An investigation into recharge mechanisms in a weathered crystalline aquifer in Ouagadougou, Burkina Faso

Word count: 10340

Thesis submitted for consideration towards a degree of
MSc Environmental Modelling,
Dept of Geography,
UCL (University College London)

September 2020

Abstract

Groundwater is a critical resource in sub-Saharan Africa, and in the semiarid Sahel it provides an essential buffer against unreliable surface waters and highly variable rainfall. Shallow aquifers of fractured crystalline rock are some of the most widely-exploited in the region, yet there is limited knowledge about their properties, and long-term sustainability as a water resource. Here, an investigation is undertaken into the recharge mechanisms occurring in a shallow crystalline aquifer located in Ouagadougou, Burkina Faso, where a recent study identified focused recharge from a nearby reservoir as an important driver of seasonal and decadal groundwater level fluctuations, in contrast to previous work which has suggested that diffuse recharge was the most influential process. Three groundwater models were developed to investigate the recharge mechanisms in the aquifer and assess the evidence for the conflicting conceptual models. The results suggest that while the magnitude of seasonal fluctuations is linked to annual rainfall totals, focused recharge from the barrage influences the timing of the annual groundwater rise and moderates the rate of groundwater recession in the aquifer. A significant amount of recharge is likely to occur via preferential flow processes, especially during drier years. Land use change may also affect runoff at a larger scale. The causes of decadal fluctuations in the time series are more difficult to constrain, and information gaps and uncertainties associated with the modelling limit the conclusions it is possible to draw from the available data.

Acknowledgements

I am extremely grateful to Richard Taylor for his assistance in setting the direction of this project and ongoing support in keeping things on track. None of this would have been possible without the hydrogeology masterclasses!

Mark Cuthbert was also very generous with his time and provided several avenues of exploration for the MODFLOW model development, as well as sharing some very useful bits of code related to soil moisture balance models.

Rebecca, George and Xiao Yi provided the sanity checks, and my sisters, the dog photos. My parents, the tolerance and the biscuits.

Table of Contents

List of abbreviations

CIEH	Comité Interafricain d'Etudes Hydrauliques (Inter-African Committee of Hydraulic Studies)
DEM	Digital Elevation Model
FAO	Food and Agricultural Organization of the United Nations
MEE	Ministère de l'Environnement et de l'Eau (Ministry of the Environment and Water, Burkina Faso)
SSA	Sub-Saharan Africa
SMBM	Soil Moisture Balance Model
SMD	Soil Moisture Deficit
S_s	Specific storage
S_y	Specific yield
WTFM	Water Table Fluctuation Model

1. Introduction

1.1 Groundwater in sub-Saharan Africa

Groundwater accounts for 35% of annual gloabl freshwater withdrawals (Döll *et al.*, 2014), and is of particular importance in sub-Saharan Africa (SSA), where over half the population is dependent on groundwater for domestic water supply (Xu *et al.*, 2019). In a region where rainfall is highly variable and surface water resources are unreliable, groundwater is often the main source of fresh water, and is an important buffer against water shortages and droughts (Famiglietti, 2014). Relatively little work has been done to characterise groundwater resources in this region, and there are still significant knowledge gaps surrounding groundwater availability and sustainability (Xu *et al.*, 2019). As climate change drives intensification of the hydrological cycle and increasing unpredictability in precipitation patterns (Giorgi *et al.*, 2011), rising populations and increasing levels of populations are likely to put considerable pressure on groundwater supplies in the coming decades (Carter and Parker, 2009).

1.2 Hydrological processes of West Africa

1.2.1 Climate

Groundwater is a key water resource in arid and semiarid West Africa, where the climate dominated by the West African Monsoon, with a single rainy season lasting from May to September (Lafore *et al.*, 2011). The recent decadal variability of precipitation in this region is the greatest observed of anywhere in the world (Sanogo *et al.*, 2015). The first decades of the twentieth century were marked by high levels of rainfall, which declined by 25-50% during the 1970s and 1980s (Séguis *et al.*, 2011). This remarkable variability has been linked to forcings from sea surface temperature anomalies (Rodríguez-Fonseca *et al.*, 2015), and rainfall patterns associated with the drought of the 1970s and 1980s shows that it was marked by a particular decline in rainfall through August, typically one of the wettest months (Biasutti, 2019).

Since the 1990s a gradual rise in annual rainfall totals to those similar to the 1950s and 1960s has been observed (Lebel and Ali, 2009), although some authors have questioned the extent to which this constitutes a recovery (Nicholson, 2005). The annual total figures obscure an increasing degree variability within the rainy season, with more extreme rainfall events observed, as well as an overall shortening of the rainy season (Sanogo et al., 2015; Panthou et al., 2018). In particular, the frequency of the severe storms which typically account for over 80% of the annual precipitation in the Sahel has tripled since the 1980s (Taylor *et al.*, 2007, 2017). Both the rise in annual totals and the intensification of precipitation patterns have been linked to anthropogenic climate change (Dong and Sutton, 2015). Climate modelling ensembles currently project an increase in warming across West Africa above the global mean (Diedhiou *et al.*, 2018), and a further intensification of the hydrological cycle with less overall precipitation and more frequent extreme rainfall events (Todzo *et al.*, 2020).

1.2.2 Land use, runoff and the "Sahelian Paradox"

Surface runoff in the region exhibits a high degree of variability, and the majority of West African rivers flow only seasonally (Conway *et al.*, 2009). During the drought period, runoff decreased in the more humid coastal regions of West Africa, triggering lower flows in the largest rivers in the region, the Niger and the Senegal, which are fed by tributaries in these regions (Séguis *et al.*, 2011), with a decreasing discharge into the Atlantic ocean observed for West African rivers during this period (Mahé and Olivry, 1999). However, in much of the drier parts of the region the rates of surface runoff have increased significantly during this time, despite the decline in rainfall, a phenomenon that has been termed the "Sahelian Paradox" (Descroix *et al.*, 2009).

Land cover and soil type are the most important factors influencing runoff in West Africa, more so than topography (Casenave and Valentin, 1992); consequently land use change is closely linked to hydrological system change. The apparently paradoxical rise in runoff has been attributed to widespread land clearances for agriculture, and a change in vegetation from a woody savannah to millet crops, reducing the organic content of the soil and increasing the potential for soil crusting (Leblanc *et al.*, 2008). Soil crusting decreases infiltration and increases the degree of Hortonian runoff (Horton, 1933), causing water to collect in surface depressions and gullies and increasing the density drainage network, leading to an increase in overall surface runoff (Valentin *et al.*, 2004). This phenomenon has been observed across the Sahelian region (Albergel *et al.*, 1992; Favreau *et al.*, 2002; Mahé, 2009; Gal *et al.*, 2017), and the effects appear to be continuing up until the present time (Ibrahim et al., 2014). This increased runoff from land use changes is considered a contributory factor to the extreme flooding occurring throughout the Niger basin in 2012 (Sighomnou *et al.*, 2013).

The Sahelian paradox has also been linked to rising water tables in the region, which have been observed in several locations through in-situ and satellite observations (Favreau *et al.*, 2002, 2009; Werth *et al.*, 2017). The rise in water tables in large sedimentary aquifers in Niger in particular has shown no sign of slowing, indicating that the aquifers have not yet reached equilibrium with the environmental and climatic changes (Favreau *et al.*, 2009). However, these long-term changes to the water table appear to be confined to larger sedimentary aquifers, and are not observed in the shallow crystalline aquifers that underly much of the region (Gal *et al.*, 2017). This has been attributed to the small and discontinuous nature these aquifers, which are consequently more sensitive to short-term fluctuations in climate than longer term hydrological patterns (Leduc *et al.*, 2001).

1.3 Characteristics of weathered crystalline aquifers

Approximately 40% of SSA is underlain by highly fractured Precambrian crystalline bedrock (MacDonald *et al.*, 2012). Although the low porosity and permeability of crystalline rocks make them low-yielding aquifers, at areas of tectonic discontinuities or faulting, they can be highly productive (Maréchal *et al.*, 2018). Shallow, discontinuous aquifers of this type are widely exploited owing to the ease of access, and the unreliability of surface waters (Chilton and Foster, 1995), and are likely to be of critical importance for regional water security in the future (Braune and Xu, 2010).

Fractured crystalline aquifers typically consist of a highly weathered regolith (saprolite) formed through in-situ weathering and tectonic processes (Taylor and Howard, 2000) forming the main part of the aquifer, overlying a fissure layer of rock (saprock) and impermeable basement rock (figure 1.1). Although a number of studies have addressed groundwater flow in fractured rock in Europe (Wyns *et* *al.*, 2004; Dewandel *et al.*, 2006; Roques *et al.*, 2014) and India (Maréchal *et al.*, 2004, 2018) there is less information about groundwater processes in saprolite (Taylor *et al.*, 2010).

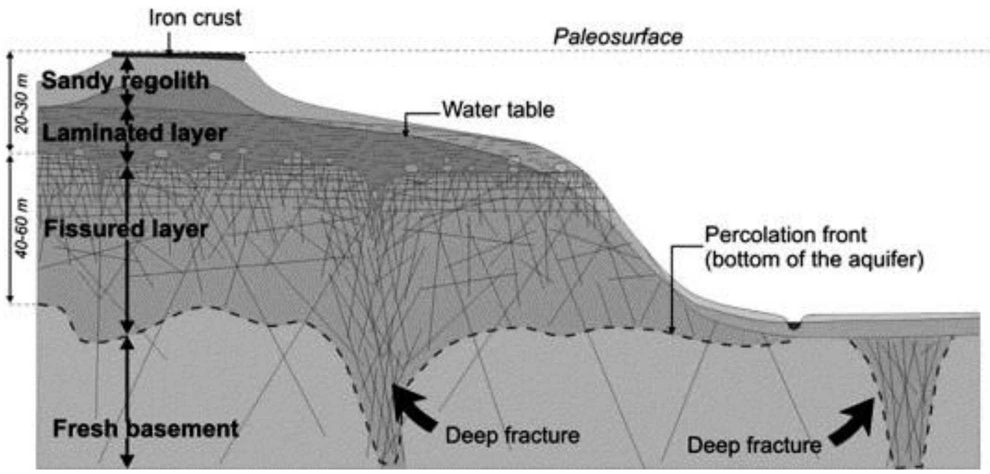


Figure 1.1: Diagram of a typical weathering profile in a fractured crystalline aquifer. Source: Dewandel et al. *(2006)*

Despite their importance, relatively little is known about the behaviour and recharge levels in the fractured rock aquifers in SSA, especially as compared to the sedimentary aquifers of western Europe (Healy and Cook, 2002) In particular, there is limited knowledge as to the extent to which the current level of exploitation is sustainable, especially under climate and demographic pressures (Maurice *et al.*, 2019).

1.4 Groundwater processes in dryland environments

The understanding of groundwater processes in arid and semiarid environments remains incomplete, due largely to a lack of observations compared to more humid regions (Wheater *et al.*, 2010). Aquifers in arid regions are often less sensitive to interannual variability due to the depth of the water table; however, they may take a much longer time to equilibrate with changes in climatic conditions, with potentially significant long-term impacts from anthropogenic climate change (Cuthbert *et al.*, 2019b).

Recharge to groundwater aquifers refers to the movement of water from the surface to the water table, and is highly dependent on climate, geology, soils and vegetation (Healy, 2010). Recharge processes include focused recharge from surface waters (also known as indirect or localised recharge), often operating on a relatively small scale, and diffuse or direct recharge from precipitation infiltrating through the soil to the water table (de Vries and Simmers, 2002). Many water sources in drylands are seasonal, and focused recharge from ephemeral streams is an important source of recharge in dry regions (Quichimbo *et al.*, 2020).

It is usually assumed that as aridity increases, focused recharge will increasingly predominate (Scanlon *et al.*, 2006). This is because as evapotranspiration demand will greatly exceed precipitation for much of the year in very dry environment, vegetation is in a state of stress and will extract water from the soil down to the water table, keeping the soil in state of moisture deficit and reducing the possibility for infiltration (Small, 2005). Figure 1.2 below summarises recharge processes in semiarid environments.

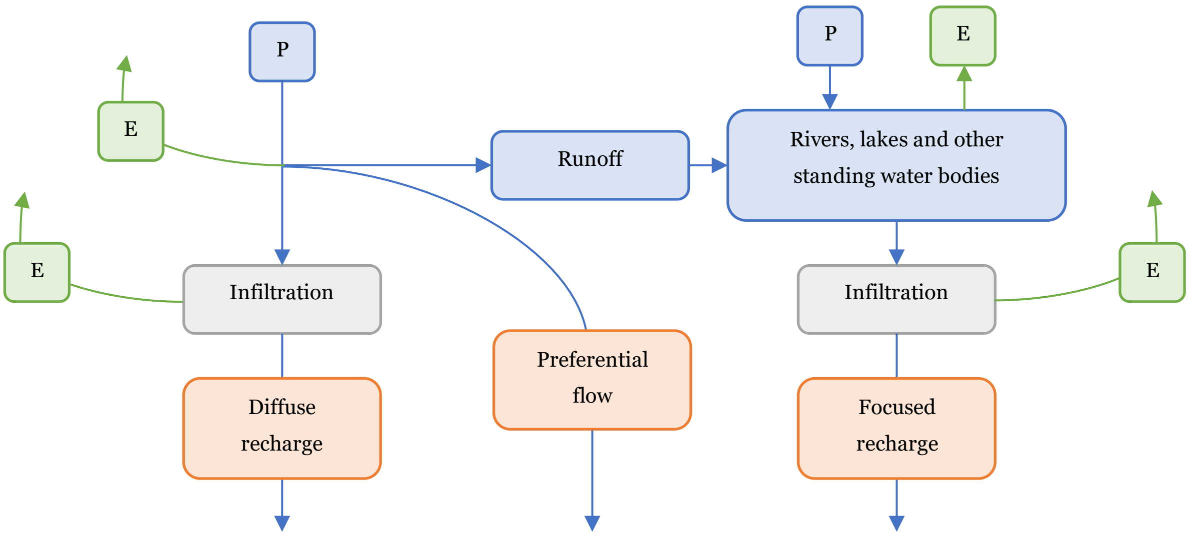


Figure 1.2: Recharge processes in semi arid environment. E = Evapotranspiration; P = Precipitation reaching the surface. Adapted from De Vries and Simmers (2002).

However, diffuse recharge is frequently observed semiarid environments, under particular climatic and geographical conditions, such as when an annual rainy season occurs, during which precipitation greatly exceeds evapotranspiration. Diffuse recharge can also occur in dry areas following extreme rainfall events that are able to overcome soil moisture deficits (Stephens, 1994). A wide body of evidence suggests that recharge in the tropics, including in many semiarid regions, preferentially occurs during such extreme events (Owor et al., 2009; Taylor et al., 2013b; Jasechko and Taylor, 2015). In certain geological environments, a large amount of recharge can occur in semiarid climates even during years of low overall precipitation if individual precipitation events reach a certain threshold of intensity (Cuthbert et al., 2019a).

Recharge in dry environments may also occur via preferential flow, referring to processes that bypass the unsaturated zone without reducing soil moisture deficit or contributing to evapotranspiration (Cuthbert *et al.*, 2013). This can occur either via macropore flow through root cracks and fissures (Beven and Germann, 2013), or as a result of unstable wetting fronts due to heterogeneity within the soil layer (de Vries and Simmers, 2002). Preferential flow occurs much more rapidly than diffuse or focused recharge, and is common in fractured, impermeable crystalline rock (Nimmo et al., 2017). It has shown to be an important process in the lateritic soils which are common in tropical regions (Ruprecht and Schofield, 1993; Langsholt, 1994). However, despite their potential significance for recharge in many environments, preferential flow processes are poorly understood, and are not incorporated into some of the most common groundwater modelling techniques (Cuthbert and Tindimugaya, 2010).

1.5 Research objective

The aim of this study is to investigate the recharge mechanisms in a shallow crystalline aquifer in Ouagadougou, Burkina Faso. A long-term (1978-2016) piezometric record is available, evidencing strong seasonal and decadal fluctuations (figure 1.3).

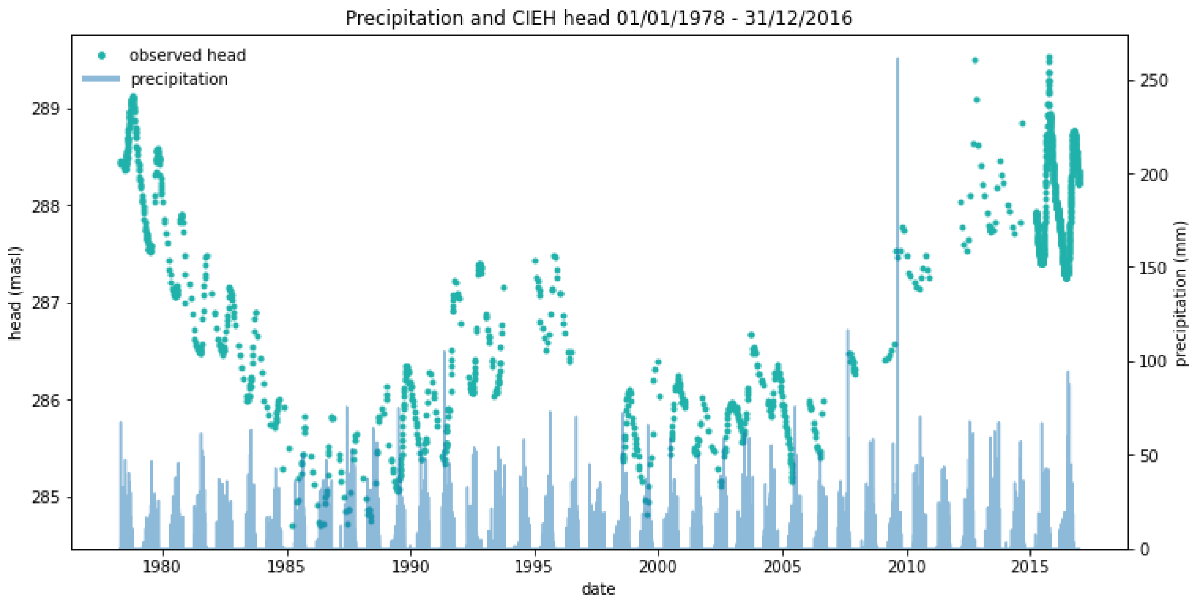


Figure 1.3: Time series of precipitation and hyraulic head for the study area in Ouagadougou, Burkina Faso.

The causes of these fluctuations have been the subject of several studies over the past decades. Recent work has characterised recharge mechanisms in the aquifer as dominated by focused recharge from a nearby reservoir, with recharge occurring above a certain threshold of annual rainfall and increasing with levels of precipitation (Cuthbert *et al.*, 2019a). Earlier studies have used a lumped model similar to a soil moisture balance model (SMBM) to model the decline in mean groundwater levels during the 1980s drought, making the assumption that recharge is dominated by diffuse processes (Martin and Thiéry, 1987; Thiéry *et al.*, 1993). Another study has linked seasonal fluctuations with precipitation, with decadal fluctuations driven by focused recharge from the reservoir (Mouhouyouddine *et al.*, 2017).

This study uses a comparative modelling approach to assess the evidence for these conflicting conceptual models and explore how climatic and environmental factors may account for the seasonal and decadal fluctuations in the groundwater record, with the aim of developing a more detailed understanding of recharge processes in a tropical semiarid environment.

2. Study area

2.1 Burkina Faso

Burkina Faso is a landlocked country of 20 million (2018), located in semiarid Sahelian region of West Africa. In common with much of West Africa Burkina Faso has experienced a high rate of demographic growth during the second half of the twentieth century (Raynaut, 2001). As a result of population increase and environmental changes, the potential for surface water irrigation in the region is expected to decline significantly (Sylla et al., 2018); groundwater is expected to meet much of the resulting demand (Altchenko and Villholth, 2015). However, the majority of aquifers in the country are low-yielding; while sedimentary aquifers occur in the northwest and southeast of the country, over 75% of Burkina Faso is underlain by Precambrian basement rocks (figure 2.1) with an estimated average recharge rate of 17 mm yr^{-1} (MEE, 2001).

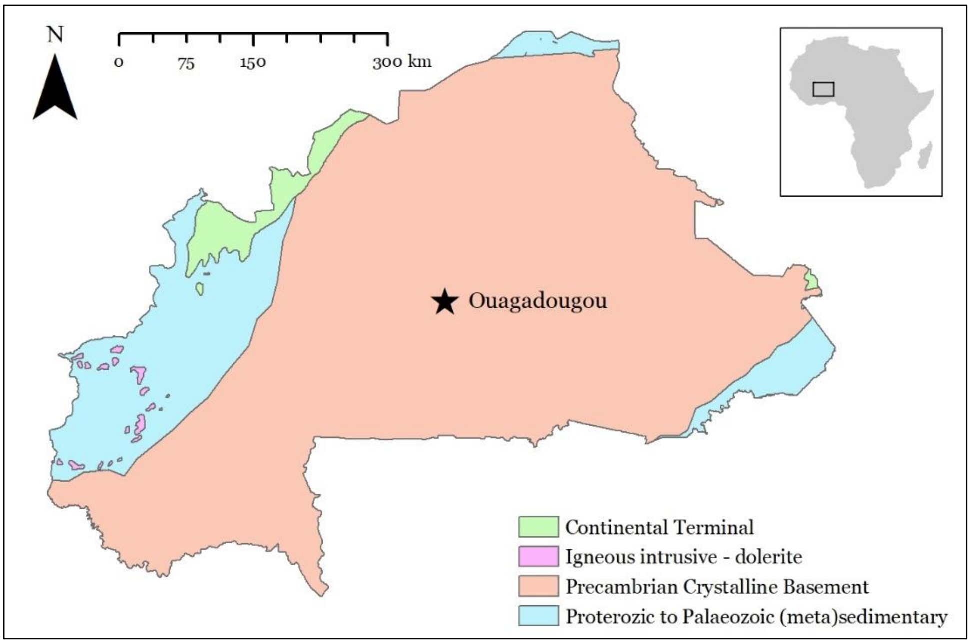


Figure 2.1: Simplified geological map of Burkina Faso. Source: British Geological Survey

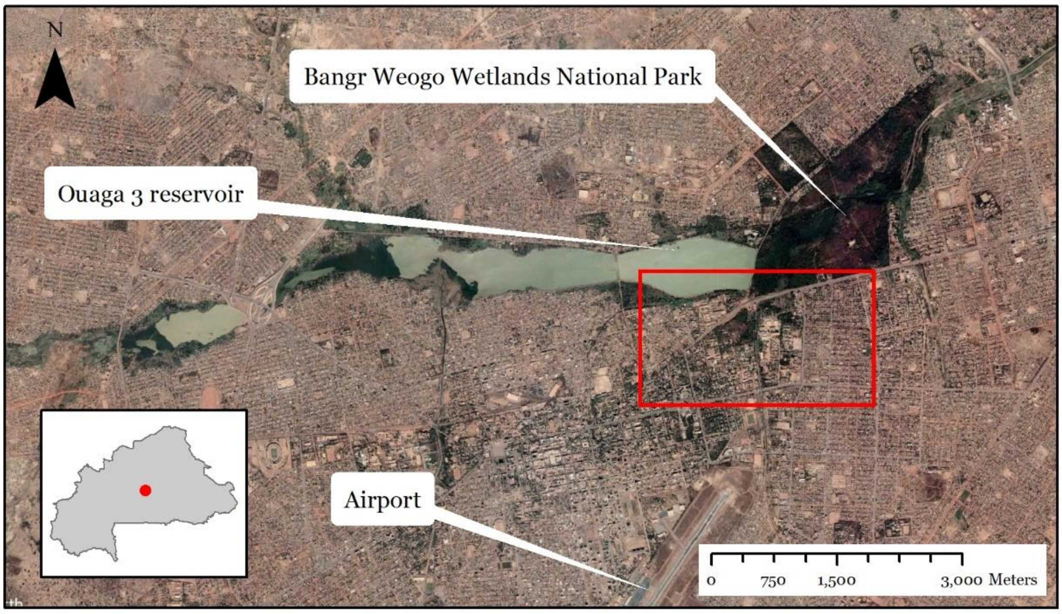
The capital Ouagadougou has a population of 2.2 million (2015), and is growing rapidly. Only 15% of its current water supply currently comes from groundwater (Pavelic *et al.*, 2012), but estimates suggest that fresh water provision from the reservoirs that currently supply the city will be inadequate to the city's needs by 2030 (Newborne and Tucker, 2015). In the absence of large-scale investments in new surface water infrastructure, the current level of groundwater exploitation for domestic use is likely to increase. Developing an improved understanding of groundwater processes in the urban aquifers is of considerable importance for the city's long-term water security (Pavelic *et al.*, 2012).

2.2 Site description

2.2.1 Location and topography

The CIEH piezometer was installed in 1978 by the Comité Interafricain d'Etudes Hydrauliques (Inter-African Committee of Hydraulic Studies; CIEH) and constitutes one of the longest unbroken piezometric records in West Africa (Cuthbert *et al.*, 2019a). It is located in the grounds of the University of Ouagadougou in the centre of the city (figure 2.2). Analysis of a digital elevation model (DEM) indicates that the local topography is largely flat, with a gentle slope (1.8%) towards the north east (Jarvis *et al.*, 2008). Surface water drains in this direction to the Bangr Weogo Wetlands National Park.

a) Central Ouagadougou



b) Study area

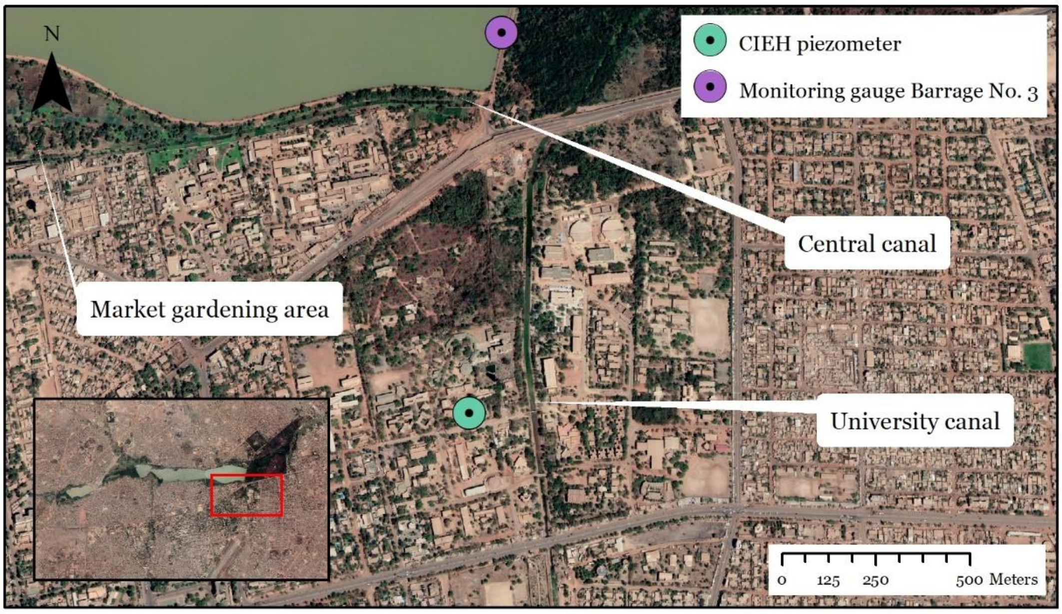


Figure 2.2: Annotated satellite images showing the study area and locations mentioned in the text. Image source: LANDSAT8 via Google Maps. Capture date a) Dec 2019; b) May 2020.

The most significant surface water feature in the vicinity is Reservoir No. 3 (Ouaga 3), located approximately 1 km to the north of the piezometer. One of three reservoirs that were formerly an important source of fresh water for much of the city, most withdrawals are now for irrigation in small agricultural plots on the norther and southern shores (Korbéogo, 2018). A nearby storm drain, the university canal, drains rainfall and sewage from much of the centre of Ouagadougou, while a second channel (the central canal) flows along the south shore of the reservoir.

Land use in the catchment is mixed, with the Bangr Weogo Wetlands comprising a vegetated area of deeply rooted trees and shrubs, and large parts of the university campus planted with ornamental vegetation. Mixed housing and commercial plots are located to the south and the east of the university site (Cuthbert *et al.*, 2019a). Roads are unpaved, and the only impermeable surfaces are the roofs of buildings (Mouhouyouddine *et al.*, 2017). The area immediately to the south of the reservoir is occupied by agricultural plots farmed by local residents, which comprise an important source of livelihood (Korbéogo, 2018). Due to the flat topography, areas close to the reservoir and parts of the Bangr Weogo Wetlands National Park are regularly flooded for several days at a time during the rainy season (Tazen *et al.*, 2019).

2.2.2 Climate

Ouagadougou experiences a Sudano-Sahelian climate, with a mean annual rainfall of 741 mm between 1978 and 2016, and a mean annual temperature of 28.2 °C. Average temperatures have been rising since the 1950s, with an increase in the number of extreme high temperatures, and an overall decrease in diurnal temperature variability (De Longueville *et al.*, 2016). The highest rainfall occurs in August, and almost no rain falls during the dry season (figure 2.3). Mean annual precipitation is highly variable, with many extreme rainfall events (figure 2.4); in common with the rest of the region, Burkina Faso was severely affected by the West African drought of the 1970s and 1980s, experiencing a 20% drop in annual precipitation relative to the 1950s during this period (Lodoun *et al.*, 2013). Although there has been a significant recovery in annual rainfall totals since 2000, there is a trend

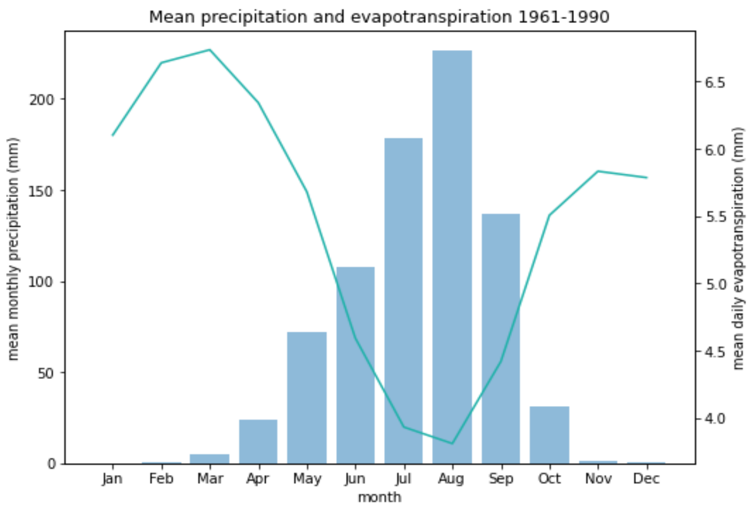


Figure 2.3: Mean monthly precipitation and reference evapotranspiration for Ouagadougou

towards a later onset of the rainy season, and an overall intensification of precipitation events (Lodoun *et al.*, 2013).

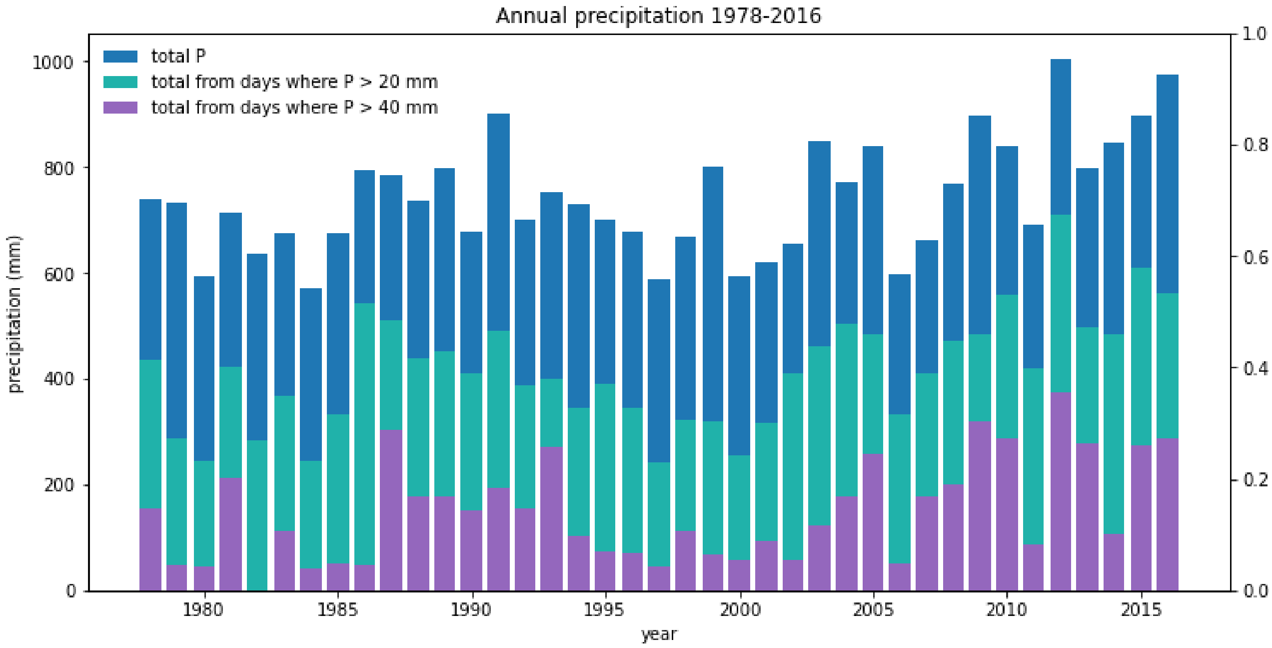


Figure 2.4: Annual rainfall totals for Ouagadougou 1978-2016, including total from all precipitation (P), total from precipitation events > 20 mm d^{-1}, and > 40 mm d^{-1}.

2.2.3 Geology and hydrogeology

The geology comprises weathered granitic saprolites overlying granite base rock. The basement rock is heavily fractured in the northeast-southwest direction, and moderate-yield wells (> 10 m^3 hr^{-1}) occur along these fractures (Yameogo *et al.*, 2006); shallow well yields are otherwise low, of the order of 2 m^3 hr^{-1} or less (MEE, 2001). No drilling log is available for the CIEH borehole, although it has been reported that it is screened from 6 m – 20 m below ground level, with the profile consisting of 5 m of weathered sand and saprolite, 4 m of weathered granite, and 6 m of basement rock (Martin and Thiéry, 1987). A similar profile is reported for other boreholes in the area surrounding Ouagadougou (Bazie *et al.*, 1995; Yameogo *et al.*, 2006).

There are few direct measurements of hydrogeological parameters in the study area. Transmissivity has been estimated between 2.5 and 8.6 m^2 d^{-1}, based on a brief pumping test (Martin and Thiéry, 1987) which is consistent with values reported for other locations in the country (Filippi *et al.*, 1990). Previous studies have assigned a value to the specific yield (S_y) of between 0.01 and 0.05 (Martin and Thiéry, 1987; Filippi *et al.*, 1990; Yameogo, 2008; Mouhouyouddine *et al.*, 2017), although observed values for fractured rock aquifers are often reported to be much lower (< 0.01, e.g. Taylor *et al.* 2010).

3. Materials and methods

3.1 Datasets

3.1.1 Climate data

Daily precipitation and reference evapotranspiration data were obtained from the closest weather station at Ouagadougou Airport, approximately 4 km southwest of the study area. For the few missing days of precipitation data, a value of zero was assumed. A three-day rolling average was used from these datasets for model inputs.

Reference evapotranspiration (ET_0) data (Penman-Monteith) is available until 2010 only; ET_0 estimates for the period 2010-2016 were calculated from the daily maximum and minimum temperature using the ETo Python package (Kittridge, 2018). This uses the Hargreaves equation to calculate ET_0 which is recommended when insufficient data is available to calculate Penman-Monteith values (Allen *et al.*, 1998) and has been shown to produce similar values when the quality of the input data is high (Kingston *et al.*, 2009). Since daily maximum and minimum temperatures are not available for the period 1978-2004, it has not been possible to use a single method to estimate ET_0 for the entire time series; consequently the mean daily value of ET_0 for 2011-2016 is approximately 7% lower than the mean value for 1978-2010.

3.1.2 Piezometric data

Data are available for the period 1978-2016, with observations taken by dipper from 1978 to 2015 at weekly to monthly intervals, with some gaps, and daily by datalogger since 2015. Annual groundwater rise was defined as the change in hydraulic head between the lowest annual value (usually in May or June), and the subsequent annual peak (usually in October or November). Annual decline was defined as the change in head between the annual maximum and the subsequent year's minimum. For correlation analysis, years were discarded when there were insufficient observations to determine the annual maximum or minimum, or observations were not representative of the whole hydrological year.

3.1.3 Reservoir data

Daily water level data from Reservoir No. 3 is available from March 2012 to December 2016, measured at a gauge located on the barrage (figure 2.2). Annual water level rise was defined as the change in water level between the lowest value and the mean value of the subsequent peak. For modelling, missing data points were filled using linear interpolation.

3.2 Groundwater models

3.2.1 Modelling approach

The selection of appropriate techniques for modelling groundwater recharge is highly dependent on local environment, timescale, and data availability, and the use of multiple model types is recommended in order to obtain a thorough understanding of the processes occurring at a particular site (Scanlon *et al.*, 2002; Healy, 2010).

Numerical models using software that solves the groundwater flow equations are highly dependent on parameterisation that requires a detailed knowledge of the hydrogeological characteristics of the modelled area, which is rarely available (Wheater *et al.*, 2010). The most common water budget modelling approaches such as the water table fluctuation model (WTFM) are straightforward to implement and require limited data, but provide little information on the recharge mechanisms (Scanlon *et al.*, 2002). However, coupling these with models of flow in the unsaturated zone can provide a means of investigating diffuse recharge processes.

Most physically-based methods of estimating water table were developed for use within sedimentary aquifers, and there is relatively little work on hydrographic response in fractured, low-porosity rock where specific yield values are highly heterogeneous and difficult to constrain (Healy and Cook, 2002). However, physically-based models including the WTFM have been used with success in fractured crystalline aquifers (Taylor and Howard, 1999; Mileham *et al.*, 2008; Maréchal *et al.*, 2018; Kotchoni *et al.*, 2019). In this case, the aim of the study was to investigate recharge processes, so modelling approaches were chosen with this in mind, as well as an awareness of the geographical setting and the data constraints outlined above.

3.2.2 Conceptual model

Two conceptual models were developed: a) that focused recharge from Reservoir No. 3 is the dominant recharge mechanism, controlling both annual and decadal fluctuations, with precipitation and evapotranspiration having a negligible effect on recharge; and b) that alternative recharge mechanisms predominate, with focused recharge from the reservoir either negligible, or exerting some control on the annual fluctuations only. Three models were developed to test these hypotheses: a numerical model using MODFLOW to assess the role of focused recharge from the reservoir; a simple water table fluctuation model (WTFM) based on the work of (Cuthbert *et al.*, 2019a) to assess recharge levels and provide an indication of the relationship between precipitation and recharge; and a soil moisture balance model (SMBM) to explore the possible roles of runoff, preferential flow and other factors which affect groundwater levels. A summary of the models together with their references in the text is given in table 3.1 below.

Table 3.1: Summary of models developed for this investigation.

Model name	Modelling approach	Model description	Key reference
Model 1A	Numerical model, MODFLOW	Single layer 1D model, driven by focused recharge only	Harbaugh (2005); Leake and Lilley (1997)
Model 1B	Numerical model, MODFLOW	Single layer 1D model driven by focused recharge and precipitation	Harbaugh (2005)
Model 2	Simple WTFM	Forward WTFM balancing recharge and drainage	Cuthbert *et. al* (2019a)
Model 3	Simple SMBM	SMBM based on rooting constant C	Taylor and Howard (1999)

3.2.3 Numerical model (MODFLOW)

The numerical model was developed using MODFLOW, an open access groundwater modelling software developed by the US Government that uses a finite-difference approach to solve the groundwater flow equations (Harbaugh, 2005). Model development and post-processing were conducted using the Python package FloPy (Bakker *et al.*, 2016, 2020) to implement MODFLOW-2005 (Harbaugh, 2005; Harbaugh *et al.*, 2017).

Due to the complexity of the local geology and the limited hydrogeological data available, a simplified model was developed of a single-layer unconfined aquifer of length 6000 m with a thickness of 30 m and uniform hydraulic conductivity. The initial model set up consisted of a 1D model of 200 columns of cells of width 30 m and depth 30 m with Reservoir No. 3 at one boundary (A) and the piezometer 1020 m away (B) (figure 3.1). The reservoir is connected directly to the aquifer, and controls the flow of water within the system. Focused recharge from the nearby university canal was assumed to be negligible compared to recharge from the barrage, and was not included in the model.

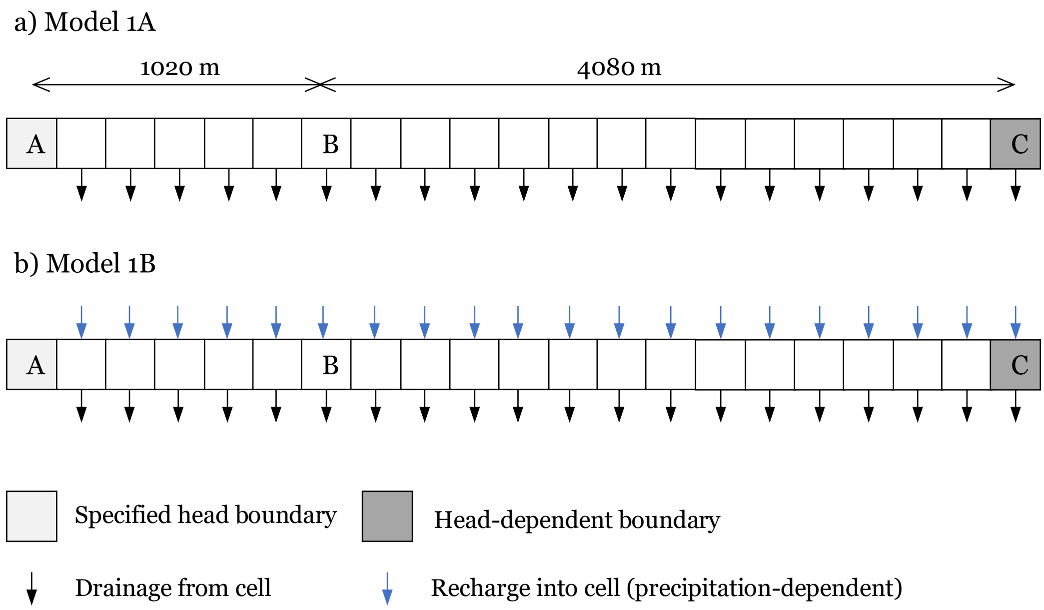


Figure 3.1: Model schematic of the MODFLOW models developed to represent focused recharge processes in the study area.

Following Reilly (2001) the reservoir was modelled as a limited specified head (Dirichlet) boundary, as the stage in the reservoir was not expected to be affected by the behaviour in the groundwater system. In order to allow the head at the barrage to vary within a stress period, a flow and head boundary (FHB; Leake and Lilly, 1997) was used to model the barrage, with head varying on a daily timestep. The boundary at C was modelled as a head-dependent (Cauchy) boundary (Franke *et al.*, 1987) using a general head boundary (GHB; Harbaugh, 2005) with flow proportional to modelled head within the unconfined aquifer. Since the boundary at C does not represent a real physical boundary, it was placed at a significant distance (5 km) from the piezometer in order to limit errors associated with this boundary. Drainage within the groundwater system was modelled by placing drains in each node at an elevation equal to the base of the aquifer, with constant drain conductance in each cell.

The model was first run driven solely by the changing water levels at the reservoir, and then with a recharge component applied across the whole model domain. Recharge was defined as equivalent infiltration In , calculated as that part of precipitation P which enters the unsaturated zone, defined as the precipitation minus runoff Ro and the reference evapotranspiration ET_0 .

$$In = P - Ro - ET_0 \quad \text{Eq. 1}$$

The model was run with an initial steady state period to induce the initial conditions within the aquifer, followed by 1767 transient daily timesteps. The model was calibrated for values of S_y and hydraulic conductivity k.

3.2.4 Water Table Fluctuation Model

In a basic WTFM, hydraulic head can be modelled as a function of recharge and the drainage. For a timestep of length Δt, the head at time t h_t can be calculated as followed, based on the specific yield S_y, recharge R_t and drainage D_t:

$$h_t = h_{(t-\Delta t)} + \left(\frac{R_t - D_t}{S_y}\right)\Delta t \quad \text{Eq. 2}$$

Recharge can then be estimated for each timestep:

$$R_t = \frac{S_y\left(h_t - h_{(t-\Delta t)}\right)}{\Delta t} + D_t \quad \text{Eq. 3}$$

Following Cuthbert *et al.* (2019a), groundwater recession was calculated from the dry season hydrograph using an exponential model to account for the fractured nature of the aquifer, where h_b is the head at the assumed drainage boundary and d is a decay constant:

$$D_t = d(h_{t-1} - h_b) \quad \text{Eq. 4}$$

Recharge occurs only when precipitation exceeds a threshold value P_{thresh}. The model was calibrated for values of d, S_y and P_{thresh} .

3.2.5 Soil Moisture Balance Model

The water table fluctuation approach is frequently combined with a model of flow through the unsaturated zone to produce a soil moisture balance model (Penman, 1950; Grindley, 1967; Rushton and Ward, 1979; Sophocleous, 1991). Initial investigations were conducted using a simple SMBM after Taylor and Howard (1999). Infiltration In is calculated as in equation 1 above. A soil moisture deficit SMD occurs when the soil moisture is less than the root constant C, equivalent to half the rooting depth multiplied by the soil porosity. Thus recharge on day t R_t occurs when infiltration exceeds the previous day's deficit SMD_{t-1}, and is otherwise zero.

Where $In_t > 0$ and $In_t > SMD_{t-1}$:

$$\begin{aligned} R_t &= In_t - SMD_{t-1} \\ SMD_t &= 0 \end{aligned} \quad \text{Eq. 5}$$

Where $In_t < 0$ or $In_t < SMD_{t-1}$:

$$\begin{aligned} R_t &= 0 \\ SMD_t &= SMD_{t-1} - In_t \end{aligned}$$

When SMD exceeds C, evapotranspiration occurs at a lower rate, only 10% of ET_0 (Grindley, 1967). SMD can increase by another 51 mm until the wilting point W is reached, beyond which no evapotranspiration takes place, and the SMD cannot increase any further. Runoff was calculated as a scalar of precipitation n, and the model was calibrated for values of C and n. The calibrated model was then used to explore the extent to which the model exhibited threshold-dependent behaviour, by assigning pathways for preferential flow, varying the precipitation-runoff relationship, and investigating any possibly modifying influence from the reservoir.

3.2.6 Model calibration and validation

For the water budget models a split-sample calibration and validation approach was taken (Klemeš, 1986). For the WTFM and SMBM, each model was calibrated against the period 1978-1996, a period of regular observations (weekly or more frequent) and consistent decadal fluctuations, and then validated against the period 1997-2016, where observations are more infrequent. Parameter values were optimised by maximising the log-likelihood of the cost function (Ross, 1982). Since reservoir water level data was only available for the period 2012-2016, a period for which regular groundwater observations were only available from March 2015, calibration and optimisation were undertaken manually.

Evaluation of model performance

Model performance was evaluated using two approaches. The Root Mean Square Error (RMSE) and the Nash-Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970) were applied to model data using the Python HydroStats package (Roberts *et al.*, 2018). These metrics assess the extent to which predicted head h_{pred} matches observed head h_{obs} for each model and are widely used in hydrology.

$$RMSE = \sqrt{\frac{\sum_{t=1}^{n}(h_{obs}^{t} - h_{pred}^{t})^2}{n}} \quad \text{Eq. 6}$$

$$NSE = 1 - \frac{\sum_{t=1}^{n}(h_{obs}^{t} - h_{pred}^{t})^2}{\sum_{t=1}^{n}(h_{obs}^{t} - \bar{h}_{pred})^2} \quad \text{Eq. 7}$$

For performance evaluation, values of RMSE should be minimised, while the NSE should ideally be between 0 and 1, with values between 0.85 and 1 constituting "excellent" performance, and 0.65 to 0.85 "very good" (Henriksen *et al.*, 2003).

Models were also evaluated via analysis of model residuals. Although not frequently used in analysis of hydrological models, residual analysis can provide insights into how well the model structure performs, separate from the goodness of fit measured using statistical metrics described above (Xu, 2001). Examination of model residuals can also allow for analysis of how well the model represents particular elements of a hydrograph such as the recession curve (Bieger *et al.*, 2012).

3.3 Specific objectives

In light of the available data for the study area and the development of the models outlined above, the research goals were defined more concretely, with the goal of this study to answer the following questions:

- To what extent does the evidence support the thesis of Cuthbert *et al.* (2019a) that focused recharge is the dominant mechanism in the aquifer?
- To what extent does the available evidence point towards other recharge processes occurring in the study area, including diffuse recharge and preferential flow?
- Is there evidence for environmental and climatic changes influencing the decadal variations in the hydrograph?

4. Results

4.1 Model calibration

An initial sensitivity analysis identified the most sensitive parameters as hydraulic conductivity and specific yield (models 1A and 1B), and drainage constant, runoff coefficients and recharge threshold (models 2 and 3), so calibration was initially conducted for these values, before final model tuning was conducted manually. Calibrated values of all model parameters are summarised in table 4.1 below.

Table 4.1: Values for calibrated model parameters.

Parameter	Model 1A (MODFLOW)	Model 1B (MODFLOW)	Model 2 (WTFM)	Model 3 (SMBM)
Specific yield S_y (-)	0.005	0.038	0.064	0.06
Drainage coefficient d (-)	-	-	0.04	0.04
Recharge threshold P_{thresh} (mm)	-	-	6.6	10
Runoff coefficient WTFM m (-)	-	-	0.16	-
Runoff coefficient SMBM n (-)	-	-	-	0.15
Root constant C (mm)	-	-	-	38
Specific storage S_s (-)	1×10^{-6}	5×10^{-5}	-	-
Hydraulic conductivity k (m d^{-1})	7	1.75	-	-

4.2 Model performance

4.2.1 Numerical models

Model 1A (focused recharge only, figure 4.1) achieved a very good fit (NSE=0.63) for the period 2012-2017 (figure 4.1). However, the calibration required a very low value of specific yield (S_y = 0.005) in order to achieve an approximately correct amplitude of seasonal fluctuations, and a very high value of hydraulic conductivity (k = 7 m d^{-1}) to achieve a sufficiently fast model response time. The calibrated model does not reproduce the characteristic steep recession pattern of the CIEH time series, instead following a shallower peak and decline, unsurprisingly similar to that observed in the reservoir data.

Adding a recharge component equivalent to effective precipitation to the model resulted in a model which reproduced the recession pattern much more successfully, despite technically achieving a less good fit overall (NSE=0.19) (figure 4.2). The hydraulic conductivity is still relatively high (1.75 m d^{-1}) , but it captures the response time and amplitude well for each year except 2014 and 2016. This version of the model is also much more sensitive to changes in the value of specific storage than the previous model.

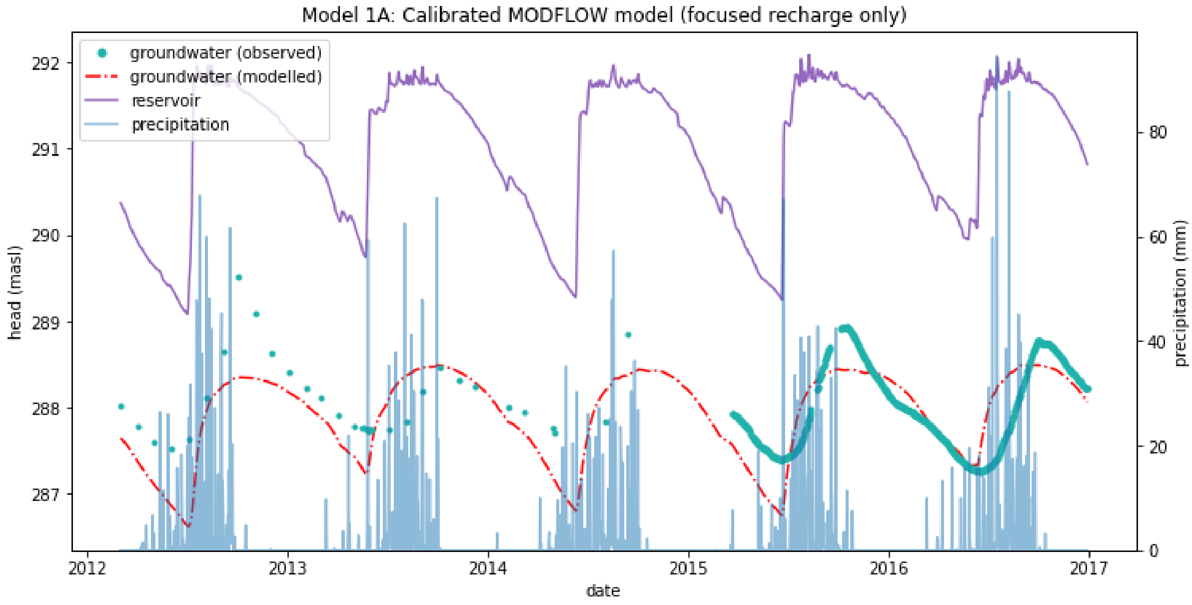


Figure 4.1: Calibrated numerical model driven by fluctuations in water level at the reservoir only.

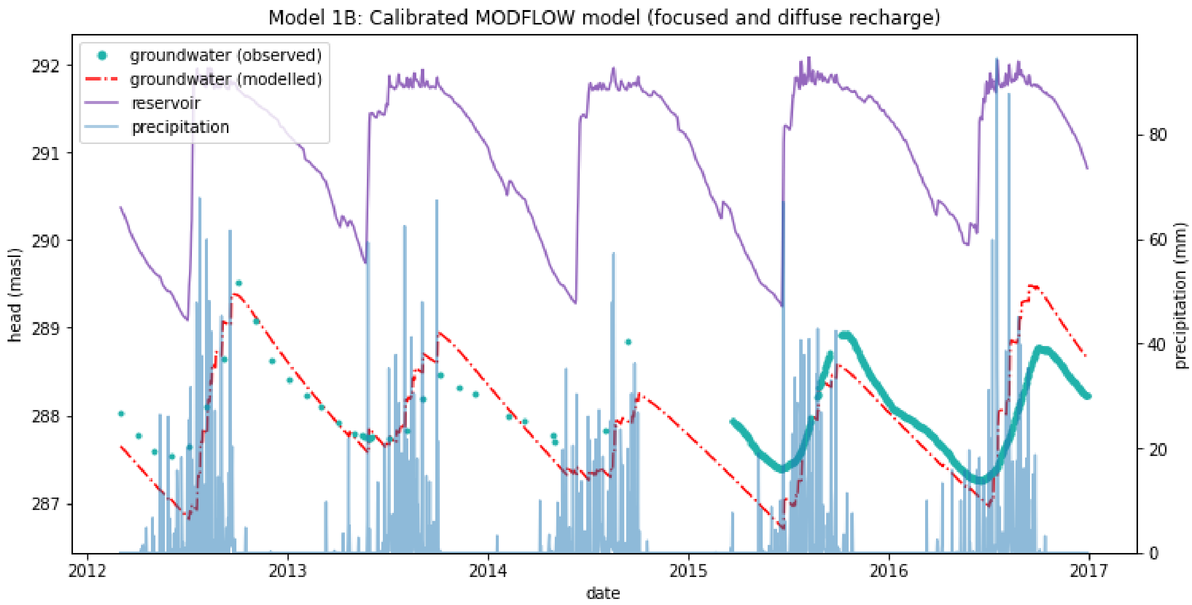


Figure 4.2: Calibrated numerical model driven by focused and diffuse recharge. NB improved recession pattern.

4.2.2 Water table fluctuation model

The recalibrated version of the Cuthbert *et al.* (2019a) WTFM (Model 2, figure 4.3) provided the best fit to the observations in terms of the descriptive statistics, achieving an excellent fit (NSE=0.86) for the calibration period and a very good fit (NSE=0.76) for the full time series. In particular it modelled the amplitude of the seasonal fluctuations well compared to the other models, although it failed to respond adequately to the most extreme events (rainfall > 80 mm d^{-1}). It captured the magnitude of the longer-term trends less well, in particular the rise in water levels after 2000. Similar goodness of fit indicators could be achieved with multiple combinations of parameters, in particular by varying the runoff threshold and the runoff coefficient. However, unlike Model 1A, it was not possible to achieve a sensible fit with values of S_y below 0.01.

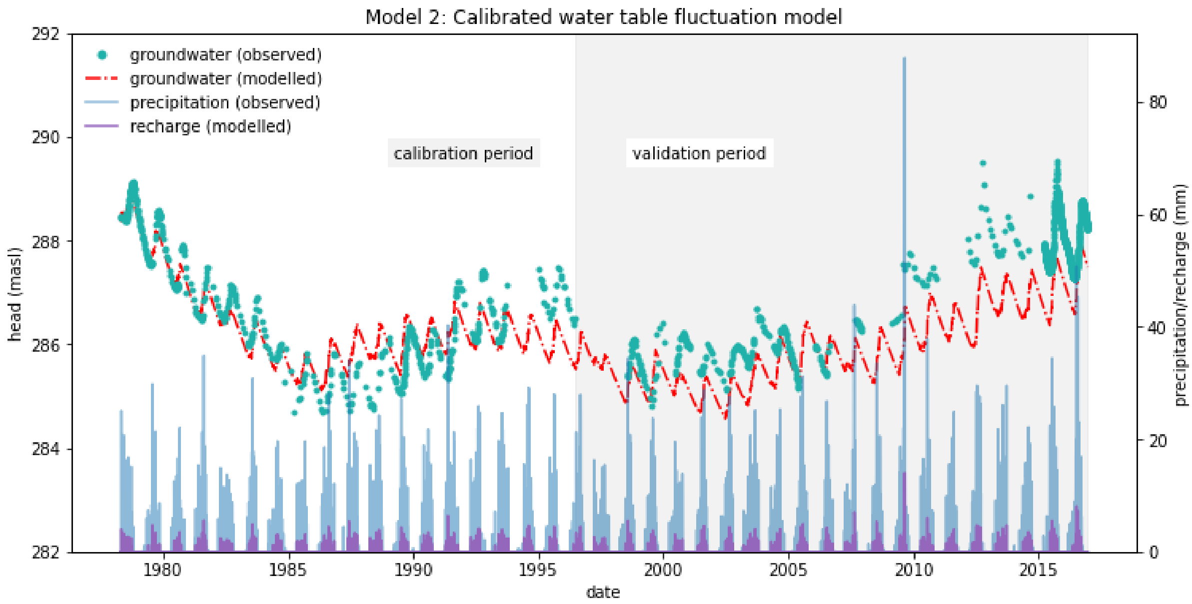


Figure 4.3: Calibrated forward water table fluctuation model.

4.2.3 Soil moisture balance model

The calibrated SMBM performs less well (NSE = -4.6 for the entire series) but captures the longer-term mean ground water level rather better than the WTFM (r = 0.92 vs. r = 0.82). However, the modelled amplitudes from 2010 in particularly far too extreme (figure 4.4).

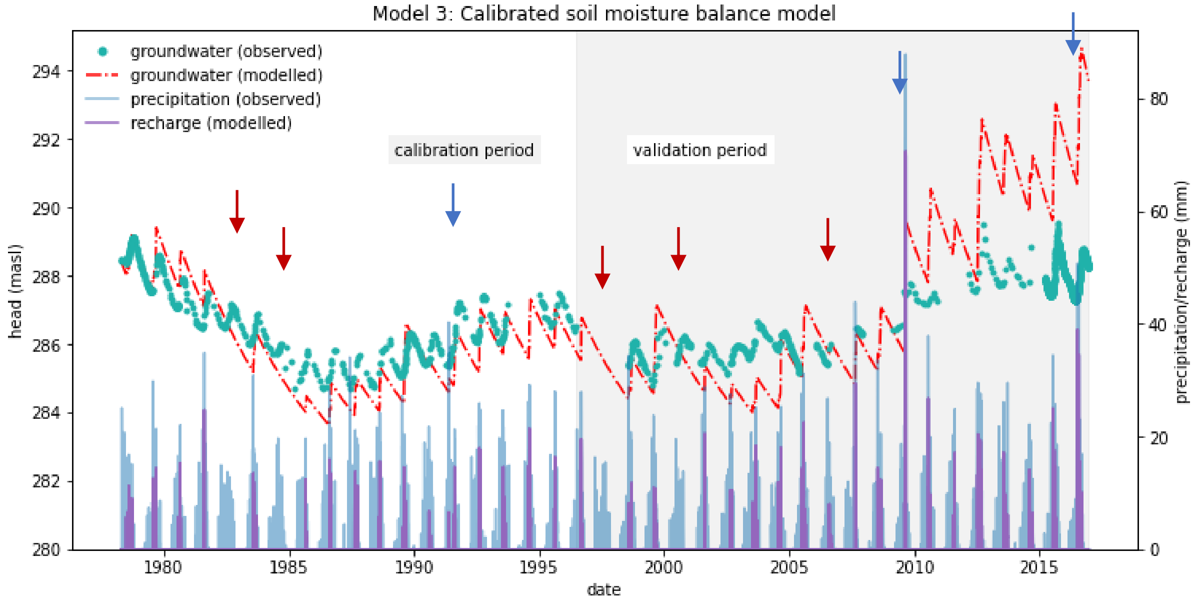


Figure 4.4: Calibrated SMBM. Red arrows indicate years where total annual rainfall < 600 mm and the model underestimates recharge; blue arrows indicate years where total annual rainfall > 800 mm and the model overestimates recharge.

The model underperforms in two key areas: it fails to predict observed recharge in low rainfall years, and it over-predicts recharge in years with extreme rainfall events. In years with total precipitation of less than 600 mm (indicated by red arrows in figure 4.4) the model fails to register any recharge at all, as the SMD does not reach zero. In years with high annual totals, and those with extreme events (e.g 2009) the model predicts extremely high levels of recharge which are not observed in the record. It particularly over-responds to extreme rainfall events occurring late in the season (i.e. in August or September), when the SMD has already reached zero and therefore high levels of recharge occur.

Performance evaluation metrics for all the calibrated models are summarised in table 4. 2 below.

Table 4.2: Summary of performance metrics for all models for calibration (cal.), validation (val.), and complete (all) time periods. r *all is the correlation coefficient between all observed and modelled values,* r *annual mean between observed and modelled mean,* r *annual rise between observed annual max and min values. NB* r *annual mean and* r *annual rise are not calculated for 1A and 1B as the time series is too short to be meaningful.*

Model	Period	NSE	RMSE	*r* all	*r* annual mean	*r* annual rise
1A	all.	0.63	0.30	0.83	-	-
1B	all	0.19	0.44	0.86	-	-
2	cal.	0.89	0.41	0.94	0.87	0.69
	val.	0.27	0.91	0.95	0.96	0.53
	all.	0.56	0.76	0.89	0.82	0.58
3	cal.	0.73	0.64	0.94	0.96	0.64
	val.	-9.6	3.5	0.94	0.96	0.57
	all.	-4.6	2.7	0.85	0.92	0.54

4.2.4 Exploring threshold-dependent behaviour

A number of adjustments were made to the calibrated SMBM to test if a better fit could be obtained via changes to the recharge processes (figure 4.5).

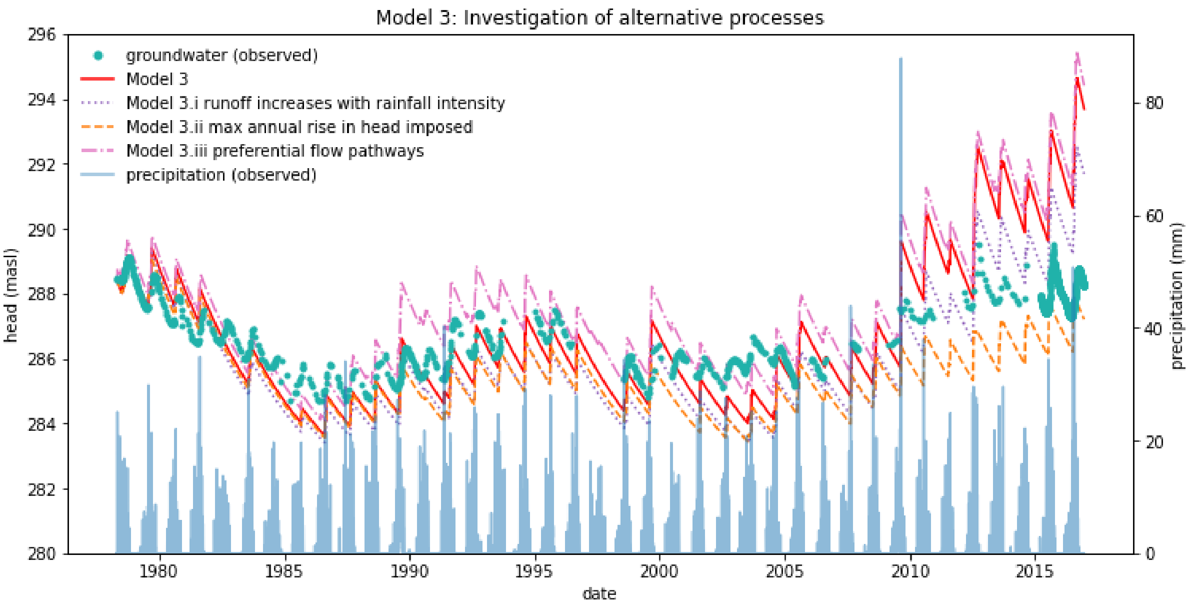


Figure 4.5: Using the calibrated SMBM to investigate alternative recharge mechanisms in the study area: changes to the rainfall/runoff relationship; a maximum annual rise in head; preferential flow pathways.

Increasing the amount of runoff for higher degrees of rainfall (>40 mm d^{-1} in Model 3.i) limited the recharge occurring after 2009, and especially reduced the large runoff response to the 2009 extreme event. Preferential flow pathways were modelled by assigning some proportion of rainfall above a certain intensity (15 mm d^{-1} in Model 3.iii) to recharge without reducing SMD; this led to some limited increase in recharge during years which are missed by the SMBM. The increase in rise in head observed after 2009 is most effectively managed by imposing a maximum allowable annual rise in head (1.5 m in Model 3.ii), and could be better tuned by adjusting the drainage, but does raise questions as to through what mechanism this could be imposed.

4.3 Relationships between rainfall and change in groundwater levels

4.3.1 Recharge/rainfall relationships

A moderate positive correlation (r = 0.60, p < 0.01) is observed between annual rainfall totals and annual rise in groundwater head. The correlation is slightly greater for total rainfall in events of above 5 mm d^{-1} (r = 0.60, p < 0.01); however, both correlation and level of confidence decrease for rainfall totals from more extreme events (table 4.3). A much weaker correlation and confidence below the significant level ($p \leq 0.05$) is observed between annual rainfall totals and mean annual head.

Table 4.3: Correlation between annual rainfall totals and annual seasonal rise in head.

Variable	Correlation with annual rise in head r (p)	Correlation with mean annual head r (p)
Total annual rainfall	0.60 (< 0.01)	0.26 (0.18)
Total rainfall from events > 5 mmd^{-1}	0.62 (< 0.01)	0.24 (0.22)
Total rainfall from events > 10 mmd^{-1}	0.56 (0.02)	0.29 (0.14)
Total rainfall from events > 20 mmd^{-1}	0.38 (0.05)	0.14 (0.48)
Total rainfall from events > 40 mmd^{-1}	0.20 (0.32)	0.22 (0.28)

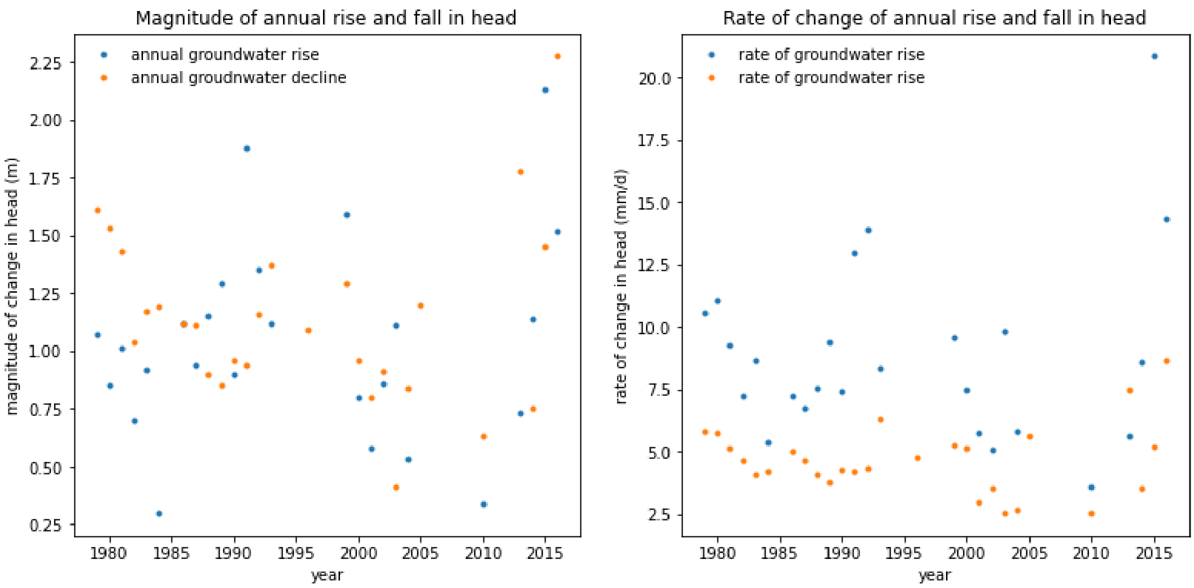


Figure 4.6: Observed changes in magnitude and rate of change in seasonal head fluctuations.

Both the magnitude and rate of change of the annual variations in head appear to undergo a gradual decline until 2005, and then increase rapidly after 2010 (figure 4.6). The period from 2005-2015 has considerable inconsistencies in groundwater observations, so this apparent trend should be treated with caution; however it may be indicative of some changes to the water balance after 2010.

4.3.2 Triggers of annual groundwater rise

With few exceptions, the pattern of the annual fluctuation in head remains consistent across the time series, with head rising at a steady rate once the annual rise is triggered. What triggers this rise is under question. Unfortunately the short time period for which detailed data about the reservoir water levels coincides with a period of inconsistent groundwater observations, making it difficult to assess the extent to which groundwater level rise might be triggered by the rise in water in the reservoir (figure 4.7). An initial examination of the groundwater and reservoir data for 2015 and 2016 shows that for three years (2013, 2015 and 2016) the annual rise in head occurs almost simultaneously (+/- 3 days) or sometime after the rapid rise in the water levels at the reservoir. This could indicate either that the rise in water at the reservoir is triggering a very rapid response in groundwater levels at the piezometer, or that both groundwater and reservoir water levels are responding to a common external stimulus (most likely rainfall).

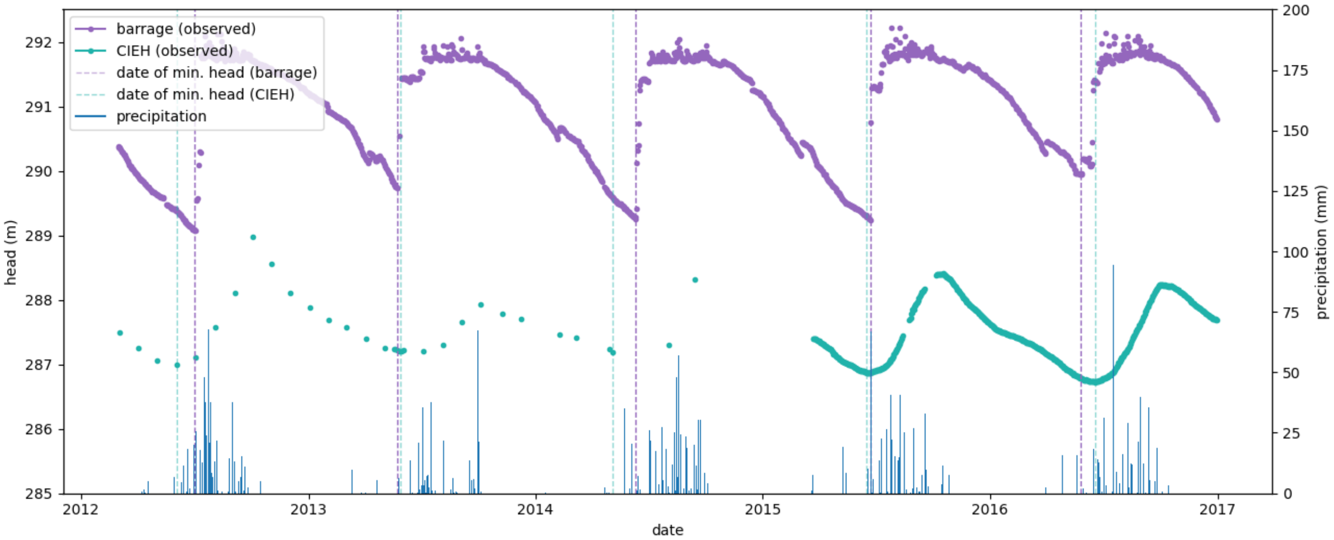


Figure 4.7: Dates of minimum head (start of water level rise) for the piezometer and the reservoir (barrage) for the period 2012-2016.

There is no obvious pattern in the total amount of rainfall occurring ahead of the date of the spring minimum, either cumulatively or in terms of individual events. Cumulative rainfall amounts for the year before the date of rise range from less than 40 mm in 1986, to above 300 mm in 2004. Assuming that some of the more extreme values are due to poor constraints on the date of the start of rise, the majority of values still lie between 100 and 250 mm, implying either that very little rainfall is required to trigger some degree of groundwater level rise, or that water levels in the barrage do in fact strongly influence the date of initiation of annual rise.

5. Discussion

5.1 Evidence for focused recharge

5.1.1 Focused recharge from the reservoir

The strong seasonal fluctuations in the water level at the barrage combined with the geological setting and the semiarid climate makes a focused recharge-dominated conceptual model an attractive hypothesis. However, the modelling results do not immediately support this. Although the MODFLOW focused recharge model achieved a good fit (NSE = 0.63) the parameters used to achieve this raise questions about the legitimacy of this model. In order to achieve an appropriate response time, a high value of hydraulic conductivity (k = 7 m d^{-1}) was required, while in order to achieve the required amplitude in annual fluctuations, an extremely low value of specific yield (S_y= 0.005) was used. This value of S_y, while differing by an order of magnitude from that previous studies, is in line with values determined at other locations in similar hydrogeological settings (Cuthbert and Tindimugaya, 2010; Kotchoni *et al.*, 2019). However, such a high value of k implies values of transmissivity far in excess of those observed at the site (Martin and Thiéry, 1987).

The shape of the modelled rate of recession in Model 1A also casts doubt on focused recharge being the only driving mechanism. Unsurprisingly for a model driven solely by a variable head boundary, the pattern of rise and fall most closely resembles that of the reservoir itself. A more convincing fit is achieved when recharge is applied across the domain in Model 1B, although here the fluctuations from the recharge appear to dominate the model processes much more than fluctuations from the water level at the reservoir.

However, other pieces of evidence support the theory that water levels in the reservoir exert a strong influence over both the timing of the annual groundwater rise, and the rate of recession. The almost simultaneous, or very slightly lagged, initiation of the annual rise soon after the reservoir fills implies a direct relationship and a rapid response (figure 4.7). This is consistent with the observation that the extreme levels of recharge generated by the calibrated SMBM are modified when a maximum annual rise in head is imposed roughly equivalent to the mean annual rise in head at the reservoir (figure 4.5).

Mouhouyouddine *et al.* (2017) report that the level of the spillway at the east end of Reservoir No. 3 was raised between 2000 and 2002, resulting in an increase in mean water levels of 1.2 m, and an overall rise in annual amplitude of water level change at the barrage. If focused recharge from the reservoir was the dominant mechanism controlling groundwater levels at the piezometer, a subsequent rise in average groundwater levels would be expected in the period after 2002. No such rise is observed between 2002 and 2007 (a brief 2003 rise seems to be associated with high levels of rainfall that year). Mean groundwater levels do rise between 2007 and 2012, although gaps in the record make it difficult to determine exactly when and how rapidly this rise occurs, and this also rise also coincides with a period of increase in annual rainfall totals (figure 2.4).

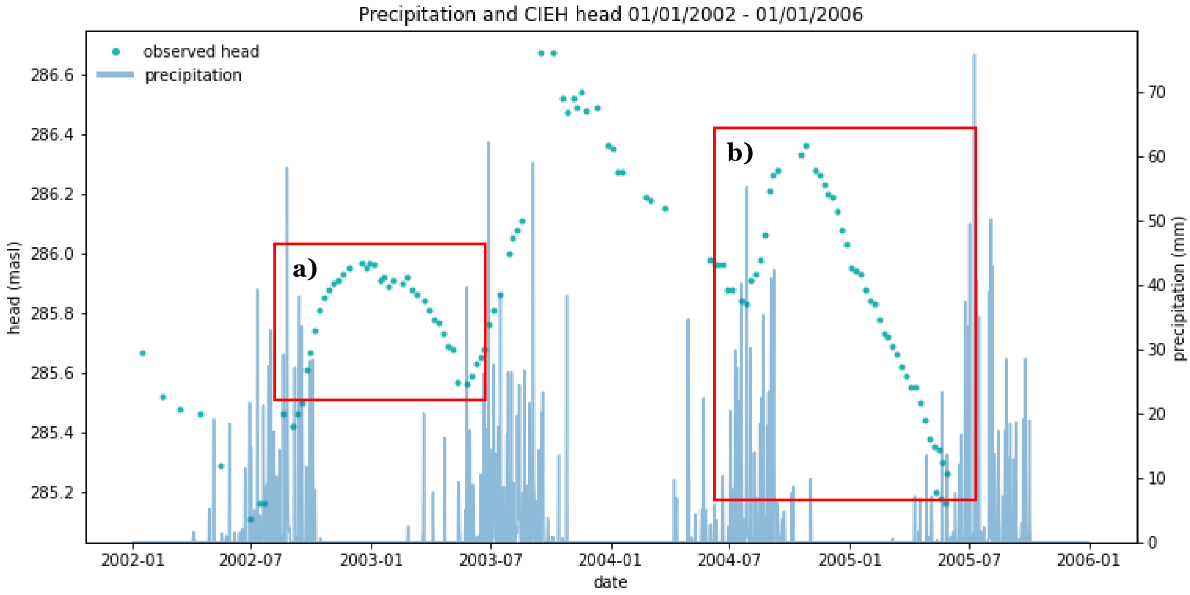


Figure 5.1: Groundwater observations 2002-2006m with two key areas of interest highlighted.

However, the 2002-03 hydrograph shows a distinctive pattern with a much more gradual rate of recession than usual (figure 5.1 a), which is not observed in any other year in the record. It does, however, resemble the recession pattern produced by the focused recharge model 1A (figure 4.1), and it is possible that this is indicative of an increase in water level in the reservoir moderating the rate of recession for that season, achieving rapid equilibrium so that an equivalent effect is not observed in subsequent years.

5.1.2 Focused recharge from storm drains

While the numerical model considered focused recharge from the reservoir only, there are other possible sources of focused recharge in the study area. Two sources are the nearby storm drains (the central canal and the university canal), particularly the university canal which passes less than 400 m from the piezometer. These channels drain a large proportion of the central city, and are frequently blocked by debris, resulting in standing water and occasional flooding, although flow is highly sporadic particularly outside of the rainy season (Bani and Yonkeu, 2016).

It is reported that the university canal channel was lined with concrete 2004 (Mouhouyouddine *et al.*, 2017), presumably reducing any potential role as a source of focused recharge. Interestingly, the rate of decline in groundwater head following the 2004 peak was one of the greatest on the record, occurring a rate of 5.6 mm d^{-1} (figure 5.1 b). The observed increase in magnitude and the rate of decline in head from the late 2010s (figure 4.6), which would be consistent with a reduction in focused recharge from this source, which might otherwise have modified the rate of recession.

5.1.3 Focused recharge from flooding

The area around the reservoir, particularly the agricultural plots on the south shore (figure 2.2) are highly prone to flooding during the rainy season, where due to poor drainage flood waters frequently remain for many days (Soma *et al.*, 2017; Korbéogo, 2018). During extreme events, such as the floods triggered by heavy rainfall in September 2009, floodwater has reached as far as the piezometer (Tazen *et al.*, 2019). Focused recharge from floodwaters has been observed in tropical semiarid environments (Taylor *et al.*, 2013) and it is likely that some degree of localised focused recharge occurs during these floods, especially when they occur on the vegetated areas within the catchment. However, satellite imagery and news reports were too sparse to accurately constrain the timing of floods occurring during this time period.

5.2 Evidence for other recharge mechanisms

5.2.1 Diffuse recharge

Despite the semiarid climate, conditions do exist for diffuse recharge to occur in the study area: during the rainy season, mean daily precipitation greatly exceeds reference evapotranspiration demand, and daily rainfall within the rainy season is highly variable, with events of > 40 mm in 24 hours occurring most years, providing the opportunity for individual events to overcome soil moisture deficits and trigger recharge (Small, 2005). The positive correlation between the total annual rainfall and the observed rise in head indicate that precipitation has at least some influence on the groundwater processes. It is perhaps surprising that there is no strong relationship between rainfall intensity and seasonal or interannual fluctuations, as this has been observed extensively in other locations in the tropics (Cuthbert *et al.*, 2019a), although this could in part be due to inaccuracies in the estimated changes in head due to the limited number of observations.

However, despite optimising for precipitation thresholds in both the WTFM and the SMBM, it has been difficult to identify clear recharge thresholds in either the annual totals, or short-term triggers for interannual fluctuations (see 4.3.2 above). Contrary to estimations in the literature that a minimum of 750-800 mm yr^{-1} is required for recharge to occur (MEE, 2001; Cuthbert *et al.*, 2019a), recharge clearly does occur even during the driest years. Mouhouyouddine (2015) reports the water levels in the reservoir drying almost completely between 1982 and 1984, limiting any capacity for focused recharge from that source, yet recharge also occurred for both these years.

5.2.2 Preferential flow

Preferential flow is known to occur in lateritic soils in the tropics (Cuthbert and Tindimugaya, 2010), and given the shallow water table and the highly fractured nature of the aquifer, it would be surprising if preferential flow processes were not occurring in this location. There fact that there is no clear rainfall threshold that triggers groundwater rise may indicate that preferential flow pathways are accessible at very low levels of precipitation, especially early in the season when the SMD is still high.

Rapid recharge from preferential flow combined with rapid decline linked to the heavy fissuring in the aquifer may account for two apparently anomalous groundwater peaks from the 2015 daily observations (figure 5.2). These consist of a rise in groundwater of approximately 0.7 m and a decline to background levels over a period of about ten days, and are not associated with unusually rainfall patterns in the days leading up to the event. While it cannot be discounted that these events represent observational errors, the fact that they occur twice, and over a period of several days, suggest they represent real short-term fluctuations that are only possible to detect with higher frequency observations.

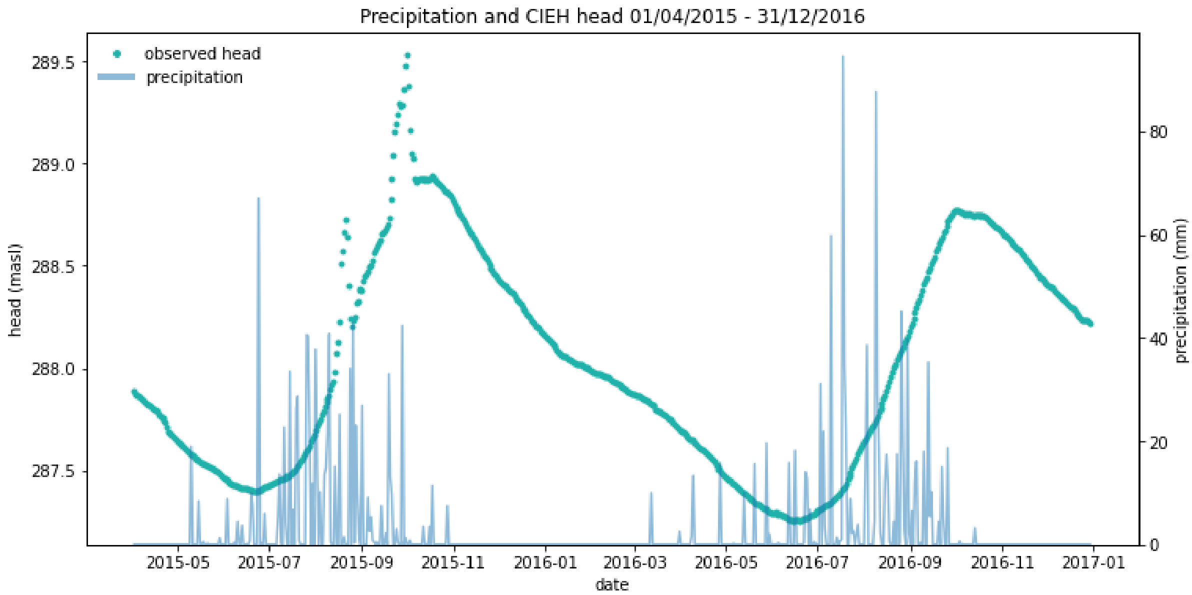


Figure 5.2: Short-term fluctuations observed in the 2015-2016 groundwater observations.

Mouhouyouddine *et al.* (2017) report similar results in their detailed observations of the 2013-2014 hydrological year, where there are extremely rapid (< 8 hours) responses to extreme rainfall events in wells located close to the reservoir. This would suggest, per Cuthbert *et al.* (2013) that these pathways can be accessed at certain intensities of rainfall. However, no equivalent rapid rises are visible in the 2016-2017 hydrograph, despite a greater overall annual rainfall and more extreme individual events in 2016. This may indicate that these rapid recharge events are influenced by localised recharge from events such as flooding (see 5.1.3 above). It is possible that some of the apparently anomalous data points in the longer groundwater record in fact represent such short-term responses, rather than representative of the background trend.

5.3 Land use change and environmental factors

5.3.1 Land use change and rainfall/runoff partition

Elsewhere in the Sahel, land use change has exerted a strong influence on runoff and in some areas, water table fluctuations (Albergel *et al.*, 1992; Favreau *et al.*, 2009). The Sahelian Paradox described above occurs because drainage networks are becoming more dense as a result of increased soil crusting and there is no evidence that this is happening in the immediate vicinity of the piezometer. The SMBM calibrated value for root constant C of 38 mm implied rooting depth of approximately 250 mm which is shallow for vegetation in a semiarid climate (Small, 2005), but perhaps not surprising given only a small proportion of the catchment was heavily vegetated.

The area within the local drainage boundaries has been largely built-up (with the exception of the Bangr Weogo Wetlands) since the beginning of the time series, and there is no evidence that there has been large-scale alteration of surfaces, as roads have never been paved. Unfortunately, high-resolution satellite imagery of the study area is not available before 2002, but no significant differences in terms of vegetated area or land use are detectable between 2002 and 2016.

However, altering the relationship between rainfall intensity and runoff improved the fit of the original SMBM (figure 4.5), and certainly modelling the rainfall-runoff-recharge relationship purely as a scalar is not very satisfactory, as the relationship is usually more complex (Eilers *et al.*, 2007) .

It has been assumed for the purposes of this investigation that groundwater hydrology in the study area is not affected by environmental processes occurring outside the immediate drainage basin. However, that may not be the case, especially if the university canal, which drains a much larger area, has historically contributed to focused recharge, and certainly urbanisation will have affected land use in the wider area since 1978. It is possible that land use changes in the wider basin may have some influence on the decadal fluctuations in groundwater levels, which are otherwise difficult to constrain with the limited evidence available.

5.3.2 The role of abstraction

Given the location in central Ouagdougou, where access to piped fresh water and irrigation water from the reservoir is widespread (Newborne and Tucker, 2015), it has been assumed that groundwater levels in the study area are not significantly affected by withdrawals (Martin and Thiéry, 1987; Cuthbert *et al.*, 2019a). However, this may not be the case: it is possible that sporadic groundwater abstraction occurs to support gardening and small-scale agriculture, especially during the dry season and in years with overall total annual rainfall, and this may be reflected in the annual groundwater recession patterns.

A previous model of processes in this aquifer was fitted by adjusting a certain level of abstraction (Mouhouyouddine *et al.*, 2017), and it is a reasonable assumption that during the driest years of the 1980s when the water level in the reservoir was close to zero, the rate of groundwater abstraction from hand pumps rose. However, the yield of most pumps in the area is known to be low ($< 2\ m^3\ hr^{-1}$) and without a more realistic constraint of the basin size and hydrological processes it is difficult to assess to what degree such withdrawals would be visible in the groundwater level. There is no obvious increase in the rate of recession during particularly dry years (e.g. 1984, 2009, 2013) compared to that of wet years (e.g. 2012, 2016). However, following the severe flooding in September 2009, a number of shallow wells for agriculture were installed by the FAO in the market gardening area to the south of the reservoir (Korbéogo, 2018) which may have contributed to the observed increase in rate of groundwater recession since 2010 (figure 4.6). Local news articles[1] regularly mention that water levels in the reservoir are frequently very low due to extraction, with high degrees of siltation and plant overgrowth, which may also affect degree of flow within the aquifer.

[1] E.g. “Barrages n°1, 2 et 3 de Ouagadougou : des réservoirs d’eau en péril” http://lefaso.net/spip.php?article54622; “Le principal barrage de Ouagadougou envahi par la jacinthe d’eau: https://www.voaafrique.com/a/le-principal-barrage-de-ouagadougou-envahi-par-la-jacinthe-d-eau-/5095054.htm

5.4 Sources of uncertainty related to groundwater models

Aside from the limitations in data availability discussed above, there are three key sources of uncertainty associated with groundwater modelling which are likely to affect the quality of the results. These are uncertainty related to quality of model input data; uncertainty in model parameterisation; and uncertainty associated with the choice of model (Højberg and Refsgaard, 2005), and are discussed in more detail below.

5.4.1 Uncertainties associated with model inputs

The quality of the model input data will necessarily affect the quality of conclusions that can be drawn from any results. The precipitation time series are from a single source and are almost complete for the entire period of interest with very few data gaps. There is a degree of uncertainty related to the precise datum from which measurements are taken at the reservoir and at the piezometer; however, as a systematic error throughout the time series this is unlikely to have a significant negative effect on model output.

Of more concern are the gaps in the piezometric time series, since these observations are the basis of all model calibration and assessment. The model calibration period was specifically chosen because of the regular observations during this time (see 3.2.6 above). However, since the observations become much less regular during the late 1990s and early 2000s, models are less likely to be able to replicate system behaviour during this period.

Inconsistent groundwater observations also mean that the accuracy of calculated values for annual rises and falls in groundwater level is likely to vary widely across the time series. Although care has been taken to exclude years where a lack of observations preclude meaningful analysis, inevitably there will be a lower degree of accuracy for years when there are fewer observations, while analyses that involve the comparison annual groundwater statistics (e.g. mean groundwater level) will be biased towards years earlier in the series, where there are more regular observations and fewer excluded years.

5.4.2 Uncertainties associated with model parameterisation

Model parameterisation is a key source of error associated with numerical groundwater modelling (Refsgaard *et al.*, 2012), especially for the geological parameters which vary both spatially and temporally, and are difficult to constrain even with extensive field observations (Carrera *et al.*, 2005). Here, the very limited observations available meant that a number of assumptions were made to simplify the modelling processes, likely resulting in parameterisation errors. In particular, values of S_y are notoriously difficult to constrain, especially in fractured rock aquifers where they are likely to vary considerably with depth (Healy and Cook, 2002). In variably weathered saprolitic aquifers values of S_y are likely to be highly anisotropic (Taylor *et al.*, 2010), and the values in fractured systems have been reported to be extremely low (< 0.01), although this is highly dependent on location within the aquifer. Transmissivity values also vary widely in aquifers of this type (Maurice *et al.*, 2019), so even when fitting models requires significant differences in parameterisation, this may simply reflect an incomplete understanding of the hydrogeological processes.

5.4.3 Uncertainties associated with choice of model

Errors in model conceptualisation are a frequently-overlooked source of error in groundwater modelling (Rojas *et al.*, 2008). A good fit and calibration does not necessarily mean that the choice of conceptual model is a good one, and data may fit more than one conceptual model well (Bredehoeft, 2005). Since the aim of this investigation was to explore the evidence to support different conceptual models, it has been possible to follow good practice through iteratively refining the initial conceptual models to come to better understanding of processes in the study area (Guillaume *et al.*, 2016).

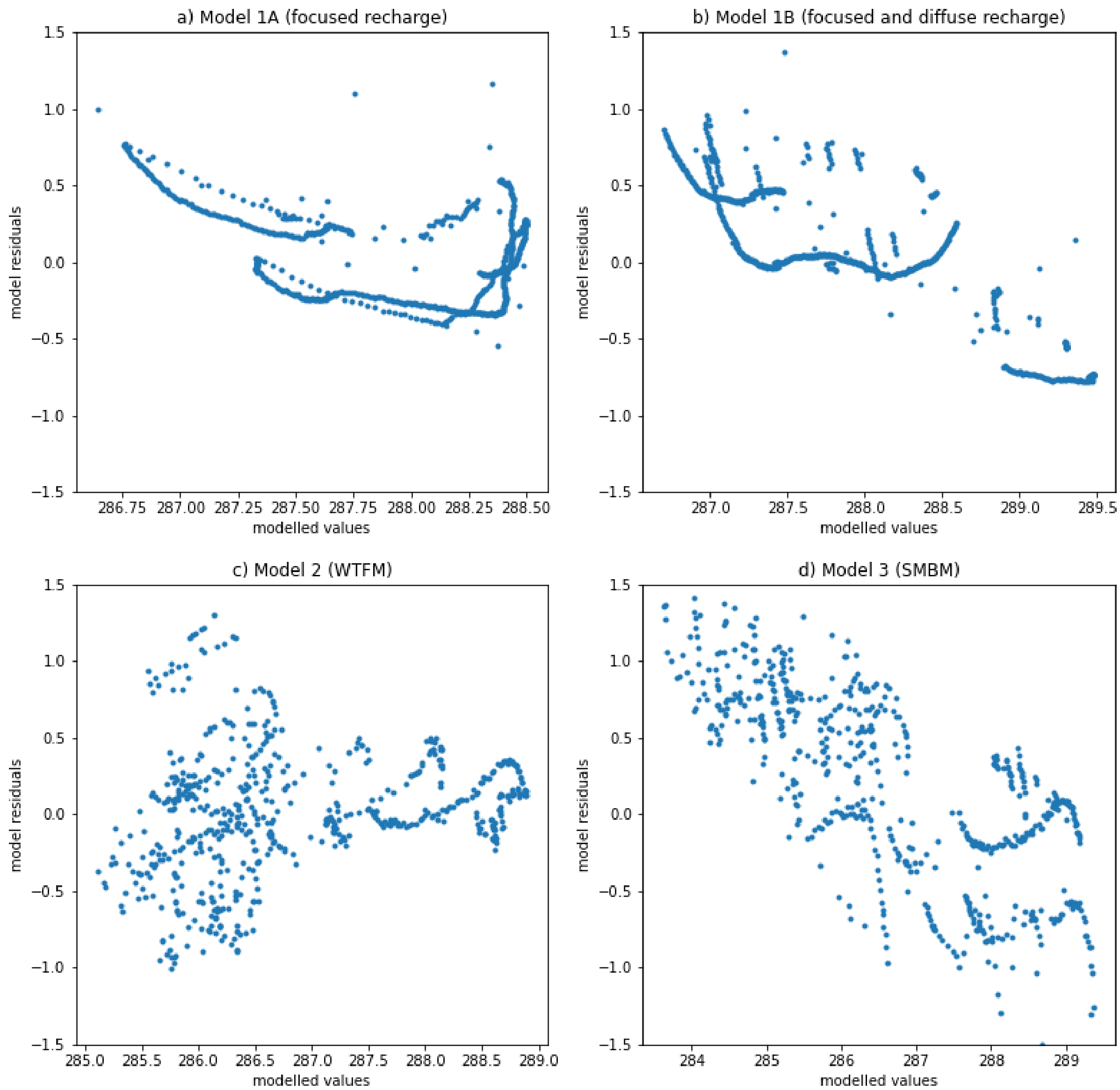


Figure 5.3: Residuals plots of the four calibrated models.

The residuals plots of the calibrated models (figure 5.3) should in the ideal case be normally distributed, assuming that sources of error are independent from each other (Xu, 2001). The strong patterns indicate weaknesses in each model, particularly visible in Model 3, where the plot highlights the systematic underestimation of high values and overestimation of low values.

5.5 Implications for groundwater management in Ouagadougou

The heterogeneity of the hydrogeology in Ouagadougou makes it difficult to draw wide-ranging conclusions from the results here that are applicable across the city. However, the relationship between the total annual rainfalls and the changes to the groundwater levels suggests that water tables in the study area respond rapidly to annual decreases in rainfall, and consequently the aquifers may become less productive under a more sustained decline. Most climate model ensembles suggest that the Sahel will see declining rainfall totals but an increase in extreme rainfall events (De Longueville *et al.*, 2016); this combined with increasing demand from fresh water expected as a result of the rapidly urbanising population and diminishing surface water resources (Newborne and Tucker, 2015) point to careful management of local aquifers being required if groundwater is to become a sustainable long-term aspect of the city's freshwater supply.

Similarly, the indications that preferential flow mechanism are important in the fissured aquifers in the study locations highlight the risks of aquifer contamination. Although the groundwater quality in Ouagadougou is generally adequate, the sewage system is not robust, and shallow aquifers are vulnerable to bacterial contamination, as well as agricultural chemicals which are often discharged directly into the reservoir (Yameogo *et al.*, 2006). Since preferential flow pathways are a known source of rapid transmission of aquifer contaminants (Nimmo *et al.*, 2017), this should be taken into consideration if groundwater is expected in the future to supplement piped water from reservoirs as a source of drinking water in the city.

6. Conclusion

6.1 Concluding discussion

The evidence from this investigation suggests that multiple recharge processes occur in this aquifer. There is evidence to support the theory of Cuthbert *et al.* (2019a) that focused recharge from the barrage is the dominant mode of recharge, with the filling of the reservoir likely to control the timing of the seasonal fluctuations, although this is based on a brief and incomplete time series of reservoir and groundwater data. However, given the lack of a clear trigger from any other factor, particularly a short term or cumulative precipitation threshold, the balance of evidence at the moment tilts in this direction.

There is a stronger basis for the assertion that annual precipitation totals influence the magnitude of the groundwater rise. Unlike other location in similar environments, the annual distribution of rainfall intensity appears to be less important. Gaps in the observations during the 1990s and between 2005 and 2012 make it difficult to fully analyse the groundwater response to the increasing number of extreme rainfall events that Ouagadougou has experience during the latter half of the time series. There is little evidence to support rapid groundwater response to such events (except, perhaps, the record-breaking rainfall of September 2009), largely due to the sparseness of the observations.

However, contra MEE (2001) and Cuthbert *et al.* (2019a) there does not appear to be a minimum threshold of annual rainfall for recharge to occur, with some rise in the water table observed for every year. This, together with the favourable geological environment, supports the theory that a certain amount of water reaches the water table via preferential flow processes, likely to be accessible even at relatively low levels of rainfall, and extremely important during the driest years.

Focused recharge from the reservoir may moderate the rate of groundwater recession within the aquifer, including a change from a rapid linear decline to a more exponential pattern (Cuthbert, 2014) that is most noticeable during the time series 2015. Focused recharge from other sources, including (until 2004) the nearby storm drain and areas of standing water after floods, may act as sporadic sources of localised recharge, causing short-term fluctuations in the head, while land use change and abstraction may also influence short and long term fluctuations in head. The causes of the decadal fluctuations and any link to focused recharge form the barrier remain uncertain, given the data limitations of this study.

6.2 Further work

The conclusions above would benefit from extensive validation from in-situ observations. This would improve the conceptual model of groundwater hydrology in the study area through an improved understanding of the local geology and hydrology, and also help to constrain the timing of key events such as flood occurrences, infrastructure construction, and land use change. Many of the data gaps here can be filled with existing datasets that were not available for this study. The full time series of reservoir water level data and complete climate data from the Ouagadougou weather station for the period of study would improve the quality of the model input data, and allow a more in-depth analysis of the long-term relationship between water level in the reservoir and head observed at CIEH. With sufficient resources, a detailed investigation of recharge processes using chemical tracers and direct observation would constrain many of the open questions about the fraction of recharge occurring via each mechanism.

With further tuning of the models developed in this study, a more in-depth exploration could be conducted of the relationship between precipitation intensity, runoff and land use. The scalar rainfall/runoff relationship used here clearly did not capture the complexities of the relationship, and it is possible that land use change on a larger scale has some influence on the longer-term fluctuations in the groundwater record.

Time constraints prevented a planned comparison between groundwater levels at the CIEH piezometer and those in Silmissin, 10 km to the south of Ouagadougou, where decadal fluctuations do not reflect the patterns observed in central Ouagadougou (Cuthbert *et al.*, 2019a). A comparative study would do much to assess the relationship between rainfall, runoff, and further build understanding of the recharge processes in weathered crystalline aquifers.

Auto-critique

It is safe to say that groundwater was not a subject that I had considered deeply before the beginning of this degree. However, I was drawn to the exploratory aspect of the proposal, and eager to get to grips with a field which was mostly new to me, but nonetheless fit well with my interest in climate change impacts on water resources.

Between the Covid-19 outbreak and the ongoing political crisis in Burkina Faso, there was no possibility of carrying out fieldwork, or of obtaining any extra data from local partners. While at times it was frustrating to have to work around information gaps that could have been filled by five minutes of face-to-face conversation, I began to enjoy the challenge of digging into every piece of secondary and tertiary literature I could find to triangulate information. I was pleased with how far I was able to take the investigation, in spite of these restrictions.

I particularly enjoyed the opportunity to develop the Python skills I had developed during the Masters, and I became much more comfortable with numerical modelling and statistical analyses during the course of the investigation. It was extremely satisfying to get to grips with running MODFLOW using FloPy, although another time I might not have spent quite so long wrestling with the programming, I believe that one of the strengths of this thesis is the wide variety of models used to investigate groundwater processes.

One of the challenges of this kind of exploratory investigation is that it is very easy to get side-tracked. The scope of the study ended up narrowing considerably from the original proposal, and the self-control required to stay focused on this was one of the most important things I learned. On future occasions I would take greater care in constraining the objectives and research questions right at the beginning, and taking regular checks to ensure that I wasn't getting too far off track.

As a student conducting research in a region I had never visited, I was keen to ensure that I was citing local scientists as widely as I could, rather than relying solely on authors based outside of the country. While there are good reasons for discouraging citations of articles in predatory journals, these articles were frequently the most up-to-date and sometimes the only source of information I had access to. I felt that as a result of this I developed better abilities to judge the merits of the science in an academic paper, and certainly I have become more aware of the numerous barriers to academic publishing faced by many scientists working outside Western institutions.

Original dissertation proposal

This project aims to develop a model of focused groundwater recharge in an aquifer in Ouagadougou, Burkina Faso, under conditions of seasonal flows. Existing code in FloPy representing focused recharge from ephemeral streams will be modified and applied to the Ouagadougou case. The model will be validated using existing hydrogeological data, and the validated model applied to a second aquifer in suburban Ouagadougou to investigate possible explanations for an observed decline in groundwater levels, including changes in rainfall and/or land use. This aspect of the project is exploratory in nature and will include the use of satellite images to analyse localised changes in land cover and constrain the timing of the construction of a small dam. Rainfall and groundwater level records will be analysed to ascertain what potential changes in the terrestrial water balance have occurred. Key anticipated outcomes of this project are a better understanding of the controls on groundwater recharge in a tropical semi-arid environment, and an improved model of focused recharge under these conditions.

References

Note on predatory journals

In general, the citation of articles published in predatory journals is not encouraged in academic writing, regardless of the quality of individual studies. However, barriers to traditional academic publishing are considerably higher for scientists in developing countries, and such journals may be the only route to publication. Much of the most recent work and observations for the study area has been conducted by scientists based in Burkina Faso, some of which has been published in predatory journals or other publications which are not indexed in SCOPUS. In order to draw on local expertise and access the most up-to-date information, a small number of such publications have been consulted, with due consideration given to the quality of the science. They are referenced as usual in the main text, but are marked here with an asterisk (*).

Albergel, J., Casenave, A., Ribstein, P. and Valentin, C. (1992) 'Aridité climatique, aridité édaphique : étude des conditions de l'infiltrabilité en Afrique tropicale sèche', in Le Floc'h, E., Grouzis, M., Cornet, A., and Bille, J.-C. (eds) *L'aridité : une contrainte au développement : caractérisation, réponses biologiques, stratégies des sociétés*. Paris: ORSTOM (Didactiques), pp. 123–130. Available at: http://www.documentation.ird.fr/hor/fdi:37354.

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. (1998) *Crop Evaporation - Guidelines for computing crop water requirements*. 56. Rome, Italy: Food and Agriculture Organization of the United Nations. Available at: http://www.fao.org/docrep/x0490e/x0490e07.htm.

Bakker, M., Post, V., Langevin, C. D., Hughes, J. D., White, J. T., Leaf, A. T., Paulinski, S. R., Larsen, J. D., Toews, M. W., Morway, E. D., Bellino, J. C., Starn, J. J. and Fienen, M. N. (2020) *FloPy v3.3.2 - release candidate*. (U. S. Geological Survey Software Release). Available at: http://dx.doi.org/10.5066/F7BK19FH.

Bakker, M., Post, V., Langevin, C. D., Hughes, J. D., White, J. T., Starn, J. J. and Fienen, M. N. (2016) 'Scripting MODFLOW Model Development Using Python and FloPy', *Groundwater*, 54(5), pp. 733–739. doi: 10.1111/gwat.12413.

Bani, S. S. and Yonkeu, S. (2016) 'Risques d'inondation dans la ville de Ouagadougou: Cartographie des zones a risques et mesures de prevention', *Journal Ouest-Africain des Sciences de Gestion*, 1(1), pp. 1–109.

Bazie, P., Dieng, B. and Ackerer, P. (1995) 'Bilan des transferts verticaux d'eau en zone non-saturée sous climat soudano-sahélien: application à l'estimation de la recharge des nappes', *Revue des sciences de l'eau / Journal of Water Science*, 8(2), pp. 237–260. doi: https://doi.org/10.7202/705221ar.

Beven, K. and Germann, P. (2013) 'Macropores and water flow in soils revisited', *Water Resources Research*, 49(6), pp. 3071–3092. doi: 10.1002/wrcr.20156.

Biasutti, M. (2019) 'Rainfall trends in the African Sahel: Characteristics, processes, and causes', *WIREs Climate Change*, 10(4), p. e591. doi: 10.1002/wcc.591.

Bieger, K., Hörmann, G. and Fohrer, N. (2012) 'Using residual analysis, auto- and cross-correlations to identify key processes for the calibration of the SWAT model in a data scarce region', in *Advances in Geosciences. Proceedings of the 14th Workshop on Large-scale Hydrological Modelling, 3-5 November 2010*, Tutzing, Germany: Copernicus GmbH, pp. 23–30. doi: https://doi.org/10.5194/adgeo-31-23-2012.

Braune, E. and Xu, Y. (2010) 'The Role of Ground Water in Sub-Saharan Africa', *Groundwater*, 48(2), pp. 229–238. doi: 10.1111/j.1745-6584.2009.00557.x.

Bredehoeft, J. (2005) 'The conceptualization model problem—surprise', *Hydrogeology Journal*, 13(1), pp. 37–46. doi: 10.1007/s10040-004-0430-5.

Carrera, J., Alcolea, A., Medina, A., Hidalgo, J. and Slooten, L. J. (2005) 'Inverse problem in hydrogeology', *Hydrogeology Journal*, 13(1), pp. 206–222. doi: 10.1007/s10040-004-0404-7.

Carter, R. C. and Parker, A. (2009) 'Climate change, population trends and groundwater in Africa', *Hydrological Sciences Journal*, 54(4), pp. 676–689. doi: 10.1623/hysj.54.4.676.

Casenave, A. and Valentin, C. (1992) 'A runoff capability classification system based on surface features criteria in semi-arid areas of West Africa', *Journal of Hydrology*, 130(1), pp. 231–249. doi: 10.1016/0022-1694(92)90112-9.

Chilton, P. J. and Foster, S. S. D. (1995) 'Hydrogeological Characterisation And Water-Supply Potential Of Basement Aquifers In Tropical Africa', *Hydrogeology Journal*, 3(1), pp. 36–49. doi: 10.1007/s100400050061.

Conway, D., Persechino, A., Ardoin-Bardin, S., Hamandawana, H., Dieulin, C. and Mahé, G. (2009) 'Rainfall and Water Resources Variability in Sub-Saharan Africa during the Twentieth Century', *Journal of Hydrometeorology*, 10(1), pp. 41–59. doi: 10.1175/2008JHM1004.1.

Cuthbert, M. O. (2014) 'Straight thinking about groundwater recession', *Water Resources Research*, 50(3), pp. 2407–2424. doi: 10.1002/2013WR014060.

Cuthbert, M. O. *et al.* (2019a) 'Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa', *Nature*, 572(7768), pp. 230–234. doi: 10.1038/s41586-019-1441-7.

Cuthbert, M. O., Gleeson, T., Moosdorf, N., Befus, K. M., Schneider, A., Hartmann, J. and Lehner, B. (2019b) 'Global patterns and dynamics of climate–groundwater interactions', *Nature Climate Change*, 9(2), pp. 137–141. doi: 10.1038/s41558-018-0386-4.

Cuthbert, M. O., Mackay, R. and Nimmo, J. R. (2013) 'Linking soil moisture balance and source-responsive models to estimate diffuse and preferential components of groundwater recharge', *Hydrology and Earth System Sciences*, 17(3), pp. 1003–1019. doi: https://doi.org/10.5194/hess-17-1003-2013.

Cuthbert, M. O. and Tindimugaya, C. (2010) 'The importance of preferential flow in controlling groundwater recharge in tropical Africa and implications for modelling the impact of climate change on groundwater resources', *Journal of Water and Climate Change*, 1(4), pp. 234–245. doi: 10.2166/wcc.2010.040.

De Longueville, F., Hountondji, Y.-C., Kindo, I., Gemenne, F. and Ozer, P. (2016) 'Long-term analysis of rainfall and temperature data in Burkina Faso (1950–2013)', *International Journal of Climatology*, 36(13), pp. 4393–4405. doi: 10.1002/joc.4640.

Descroix, L., Mahé, G., Lebel, T., Favreau, G., Galle, S., Gautier, E., Olivry, J.-C., Albergel, J., Amogu, O., Cappelaere, B., Dessouassi, R., Diedhiou, A., Le Breton, E., Mamadou, I. and Sighomnou, D. (2009) 'Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa: A synthesis', *Journal of Hydrology*, 375(1), pp. 90–102. doi: 10.1016/j.jhydrol.2008.12.012.

Dewandel, B., Lachassagne, P., Wyns, R., Maréchal, J. C. and Krishnamurthy, N. S. (2006) 'A generalized 3-D geological and hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering', *Journal of Hydrology*, 330(1), pp. 260–284. doi: 10.1016/j.jhydrol.2006.03.026.

Diedhiou, A., Bichet, A., Wartenburger, R., Seneviratne, S. I., Rowell, D. P., Sylla, M. B., Diallo, I., Todzo, S., Touré, N. E., Camara, M., Ngatchah, B. N., Kane, N. A., Tall, L. and Affholder, F. (2018) 'Changes in climate extremes over West and Central Africa at 1.5°C and 2°C global warming', *Environmental Research Letters*, 13(6), p. 065020. doi: 10.1088/1748-9326/aac3e5.

Döll, P., Schmied, H. M., Schuh, C., Portmann, F. T. and Eicker, A. (2014) 'Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites', *Water Resources Research*, 50(7), pp. 5698–5720. doi: 10.1002/2014WR015595.

Dong, B. and Sutton, R. (2015) 'Dominant role of greenhouse-gas forcing in the recovery of Sahel rainfall', *Nature Climate Change*, 5(8), pp. 757–760. doi: 10.1038/nclimate2664.

Eilers, V. H. M., Carter, R. C. and Rushton, K. R. (2007) 'A single layer soil water balance model for estimating deep drainage (potential recharge): An application to cropped land in semi-arid North-east Nigeria', *Geoderma*, 140(1), pp. 119–131. doi: 10.1016/j.geoderma.2007.03.011.

Famiglietti, J. S. (2014) 'The global groundwater crisis', *Nature Climate Change*, 4(11), pp. 945–948. doi: 10.1038/nclimate2425.

Favreau, G., Cappelaere, B., Massuel, S., Leblanc, M., Boucher, M., Boulain, N. and Leduc, C. (2009) 'Land clearing, climate variability, and water resources increase in semiarid southwest Niger: A review', *Water Resources Research*, 45(7). doi: 10.1029/2007WR006785.

Favreau, G., Leduc, C., Marlin, C., Dray, M., Taupin, J.-D., Massault, M., Salle, C. L. G. L. and Babic, M. (2002) 'Estimate of Recharge of a Rising Water Table in Semiarid Niger from 3H and 14C Modeling', *Groundwater*, 40(2), pp. 144–151. doi: 10.1111/j.1745-6584.2002.tb02499.x.

Filippi, C., Milville, F. and Thiéry, D. (1990) 'Evaluation de la recharge naturelle des aquifères en climat Soudano-Sahelien par modelisation hydrologique globale: Application a dix sites au Burkina Faso', *Hydrological Sciences Journal*, 35(1), pp. 29–48. doi: 10.1080/02626669009492403.

Franke, O. L., Reilly, T. E. and Bennett, G. D. (1987) *Definition of boundary and initial conditions in the analysis of saturated ground-water flow systems – An introduction*. Book 3, Chapter B5. Techniques of Water Resources Investigations of the U.S. Geological Survey.

Gal, L., Grippa, M., Hiernaux, P., Pons, L. and Kergoat, L. (2017) 'The paradoxical evolution of runoff in the pastoral Sahel: analysis of the hydrological changes over the Agoufou watershed (Mali) using the KINEROS-2 model', *Hydrology and Earth System Sciences*, 21(9), pp. 4591–4613. doi: https://doi.org/10.5194/hess-21-4591-2017.

Giorgi, F., Im, E.-S., Coppola, E., Diffenbaugh, N. S., Gao, X. J., Mariotti, L. and Shi, Y. (2011) 'Higher Hydroclimatic Intensity with Global Warming', *Journal of Climate*, 24(20), pp. 5309–5324. doi: 10.1175/2011JCLI3979.1.

Grindley, J. (1967) 'The estimation of soil moisture deficits', *The Meteorological Magazine*, 96(1137), pp. 97–108.

Guillaume, J. H. A., Hunt, R. J., Comunian, A., Blakers, R. S. and Fu, B. (2016) 'Methods for Exploring Uncertainty in Groundwater Management Predictions', in Jakeman, A. J., Barreteau, O., Hunt, R. J., Rinaudo, J.-D., and Ross, A. (eds) *Integrated Groundwater Management: Concepts, Approaches and Challenges*. Cham: Springer International Publishing, pp. 711–737. doi: 10.1007/978-3-319-23576-9_28.

Harbaugh, A. W. (2005) *MODFLOW-2005, the U.S. Geological Survey Modular Ground-Water Model—The Ground-Water Flow Process*. 6-A16.

Harbaugh, A. W., Langevin, C. D., Hughes, J. D., Niswonger, R. N. and Konikow, L. W. (2017) *MODFLOW-2005, the U.S. Geological Survey modular groundwater model: U.S. Geological Survey*

Software Release, 03 February 2017. U.S. Geological Survey. Available at: http://dx.doi.org/10.5066/F7RF5S7G.

Healy, R. W. (2010) *Estimating Groundwater Recharge*. Cambridge: Cambridge University Press. doi: 10.1017/CBO9780511780745.

Healy, R. W. and Cook, P. G. (2002) 'Using groundwater levels to estimate recharge', *Hydrogeology Journal*, 10(1), pp. 91–109. doi: 10.1007/s10040-001-0178-0.

Henriksen, H. J., Troldborg, L., Nyegaard, P., Sonnenborg, T. O., Refsgaard, J. C. and Madsen, B. (2003) 'Methodology for construction, calibration and validation of a national hydrological model for Denmark', *Journal of Hydrology*, 280(1), pp. 52–71. doi: 10.1016/S0022-1694(03)00186-0.

Højberg, A. L. and Refsgaard, J. C. (2005) 'Model uncertainty – parameter uncertainty versus conceptual models', *Water Science and Technology*, 52(6), pp. 177–186. doi: 10.2166/wst.2005.0166.

Horton, R. E. (1933) 'The role of infiltration in the hydrologic cycle', *Transactions of the American Geophysical Union*, 14(1), pp. 446–460. doi: 10.1029/TR014i001p00446.

Jarvis, A., Reuter, H. I., Nelson, A. and Guevara, E. (2008) 'Hole-filled seamless SRTM data V4'. International Centre for Tropical Agriculture (CIAT). Available at: http://srtm.csi.cgiar.org/.

Kingston, D. G., Todd, M. C., Taylor, R. G., Thompson, J. R. and Arnell, N. W. (2009) 'Uncertainty in the estimation of potential evapotranspiration under climate change', *Geophysical Research Letters*, 36(20). doi: 10.1029/2009GL040267.

Kittridge, M. (2018) *ETo - A Python package for calculating reference evapotranspiration*. Available at: https://github.com/Evapotranspiration/ETo.

Klemeš, V. (1986) 'Operational testing of hydrological simulation models', *Hydrological Sciences Journal*, 31(1), pp. 13–24. doi: 10.1080/02626668609491024.

Korbéogo, G. (2018) 'Ordering urban agriculture: farmers, experts, the state and the collective management of resources in Ouagadougou, Burkina Faso', *Environment and Urbanization*, 30(1), pp. 283–300. doi: 10.1177/0956247817738201.

Kotchoni, D. O. V., Vouillamoz, J.-M., Lawson, F. M. A., Adjomayi, P., Boukari, M. and Taylor, R. G. (2019) 'Relationships between rainfall and groundwater recharge in seasonally humid Benin: a comparative analysis of long-term hydrographs in sedimentary and crystalline aquifers', *Hydrogeology Journal*, 27(2), pp. 447–457. doi: 10.1007/s10040-018-1806-2.

Lafore, J.-P., Flamant, C., Guichard, F., Parker, D. J., Bouniol, D., Fink, A. H., Giraud, V., Gosset, M., Hall, N., Höller, H., Jones, S. C., Protat, A., Roca, R., Roux, F., Saïd, F. and Thorncroft, C. (2011) 'Progress in understanding of weather systems in West Africa', *Atmospheric Science Letters*, 12(1), pp. 7–12. doi: 10.1002/asl.335.

Langsholt, E. (1994) 'Water balance modelling in lateritic terrain', *Hydrological Processes*, 8(1), pp. 83–99. doi: 10.1002/hyp.3360080107.

Leake, S. A. and Lilly, M. R. (1997) *Documentation of a Computer Program (FHB1) for Assignment of Transient Specified-Flow and Specified-Head Boundaries in Applications of the Modular Finite-Difference Ground-Water Flow Model (MODFLOW)*. Open-File Report 97–571. U.S. Geological Survey, p. 56.

Lebel, T. and Ali, A. (2009) 'Recent trends in the Central and Western Sahel rainfall regime (1990–2007)', *Journal of Hydrology*, 375(1), pp. 52–64. doi: 10.1016/j.jhydrol.2008.11.030.

Leblanc, M. J., Favreau, G., Massuel, S., Tweed, S. O., Loireau, M. and Cappelaere, B. (2008) 'Land clearance and hydrological change in the Sahel: SW Niger', *Global and Planetary Change*, 61(3), pp. 135–150. doi: 10.1016/j.gloplacha.2007.08.011.

Leduc, C., Favreau, G. and Schroeter, P. (2001) ‘Long-term rise in a Sahelian water-table: the Continental Terminal in South-West Niger’, *Journal of Hydrology*, 243(1), pp. 43–54. doi: 10.1016/S0022-1694(00)00403-0.

Lodoun, T., Giannini, A., Traoré, P. S., Somé, L., Sanon, M., Vaksmann, M. and Rasolodimby, J. M. (2013) ‘Changes in seasonal descriptors of precipitation in Burkina Faso associated with late 20th century drought and recovery in West Africa’, *Environmental Development*, 5, pp. 96–108. doi: 10.1016/j.envdev.2012.11.010.

MacDonald, A. M., Bonsor, H. C., Dochartaigh, B. É. Ó. and Taylor, R. G. (2012) ‘Quantitative maps of groundwater resources in Africa’, *Environmental Research Letters*, 7(2), p. 024009. doi: 10.1088/1748-9326/7/2/024009.

Mahé, G. (2009) ‘Surface/groundwater interactions in the Bani and Nakambe rivers, tributaries of the Niger and Volta basins, West Africa’, *Hydrological Sciences Journal*, 54(4), pp. 704–712. doi: 10.1623/hysj.54.4.704.

Mahé, G. and Olivry, J.-C. (1999) ‘Assessment of freshwater yields to the ocean along the intertropical Atlantic coast of Africa (1951–1989)’, *Comptes Rendus de l’Académie des Sciences - Series IIA - Earth and Planetary Science*, 328(9), pp. 621–626. doi: 10.1016/S1251-8050(99)80159-1.

Maréchal, J. C., Dewandel, B. and Subrahmanyam, K. (2004) ‘Use of hydraulic tests at different scales to characterize fracture network properties in the weathered-fractured layer of a hard rock aquifer’, *Water Resources Research*, 40(11). doi: 10.1029/2004WR003137.

Maréchal, J.-C., Selles, A., Dewandel, B., Boisson, A., Perrin, J. and Ahmed, S. (2018) ‘An Observatory of Groundwater in Crystalline Rock Aquifers Exposed to a Changing Environment: Hyderabad, India’, *Vadose Zone Journal*, 17(1), p. 180076. doi: 10.2136/vzj2018.04.0076.

Martin, J. and Thiéry, D. (1987) ‘Analyse d’une longue série piézométrique au Burkina Faso - Étude de la variabilité climatique’, *Hydrogéologie*, (2), pp. 137–145.

Maurice, L., Taylor, R. G., Tindimugaya, C., MacDonald, A. M., Johnson, P., Kaponda, A., Owor, M., Sanga, H., Bonsor, H. C., Darling, W. G. and Gooddy, D. (2019) ‘Characteristics of high-intensity groundwater abstractions from weathered crystalline bedrock aquifers in East Africa’, *Hydrogeology Journal*, 27(2), pp. 459–474. doi: 10.1007/s10040-018-1836-9.

MEE (2001) *État des lieux des ressources en eau du Burkina Faso et de leur cadre de gestion*. Ministère de l’Environnement et de l’Eau. Available at: https://www.eauburkina.org/images/GIRE/GIRE_Etat_des_lieux_vf.pdf.

Mileham, L., Taylor, R., Thompson, J., Todd, M. and Tindimugaya, C. (2008) ‘Impact of rainfall distribution on the parameterisation of a soil-moisture balance model of groundwater recharge in equatorial Africa’, *Journal of Hydrology*, 359(1), pp. 46–58. doi: 10.1016/j.jhydrol.2008.06.007.

*Mouhouyouddine, A. H., Yameogo, S., Genthon, P., Paturel, J. E. and Guilliod, M. (2017) ‘Groundwater Level Changes since 1978 in an African City on Basement Rocks: The Case of the CIEH Borehole in Ouagadougou (Burkina Faso)’, *Journal of Water Resource and Protection*, 9(10), pp. 1097–1118. doi: 10.4236/jwarp.2017.910072.

Nash, J. E. and Sutcliffe, J. V. (1970) ‘River flow forecasting through conceptual models part I — A discussion of principles’, *Journal of Hydrology*, 10(3), pp. 282–290. doi: 10.1016/0022-1694(70)90255-6.

Newborne, P. and Tucker, J. (2015) *The urban–rural water interface: A preliminary study in Burkina Faso*. Working Paper. London, UK: Overseas Development Institute. Available at: https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/10221.pdf.

Nicholson, S. (2005) ‘On the question of the “recovery” of the rains in the West African Sahel’, *Journal of Arid Environments*, 63(3), pp. 615–641. doi: 10.1016/j.jaridenv.2005.03.004.

Nimmo, J. R., Creasey, K. M., Perkins, K. S. and Mirus, B. B. (2017) 'Preferential flow, diffuse flow, and perching in an interbedded fractured-rock unsaturated zone', *Hydrogeology Journal*, 25(2), pp. 421–444. doi: 10.1007/s10040-016-1496-6.

Pavelic, P., Keraita, B., Ramesh, V. and Rao, T. (2012) *Groundwater availability and use in Sub-Saharan Africa: A review of 15 countries*. Colombo, Sri Lanka: InternationalWater Management Institute (IWMI).

Penman, H. L. (1950) 'The water balance of the Stour Catchment area', *Journal of the Institute of Water Engineers*, 4(6), pp. 457–469.

Quichimbo, E. A., Singer, M. B. and Cuthbert, M. O. (2020) 'Characterising groundwater–surface water interactions in idealised ephemeral stream systems', *Hydrological Processes*, 34(18), pp. 3792–3806. doi: 10.1002/hyp.13847.

Raynaut, C. (2001) 'Societies and nature in the Sahel: ecological diversity and social dynamics', *Global Environmental Change*, 11(1), pp. 9–18. doi: 10.1016/S0959-3780(00)00041-8.

Refsgaard, J. C., Christensen, S., Sonnenborg, T. O., Seifert, D., Højberg, A. L. and Troldborg, L. (2012) 'Review of strategies for handling geological uncertainty in groundwater flow and transport modeling', *Advances in Water Resources*, 36, pp. 36–50. doi: 10.1016/j.advwatres.2011.04.006.

Reilly, T. E. (2001) *System and Boundary Conceptualization in Ground-Water Flow Simulation*. Book 3, Applications of Hydraulics, Chapter B8. Techniques of Water Resources Investigations of the U.S. Geological Survey.

Roberts, W., Williams, G. P., Jackson, E., Nelson, E. J. and Ames, D. P. (2018) 'Hydrostats: A Python Package for Characterizing Errors between Observed and Predicted Time Series', *Hydrology*, 5(4), p. 66. doi: 10.3390/hydrology5040066.

Rodríguez-Fonseca, B. *et al.* (2015) 'Variability and Predictability of West African Droughts: A Review on the Role of Sea Surface Temperature Anomalies', *Journal of Climate*, 28(10), pp. 4034–4060. doi: 10.1175/JCLI-D-14-00130.1.

Rojas, R., Feyen, L. and Dassargues, A. (2008) 'Conceptual model uncertainty in groundwater modeling: Combining generalized likelihood uncertainty estimation and Bayesian model averaging', *Water Resources Research*, 44(12). doi: 10.1029/2008WR006908.

Roques, C., Bour, O., Aquilina, L., Dewandel, B., Leray, S., Schroetter, JM., Longuevergne, L., Le Borgne, T., Hochreutener, R., Labasque, T., Lavenant, N., Vergnaud-Ayraud, V. and Mougin, B. (2014) 'Hydrological behavior of a deep sub-vertical fault in crystalline basement and relationships with surrounding reservoirs', *Journal of Hydrology*, 509, pp. 42–54. doi: 10.1016/j.jhydrol.2013.11.023.

Ross, G. J. S. (1982) 'Least Squares Optimisation of General Log-likelihood Functions and Estimation of Separable Linear Parameters', in Caussinus, H., Ettinger, P., and Tomassone, R. (eds) *COMPSTAT 1982 5th Symposium held at Toulouse 1982*. Heidelberg: Physica-Verlag HD, pp. 406–411. doi: 10.1007/978-3-642-51461-6_62.

Ruprecht, J. K. and Schofield, N. J. (1993) 'Infiltration characteristics of a complex lateritic soil profile', *Hydrological Processes*, 7(1), pp. 87–97. doi: 10.1002/hyp.3360070109.

Rushton, K. R. and Ward, C. (1979) 'The estimation of groundwater recharge', *Journal of Hydrology*, 41(3), pp. 345–361. doi: 10.1016/0022-1694(79)90070-2.

Sanogo, S., Fink, A. H., Omotosho, J. A., Ba, A., Redl, R. and Ermert, V. (2015) 'Spatio-temporal characteristics of the recent rainfall recovery in West Africa', *International Journal of Climatology*, 35(15), pp. 4589–4605. doi: 10.1002/joc.4309.

Scanlon, B. R., Healy, R. W. and Cook, P. G. (2002) 'Choosing appropriate techniques for quantifying groundwater recharge', *Hydrogeology Journal*, 10(1), pp. 18–39. doi: 10.1007/s10040-001-0176-2.

Scanlon, B. R., Keese, K. E., Flint, A. L., Flint, L. E., Gaye, C. B., Edmunds, W. M. and Simmers, I. (2006) 'Global synthesis of groundwater recharge in semiarid and arid regions', *Hydrological Processes*, 20(15), pp. 3335–3370. doi: 10.1002/hyp.6335.

Séguis, L. *et al.* (2011) 'Contrasted land-surface processes along the West African rainfall gradient', *Atmospheric Science Letters*, 12(1), pp. 31–37. doi: 10.1002/asl.327.

Sighomnou, D. *et al.* (2013) 'La crue de 2012 à Niamey : un paroxysme du paradoxe du Sahel ?', *Science et changements planétaires / Sécheresse*, 24(1), pp. 3–13. doi: 10.1684/sec.2013.0370.

Small, E. E. (2005) 'Climatic controls on diffuse groundwater recharge in semiarid environments of the southwestern United States', *Water Resources Research*, 41(4). doi: 10.1029/2004WR003193.

Soma, A., Wetta, C. and Sampana, L. (2017) *Gestion des inondations dans les villes de Ouagadougou et de Bobo-Dioulasso dans un contexte urbain – entre jeux d'acteurs et logiques territoriales*. Working Paper. London, UK: Overseas Development Institute. Available at: http://prise.odi.org/wp-content/uploads/2018/09/Gestion-des-inondations-dans-les-villes-de-Ouagadougou-et-Bobo-Dioulasso_Low-Res.pdf.

Sophocleous, M. A. (1991) 'Combining the soilwater balance and water-level fluctuation methods to estimate natural groundwater recharge: Practical aspects', *Journal of Hydrology*, 124(3), pp. 229–241. doi: 10.1016/0022-1694(91)90016-B.

Stephens, D. B. (1994) 'A Perspective on Diffuse Natural Recharge Mechanisms in Areas of Low Precipitation', *Soil Science Society of America Journal*, 58(1), pp. 40–48. doi: 10.2136/sssaj1994.03615995005800010006x.

Taylor, C. M., Belušić, D., Guichard, F., Parker, D. J., Vischel, T., Bock, O., Harris, P. P., Janicot, S., Klein, C. and Panthou, G. (2017) 'Frequency of extreme Sahelian storms tripled since 1982 in satellite observations', *Nature*, 544(7651), pp. 475–478. doi: 10.1038/nature22069.

Taylor, C. M., Parker, D. J. and Harris, P. P. (2007) 'An observational case study of mesoscale atmospheric circulations induced by soil moisture', *Geophysical Research Letters*, 34(15). doi: 10.1029/2007GL030572.

Taylor, R. G. and Howard, K. W. F. (1999) 'The influence of tectonic setting on the hydrological characteristics of deeply weathered terrains: evidence from Uganda', *Journal of Hydrology*, 218(1), pp. 44–71. doi: 10.1016/S0022-1694(99)00024-4.

Taylor, R. G., Todd, M. C., Kongola, L., Maurice, L., Nahozya, E., Sanga, H. and MacDonald, A. M. (2013) 'Evidence of the dependence of groundwater resources on extreme rainfall in East Africa', *Nature Climate Change*, 3(4), pp. 374–378. doi: 10.1038/nclimate1731.

Taylor, R. and Howard, K. (2000) 'A tectono-geomorphic model of the hydrogeology of deeply weathered crystalline rock: Evidence from Uganda', *Hydrogeology Journal*, 8(3), pp. 279–294. doi: 10.1007/s100400000069.

Taylor, R., Tindimugaya, C., Barker, J., Macdonald, D. and Kulabako, R. (2010) 'Convergent Radial Tracing of Viral and Solute Transport in Gneiss Saprolite', *Groundwater*, 48(2), pp. 284–294. doi: 10.1111/j.1745-6584.2008.00547.x.

Tazen, F., Diarra, A., Kabore, R. F. W., Ibrahim, B., Bologo/Traoré, M., Traoré, K. and Karambiri, H. (2019) 'Trends in flood events and their relationship to extreme rainfall in an urban area of Sahelian West Africa: The case study of Ouagadougou, Burkina Faso', *Journal of Flood Risk Management*, 12(S1), p. e12507. doi: 10.1111/jfr3.12507.

Thiéry, D., Diluca, C. and Diagana, B. (1993) 'Modelling the aquifer recovery after a long duration drought in Burkina Faso.', in. *Extreme Hydrological Events: Precipitation, Floods and Droughts - Yokohama (Japon)*, p. pp 43-50. Available at: https://hal-brgm.archives-ouvertes.fr/hal-01062478 (Accessed: 21 September 2020).

Todzo, S., Bichet, A. and Diedhiou, A. (2020) 'Intensification of the hydrological cycle expected in West Africa over the 21st century', *Earth System Dynamics*, 11(1), pp. 319–328. doi: https://doi.org/10.5194/esd-11-319-2020.

Valentin, C., Rajot, J.-L. and Mitja, D. (2004) 'Responses of soil crusting, runoff and erosion to fallowing in the sub-humid and semi-arid regions of West Africa', *Agriculture, Ecosystems & Environment*, 104(2), pp. 287–302. doi: 10.1016/j.agee.2004.01.035.

de Vries, J. J. and Simmers, I. (2002) 'Groundwater recharge: an overview of processes and challenges', *Hydrogeology Journal*, 10(1), pp. 5–17. doi: 10.1007/s10040-001-0171-7.

Werth, S., White, D. and Bliss, D. W. (2017) 'GRACE Detected Rise of Groundwater in the Sahelian Niger River Basin', *Journal of Geophysical Research: Solid Earth*, 122(12), p. 10,459-10,477. doi: 10.1002/2017JB014845.

Wheater, H. S., Mathias, S. A. and Li, X. (eds) (2010) *Groundwater Modelling in Arid and Semi-Arid Areas*. Cambridge: Cambridge University Press (International Hydrology Series). doi: 10.1017/CBO9780511760280.

Wyns, R., Baltassat, J.-M., Lachassagne, P., Legchenko, A., Vairon, J. and Mathieu, F. (2004) 'Application of proton magnetic resonance soundings to groundwater reserve mapping in weathered basement rocks (Brittany, France)', *Bulletin de la Société Géologique de France*, 175(1), pp. 21–34. doi: 10.2113/175.1.21.

Xu, C. (2001) 'Statistical Analysis of Parameters and Residuals of a Conceptual Water Balance Model – Methodology and Case Study', *Water Resources Management*, 15(2), pp. 75–92. doi: 10.1023/A:1012559608269.

Xu, Y., Seward, P., Gaye, C., Lin, L. and Olago, D. O. (2019) 'Preface: Groundwater in Sub-Saharan Africa', *Hydrogeology Journal*, 27(3), pp. 815–822. doi: 10.1007/s10040-019-01977-2.

Yameogo, S. (2008) *Ressources en eau souterraine du centre urbain de Ouagadougou au Burkina Faso, qualité et vulnérabilité*. Unpublished PhD thesis. University of Avignon.

Yameogo, S., Savadogo, A. N. and Koussoube, S. N. & Y. (2006) *Spatial and temporal variations of groundwater pollution in Ougadougou City, Burkina Faso*, *Groundwater Pollution in Africa*. CRC Press. doi: 10.1201/9780203963548-26.

Annex A: Supplementary information

Years excluded from data analysis

Data from the years below was excluded from analyses of the groundwater series. Years were excluded when data points were insufficient to provide a meaningful descriptive statistic (e.g. no clear annual max or min, or not enough observations to produce a meaningful value for mean groundwater level). The complete list of years is as follows: 1978, 1985, 1994, 1997, 1998, 2006, 2007, 2008, 2009, 2011, 2012.

Initial parameter estimates and sources for model calibration

Parameter	Initial estimate	Source
Specific yield S_y (-)	0.05	Martin and Thiéry (1987)
Horizontal hydraulic conductivity k (m d^{-1})	0.1	Martin and Thiéry (1987)
Specific storage S_s (-)	1 x 10^{-6}	Martin and Thiéry (1987), Bazie *et al.* (1995)
Drainage constant d (-)	0.04	Cuthbert *et al.* (2019a)
Runoff constant m (-)	0.13	Cuthbert *et al.* (2019a)
Runoff threshold P_{thresh} (mm)	10	Taylor and Howard (1999)
Rooting constant C (mm)	180	Taylor and Howard (1999), Allen *et al.* (1997).

Annex B: Code extracts

Below are extracts of the code used to run the groundwater models described in chapter 3. All code will be made available in full via https://github.com/lcawhitlock.

Simple water table fluctuation model

```
def WTF_basic(z):
    '''basic water table fluctuation model for optimisation. Returns dataframe of
    Arguments:
    =========
    a = rainfall/runoff coefficient
    b = drainage coefficient'''

    P = P1
    Sy = z[1]
    m = z[0]
    d = 0.04
    thresh = z[2]
    base = 280
    n = len(dates)

    #initiate some arrays for calculations
    dr = np.zeros(n)          #drainage
    R = np.zeros(n)           #recharge
    model = np.zeros(n)       #modelled GWL

    #initiate values
    model[0] = gwl[0]


    #loop through timesteps
    for t in range(1,n):
        if P[t] > thresh:

            R[t] = m * P[t]
        else:
            R[t] = 0

        if model[t-1] > base:
            dr[t] = d * (model[t-1] - base)
        else:
            dr[t] = 0

        model[t] = model[t-1] + ((R[t] - dr[t])/1000/Sy)

    dfout =  pd.DataFrame({'date': dates, 'rainfall': P, 'recharge': R, 'drainage': dr, 'model': model})

    return dfout
```

Soil moisture balance model

After Mileham *et al.* (2008). I am grateful to acknowledge Mark Cuthbert (Taylor and Howard, 1999)

```
########################################
# SWB Uganda (Taylor and Howard, 1999 #
########################################

#set parameters
P = Pma3
ETo = Ema3
dates = dates3
Ro = 0.13                           #percentage of P as runoff
Sy = 0.05                           #specific yield
SMD = 45                            #starting SMD
Rd = 300                            #root depth mm
sp = 0.35                           #soil porosity
C = 35.6 #0.5*Rd*sp (porosity)            #root constant = 0.5*Zr*n
WP = C+51
start = gwl[0]

D = 0.2335                          #fixed drainage (mm/d)
base = 280                          #aquifer baseline
dc = 0.04                           #decay constant for drainage
thresh = 10.9                          #threshold above which recharge occurs

n = len(dates)

ro = np.zeros(n)                   #runoff
smd = np.zeros(n)                  #soil moisture
re = np.zeros(n)                   #recharge
dr = np.zeros(n)                   #drainage
cv = np.zeros(n)
wpv = np.zeros(n)
model = np.zeros(n)                #model

#initiate some stuff
smd[0] = SMD
model[0] = start


for t in range (1, n):

    #runoff is precipitation above a threshold
    if P[t] > thresh:
        ro[t] = Ro * P[t]

        if P[t] > 40:
            #kp = P[t]/250
            #ro[t] = kp*P[t]
            ro[t] = rofunc(P[t])*P[t]

        else:
            ro[t] = Ro * P[t]

    else:
        ro[t] = 0

```

```
    #drainage is head-dependent
    if model[t-1] > base:
        dr[t] = (model[t-1] - base)*dc

    else:
        dr[t] = 0


    if P[t] - ro[t] - ETo[t] > 0:

        #case where there is penty of water and recharge occurs, smd to 0
        if P[t] - ro[t] - ETo[t] > smd[t-1]:

            re[t] = P[t] - ro[t] - ETo[t] - smd[t-1]
            smd[t] = 0

        #case where there is sufficient water only to access pref pathways
        elif smd[t-1] < 40:
            re[t] = 0.5*(P[t] - ro[t] - ETo[t])
            smd[t] = smd[t-1] - 0.5*(P[t] - ro[t] - ETo[t])

        #otherwise no recharge, and smd decreases by the amount of effective P
        else:
            re[t] = 0
            smd[t] = smd[t-1] - (P[t] - ro[t] - ETo[t])

    else:
        re[t] = 0

        #case where morning SMD > C
        if smd[t-1] - (P[t] - ro[t] - ETo[t])  > C:

            #if morning SMD > WP, smd stays at WP
            if smd[t-1] - (P[t] - ro[t] - ETo[t]) > WP:

                smd[t] = WP

            #otherwise if old SMD > C, new smd increases by 10% of effective P
            elif smd[t-1] > C:

                smd[t] = smd[t-1] - 0.1*(P[t] - ro[t] - ETo[t])

            #otherwise
            else:
                smd[t] = C - 0.1*(P[t] - ro[t] - ETo[t])

        else:
            smd[t] = smd[t-1] - (P[t] - ro[t] - ETo[t])


    model[t] = model[t-1] + ((re[t] - dr[t])/1000/Sy)

    #if t > 100:
        #if model[t] - np.min(model[t-100:t-1]) > 1.5:
            #model[t] = np.min(model[t-100:t-1])+1.5

    dfout = pd.DataFrame({'date': dates, 'rainfall': P,'ET0': ETo,
```

```
                             'runoff': ro, 'SMD': smd,
                             'recharge': re, 'drainage': dr,
                             'model': model})
```

Optimisation for water budget models

```
# optimisation approach adapted from P.Lewis, code available at
Github https://github.com/profLewis/geog0111/blob/master/Chapter6_NonLinear_Model_Fitting_Solutions.ipynb

#################
# LOSS FUNCTION #
#################

def loss_function(z,y_obs,sigma_obs,func=WTF_basic):
    df2 = func(z)
    df3 = pd.merge(df2,df1,how='inner',on='date')
    y_pred = df3.model.to_numpy()
    loss = -0.5*((y_pred - y_obs)**2/sigma_obs**2)

    return -loss.sum()

######################
# TEST LOSS FUNCTION #
######################

y_obs = gwl.to_numpy()
sigma_obs = 0.03
testloss = loss_function(z,y_obs,sigma_obs)
#print(testloss)

##################
# GET OPTIMISING #
##################
method = 'Nelder-Mead'
retval = minimize(loss_function,z,method=method,args=(y_obs,sigma_obs))
print(retval)
if retval.success:
    print('Success!!!!')
    #print(f'Cost value at the minimum: {retval.fun:g}')
    print(f'Value of the solution: {str(retval.x):s}')
    print(f'Cost value at the minimum: {retval.fun:g}')

############################
# check error coefficients #
############################

zopt = retval.x
wtfopt = WTF_basic(zopt)

y_pred = pd.merge(wtfopt,df1,how='inner',on='date')
y_pred = y_pred['model'].to_numpy()

print(f'RMSE = {he.rmse(y_pred,y_obs)}')
print(f'NSE = {he.nse(y_pred,y_obs)}')
print(f'Modified NSE = {he.nse_mod(y_pred,y_obs)}')
```

MODFLOW

The code to run FloPy is largely adapted from the guidance and tutorials provided under the most recent release of the software (Bakker *et al.*, 2020).

```
#create model object
modelname = 'preciptest'
exe_name = r'C:\Users\lcawh\Documents\mf2005\bin\mf2005'
workspace = os.path.join('model3')
if not os.path.exists(workspace):
    os.makedirs(workspace)

mf = flopy.modflow.Modflow(modelname,
                           exe_name=exe_name, model_ws = workspace)

#define model grid and domain
Lx = 6000
Ly = 1
ztop = 290
zbtm = 260
nlay = 1
nrow = 1
ncol = 200
delr = Lx / ncol
delc = Ly / nrow
delv = 30
btm = np.linspace(ztop, zbtm, 2)
hk = 0.5
vka = 1
sy = 0.04
ss = 1.e-5
laytyp = 1

#define cell types (all variable heads)
ibound = np.ones((nlay, nrow, ncol), dtype=np.int32)

#starting heads
strt = 287*np.ones((nlay, nrow, ncol), dtype=np.float32)
strt[0,0,0] = 290.38 #first value of data
strt[0,0,-1] = 261 #low gradient

#define stress periods
nper = 1765
perlen = [1]*1765
nstp = [1]*1765
steady = [True]+[False]*1764


#create time invariant objects
dis = flopy.modflow.ModflowDis(mf, nlay, nrow, ncol, delr=delr,
delc=delc,
        top=ztop, botm=btm[1:], nper=nper, itmuni=4,
        lenuni=2, perlen=perlen, nstp=nstp, steady=steady)
bas = flopy.modflow.ModflowBas(mf, ibound=ibound, strt=strt)
lpf = flopy.modflow.ModflowLpf(mf, hk=hk, vka=vka, sy=sy, ss=ss,
            laytyp=laytyp, ipakcb=53)
pcg = flopy.modflow.ModflowPcg(mf)

#ghb data
```

```
stageright = 261
condright = hk * (stageright - zbtm) * delc

keys = range(1769)
values = [[[0,0,199,stageright,condright]]]*1765

stress_period_data = dict(zip(keys,values))


#stress_period_data = {0: [[0,0,199, stageright, condright]],
                       #1: [[0,0,199, stageright, condright]]}
#stress_period_data[0]

ghb = flopy.modflow.ModflowGhb(mf,
stress_period_data=stress_period_data)
rkeys = range(1,1765)

#recharge time
rkeys = range(1,1765)
rvalues = recharge
rech1 = dict(zip(rkeys,rvalues))
rech1[0] = 0

rch = flopy.modflow.ModflowRch(mf,nrchop=1,rech=rech1)

#set up variable head
R_all = Rma3.tolist()
ds7 =[0,0,0,0]
for i in R_all:
    ds7.append(i)
ds7=[ds7]

#generate list of timesteps
bdtime = [i for i in range(0,1765)]

fhb = flopy.modflow.ModflowFhb(mf, nbdtim=1765, nhed=1,
              bdtime=bdtime, ds7=ds7)

#try drains
elev = 261
#cond = 0.0001*hk*(277 - zbtm) / delr
cond = 2.5e-4
drn_sp2 = []
for n in range(ncol):
    drn_sp2.append([0,0,n,elev,cond])
spd = {0: 0, 1: drn_sp2}
drn = flopy.modflow.ModflowDrn(mf, stress_period_data=spd)


#saving data
stress_period_data = {}
for kper in range(nper):
    for kstp in range(nstp[kper]):
        stress_period_data[(kper, kstp)] = ['save head',
                                            'save drawdown',
                                            'save budget',
                                            'print head',
                                            'print budget']
oc = flopy.modflow.ModflowOc(mf,
stress_period_data=stress_period_data,
          compact=True)
```

```

#write model input
mf.write_input()

# remove existing heads results, if necessary
try:
    os.remove(os.path.join(model_ws, '{0}.hds'.format(modelname)))
    os.remove(os.path.join(model_ws, '{0}.cbc'.format(modelname)))
except:
    pass

#run model
success, mfoutput = mf.run_model(silent=True, pause=False, report=True)
if not success:
    raise Exception('MODFLOW did not terminate normally.')


#get headobs
headobj = bf.HeadFile(workspace + '/' + modelname + '.hds')
headobj.list_records()
```