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Exploring the urban water-energy-food nexus under environmental hazards within the Nile

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Abstract

The integrative approach of water, energy, and food nexus (WEF nexus) is now widely accepted to offer better planning, development, and operation of these resources. This study presents a first attempt towards understanding the WEF nexus of urban environments in the Nile River Basin under conditions of hydrological droughts and fluvial floods. A case study was conducted for the capital of Sudan, Khartoum, at the confluence of the White Nile and the Blue Nile for illustration. The results were based on analyses of river flow and water turbidity data, field observations, a printed questionnaire and an interview of farmers practicing irrigated agriculture, and hydropower modelling. The study analyzes indicators for the association of river water resources environment (intra-annual regime, quantity, and quality), the status of urban irrigated agriculture, water treatment for domestic use, and hydropower generation under hydrological extremes, i.e. droughts and fluvial floods. It additionally examines the consequent interactions between the impacts on three sectors. The present study shows how floods and droughts impose impacts on the seasonal river water quality and quantity and, in turn, on the water treatment for domestic use , irrigated agriculture, and hydro-energy supply in an urban environment. The results demonstrate how the two hydrological phenomena determine the state of hydropower generation from dams, i.e. high energy production during floods and vice versa during droughts. Hydropower dams, in turn, could induce cons in the form of low fertile soils in the downstream due to retaining sediment. Finally, present and potential options to minimize the above risks are discussed. This study is hoped to offer a good support for integrated decision making on increased resource efficiency over the urban environment within the Nile Basin.

Keywords: Hydrological drought; Fluvial flood; Water turbidity; Urban irrigated agriculture; Water treatment; Hydropower

1 Introduction

Weather- and water-related disasters occurring as a result of random processes, such as droughts and floods, have grown rapidly and they affect human beings, bringing suffering, death, and immense material losses (Kundzewicz et al. 2003, 2007). On one hand, floods affect human activities and economy through many sectors including water supply, health, agriculture, transportation, navigation systems, and fisheries (Posthumus et al. 2009, Du et al. 2010, Merz et al. 2010; Abbas and Routray 2013, Dewan 2015, Sultana and Thompson 2018). Despite the debate on the cause of extreme river floods, these events have underscored several lessons as stated by Savenije (1995). These lessons state that: (1) previous knowledge about our rivers are out of date since considerable changes have taken place in these rivers, (2) our understanding of the physical processes of rivers is insufficient, and (3) there is a societal lack of awareness of the hydrological systems in which we are living. On the other hand, large urban centres, with their high populations, are water-sensitive areas since they require large amounts of fresh water for consumption and sanitation (Leathers et al. 2000, Boadi et al. 2005). Bordi et al. (2009) stated that "the degree of a region's vulnerability depends on many environmental and social factors as well as on the ability to anticipate, cope with, and recover from drought". This statement further means that drought severity is dependent on water shortage as well as on water use (Rao and Voeller 1997). In addition to water supply, soil erosion, crop production, and hydroelectric power generation are also severely affected by the events of drought (Landsberg 1982). Water utilities are prioritized by managing water-supply droughts (Walker and Smithers 1995), and the measures used to assess drought in terms of impacts on water utilities are categorized as water resources indicators

(Mawdsley et al. 1994). Both droughts and floods can have serious impacts on water quality (Hrdinka et al. 2012). Therefore, freshwater planning and management merits advanced understanding and assessment of historical drought and flood hazards and their impacts at both regional and local levels (Leathers et al. 2000, Merz et al. 2010, Mishra and Singh 2010) on the different resources, such as water, food, and energy. Traditionally, each of these resources and their utilities are planned, developed and managed in isolation of the others; however, "balancing different resource user goals and interests – while maintaining the integrity of ecosystems" (FAO 2014) is nowadays becoming a concern mainly tackled by the water-energy-food nexus (WEF nexus) concept. To improve the current status of developing the integrative concepts of the nexus, Al-Saidi and Elagib (2017) recommend exploring driving forces and interactions of the resources on different scales and across different sectors. The WEF nexus becomes even more complicated under stochastic phenomena, such as droughts and floods.

Like many African countries, the pursuit of human advancement and urbanization in the countries within the Nile River Basin has created an imbalance between socio-economic development and environmental welfare, especially in large cities. The uneven spatial development of services across several countries resulted in a rapid growth in urban populations due to rural-urban migration because of the deteriorating rural livelihoods (Boadi et al. 2005). In this regard, the capital of Sudan, Khartoum State, has become progressively urbanized in many aspects, such as outstanding population agglomeration accompanied by expansion of construction and other human activities (Elagib 2011). What makes Khartoum State vulnerable to fluvial flooding is that it is incised by the flow of two rivers, i.e. the Blue Nile and the White Nile, which confluence in the middle of the state (Fig. 1). For several decades, Khartoum State has been pinpointed as a region with high inter-relationship between socio-economic development and urbanization (El Nour and Balla 1989). Urban agriculture in Khartoum State is a common practice along, and in the periodically flooded soils adjacent to, the River Nile banks

(Abdalla et al. 2012). Expansion of land for urban agriculture has led to substantial increases in water use during the last five decades (Schumacher et al. 2009). In comparison to other urban centres in Sudan, faster interactions between intensified desert conditions and rapid urbanization were clearly exemplified by Babiker (1982) in the case of Khartoum, not only because Khartoum is the largest urban centre with the highest rate of population growth, but also because of its location in a more ecologically vulnerable region. It is generally accepted that supply of water resources is affected by different climatic, hydrological and anthropogenic factors. These factors operate differently at various temporal and spatial scales. Although Khartoum is rich of water resources, and despite the substantial progress in the improvement of the water supply and distribution system, these systems are still largely inadequate to meet the demands; hence, water supply and accessibility still induce considerable challenges to the governmental water supply system of the state (Abdalla et al. 2010).

In the last couple of years, considerable efforts have been made to understand the inseparable links between the water, energy and food resources of the Nile using the WEF nexus approach. For example, Al-Saidi et al. (2017) used this approach to highlight the issues for transboundary cooperation within the Eastern Nile Basin. Further, Al-Saidi and Hefny (2018) utilized the interlinked water, energy and land resources approach to conceptualize the process of transboundary cooperation and address the underlying water diplomacy challenges within the Eastern Nile Basin. Another study (Basheer et al. 2018) developed a daily hydro-economic model of the Blue Nile Basin to quantify the long-term direct economic gain from implementing infrastructure development plans for Sudan, Ethiopia and the whole basin. Basheer and Elagib (2018) introduced the concept of water-energy productivity to explore the sensitivity of water-energy interdependencies to dam operation by modeling the White Nile, including Jebel Aulia Dam, in Sudan. Stamou and Rutschmann (2018) assessed the water resources in the Upper Blue Nile Basin by optimizing the interacting WEF sectors to enable a co-benefit scenario.

Al-Saidi and Elagib (2017) concluded that the WEF nexus should be analysed on a case-by-case basis without generalization or pushing an ultimate model. Despite the aforementioned research on improving the understanding of the WEF nexus in the context of the Nile, the urban facet of the nexus does not seem to feature in the ongoing discourse. Roidt and Avellán (2019) defines the integrated management approach of the WEF nexus, i.e. water supply, food and energy sectors, in terms of concept of integration category and an aspect as follows. The former describes the connection between two aspects whereas the latter is defined as a particular part or feature of the approach and includes the systems, i.e. water, energy and food. Thus, when adopting the nexus, they consider water to generate energy, energy to supply water, water to grow food, food to produce energy, etc. as representing the categories to be integrated, either partly or all. Zhang et al. (2018) identify the research priorities for the interdependency of the WEF systems and suggest research method for their implementation for each system scale. They emphasize the need for representing more detail of the inner social and physical mechanisms of the nexus system on the small research scale of a city.

Therefore, the objectives of this study are: (1) to analyze possible urban WEF nexus indicators under hydrological drought and riverine flood, (2) to examine how extreme such hazards are in terms of seasonal and cumulative environmental consequences assessed by the nexus linkages within three activities ,namely urban farming, water treatment for domestic use and hydropower generation, and (3) to discuss and offer recommendations to minimize the associated risks and secure WEF resources within the three sectors, i.e. domestic water supply, urban agriculture and hydropower energy, if there would be a return of hydrological hazards.

2 Study area

Figure 1 shows the location of the study area. Khartoum State, the capital of Sudan, has an area of around 21,000 km^2 which accounts for approximately 0.01% of the total area of the country. Conversely, Khartoum is characterised by a rapid population growth with nearly 20% of the population of Sudan residing within the state. The population of Khartoum is between 6 to 7 million as estimated by the Sudan Population (2018). Khartoum has a unique location due to the confluence of the two main tributaries of the Nile River, i.e. the Blue and the While Niles, within the state to form the Main Nile. The three river courses divide the state into three parts: Khartoum City which is located between the Blue Nile and the White Nile; Khartoum North (Bahri) which is located between the Blue Nile and the Main Nile; Omdurman which is located west of the White Nile and the Main Nile. Whereas high seasonality characterises the flow of the Blue Nile with nearly 80% of the annual flow occurring from July to October (Conway 1997), relatively regular flow is a feature of the White Nile due to the presence of the Sudd swamps in its upstream (Sutcliffe and Parks 1999, Basheer and Elagib 2018). The Blue Nile and the White Nile contribute around 57 and 30%, respectively, of the flow of the Nile River measured near the Sudanese-Egyptian border (NBI 2012). Khartoum State is featured by fast expansion of settlement, industrial, and business areas and extreme hydro-meteorological phenomena, such as urban heat island, intensifying aridity, and pluvial and fluvial floods (Sutcliffe et al. 1989, Walsh et al. 1994, Davies and Walsh 1997, Elagib 2009, 2011, Elagib and Elhag 2011, Mahmoud et al. 2014, Mahmood et al. 2017).

Khartoum is supplied with electricity through the national Sudanese grid which combines energy generation from several hydro- and thermal-power sources around the country. Two of the hydropower sources that feed the Sudanese grid and supply Khartoum State are Roseires and Jebel Aulia dams. The construction of the first phase of Roseires Dam was completed in 1966 to provide

Gezira Scheme with irrigation water and to generate hydropower through seven 40-MW turbines (MoIHES 1977). The second phase of the dam was completed in 2013 to add 10 m to its original height (DIU 2016). Despite that the construction of Jebel Aulia Dam was completed since 1937 (Sobeir 1983), it was not until 2002-2005 that hydropower unites were added to the dam with a total capacity of 30.4 MW (ANDRITZ Hydro 2013). Lastly, several Water Treatment Plants (WTPs), along with groundwater wells with varying depths and productivity, supply drinking water to Khartoum State. Those WTPs have been installed along the Nile during the period 1924 to 2010 (Fig. 1), and the evolution of their number indicate an increasing water demand within the state.

3 Data and methods

3.1 Data used

The present work integrates several kinds of data to understand the urban WEF nexus under the hydrological risk in the Nile basin as follows:

- Hydrological observations: Monthly river flow at Khartoum gaging station on the Blue Nile from the Ministry of Water Resources, Irrigation, and Electricity of Sudan for the period 1965-2017.
- Daily water turbidity measurements for the Blue Nile near Bahri Water Treatment Plant (WTP) for the period 2007–2010. These data were acquired from the Sudanese Central Laboratory and Bahri WTP. Even though the turbidity time series had gaps ranging from one day to several days, the gaps represent <10% of the dataset. The Gaps were filled by using a cubic spline calculation (Lewis and Eads 2009) such that (1) daily mean turbidity of the estimated data matched the daily mean observed turbidity, (2) estimated data were calculated at the same time intervals and are continuous with respect to observed data and to first and second derivatives,

and (3) the turbidity data were correlated using observed data from a nearby point with a concurrent record.

- Structured questionnaire consisting of a series of printed multiple choice question that took place during 2017 with 50 farmers who practice irrigated agriculture along the Nile bank in four locations, namely Elgezira Slang, Shambat, Elfaki Hashim and Elgeraif, in Khartoum State (Fig. 1). The details of the questionnaires as regards the survey administration, the selection of respondent farmers and nature of the questions will be described later in the following methods.
- Interviews carried out during a field visit in March 2015 with farmers who cultivate on the river banks to express their views on the impacts of sedimentation and river erosion.
- Several kinds of data were used to estimate the daily energy production for Roseires and Jebel Aulia dams by river basin modelling. These data included river flow, rainfall, water demands of large-scale irrigation, and outlets capacities, operating policies, turbines specifications, and reservoirs geometry of dams. These data were obtained from several sources including the Ministry of Water Resources, Irrigation, and Electricity of Sudan, the Sudan Meteorological Authority, the Eastern Nile Technical Regional Office of the Nile Basin Initiative, and Wheeler et al. (2016). Moreover, the African Rainfall Climatology Version 2 (ARC2; Novella and Thiaw (2013)) satellite data were used, after evaluation, to substitute the sparse ground rainfall data in the study region. The reader is referred to Basheer et al. (2018) for more information about the procedure that has been followed to evaluate ARC2. Shuttle Radar Topography Mission (SRTM; Jarvis et al. (2008)) topographic data were used to delineate sub-basins and the Moderate Resolution Imaging Spectroradiometer Global Evapotranspiration Project (MOD16; Mu et al. (2011) data were used to estimate average actual evapotranspiration from

the sub-basins. Section 3.4 describes the modelling approach followed to derive the energy data.

3.2 Nexus concept of the present study

With the nexus background reviewed in the introduction, the understanding of the impact of hydro-environmental hazards on the urban WEF nexus within the Nile is built herein on the conceptual framework shown in Fig. 2. It is not claimed that this framework is a comprehensive one, but it is rather deemed a first-step towards this understanding. In this approach, climate variations are considered as a trigger of the hydrological hazards, i.e. drought and floods. These hazards reflect into indicators of nexus systems, i.e. water, energy and food, and are represented respectively by the status of water quality and quantity (water environment), hydropower generation from dams, and urban agricultural activities. These indicators translate into understanding of the interlinked impacts between the corresponding water, energy, and food securities. As indicated by the up-down arrows in Fig. 2, the interlinkages were discussed in three dimensions. In the first dimension, the WEF nexus in urban agriculture was investigated in view of, for example, the influence of floods and droughts on the pumping energy (water-energy nexus), which in turn necessary for facilitating crop irrigation of (WEF nexus), and on the availability of land for cropping. The influence of energy availability on transporting food crops (energy-food nexus) within the capital was also discussed. Secondly, the implications of several environmental problems, such as algal growth and siltation, for the water-energy nexus in the process of river water treatment for domestic use were demonstrated under drought and flood events. The third dimension demonstrates the influence of hydrological droughts and floods on the water-energy nexus in hydropower production from two dams which supply energy to Khartoum. Finally, the established understanding of the impacts on the WEF nexus would lead to interventions to adapt to hydro-environmental hazards within urban environments through measures to secure water, energy and food. To achieve the above understanding, several methods and data have been employed as described in the following part of Section 3.

3.3 Analysis of flood and drought events using streamflow drought index

The streamflow drought index (SDI) is widely used to characterize hydrological droughts (Shukla and Wood 2008; Nalbantis and Tsakiris 2009) in terms of wet and dry years relative to the average condition. In this study, a temporal analysis of monthly and annual river flow data was performed to develop the SDI for 1965 to 2017 as follows. The distribution of flow data was checked for normality by calculating the skewness coefficient (Sk). If the Sk was far from zero, the data were normalized by attempting several transformation functions, such as logarithmic, square root, etc until near-zero Sk was reached. The mean, the standard deviation, and the deviation from the mean of the transformed (normal) flow data set were then calculated. Those deviations (anomalies) were finally divided by the standard deviation to obtain the SDIs. Positive anomalies refer to wet events whereas negative anomalies indicate dry events with respect to the average river flow. To identify the monthly contribution to annual drought/flood incidences, the relationship between the annual and monthly SDIs for 1965 to 2017 was examined using the non-parametric, one-tailed Kendal tau correlation test (Kanji 2006). Then, recently reported river flood and drought years, i.e. respectively 2006 and 2010, were selected to examine the urban WEF nexus under these two conditions.

3.4 Hydropower modeling

Daily energy production data for Roseires and Jebel Aulia dams for the period 2006-2010 were generated utilizing river basin models of the Blue Nile and the White Nile. The two models have been developed for the two rivers respectively by Basheer et al. (2018) and Basheer and Elagib (2018). The Blue Nile and the White Nile models have daily and monthly time steps, respectively. For this study, the monthly White Nile model was transformed into a daily model to produce daily energy generation data for Jebel Aulia Dam. This transformation was performed by replacing the monthly river flow and water abstractions with daily data and adjusting the system operating rules. The two models were created using a river and reservoir simulation tool, i.e. RiverWare (Zagona et al. 2001), and a rainfall-runoff modelling tool, i.e. The Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS; HEC (2000)). RiverWare is an object-oriented water allocation modelling tool that supports prioritized rule-based simulation (Zagona et al. 2001). RiverWare has a policy language that provides flexibility in modeling dam operating rules (Wheeler et al. 2018). HEC-HMS is a tool that simulates rainfall-runoff of dendritic watersheds using mostly lumped conceptual and empirical methods. In developing the Blue Nile and the White Nile models, constant travel times and loss percentages were used to simulate lag time and transmission losses, respectively. Moreover, the models used a soil deficit accounting method to simulate soil infiltration and percolation, a constant capacity to simulate canopy interception, and Snyder unit hydrograph to simulate water transformation in sub-basins.

3.5 Analysis of flow, turbidity, and hydro-energy

In this analysis, the annual cycles of both the river flow and turbidity were compared for index wet and dry years (2006-2010) to study the influence of floods and droughts, respectively, on the occurrence of peaks of the two variables, the time lag between those peaks, and the seasonal behaviour of the river flow and turbidity. Furthermore, the relationship between the two elements was investigated for different seasons. The results of these analyses were used in the discussion of the influence of hydro-environmental hazards on the WEF nexus.

Regarding the hydro-energy, the probability of exceedance of the daily energy generation was calculated and compared to illustrate the influence of floods and droughts on the water-energy nexus as indicated by the firm energy generation, the probability of energy generation at the installed capacity, and the total annual energy generation. Moreover, the annual hydro-energy generation was studied to understand the interplay of system operating policies and energy generation in the events of floods and droughts.

3.6 Questionnaire about adaptation of urban agriculture to hydro-environmental hazards

A questionnaire was randomly distributed to a total of50 famers in five locations as follows: 10 farmers in Elgezira Slang, 10 farmers in Shambat, 14 farmers in Elfaki Hashim, and 16 farmers in Elgeraif. Figure 1 shows the five locations and Table 1 presents the nature of the questionnaire questions. The questionnaire was translated from English into Arabic to facilitate communication with the respondents. In each case, the farmer requested to be informed of the content of the questionnaire before consenting and responding to it. Filling each questionnaire form took 5 to 10 minutes, and was under close supervision and full participation of the researcher. Selection of the farmers was aimed to achieve certain criteria, including a wide-range of household characteristics, crop type, and cultivars. All farmers were males (a characteristic of urban agriculture) who were the fathers and heads of their families and were aging from 30 to 70 years old, working in farming for 8 to 55 years. Around 94% of the interviewed farmers had primary, intermediate, and secondary level of education and all of them had a family size of 3 to 12 persons. Three main kinds of occupation were identified for the farmers:

farming was identified for 72% of them while farming and pastoralism or farming and trading was recognized for 28% of the households. Farming represents the main source of income for all except one of the households. All the farmers produce onion, potato or other kinds of vegetables and sell their products solely in the local market.

The purpose of the questionnaire was to explore how farmers perceive the impacts of climate variations-induced consequences, i.e. hydrological drought and/or flood, on urban agriculture and how they respond to these risks, which lead to crop loss and decline of crop productivity. Therefore, the topics investigated among the farmers included their perceptions of the reasons behind the decline of production, farmers' adaptation options, and barriers to farmers' adaptive capacities (Table 1). In formulating the questionnaire, a recent experience in Sudan was taken into account (Elagib et al. 2017). The respondents were allowed to select more than one answer.

4 Results and discussion

4.1 Flood and drought events

Fig. 3 shows the temporal SDI of the monthly and annual time scales for the Blue Nile at Khartoum gaging station. April and September were selected to represent a summer-dry and a summer-wet month (Conway 1997), respectively. Since July-September is the main rainfall season across the Blue Nile, rainfall in this period contributes the major volume of flow as will be shown by the hydrograph in the next section. Therefore, September SDI time series correlates significantly (tau = 0.644; p = 0.001) with the annual SDI unlike the case of April SDI time series. During the 53-year period, the 1980s represented the driest decade, which is characterized by successive dry years. This drought period (referred to as the Sahel drought) is well documented in the literature (Sutcliffe and Parks 1999). The temporal analysis of SDIs reveals 27, 28 and 24 negative anomalies but 26, 25 and 29 positive anomalies, respectively for April, September, and annual time series. The above- and below-average flows within the present up-to-date data also confirm the characteristic fluctuations exhibited by the Nile flows during earlier decades (Conway and Hulme 1993). Another up-to-date feature is the increased and successive number of years of positives anomalies during the 20th century. These observations could be a result of extensive land use and land cover changes (Tekleab et al. 2013; Woldesenbet et al. 2017) and significant increase in heavy and extreme rainfall events (Degefu and Bewket 2014; Worku et al. 2018) in the Upper Blue Nile in Ethiopia during the recent years. Increasing trends of maximum and minimum flows at an upstream gaging station of the Blue Nile in Sudan was reported by Taye et al. (2015) up to the year 2009. The year 2007 was the wettest during the period of recovery from the Sahel drought (Figs. 3b and 3c). This observation corresponds to reports of exceptional rains and floodings in the Sahel and sub-Saharan Africa (Paeth et al. 2011; Samimi et al. 2012). Of particular interest for the present study are the years 2006 and 2010 for which the SDIs indicate a fluvial flood event in September and a hydrological drought occurrence in April, respectively, the impacts of which will be elaborated in the following sections. The SDI show a value of 1.73 for September 2006 but a value of −1.78 for April 2010. It is interesting to note as well that the overall annual flow during the year 2009 was also low (Fig. 3c), thus aggravating the drought situation of the dry early part of the year 2010. It is worthwhile noticing, on the other hand, that multi-year drought events have also occurred during the 20th century (Fig. 3).

4.2 Water environment during flood and drought

The water environment in the present study refers to the quantity and quality of the Nile water resource. The annual cycle of both the flow and turbidity levels is exhibited in Fig. 4 for five and four years, respectively. To discuss the pattern of these cycles, one needs to put it in context of the drought and flood events indicated by the SDIs in Fig. 3. On the annual scale, four years are characterized by above-average flows, namely 2006, 2007, 2008 and 2010, whereas 2009 indicates below–average flow. The peak flow always occurs during late August to early September (Table 2); however, two secondary peaks occur before and after the wet season (July to September), as seen in Fig. 3, which resemble the climatological rainy season in East Africa (Seregina et al. 2018). The one preceding the wettest part of the year is recorded during June/July whereas the one following the wet season is registered in October/November. As reported in Table 2, the intra-annual variability was lowest (~130%) during the wettest year (2007) but highest (>150%) during the driest year (2009) or the year that encountered too dry summer season (April 2010). This behaviour is even more pronounced for the wet season flow data when the intra-annual coefficient of variation dropped to 32.7% but escalated to 75.7% in 2007 and 2009, respectively.

As for the turbidity annual cycle (Fig. 4), notably high turbidity levels occur during the wet season (July–September) with always a sharp peak during July, i.e. much earlier to the flow peak (Table 2). In 2010, when the preceding season to the wettest part of the year was too dry, the time lag between the turbidity and flow peaks was the shortest, i.e. only 12 days, compared to the longest lag (as long as 66 days) evidenced in the wettest year 2007. The delay of flow peaks behind turbidity peaks could be a result of sediment transport regime in this area; however, this causation needs more investigation of sediment criteria. A study from the United States of America showed coincidence of flow and turbidity peaks in snow melting seasons, and that the change in level of suspended solids in rivers (and hence turbidity) with changing water depths and velocities is rapid and unpredictable (Susfalk et al. 2008). The same study also emphasized that adequate characterization of the inherent temporal variability of the process will require a large number of water quality samples. In the present study, the highest turbidity level was recorded during the year with the lowest flow (2009). Similarly, the highest intra-annual coefficient of variability of turbidity (84.1%) was found to characterize the wet season of this driest year (see Table 2).

Figure 5 shows a well-established linear relationship between the Blue Nile river flow at Khartoum station and turbidity level on a log-log scale, with a variation among the years and the seasons of the year. Such seasonal flow-versus-turbidity relationships are quite informative. It can be clearly noticed that the turbidity level increases with increasing flow with the strongest relationship obtained for the dry season followed by the hot season. Also noticeable is the higher turbidity levels during the wet season than in the other seasons. The correspondence between high levels of both turbidity and flow for the Nile as reported in the present work is supported by earlier results for Atbara River, which brings more than 25 million tons of silt to the downstream during the wet season (Zaghloul et al. 2007). A wide scatter of the data points is noticeable in Fig. 5 for the wet season with the best-fit is achievable for August and September. To interpret this relationship, the cause of turbidity must be discussed which is simply the load of suspended solids in the river. A previous study for the Blue Nile in Khartoum State concluded that the turbidity is potentially a viable surrogate measurement for determining the concentrations of total suspended solids, with the analysis showing a strong positive linear relationship between the two parameters for the flood season (Musnad et al. 2015). Similar results were obtained for rivers in the United States and Sri Lanka (Ellison et al. 2010, Wickramaarachchi et al. 2013). The analysis of the relationship between turbidity and flow is very complicated because it is related to the cause of suspended solids mobilization and its importance which vary from site to another as stated by Göransson et al. (2013). Most of the studies dealing with the sediment yield on the Upper Blue Nile in Ethiopia indicate a space-time variation of sediment supply and transport (Easton et al. 2010, Tilahun et al. 2013, Ebabu et al. 2018). These studies also emphasize the importance of identifying the runoff-contributing areas and time for the investigation of the sedimentation dynamics and the discharge–

sediment relationships. Since the majority of the Blue Nile flow is derived from Lake Tana and the runoff from the river catchment area in Ethiopia, the suspended solids mobilization should be understood in the context of significant increasing trends of wet-season runoff and sediment load in the Upper Blue Nile (Gebremicael et al. 2013), which also reflect in positive flow anomalies at Khartoum in the downstream (Fig. 3). Sediment load of a river influences the flood regime (Owens et al. 2005), and high sediment loads of floods complicate the performance of the flood regulation schemes (Vanmaercke et al. 2011).

4.3 Urban nexus under flood and drought

4.3.1 Water-energy-food nexus in urban agriculture

Many vegetables are grown under irrigation along the Nile banks to supply Khartoum State with its daily needs from these products. Farmers sell by themselves in nearby markets or through some local merchants (Abdalla et al. 2012). Transportation of these vegetables is facilitated by small or large vehicles that use different types of fuel; thus, the vegetables price is largely related to the oil prices in local and international markets, as explained by Headey and Fan (2008) who regards “the larger rise in oil prices—as a greater macroeconomic threat to the developing countries” and also by Esmaeili and Shokoohi (2011), who determined a positive relationship between the world crude oil prices on the world food prices and food security. Pumping of water from the Nile to the urban farms also needs energy, and different types of pumps are used like electrical pumps, which take electricity from the local grid, diesel pumps (Khalid 2003) as well as kinds of solar pumps in some schemes (Elzubeir 2016).

Food production at urban farms in Khartoum State is strongly linked to energy production through irrigation and transportation. During the flood season, and because of the high water level of the Nile, pumping of water may not be needed for farms adjacent to the Nile banks as pumps can be damaged by the floodwater. Contrarily, more pumping power for irrigation is needed in drought times to overcome the reduction of water level. Transportation of crops from the urban farms is affected greatly during the flood season, which is mostly associated with heavy rains in Khartoum State when roads become inundated due to deficient drainage system (Mahmoud et al. 2014, Mahmood et al. 2017) causing deterioration to transportation. Transportation cost increases greatly in this season and sometimes fails to supply markets thereabout with vegetables (Babiker 2017). Elbashir and Imam (2010) consider poor transportation as one of the major constrains to fruits and vegetables production in Sudan, including Khartoum State. Babiker (2017) estimates the irrigation cost in Khartoum State to represent 7.2-8.6% of the production cost of different vegetables whereas the transportation cost can represent 6.8-24.8 % of the vegetables price in the market.

Using agricultural products as biomass to produce energy is a widely-known practice in Sudan. Biomass (especially fuelwood) has a high share of 87% of the total energy production, and the techniques for converting it to useful energy is easy (Omer 2005). Normally this type of energy production is practiced in the rural areas but is also available rarely in Khartoum State.

When the farmers were asked about the factors behind them perceiving declining crop production, they mentioned one or a mix of factors summarized as aridity and weed invasion (80% of the farms), poor soil in 66% of the farms, inferior seeds in 68% of the farms, and pest invasion in 52% of the farms. In times of drought, and due to direct competition between irrigation in urban agriculture and other high priority water use, such as drinking and domestic water uses, water availability can get quite limited (Maheshwari and Bristow 2016). Since urban agriculture in Khartoum can only be met by irrigation, the water demand has shown a steady increase (Schumacher et al. 2009). In drought-prone areas where application of fertilizers, pesticides and weed-killers is limited, droughts and land degradation increase weed infestations, and spread of infestation occurs under conditions of contaminated seeds and soils, eroding soils, improper disposal of weeds, etc. (Bussmann et al. 2016). It should also be mentioned that the Nile water can also transport deleterious types of weeds (e.g. hyacinth), which has become a major weed type (Beshir and Bennett 1984; Mailu 2001). Infestation and re-infestation by weeds and other aquatic vegetation types can also occur through irrigation and during flooding times (Khedr and El-Demerdash 1997).

One of the impacts of the 2006 flood was the inundation of farmlands on the river banks (Fig. 6a). The interviewed farmers on the impacts of sedimentation and river erosion mentioned that sedimentation has occurred on the western side of the Nile, resulting in an increase of the cultivation area while on the eastern bank of the Nile, bank erosion has led to loss of the farming lands. Such morphological changes could be attributed to fast human interventions, i.e. land-use and land-cover changes at the expense of the natural forest to agricultural lands and firewood trees (Woldesenbet et al. 2017), thus exacerbating the soil erosion process in the basin (Gebremicael et al. 2013) and increasing sedimentation process further downstream in reservoirs (Betrie et al. 2009, Alrajoula et al. 2016) and irrigations schemes (Ahmed 2009) in Sudan. Urban agriculture can be blessed by sediment deposits from the periodic floods of the Nile River since they represent an important source contributing significantly to soil fertility maintenance (Abdalla et al. 2012).

4.3.2 Water-energy nexus in water treatment for domestic use

During the flood event of 2006, the Nile water levels increased to the extent of inundating the banks, thus reaching the housing areas (Figs. 6b and 6c). The old intake of Bait Elmal WTP, which was established in 1927 by the British Administration to supply water to old Omdurman area, was well submerged during this flood event (Fig. 6d). However, observations reported during the river drought in April 2010 indicate remarkable morphological change in the Blue Nile, which manifested in the appearance of several islands close to Bahir WTP on the Blue Nile (Figs. 7a and 7b).

Bait Elmal WTP is taken herein as an illustrative case study as it has been suffering from several environmental problems for several years now that can be ascribed to several drought- and flood-related factors in addition to human factors. These problems, discussed below, had implications for the water and energy nexus of the treatment plant.

a) ***Algal growth*** was observed on Nile during the drought of April 2010 drought year (Fig. 7c). Algal growth on Nile River has been clearly noticed in recent decades (Caspers 1977, Sinada and Abdel Karim 1984, Kheiralla et al. 2014). Accumulation of algal plankton in pumping and filtration units of Bait Elmal WTP leads to continuous failures and deteriorating efficiency.

b) ***Human interventions*** play a great role in changing the river morphology. Changing river channels in response to engineering works is well documented in the literature (Gregory 2006; Sun et al. 2012). The deposit of sediments has accumulated through the years, and now has led to changing the direction of water flow of the Nile and prevented it from entering the plant intake during the drought of April 2010. Therefore, a new intake was constructed (Figs. 7d and 7e) at a lower water level which entails more pumping energy needs. A plausible reason for this sediment accumulation is, for example, Shambat Bridge (Fig. 8a) that is situated on the Main Nile close to Bait Elmal station intake. It was constructed to connect two of the three main cities of Khartoum State, i.e. Omdurman with the Bahri areas. It has caused scouring, sediment deposition around the bridge piers, and changed the river cross-section by narrowing the river width near this area. Similar findings for the Nile demonstrate changes in the river resulting from the construction of bridges and other structures (Raslan 2010, Raslan and Salama 2015).

c) ***Siltation*** has become the most pressing concern of the water supply mangers in Khartoum State. In fact, Bait Elmal WTP has been seriously affected by dramatic increase in the amount of sediment load into the Nile River that has led to clogging of pumps of water plants and resulting into constant malfunctioning of the plant (Fig. 8b). Since 2005, the station has been facing serious siltation problem which led to the closure of the station. Recently, due to this problem, the plant is functioning as a storage station only, taking treated water from Bahri WTP and distributing it to the old Omdurman area.

4.3.3. Water-energy nexus in hydropower production

In order to understand the pattern of hydropower generation from Roseires and Jebel Aulia dams during 2006-2010 (Fig. 9), one must first know the operation criteria of the two dams. The operation of dams in Sudan is normally aligned with the hydrologic year, thus starts on 1st June and ends on 31st May of the next year. The main purpose of Roseires Dam is to store water during the flood season to be used in large-scale irrigation during the dry season (MoIHES 1977). The following information on the operation of Rosieres Dam was obtained from MoIHPS (1968) and Basheer et al. (2018). Due to the high sediment load of the Blue Nile during the flood season, and to prolong the lifetime of the Dam, the reservoir is normally kept at the Minimum Operating Level (MOL) from the 1st of June until a date determined based on the following criteria: (1) September 1st if the dam inflow is below 350 MCM/day by this date, (2) A date between September 1st and September 26th in which the inflow falls from above to below 350 MCM/day, or (3) September 26th if the inflow is still higher than 350 MCM/day by this date. Thereafter, the reservoir is filled in 45 days and kept at the Full Supply Level (FSL) until the water demands exceed the river flow. The reservoir storage is used to meet the difference between the river flow and the water demands until May 31st. Hydropower generation from the dam is a by-product of the above operating rules. It is important to note that the above-mentioned rules of Roseires Dam have been changed in 2013 after the dam was heightened. On the other hand, the operation of Jebel Aulia Dam is based on target reservoir water levels as follows (Basheer and Elagib 2018): (1) MOL from June 1st until June 30th, (2) from July 1st to July 31st, the reservoir water level is raised from the MOL to 372.5 m asl, (3) 372.5 m asl from August 1st until August 31st, (4) from September 1st to September 30th, the reservoir water level is raised from the 372.5 m asl to FSL, (5) FSL from October 1st until March 14th, (6) from March 15th to May 15th, the reservoir water level is lowered from FSL to MOL, and (7) MOL from May 16th until May 31st. Hydropower generation from the Jebel Aulia Dam is a by-product of the above target reservoir water levels.

Figures 9a and 9b show energy generation from Roseires Dam. It is evident that the highest energy generation during 2006-2010 was in 2008 with around 1860 GWh while the lowest was in 2010 with around 1580 GWh. Whereas the highest annual energy occurred in a year that follows the wettest year (i.e. 2007), the lowest happened in a year that comes after the driest year (i.e. 2009), as can also be compared with SDIs in Figs. 3b and 3c. This attribute can be explained by the operating policy of the dam which follows the hydrologic year, resulting in filling and emptying the reservoir in two different calendar years as explained earlier. Fig. 9b gives more insights into the impacts of drought and flood on energy generation through the probability of exceedance of daily energy generation from Roseires Dam for each of the years from 2006 to 2010. The lowest firm daily energy generation was recorded in 2010 (around 0.46 GWh) and the highest was found in 2007 (approximately 1.68 GWh). The years 2008 and 2009 had approximately similar firm energies of around 1.48 GWh/day whereas 2006 recorded a value of 0.83 GWh/day. The figure suggests that the turbines of Roseires Dam operated at their installed capacity (i.e. 280 MW) 47% of the year in 2008, 45% of the year in 2007, 40% of the year in 2006, 36% of the year in 2010, and 31% of the year in 2009. Drought can be shown to influence the energy generation for instance in April 2010 in comparison to its counterparts in other years. In April 2010, the total monthly energy amounted to around 20 GWh whereas the firm daily energy generation was approximately 0.46 GWh, as compared to averages for the 2006-2010 levels, which amount to 47 and 1.2 GWH, respectively.

Regarding Jebel Aulia Dam, all years from 2006 to 2010 have approximately similar annual energy generation. This similarity is due to the regular flow of the White Nile because of the presence of the Sudd swamps in the upstream as explained in Section 2. The highest annual energy generation characterizes 2010 with around 0.063 GWh while the lowest is an attribute of 2009 with roughly 0.056 GWh (Fig. 9c). Furthermore, as Fig. 9d shows, the installed capacity of the dam was never reached during 2006 to 2010, and a zero firm energy was noted within the same period. The latter characteristic occurred due to the regular total closure of all the outlets of Jebel Aulia Dam during the high flood period of the Blue Nile. This action is important to avoid any damage to the dam equipment as a result of the backflow from the Blue Nile into the White Nile (Sobeir 1983, Basheer and Elagib 2018).

4.4 Possible mitigation and adaptation measures

4.4.1. Measures to secure water for domestic use

Water treatment plants located on the Nile are designed mainly to remove turbidity and microorganisms. As noticed from the above results, turbidity is very high during the rainy season, thus creating high load in treatment plants all along the Nile where filtration is the main process of purification. High turbidity levels of Nile water during the wet season cause difficulties to drinking water treatment plants.

In rapid filtration systems, chemicals are used in coagulation/flocculation process to enhance the sedimentation of great percentages of suspended solids and in turn enable high rate of filtration. These chemicals, which are mostly aluminium salts imported from outside Sudan, are very expensive (Awad et al. 2013) and with debatable health impacts when used in large quantities (Ahmed 2004, World Health Organization 2010). In slow filtration systems, high turbidity greatly reduces the plant efficiency due to the accumulation of suspended solids on filter surface, and also reduces the quality and quantity of the finished product. To avoid these effects and at the same time insure meeting the quality standards of the finished product, pre-treatment must be facilitated in all plants (rapid or slow filtration systems) to equalize the turbidity in the treatment plant influent water. Some common methods that can be used in designing water treatment plants are:

a) ***Plain sedimentation process (Pre-Sedimentation)*****:** The quality of water can be improved by holding or storing the water undisturbed and without mixing long enough for larger particles to settle out or sediment by gravity. The settled water can then be carefully removed and recovered by decanting, ladling or other gentle methods that do not disturb the sedimented particles. In Sudan, multiple of studies recommended plain sedimentation as a pre-treatment method in the Nile plants but the implementation of such a measure has not yet started (Ahmed 2004, Musnad and Siyam 2016). Studies elsewhere also showed the improvement of water quality and reduction in coagulants usage when using sedimentation as a pre-treatment, especially in flood seasons (Ahamad et al. 2014, Taghizadeh 2018).

b) ***Constructed wetlands or reed-beds*****:** These techniques have a strong potential for application in the small rural communities in the developing countries since they are less expensive, easily operated and maintained (Kurzbaum et al. 2012). Their use in treating the river water and residual water has been studied in a number of countries, and the problems associated with it have also been studied (Borges et al. 2008). A research paper reported the high performance of a pilot-scale floating constructed wetland in the Buriganga River in Bangladesh for the treatment of polluted water (Saeed et al. 2016). Another study proved the high efficiency of this method in reducing pollutants load in relatively low-polluted water like storm runoff, i.e. similar to river water quality (Vincent et al. 2018). Nevertheless, the employment of these techniques in purifying the river water for improving the drinking water quality is still uncommon (Kurzbaum et al. 2012). The use of this method could reduce the high turbidity levels on the Nile water by feeding the water plant intakes from constructed horizontal flow wetlands or reed beds beside the Nile – as branched shallow canals fitted with flow regulators at entrances like weirs or sluice gates – to reduce the scouring velocity. The method needs to be tested on a pilot scale before application.

c) ***Natural coagulants:*** They have been investigated by research to deal with the problems caused by the chemical coagulants (Saritha et al. 2017). Simple natural materials like types of soils or some species of plants were tested as coagulant elsewhere and gave very good results (Jahn and Dirar 1979, Birima et al. 2013, Ramavandi 2014). Research in this point can lead to great achievement in reducing treatment cost and enhancing the finished product quality.

4.4.2. Measures to secure food within urban agriculture

The capacity of the Nile countries to address current and future impacts of climate change needs to be enhanced (UNEP 2015). Dubbeling and De Zeeuw (2011) stated that the urban farmers will be hit hardest by climate-related impacts because they are often located in the most vulnerable parts of the cities and lacking the capacity to adapt. Based on the present results of the farmers' interview for Khartoum State, 88% of the respondents mentioned that they cultivate earlier and adopt crop rotation. The former measure can be interpreted as a useful strategy during the short-term rainy season Nile flows to avoid heavy use of energy for pumping and, additionally, the damage to crops induced during the flood events, if there are any. Such an interpretation can be asserted by the least number of respondents (only 12%) who delay cultivation. The second most iterated adaptation strategy by the farmers was frequent weeding times (68% of the respondents) followed by soil conservation, which was mentioned by 62% of the farmers. Among the 50 interviewed farmers, 48% indicated that they cultivate early maturing crops. This strategy could also be understood to make use of the advantage of early cultivation as discussed above. Intercropping and use of fertilizations and pesticides are only adopted by 20% and 16% of the farmers respectively.

4.4.3. Measures to secure energy

Despite that hydropower generation from Rosieres and Jebel Aulia dams is a by-product and not the main target of the dams, the impact of hydrological extremes on hydropower can be profoundly observed. The operation of the two dams is closely related to, and limited by, the annual cycle of the Nile flows. Several studies have shown that basin-wide coordination of dam operation in the Nile Basin can increase hydropower generation and reduce water supply shortages considerably (Wheeler et al. 2016, Digna et al. 2018). The Grand Ethiopian Renaissance Dam (GERD: DoP (2015)), an under construction multi-year storage dam on the Blue Nile in Ethiopia, is expected to be completed in 2019. The dam is expected to regulate the flow of the Blue Nile and to reduce the sediment load that passes to Sudan. Several studies recommend operating all the Sudanese dams on the Blue Nile, including Roseires Dam, at their FSLs all the year round due to the decrease in sediment load and to maximize the energy generation (MoWRI Egypt 2014, Wheeler et al. 2016, Basheer et al. 2018). Basheer et al. (2018) recommend the installation of turbines with higher capacity in Roseires Dam to exploit the increase in energy potential due to both the heightening of the dam and the anticipated regulation effect of the GERD. Basheer and Elagib (2018) recommend modifying the operation of Jebel Aulia Dam after the construction of the GERD because the original operation takes into account the natural flow regime of the Blue Nile.

In light of the above recommendations, there is now doubt that modifying the operation of Roseires and Jebel Aulia dams would be essential in the near future to optimize the use of water for hydro-energy generation. It is worth mentioning, however, that there are also fears of adverse effects of the GERD in the form of: (1) reduced fertility of the soils downstream due to the expected attenuation of sediment load (Alrajoula et al. 2016) and (2) decreased areas of recession agriculture (Mohammed 2015, Basheer et al. 2018).

5. Conclusions

As concluded by Engström et al. (2017), a full climate, land, energy and water (CLEW) nexus approach to assessing the inter-linked impacts, trade-offs and co-benefits from interventions in urban resource systems holds a promising support for increased resource efficiency through integrated decision making. In the present study, an urban-level WEF nexus is analyzed under conditions of drought and flood in the Nile by drawing upon the case study of Khartoum State. The results presented herein for Khartoum State, which encompasses the confluence of the White Nile and the Blue Nile, suggest several indicators to explain the interactions between, and the impacts on, the water, energy and food systems in association with drought and flood hazards within the urban environment. Floods and droughts determine the water environment, i.e. the water amount and quality, which influence the integrated relationship between the WEF systems. Both environmental hazards, and in turn the water environment, impose risks to water treatment and supply. Activities within the urban agriculture sector, such as land availability for farming, pumping energy for irrigation, and water for food production, are impacted both positively and negatively by floods and droughts, as these events can largely determine the facets of urban agriculture, such as availability of land for cultivation, energy requirements for irrigation, productivity levels for food supply to the capital, and energy production from agricultural residues. The water environment under drought and flood times brings about cons and pros to energy production for Khartoum State. While high floods can give rise to hydropower generation due to water abundance, they can also pose difficulties to it through the increased levels of sediment loads, which are transferred to hydropower dams through runoff generated in highly degraded lands and, in turn, erosive soils. Droughts, on the other hand, induce enormous shortages in hydropower generation. In terms of measures to secure the WEF resources, it has also been shown that cons and pros would also be anticipated from managing the nexus. For instance, dams constructed to secure hydro-energy and regulate the sediment load that affects the water security could, on the other hand, pose risks to agricultural activities downstream due to anticipated less fertility of the lands. Hence, the results of the present research confirm the conclusion drawn by Hu et al. (2018) that for integrated and efficient resource policy implementations, research aiming at quantifying and analyzing the integrated and cooperative management of hydropower generation and water supply of reservoir systems is quite relevant.

This study was an attempt of analyzing the resource linkages toward understanding the nexus of a city within the Nile Basin. It is believed that other dimensions of the urban nexus could be further investigated in the future. For example, the industrial and economic dimensions of the nexus under scenarios of future climate change and consequent floods and drought constitute rich areas of research. The urban institutional role in operationalizing the nexus is another area worth investigation. As a measure to adapt to climate change, quantification of the benefits from operationalizing the huge and expensive amount of natural resources consumed and the wastes resulting from this consumption could also be carried out, considering the lessons learnt in the pilot study of a developed urban city (Gondhalekar and Ramsauer 2017).

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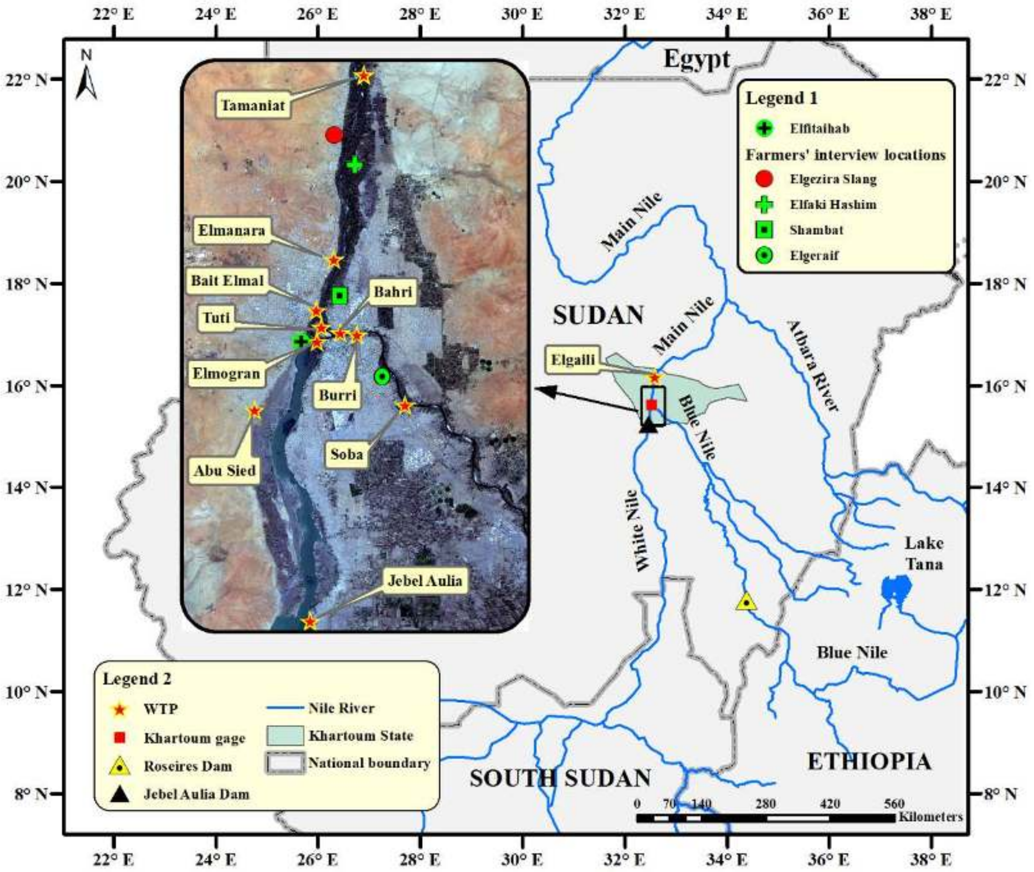

Fig. 1 Map of Sudan showing the study area (the capital of Sudan, Khartoum State), the Nile River, locations of respondent farmers to the questionnaire, and the water treatment plants (WTP) and two hydropower dams serving the capital

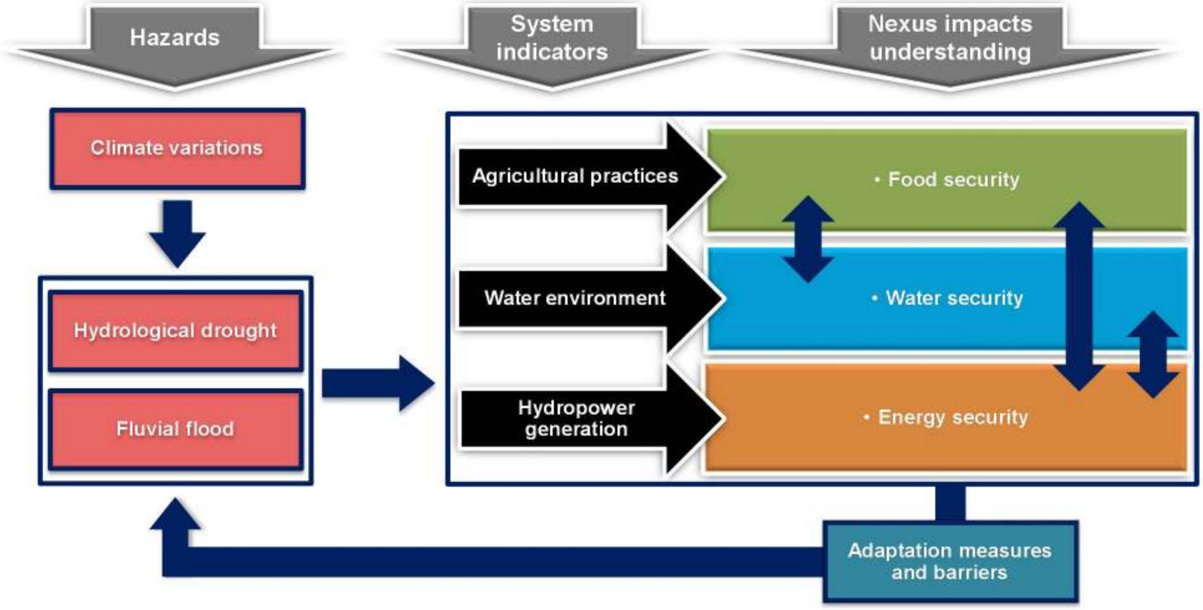

Fig. 2 Conceptual framework of urban water-energy-food (WEF) nexus under environmental hazards in the Nile as investigated in the present study. The up-down arrows refer to nexus or categories to be integrated with each other in the present study

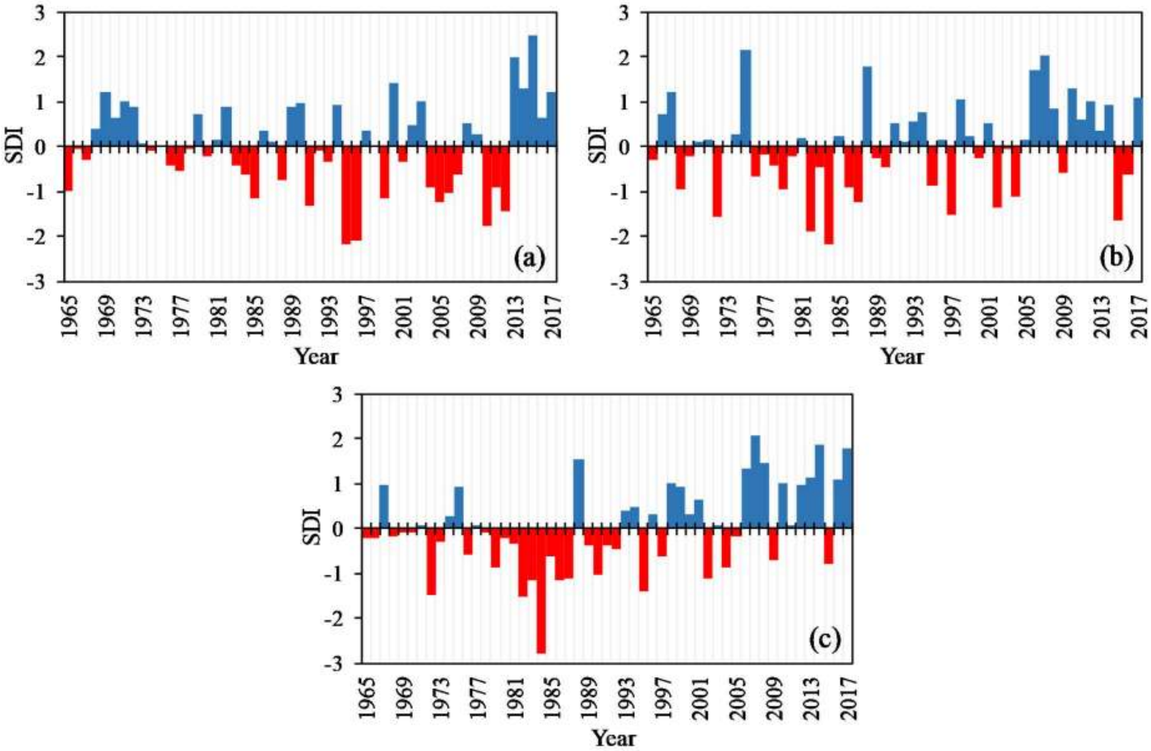

Fig. 3 Temporal analysis of river flow at Khartoum gaging station: a) April, b) September, and c) annual

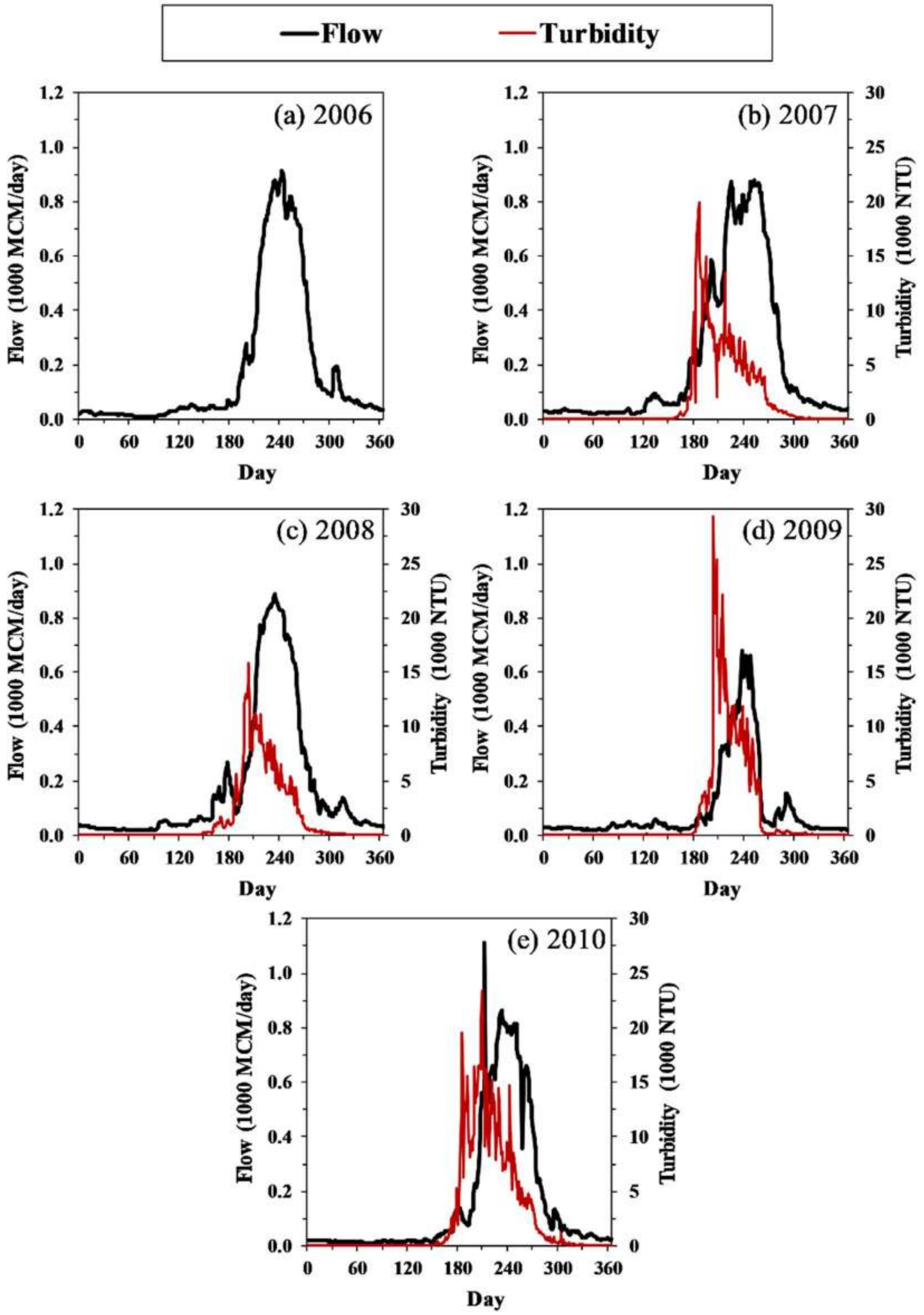

Fig. 4 Annual cycle of turbidity and river flow for Bahri water supply plant for 2006 to 2010 (2006: flood year; 2009: drought year)

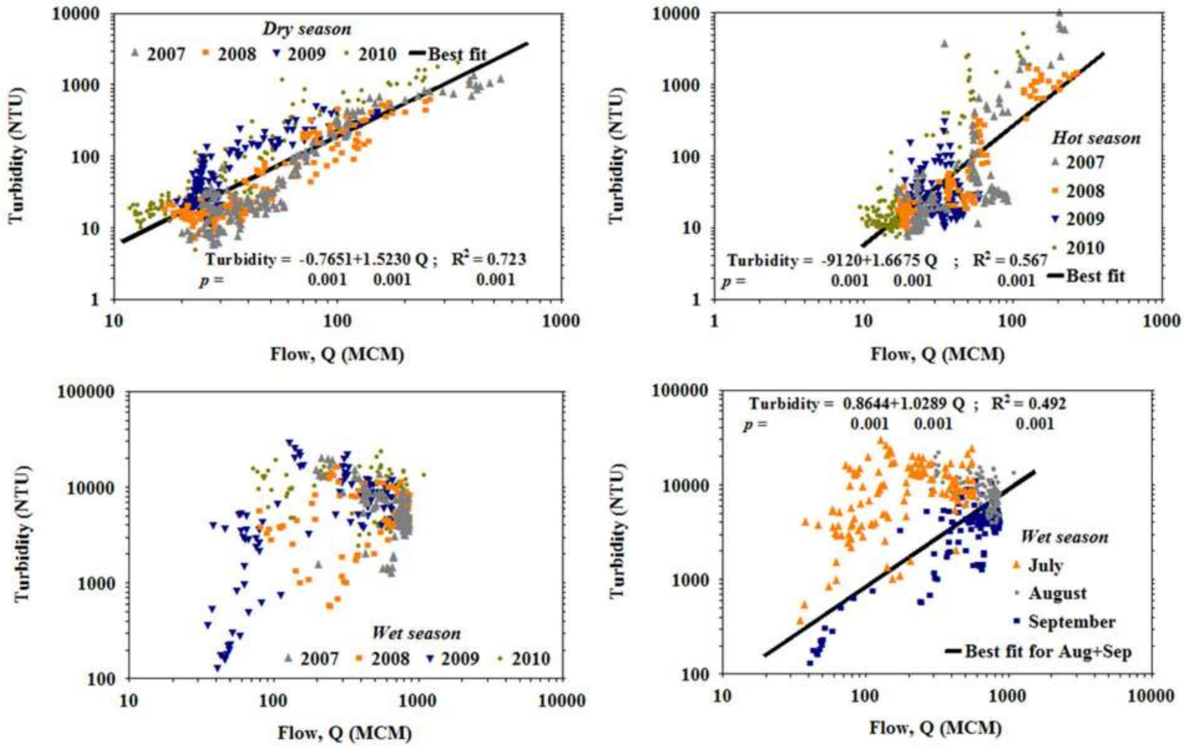

Fig. 5 Turbidity versus flow (Q) for the three seasons for Bahrai Water Treatment Plant. Dry season: Oct to Feb; hot season: Mar to Jun; wet season: Jul to Sep

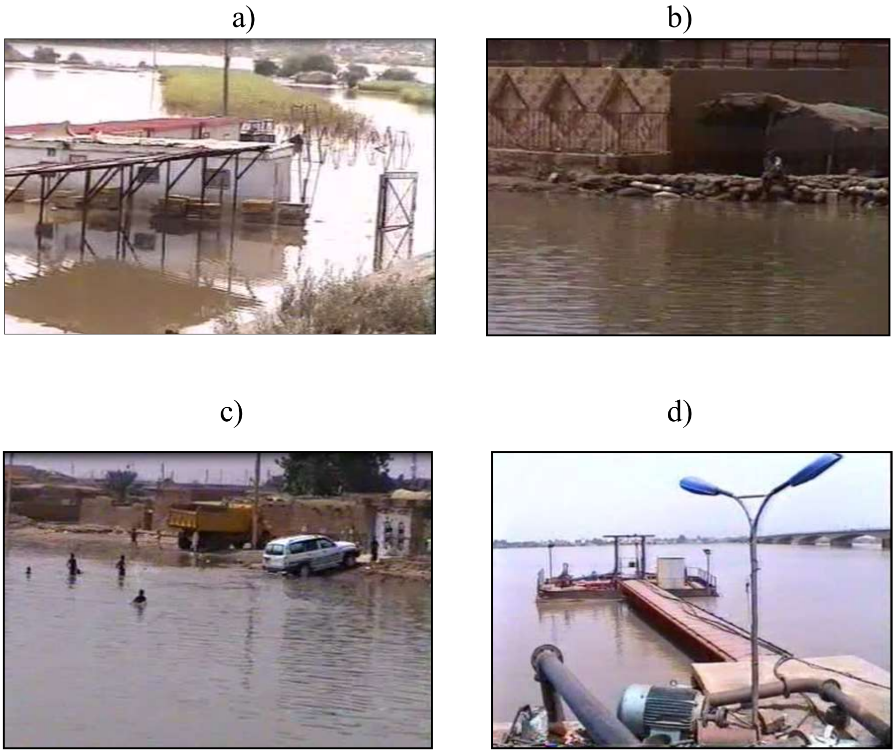

Fig. 6 Flood severity in Khartoum State during September 2006: a) A view from Shambat Bridge, Bahri (Khartoum North, of inundated agricultural lands on the banks of the Main Nile. b) and c) Nile floodwater reaching housing areas at Elfitaihab, Omdurman, and d) Old intake at Bait Elmal Water Treatment Plant within the river course (flooded area) (Photos: Elagib, 5 September 2006)

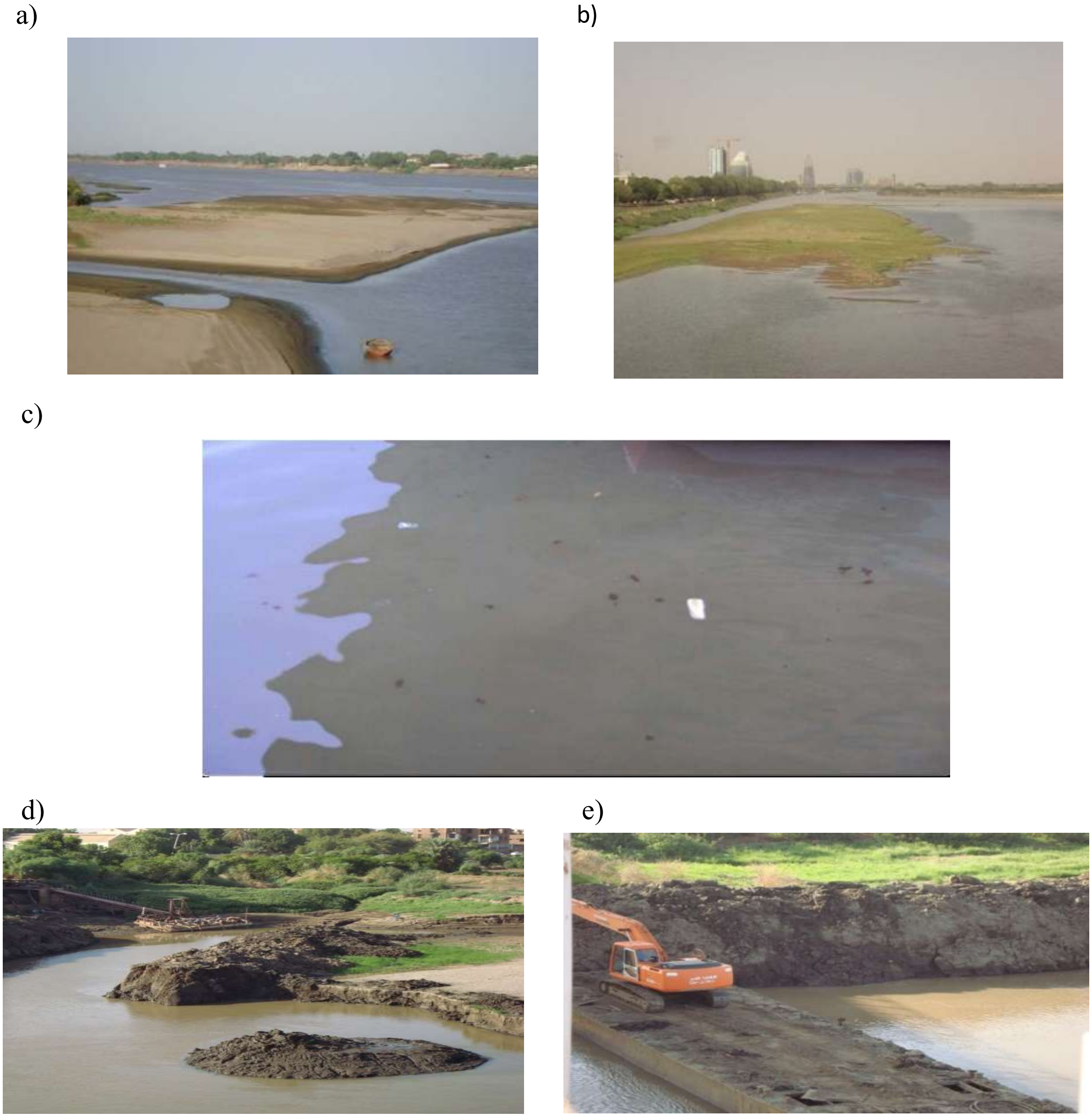

Fig. 7 Drought severity in Khartoum State during April 2010: a) and b) Islands formation in the Nile near Mek Nimer Bridge on the Blue Nile close to Bahri Water Treatment Plant (WTP), c) Algal blooms in Blue Nile, and d) and e) Construction of a new intake for Bait Elmal WTP (see Fig. 1) due to decreased river water level (compare with Fig. 6d). (Source of photos: A. Abdallah).

Fig. 8 Impacts of sedimentation problem: a) Narrowed river width near Shambat Bridge on the Main Nile due to accumulation of sediment and b) High turbidity level during the water treatment process at Bait Elmal Water Treatment Plant (Photo: Gore, March 2015).

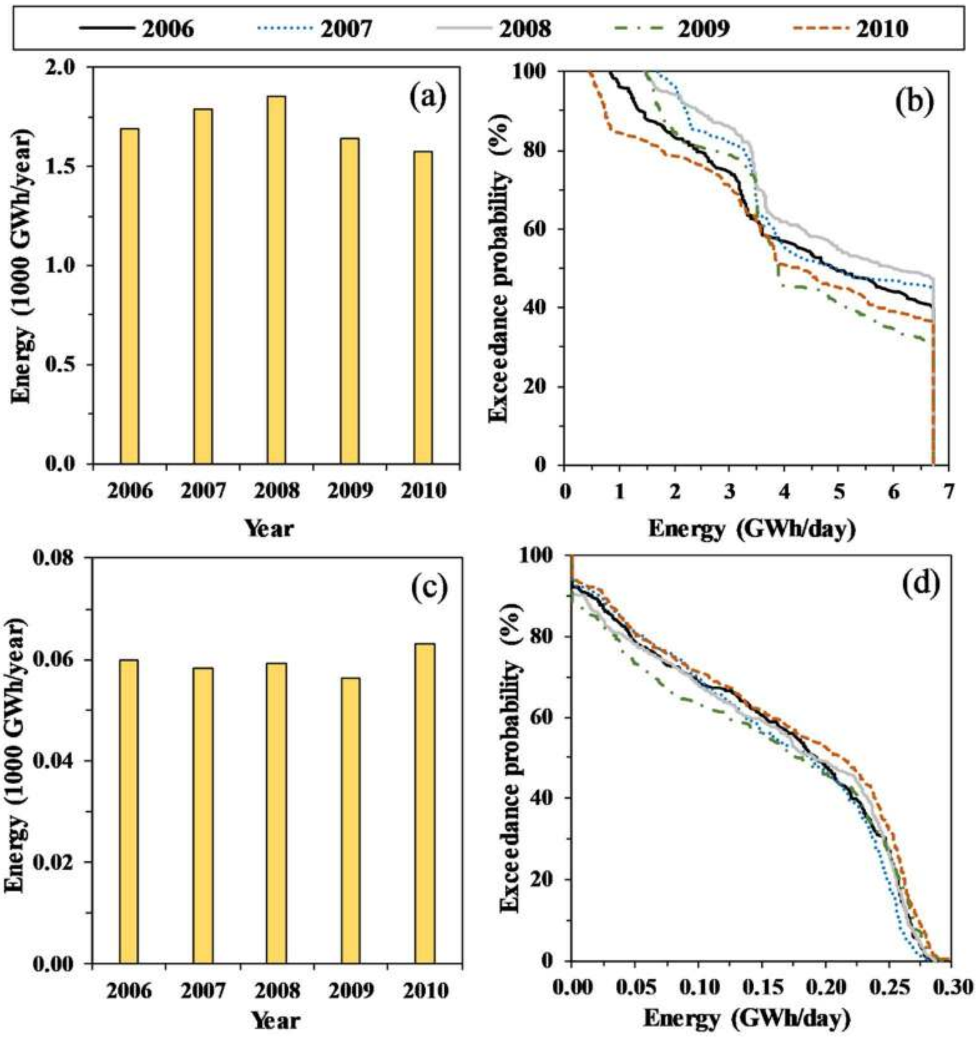

Fig. 9 Hydropower generation and corresponding probability of exceedance during 2006-2010: a) and b) Roseires Dam and c) and d) Jebel Aulia Dam

Table 1 Nature of questions used in the interviews

Question	Answer
I. When did you start observing climate variations-induced changes leading to the loss of crop productivity	a. last 5 years
	b. last 10 years
	c. the start of my working years
	d. since childhood
	e. never
II. Perception of decline of crop productivity	
1) What are the types of crops you are cultivating?	
2) If you observe decline of crop productivity, what are the reasons?	a. Increasing aridity
	b. Poor soil fertility
	c. Weed invasion
	d. Inferior seeds
	e. Insect and pest invasion
	f. Others (specify)
III. Adaptations options	
1) What are the agricultural adaptation strategies (measures) you have taken to cope with climate change and aridity	a. Early cultivation
	b. Delayed cultivation
	c. Cultivation of early maturing varieties
	d. Crop rotation
	f. More weeding times
	g. Soil conservation
	h. Intercropping
	i. Practice supplementary irrigation/modern irrigation
	j. Fertilizers and pesticides
	k. Mulching
	l. Others (specify)
2) What are the main barriers/challenges facing you as a farmer to adapt to changing climate?	a. Lack of machinery
	b. Lack of finance/credit
	c. Lack of improved seeds
	d. Shortage of labour
	e. Insects and pests
	f. Lack of meteorological information
	g. Others (specify):

Table 2 Characteristics of yearly flow and turbidity for selected years. Cv is the intra-annual coefficient of variation

Year		2006	2007	2008	2009	2010
Flow data						
	Annual (MCM)	253.9	277.0	257.2	188.6	243.6
	Peak (MCM)	912.4	878.9	887.2	679.5	1109.9
	Date of peak	01-Sep-06	10-Sep-07	22-Aug-08	26-Aug-09	10-Sep-10
	Annual Cv (%)	148.1	130.3	137.9	154.3	155.6
	Wet season Cv (%)	53.8	32.7	51.3	75.7	50.8
Turbidity data						
	Peak (NTU)		19870	15856	29351	23388
	Date of peak		6-Jul-07	22-Jul-08	23-Jul-09	29-Jul-10
	Annual Cv (%)		187.8	189.5	232.7	181.0
	Wet season Cv (%)		59.8	58.5	84.1	48.4
Time lag between peaks			66	31	34	12