifer is characterized by three different units: The granitic formations are intrusive into the birrimian schist formation (Figure 2a). However, this geological configuration is simplified in the model (Figure 2b) by considering the granitic aquifer at the bottom of the model and the schists aquifer at the top of the granitic layer. The third aquifer is composed of the weathered formation, consisting to the undifferentiated weathering horizons of both granites and schist formations.

2.4.1 Boundary conditions

The modeled domain corresponds to Niamey watershed as delineated by the hydrogeological watershed of the city and its surrounding villages. No flow boundary conditions were assigned to all outer subsurface model domain boundaries, and groundwater flow divides are assumed to correspond to the hydrological watershed limits. Four additional boundary conditions types were applied to the top surface of the model domain: precipitation, potential evapotranspiration (PET), critical depth and surface water flux. Precipitation and PET were assigned to the top of the model as hydroclimate forcing variables. A critical depth boundary condition was applied at the outer edge boundary of the model to let surface water flow out of the model domain. The critical-depth boundary condition is implemented to simulate conditions at the lower boundaries of a hill slope. This boundary condition forces the water elevation at the boundary to be equal to the water elevation for which the energy of the flowing water relatively to the stream bottom is minimum (Hornberger et al., 1998; Therrien et al., 2005; Aquanty, 2018). A surface water flux boundary condition was assigned at the most northern point to represent the Niger River inflow coming from upstream which was not generated in the modeled hydrogeological watershed. We acknowledge that the flow at the surface water flux boundary condition is affected by the precipitation between the Kandadji gauging station and the inlet of the model. However, we herein assume that this amount of precipitation is negligible compared to the flow of the River, as Niger River flow at Niamey is more influenced by the Guinean rainfall regime (1400mm/year) than Sahelian rainfall (400 mm/year) as previously shown by Amogu et al, (2010) . We therefore assumed that the flow at the Kandadji station could reasonably represent the flow at the inlet of the model as the area between Kandadji and the inlet of the watershed still under Sahelian rainfall regime.

2.4.2. Model Discretization

The surface domain of the model was discretized into triangular mesh elements with a resolution ranging from 300 m on average to 70 m near surface flow features. The subsurface model consists of triangular prism-shaped elements which are each defined by 6 nodes.The model has eleven layers with a total of 516,901 nodes, and 927,030 elements. In order to represent the surface water-groundwater exchange and evapotranspiration processes more accurately near the top surface, the first three meters were discretized vertically into five layers at 0.1, 0.15, 0.25, 0.5 and 1.5 meters resolution. The interpolated geological materials from the boreholes were used for the remaining six lowest bedrock layers. The digital elevation model (DEM) of 30 m x 30 m was used to assign elevations to the top most 2D layer. The DEM was hydrologically corrected to avoid artificial lakes along stream channels by modifying nodal elevations to decrease from upstream to downstream.

2.5. Calibration Approach

The calibration procedure adopted in this study is done in three steps (Figure 3).

<u>Step 1: Steady State Calibration</u>

The steady state calibration involved forcing the model with a 30 year (1980-2005) long-term average net precipitation and potential evapotranspiration. The net precipitation was calculated based on the increase in average stream flow across the study area (Equation 7):

$$P_{net} = (Q_{in} - Q_{out}) / A \quad (7)$$

where P_{net} is the net precipitation, Q_{in} corresponds to the river inflow, and Q_{out} is the surface water outflow, at the outer edge of the basin and A represents the surface area the watershed between the Kandadji and Niamey stations. The detailed equations of net precipitation calculation in integrated hydrological models are provided in Hwang et al., (2014). This approach enables also to take into consideration the inflow part of the river hydrograph that is not generated due to local precipitation, and also to better represent the river aquifer interaction at the early stage of the model calibration.

<u>Step 2: Dynamic Equilibrium</u>

The second model calibration step is intermediate between steady state and daily transient simulations referred here as dynamic equilibrium. It consists of forcing the model with monthly normal precipitation and PET and while using steady state results as initial conditions. Essentially, the long-term hydro climate forcing data (1980-2005) used to force the model are aggregated into one synthetic year of twelve months, representing the average seasonal cycle. The monthly normal forcing data are considered to represent the long-term average seasonal cycle. This forcing data is repeatedly applied to the model until dynamic equilibrium is achieved. Dynamic equilibrium is determined to have been reached when no significant variations of the river and groundwater hydrographs are observed from year to year. This approach has the advantage of training the model from theoretical steady state to a more naturally occurring transient conditions represented by the monthly normal forcing. It is particularly important for the dry climate conditions, where monsoonal intermittent precipitations are driving the hydrological cycle and will allow for providing reasonable initial conditions to the daily transient simulations. The dynamic equilibrium is considered here to be a transitional state much closer to natural equilibrium than a traditional steady state conditions (Erler et al., 2018).

The model state at the end of the dynamic equilibrium is then used as an initial condition for the daily transient simulations. The daily transient is run for the period of 2011-2017 where continuous groundwater observation data are available. Manual calibration was performed by trial and error until a satisfactory match was achieved between simulated and observed groundwater heads and surface water flow rates.

<u>Step 3: Daily Transient Calibration</u>

The initial conditions at the end of the dynamic equilibrium are then used to force the model for the daily transient simulations. The daily transient is run for the period of 2011-2017 where continuous groundwater observation data are available. Manual calibration was performed until a satisfactory match was found between simulated and observed groundwater head, and surface water flow rate.

The Hydrologic parameters used for the simulation at the steady state (step1) are provided in Table 1. Calibration at the dynamic equilibrium and transient simulations steps further show that model is only sensitive to the parameters provided in the Tables 2 and 3. Therefore, the calibration at dynamic equilibrium and transients conditions was performed by manually adjusting the sensitive parameters (Tables 2 and 3) to both groundwater and surface water flow rates, representing the objective function.

Also, during the model calibration, we have first used the average long term precipitation and observed PET at Niamey climate station (shown in Figure 1), but the resulting hydrologic regime was too dry. This is because, the intermittency of precipitation is lost, and average PET will always be grater that precipitation and the system will dry completely. The equation 7 represents a methodological approach of spinning up model at the early stages of calibration in such a dry (Sahelian) rainfall regime.

3. Results and Discussion

3.1 Parameter estimation

3.1.1 Hydraulic conductivity and Van Genuchten parameters

Calibrated hydraulic conductivity (*K*) values, residual water saturation and van Genuchten parameters for the different hydrogeological units are shown in Table 2. The CT3 aquifer, which is pinching out over the basement aquifer, has a calibrated hydraulic conductivity of 1.12 $x10^{-5}$ m/s. This value agrees well with the calibrated value from Favreau (1996) for the CT3 aquifer at the Wankama site. No previous studies have estimated the *K* of the Precambrian basement aquifers. Calibrated *K* values (Table 2) for the Precambrian basement aquifers are generally within the literature reported range (Domenico and Schwartz, 1990). The calibrated *K* of the granitic aquifer is one order magnitude greater than the calibrated value for the schist aquifer (Table 2). The calibration process also revealed a structural control on the *K* values for different hydrogeological units. The calibration process further showed a kind of geologic and or structural control on the hydraulic conductivities values for different hydrogeological units. Although this control depends on very localized geologically phenomenon (fracture density, weathering process), the granitic aquifer, when altered mechanically and or fractured, has a higher *K* than the schist aquifer, of which the alteration products are generally composed of clayey materials, and are less likely to fracture.

3.1.2 Evapotranspiration and overland flow parameters

Calibrated actual evapotranspiration and overland flow parameters are presented in Table 3, for each land use type. Maximum Leaf Area Index values range from 0.01 for urban area, to 1.25 for Savanna, with Agriculture and Steppe having the same maximum LAI values of 1.2. Root depth values for Savanna (4.5 m) are three times more than for agriculture (1.5m), with steppe having a root depth value of 1 m. Root depth of urban and bare soil land use are respectively of 0.1, and 0.01 meters. The calibrated root depth values of savanna and agricultural land are in good agreement with values presented in Ibrahim et al. (2014). Calibrated Manning friction coefficients for overland flow range between 0.016 to 0.43 (s. $m^{-1/3}$) for different land use types, and coupling length values range from 0.01 to 0.1 m (Table 3).

3.2. Comparison of simulated and observed hydraulics heads and surface water flow rates

Long term steady state calibrated groundwater heads for 25 observations wells are plotted against available long term measured groundwater heads for both the CT and Fractured aquifer (Figure 4 a). The long term average period considered is 1980-2005, and simulated groundwater heads reasonably approach the observed head with an R^2 value of 0.82. The level of agreement between groundwater heads for the fractured aquifer is higher than for the CT, because a higher weighting was placed on the fractured aquifer calibration performance as it has more reliable long term groundwater heads measurements. The steady state calibration is the first step of the calibration approach followed by the dynamic equilibrium calibration, for groundwater heads (Figure4b) and surface water flow rates (Figure 4c). The simulated seasonal cycle of groundwater heads (Figure4b) at Kossey Djerma observation well after 15 years of monthly normal simulations follows the measured groundwater heads reasonably well, but with a time lag bias in the simulated hydraulic heads. Calibration further showed that groundwater wells located near the river reached the dynamic equilibrium more rapidly, within 10 years simulation, more than 10 years was required for wells that are further from the river. Also, surface water flow was found to stabilize in less than 2 years of simulation, similar to the findings of Goderniaux et al. (2009). The calibration of monthly normal groundwater levels show good agreement with observed groundwater levels for both mean values and seasonal amplitude, however, a time lag bias is present in the simulated heads which is suspected to be a result of the EPM conceptualization of the fractured rock aquifer. The time lag bias between the simulated and observed groundwater levels for the Dynamic Equilibrium calibration step were not rigorously addressed to avoid overfitting, and to maintain calibrated values within physically reasonable ranges. The simulated seasonal cycle of surface water flow rates at Niamey station are in good agreement with observations (Figure4c), with both river peaks during the local rainy season and of the inflow from upstream well captured by the model with a slightly positive bias during the peak of September. In fact calibrating integrated hydrological models with both surface water flow rate and groundwater wells is not a very common practice (Goderniauxet al., 2009; Jones, 2005; Li et al., 2008; Sudickyet al., 2008) in integrated hydrological model calibration, and as the calibration level will allow to reasonably reach the objective of the model development (water balance, GW-SW) considering the EPM approach, the monthly normal calibration results are considered satisfactory and are used as initial conditions for daily transient simulations (Figure 5).

Daily transient simulations results for three observations wells that have available groundwater head measurements (Figure 5) show acceptable agreement between observed and simulated groundwater heads for 5 years (2013-2017). The first two years (2011-2013) are considered as model spin up period. The three observation wells (Figure 5) are located in the fractured aquifer, because no continuous groundwater measurements heads are available for the CT aquifer. Compared to the monthly normal simulations, simulated daily transient groundwater heads have less time lag, and in all the three wells, simulated mean heads approach the measured heads very closely. The time lag bias observed from daily transient wells is different for the three observations wells, implying highly variable hydraulic conductivities in the fractured aquifer, controlled by localized geological features (fractures density, aperture, weathered zone thickness) that the current EPM conceptualization of the model may not be able to capture. The EPM representation appears to be useful in regional groundwater flow system characterization, but may be too simple to capture the complexity of local geological conditions (Anderson and Woessner, 1992).

In order to improve the calibration results of groundwater heads, especially the observed lag between simulated and observed groundwater levels in the transient simulations, advanced model calibration methods using pilot points may be used. This method would allow the use of spatial heterogeneities in the sensitive hydrologic parameters for improving the objective function. Detailed information and a tutorial on this advanced calibration method can be found in Moeck and Brunner (2014).

Daily transient simulated surface water flow rates at the Niamey gauge (Figure 6) are relatively well reproduced by the model, with the local flow peak (rainy season) and Guinean flow peak captured in August and December respectively.

3.3 Exchange flux

The simulated exchange flux from five years of daily transient simulation (2013-2017) has been aggregated into monthly normal exchange flux (Figure 7) in units of mm/day. Positive values (red) represent the exfiltration from the porous medium to the surface, while negative values (blue) correspond to the water infiltrating from the surface to the subsurface. The 2D spatial representation of the exchange flux is used to qualitatively characterize the process of exchange between the surface water bodies and the aquifer system. The distribution of the exchange flux values (Figure7) shows that the model is able to reproduce the importance of the monsoonal rainfall in groundwater infiltration occurring only in the rainy season. July and August are the most important periods of infiltration with an average value of up to 8 mm/day. In June and September, infiltration is localized at the right bank of the Niger River (upstream) where irrigation occurs. The rest of the season is dry, and there is no infiltration. Groundwater exfiltration shows different patterns depending on the surface water bodies considered. The Niger River acts as a gaining stream where groundwater exfiltrates to the river during the rainy and dry seasons. Although, it is clear that the River is gaining, the exfiltration rates are very small, relative to the total flows in the river, and the process is only important for few months of the year (August, February and March). Using a piezometric map of Niamey, Hassane et al. (2016), have already shown the CT aquifer discharges to the Niger River which agrees with this study.

Considering the ponds and ephemeral streams, the exchange flux processes are a bit more complex, and result from more local hydrogeological conditions (topography, hydrologic conductivities), with some ponds acting as depressions focused recharge areas and others as groundwater discharge area. The channels of the ephemeral streams are predominantly groundwater discharge areas while the main stream course is mainly a recharge area. This phenomenon of ponds and parts of ephemeral streams acting as groundwater discharge zones may be related to the recent changes of land use resulting in the creation of temporary ponds (Favreau et al., 2009; Mamoudou et al., 2015).

While monthly normal exchange fluxes provide a qualitative understating of the seasonal cycle of river-aquifer exchange (Erler et al., 2018), they do not carry sufficient temporal resolution to quantify and understand the highly transient relationship between surface and subsurface exchanges fluxes for this dry environment with intermittent precipitation. For this watershed daily exchange fluxes are required (Figure 8)

Daily time series of exchanges flux have been derived at multiple locations (Figures 8 and 9) in order to characterize the surface water groundwater interactions depending on the type of the surface water features considered (i.e., Niger River, ponds, ephemeral stream)

Figures 8a and 8b show the daily time series profile of ponds-aquifer exchange flux for the Zarmagande pond and Koungou pond respectively. Exchange flux at Zarmagande pond (Figure 8a) is dominated by groundwater discharge during the rainy season (July to September), and by groundwater recharge in the dry season (October to June). In the rainy season, when groundwater is discharging into the ponds, the volume discharging into the pond is more important during intense rainfall events (Figure 8a) with an exfiltration rate of up to 40 mm/day, which is considerably greater than actual evapotranspiration rate of 2 -3 mm/day. In contrast, infiltration of up to 20 mm/day may occurs from pond to aquifer during the dry season, which lead to about 17to 15 mm/ day of recharge after removing actual evapotranspiration rate (3to 5 mm/day). At Koungou pond (Figure8b), located 500 m away from Zarmagande pond , at a lower altitude , the exchange flux is exclusively characterized by infiltration of pond water into groundwater. The infiltration rate, which is dependent on rainfall intensity, can reach up to 50 mm/day during intense precipitation events (i.e., 120 mm/day). The difference in the exchange flux of the two ponds may be related to local topography, with Zarmagande pond located in a topographically low area (196 m.a.s.l), and Kongou pond, at greater elevations (201 m.a.s.l). Furthermore, the phenomenon of groundwater discharge into ponds, may be a result of recent land use change and climate induced groundwater table rise well documented in the study area from rural zones (Favreau, 2000; Favreau et al.,2009) to urban area(Hassane et al., 2016).

While there is significant groundwater recharge in the vicinity of the two ponds, there is a qualitative difference to the spring at Gounti Yena (Figure 8c) where the exchange flux is characterized by a continuous groundwater discharge throughout the year. The main peak of the exfiltration occurs during the late rainy season and decreases during the dry season. The more intense the rainfall event is, the greater the exfiltration rate. During the late dry season (May, June) and early rainy season (July), little infiltration occurs, as evapotranspiration is the dominant process and considerably reduces the amount of water available to infiltrate. The ephemeral stream, Gounti Yena, is a groundwater discharge area, and its discharge rates can serve as a precursor to groundwater flooding especially during extreme precipitation event. Another ephemeral stream at Gorou Kirey shows a different exchange flux behavior (Figure 8d) with surface water infiltrating into groundwater and producing a significant groundwater recharge.

Figure 9 shows exchange flux time series between the Niger River and the underlying aquifer at two locations, to characterize groundwater-surface water interactions. The time series (Figure 9) are considered to represent the main types of interactions in the vicinity of the permanent river in the study area. The simulation results further show that when there is a significant interaction between the river and underlying aquifer, the river is acting as either gaining, or losing stream depending on the zone considered. While the monthly normal exchange flux discussed earlier showed the Niger River to mainly have a gaining stream profile, the daily exchange flux time series allows for a more detailed profile.

Therefore, Niger River acts as loosing stream is some zones (Figure 9a), and gaining stream (Figure9b) in others zones. In general, the losing zones are located near faults zones, where fractures are dense, and allow significant surface water infiltration into groundwater. One important aspect to notice is that no infiltration occurs during the Guinea river peak flow from November to February. Infiltration occurs only during the rainy season, during the local peak of the river, resulting in groundwater recharge of up to 50 mm/day during intense rainfall, as actual evapotranspiration (Figure 9a) is low during these events, allowing significant groundwater recharge to occur. However, the losing zones of the river are only localized near important fractures zones, and in most area, models results do not show significant infiltration processes in other zones of the river. It is also worth noting that the infiltration rate of river water is more dependent on the intensity of individual rainfall events, than the mean monthly or annual rainfall. The importance of fractures zones in groundwater recharge has been shown by Girard (1993) for this study area using hydrochemicals and isotopes methods.

Apart from above mentioned localized fractures zones where the river water recharges groundwater, the remaining part of the Niger River is gaining from underlying aquifer (Figure9b). The exchange flux profile at gaining parts of the river (Figure9b) is dominated by groundwater exfiltration in the rainy season, with an exfiltration rate of up to 20 mm/day. This exfiltration rate results in baseflow of up to 15 mm/day when actual ET (less than 5mm/day) is considered (Figure 9b), and shows two peaks, one at the end of the dry period (April –May), and another in the earlier rainy season (June-July). This shows that groundwater is sustaining the baseflow of the river during the dry season, and at the beginning of the rainy season. The exfiltration rate then decreases from the middle of the rainy season (August) to reach zero by the end of the Guinea high peak flow period (November-February). This is because groundwater heads are almost always above the Niger River levels (Hassane et al., 2016), and particularly, during the dry period. Figure 9b also shows that there is slight infiltration occurring during the high Guinea flow of the river resulting in low groundwater recharge rate (less than 5 mm/day). The Niger River peak that is generated by the Guinea flow peak upstream, in the upper Niger basin does not contribute to groundwater recharge in the study area. This may be explained by the relatively slow flow of the Guinea flow compared to the local flow peak, which is characterized by intermittent precipitation flashy stream flow behavior.

In order to confirm the relative position of the Niger River to groundwater, 3D map of the depth to groundwater table (Figures 10a and 10b) and groundwater heads (Figures 10c and 10d) are shown for different seasons of the year. During the dry season, the depth to the groundwater table ranges from less than 5 meters near the Niger River and ephemeral streams (Figure10a), to 65 meters in topographically high areas. In most areas the groundwater table is at a shallow depth during the rainy season (Figure10b).

Both depth to groundwater table and groundwater heads show the topographical control on the groundwater flow system. The Niger River as well as many ephemeral streams act as natural groundwater discharge areas. A good illustration of the seasonal variability of groundwater flow is shown in the Figure 10c and 10d. Groundwater heads during the dry season (Figure 10c) are almost always less than model calculated heads during the rainy season where many piezometric domes appeared as a combined effect of topographical control and groundwater table rise (Figure 10d) . The observed heads difference is a result of groundwater recharge occurring in the rainy season.

3.4 Water balance

This modelling work has highlighted that different surface water features (i.e., ponds, ephemeral stream, the Niger River, and springs) exhibit different type of exchange flux profiles. In this section, the water balance for different land use types will be presented as well as the basin average water balance. We also qualitatively present model calculated recharge for different land use types which is one of the most problematic parameters to estimate in semi-arid climate (Simmers, 1997).

3.4.1 Water balance by land use type

The different land use types considered as along with relevant water balance components are presented in Table 4. Ponds that are similar to Zarmagandé pond (ponds type 1), discussed in section 3, have a recharge rate of up to 203 mm/year, and a discharge from groundwater reaching 213 mm/year. The infiltration rate calculated from the exchange flux is 203 mm/year and is assumed to represent groundwater recharge because the surface evaporation representing the main ET process is removed in the exchange flux. The total actual ET represented mainly by surface evaporation is of 101 mm/year. Groundwater recharge at the vicinity of the pond type 2 (Koungou pond) is 174 mm/year, with total actual ET (mainly surface evaporation) of 97 mm /year (Table 4). However, the recharge values calculated here are point values (less than a m²); in order to qualitatively understand the exchange flux profile at the vicinity of the ponds. Previous studies (Favreau, 1998; Disconnets et al., 1997) have highlighted the strong spatial and temporal variability of focused recharge near ponds, depending on the size of the ponds drainage area, which is critical to exactly compute in an endoreic basin (Favreau, 2000).

Groundwater infiltration at agricultural sites is 119 mm/year, with total actual ET of 51 mm/year and groundwater recharge of 68 mm/year. In contrast, no groundwater recharge was recorded at Savanna site, where total ET is greater than the infiltrated water (93 mm/year). While, the infiltration values of agriculture and Savanna land use are in the same order of magnitude (119 and 93mm/year respectively), and consistent with measured values (160 –290 mm/year) by Rockstromet al. (1998) under millet fields at 1.8 m depths, Total actual ET of Savanna (101 mm/year) is twice the actual ET of agriculture. The main reason for this difference is probably the temporal activity of the root as well as the root depths. Agricultural land use is characterized by millet and/or maize crops, with average root ET activity lasting 3 months (only during the rainy season) and a root depth of 1.5 m, while the Savanna consist of shrubs that transpire continuously throughout the year and have a root depth of more than 5 m.

Ephemeral streams can have a groundwater infiltration rate of up to 70 mm/day, resulting in groundwater recharge of the same rate and total ET of 49 mm/year. In contrast to ephemeral streams that always act as depressions focused recharge areas (Table 4), ponds act either as groundwater recharge areas or groundwater discharge zones.

3.4.2 Basin average water balance

The basin average water balance (Table 5) is computed from HGS water balance output file, and averaged over the study area. The calculated five years (2013-2017) basin average groundwater recharge is 28 mm/year representing 4.92 % of the total mean annual rainfall (580 mm). Total actual evapotranspiration over the basin is 386 mm/year, accounting for 66% of the total rainfall. The total ET is highly dominated by transpiration, which is 58% of the total ET, while surface evaporation is only 8.65 %. Infiltration over the basin represents 15.9 % of the water balance and overland flow constitutes 10.91%.

Simulated groundwater recharge (28 mm/year) is consistent with previous recharge rate of 36 mm/year found by Hassane et al. (2016) using a water table fluctuation method, considering a value of 1.2 m of water table rise. Favreau, et al.,(2009) estimated a net groundwater recharge rate of 25 ± 7 mm/year using combined water table fluctuations and geophysical methods,50 km east of the study area.

Actual evapotranspiration as simulated by HGS is in agreement with previous measurements and modeling results, focused on millet and fallow sites with total actual ET in the range of 50 to 44% of total rainfall (Ibrahim et al.,2014), and up to 65% to 45% (Boulain et al. 2009;Ramier et al., 2009) for fallow and millet respectively.

4. Conclusion and Perspectives

An equivalent porous medium approach was used to characterize groundwater surface water interaction in geologically complex fractured and sedimentary aquifers, with a high resolution fully integrated surface-subsurface hydrological model. The finite element HydroGeoSphere model has a horizontal resolution ranging from 300 m to 70 m and eleven vertical layers resulting in a total of 516901 nodes and 927030 elements. The model was calibrated using a 3-step methodology: 1) steady state, 2) dynamic equilibrium and 3) daily transient. The model results allowed for both a qualitative and quantitative evaluation of groundwater-surface water interactions for different land uses categories. In general, the groundwater flow system is controlled by local topography, and the Niger River showed mainly a gaining stream profile with groundwater discharge rate of up to 20 mm/day in the rainy season. However, the river may act as losing stream near main faults, with an infiltration of up to 50 mm/day during intense rainfall events. Ephemeral streams occur in areas of focused groundwater discharge, while ponds exchange flow profile is controlled by local topography, and they act as groundwater recharge or discharge areas. Significant groundwater recharge occurs in agriculture /fallow land use, in contrast of Savanna where all the infiltrated groundwater are lost by intense evapotranspiration processes. The calculated 5 years average groundwater recharge over the basin is 28.6 mm/year with actual evapotranspiration accounting for 66.31% of the total mean annual rainfall (580 mm), and slight groundwater contribution to baseflow (1.66¨%).

Large scale integrated hydrological models have attracted considerable interest over the past 10-15 years, largely due to better availability of input data and high-performance computing capacity (Bergand Sudicky,2018). The study described here confirms that the application of fully integrated hydrological models to address real world problems is feasible, even with modest computing resources and in regions where less data is available. While most developing countries are facing challenges in water resources management, due to high population growth combined with climate change, we have demonstrated that integrated hydrological models help to address some of these water management challenges. Integrated hydrological models constitute a useful tool for helping developing countries achieve successful integrated water resources management.

Figures and Tables

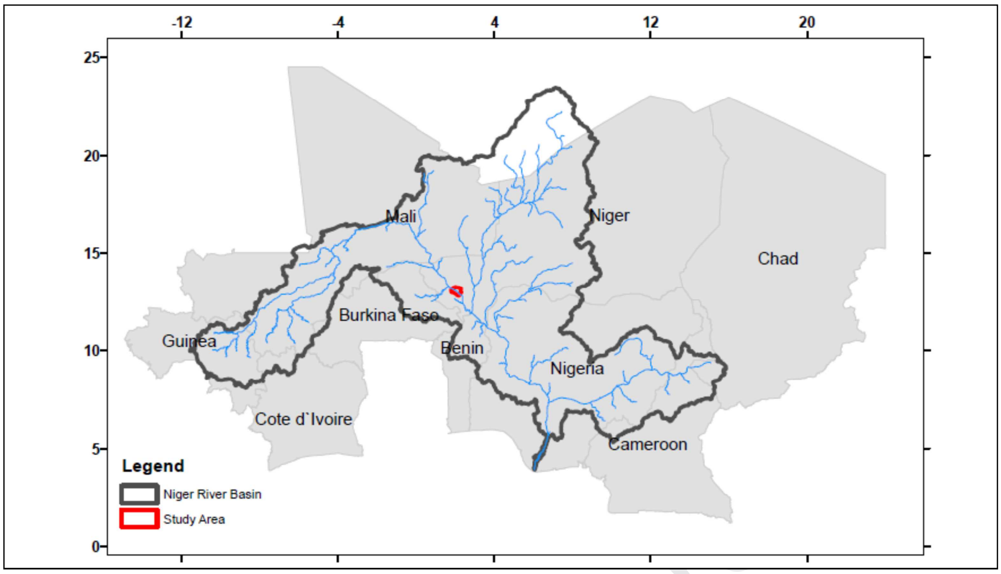

Figure 1a: Study area location within the Niger River basin

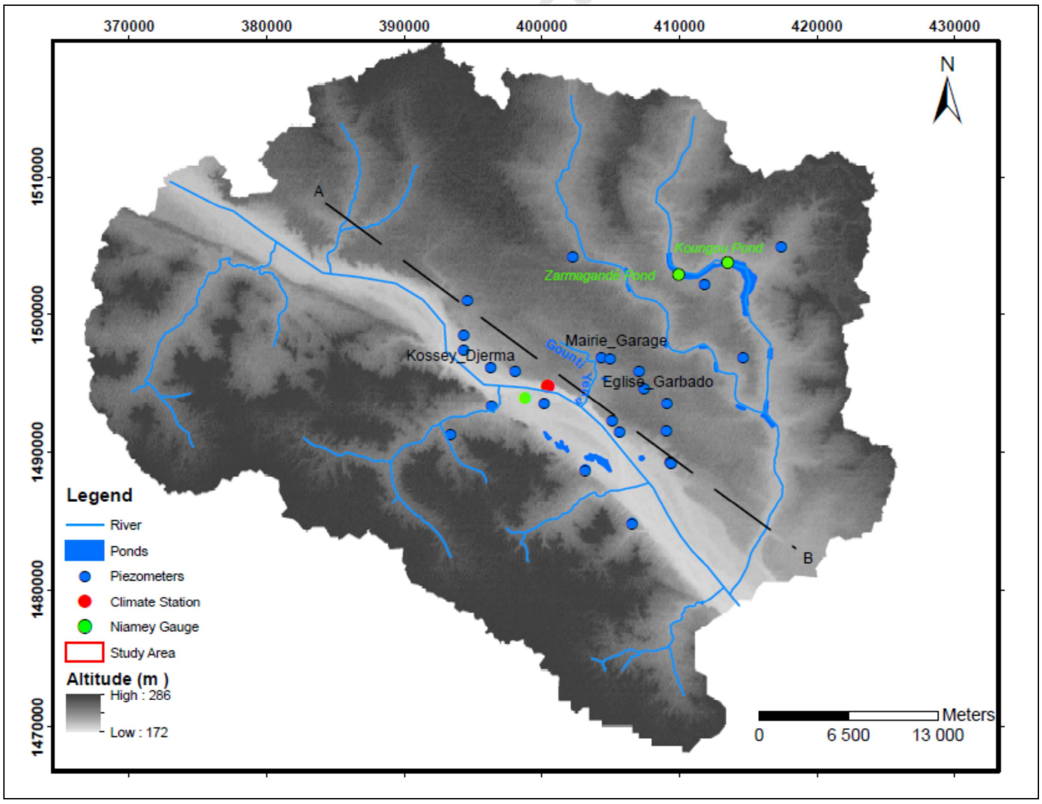

Figure 1b: Local context of the watershed, black dashed line is the x-section location shown in Figure 2

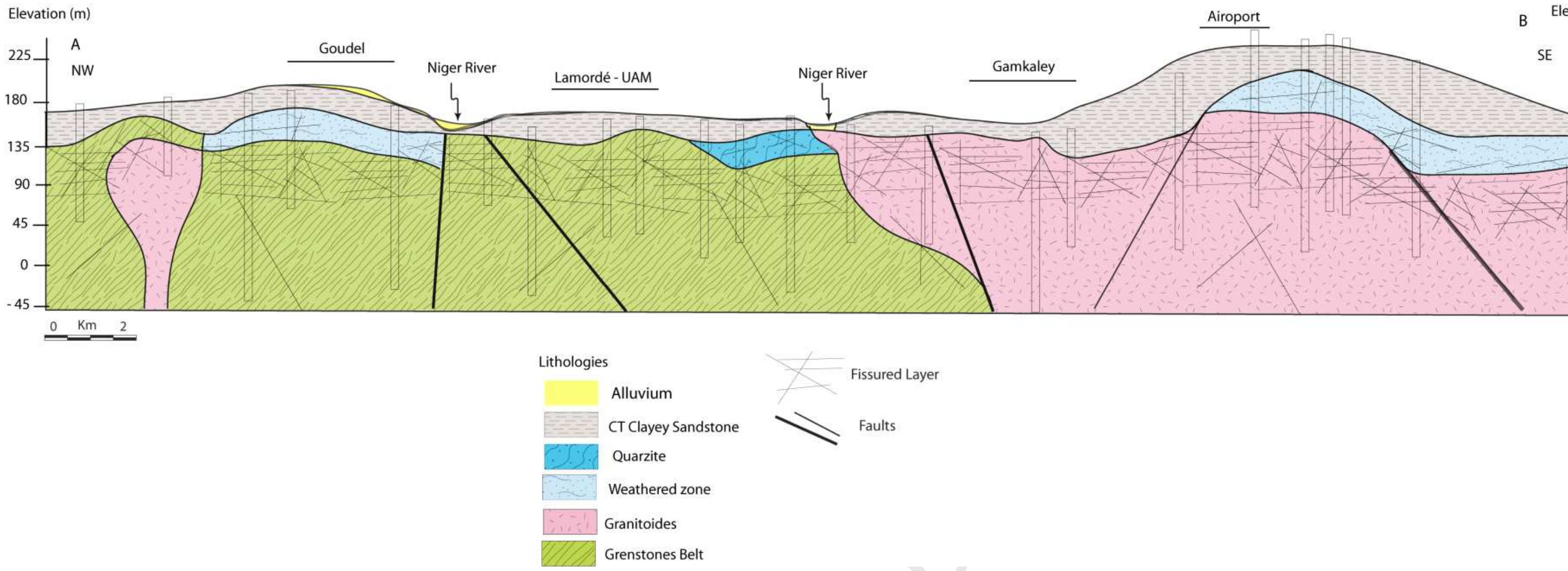

Figure 2a: Conceptual model representing the Hydrogeological conditions in the study area

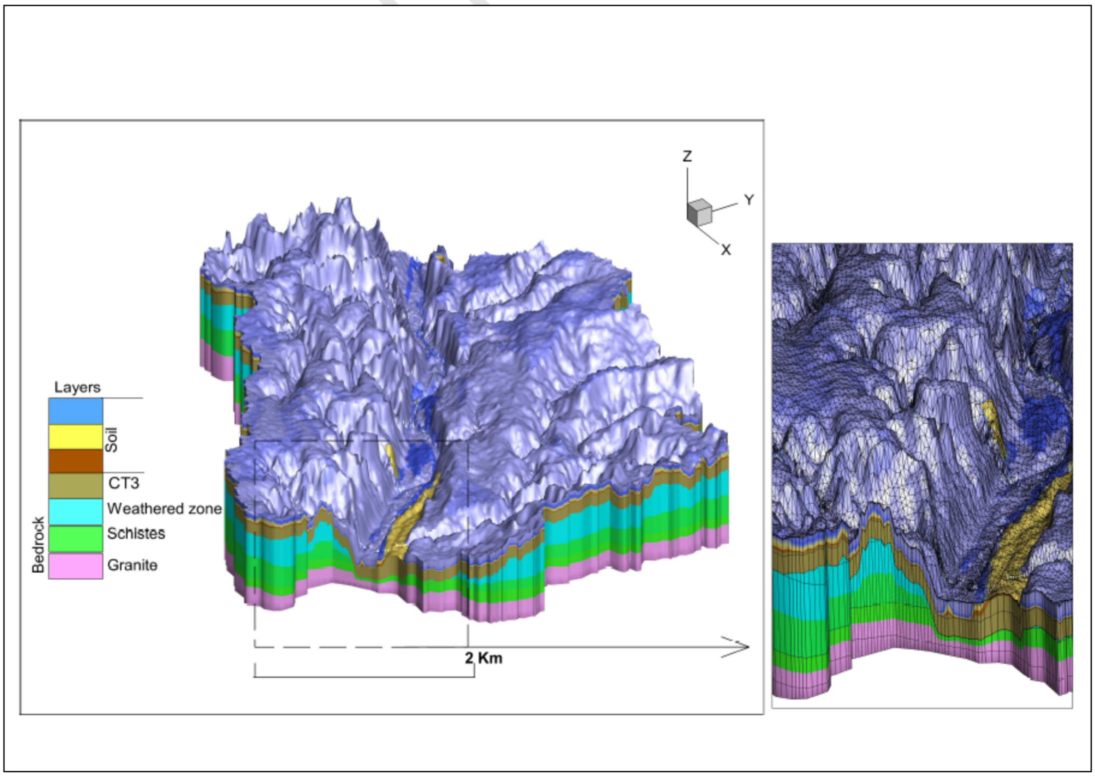

Figure 2b: 3D surface-subsurface model of the study area

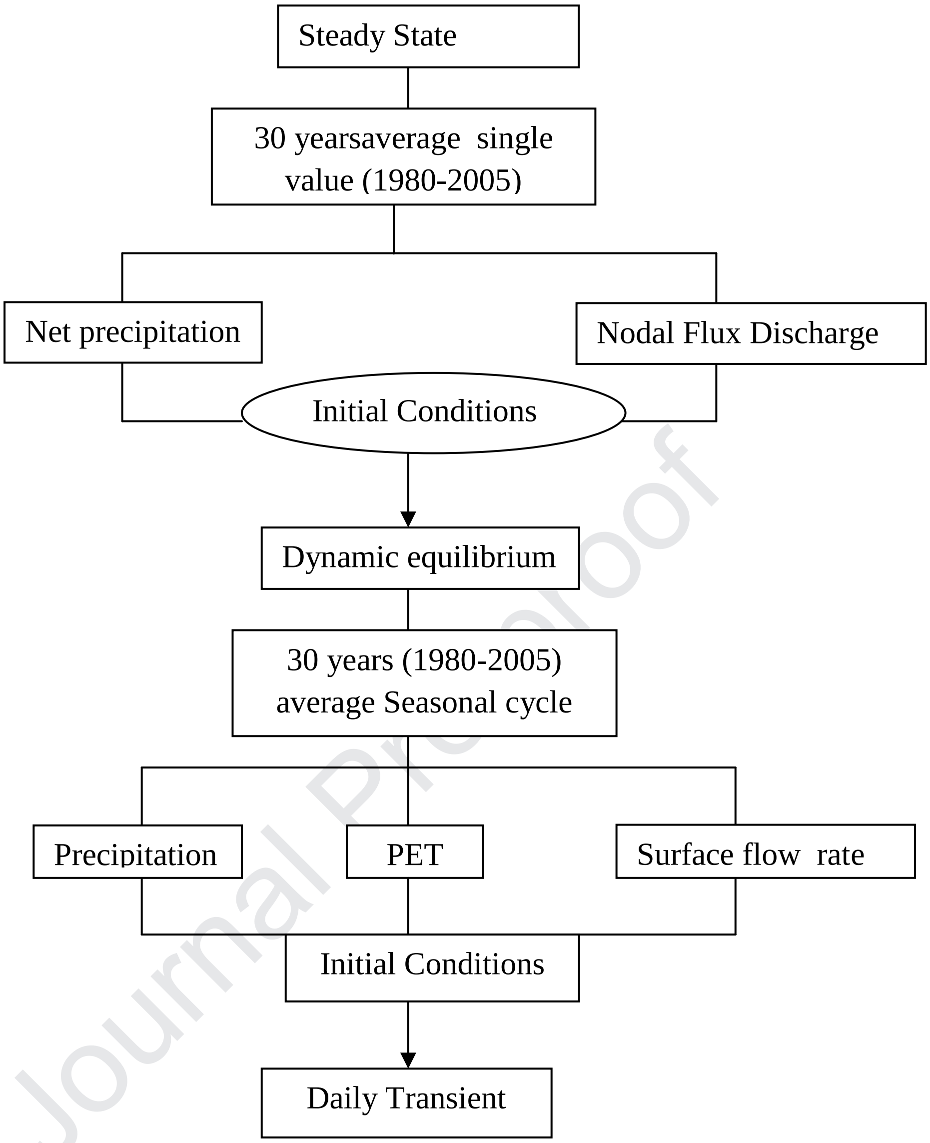

Figure 3: Calibration method flow chart

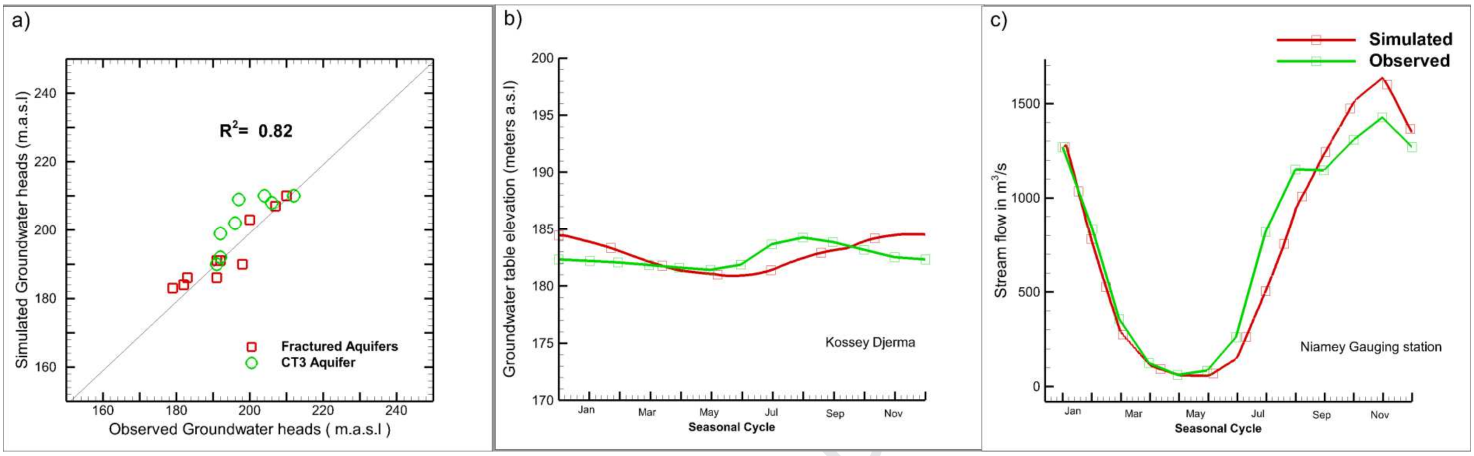

Figure 4: Steady state (a) and groundwater head calibration under dynamic equilibrium (b) and surface water flow rate calibration under dynamic equilibrium (c)

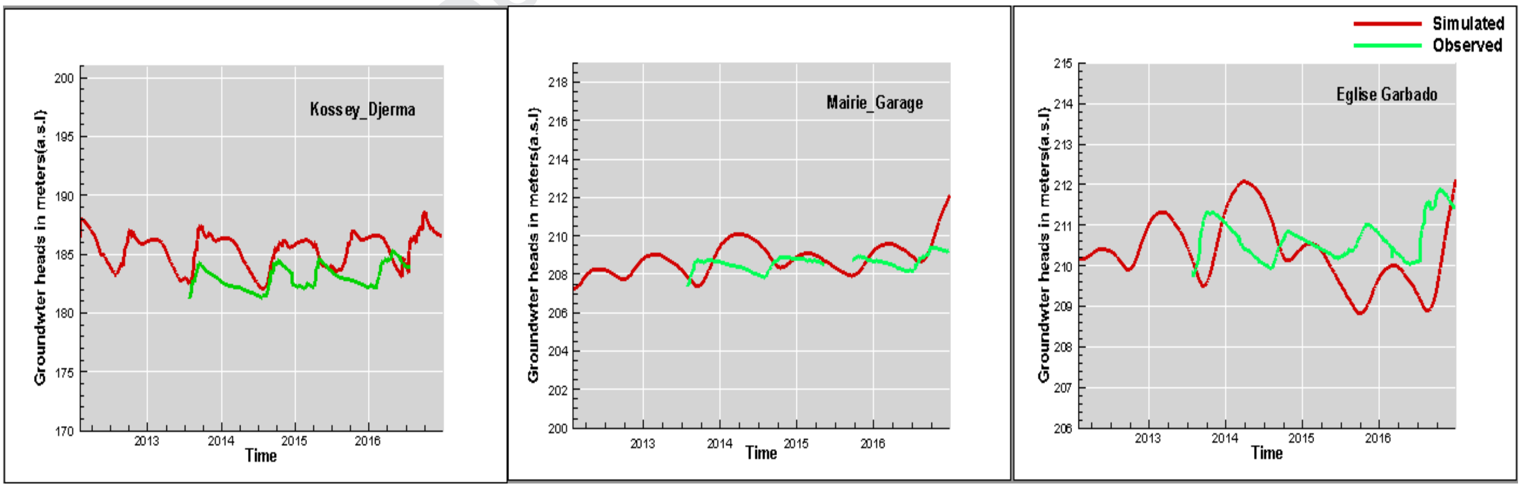

Figure 5: Comparison of simulated and observed daily transient groundwater heads

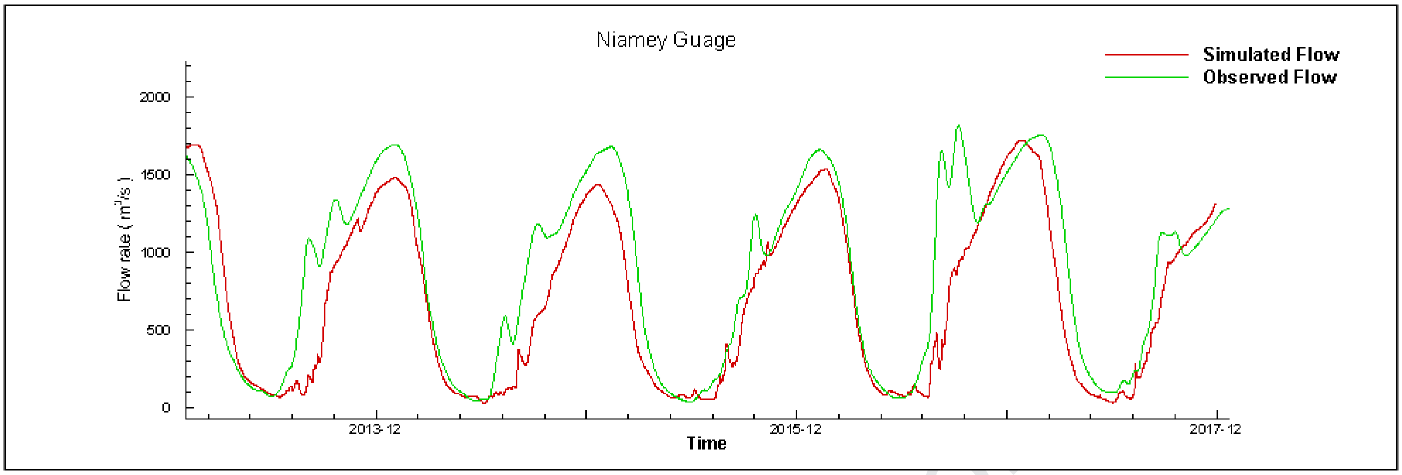

Figure 6: Comparison of simulated and observed daily surface water flow rate at Niamey gauge

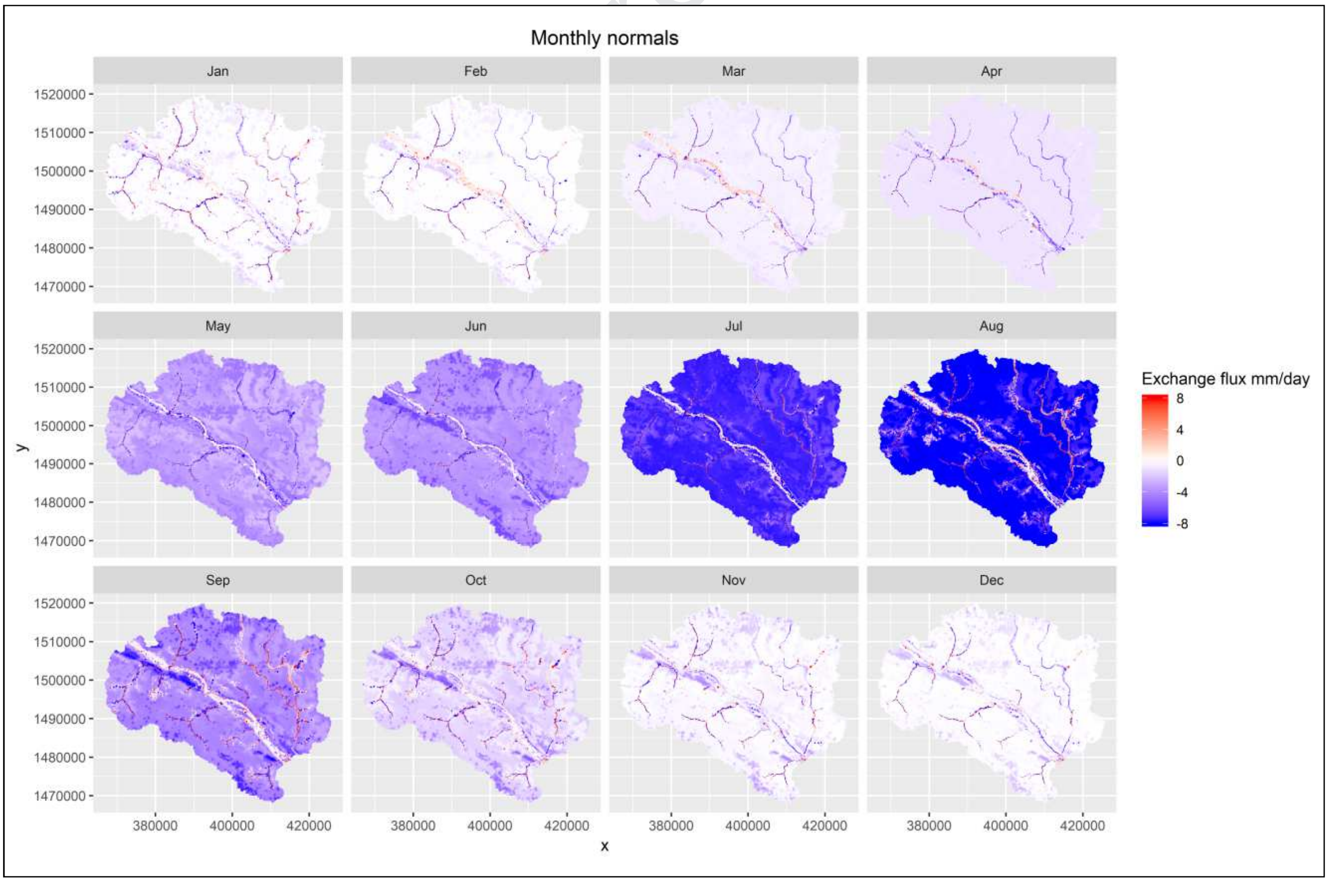

Figure 7: 2D spatial monthly normals Exchange flux

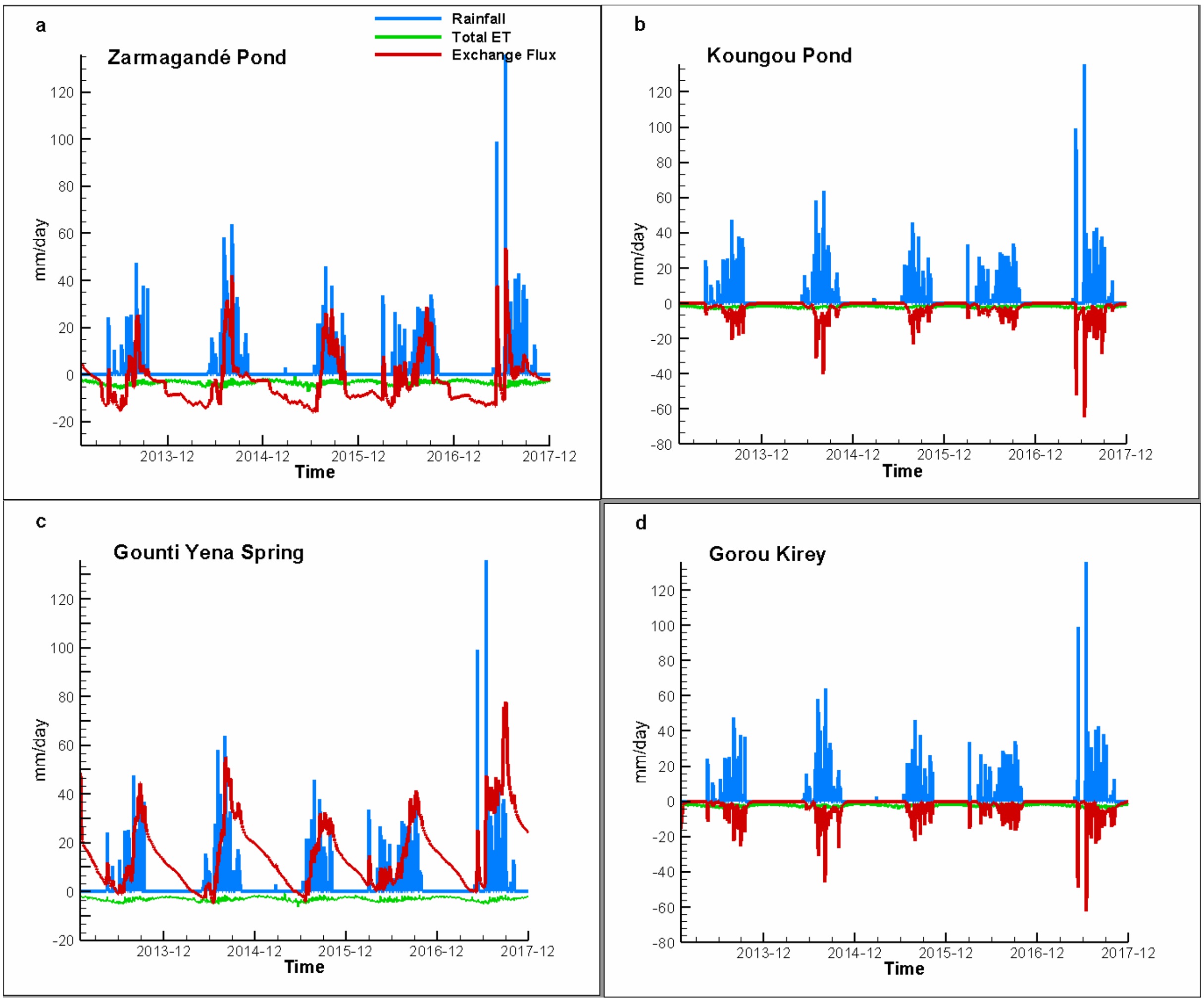

Figure 8: Exchange Flux profile for ponds (a, b) and Ephemeral Stream (c,d)

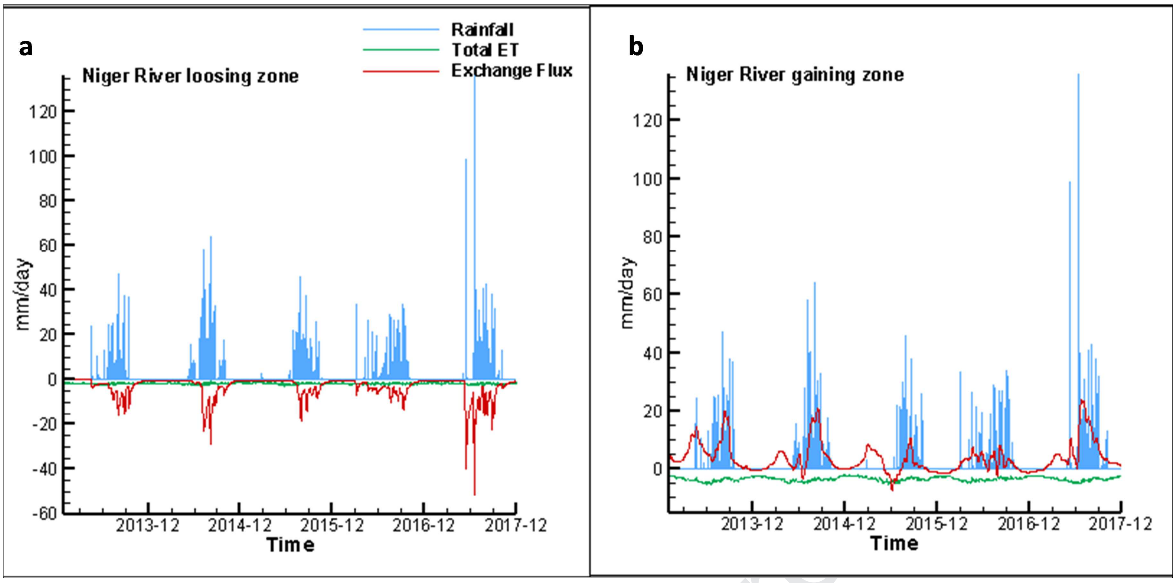

Figure 9: Exchange Flux at Niger River showing loosing (a) and gaining zone (b) profiles

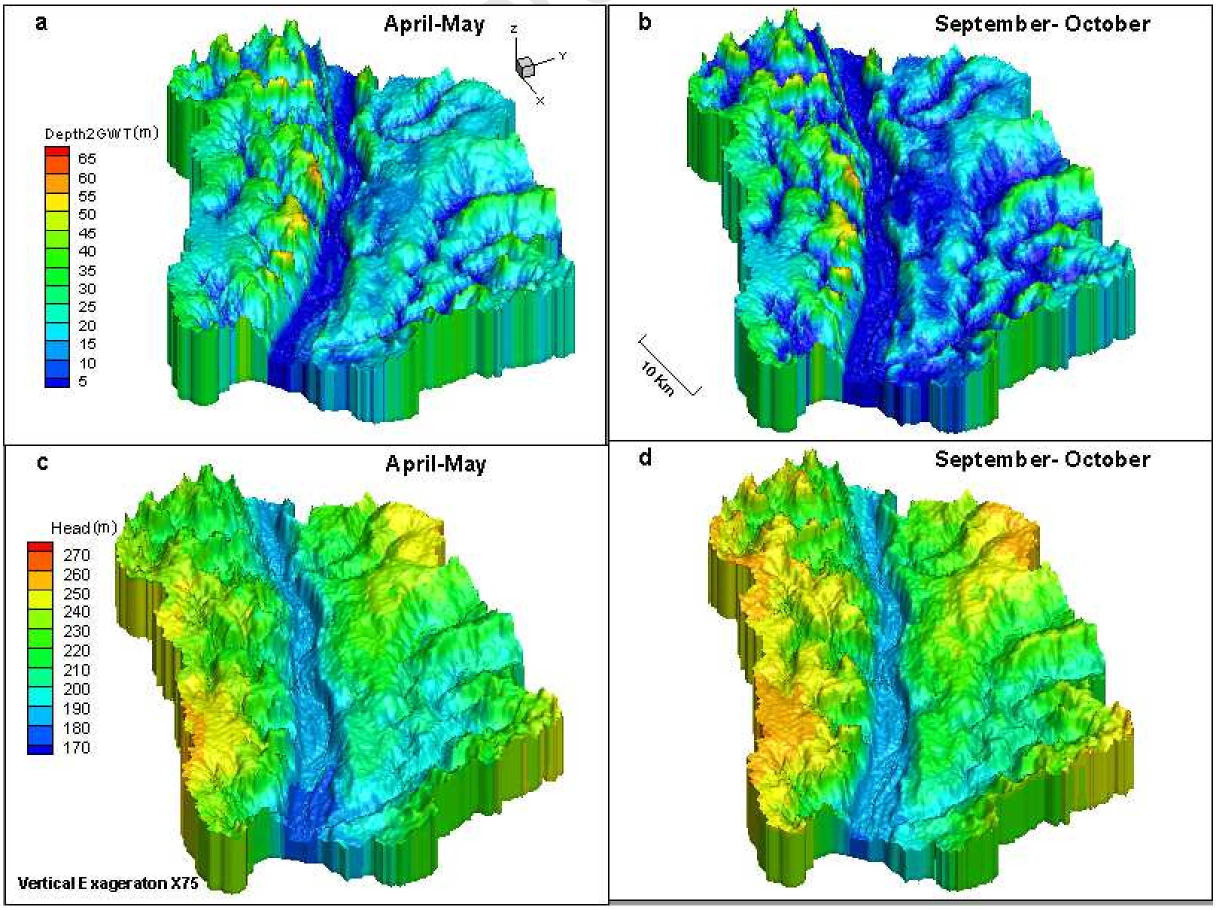

Figure 10: Simulated 3D Spatial Depth to groundwater table (a, b) and groundwater heads (c, d) at different periods

Table 1: Hydrologic parameters used at the steady state step

Parameters	Symbol	Units
Saturated hydraulic conductivity	K	[m/s]
Total porosity	n	[-]
Specific storage	S_s	[m^{-1}]
Van Genuchten parameter	α	[-]
Van Genuchten parameter	β	[m^{-1}]
Residual water saturation	S_{wr}	[-]
Coupling length	L_c	[m]
Manning roughness coefficient	n_x	[$m^{-1/3}$ s]
Manning roughness coefficient	n_y	[$m^{-1/3}$ s]
Evaporation depth	L_e	[m]
Evaporation limiting saturations	θ_{e1} θ_{e2}	[-]
Leaf Area Index	LAI	[-]
Root depth	L_r	[m]
Transpiration fitting parameters	C1, C2, C3	[-]
Transpiration limiting saturations	θ_{t1} θ_{t2}	[-]
Canopy storage parameter	C_{int}	[m]

Table 2: Calibrated saturated hydraulic conductivities and Van Genuchten parameters.

Units	K[m/s]	Residual water saturation	Van Genuchten parameters	
Continental Terminal	$1.12 \cdot 10^{-5}$	0.023	0.088	1.113
Weathered zone	$1.24 \cdot 10^{-6}$	0.042	0.166	1.128
Schistes	$6.36 \cdot 10^{-9}$	0.042	0.100	1.153
Granites	$9 \cdot 10^{-8}$	0.079	0.134	1.34

Table 3: Calibrated Transpiration and Overland flow parameters

Parameters	Agriculture	Savanna	Steppe	Urban	Bare soil
Max Leaf Area Index [-]	1.2	1.25	1.2	0.2	0.01
Root depth [m]	1.5	4.5	1	0.1	0.01
Manning friction Coefficients [$m^{-1/3}$ s]	0.139	0.187	0.154	0.016	0.43
Coupling Length [m]	0.01	0.01	0.01	0.1	0.01

Table 4: Water balance profiles for different land use types

Land Use	Infiltration (mm/year)	Total ET	Recharge	Groundwater Discharge
Fallow/ Agriculture	119	51	68	0
Sahelian Savanna	93	103	0	0
Pond type 1	203	101	203	213
Pond type 2	174	97	174	0
Niger River (loosing zone)	98	67	98	0
Niger River (Gaining zone)	138	112	0	138
Ephemeral Stream	70	49	70	0

Table 5: Basin Average water balance (5 Years)

Rainfall	Infiltration	Surface Evaporation	Overland Flow	Transpiration	Total ET	Recharge	Groundwater Discharge	Balance Error
580.88	92.4	139	63.4	247	386	28.6	9.66	0.82
100%	15.9	8.64	10.91	58.01	66.31	4.92	1.66	0.14

References

Amogu O, Descroix L, Yéro S Kadidiatou , Le Breton E , Mamadou I , Ali A, Vischel T, Bader J Claude , Moussa B Ibrahim , Gautier E , Boubkraoui S and Belleudy P (2010) Increasing River Flows in the Sahel? Water, ISSN 2073-4441

Andersson Jafet C.M., Ali Abdou , Arheimer Berit, Gustafsson David , Minoungou Bernard (2017) . Providing peak river flow statistics and forecasting in the Niger Riverbasin. Physics and Chemistry of the Earth 100 3- 12

Andersen, I., O. Dione, M. Jarosewich-Holder, and J. C. Olivry (2005). The Niger River basin: A vision for sustainable management,World Bank Publications. [Available at http://siteresources.worldbank.org/INTWAT/Resources/4602114-1206643460526/ Niger_River_Basin_Vision_Sustainable_Management.pdf.

Aquanty Inc. (2017). HGS User Manual. Available athttps://static1.squarespace.com/static/54611cc8e4b0f88a2c1abc57/t/59cea33846c3c4384b8e5de1/1506714438873/hydrosphere_user.pdf

Barthel, R., and Banzhaf, S. (2016). Groundwater and surface water interaction at the regional-scale–a review with focus on regional integrated models. Water resources management, 30(1), 1-32

Berg, S.J. and Sudicky, E.A., 2019. Toward Large□Scale Integrated Surface and Subsurface Modeling. Groundwater, 57(1), pp.1-2.

Bernert G, Dehays H, Garin H, Zunino C (1985) Programme d'urgence pour le renforcement de l'alimentation en eau potable des quartiers périphériques de Niamey (Niger): exécution de 50 forages productifs [Emergency program to strengthen the supply of drinking water in suburban areas of the city of Niamey (Niger): execution of 50 productive boreholes]. Technical report BRGM/MHE, BRGM, Orléans, France, 52 pp

Boulain N, Cappelaere B, Ramier D, Issoufou HBA, Halilou O, Seghieri J, Guillemin F, Oï M, Gignoux J, Timouk F (2009) Towards an understanding of coupled physical and biological processes in the cultivated Sahel: 2. vegetation and carbon dynamics. J Hydrol 375:190‑203

Brooks, R.H., Corey, A.T., (1964) . Hydraulic properties of porous media andt heir relation to drainage design. Trans. ASAE 7 (1), 26–0028

Chardon D., Grimaud J-L., Beauvais A. and Bamba O. (2018). West African lateritic pediments: Landform-regolith evolution processes and mineral exploration pitfalls. Elsevier, Earth-Science Reviews, 124–146p

Chen, J., E.A. Sudicky, J.H. Davison, S.K. Frey, Y. -J. Park, H. -T. Hwang, A.R. Erler, S.J. Berg, M.V. Callaghan, K. Miller, M. Ross, W.R. Peltier. Towards a Climate-Driven Simulation of Coupled Surface-Subsurface Hydrology at the Continental Scale: A Canadian Example. Canadian Water ResourcesJournal: Under Review

CILSS (2016) Landscapes of West Africa – A Window on a Changing World. U.S. Geological Survey EROS, 47914 252nd St, Garretson, SD 57030, UNITED STATES

Dai Aiguo,, Lamb J Peter.,, Trenberth E Kevin.,, Hulme Mike,, Jones D Philip., And Xie Pingping (2004). Comment The recent Sahel drought is real. Int. J. Climatol. 24: 1323-1331

Dehays H, Garin H, Zunino C (1986) Programme d'urgence pour le renforcement de l'alimentation en eau potable des quartiers périphériques de Niamey (Niger): deuxième phase—exécution de 68 forages [Emergency program to strengthen drinking water supply in suburban areas of the city of Niamey (Niger): second phase— execution of 68 boreholes]. Technical report BRGM/MHE, BRGM, Orléans, France, 30 pp

Desconnets JC, Taupin JD, Lebel T, Leduc C (1997). Hydrology of the Hapex-Sahel Central Super-Site: surface water drainage and aquifer recharge through the pool systems. J Hydrol 188–189:155–178

Erler, A. R., Frey, S. K., Khader, O., d'Orgeville, M., Park, Y.-J., Hwang, H.-T., et al. (2019). Simulating climate change impacts on surface water resources within a lake-affected region using regional climate projections. Water Resources Research, 55, 130–155. https:// doi.org/10.1029/2018WR024381

Favreau G, Cappelaere B,Massuel S, LeblancM, Boucher M, Boulain N,Leduc C (2009) Land clearing, climate variability and water resources increase in semiarid southwest Niger: a review. Water Resour Res 45:W00A16

Favreau G (2000) Caractérisation et modélisation d'une nappe phréatique en hausse au Sahel: dynamique et géochimie de la dépression piézométrique naturelle du kori de Dantiandou (sud-ouest du Niger) [Characterization and modelling of a rising water table in the Sahel: dynamics and geochemistry of the Dantiandou kori natural piezometric depression (southwest Niger)]. PhD Thesis, Univ Paris XI, Orsay, France, 258 pp

Favreau, G.,(1996). Modélisation locale de la recharge de la nappe phréatique sur le site de Wankama (sud-ouest du Niger). Mémoire de 3” cycle universitaire (DEA), 75 p. Université de Paris-sud / Orsay, France.

Favreau, G., Leduc, C.,(1998). Fluctuations à long terme de la nappe phréatique du Continental Terminal près de Niamey (Niger) entre 1956 et 1997. in : “Variabilité des ressources en eau en Afrique au XXème siècle”, conférence Abidjan’98, 1998. AISHPubl., 252,253-2588.

Girard P (1993) Techniques isotopiques (15N, 18O) appliquées à l’étude des nappes des altérites et du socle fracturé de l’Ouest Africain: l’Ouest du Niger [Isotopic techniques applied to groundwaters of alterites and fractured basement aquifers inWest Africa: theWestern Niger]. PhD Thesis, Univ of Quebec at Montreal, Canada, 141 pp

Girard P, Hillaire-Marcel C, Oga MS (1997) Determining the recharge mode of Sahelian aquifers using water isotopes. J Hydrol 197:189– 202

Goderniaux, P., Brouyère, S., Fowler, H. J., Blenkinsop, S., Therrien, R., Orban, P., & Dassargues, A. (2009). Large scale surface–subsurface hydrological model to assess climate change impacts on groundwater reserves. Journal of Hydrology, 373(1-2), 122-138

Hassane, Aïssata B., Christian, L ., Favreau, G., Barbara,A. B., Thomas, M (2016) . Impacts of a large Sahelian city on groundwater hydrodynamicsand quality: example of Niamey (Niger). Hydrogeology Journal,

Hornberger, M.G., Raffensperger, J.P., Wilberg, P.L., Eshleman, K.L., 1998. Elements of Physical Hydrology. JUH Press. 312 pp.

Hwang, H.T., Park, Y.J., Sudicky, E.A., Berg, S.J., McLaughlin, R. and Jones, J.P.,2018. Understanding the water balance paradox in the Athabasca River Basin, Canada. Hydrological processes, 32(6), pp.729-746.

Hwang, H.T., Park, Y.J., Frey, S.K., Berg, S.J. and Sudicky, E.A., 2015. A simple iterative method for estimating evapotranspiration with integrated surface/subsurface flow models. Journal of Hydrology, 531, pp.949-959.

Hwang, H. T., Y. J. Park, E. A. Sudicky, P. A. Forsyth (2014) A parallel computational framework to solve flow and transport in integrated surface–subsurface hydrologic systems, Environ Model Software, 61 (0), 39-58.

Ibrahim. M., Favreau.G., Scanlon, R.B ., Luc,S.J., Le Coz, M., Demarty. J., Cappelaere.B (2014) . Long-term increase in diffuse groundwater recharge followingexpansion of rainfed cultivation in the Sahel, West Africa1293–1305 Hydrogeology Journal

Jones, J.-P., (2005). Simulating hydrologic systems using a physically-based surface subsurface model: issues concerning flow, transport and parameterization. Ph.D. Thesis, University of Waterloo, Waterloo (Canada), 145 pp.

Kristensen, K.J., Jensen, S.E., (1975). A model for estimating actual evapotranspiration from potential evapotranspiration. Nordic Hydrology 6, 170–188.

Lebel, T; Ali, A.,(2007). Recent trends in the Central and Western Sahel rainfall regime (1990–2007)Journal of Hydrology 375 52–64

Lebel .T, Taupin .J.D, D'Amato .N . (1997) . Rainfall monitoring during HAPEX-Sahel. 1. General rainfall conditions and climatology. Journal of Hydrology 74-96

Leduc C, Favreau G, Schroeter P (2001) Long-term rise in a Sahelian water-table: the Continental Terminal in south-west Niger. J Hydrol 243:43–54

Levy P.E., Jarvis P.G. (1997). Direct and indirect measurements of LAI in millet and fallow vegetationin HAPEX-Sahel . Agricultural and Forest Meteorology 97 199–212

Li, Q., Unger, A.J.A., Sudicky, E.A., Kassenaar, D., Wexler, E.J., Shikaze, S., (2008) .Simulating the multi-seasonal response of a large-scale watershed with a 3D physically-based hydrologic model. Journal of Hydrology 357 (3–4), 317–336.

Luigi P., Giovanna, A.D., Manuela. L., Konaté.M., Francesco.S, Guero. Y., A., Tankari,D.B., Domenico.A.De.L (2016). Monitoring of urban growth and its related environmental impacts: Niamey case study (Niger). *Energy Procedia, 97* (2016) 37 – 43.

Machens E. (1973). Contribution à l'étude des formations du socle cristallin et de la couverture sédimentaire de l'Ouest de la République du Niger, 3 Mém. BRGM, Fr.,1973, n° 82, 167 pages.

Mahé, G., F. Bamba, A. Soumaguel, D. Orange, and J. C. Olivry (2009), Water losses in the inner delta of the River Niger: Water balance andflooded area, Hydrol. Process., 23, 3157–3160.

Mascaro, G., D. D. White, P. Westerhoff, and N. Bliss (2015), Performance of the CORDEX-Africa regional climate simulations in representing thehydrological cycle of the Niger River basin, J. Geophys. Res. Atmos., 120,12,425–12,444, doi:10.1002/ 2015JD023905

Mamadou I., Gautier E., Descroix L., Noma I., Bouzou Moussa I., Faran Maiga O., Genthon P.,Amogu O., Malam Abdou M., Vandervaere J.P., (2015). Exorheism growth as an explanationof increasing flooding in the Sahel. Catena 131, 130-139.

Massuel S, Cappelaere B, Favreau G, Lebel T, Vischel T (2011) Integrated surface water-groundwater modelling in the context of increasing water reserves of a regional Sahelian aquifer. Hydrol Sci J 56:1242–1264

Moeck C, Hunkeler D, and Brunner P (2015). Tutorials as a flexible alternative to GUIs: An example for advanced model calibration using Pilot Points. Environmental Modelling & Software 66-78e86

Ramier D, Boulain N, Cappelaere B, Timouk F, Rabanit M, Lloyd CR, Boubkraoui S, Metayer F, Descroix L, Wawrzyniak V (2009) Towards an understanding of coupled physical and biological processes in the cultivated Sahel: 1. energy and water.J Hydrol 375:204‑216

Rockstrom J, Jansson PE, Barron J (1998) Seasonal rainfall partitioning under runon and runoff conditions on sandy soil in Niger: on-farm measurements and water balance modeling. J Hydrol 210:68‑92

Schaap, M.G., F.J. Leij, and M.T. Van Genuchten. (2001). ROSETTA: A computer program for estimating soilhydraulic parameters with hierarchical pedotransfer functions. Journal of Hydrology 251, no. 3: 163–176.

Soumaïla A. et Konaté M. (2005). Caractérisation de la déformation dans la ceinture birimienne (paléoprotérozoïque) de Diagorou-Darbani (Liptako nigérien, Afrique de l'Ouest). *Africa Geoscience Review*, 2005, Vol. 12, No. 3, pp. 161-178.

Sudicky, E.A., Jones, J.-P., Park, Y.-J., Brookfield, E.A., Colautti, D., (2008). Simulating complex flow and transport dynamics in an integrated surface-subsurface modeling framework. Geosciences Journal 12 (2), 107–122.

.Tarhule A and Lamb J. P (2003). Climate Research and Seasonal Forecasting for West Africans: Perceptions, Dissemination, and Use?: Perceptions, Dissemination, and Use? .

Therrien, R., McLaren, R.G., Sudicky, E.A., Panday, S.M., 2005. HydroGeoSphere. A three-dimensional numerical model describing fully-integrated subsurface and surface flow and solute transport, 5, 343 pp

Van Genuchten, M.Th., (1980). A closed-form equation equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 44, 892{898.

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Characterization of groundwater –surface water interactions using high resolution integrated 3D hydrological model in semiarid urban watershed of Niamey, Niger.

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Highlights:

- A methodological framework for integrated hydrological model calibration in a data scarce watershed is described
- The Niger river acts as a natural groundwater discharge zone
- Intense rainfall has significant impact on river aquifer exchange fluxes
- Plant transpiration dominates the water balance.

Keywords: Groundwater –Surface water interactions, calibration, integrated hydrological model, semi arid.

Declarations of interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.