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Integrated Assessment of Interactions Between Surface Water and Groundwater Under Climate Variability and Change in The White Volta Basin, Ghana

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Abstract

The Nasia River, a tributary of the White Volta River system in Northern Ghana, is an important water resource for the area. In this research, a hydrological model that is able to simulate surface and subsurface flows in the Nasia catchment reasonably well was developed. The model was calibrated and verified using discharge and hydraulic head observations for the period 2000–2010. The complete simulation showed that the model was able to simulate the streamflow at the Nasia outlet quite well (Nash-Sutcliffe coefficient of 0.65, and correlation coefficient 0.805). The flow dynamics at three groundwater monitoring stations (HAP5, HAP10, and HAP11) were also realistically reproduced although the model generally overestimated the heads. For the purpose of climate change impact assessment, the calibrated/validated model provided a baseline condition to quantify evolving sensitivities of the Nasia catchment to climate variability and change. Climate projections drawn from eight Coupled Model Intercomparison Project phase 5 (CMIP5) global climate models (GCMs) were used to explore potential impacts on the catchment over three future time slices (2011–2025, 2026–2040, 2041–2055). When the climate scenarios were applied to the flow model, increasing trends in simulated evapotranspiration and streamflow from 2011 through 2055 were shown for all but one of the GCM scenarios. Projected rainfall changes dominated over evapotranspiration changes in terms of their impacts on streamflow for all three time periods. The results thus indicate that streamflow responses to climate changes in the Nasia Catchment are mainly driven by rainfall changes. The results also suggests that the conjunctive use of surface and groundwater resources to support local irrigation schemes in the basin might be a sufficient buffer against the effects of changing rainfall patterns on agriculture in the basin.

MONTCLAIR STATE UNIVERSITY

INTEGRATED ASSESSMENT OF INTERACTIONS BETWEEN SURFACE WATER AND GROUNDWATER UNDER CLIMATE VARIABILITY AND CHANGE IN THE WHITE VOLTA BASIN, GHANA

by

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Table of Contents

List of Tables

List of Figures

CHAPTER 1

Introduction

Background and Problem statement

Water resource management in Ghana dates back from prehistoric times through independence to present in response to seasonal variability in water availability. During this period, sustainable management and utilization of water was not an issue; and never required any technical intervention. Management of the resource became crucial during the transition from hunting and gathering to farming and more critical with the emergence and birth of cities, industrial and administrative centers. The issue of water management was only associated with cultural, social and religious arrangement of great diversity.

The paradigm, however, has shifted in recent times. Management and utilization of water resources have seen many challenges evolving from factors such as environmental, political, economic, socio-cultural, and ecological constraints. The state of performance of current water management systems in the country is driven by the economic reforms which begun in the 1980s under the economic recovery program (ERP); including the ten-year (1983-1993) structural adjustment program (SAP), and the program of action for the first medium term development plan (1997 to 2000) of Ghana, Vision 2020 (NDPC, 1998). Thus, in light of following the International Drinking Water Decade (1981–1990), it became expedient that water sectors initiate reforms which will speed up coverage of communities with safe drinking water. In that regard a new policy was enacted to ensure that the water supply to rural communities was demand driven and community managed. Beyond the effort to manage water resource, Government of Ghana (GoG) has made remarkable progress; particularly in areas of policy making and finance. Her attempts to provide concrete national programs for water resource management led to the establishment of coherent institutional structures and legislations such as Ministry of water resources, work and housing, Water Research Institute (WRI), Water Resource Commission , Community and Water Sanitation Agency (CWSA), Ghana Water Company Limited (GWCL), Environmental Protection Agency (EPA) among others; and other non-governmental agencies that are directly or indirectly related with water resource and its utility. In terms of finance, GoG, between 1996 and 1998, spent an average of US$1.95 million per annum as part of the Water Sector Rehabilitation project while donor contribution went up to US$34.2 million in 1998 (Gyau-Boakye and Ampong, 2003). Just recently, the concept of "Integrated Water Resource Management" (IWRM) has been embraced; with the hope of providing a holistic approach of managing water resource at the basin and sub-basin level. A project was proposed whereby decision support tools based on computer models that capture the hydrological and socio-economic interactions have been suggested as a promising tool for improving water resource management in the White Volta Basin (Birner et al. 2005). . While this concept has proposes a way forward as an efficient, equitable and sustainable scheme for development and management of water resources, it seems very unlikely that its applicability will work efficiently for a region already subject to water stress, and possessing weak and inadequate water management infrastructure, Ghana.

The White Volta Basin (Fig.1), located within the semiarid climate zone in northern Ghana, is a region where challenges owing to environmental, political, economic, socio-cultural, and ecological constraints continue to undermine the sustainable development and management of water resources. In addition, erratic spatiotemporal distribution of rainfall in recent years, has led to dwindling fortunes in the rain-fed agricultural enterprise that communities in the basin and the country at large are heavily reliant upon. Further aggravating these challenges is the current threat of climate change/variability, coupled with recent population boom, which has translated into growing demand for water resource in the region. As water use increasingly outpaces population growth, the growing demand for water will frequently impinge on the available supply thereby creating both hydraulic and hydrologic stress conditions with which aquifers underlying the area must suffer to bear. With the effect of high spatial and temporal rainfall variability already being registered, and the future prediction of reduced rainfall and soil moisture (Alo and Wang, 2010) pronounced for the region also looming, it is expected that the coming decades will see a much more pronounced impact of unbearable climate conditions.

Within the White Volta Basin, surface water and groundwater resources are available in enough measure to meet the domestic, agricultural, and industrial needs of communities in the basin. However, the poor development and management of the resource in the area has put the resource in deplorable and unsustainable conditions. Reliable surface water resources are relatively nonexistence and inhabitants rely on surface impoundments, dugouts and ephemeral streams which are often polluted and are insufficient to meet the rising water needs. In addition, these sources are exposed to high temperatures and evaporation conditions, and thus quickly dry out within short periods after the end of the rainy season. As home to numerous peasant farmers, with rain-fed agricultural as the main source of employment, attended by distorted rainfall pattern, the enterprise is rendered unsustainable; further compounding economic situations in the basin. Thus in the long round groundwater resource constitute the best solution to the water delivery system in the area. It has been identified as well suited to meet the dispersed demand of the growing rural population, which represents the larger proportion of the total population (Obuobi et al. 2012). Groundwater resource is also envisaged as the most viable solution to increasing rural water supply problems in the communities within the basin, and holds promise in terms of irrigation potentials if fully developed. The resource also forms the 'umbilical cord' to sustainable socioeconomic development in the basin and the country at large if properly managed. Sustainable delivery of the resource in a significantmeasure will go a long way to satisfying the growing domestic and irrigation needs in the basin. The increasing popularity of groundwater resource as a viable solution to water supply problems in the basin centers on its reliability, consistency, safety, and more importantly its accessibility owing to the geographical spread of aquifers underlying the area and its shallowness. The adequate aquifer protection also affords groundwater an excellent microbiological and chemical quality which requires little or no treatment. Additionally, the resource responds more slowly to changes in rainfall, making it less vulnerable to drought compared to surface water.

The success of sustainable groundwater resources is based on the level of understanding of the hydrogeological conditions of the underlying aquifers and the general flow pattern. Attempts to gain such insights have led to the development of groundwater flow simulations which have served well as effective decision support systems for water resource management, and have gained global acceptance as a useful tool. Numerous applications of these tools have been utilized in countries like China, India, USA (eg.

Senthilkumar, & Elango, 2004; Rejani et al. 2009; Kite, 2001; Zhou et al. 2000; Winter,1999; Arnold et al., 2000; BLISS, 2003). In Ghana, a handful of studies have utilized groundwater flow models to effect water resource management decisions. The very few comprehensive studies to understand the groundwater flow regime were undertaken by Lutz and Yidana. Within the White Volta Basin of Ghana, Lutz et al., 2007 applied a three dimensional steady state model to the Nabogo sub-catchment to address groundwater resource sustainability concerns. Yidana et al. 2008, likewise, determined estimates of hydraulic conductivity and the distribution of recharge from precipitation for some aquifers of the southern Voltaian sedimentary system. It is worth noting, however that, while groundwater flow models are useful decision support tools, they do have some limitations in terms of representing some key processes associated with hydrological systems. Often, groundwater models rely on specified recharge rates as the primary input of water into the model. Groundwater flow models also simplify or neglect surface processes and only solve for the flow gradient within the subsurface. Given that hydrologic models have become the central input to watershed management decisions, research efforts need to improve scientific understanding of hydrology and how it interacts with the broader environment (Duggan et al., 2008). To date, there have been limited studies looking at a long term effective management of the water resource in Ghana from an integrated point of view. Owing to the critical issues related to water resource availability and sustainability hitches, the need to integrate GW-SW interaction in both groundwater and surface water models have become paramount. Integrated models incorporate the individual characterization of flow processes within the hydrologic regime. Both surface and subsurface systems are simulated simultaneously, allowing feedback from one model to be accounted for by the other. Thus, integrated models provide a way forward to understanding the interactions within the hydrological regime thereby enhancing a more complete evaluation of water budget. A number of hydrologic models that incorporate the representation of groundwater surface water exchanges include for example HydroGeoSphere (Goderniaux et al., 2009), CATHY (Camporese et al.,2010), GSFLOW (Markstrom et al. 2008), MODHMS (Panday & Huyakorn, 2004), InHM (Vanderkwaak & Loague, 2001), HYDRUS3D (Simunek et al., 2006), MIKE SHE (DHI,2014), ParFlow (Maxwell & Kollet, 2008). Application areas range from water resource assessment studies, flood control and forecasting, watershed hydrological analysis, flood plain/fluvial hydraulic analysis to climate change impact assessment and predictive purposes (Downer and Ogden, 2004; Sophocleous & Perkins, 2000;Huang et al., 2010; Bauer et al. 2006; Kollet & Maxwel, 2006; Krause & Bronstert, 2007). MIKE SHE in particular, has been used extensively in application areas spanning from conjunctive surface water and groundwater studies (Graham & Refsgaard, 2001), river basin management and modeling (Henriksen et al., 2003), groundwater pollution, remediation and water quality modeling (Christiaens et al., 2002), Irrigation (Carr et al., 1993), land use changes and anthropogenic effects (Morgan et al., 1999) through to Remote sensing–weather radar and satellite (Boegh et al., 2004), and hydrological impacts of climate change (Thompson et al., 2009).

Recent studies have demonstrated the potential of an integrated modeling approach to assess surface water groundwater interaction under climate variability and change (Scibek et al. 2007; Ferguson & Maxwell, 2010; Allen et al., 2004; Jyrkama & Sykes, 2007; Goderniaux et al., 2009). Ferguson & Maxwell (2010) used an integrated, distributed groundwater-surface water-land surface model, ParFlow, to analyze integrated watershed response and groundwater-land surface feedbacks in the Little Washita River watershed in North America, under perturbed climate conditions. They found that the influence of groundwater feedbacks on sensitivity of surface fluxes to changing climate was dependent on the changes in both moisture and energy availability over the watershed. Their results indicated that while local and watershed response to global climate change depends on groundwater feedbacks, the magnitude and seasonality of these feedbacks is also sensitive to changes in climate.

Within the unconfined Grand Folks aquifer in south-central British Columbia, Canada, Allen et al. (2004) modeled the sensitivity of an aquifer to changes in recharge and river stage which was consistent with projected climate-change scenarios for the region. Their results revealed that variations in recharge to aquifer under the different climate-change scenarios, modeled under steady state conditions, have a much smaller impact on the groundwater system than changes in river-stage elevation of the Kettle and Granby Rivers, which take their course through a valley. In the same study area, Scibek et al. (2007) used a three dimensional transient groundwater flow model to simulate a three climate time periods for estimating future impacts of climate change on groundwater–surface water interactions and groundwater levels. Canadian Coupled Global Model 1(CCGM1) downscaling was used to predict basin-scale runoff for the Kettle River upstream of the study area, and the results converted to river discharge along the Kettle and Granby River reaches. Future climate scenarios indicated a shift in the river peak flow to earlier date in the year. Although they observed no changes in the overall hydrograph shape, the study finds the shift in river peak for the 2040–2069 climates came out larger than that for 2010–2039.

Providing estimates of the impact of climate change on water resource is one of the most difficult challenges faced by water resource managers. These difficulties arise from the simplified representation of the hydrologic regime which often leads to discrepancies in projections. In their study, Goderniaux et al. (2009) provides an improved methodology for the estimation of climate change impact on groundwater reserves. They combined a physically-based surface–subsurface flow model, HydroGeoSphere, with advanced climate change scenarios for the Geer basin in Belgium. The models provided a consistent projection pattern of much hotter and drier summers and warmer and wetter winters. Their results showed that when climate scenarios are applied to the flow model, significant decreases are expected in groundwater elevations by 2041–2070, with much larger decreases by 2071–2100. Similarly, surface flow rates are expected to decline during summer, with stronger and longer periods of low water discharge. Jyrkama & Sykes (2007) in likewise manner presented a physically based methodology capable of characterizing both the temporal and spatial effect of climate change on groundwater recharge. The method, based on the hydrologic model HELP3, was used to simulate past conditions, with 40 years of real weather data, and future changes in the hydrologic cycle of the Grand River watershed, Ontario, Canada. The impact of climate change was modeled by perturbing the model input parameters from predicted changes in the regions climate. The results revealed that the overall rate of groundwater recharge is predicted to increase as a result of climate change. And the increased intensity and frequency of precipitation will also contribute significantly to surface runoff.

The above literatures highlight that watershed responses to groundwater feedbacks are sensitive to climate change, and should be investigated using spatially distributed, physically-based hydrologic model. Similarly recharge represents an interdependent process within the hydrologic system which is crucial to estimating climate change impact on groundwater resource. This is because, recharge to groundwater aquifers are mainly by precipitation or through interaction with surface reservoirs. Thus the direct influence of climate change on precipitation and surface water will eventually affect groundwater systems.

Within the White Volta Basin, the major gaps, despite the recognition of the importance of developing groundwater resource, are our basic understanding of how surface water interacts with groundwater as a single resource, and the impact of a changing and variable climate on the resource. As a component of the hydrologic cycle, groundwater systems become responsive to changes in recharge (which can be linked to precipitation and evapotranspiration), and potentially by changes in the nature in which groundwater interacts with surface water; inducing a change in the use related to irrigation (Singh & Kumar, 2010). Thus detailed hydrological information and understanding is central to the success of sustainable management of groundwater resource. The development of groundwater resources for large scale abstraction for irrigation will therefore call for detailed assessment of groundwater recharge, the interaction between surface flows and subsurface flows, and the general groundwater flow pattern in the basin, within the context of climate change. With changes in climate directly affecting the amount and seasonal distribution of precipitation and evapotranspiration, improvement in our ability to predict the impact on surface flow as well as groundwater recharge will also require comprehensive understanding of aquifer properties and characteristics. Therefore the significant potential for models that can accurately represent the often complex hydrological situations is seen as a way forward in achieving the set goals.

With focus on the Nasia sub-catchment, this study attempts to develop a robust surface-subsurface flow model intended to capture all surface and subsurface flows in the basin which is pertinent with regard to any climate change impact assessment on the hydrologic regime. The MIKE SHE flow model is employed herein. It is a comprehensive, deterministic, distributed, and physically based modeling system capable of simulating all major processes of the hydrological cycle (DHI, 2014). The model duly calibrated and verified, will be forced with output from a climate model to simulate the effects of various scenarios of rainfall and groundwater surface water responses due to climate change/variability.

Study Objectives

The specific objectives of the project would be to:

- Develop a coupled surface-subsurface hydrologic model for the basin
- Calibrate and verify the hydrologic model
- Drive the hydrological model with output from a climate model to simulate impact of climate change on the water system
- Obtain a detailed knowledge of the key hydrologic processes controlling both surface and subsurface flows over the basin

Study Area

Physical setting and socioeconomic activities

The Nasia river catchment, bounded by 9°55' and 10°40' latitude and 1°05'W and 0°15'E longitude, is one of the sub-catchments of the White Volta river system at the north-eastern part of Ghana. Its total area is approximately 5300km^2 with drainage forming one of the left bank tributaries of the White Volta. The relief of the area is marked by undulating and a gently rolling topography with minimum and maximum elevations ranging from 112 to 448m respectively (Figure 1).

The agricultural sector is the largest employer in the area, employing about 97% of the active population (Attandoh et al. 2013). Peasant rain fed farming is the main source of subsistence and the typical crops grown include yam, maize, rice, groundnuts, cowpea, and soya beans. Unfortunately, agricultural activities are constrained by unreliable rainfall, inadequate irrigation facilities, and difficulty in loan accessibility and lack of storage or processing units leading to post harvest losses (Armah et al. 2010).

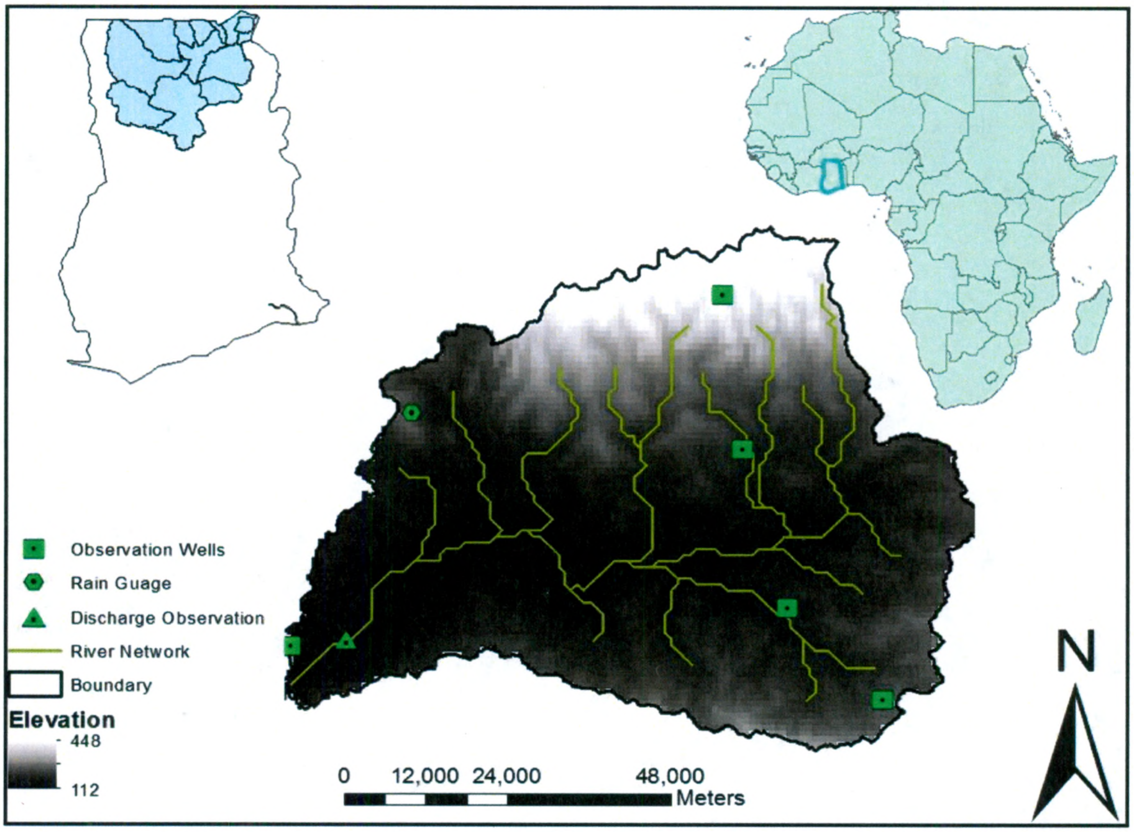


Figure 1 | Location map of the Nasia sub-catchment within the White Volta Basin of Ghana displaying topography and hydroclimatic stations.

Climate, Rainfall, and Surface runoff

The climate in Northern Ghana is influenced by movement of the Inter Tropical Convergence Zone (ITCZ) which generates unimodal rainfall season within the area. The ITCZ is an interface where two subtropical air masses, continental and maritime, overlap. The continental air mass blow warm, dry, and dust-laden wind from North East (Central Sahara) extent across the Atlantic Ocean while the maritime is associated with humid air stream blowing from the Gulf of Guinea (also within the Atlantic Ocean) across the inland regions of West Africa. As a result of these oscillating air masses two seasons, dry and wet seasons, are distinguished in the region of the study area.

The frontal activity and the relative movement of the two air masses control the amount and duration of rainfall. The manner of rain in the region is generally of short duration, high intensity and often preceded by thunderstorms and line squalls that start intermittently between the months of March and April through August to September when it turns stable and very heavy (Dickson and Benneh, 2004). Rainfall measurements for the area are based on political, watershed, temporal, and agro-ecological boundaries. The mean annual estimates vary within 900 and 1140mm (Friesen, 2002; Apambire, 2000).

Surface runoff occurs when the rate of precipitation exceeds the rate of infiltration and through flow under the influence of both climatic and physiographic factors. According to the water balance developed by Andreini et al. (2000) for the entire basin, it was indicated that about 17% of total rainfall within the White Volta Basin result in runoff to the Lake Volta.

Temperature and Evapotranspiration

Temperatures largely show decreasing north-to-south trend in the basin. In the north mean monthly temperature vary from 36°C to 27°C in March and August respectively with southern temperatures ranging between 30°C and 24°C in same respective months (Oguntunde et al. 2006). The dry seasons are pronounced with temperature ranging between 18°C and 42°C. Relative humidity during the wet season is within the range of 40–70% and declines to around 15% during the rest of the year (Benneh and Dickson, 2001). The observed low humidity and high temperatures have led to high potential and actual evapotranspiration rates in the basin.

In northern Ghana, evapotranspiration pattern is spatio-temporal; varying by season and location, and by local vegetation type and density. Estimates of annual mean potential evapotranspiration ranges from 1600 to 2500mm (Kranjac-Berisavljevic, 1999; Amisigo, 2005; Kasei, 2005; Fugger, 1999). It is estimated that approximately 91% of precipitation in the White Volta Basin is subject to evapotranspiration, and the remainder forms surface runoff or is recharged to aquifers (Andreini et al., 2000). The Guinea Savannah woodland is the major vegetation cover consisting of grass with scattered drought resistant trees such as the shea, the baobab, dawadwa, acacias, and neem.

Geology and Hydrogeology

The Nasia sub-basin lies entirely within the Paleozoic consolidated sedimentary formation (locally known as the Voltaian Group). The bedrock lithology within the Voltaian Basin cover an area of about 103600 km^2, almost one-third the area of Ghana (Kesse, 1985). The Voltaian strata are unmetamorphosed and nearly horizontal beds composed of mudstone, arkose, sandstone, shale, conglomerates, and limestone (Kesse, 1985). The poor exposure and the lack of laterally persistence lithological marker beds of the group impose some difficulty in attempting to subdivide it. However, Junner and Hurst (1946) managed to subdivide the Voltaian sediments on the bases of lithology and field relationships into Lower, Middle, and Upper units. The study area is mainly underlain by rocks of the middle Voltaian, which is the most extensive sedimentary formation in Ghana. The Middle Voltaian comprises the Oti beds. Overall rocks of the Voltaian dips 5-degrees in the southeast direction, and are gently folded (Adu, 1995). The dip of the strata suggest that the basin formed by lithospheric flexure during the Pan-African Orogeny. The structure of the Voltaian has been dealt with in details by Ako and Wellman (1985), based on their reviews of gravity and magnetic data for the basin.

The hydrogeological provinces of Ghana are defined primarily on the basis of geology, which influences the availability and occurrence of groundwater (Gill, 1969). The Voltaian system is one of two major provinces in northern Ghana. The rocks are largely well consolidated and inherently impermeable, so that the occurrence of groundwater is associated with the development of secondary porosity through fracturing, faulting, and to a lesser extent, weathering. Compaction and slight metamorphism is believed to have destroyed the primary porosity (Dapaah-Siakwan & Gyau-Boakey, 2000), which have given way to considerably reduced inherent primary permeabilities. However, where intense weathering occurs, the rocks serve as better aquifers with significantly enhanced hydraulic and storage properties. The nature, aperture and degree of interconnection between joints determine the hydrogeological fortunes of the rocks (Junner and Service, 1935; Junner and Hirst, 1946; Acheampong, 1996; Yidana et al. 2008). The thickness of the regolith over the Voltaian sedimentary rocks can range from 6m to as high as 50m or more at various locations (ACCESS, 2008). Areas with relatively thin regolith are partially due to the stable clay (shale) or quartz (sandstone) composition or by the fine texture or ductile exposed in the Voltaian system (ACCESS, 2008). Because the regolith is often too thin to store significant amounts of water, the main aquifers within the sedimentary rocks of the Voltaian are generally located in fractured rocks. Deep weathering may however occur in areas where weathering is intense. Consequently, because much of the study area is characterized by arkose and arkosic sandstone, which more easily weathers K-feldspar to Quartz and clay minerals, it is obvious that the thickness of the overburden will be relatively high; which will result in fracture zones developing at quite high depths below groundwater surface. Thus enhanced well yield is expected to occur at much greater depth in the area. The weathered zone is variably conductive due to the variability of clay content. Areas with considerably high clay content exhibit a much reduced vertical percolation of rainfall while areas where relatively thin and sandy regolith develop over sandstones and siltstone exhibit well enhanced recharge rates (Oteng, et al. 2014).

CHAPTER TWO

Preliminary work

In regional hydrogeological studies and groundwater resources assessments, accurate estimates of groundwater recharge are required to ensure proper water balance studies and evaluation of groundwater resources for productive uses. Bearing in mind that recharge is one of the uncertain parameters in model calibration and also regarded as one of the major parameters which determine the accuracy and reliability of predictive surface and groundwater flow models, it was necessary that representative groundwater recharge estimates through Chloride Mass Balance (CMB) and isotopic methods suited for a semiarid environment like the White Volta basin be performed to validate future research in the area.

In the study of Oteng et al. (2014), the sources and origin of groundwater recharge in the Voltaian was assessed using stable isotope data of precipitation (rainfall), groundwater, and surface water from parts of the Voltaian. Historical stable isotope data ($\delta^{18}O$ and δ2H) for groundwater, surface water, and rainfall were plotted on a biplot for the purposes of ascertaining the sources and/or evolution of groundwater in the area. Isotope tracers are amongst the most frequently used to trace the sources and/or genesis of water reservoirs and contaminants and have been noted to provide useful insights to guide further detailed investigations. The ratio of the rarer (and most often the heavier) isotope to the more abundant (often the lightest) isotope provides an indication of the relative enrichment of the two isotopes in the medium or the original source of recharge. It is such a ratio that provides indications of the climatic conditions prevailing at the period and location of recharge and can therefore be used qualitatively to infer the age of a water body. These ratios are expressed in relation to an international standard which provides some uniformity for comparing environments or reservoirs on a global scale, and is often expressed in the delta (δ) notation as indicated in:

$$\delta^{18}O= \left[\frac{\left(\frac{^{18}O}{^{16}O}\right)sample}{\left(\frac{^{18}O}{^{16}O}\right)V-SMOW}\right]\times 1000$$

(1)

$$\delta^{2}H= \left[\frac{\left(\frac{^{2}H}{^{1}H}\right)sample}{\left(\frac{^{2}H}{^{1}H}\right)V-SMOW}\right]\times 1000$$

where the terms in the numerator and denominator, respectively, denotes the ratio of heavier to the lighter isotope in the sample and international standard, respectively.

The global meteoric water line (GMWL), first published by (Craig 1961), and has become a very convenient reference for understanding and tracing water origin. It is based on the linear relation of the form:

$\delta^2H= 8\delta^{18}O + d,$ (2)

where d, the y= intercept, is the deuterium excess (or d-excess) parameter when the slope = 8 (Konikow and Bredehoeft, 1992). From Craig's MWL, d = 10 at this slope and is indicative of no evaporative effect during precipitation. The underlying assumption is that water with an isotopic composition that falls along the GMWL originates from the atmosphere and is relatively unaffected by isotopic processes. Isotopic signatures from different reservoirs are often discussed in relation to (Healy and Cook, 2002). The study finds that groundwater recharge in the area appears to be of meteoric origin as the groundwater data plots close to the GMWL, albeit with shallower slope and intercept, which suggest some degree of enrichment of the heavier isotope relative to the lighter ones (Figure 2). The observed pattern is akin to conditions of lower relative humidity than 100% and high ambient temperatures as is common in the study area. The shallower slope and *d*-excess values result from evaporation of raindrops due to low relative humidity during the course of the rains.

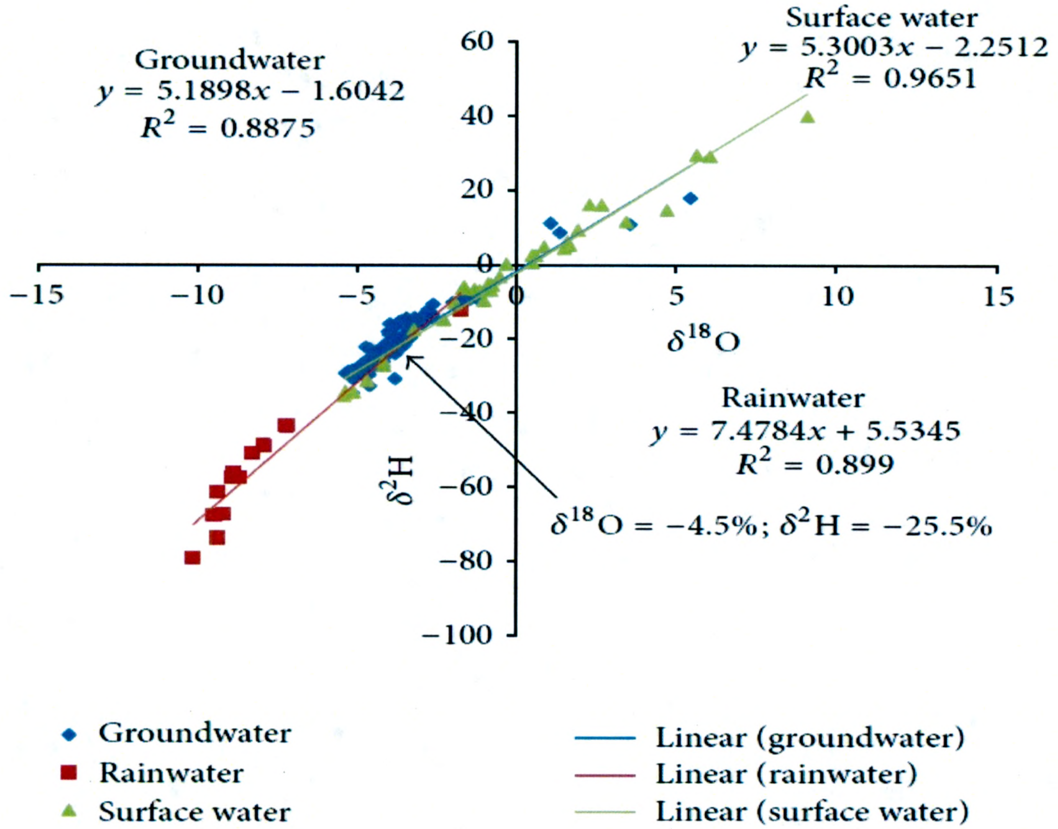


Figure 2 | Stable isotope signatures of rainwater, surface water, and groundwater from parts of the White Volta Basin, Ghana (Oteng et al., 2014).

There is an apparently high variability in direct groundwater recharge from precipitation in the area and much of the Voltaian basin. This observation is consistent with the nature of the material in the unsaturated zone which varies in space in terms of the clay content. Where the clay content is high, vertical percolation is significantly restricted, and the resulting recharged groundwater is significantly enriched due to evaporative effects of high temperatures and low humidities. It can be seen that the surface water data fall close to the Global Meteoric Water Line, GMWL, whereas both the rainwater and groundwater samples are relatively enriched, with shallower slopes and deuterium excess (d-excess) values (Figure 2). The rainwater samples were taken during three events in the major rainy season and may not adequately reflect the signature for the entire year. However, studies conducted in the southern parts of the basin using data mainly of the dry season precipitation suggest significant enrichment (Acheampong and Hess, 2000). A solution of the equation for the Local Meteoric Water precipitation data and the local Groundwater Line (LGWL) developed from the groundwater isotope data provides the isotopic signature of the most probable source precipitation of the groundwater in the area. The intersection of the LGWL and LMWL in Figure 2 provides such a signature. The isotopic signature at the point of intersection of these two lines ($\delta 18O = -4.5$; $\delta 2H = -25.5$; Figure 2) suggests that the source of recharge is recent meteoric water or a mixture of precipitation types which are of recent origin. The local surface water line (LSWL) is similar to the groundwater line in terms of slope and intercept (Deuterium excess) and suggests that both have a similar source and may have been affected by similar processes overtime. A recent assessment of the isotope characteristics of the entire Voltaian indicated a similar isotopic signature of the source water of groundwater recharge in the basin (Yidana, 2013) and indicated that the processes of infiltration and percolation of precipitation water may be variably slow in the terrain, due to the variability in the nature of the overburden even within short distances.

Estimated groundwater recharge from the CMB suggests annual recharge in the range of 0.9%–21% of the total annual precipitation. This is consistent with the observation of high evaporation rates estimated for the entire basin and suggests that much more water may have been lost to transpiration than is recharged to groundwater. However, this much of groundwater recharge suggests high fortunes in terms of commercial groundwater resources development in the area, if a significant proportion of it is available for abstraction. The wide range in the estimated data and the high standard deviation suggests significant spatial variation in groundwater recharge rates in the study area. This may be related to the nature of the unsaturated zone material and its variability in the space of the domain of this study. The average rate of about 5.5% is significant and compares favorably estimates in other parts of the terrain. There is an apparently high variability in direct groundwater recharge from precipitation in the area (Figure 6) and much of the Voltaian basin. This observation is consistent with the nature of the material in the unsaturated zone which varies in space in terms of the clay content. Where the clay content is considerably high, vertical percolation of rainwater is much reduced; leading to reduced vertical recharge. Infiltrating rainwater experiencing such restricted vertical flow therefore undergoes significant evaporation such that a high percentage is lost to the atmosphere.

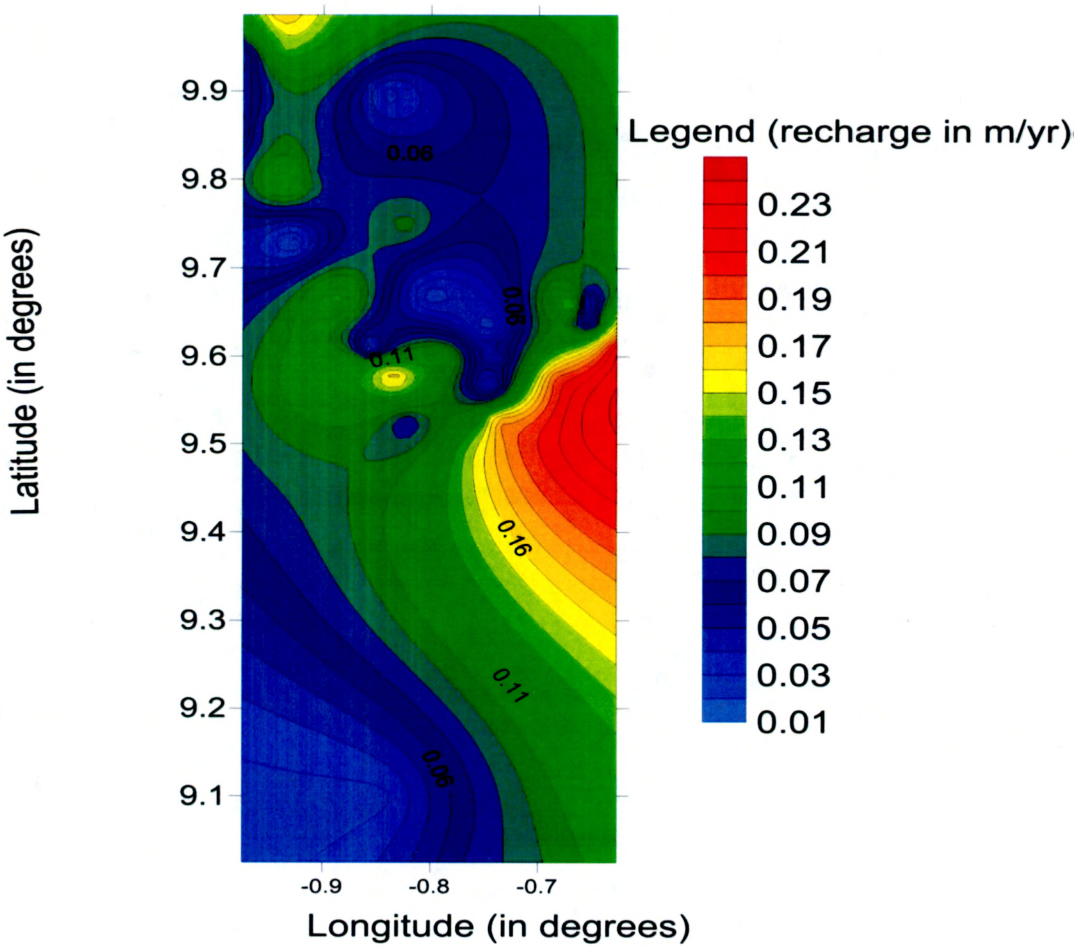


Figure 3 | Spatial distribution of estimated groundwater recharge in Savelugu and surrounding sub-catchment of the White Volta Basin.

The results from the CMB and environmental tracers study provided significant insights into this present work. The similarity in the isotopic signatures of both groundwater and surface water in the area in terms of their slope and intercept (deuterium excess), indicates that the surface water bodies somehow feed or are fed by groundwater flow within aquifers of the study area. The relative high evaporative rate in the area which results in isotopic enrichment with respect to ^{18}O and deuterium for groundwater and surface water was successfully used as a tracer to determine leakage from the rivers to the aquifers. Also conceptualization of the various lithological units that underlie the surface water bodies, their hydraulic characteristics, and their interrelation with the surface waters and other hydrological information for the catchment is of critical importance for any future modelling exercise. The environmental Isotopes complemented with all geological, hydrological, and physical information–including the spatial distribution of clay materials–assisted in developing a conceptual model of the aquifer-river interaction within the Nasia sub-catchment. The results indicated a close hydraulic link between surface water and groundwater in the area.

CHAPTER THREE

Methodology

The development of the Nasia model evolved following the underlying steps: identification of all major processes and available information; data collation and processing; model set up and calibration; and embarking on a predictive model simulation to evaluate the impact of climate change on water resource. The hydrological information available for the Nasia sub-catchment is also described below.

Model set up and calibration

The hydrologic model of the Nasia sub-catchment within the White Volta Basin of Ghana is based on the MIKE SHE modelling package. MIKE SHE is an advanced, flexible framework for hydrologic modeling (Graham and Butts, 2005) that comprises a full suite of pre- and post-processing tools, with a flexible combination of advanced and simple solution techniques for the individual processes within the hydrologic cycle. Its flexibility lies in the level of detail in which each hydrologic process is simulated. The MIKE SHE Water Movement module has been designed with a modular structure in which a range of options are available to model the major processes within the land phase hydrological cycle, and include process models for evapotranspiration and interception, overland flow and channel flow, unsaturated flow, groundwater flow, and river-aquifer interactions. Each of these processes can be represented at different levels of spatial distribution and complexity, according to the specific questions that need to be addressed by the model, and the availability of input data with which to construct and calibrate the model. The following sections present the utility of each component in the model environment.

Evapotranspiration and interception component

The computation of evapotranspiration requires meteorological and vegetative data as input variables to predict the total evapotranspiration and net rainfall amounts due to processes such as interception of rainfall by the canopy, drainage from the canopy, evaporation from the canopy surface, evaporation from the soil surface, and finally, uptake of water by plant roots and its transpiration. This component interacts with the unsaturated zone component, providing net rainfall and evapotranspiration loss rates and using information on soil moisture conditions in the root zone. The ET model is based on empirically derived equations antecedent to the study by Kristensen and Jensen (1975), which was carried out at the Royal Veterinary and Agricultural University in Denmark. The calculated actual evapotranspiration is based on potential evaporation rate and the actual soil moisture status in the root zone, which are required as input data.

Overland flow and channel flow components

If net rainfall exceeds the infiltration capacity of the soil, overland runoff or ponded water is generated. The surface runoff can be simulated either in a lumped, or a distributed approach. The lumped method divides the model domain into catchments, where runoff generated is routed downhill towards the river system within the catchment. The routing method employed in the lumped approach is an empirical relationship between flow depth and surface detention together with the Manning equation. In the distributed approach, the 2D diffusive wave approximation of the St. Venant equation is used. The direction and velocity of overland flow are controlled by the topography and flow resistance as well as by losses due to evaporation and infiltration along the flow path. Overland runoff, interflow and groundwater discharge enters the stream channel and is routed downstream. Here, available routing methods range from a relatively simple Muskingum equation to the dynamic Wave formulation of the St. Venant equations. The fully dynamic Saint Venant equations can be expressed in the form (Tucciarelli, 2003):

$$\frac{\partial \sigma}{\partial t} + \frac{\partial q}{\partial x} = Q \tag{3}$$

and

$$\frac{\partial y}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q^2}{\sigma}\right) + g\sigma\frac{\partial H}{\partial x} + \frac{gn^2q^2}{\sigma\Re^{4/3}} = 0 \tag{4}$$

where σ represent the flow section, q is the river discharge, h is the water depth, n is Manning's coefficient, H is the water depth plus bed elevation (total water level), g is the gravitational constant, $\Re$ is the hydraulic radius and Q represents the inflow discharge per unit length.

Unsaturated zone component

Available water after canopy interception and snowmelt have been accounted for is supplied to the ground surface as infiltration. Flow within the unsaturated zone is assumed to be primarily vertical owing to the dominant effect of gravity on infiltration. Although such an assumption is sufficient for most application, it may not be valid, for example, on step hill slopes. There exist three main options for processes taking place within the unsaturated zone. These include the 1-D finite difference approximation of Richards's equation; gravity flow; or a 2-layer water balance with Green-Ampt infiltration as an option. The cyclic fluctuation in the soil moisture within the unsaturated zone is partly a function of the soil property. Therefore prior knowledge about soil physical properties is a requirement in order to obtain an expected solution. The root zone, necessary for transpiration, forms the upper portion of the unsaturated zone. The process of transpiration is explicitly incorporated in Richards's equation (Equation 5) by sink terms. The integral of the sinks over the entire root zone depth amounts to the total actual evapotranspiration. Soil evaporation is catered for in the first sink term below the land surface. The exchange between the unsaturated and saturated zone is solved by an iterative mass balance procedure. The UZ-SZ is coupled explicitly (i.e they run in parallel and exchange water only at specific times), to allow for separate time steps that are representative of the UZ (minutes to hours) and the SZ (hours to days) domain.

$$C\frac{\partial\psi}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial\psi}{\partial z}\right) = \frac{\partial K}{\partial z} - S \tag{5}$$

where $C = \partial\Theta/\partial\psi$ is the soil water capacity; z is the elevation, ψ is the pressure head, K is the unsaturated hydraulic conductivity, S is the root extraction sink term.

Saturated zone component

Water exchange from the unsaturated zone to the saturated zone represents the groundwater recharge. In MIKE SHE the water movement module saturated flow can be represented by one of two methods. The first is a lumped, sub-watershed based method that incorporates the linear reservoir approximation. The linear reservoir method is a very simplified representation of the groundwater system. Recharge produced by cells within each catchment is routed through a linear reservoir and eventually supplied to the river system as baseflow within the catchment. The method does not simulate groundwater flow, heads, or interactions with the surface water system. The second method utilizes a fully 3-D Darcy equation (equation 6) and solved numerically by an iterative implicit finite difference technique. MIKE SHE provides the option of selecting an appropriate solver type; a preconditioned conjugate gradient (PCG) solver; or the successive over-relaxation (SOR) solver.

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right)-Q=S\frac{\partial h}{\partial t} \tag{6}$$

where *Kx, Ky, Kz* represent hydraulic conductivity along the *x, y, z* axes, *h* represents the hydraulic head, *S* represents the specific storage coefficient and *Q* represents the source/sink terms.

River-aquifer exchange component

This component of MIKE SHE couples the sub-surface processes directly and dynamically to the river hydraulic program MIKE 11. MIKE 11 comes with comprehensive facilities for modeling complex channel networks, lakes and reservoir, and river structures like gates, sluices, and weirs. The MIKE SHE/MIKE 11 coupling is such that, the river network is interpolated to the edges of MIKE SHE's rectangular grid to allow for overland and saturated flow exchange with the MIKE 11. It incorporates the general assumption that, in catchment modeling, river network can be considered as line located between model grid cells. This, for many applications, is valid provided river width is small relative to the model grid cells dimension (i.e a little more than half of the cell size). In this case the river-aquifer exchange can be computed as inflow to and from both sides of the river, depending on the head gradient to the adjacent groundwater cells. Similarly overland-river exchange also occurs along a line separating inflow over the right and left river banks.

Application of MIKE SHE in the Nasia sub-catchment

The MIKE SHE model allows for representation of watershed characteristics and data input via horizontal discretization model domain into orthogonal network which comprises grid square elements and reach links. The Nasia sub-catchment was divided into a number of computational grids for the numerical solution of the governing equations. To describe the watershed in a finer detail, a high resolution grid is recommended. This, however, will be at the expense of computer processing time and density of available data. With this in mind, a grid size of 300m x 300 m was selected which amounted to about 6500 horizontal grids over the entire watershed. The input topography map was derived from a 90m resolution Digital Elevation Model (DEM) data downloaded from the NASA Shuttle Radar Topographic Mission (SRTM) database. These data were resampled to the 100 x 100 m MIKE SHE grid as advised by the similar hypsometric curves obtained for the sub-catchment which gave a good representation of topographic characteristics within the terrain.

The MIKE SHE model requires precipitation and potential evapotranspiration as the climatic variables. Daily rainfall data from a nearby weather recording station provided precipitation input to the model. It was spatially distributed uniformly over the model domain in a time varying temporal distribution. A time series of potential evapotranspiration rates was also required for estimating soil evaporation and plant transpiration. As no meteorological station is located within the catchment area to provide data to evaluate potential evapotranspiration (PET), available daily minimum, mean and maximum temperatures and humidity were acquired for the period of the simulation, and PET calculated according to the Linacre (1977) method (Eqn 1). The Linacre method has provided accurate estimate of PET in a variety of climate settings (Anyadike, 1987; Jewitt, et al., 2004; Thornton et al., 2009; Xu et al., 2001). The equation requires dew point temperature calculated from measured air temperature and relative humidity over a specified range based on the Magnus-Tentens formula with dew point temperature uncertainty as +/-0.4 °C. A radiation-based method for calculating the PET such as the widely used FAO Penman-Monteith method could not be applied in the study due to insufficient data of climate records.

$$PE = \frac{\frac{500Th}{(100-A)}+15(Ta-Td)}{80-Ta} \tag{7}$$

where A is the Latitude of the Station; *Th=Ta+0.006h* where h is the altitude (m); and Td is dew point temperature (°C)

The MIKE HYDRO river module incorporated in MIKE ZERO provides a modelling framework for defining and executing one-dimensional river model (DHI, 2014). Based on a digital elevation model for the area, river branches and cross-sections were generated in MIKE HYDRO and used to define MIKE 11 river networks for the sub-catchment. Cross sections were specified as depths relative to the top of the ditch bank taken from the appropriate grid square of the MIKE SHE topographic grid (Thompson et al. 2004). In all, a total of 11 branches were established as part of the river hydraulic model. An Inflow boundary condition was applied to the upstream end of the main branch and all other tributaries in the MIKE 11 river network. A water level boundary type was used at the downstream end of the main branch. All reaches were finally coupled to MIKE SHE model. The MIKE SHE river links defined the locations where the overland, drainage, and baseflow components interact with MIKE 11. A full contact river-aquifer exchange method was specified. This was based on the assumption that, the river is in full contact with aquifer materials so that the hydraulic conductivity of the aquifer rather than the river bed directly influence exchange between the river and the aquifer (DHI, 2014). This assumption was deemed appropriate for the area under study.

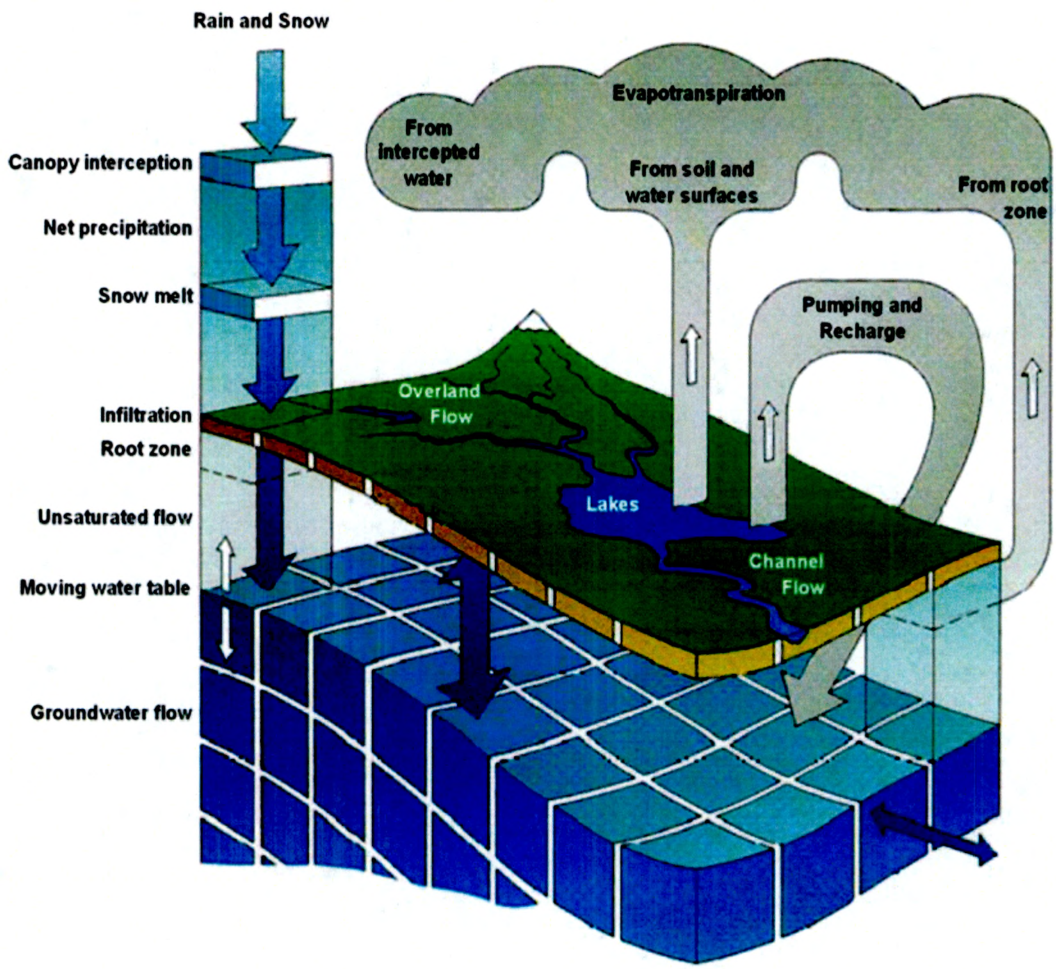


Figure 4 | Hydrologic processes simulated by MIKE SHE (DHI, 2014).

The unsaturated zone represents the vertical soil profile that interacts with both the overland flow and the saturated zone. The lower boundary condition for this zone was defined by the location of the groundwater table. Given the predominantly fine soils featured in the area, and based on available data and computational requirement, the Richards equation (equation 5) was used to represent the infiltration in the unsaturated zone calculated in all grid cells. The MIKE SHE needs the water retention and unsaturated hydraulic conductivity function to estimate the water content of the unsaturated soil during simulation. This study employed the Van Genuchten equation to describe retention curve and hydraulic conductivity. Soil parameters required as input to the Van Genuchten equation was obtained from literature. With savannah grassland as the dominant vegetation cover, time series for leaf area index (LAI) and root depth (RD) were obtained for the simulation period to estimate transpiration from vegetation.

Within the saturated zone, the finite-difference method was employed. The single layer model was represented based on available groundwater data for the area. Because of the absence of detailed hydrogeological observations, ranges of vertical and horizontal hydraulic conductivity, and specific yield and storage were obtained from published works in the area; which were also specified as calibration parameters. Fixed head boundary conditions have been applied at the outlet region where the Nasia River joins the main White Volta River and no flow along the rest of the boundary layer. A preliminary calibration was performed under steady state conditions, using the mean head data of the hydrologic year 2007–2010, and the results were used as initial conditions for the transient simulations.

Calibration in MIKE SHE can be performed either manually using a trial and error method on parameters or by employing the automatic calibration tool–AUTOCAL– for parameter optimization, sensitivity analysis and scenario management. Prior to calibration, initial values and ranges of primary parameters from measured field data, general characteristics of model structure, and the modelling experience were assessed. The trial and error procedure was first applied to examine the influence of various model parameters through statistical criteria. This also served to properly test the simulation model and to create output files needed to set up AUTOCAL. In this study, a full length calibration was performed for a 10-year period (1/1/2000-05/31/2009) against stream-flow data collected at the outlet of the watershed. The first four months were included as a spin-up period to curtail the effect of initial conditions but the results excluded from evaluation of model performance. Given that the number of parameters subject to adjustment during calibration of a distributed hydrological model should be as small as possible (Refsgaard et al., 1995), the calibration parameters were restricted to the hydraulic conductivity of the saturated zone, the storage parameters (specific yield and specific storage), and the detention storage and Manning's M roughness for overland flow. The Population Simplex Evolution (PSE) method was selected for parameter optimization algorithm; suited especially for parallel execution using the simultaneous option in AUTOCAL. In line with Butts et al. (2004) two equally weighted calibration criteria, the absolute value of the average error and the RMSE, were employed and these were aggregated into one measure using a transformation that compensates for differences in the magnitudes of the different criteria (Madsen 2003). Standard calibration statistics calculated based on the differences between measured observations and the simulated values at calibration points are used in the MIKE SHE environment to determine model efficiency and to serve as indicators for model performance. The four main statistical criteria used include, mean error (ME), root mean square error (RMSE), correlation coefficient (R), and the widely used Nash-Sutcliffe coefficient (R2). These were computed for each model run and used to refine the final calibration:

$$ME_i = \frac{\sum_t (Obs_{i,t} - Calc_{i,t})}{n} \tag{8}$$

$$RMSE = \frac{\sqrt{\sum_t (Obs_{i,t} - Calc_{i,t})^2}}{n} \tag{9}$$

$$R = \sqrt{\frac{\sum_t (Calc_{i,t} - \overline{Obs_i})^2}{\sum_t (Obs_{i,t} - \overline{Obs_i})^2}} \tag{10}$$

$$R2 = 1 - \frac{\sum_t (Obs_{i,t} - Calc_{i,t})^2}{\sum_t (Obs_{i,t} - \overline{Obs_i})^2} \tag{11}$$

where t is the simulation time in day; n is the total simulation days; i is the calibration point i; $Obs_{i,t}$ is the observed daily discharge at location i at day t; $\overline{Obs_i}$ is the mean of the observed discharge at location i for the simulation period, and $Calc_{i,t}$ is the simulated discharge at location i at day t.

The impact of climate change and variability over the watershed was assessed in two stages. The already calibrated/validated model comprised the first stage. Next, the timeframe of the model was extended by 45 years from 2010 to 2055. And time series outputs of 8 CMIP5 (Couple Model Intercomparison Project Phase 5) global circulation model (GCM: ACCESS1-3, CCSM4, CESM1-CAM5, CNRM-CM5, CSIRO-Mk3-6-0, HadGEM2-ES, INM-CM4, MRI-CGCM3) with regard to temperature (which is a function of potential evapotranspiration) and precipitation served as input to drive the Nasia hydrologic model. Future climate change simulations were run for the Nasia sub-catchment for the complete 45-year period (01/01/2010-01/01/2055) with an initial 4-month spin up period to analyze climate change trends.

CHAPTER FOUR

Results and discussion

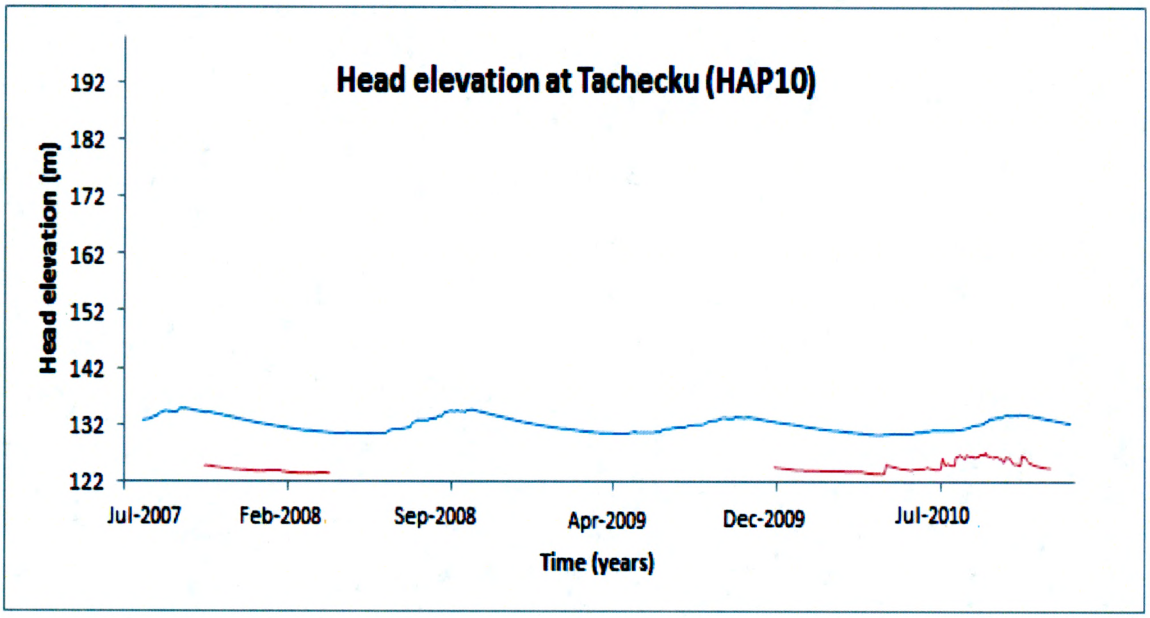
The model calibration spanned a 10-year period from 2000 to 2009 based on available historical data. The key emphasis of the calibration process was to establish a good match between simulated and observed streamflow and groundwater elevations necessary for predictive simulation. The calibration performance can be measured by the ability of the model to simulate and predict historical trends of streamflow and groundwater levels over the calibration/validation period. As suggested by Refsgaard et al. 1995, the number of parameters subject to adjustment during calibration of a distributed hydrological model such as MIKE SHE should be as small as possible. Thus the calibration parameters were restricted to the hydraulic conductivity and storage parameters for the saturated zone, and the detention storage and Manning's M roughness for the overland flow. Within the MIKE 11 hydrodynamic model, two parameters were used in calibration; the manning's roughness coefficient for the channels within the river network and the bed leakage coefficient within the MIKE SHE coupling. These were assigned uniform values throughout the river network. The coupled nature of the model required that both MIKE SHE and MIKE 11 were calibrated simultaneously since modifications to a calibration parameter within one model could influence results in the other. For instance, saturated hydraulic conductivity tends to exert a major control on simulated water table elevation which consequently influences the river-aquifer exchange and hence the simulated water levels.

Results from the model runs for the simulation period are shown in Figures 5 and 6. Figure 5 presents the measured and simulated transient hydraulic heads for the three selected observation wells within the Nasia watershed. Table 1 shows the mean absolute error and the mean error values between observed and computed heads. The model appears to capture the dynamics of the groundwater heads reasonably well although it generally overestimates the heads. Mean absolute error varies from 7.4 m for HAP 10 to 13.1m for HAP 11. This statistic demonstrates the strength of the relationship between observed and simulated groundwater depths at these three locations. Although the corresponding errors for HAP5 and HAP11 are in general relatively high, they are not unreasonable and the transient dynamics of groundwater within the catchment is clearly reproduced. The higher errors for HAP 5 and HAP 11 could be explained by the proximity of the wells to the model boundary, where the boundary conditions may not be verified locally. Additionally, for a poorly gauged basin such as the Nasia, observed data resolution in space and time could impose some uncertainties during model calibration and evaluation.

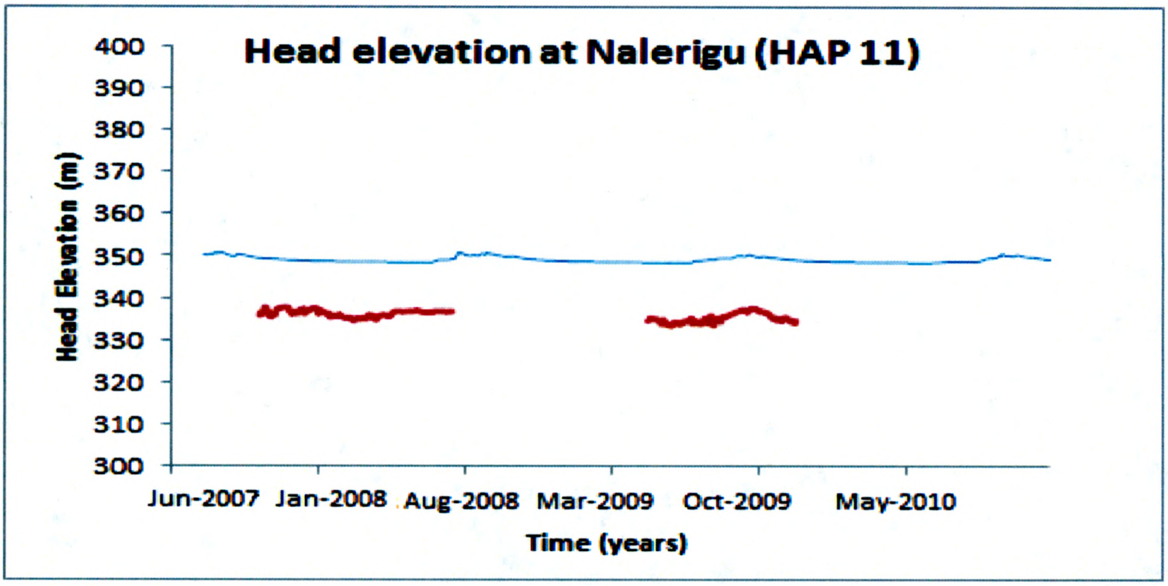
Table 1 | Mean errors between observed and computed heads for the three observation wells

Wells	Mean error	Mean absolute error
HAP 5	-13.8	13.8
HAP 10	-7.4	7.4
HAP 11	-13.1	13.1

(a)


Head elevation at Tachecku (HAP10)
Head elevation (m)
192
182
172
162
152
142
132
122
Jul-2007
Feb-2008
Sep-2008
Apr-2009
Dec-2009
Jul-2010
Time (years)

(b)


Head elevation at Nalerigu (HAP 11)
Head Elevation (m)
400
390
380
370
360
350
340
330
320
310
300
Jun-2007
Jan-2008
Aug-2008
Mar-2009
Oct-2009
May-2010
Time (years)

(c)

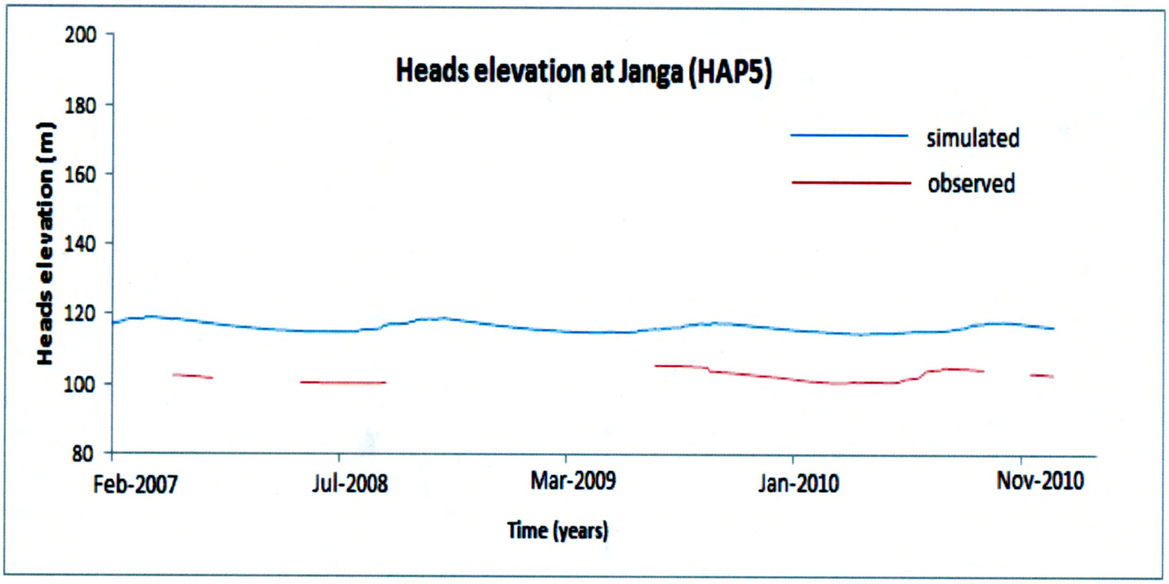


Figure 5 | Transient simulations of hydraulic heads for the three observation wells.

Figures 6(a) and (b) show the observed and simulated daily discharge at the outlet of the Nasia sub-catchment for the calibration, validation, and full simulation, respectively.

In Fig. 6 the model generally overestimated the daily discharge at the Nasia outlet with mean error of 0.72, 3.8, and 2.3m^3/s for the calibration, validation, and the complete simulation, respectively (Table 3). The simulated streamflow showed a somewhat flashier response than the observed hydrograph (Fig. 6a), especially during the years of 2000 and 2007. However, it generally represented the dynamic variation of the streamflow with acceptable R2 (0.64, 0.649 and 0.65) and R (0.8, 0.805 and 0.805) for the calibration, validation, and the full simulation, respectively. Table 2 shows the final values of key hydrologic parameters at the end of the simulation period. The performance measures for observed daily streamflow against the simulated are compared and presented in Table 3.

Table 2 | Calibrated MIKE SHE parameter values for the Nasia sub-catchment

Parameter	Calibrated Value
Hydraulic Conductivity (m/s)	$4.8 \times 10^{-8} – 1.7 \times 10^{-7}$
Unsaturated infiltration rate (m/s)	2.6×10^{-6}
Manning's M roughness for overland flow ($m^{1/3}/s$)	51.81

Table 3 | Model calibration and validation for daily streamflow in the Nasia sub-catchment

Statistical criteria	Calibration	Validation	Full Period
Mean daily streamflow (m^3/s)			
Observed	29.6	37.6	35.1
Simulated	28.9	33.7	32.7
Correlation coefficient	0.8	0.81	0.81
Model efficiency (Nash and Sutcliffe 1970)	0.64	0.649	0.653
Root mean square error (m^3/s)	35.2	46.85	41.86
Mean absolute error (m^3/s)	0.72	3.8	2.3

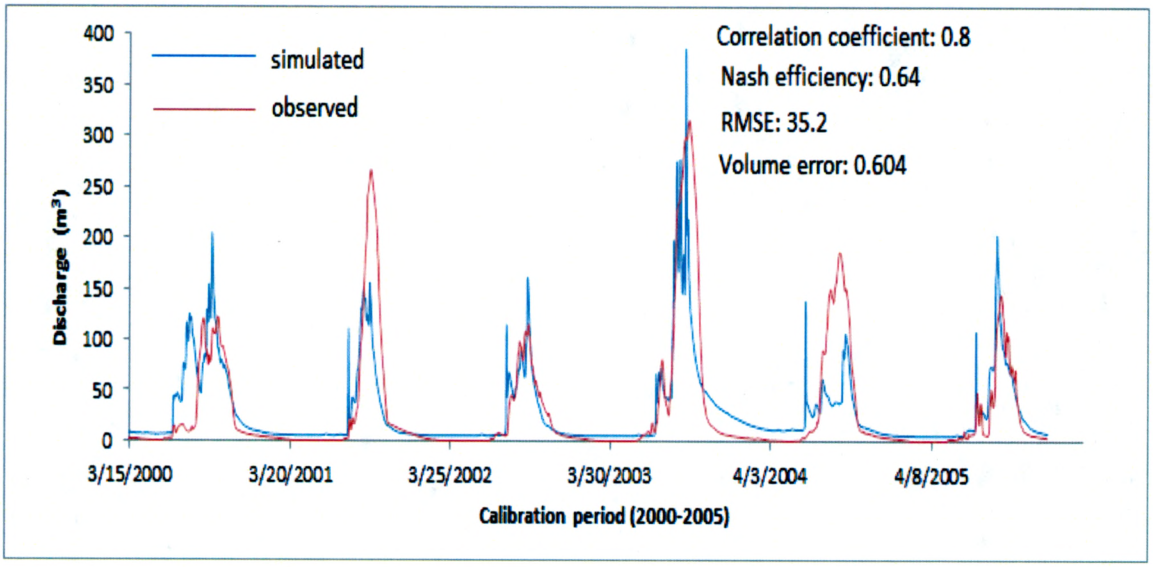
Both R2 and R indicated that the model generally performed well in simulating hydrograph of the Nasia station (Table 4). The satisfactory model performance as indicated by R2 at Nasia outlet can be attributed to the model's ability to mimic peak flows and median flows. Studies show that R2 statistics give more weight to peak flow simulation (Henriksen et al., 2003). Thus, in the wake of extreme storm events, the model can provide an acceptable R2 and R-values much easier than runs for the dry periods with low flows.

Table 4 | Performance criteria for model evaluation

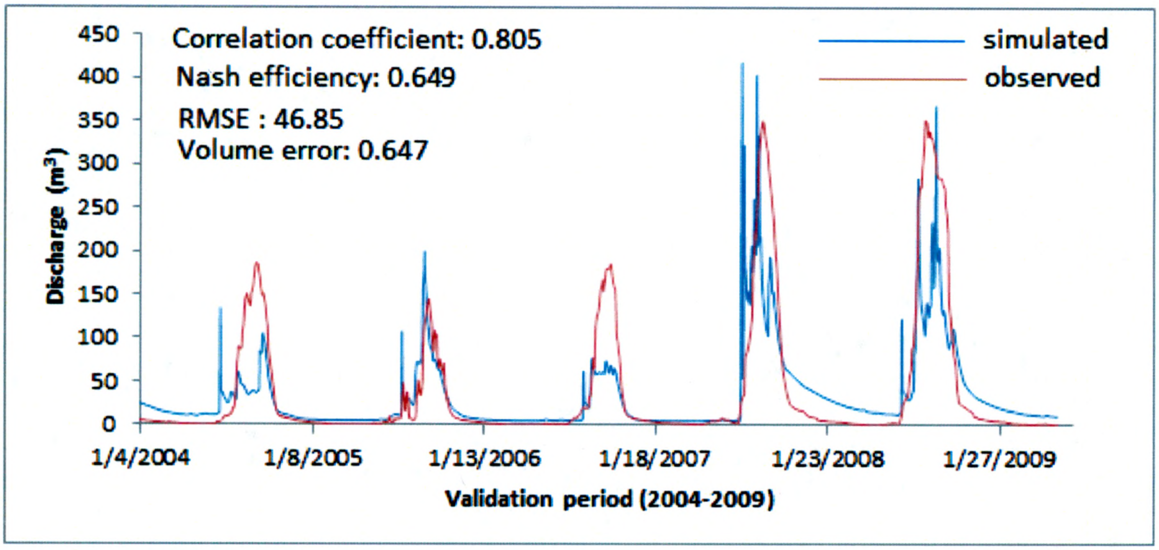
Performance indicator	Excellent	Good	Fair	Poor
Nash-coefficient (R2)	>0.85	0.65–0.85	0.5–0.65	< 0.5
Correlation coefficient (R)	>0.95	0.85–0.95	0.85–0.75	< 0.75

The results also indicated that the model generally underestimated the low streamflows, and over-predicted median flows (Fig. 6). The systemic underestimation for the low flows suggests that there existed errors with groundwater simulation. Refsgaard (1997) reported that underestimation of baseflow could be mainly explained by the bias introduced as a result of incorrect representation of internal groundwater divide and boundary conditions. Where sufficient data is not available to represent the saturated zone, a simplified conceptualization is assumed. This has implications on the model's ability to consistently represent observed phenomenon. Thus the lack of information to effectively represent the groundwater system in the area could partly explain the underestimation of low streamflow as observed in the hydrograph (Fig. 6). Additionally, the artifacts of the MIKE SHE model do not allow for a river/stream to dry out (Lu et al., 2006; Dai et al., 2010), which has a potential impact on model performance. This type of uncertainty within the SHE model mainly pertains to the incorrect representation of the spatial distribution of hydrologic processes and hydro-geologic properties. For example a parameter such as Manning's roughness, which demonstrates a certain level of influence on model performance, was assigned a uniform value across the watershed due to the absence of detailed information. This obviously is not consistent with reality, and in the long run can impede the overall performance of the model if not well calibrated. Although the performance measures for the Nasia model fall within acceptable range, the model's behavior could further be improved when detailed spatially varied information of geo-hydrological properties become available.

(a)



(b)



(c)

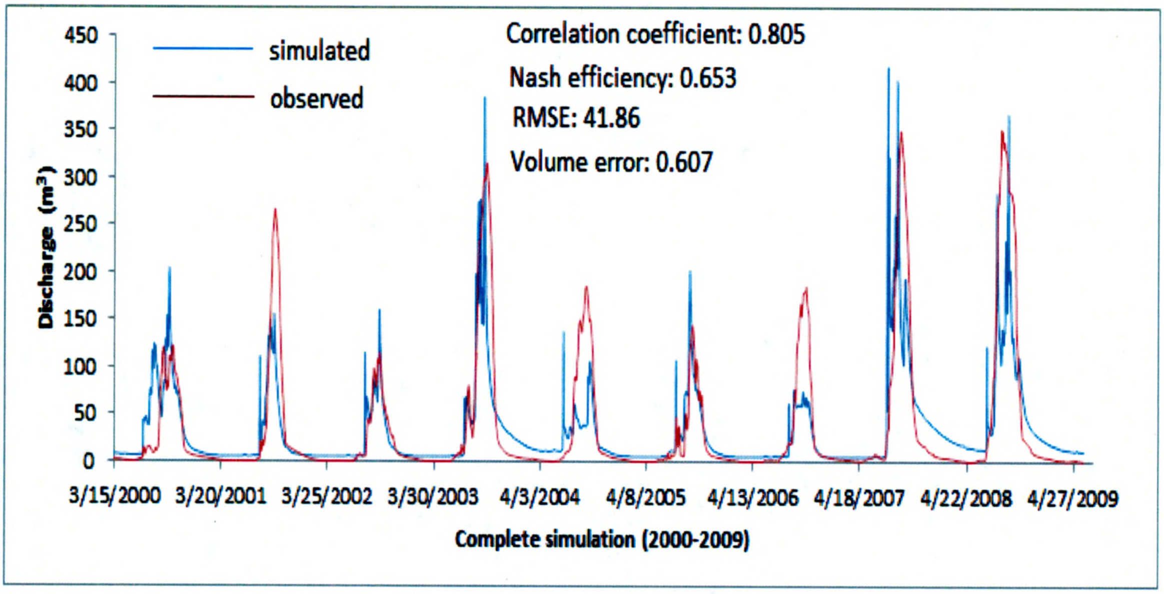


Figure 6 | Comparison between observed and simulated discharge of the Nasia sub-catchment: (a) daily discharge - calibration period (2000- 2005); (b) daily discharge - validation period (2004-2009); (c) daily discharge - full 10-year period (2000- 2009).

Simulation of climate change scenarios

As a basis of estimating climate change impacts on water resources, general circulation models (GCMs) have become a useful tool for providing climate change scenarios. Outputs from GCMs can be forced with hydrologic models to identify climate change impacts. In view of this, the integrated Nasia model has been specially developed to assess the possible impacts of climate change and variability on water resources over the region. The calibrated/validated model provided a baseline condition to quantify evolving sensitivities of the Nasia catchment to climate variability and change based on eight climate scenarios over three time slices: 2011-2025, 2026-2040, and 2041-2055. It is worth pointing out that these climate outputs are not bias-corrected. Thus model outputs have not been corrected towards observation. This certainly may introduce some degree of uncertainty in model's prediction. Also owing to the fact that GCMs come in a very low resolution, they barely provide sufficient spatial resolution for regional and local applications. The usual practice therefore is to apply a downscaling technique on the GCM to correspond to the size of the area under study. Although the downscaling approach adds additional value in terms of keeping the physical consistency between variables, and also accounting for temporal feedback mechanisms forced from GCM changes in the system, it comes with its own uncertainties such as the choice of downscaling method and assumptions used. More so apart from uncertainties in model formulation as well as emission scenarios, there exist uncertainties introduced by internal variability in the climate system such as long term variability of the frequency of El Nino Southern Oscillation (ENSO) events, decadal-scale fluctuations in sea surface temperatures (SST) among others. For these kinds of uncertainties, a common way to address and narrow it down is by use of multiple GCMs and several ensemble members of climate change simulations (Andersson et al., 2011). Thus the choice of 8 GCMs over three ensembles in this study serves to control evolving uncertainties, while interpretation of results is also done with caution. On the flip side, the outcome can be compared to bias-corrected and regionalized models in future study to display the influence of bias correction on the CMIP5 climate models for the study area.

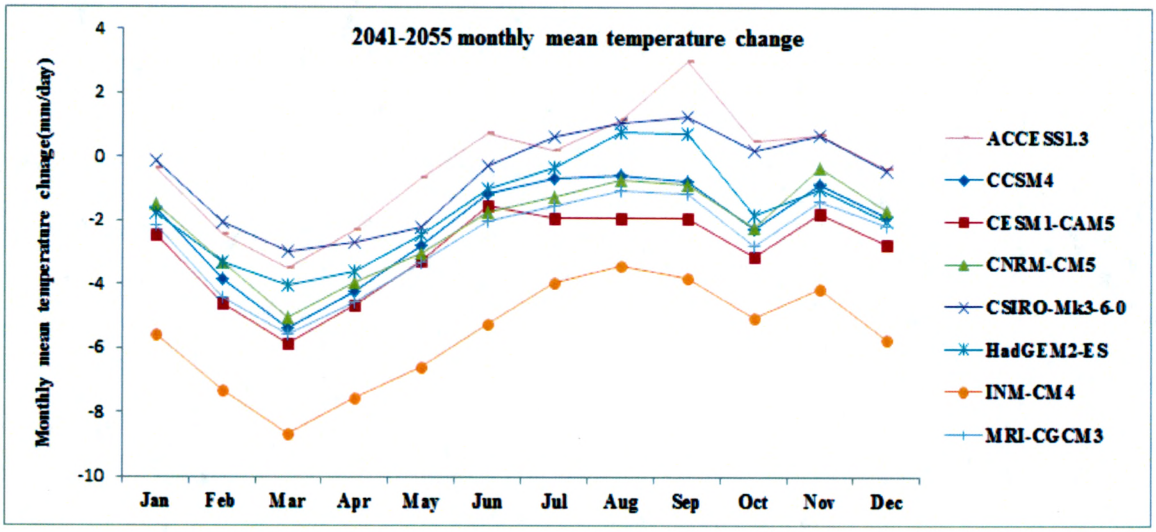
For each climate model, future changes are expressed relative to a control simulation driven by the observed data. Mean daily temperature and daily total precipitation has been extracted for the control and future time periods overlying the Nasia sub-catchment (Fig. 1).

Rainfall and temperature, for the most part, are the key drivers in the hydrological regime of rivers, and climate change/variability has its major control through changes in these two variables. Figures 7a and b show the monthly mean change for these two parameters from 2041 to 2055 projected by the 8 CMIP5 models for the Nasia catchment. The seasonal changes between mean monthly temperatures show a distinctly homogeneous pattern in all models (Fig7a). The monthly mean temperature decreases over the Nasia between -5.6 (INM-CM4) to -0.3 (ACCESS1.3). With the exception of INM-CM4, all 7 models project a somewhat homogeneous decrease throughout the year. INM-CM4 output is most extreme with decreases between -3.4 and -9. There seem to be an exaggeration in the projected temperature trend unfamiliar with the climatic region in which Nasia is located. The associated uncertainties for both short- and long-term seem striking and completely contradictory seeing that, in the same catchment, actual evapotranspiration which is a function of temperature shows an increasing trend in the future climatology (Fig.8a). This underestimation in temperature probably is a result of the models being bias uncorrected. Bias correction serves to provide a satisfactory agreement between statistical characteristics of observed and GCMs generated precipitation and potential evaporation data (or temperature) at the sub-basin level for a historical period of monitored data is available. Minus this such uncertainties are bound to occur. There is also a possibility that the observational temperature data used in the analysis may have been incorrect due to systematic error in measurement which probably has generated this large uncertainty.

Rainfall trends for the 8 CMIP5 models all agree on an overall annual increase from -0.2 (CSIRO-Mk3-6-0) to 5.0 (MRI-CGCM3). CSIRO-Mk3-6-0 however shows a major decrease in the months from June to September. Regarding the CSIRO-Mk3-6-0 model, the study finds that it consistently shows outlying decreases not only in rainfall but in actual evapotranspiration, and consequently streamflow, which is distinctly different from the other results. This deviation from other 7 models is probably a consequence of the boundary condition or the atmospheric processes represented in the GCM used which do not conform well to that in the study area.

Generally, there appear to be a decline in rainfall trends during wet season from June through to late August. (Fig.7b). The decline in rainfall during the wet months can be interpreted as an offset created by a large increase in previous drier months. This decline obviously has a consequence in streamflow regime within the wet months. Fig. 10a however shows a contrasting result in capturing the variability in streamflow dynamics in the wet seasons. There seems to be a significant lag in streamflow response to rainfall changes. Therefore the rainfall decreases in June-July-August during 2041-2055 may result in reduced streamflow later in the century.

(a)



(b)

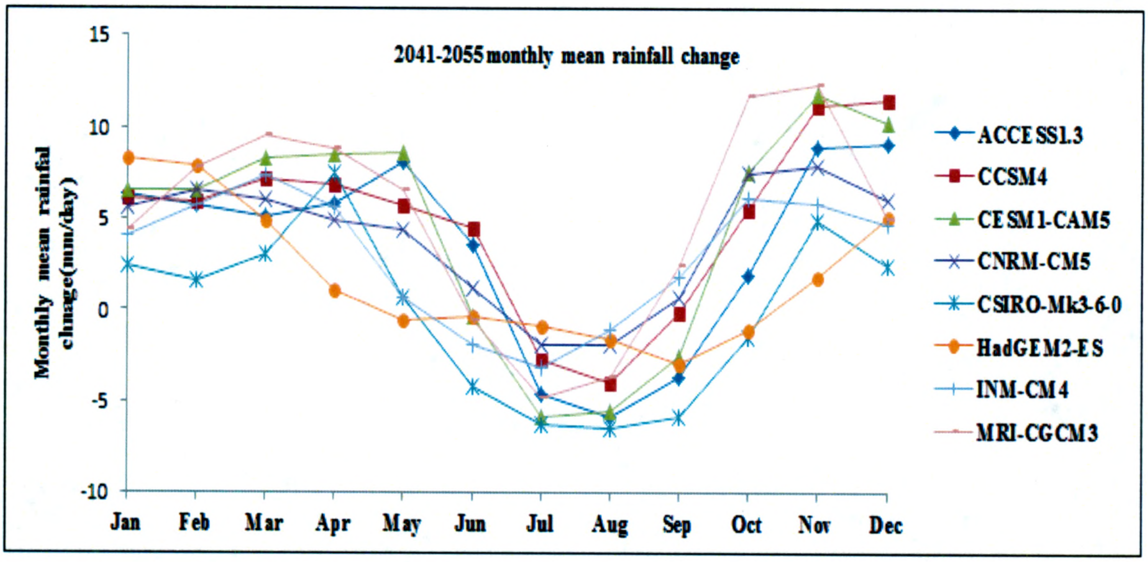
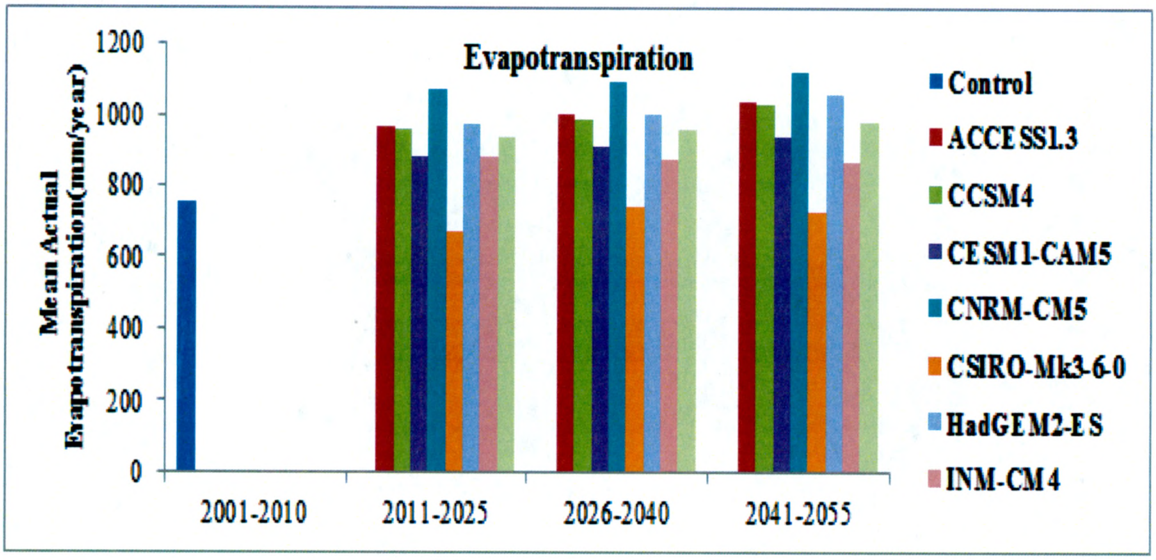
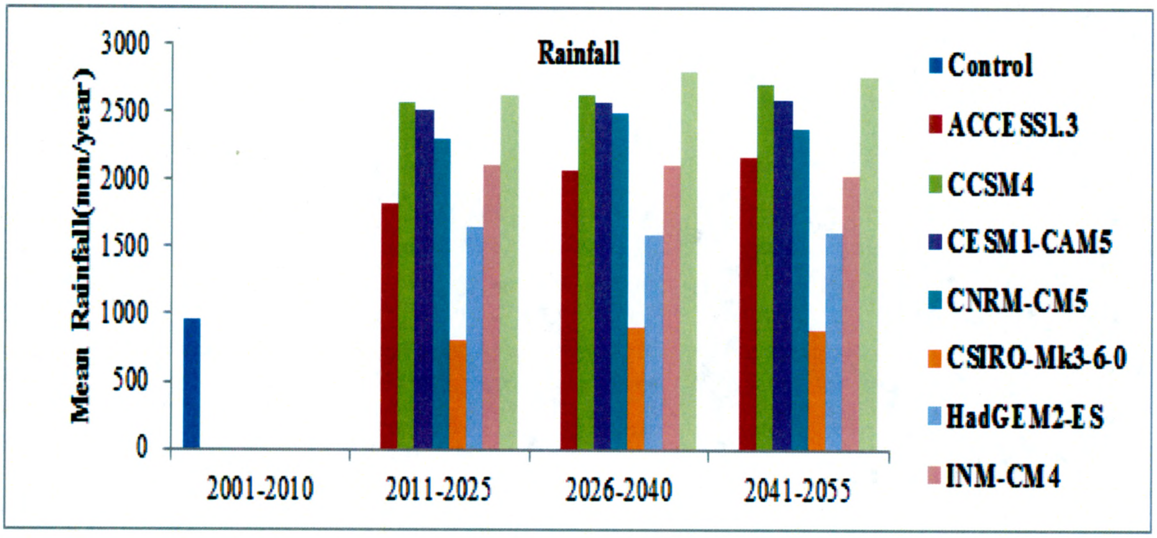


Figure 7 | Monthly climatic changes for each climate change scenario (2071–2100); (a) Temperature and (b) Rainfall – over the Nasia.

(a)



(b)



(c)

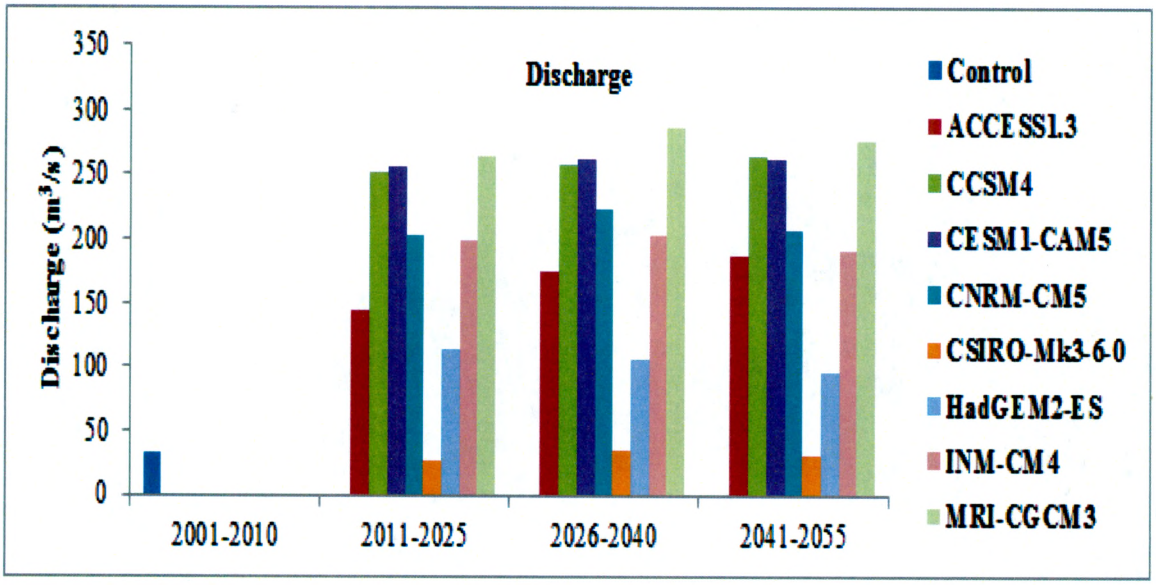
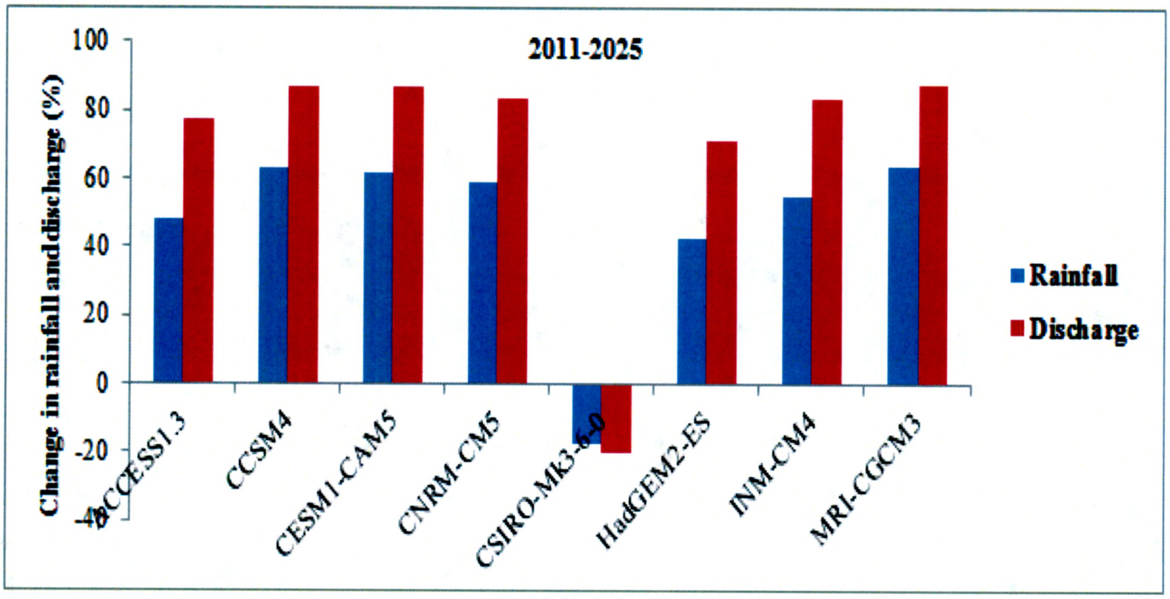


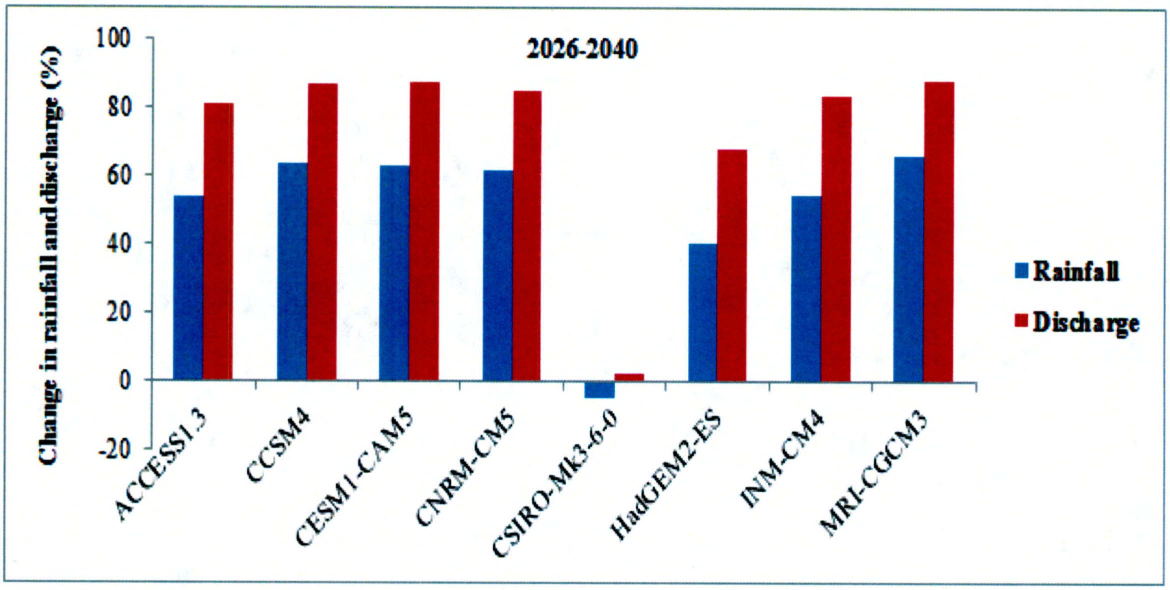
Figure 8 | Variations on mean annual evapotranspiration, rainfall, and discharge for each climate scenario and time interval.

Figures 9(a), (b), and (c) illustrate the evolving sensitivity of river discharge to climate variability and change in the Nasia sub-catchment based on all 8 models over the three time slices. Shown are responses to changes in annual discharge augmented with regard to percent change in rainfall for the Nasia. The response to changes in rainfall in the three time intervals does not appear to follow a linear process and is rather believed to depend largely on the catchment characteristics among others. Changes in rainfall are shown in the range from −17 to 64%, -5 to 66%, and -7 to 65% for time periods 2011-2025, 2026-2040, and 2041-2055 respectively; and for discharge, changes range from -21 to 87%, 2 to 88%, and -7 to 88% for same respective time periods. Except for CSIRO-Mk3-6-0, which unsurprisingly shows a distinct decrease in rainfall and discharge in the three time slices, the relationship between changes in rainfall to changes in discharge over the Nasia catchment is most extreme in all models. This high sensitivity of discharge response to rainfall changes can be explained by the very low runoff coefficient, a function of overland manning's coefficient, which makes the catchment very sensitive to changes in rainfall. Thus, the Nasia catchment can be said to exhibit a high sensitivity to climate change variability and change; in that, small change in the rainfall regime tends to exert large effect on the discharge regime. Previous studies (e.g Andreini et al., 2000) in the same region demonstrated based on water balance model that streamflow was highly non-linear and very sensitive to rainfall input. This observation appears to sync well with the findings of the current study. Although all 8 models (except CSIRO-Mk3-6-0) project remarkable increase in evapotranspiration, rainfall and streamflow, it can be seen from the results that the amount of rainfall subject to evapotranspiration is so insignificant that, much of rainfall is converted to streamflow (Fig.8). It can therefore be concluded that rainfall changes over the Nasia catchment dominates evapotranspiration changes in terms of their impacts on streamflow for all three time periods.

(a)



(b)



(c)

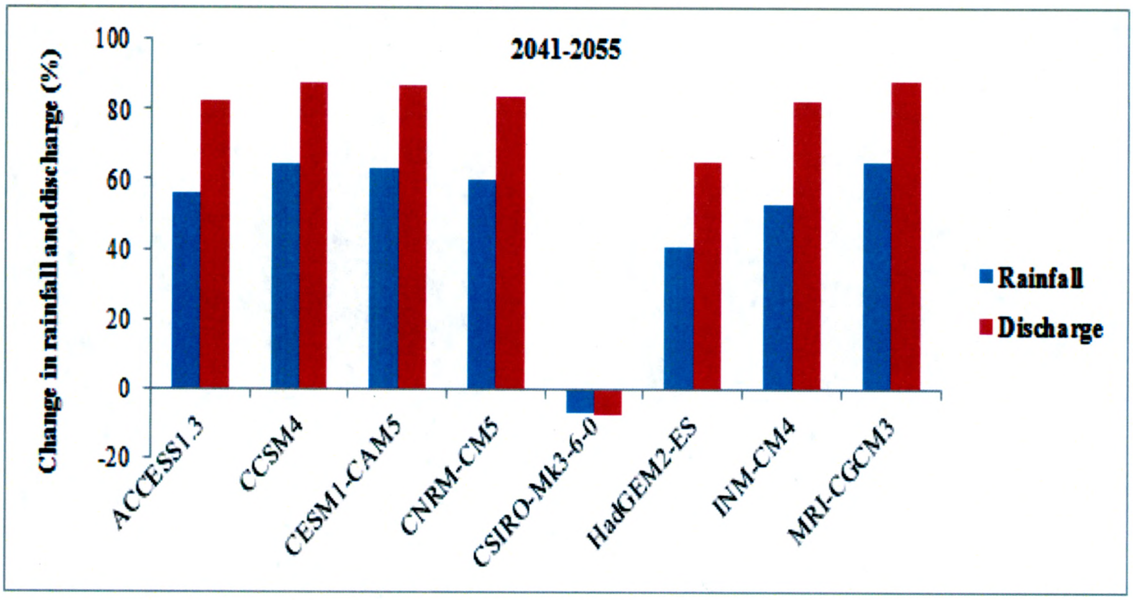
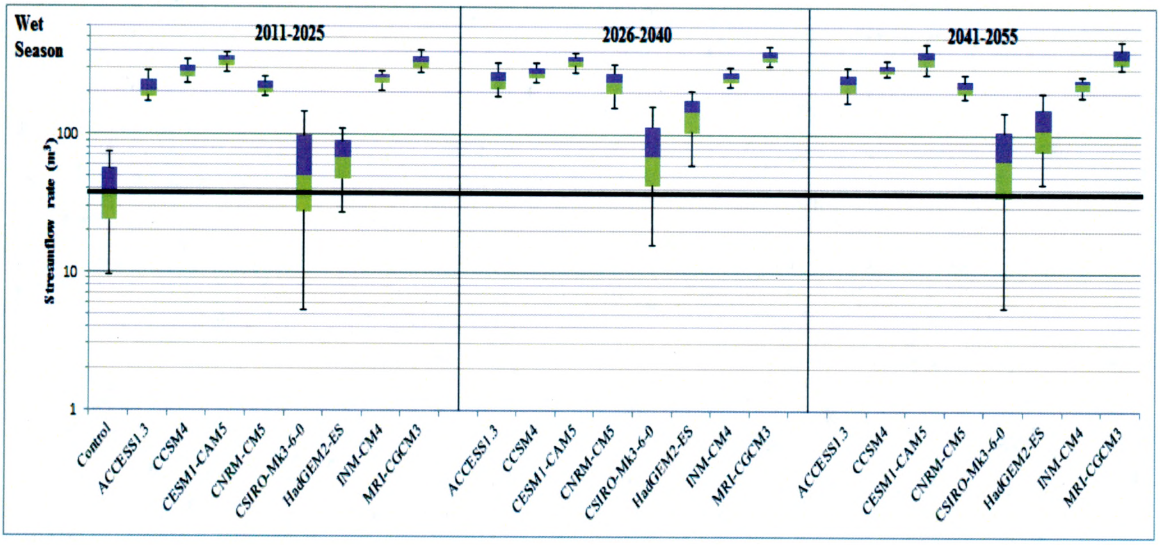


Figure 9 | Climate sensitivity for the Nasia hydrologic regime: Changes in annual discharge to changes in rainfall for each climate model and time interval– (a) 2011-2025; (b) 2026-2040; (c) 2041-2055.

Figure 10 (a) and (b) present the wet and dry season flow statistics at the Nasia gauging station for each time period and each climate scenario. For the period 2011–2040, one would have expected that no significant change in mean flow from the control simulation 2001-2010 would be observed, but there exist large uncertainty projected in the direction of change for both surface flow rates. This wide uncertainty in streamflow is largely influenced by both, temperature and precipitation, derived mainly from uncertainties in precipitation change. Probably if the models were bias corrected, these uncertainties could have been reduced. The projected increase in mean flow continued to follow a consistent pattern model-wise even by periods 2026–2040 and 2041–2055 relative to the control simulation. Although there exist a significant increase in wet season flows for all three time periods, mean flow values and inter-quartile ranges of ACCESS1.3 and HadGEM2-ES models in the dry season are lower than the mean flow value of the control for periods 2011-2025 and 2026-2040. CSIRO-Mk3-6-0 model on the other hand projected increased mean flow in the wet season and a decreased mean flow in the dry season for all three periods. Generally, the greatest changes are projected by MRI-CGCM3, which predicts large rainfall increases during almost the whole year for all time slices (Fig. 8). The smallest changes obviously are projected by CSIRO-Mk3-6-0, which consistently predicts minor rainfall decreases for all time slices. The extreme discharge resulting from the simulation can be explained by the extremely high rainfall. As indicated earlier, the high sensitivity to rainfall extremes most often results in the very high discharge. It should be noted however that, for most part, high uncertainties do not only originate from the climate models. Uncertainties can also be propagated by the hydrological model where the performance in simulating peak discharge tends to be weak. In addition, the availability and quality of the input data can also impose a level of uncertainty in the future projections. Data requirements tend to grow with a large catchment size; and even more influential are the basins characteristics in terms of heterogeneity and complexity.

(a)



(b)

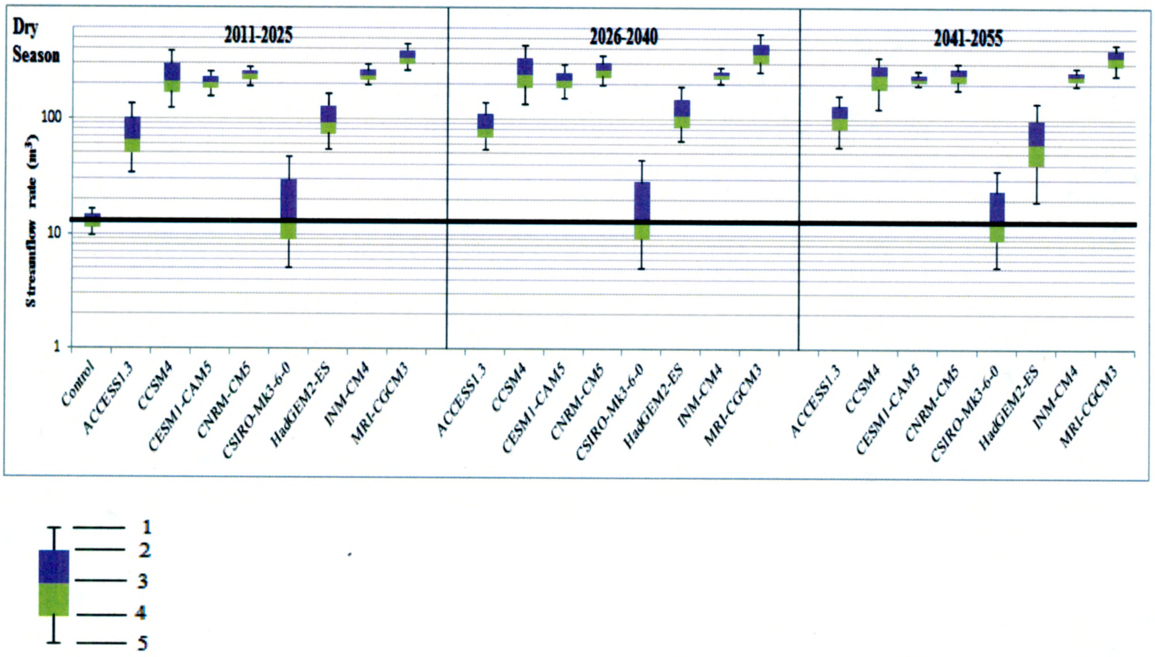


Figure 10 | Evolution of flow rates at the Nasia gauging station for each climate change scenario and time interval for wet seasons (a) and dry season (b) . Numbers 1, 2, 3, 4, and 5 denote maximum flows, flows at 75th percentile, flows at 50th percentile, flows at 25th percentile, and minimum flows.

The results presented above are highly important for water resource management in the basin. Projected increasing trend in rainfall through the middle of the century has a great potential of developing the aquifers in the basin for commercial abstraction to support irrigation activities. If proper management strategies are put in place, the agricultural sector will be a key benefactor form climate change trends in the foreseeable future. The potentials in irrigated agriculture can adequately be harnessed with unlimited water supply all year round. This will improve the economic status of communities in the basin and enhance national food security. Consequently the increasing trend in projected streamflow in rivers and stream can be a source of renewable water resource to meet both domestic and commercial water needs in the region.

CHAPTER FIVE

Conclusion

A hydrological model that is able to simulate surface and subsurface flows in the Nasia catchment reasonably well has been developed. The Nasia model can serve as a useful tool to help diagnose climate impacts on water resource availability in this semiarid region. The model has been calibrated and verified using discharge and hydraulic head observations for the period 2000–2010. Climate projections drawn from eight CMIP5 GCMs have been used to explore potential future impacts on the catchment simulated over three time periods (2011–2025, 2026–2040, 2041–2055). Results show that when the climate scenarios are applied to the flow model, increasing trends in evapotranspiration and streamflow through the middle of the century are simulated for all but one of the GCM scenarios. The increases in streamflow (and groundwater recharge) suggest that the conjunctive use of surface and groundwater resources to support local irrigation schemes in the basin might be a sufficient buffer against the effects of changing rainfall patterns on agriculture through the middle of the century. The study finds that an increase in evapotranspiration does not necessarily lead to a decrease in discharge but an increase in rainfall does. Rainfall changes over the Nasia catchment therefore dominate evapotranspiration changes in terms of their impacts on streamflow for all three time periods. The results indicate that streamflow responses are mainly driven by rainfall changes. The general decline in rainfall in the months of June-July-August during 2041-2055 does not produce streamflow reduction over the same period. There seem to be a significant lag of streamflow response to rainfall changes in the wet season. Therefore the rainfall decreases in June-July-August during 2041-2055 may result in reduced streamflow later in the century.

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