Modelling the sustainability of low-cost hand drilling methods of shallow groundwater abstraction: the case of the Upper Benue River, NE Nigeria

B.A. Ankidawa[1*], C. Bradley[2], P. Collins[3] and S.A.G. Leroy[4]

[1]Department of Agric. & Environmental Engineering, SEET, PMB 2076, Modibbo Adama University of Technology, Yola, Nigeria
[2]School of Geography, Earth and Environmental Sciences, B15 2TT, University of Birmingham, UK
[3]Department of Civil Engineering, SED, UB8 3PH, Brunel University London, UK
[4]Institute for the Environment, UB8 3PH, Brunel University London, UK

*Corresponding author: ankidawa03@yahoo.com

Telephone: +2348063124156

Abstract

This paper: 1. assesses whether current rates of groundwater abstraction from the alluvial aquifer of the River Benue, NE Nigeria, are sustainable; and 2. examines the significance of fluctuations in summer river levels on the floodplain water table. A conceptual groundwater flow model for a floodplain cross-section is developed using MODFLOW with stratigraphic data obtained by hand augering. Floodplain water tables are initially simulated for a 6-month period (January to June 2012); and longer model runs were completed using data collected over >50 years (from 1960 to 2012). Model output is verified using observed data from shallow piezometers installed by hand in the floodplain, with water tables logged automatically and read manually at weekly intervals. Model output is most sensitive to: 1. specific yield, and 2. hydraulic conductivity, but not to river bed conductance. The results confirm that river seepage is the primary inflow to the alluvial aquifer (~75%) and under ‘normal’ conditions, groundwater abstraction from pumping wells constitutes the largest outflow from the aquifer (~56%). The model was used to consider three predictive scenarios: 1. changes in river stage; 2. variable rates of groundwater abstraction from agricultural wells and 3. global climate change. The results suggest that low river water stages (as a consequence of upstream river regulation), continued high groundwater abstraction as a result of population increase and most probably global climate change will lead to a significant and potentially dangerous fall in the floodplain water table to depths beyond which further abstraction is no longer feasible using hand drilling methods.

Keywords: MODFLOW, Modelling, Groundwater, Surface water, River - aquifer interaction, River Benue, Alluvial floodplain, low-cost hand drilling.

1 Introduction

Alluvial groundwater is the major source of irrigation water for agriculture on the floodplain of the River Benue, North Eastern Nigeria. In common with other arid and semi-arid regions, alluvial deposits are potentially highly productive aquifers that can provide an important source of water for irrigation and domestic water supply. However, in many cases current rates of groundwater abstraction are unknown, and hence it is impossible to determine whether current rates of groundwater abstraction are sustainable in the medium to long-term. Significantly, potential future limitations in water availability constitute one of the main constraints to social and economic development in arid and semi-arid regions (Alvarez et al. 2012). In this paper we consider these questions drawing upon the example of the River Benue Basin, Yola region, NE Nigeria. In this region alluvial aquifers constitute the most dependable source of water for irrigation, especially during the annual dry season. During this time, shallow alluvial aquifers are exploited extensively and groundwaters are abstracted from multiple shallow wells installed by hand drilling. However, the sustainability of current rates of groundwater abstraction has yet to be determined although locally an increasing proportion of water used for domestic and irrigation purposes are derived from groundwater. These are potentially vulnerable to changes in recharge rates which may lead to over-exploitation of the resource (Passadore et al. 2012). It has been estimated that 75–250 million (350–600 million) people in Africa will experience increased water stress by the 2020s (2050s) (IPCC: Boko et al. 2007). Inevitably this will include parts of northern Nigeria, which have experienced significant drought in the past, most notably in 1966 and 1968. Currently there is increased demand for water in the region, for both irrigation and domestic use, due to population increase. Groundwater is likely to represent an increasingly important source of water, however, we have only a limited understanding of African groundwater resources (MacDonald et al. 2005), especially how they might respond to climate change (e.g. to changes in recharge and/or abstraction).

To address this problem, it is important to consider groundwater and surface water as a single resource (Winter et al. 1998) and it is particularly important to determine the direction and rate of Groundwater – Surface-water (GW-SW) exchange. This is critical in situations where groundwater over-abstraction could impact surface waters, and affect the water balance (Mazza et al. 2014). Zume and Tarhule (2008) have suggested that there is an urgent need to understand river – aquifer interactions in these regions. GW-SW interactions reflect *inter alia* the distribution of hydrofacies at the interface between river and aquifer (Woessner 2000; Sophocleous 2002) which vary according to topography, geology and climate. Better understanding of GW-SW exchange is required to achieve conjunctive management plans of GW-SW resources whilst minimising impacts on surface-water bodies and maintaining river flows.

Although a number of studies have investigated the impact of water demand and climate variability/change on ‘bedrock’ aquifers (Holman 2006), fewer studies have focused on shallow alluvial aquifers (Zume and Tarhule 2011). There are particular problems with respect to the latter systems: whilst initially a productive source of water, they are sensitive to over-abstraction as demonstrated by Alemayehu et al. (2007) in eastern Ethiopia. This study found that over-abstraction resulted in the drying-up of two lakes thereby compromising local groundwater inflow.

In this context, this paper aims to assess the sustainability of current rates of alluvial groundwater abstraction on the floodplain of Upper River Benue, Nigeria. Continued unregulated irrigation in this area has increased the dependence of the local population on alluvial groundwaters to meet their water requirements. Accordingly, we describe here, the hydrology of this system using a groundwater model to replicate the dynamics of the floodplain water table. Thus we are able to consider variations in the principal stresses impacting the system: 1) current global change scenarios contributing to desertification (low precipitation and high evaporation); 2) changes in the river flow regime (essentially reduced river stage) to illustrate potential impacts following flow regulation associated with dam construction upstream in Cameroon; and 3) increases in groundwater abstraction for irrigation. We first develop a conceptual model of the Upper River Benue alluvial aquifer by assembling all the available subsurface information from borehole logs, water level monitoring and groundwater abstraction. This information is then used to summarise the subsurface geology and develop a two-dimensional model of the floodplain as described below.

2 Study area

The study area comprises part of the Upper Benue Basin which has a total catchment area of ~750 km^2 (Figure 1). Surface elevations in the study area vary from 149 to 228 m above mean sea level. The prominent landforms are the Adamawa highlands characterized by high relief surrounded by irregular slopes and plains (Ankidawa et al. 2009). The region has a tropical climate: maximum (minimum) temperatures are 45°C (15°C) and the mean annual temperature is 30°C. Mean annual precipitation is ~914 mm, but there are strongly contrasting dry and rainy seasons: 85% of the precipitation falls between July to September, with greatest rainfall occurring in July and August, whilst the dry season extends from late November to May and is characterised by the Harmattan wind blowing from the Sahara Desert. Nevertheless, Inter-annual variability of precipitation is high (coefficient of variability: 25%), and consequently, the region is vulnerable to drought (Figures 2 and 3) and sporadic water shortages that have a significant impact on agriculture, with a heavy dependence on irrigation during the dry season.

The River Benue is the largest and only perennial river in the region, and is fed by two major tributaries: the River Faro and Mayo Kebbi, with the headwaters of both rivers lying in Cameroon (Figure 1). The average discharge of River Benue at Yola gauge station is about 3,500 m^3/s. The Lagdo Dam constructed in 1982 impounds the River Benue in Cameroon and has increased the flow of the River Benue in the dry season. Before the Lagdo Dam construction, minimum flow in River Benue at Yola gauge station (November to June) during the dry season period used to be 10 to 20 m^3/s (Toro, 1997). However, after the dam construction and the start of its operation in 1984, the minimum water flows rose to about 60 m^3/s, tripling the water level in the River Benue after the dam's construction. One effect of this has been to increase groundwater levels in the alluvial aquifer associated with the Benue River downstream, particularly in the Yola region.

The study area is underlain by sedimentary deposits, which comprise two stratigraphic units (Ezeigbo et al. 1996): relatively coarse Quaternary alluvium (sands and gravels) and a Cretaceous sedimentary unit - the Bima sandstone. The alluvial deposits of the River Benue and its tributaries comprise sands, clays, silts, silty-clays and pebbly-sands (Obiefuna et al. 1999). Stratigraphically, the Bima sandstone comprises alternating layers of poorly to moderately consolidated fine to coarse grained sandstones, clay-shales, siltstone and mudstone with a mean thickness of >250 m (Carter et al. 1963; Obiefuna and Orazulike 2011). Land use in the vicinity of the study area is mainly agriculture, which relies upon irrigation during the dry season. The main crops include, rice, wheat, maize, pulses, oilseeds and vegetables.

Two automatic piezometers MAlog itmsoil instrument (Itmsoil, 2012) situated 500 and 1,000 m from the river (Figure 1) were installed to continue monitoring the water levels in wells for the period of twelve months April 2012 to April 2013 to estimate the changes for the groundwater levels. The piezometers were installed to the depth of 5 m at piezometer 1 and depth of 6 m at piezometer 2 and were measured with an approximate accuracy of ± 0.0002 to 0.0003 cm. The piezometers were used to examine the variation in hydraulic head with distance from the River Benue to determine the hydrological significance of the river and to investigate the relationship of the floodplain water-table to precipitation.

3 The hydrostratigraphy of the alluvial floodplain of the research area

The floodplain stratigraphy was investigated by hand auger surveys along a 1,500 m transect, here termed transect 1 (Figure 4). Auger holes were extended to depths below the surface of 6 to 18 m, below lenses of clayey silt and sandstone prevented further excavation. The deposits consisted mainly of clayey silt, sandy silt and alluvial sands. A thick sand bed was discernible in the entire section at different depths and locations, ranging between 5 and 18 m depth on the floodplain.

Where clayey silt beds were intermixed with sandy silt, the deposits effectively consitituted an aquitard. Probably contributing to the formation of a perched aquifer at some points in the floodplain. The composition of the clayey silt lens tends to become increasingly coarse with distance from the River Benue, and it is also coarser towards the top of the formation. The sandy silt formations predominate close to the river, whilst away from river, sandy silt and clayey silt formations are more common. The sedimentary layers cannot be easily distinguished and appear to be hydraulically connected. Consequently in developing the model, one model layer was deemed sufficient. To represent the study area, cells had dimensions of 100 x 100 m to form 1 row and 100 columns a model grid.

4.0 Conceptualisation

The development of a groundwater model of the alluvial aquifer relies upon the specification of an appropriate conceptual model to assess: i. rates of groundwater; ii. flow through the floodplain; and iii. the impact of changes in the flow of the River Benue.

Preparation of a water budget involves the identification and quantification of all water flows into the system as well as flow direction and water flows out of the system. Water inflows into the system include groundwater recharge from precipitation, or recharge from surface water bodies such as rivers. Water outflows include base flow to streams, evapotranspiration and groundwater abstraction from wells.

4.1 Boundary condition

The model area was considered as a closed basin, with no lateral groundwater inflow or outflow. The only means of groundwater inflow is through the surface water outflow at the north-western boundary of the area by River Benue. No-flow boundary conditions were proscribed to the east, west and south of the model, and no water fluxes were permitted across these boundaries. The north-eastern boundary was described using a specified head boundary, as this is the point of contact between the River Benue and the floodplain. The top of the aquifer layer was taken as the river and water table elevation. The elevation of the alluvial surface was estimated from 24 resistivity sounding points in the floodplain. The bottom of the aquifer layer was assumed to be the contact between alluvium and the underlying sandstone and was represented as a no flow boundary. Bedrock elevations were also obtained from the resistivity survey. The arrangement of the top and bottom boundary conditions enables recharge cells to have a different flux values for each time period of the transient simulations.

The model was developed for the period January to June 2012. This enables determination of the aquifer response to changes in river level and abstraction during the dry season period. The period also coincides with a time when floodplain water levels were measured. The initial, starting, heads for the model were taken as the observed heads measured at the beginning of the model period (Jan 1 2012). The characteristics of the layer are summarised in Table 1.

Groundwater was assumed to be recharged solely by rainfall, which vary between 800 and >1,000 mm annually. Recharge was assigned to the top cell of the model, and was determined from weekly rainfall. ET is one of the principal mechanisms of groundwater discharge in vegetated and shallow groundwater systems of semi-arid environments (Ajami et al. 2011). Model evapotranspiration was estimated in the MODFLOW by assuming water loss across the floodplain between water table and cut-off depth. Daily evaporation recorded by the UBRBDA, at Yola weather station (Figure 2) was used to estimate evapotranspiration to the model. Any water from irrigation that are not consumed by vegetation in the landscape, stored in the soil is assumed to be evaporated, as the model only considered loss of water from the groundwater depth of 20 m. The approach taken to simulate evapotranspiration (ET) in MODFLOW is based on the following assumptions: when the water table is at or above ground level then ET losses occur at the potential rate (ET); when the depth of the water table below ground level exceeds a certain interval (termed the ET extinction depth; for which a value of 7 m was adopted, ET losses cease; and between these limits, evapotranspiration (ET) varies linearly with water table elevation.

4.2 Numerical modelling

Modelling water exchange between aquifers and rivers requires the simultaneous solution of two separate equations, which describe river flow and groundwater flow through alluvial sediments (Bradley and Petts 1995). In this study, measured floodplain water levels were used to describe the potentiometric-surface, while twelve different pumping tests were completed to estimate the hydraulic conductivity, transmisivity and storage capacity. Nielsen (1991) method for estimating hydraulic conductivity was used. As the rate of groundwater extraction by pumping wells for irrigation for the floodplain is largely unknown, pumping rates used for the pumping tests during the fieldwork for determination of hydraulic conductivity was used. The rate for the pumping tests is similar to the extraction rate used by farmers to extract groundwater for irrigation activities. Groundwater extraction was estimated considering the numbers of wells along transect 1, which are 80 wells. The rate of pumping was estimated at 172.8 m^3/day which is equivalent to the rate of pumping farmers irrigate their farms on weekly bases.

A transient two-dimensional profile model was developed using MODFLOW (McDonald and Harbaugh 1988) to investigate variations in groundwater flow between the River Benue and the shallow alluvial aquifer. The following MODFLOW packages were used: The well (WEL) package, which can simulate specified recharge or discharge features, General-Head Boundary and influent – effluent river flow were used to describe individual water fluxes through the floodplain. Figure 5 shows the simplified cross-section which was used to represent hydraulic properties along a profile at right angles to the River Benue. The floodplain is envisaged as a single hydrogeological layer with a high hydraulic conductivity (2.884×10^{-1} m/s). The River Benue is represented to the right of the cross-section and exchanges of water between the floodplain and river are assumed to occur through the river bed and the alluvial floodplain aquifer.

The cross-section in Figure 3 formed the basis for the model development, which was constructed by overlaying a rectangular model grid extending ~1,500 m to the north and 2,000 m to the east, orientated to coincide with the monitoring wells centered upon one borehole transect extending from the River Benue (transect 1). The stratigraphy in Figure 3 was represented by a single layer, which was obtained by aggregating the observed distribution of deposits to produce a simplified horizontal and vertical representation of sediments. A clayey silt layer was envisaged to underlie the whole of the model area, and formed the lower, no-flow, boundary of the model. The layer comprised sand and sandy silt deposits, which formed an unconfined layer, extending 1,500 m across the floodplain of the River Benue. Individual cells had dimensions of 100 m x 100 m, to produce a grid of 1 row and 100 columns. The choice of cell dimensions was determined based on the spacing between adjacent wells and the expected water table gradient (Grapes et al. 2005).

A summary of the model data required and an indication of how the values were obtained is provided in Table 1. Hydraulic conductivity was obtained from pumping test data, river bed conductance parameter was assumed as 1987 according to (Freeze and Cherry 1979). The river bed conductance was assumed based on the simulated hydraulic heads in the model. Boundary conditions were specified for the top, bottom and sides of the model area.

4.3 Model calibration

Model parameters, which can be adjusted during the calibration process, include hydraulic conductivity, specific yield or storativity, river bed conductance and groundwater recharge. In this case, model calibration was performed by varying the river water stage, initial head, hydraulic conductivity and specific yield with the aim of understanding the variation of hydraulic head throughout the model. Mean groundwater levels for the period January to June 2012 were used as targets for the calibration. The groundwater levels represent the weekly mean of daily measurements taken manually at wells during the dry season period. The initial water levels, comprising an interpolated array (derived from field-observations) were also used in calibration. The calibration ensures that observed and simulated groundwater level also match at various time steps, thereby reducing uncertainty in parameter estimates (e.g. Allen et al. 2004). Calibration was achieved by adjusting the specific yield until simulated heads matched weekly-observed groundwater levels in observation wells.

4.4 Sensitivity analyses

The model was calibrated by manual trial-and-error method, manual calibration may not accurately assess the model reliability result. Therefore, calibration was further carried out by detail sensitivity analysis. Sensitivity analysis is very important step in all modelling application (McDonald and Harbaugh 2005).

Aquifers parameter values, which were considered for the sensitivity analysis, include hydraulic conductivity, specific yield and river-bed conductance. The model was run with by varying values for each of these aquifer parameter values in order to assess the reliability of the model. Hydraulic conductivities were varied in the range 150 to 300 m/day, specific yield from 0.1 to 0.3 m^2/day and river bed conductance from 500 to 1,987 m^2/day. Model heads are sensitive to low values of hydraulic conductivity (<150 m^2/day). Modelled river seepage to the floodplain (effluent seepage) was most sensitive to specific yield values (<0.1 m^2/day). At values above this, much difference occurred between modelled and observed heads. The assumed river-bed conductance is increased significance at low values (<500 m^2/day).

The overall model output was most sensitive to specific yield, and then river bed conductance, but showed relatively little variation with hydraulic conductivity. As model outputs are sensitive to all these parameters and the model was generally well calibrated, the uncertainty should be small when the calibrated model is used for predictive purposes. However, the major flux in the model, i.e. river seepage, was not calibrated against any direct measurements. The calibration process found a strong correlation between river seepage and specific yield. Consequently, model predictions are still subject to some uncertainty associated with river seepage. Future investigations should focus on obtaining data that enable seepage to the river to be estimated with more confidence.

4.5 Predictive scenarios

In a predictive simulation, the hydraulic head values obtained during calibration process are used to predict the system response to future events. The model prediction depends largely on the result of the calibration and sensitivity analysis (Anderson and Woessner 1992). The model was then used for three different predictive model runs which sought to evaluate the response of the alluvial aquifer to different stress scenarios including:

i. Global climate change leading to the most likely scenario of desertification (i.e. lower precipitation and higher evaporation).

ii. Changes in river stage; specifically low, mean and high river stages for the period January to June (1960 - 2012).

iii. Changes in groundwater abstraction for agriculture: low, mean and high abstraction rates for irrigation across the floodplain.

5.0 Results

5.1 Calibration

Figure 6 indicates the strong agreement between simulated and observed hydraulic heads at the two piezometers for the transient model run. Model accuracy was estimated using the root mean square (RMS) error between actual hydraulic head measurements and model generated hydraulic head at the end of each model run:

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(h_m - h_s)^2}{n}} \qquad 1$$

Where h_m and h_s are the measured and simulated hydraulic head and n is the total number of monitoring wells (n=2). A very high value of RMS of ~0.1 m has been obtained this suggests that the model calibration under transient conditions had satisfied result. This value was based on measured (actual) versus predicted (simulated) water levels and should be <5%. The correlation coefficient is equal to 0.87.

Simulated versus measured groundwater levels are plotted in Figure 7 for points corresponding to the two observation piezometers. Well locations are shown in Figure 1, and as Figure 7 shows, there was a fairly good correspondence between simulated and measured groundwater levels at these two points. On this basis, it was concluded that the numerical model provides a reasonable representation of the variation in hydraulic heads across the modelled area of floodplain.

The water-table gradient along the modelled cross-section is plotted in Figure 8 for February, April and June 2012. Groundwater heads decrease with distance away from the River Benue. It is also clear that in February, groundwater levels were high, with lower groundwater levels in April, the peak period of the dry season. In June groundwater levels begin to rise as the rainy season approached and groundwater abstraction for irrigation slowly decreased.

5.2 Water budget for the model output

Water budgets, giving the difference between modelled water inflows and outflows, are summarised in Figure 9. The floodplain water budget includes the following fluxes: i. recharge through precipitation; ii. loss of water through evapotranspiration, iii. groundwater abstraction by pumping wells and iv. influent seepage (seepage from the river to the alluvial aquifer). Errors in the model water balance are shown in the lower panel of Figure 10, which illustrate the relationship between the timing of positive and negative water balance errors and recharge. While precipitation and evapotranspiration were estimated using data from a local weather station (as described above), seepage to and from the river is estimated from MODFLOW's water budget calculations. These are defined for each stress period by the equation:

$$\mathrm{P} + \mathrm{Inf}_{\mathrm{RIV}} + \mathrm{S}_{\mathrm{OUT}} + \mathrm{CH} = \mathrm{ET} + \mathrm{Well}_{\mathrm{IRR}} + \mathrm{S}_{\mathrm{IN}} \qquad 2$$

where inflows comprise precipitation (P), influent seepage from the river ($\mathrm{Inf}_{\mathrm{RIV}}$) water movements from storage ($\mathrm{S}_{\mathrm{OUT}}$) and flow of water from the Constant Head boundary (CH) and outflows are evapotranspiration (ET), well abstraction ($\mathrm{Well}_{\mathrm{IRR}}$) and water movement to storage (S_{IN}).

The mass balance graph in Figure 9 shows the volume of water entering and leaving the system (reflected through the boundary conditions), while the relationship between the storage terms (In and Out) to recharge and river seepage are summarised in Figure 10. The final transient state model produced a mass balance error of 0.23%. According to Anderson (1993) the discrepancy in the model should be <1%.

As expected, the mass balance data shows that river seepage is the primary water inflow (212,372 m^3/day) representing ~75% of the total input to the alluvial aquifer while rainfall (61,472 m^3/day) represents ~21.5% of the total water inflow over the period. The constant head boundary provides a significant input (10,283 m^3/day) equivalent to ~ 3.5% of the total inflow. Model outputs are dominated by groundwater abstraction by pumping wells which total 165,775 m^3/day, representing 55.5% of the total outflow while evapotranspiration (132,792 m^3/day) represents 44.5% of the total outflow.

When losses from the modelled area via groundwater abstraction from pumping wells and evapotranspiration, are subtracted from the recharge from: i. river seepage; ii. recharge from rainfall and iii. recharge from the constant head boundaries, the volume of water leaving the aquifer is ~14,400 m^3/day. Over the period modelled, the amount of water withdrawal exceeds groundwater recharge.

In the process of model calibration, the two observation wells shows slight differences between observed and modelled data at some stress period as shown in Figure 7. These discrepancies are possibly due to the effects of intensive irrigation activities locally, and some discrepancies could arise due to errors in determining surface elevations across the floodplain. Another reason for choosing this simulation period is that it coincides with the period when groundwater levels were observed for the first time in the research area.

5.3 River water stages scenario

River water stage scenarios were completed for low, mean and high river water stages to assess the implications for hydraulic heads across the floodplain. Inflow to the system consists of recharge from rainfall of 60,851 m^3/day represents 33% from low river water stages; 61,472 m^3/day represents 33.5% from average river water stages and similarly 61,472 m^3/day represents 33.5% from high river water stages. Recharge from rainfall shows no influence to the floodplain alluvial aquifer. Recharge from river seepage consists of 0% from low river water stages (Figure 11A); 101,339 m^3/day represents 44% from average river water stages and 219,546 m^3/day represents 56% from high river water stages. This shows that high river water stages have a positive impact to the alluvial aquifer while low river water stages have a significant negative impact. High water in river during the dry season increases the floodplain groundwater levels which can be abstracted easily with the hand drilling technique. They are no changes in recharges from boundary constant head for low, average and high river water stages. Model output dominated by evapotranspiration consists of 131,304 m^3/day represents 33.1% from low river water stages, 132,702 m^3/day represents 33.4% from average river water stages and 132,824 m^3/day represents 33.5% from high river water stages. This shows that there are no variations for the outflows from evapotranspiration for the river water stages scenario, despite the lower floodplain water-table. Output from wells pumping rates consists of 0% from low river stages; 165,775 m^3/day represents 50% from average river water stages and 165,775 m^3/day represents 50% from high river water stages for the outflows from the system.

5.4 Wells pumping rates scenario

Wells pumping rates scenarios were simulated at low, mean and high abstraction rates to assess the implications for hydraulic heads across the floodplain. Water inflows consisted of recharge from rainfall were 61,472 m^3/day (low wells pumping rates), 61,472 m^3/day (mean abstraction rates) and 60,851 m^3/day (high abstraction rate). This shows that there is no difference for recharge from rainfall for the three different wells pumping rates. Recharge from river seepage consists of 144,819 m^3/day represents 34% from low wells pumping rates, 283,717 m^3/day represents 66% from average wells pumping rates and 0% from high wells pumping rates (see Figure 11B). This shows that average wells pumping rates has the highest river seepage to the system and high wells pumping rates have zero river seepage to the floodplain alluvial aquifer. Outflows from the system due to evapotranspiration are similar for the three wells pumping rates. Outflows from wells pumping rates consisted of 89,856 m^3/day represents 26.5% form low wells pumping rates, 248,873 m^3/day represents 73.5% from average wells pumping rates and 0% from high wells pumping rates. It is clear that increased groundwater abstraction leads to increased river seepage. This shows that over-exploiting the shallow alluvial aquifers of the floodplain during the dry season period will lead to drying the wells on the floodplain.

5.5 Global climate change scenario

Recharge from rainfall consists of 0% to the floodplain estimated from the most likely global climate change. This is based on data for the severe drought in 1966; 100,551 m^3/day represents 70% from the less likely global climate change scenario (Figure 11C). It is based on data for the severe flood event of 2012 and 42,590 m^3/day represents 30 % from the likely global climate change scenario. Recharge from constant head consists of 16,142 m^3/day represents 42% from the most likely global climate change leading to desertification, 14,006 m^3/day represents 22% from likely global climate change and 8,612 m^3/day represents 36%

from less likely global climate change. Model output are dominated by evapotranspiration consisted of 202,706 m^3/day represents 39% from the most likely global climate change leading to desertification, 185,928 m^3/day represents 36% from the likely global climate change and 131,697 m^3/day represents 35% from less likely global climate change. The most likely global climate change leading to desertification shows high outflows from the system while the less likely global climate change leading to increased humidity shows least outflow from the system.

6.0 Discussion

The main direction of horizontal groundwater flow in the model was along east-west axis, from the River Benue towards the floodplain aquifer. This was expected from the conceptual model as groundwater flows preferentially towards the steepest hydraulic gradient (Bradley 2002). Similar flow direction was observed on the alluvial floodplain of Helwan, Nile basin in Egypt (Abadalla and Scheytt 2012). The floodplain aquifers are mostly fed by seepage from the River Benue and often partially fed by Lake Geriyo eastern part. The simulated seepage to the floodplain alluvial aquifer was determined on a weekly basis. The simulated river seepage to the floodplain is ~212,372 m^3/day and groundwater discharge to the river is zero. The simulation was considered for the dry season period (January to June), where the floodplain alluvial aquifers mostly depend on the river seepage, and this was maintained by a dam built upstream in the neighbouring country Cameroon. Lake Geriyo has water all the year round, partially contributing to the floodplain during the dry season period.

This paper describes the successful development of a transient state groundwater flow model that was calibrated against existing groundwater level data collected during field work on the floodplain of the Benue River. The modelling results provide clear evidence of variations in water seepage rates through the river bed and the alluvial aquifer. The model is useful in suggesting the importance of possible mechanisms of water flow, and enabling the examination of specific scenarios that have important water resource implications.

Low-flow in the river during the dry season period has led to drying of the floodplain in arid and semi-arid region of Australia (McCallum et al. 2013). Similarly study by Ahmed and Umar (2009) showed that low river water stages lowered the shallow alluvial aquifers across the floodplain in the Uttar Pradesh River semi-arid area of India. The low river stage scenario shows much variation in hydraulic head across the floodplain. Low river water stage has a significant negative impact that lowers the groundwater levels across the floodplain with the cessation of river seepage to the system. The consequence of this is that the floodplain water-table is lowered to a point where groundwater extraction using hand drilling techniques is no longer possible (Figure 11A). This is the critical point for farmers. The river stage scenario result shows that if the Cameroon Government decided to change the mode of operation of the Lagdo Dam, that is by diverting the flow to the other source, this will have a severe impact to the study site, since at low river water stages in River Benue during the dry season period, the floodplain groundwater abstraction is beyond the limit with the hand-drilling method. This is consistent with what was reported by Merz (2012) in the semi-arid of the Murray River Australia, reduced stream flows reduced the recharge volume into aquifers via alluvial floodplains. Study by Abu-Zeid and El-Shibini (1997) showed that the post construction of the Aswan High Dam in Egypt has cause reduction of the floodplain groundwater level in the range of 0.7 to 0.3 m. Similarly, study by Sun et al. (2012) showed that the impacts of three Gorges Dam in China caused severe reduction in groundwater level downstream in the range between 3.30 and 3.02 m. High river water stages were simulated using data from a severe flood in 2012. High river stages show positive impact contributing about 68% of the river seepage to the floodplain. This raises groundwater levels across the floodplain, which will be easier for hand drilling technique to abstract groundwater for irrigation.

The model simulations indicate that any reduction in groundwater abstraction rates have a positive impact on the alluvial aquifer. When floodplain water levels are higher, groundwater abstraction is easier for farmers (using hand drilling technique). However, when abstraction rates are increased, both river levels and the floodplain water-table fall to points below which continued abstraction is no longer possible via hand drilling methods. This is the critical depth for the farmers as hand drilling can only abstract groundwater to depths not exceeding 40 m below the surface. Rai and Manglik (2012) showed in their study that pumping rates have significant effects on the floodplain groundwater table. Elsewhere, there are examples of instances where this threshold has been passed: overexploitation of an alluvial floodplain aquifer in eastern Ethiopia has dried up two important lakes (Alemayehu et al., 2007). Study by Van Oel et al. (2013) showed that over-pumping lowered the groundwater level by 0.8 m on the alluvial floodplain in semi-arid of Kenya. Study by Arabi (2012) showed that over-exploitation lowered the shallow alluvial aquifers along the western floodplain in Nile Basin of Egypt. Similarly, study by Sidiropoulos et al. (2013) showed that overexploited aquifer on the alluvial floodplain aquifer in semi-arid area of Greece lowered the floodplain groundwater. In order to continually using hand drilling technique for abstracting the groundwater across the floodplain, excessive wells abstractions should be minimized. Alternatively, regulation for pumping rates and water wastage should be minimized. Farmers should be advised on how to utilize the water properly according to their irrigated crops demand.

Desertification was simulated with the information from the 1966 severe drought, which led to significant reductions in the flow of the River Benue and in the floodplain water-table. Similar reduction of the groundwater level was observed on the alluvial floodplain of Murray-Darling basin in semi-arid of Australia, from the climate change scenario (Kirby et al., 2013). It is hypothesised that simulating these data with the 1966 drought could show a greater negative impact on the floodplain by lowering the floodplain water table to depths beyond which continued groundwater extraction by the hand drilling is no longer possible. The results (Figure 11C) as it were expected it show a severe negative impact to the floodplain as was hypothesised, the simulation show zero river seepage (influent flow) to the floodplain. This implies that the most likely global climate change scenario have a significant negative impact. The most likely global climate change scenarios indicate that the groundwaters on the floodplain are beyond the limits of abstraction using the low-cost hand drilling.

7.0 Conclusions

Alluvial aquifers are a critical source of water in semi-arid regions all over the world. In this study area, alluvial groundwaters are the primary source of water for local farming. The study used a numerical model to evaluate the potential impact of groundwater withdrawal and variations in recharge rates. The results indicate that river seepage (influent flow) is the primary source of inflow to the modelled aquifer (~75 %) and that under normal conditions, groundwater discharge from pumping wells constitutes the largest outflows from the aquifer (~56 %).

Three predictive scenarios were simulated: i. decreased river stage; ii. increased groundwater abstraction; and iii. global climate change. The impacts of these scenarios on groundwater levels and stream – aquifer interactions were compared with the current situation (using observed data). The results show that river water stage, groundwater abstraction and the most likely global climate change leading to desertification, indicate negative impacts on the floodplain aquifer (see Figures 11 A, 11B and 11 C). At low river water stages, high abstraction rates and the most likely global climate change, both river and the floodplain alluvial aquifers go dry. This is a critical depth to abstract groundwater using the hand drilling technique. Thus, these scenarios lower groundwater levels beyond that where abstraction using hand drilling technique is possible.

In conclusion: The hand drilling methods will remain possible for abstracting the shallow alluvial aquifers on the floodplain for the farmers. Unless the following conditions occur: i. low water stages in River Benue during the dry season period due to the management of the Lagdo Dam upstream. This will lower the floodplain groundwater beyond extraction with the low-cost hand drilling method. ii. Over pumping the floodplain shallow alluvial aquifers during the dry season period for domestic use and irrigation activities. This will lower the floodplain groundwater beyond extraction with the low-cost hand drilling method. iii. the most likely global climate change for occurring of droughts in the region . This will lower the floodplain groundwater beyond extraction with the low-cost hand drilling method. The information obtained is useful for the development of the groundwater resources of the floodplain for an effective water scheme for irrigation activities for the research area and possibly beyond nearby areas with similar floodplain.

8.0 Acknowledgements

This study was funded by Petroleum Technology Development Fund (PTDF), Nigerian Government, with additional support from British Geological Survey and Brunel University for the fieldwork surveys.

9.0 Conflict of Interest

There is no any financial Conflict of Interest**.**

References

Abdalla FA, Scheytt T (2012) Hydrochemistry of surface water and groundwater from a fractured carbonate aquifer in the Helwan area, Egypt. J Earth Sys. Sci., 121(1): 109 – 124.

Abu-Zeid MA, El-Shibini FZ (1997) Egypt's High Aswan Dam. Water Resour Develop. 13(2): 209 – 217.

Ahmed I, Umar R (2009) Groundwater flow modelling of Yamuna – Krishni interstream, a part of central Ganga Plain Uttar Pradesh. J Earth Sys Sci 118(5): 507 – 523.

Ajami H, Meixner T, Maddock T, Hogan JF, Guertin DF (2011) Impact of land-surface elevation and riparian evapotranspiration seasonality on groundwater budget in MODFLOW models. Hydrogeol J 19: 1181 – 1188.

Alemayehu T, Furi F, Legesse D (2007) Impact of water overexploitation on highland lakes of eastern Ethiopia. Environ Geol 52: 147 – 154.

Allen DM, Mackie DC, Wei M (2004) Groundwater and climate change: A sensitivity analysis for the Grand Forks aquifer, southern British Columbia. Hydrogeol J 12: 270 – 290.

Alvarez MP, Trovatto MM, Hernandez MA, Gonzalez N (2012) Groundwater flow model, recharge estimation and sustainability in an arid region of Patagonia, Argentina. Environ Earth sci 66: 2097 – 2108.

Anderson MP, Woessner WW (1992) Applied groundwater modelling, Simulation of flow and Advective transport. Academic Press, San Diego. pp. 1 – 381.

Anderson PF (1993) A manual of instructional problems for the U.S.G.S MODFLOW model. U.S. Environmental Protection Agency. pp. 1 – 265.

Ankidawa BA, Hassan A, Balla SK (2009) An assessment of the impact of abattoir effluents on River Chouchi, Yola Metropolis, Adamawa State, Nigeria. Nigerian J Trop Agric 11: 174 – 184.

Arabi NE (2012) Environmental management of groundwater in Egypt via artificial recharge extending the practice to soil aquifer treatment (SAT). Int J Environ and Sust 1(3): 66 – 82.

Boko M, Niang I, Nyong A, Vogel C, Githeko A, Medany M, Osman-Elasha B, Tabo R, Yanda P (2007) Africa In: Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P Palutikof, P.J. Van der Linden and C.E. Hanson, Eds., Cambridge University Press, UK pp. 433 – 467.

Bradley C (1996) Transient modelling of water-table variation in a floodplain wetland, Narborough Bog, Leicestershire. J Hydrol 185: 87 – 114.

Bradley C (2002) Simulation of the annual water table dynamics of a floodplain wetland, Narborough Bog, UK. J Hydrol 281: 150 – 172.

Bradley C, Petts GE (1995) Observations and modelling of influent seepage from the River Wolf, Devon: In. Modelling River-Aquifer Interactions (Edited by P.L. Younger). British Hydrol Socie Occasional Paper 6. pp. 17 – 26.

Carter JD, Barber W, Tait EA (1963) The Geology of parts of Adamawa, Bauchi and Bornu Provinces in North-Eastern Nigeria. Geol Surv Nigeria Bull 30: 1 – 109.

Freeze RA, Cherry JA (1979) Groundwater. Prentice Hall, Englewood Cliffs, NJ. pp. 1 – 604.

Grapes TR, Bradley C, Petts GE (2005) Dynamics of river – aquifer interactions along a chalk stream, the River Lambourn, UK. Hydrol Process 19: 2035 – 2053.

Holman IP (2006) Climate change impacts on groundwater recharge-uncertainty, the way forward. Hydrogeol J 14: 637 – 647.

Itmsoil (2012) “Instrumentation and Monitoring MAlog User Manual”. Itmsoil holding Ltd 1 – 60.

Kirby JM., Mainuddin Md, Ahmad MD, Gao L (2013) Simplified monthly hydrology and irrigation water use model to explore sustainable water management options in the Murray-Darling Basin. Water Resour Manag 27: 4083 – 4097.

MacDonald AM, Calow RC, Chilton PJ (2005) Developing groundwater: a guide to rural water supply. Practical Action Publishing, Rugby, UK 1 – 358.

MacDonald AM, Bonsor HC, Dochartaigh BÉÓ, Taylor RG (2012) Quantitative maps of groundwater resources in Africa. Environ Res Letters 7: 1 – 7.

Mazza R, LaVigna F, Alimonti C (2014) Evaluating the available regional groundwater resources using the distributed hydrogeological budget. Water Resour Manag

McCallum AM, Andersen MS, Giambastiani BMS, Kelly BFJ, Acworth RI (2013) River-aquifer interactions in a semi-arid environment stressed by groundwater abstraction. Hydrol Proc 27: 1072 – 1085.

McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference groundwater flow model. U.S. Geological Survey Techniques of Water-Resources Investigation, Book 6, chap. A1. pp. 1 – 586.

McDonald MG, Harbaugh AW (2005) A modular three-dimensional finite-difference groundwater flow model. U.S. Geological Survey MODFLOW Manual pp. 1 – 201.

Merz SK (2012) Synthesis of groundwater – surface water connectivity knowledge for the Murray – Darling Basin. Murray-Darling Basin Authority Australia. pp. 1 – 75.

Nielsen DM (1991) Practical handbook of groundwater monitoring. Chelsea, Michigan: Lewis. pp. 1 – 717.

Nikoo MR, Karimi A, Kerachian R (2013) Optimal Long-term Operation of Reservoir-river Systems under Hydrologic Uncertainties: Application of Interval Programming. Water Resour Manag 27(11): 3865 – 3883.

Obiefuna GI, Nur A, Baba AU, Bassey NE (1999) Geological and geotechnical assessment of selected gully sites, Yola area, Northeast, Nigeria. J Environ Hydrol 7: 1 – 13.

Obiefuna GI, Orazulike DM (2011) Geochemical and Mineralogical Composition of Bima Sandstone Deposit, Yola Area, NE Nigeria. Resour J Environ Earth Sci 3(2): 95 – 102.

Passadore G, Monego M, Altissimo L, Sottani A, Putti M, Rinaldo A (2012) Alternative conceptual models and the robustness of groundwater management scenarios in the multi-aquifer system of the Central Veneto Basin, Italy. Hydrogeol J 20: 419 – 433.

Rai SN and Manglik A (2012) An analytical solution of Boussinesq Equation to predict water table fluctuations due to time varying recharge and withdrawal from multiple basins, wells and leakage sites. Water Resour Manag 26: 243 – 252.

Sidiropoulos P, Mylopoulos N, Loukas A (2013) Optimal management of an overexploited aquifer under climate change: The Lake Karle Greece. Water Resour Manag 27(6): 1635 – 1649.

Sophocleous M (2002) Interaction between groundwater and surface water: the state of the science. Hydrogeol J 10(1): 52 – 67.

Sun Z, Huang Q, Opp C, Hennig T, Marold U (2012) Impacts and implications of major changes caused by the three Gorges Dam in the middle reaches of the Yangtze River, China. Water Resour Manag 26: 3367 – 3378.

Van Oel PR, Mulatu DW, Odongo VO, Meins FM, Hogeboom RJ, Becht R, Stein A, Onyando JO, Veen AV (2013) The effects of groundwater and surface water use on total water availability and implications for water management: the case of Lake Naivasha, Kenya. Water Resour Manag 27: 3477 – 3492.

Winter TC, Havey JW, Franke OL, Alley WM (1998) Groundwater and surface water: A single resource. U.S. Geological Circular 1139: 1 – 87.

Woessner WW (2000) Stream and fluvial plain groundwater interactions: rescaling hydrogeologic thought. Ground Water 38: 423 – 429.

Zume J, Tarhule A (2008) Simulating the impacts of groundwater pumping on stream – aquifer dynamics in semiarid north-western Oklahoma, USA. Hydrogeol J 16: 797 – 810.

Zume J, Tarhule A (2011) Modelling the response of an alluvial aquifer to anthropogenic and recharge stresses in the United States Southern Great Plains. J Earth Sys Sci 120(4): 557 – 572.

Table 1: Summary of the hydrologic parameters used to describe the model cross-section of the research area

S/NO	Parameter	Value	Remarks
1	Hydraulic conductivity (K) (m/s)	0.021	Obtained from pumping tests data
2	Specific yield (S_y)	0.05	Obtained from pumping tests data
3	River bed conductance (m/d)	1987	Assumed
4	Depth to water table	Piezometer data for the period January to June 2012	Monitoring wells in the fieldwork

List of Figures;

Figure 1.

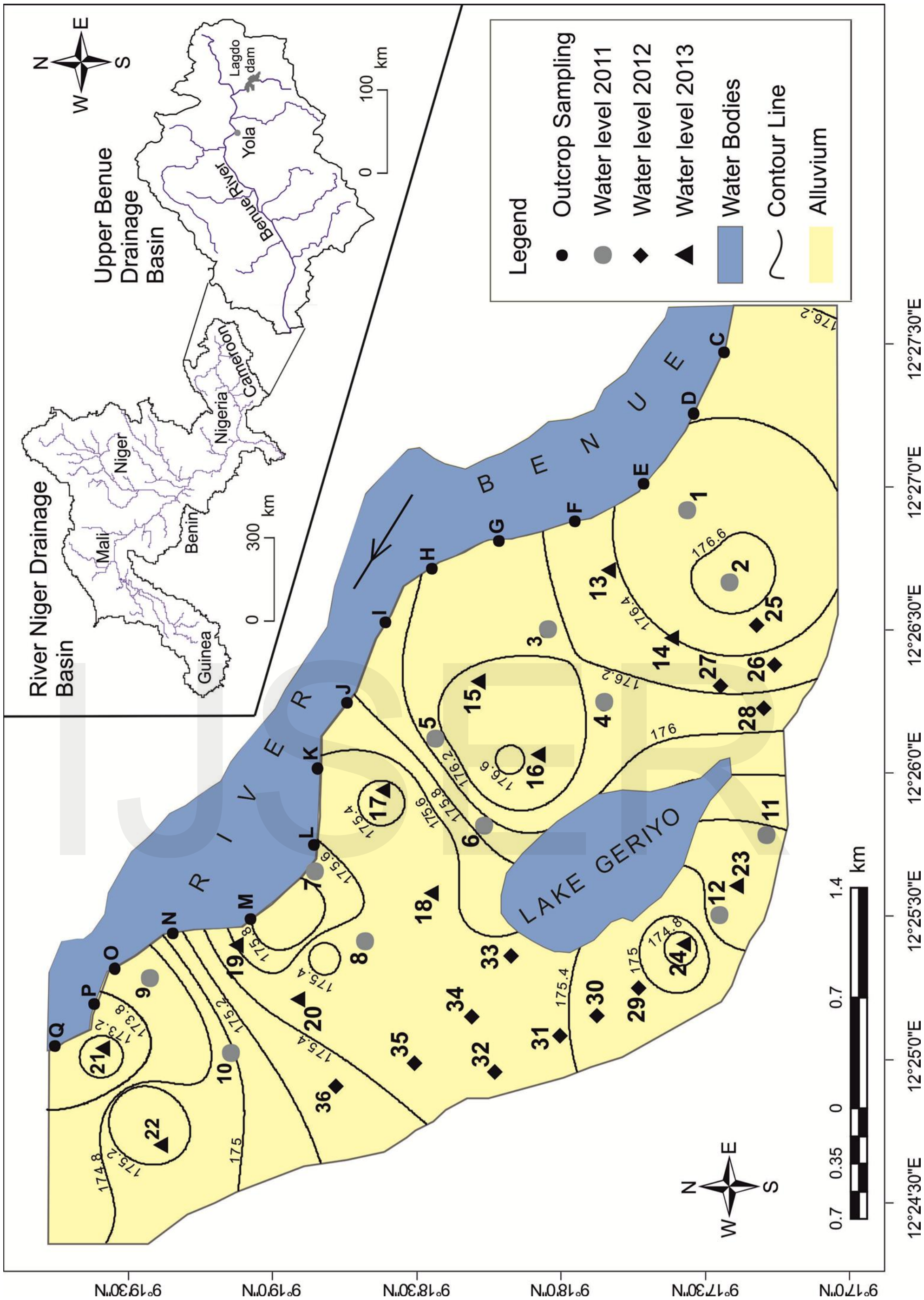

River Niger Drainage Basin
Upper Benue Drainage Basin
Legend
Outcrop Sampling
Water level 2011
Water level 2012
Water level 2013
Water Bodies
Contour Line
Alluvium
RIVER BENUE
LAKE GERIYO
km

Figure 2

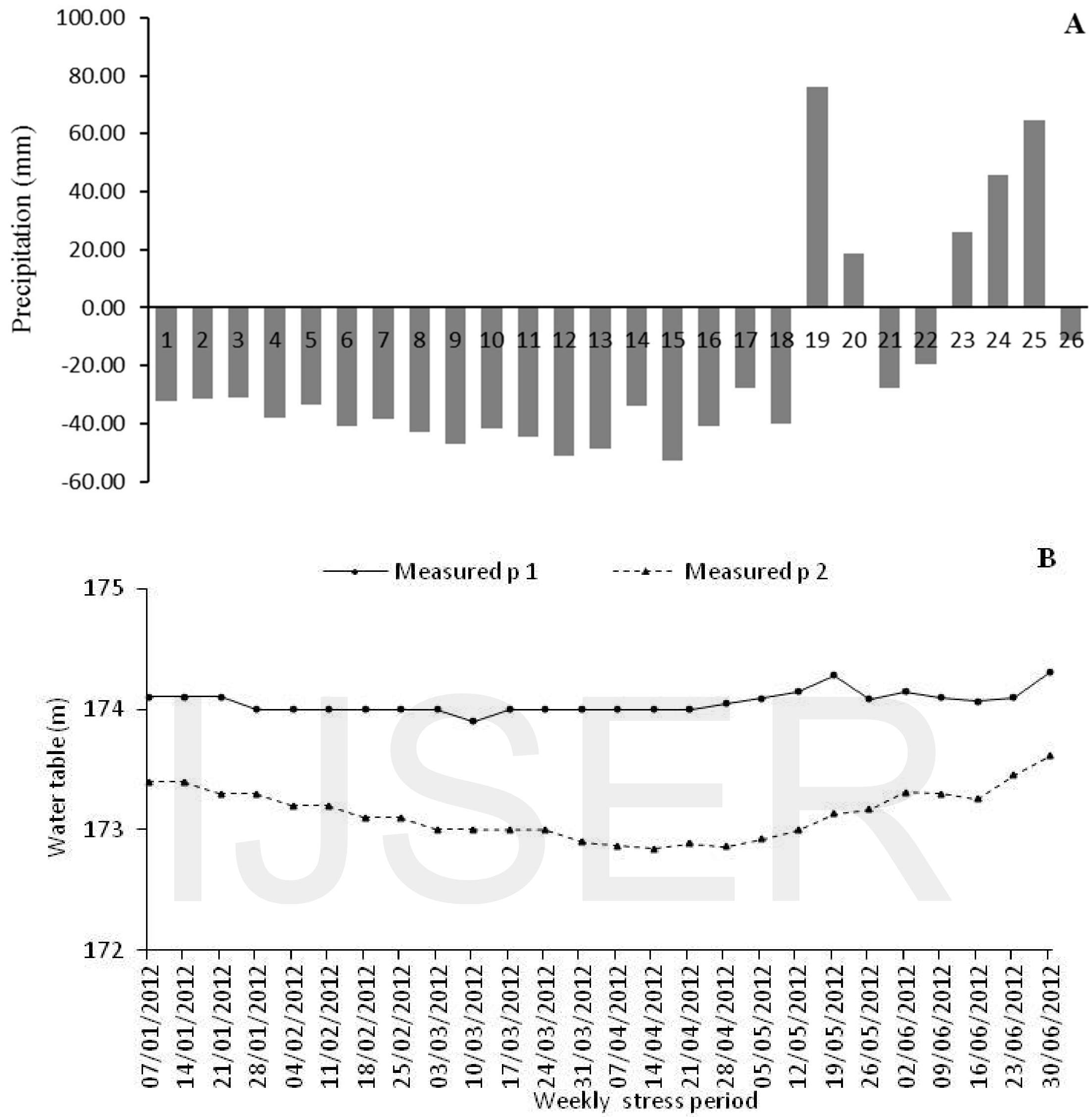

A
Precipitation (mm)
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
B
Measured p 1
Measured p 2
Water table (m)
175
174
173
172
07/01/2012 14/01/2012 21/01/2012 28/01/2012 04/02/2012 11/02/2012 18/02/2012 25/02/2012 03/03/2012 10/03/2012 17/03/2012 24/03/2012 31/03/2012 07/04/2012 14/04/2012 21/04/2012 28/04/2012 05/05/2012 12/05/2012 19/05/2012 26/05/2012 02/06/2012 09/06/2012 16/06/2012 23/06/2012 30/06/2012
Weekly stress period

Figure 3

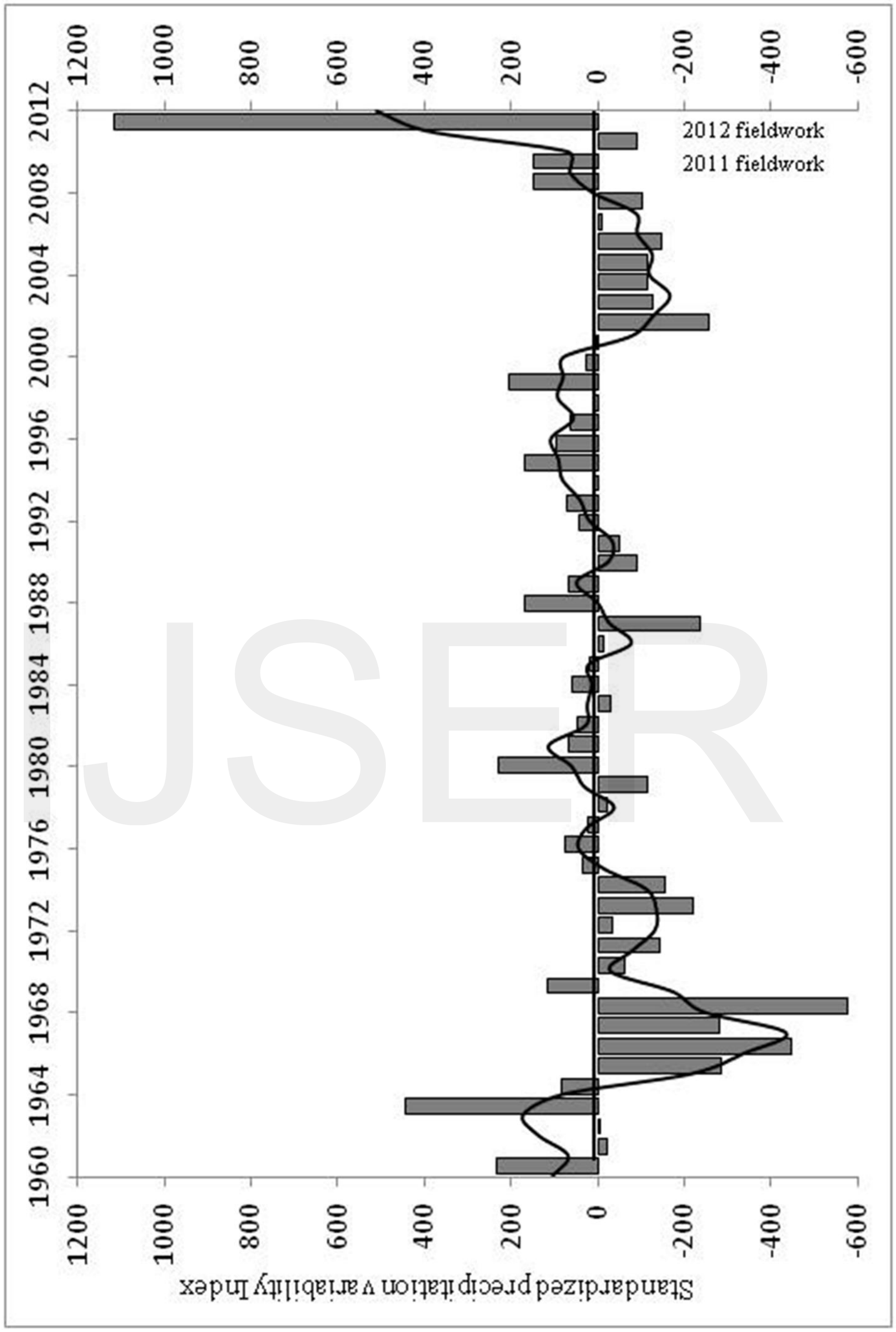

2012 fieldwork
2011 fieldwork
Standardized precipitation variability Index
1960
1964
1968
1972
1976
1980
1984
1988
1992
1996
2000
2004
2008
2012
1200
1000
800
600
400
200
0
-200
-400
-600

Figure 4.

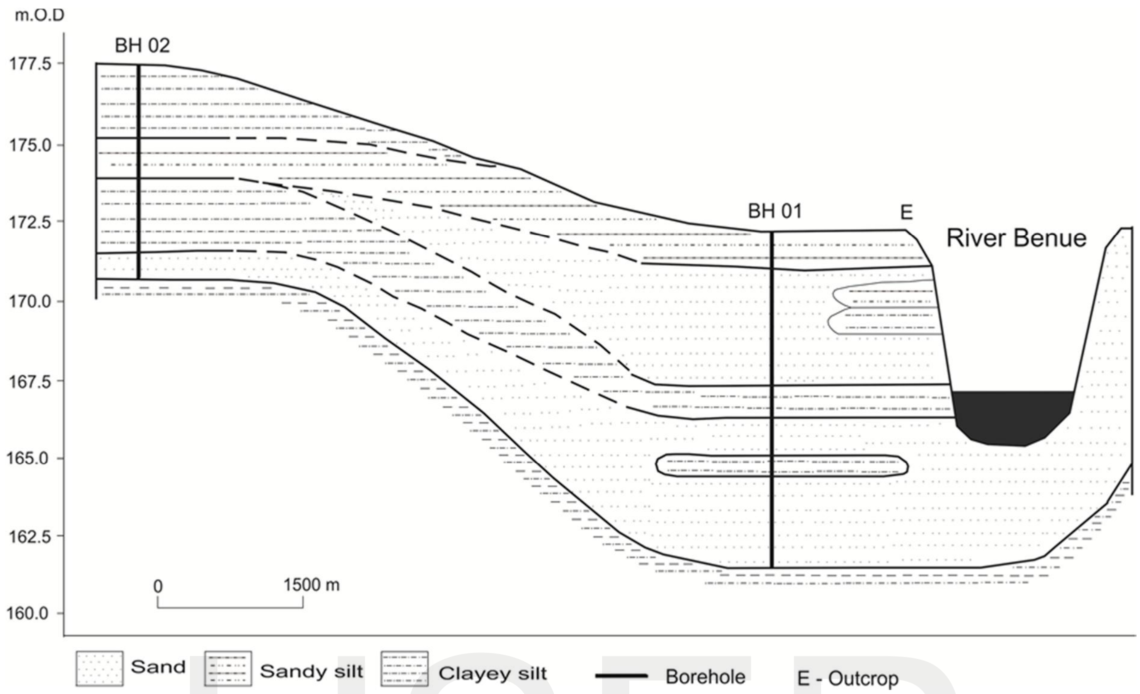


Figure 5

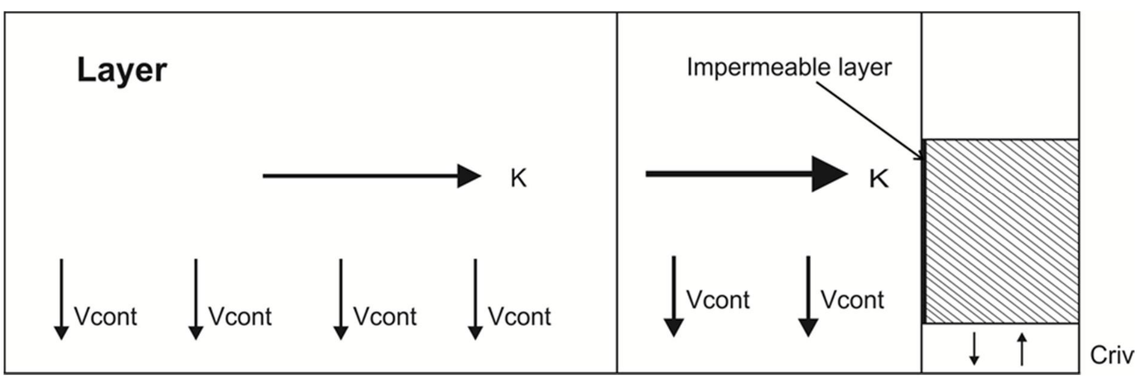


Figure 6

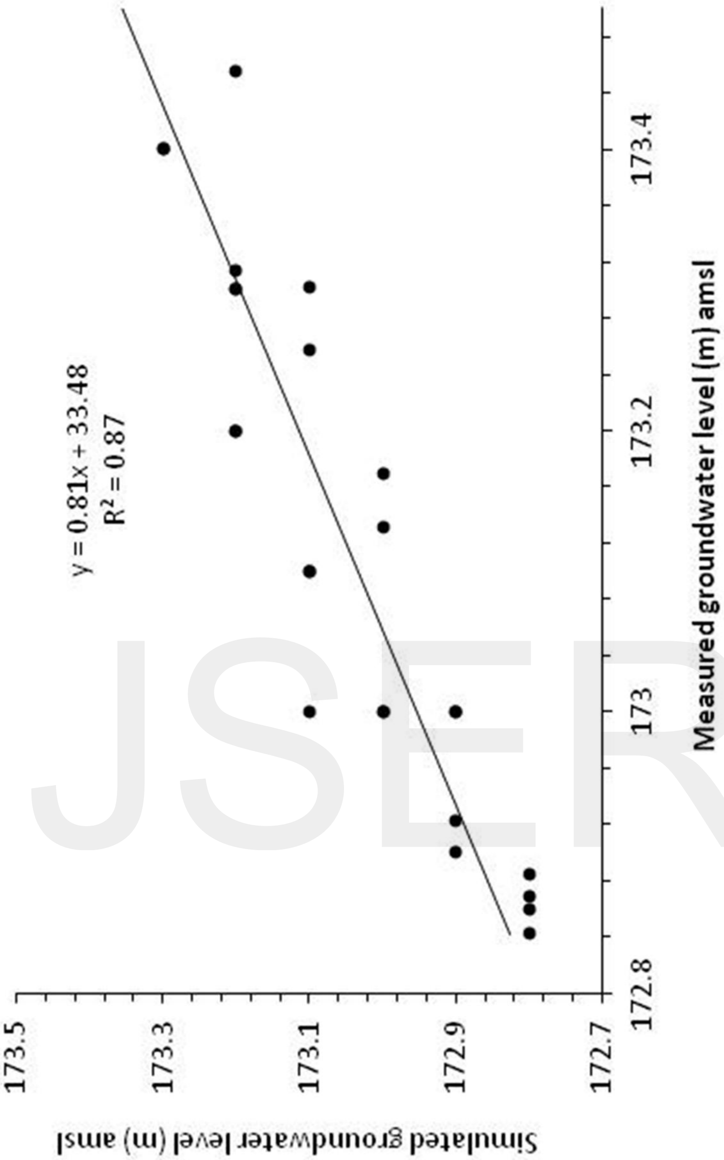

y = 0.81x + 33.48
R² = 0.87
Measured groundwater level (m) amsl
Simulated groundwater level (m) amsl
172.8
173
173.2
173.4
172.7
172.9
173.1
173.3
173.5

Figure 7

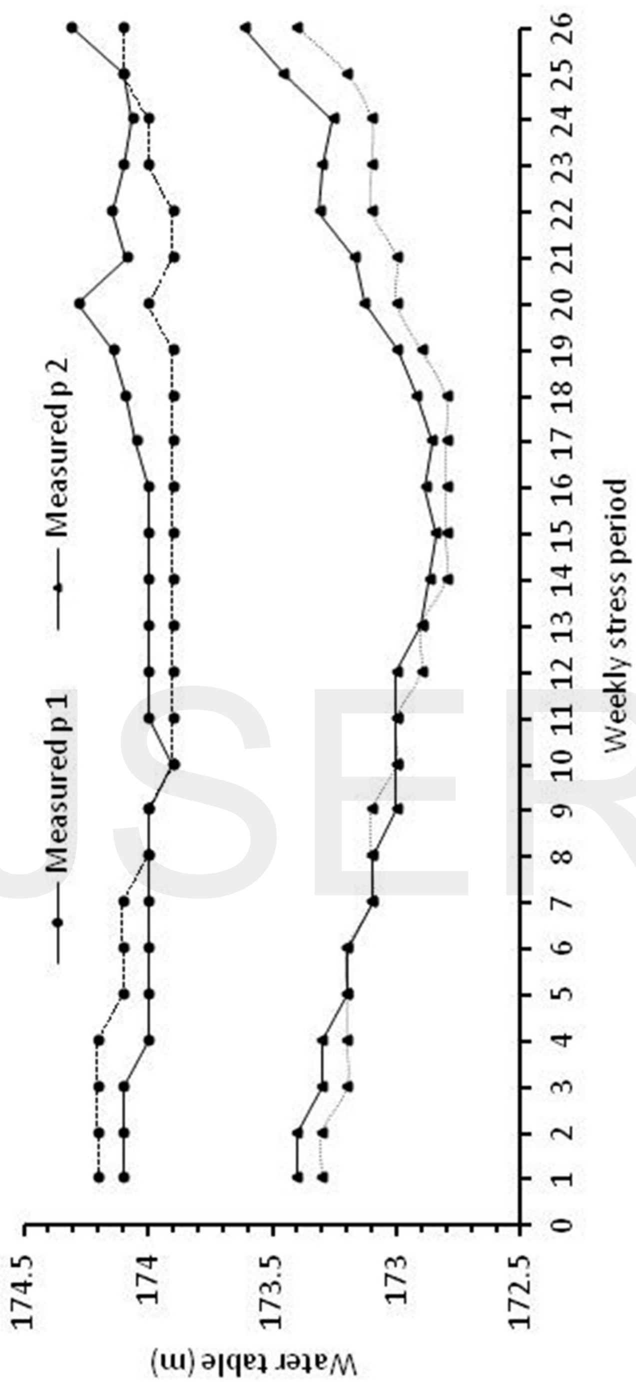

Measured p 1
Measured p 2
Water table (m)
174.5
174
173.5
173
172.5
Weekly stress period
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26

Figure 8

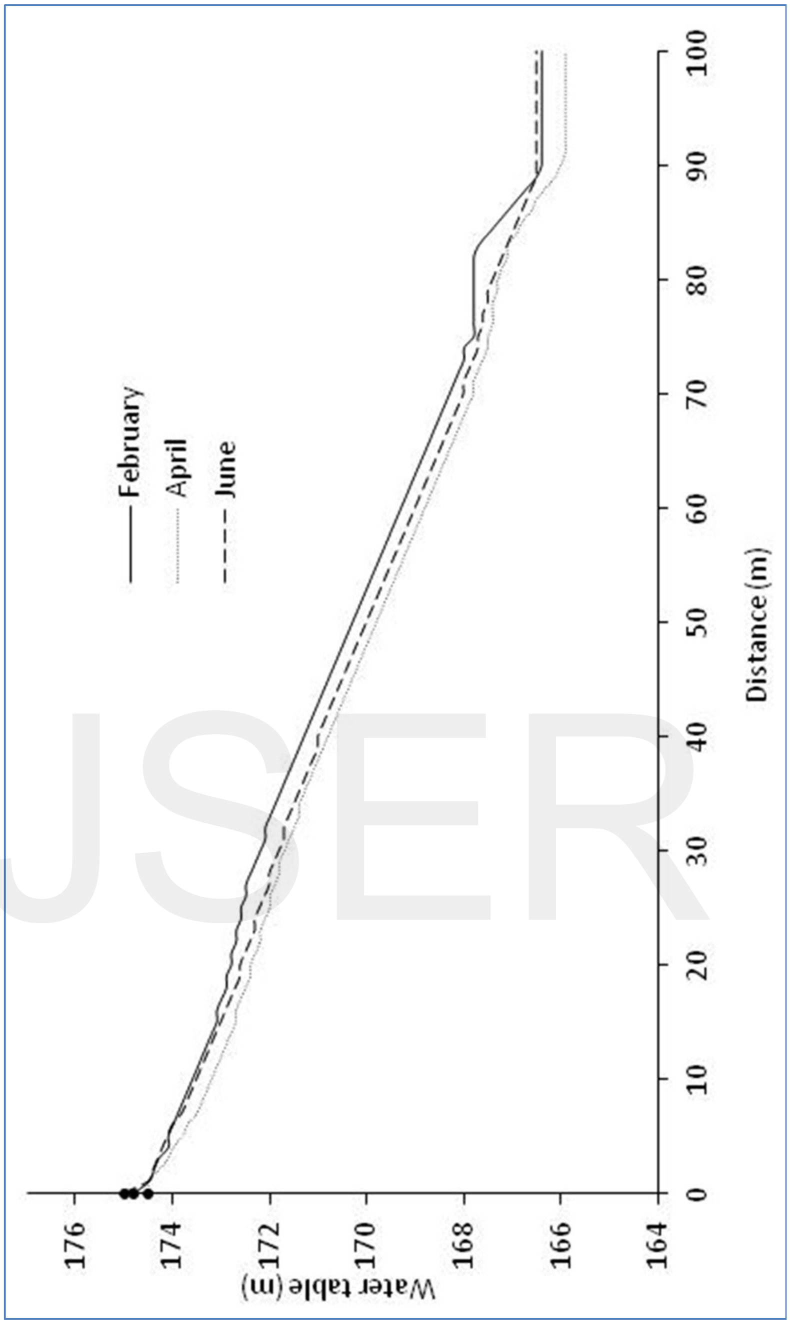

February
April
June
Water table (m)
Distance (m)
176
174
172
170
168
166
164
0
10
20
30
40
50
60
70
80
90
100

Figure 9

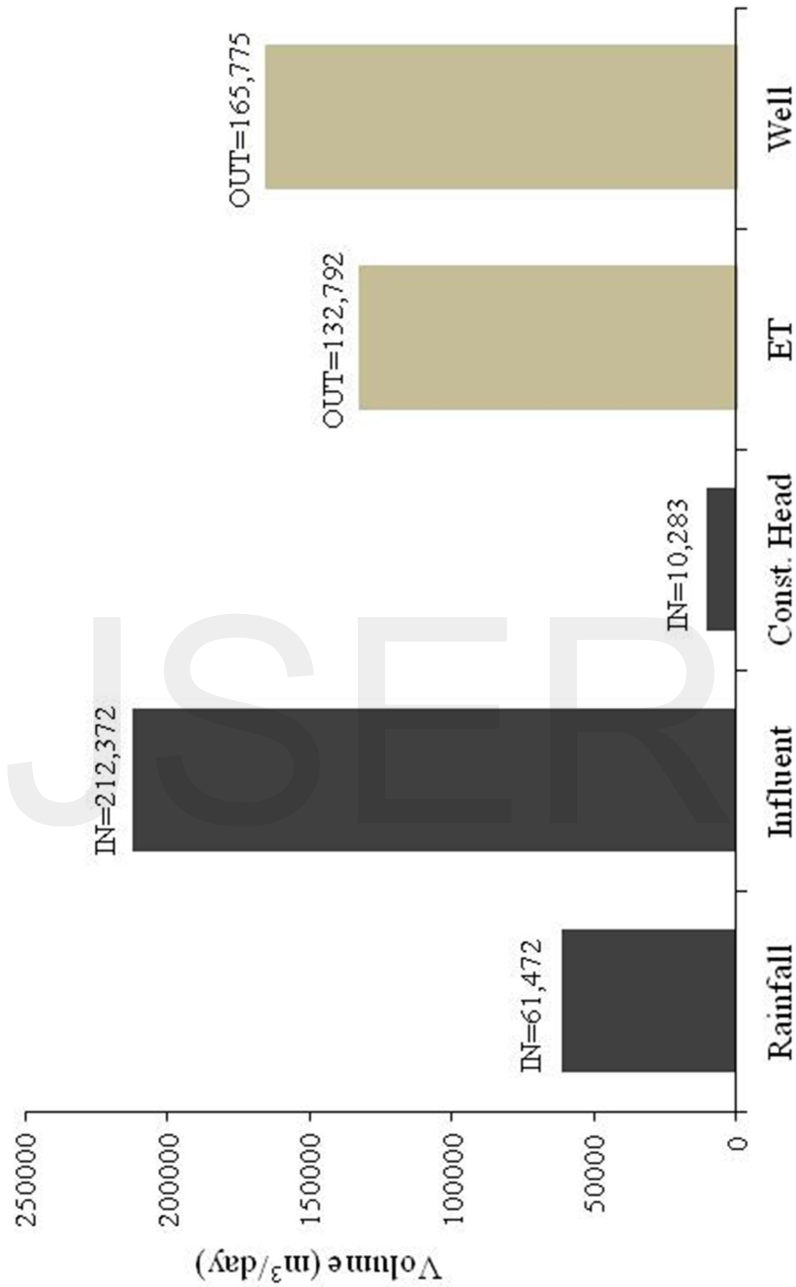

Volume (m3/day)
250000
200000
150000
100000
50000
0
Rainfall
Influent
Const. Head
ET
Well
IN=61,472
IN=212,372
IN=10,283
OUT=132,792
OUT=165,775

Figure 10

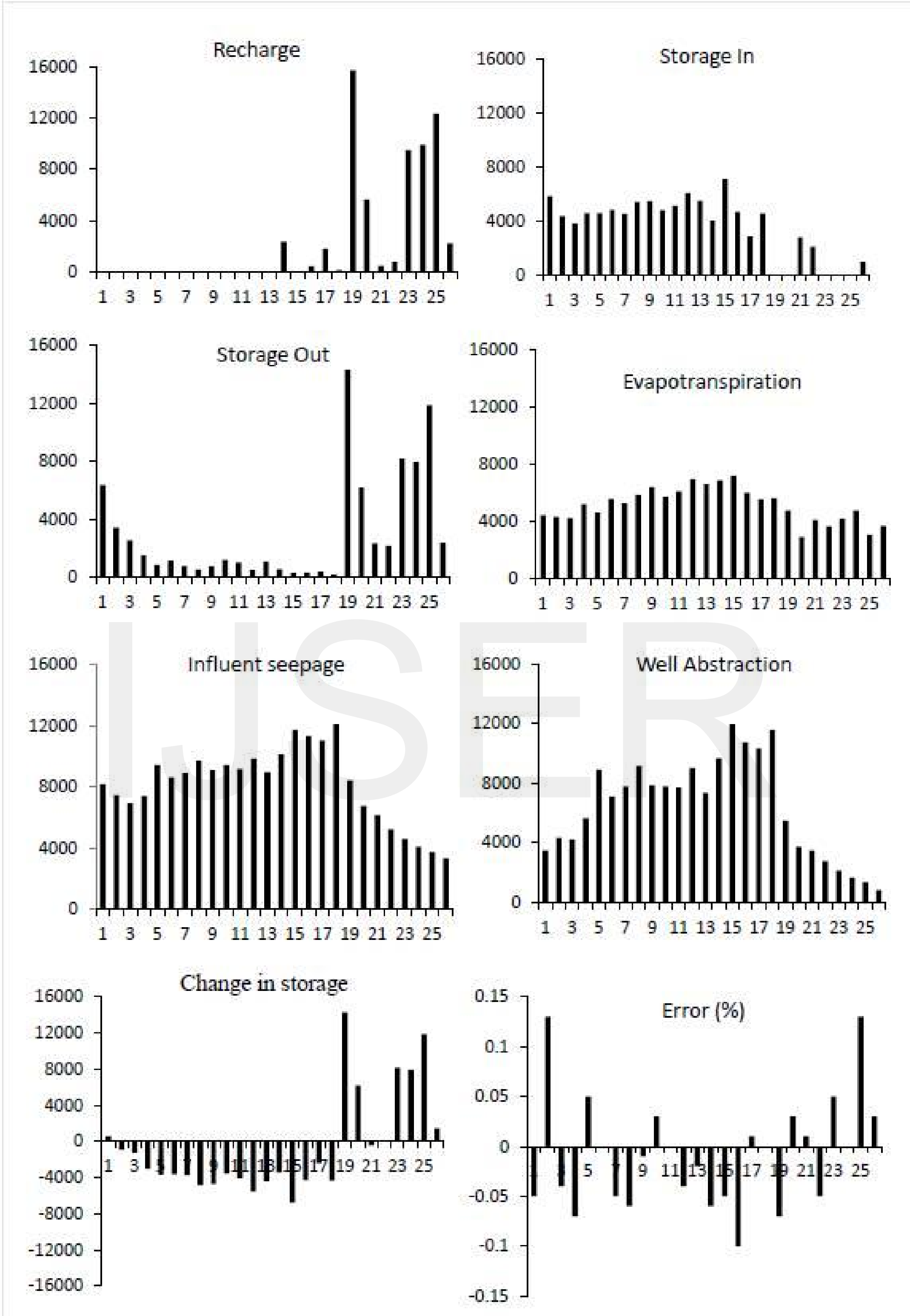
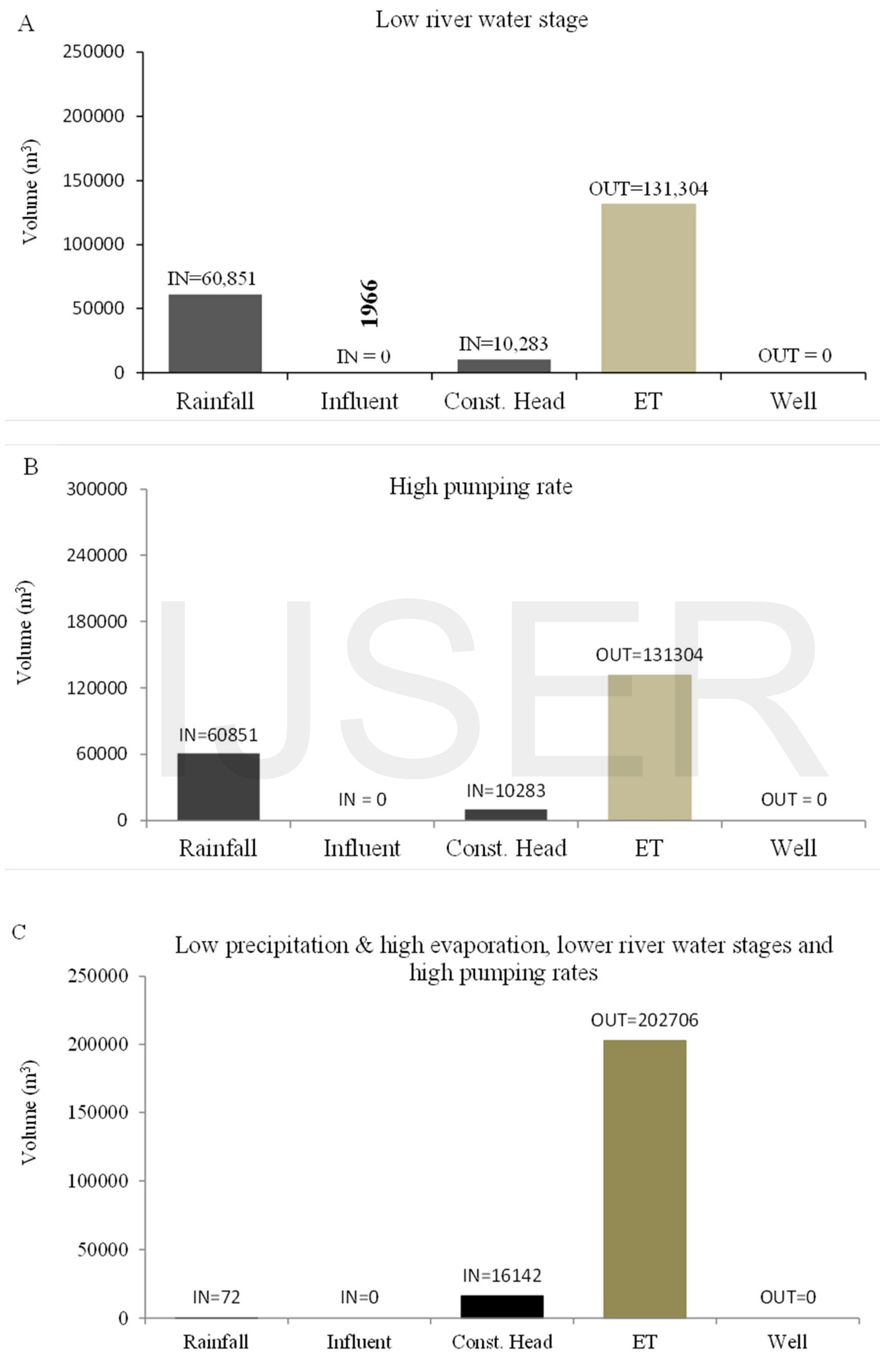

Recharge
Storage In
Storage Out
Evapotranspiration
Influent seepage
Well Abstraction
Change in storage
Error (%)

Figure 11


A
Low river water stage
Volume (m3)
250000
200000
150000
100000
50000
0
IN=60,851
1966
IN = 0
IN=10,283
OUT=131,304
OUT = 0
Rainfall
Influent
Const. Head
ET
Well
B
High pumping rate
Volume (m3)
300000
240000
180000
120000
60000
0
IN=60851
IN = 0
IN=10283
OUT=131304
OUT = 0
Rainfall
Influent
Const. Head
ET
Well
C
Low precipitation & high evaporation, lower river water stages and high pumping rates
Volume (m3)
250000
200000
150000
100000
50000
0
IN=72
IN=0
IN=16142
OUT=202706
OUT=0
Rainfall
Influent
Const. Head
ET
Well