5th International Conference on Water Resources and Arid Environments (ICWRAE 5): 134-145
7-9 January 2013, Riyadh, Saudi Arabia

The Implications of the Topographic, Hydrologic and Tectonic Settings Onthe Development of Bahr El-Ghazal Catchment, South Sudan

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Abstract: Bahr El-Ghazal is considered to be one of the most unique catchments within the Nile Basin. It receives ~1280 mm of rainfall that produces ~21.4 billion m^3 of water every years, only 0.5 billion m^3 reaches Lake No at the upstream of the White Nile.All the remaining water budget of this catchment is being consumed in theswampsregionat the lower part of the catchment, where the inflows are almost entirely lost to both evaporation and subsurface percolation. This is why the water budget of Bahr El-Ghazal catchment is considered negligible when calculating the waterresources for the downstream arid countries (Sudan and Egypt). Recent studies indicated that certain parts of the catchment are probably active. Observations from high-resolution satellite imagery indicate that there is a progressive flow-direction change in some tributaries, with the most recent ones flowing towards the swamps areas, suggestingthe presence of active tectonics during the Quaternary period. This study discusses the morpho-tectonics of the area and proposes an additional hydrological scheme to overcome the Sudd barrier through preventing water from flowing towards the low topography of the swamps region (Sudd Trough). Following the topographic gradient,the newly selected natural routes will dramatically increase the water budget of the Bahr El-Ghazal catchment and will support sustaining the currently proposed hydrological projects in the catchment.

Key words: South Sudan · Sudd · Sudd Trough · Jur River · Bahr El-Ghazal · Lake No · White Nile · Nile Basin

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INTRODUCTION

The hydrology of large transnational river basins has not only received intensive academic research but also attracted widespread public, political and economical concerns [1, 2]. There is a growing awareness of the societal importance of hydrological processes, such as fluctuations of river flows, water management strategies, climate change scenarios and the impact of these on sensitive and heavily populated deltaic systems, such as the Nile Delta [3-7]. International cooperation and treaties are widely implemented to manage and share the water resources of trans-boundary river basins (e.g. River Nile). Sadly, most of the less developed countries that share a river basin have not yet configured a common water master plan because of the diversity of the hydrological processes, lack of data, current and projected waterneeds, cooperation, trust and soon. A thorough understanding of the hydrological processes is necessary for effective water management in trans-boundary river basins, but this is a real challenge for less-developed countries, such as those linked by the Nile system.

The Nile is the world's longest river, with a total length of 6670km that drains a catchment area of ~3.2×10^6 km^2. Since prehistoric times, the inhabitants of the arid lands of northern Sudan and Egypt have mainly depended on the Nile water. It is also projected that, by the year 2020, over 300 million people will depend on the Nile basin for their water requirements [8]. The Nile system has developed through several phases, each phase is characterized by a different river system,

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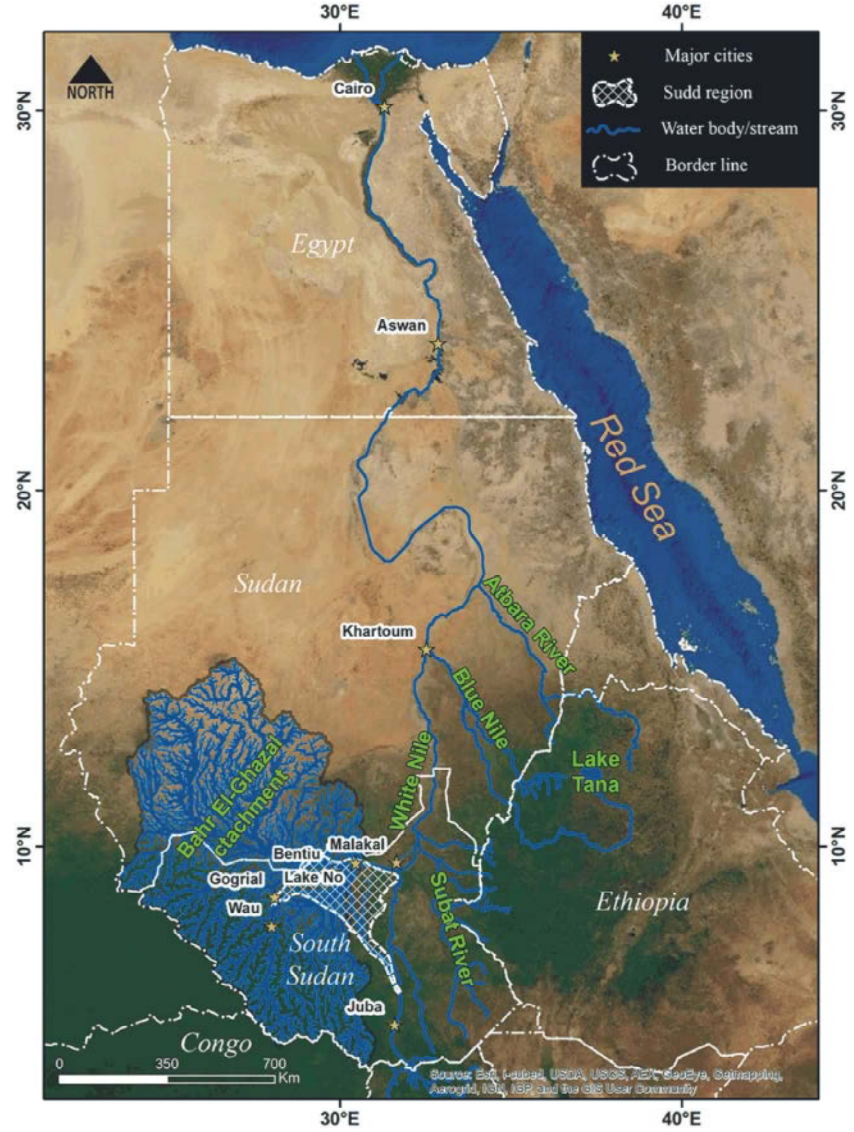

Fig. 1: A map showing the location of Bahr El-Ghazal catchment (Border lines are for some of the Nile Basin states only).

headwater extent, climate, tectonic activity and sediment composition and supply. These phases are described in more details in the study of Said [9] and have been discussed with some modifications in the study of Embabi [10]. Because of this complex evolution, the modern Nile catchment is composed of several different sub-basins, each with differing relief, climate, geology, land use and land cover, which were eventually integrated into the modern system [7]. The contribution of the differenttributaries to the natural discharge at Aswan between theyears 1912 and 1982 has been estimated as follows; the Blue Nile (58%), the White Nile and the Subat (30%) andthe River Atbara (12%). During years of high discharge,most of the additional water is contributed from the BlueNile and the River Atbara. Although the revenue from the Blue Nile and Atbara River of Ethiopia are about 80% of the total annual income of water to Egypt, the development opportunities are very weak due to several factors, most notably, the positive correlation between precipitation and water discharge amounts from the rugged terrain of the Ethiopian plateau (i.e. no barriers in the river prevents the detention of large quantities of water in lakes or swamps and succession).Although, the White Nile system does not contribute in a lot of revenue water to the Nile River [11-15], but there is lots of potentiality to increase the discharge of the basin by draining the massive swamps covering the state of South Sudan (Figure 1).

The notable surge ofrainfall over the Equatorial Lakes Plateau during the 1960s was of limited impact on the flow dischargemeasured at Aswan. Most of the flows were retained inthe source lakes and the Sudd of Sudan; the level of LakeVictoria consequently rose by 2.4 m. Furthermore, themean flooded areas of the Sudd during 1930–1931 estimated to be 8300 km^2 that has significantly increased to22000 km^2 after the 1960s [11]. Therefore, the available hydrological data of the Nile basin clearly show thatwater seepage into groundwater and storage in lakes,swamps and wetlands are high compared with the riverdischarge measured at Aswan High Dam. Because of that, the project of "Jonglei Canal" is launched in 1978 to overcome the Sudd barrier and increase the water revenue downstream. Sadly, the project has never completed due to some political issues.Yet, successful management of the River Nile up stream is critical for downstream arid countries, particularly Egypt where the demand for water is increasing rapidly. The gap could be narrowed by the implementation of regional agreements, which integrate research, social and economic strategies.

The aim of this study is to propose an additional hydrological scheme to increase the inflow to the White Nile system via increasing the discharge of swamps in South Sudan, particularly those occupying the catchment of Bahr El-Ghazal. The hydrological analysis of the catchment will integratethe available satellite images, digital elevation model (DEM) and the published hydrological and geological data, in order to determine themorpho-tectonic development of the channels. Therefore, the optimal natural channels will be delineated to bypassing the flows of Bahr El-Ghazal away from the swamps downstream [16, 17], thus increasing the water revenue of the catchment at Lake No feeding the White Nile course downstream of the Sudd region.

Study Area: Bahr El-Ghazal catchment is considered to be one of the largest catchments in the Nile Basin that covers an area of ~645,000 km^2 (Figure 1). The entire catchment area used to be occupied entirely by the Sudanese boarders until July 9, 2010 when South Sudan became an independent state, the process that resulted in dividing the catchments into two halves with the most downstream point located at Lake No in South Sudan (Figure 1). The independence negotiations of South Sudan did not include much about the water budgets/share of the country and has not been discussed until ithas been admitted as a full member to the Nile Basin Initiative in September 24, 2011. Since that day, it became of great importance to the downstream arid countries (Sudan and Egypt) to search for intuitive ways to increase their water budget since it has been threatened by South Sudan seeking for its share. The catchment attracted many authors to study its hydrological properties that made use of recent flow records to develop a water balance model for the Sudd region [11, 13, 18, 19].

The available hydrological data show that Bahr El-Ghazal catchment is one of the key tributaries to the White Nile system that annually receives upto 1400 mm of rainfall. The catchment is drained by a number of seasonal tributaries (e.g. Jur, Lol and Tonj), which are annually discharging about 12 billion cubic meters of water into the swamps downstream [11]. The flows of Bahr El-Ghazal have been measured and estimated at several gauging stations on the main tributaries since 1904. These measurements are encountered by gaps interrupting the continuity of records along with problemsof standardization of the collected data at different periods and localities.Notwithstanding, the meteorological data are collected at only few stations. Furthermore, the swamps of Bahr El-Ghazal usually receives variable amounts of water being spilled by Bahr El-Gabal to the east. Indeed, all these variables and limitations have affected the accuracy of previous hydrological research; thus there are significant discrepancies among the developed water balance models. Anyhow, the main finding of these models is that most of the flows of Bahr El-Ghazal are lost to evaporation and subsurface percolation; thus the outflows of the swamps to the White Nile system downstream are almost negligible. The river of Jur is the most significant tributary of Bahr El-Ghazal basin.Approximately, it contributes about 39% of the total annual flows in Bahr El-Ghazal [20]. Shortly after the independence of South Sudan, the development of the Jur River became of a priority for both the country, to be used as a seasonal navigational route and the downstream arid countries, to increase their water revenue.

Overall, the measured flows of the main Bahr El-Ghazal tributaries are low (3-7%) whenexpressed as percentages of rainfall, as most of the produced runoff are delivered to the swamp areas occupying the so called " Sudd Trough" (Figure 2). The extensive geophysical work in the central part of Bahr El-Ghazal Basin, revealed the presence of more than 5 kilometers thickness of sediments [21], now known as Muglad Rift Basin (Figure 2). Muglad Rift Basin is one of the rift related basins in South Sudan that has been developed in the late Jurassic time to the south of the Central Africa Rift System (CARS) that cut across Africa as a result of the separation of east and

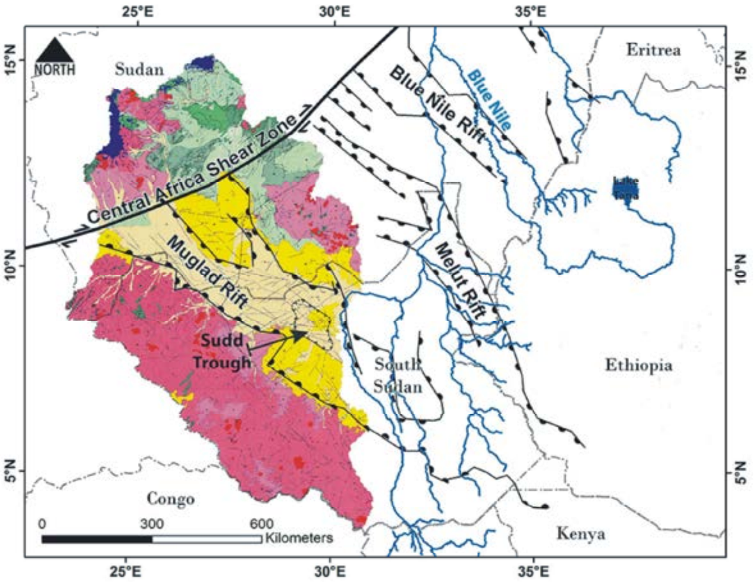

Fig. 2: A map showing Bahr El-Ghazal basin (colors represent lithology, for more details refer toFigure 3) with the relative location of the Central African Shear Zone and its associated Muglad rift basin and Sudd Trough (Modified after Gani *et al*., 2009).

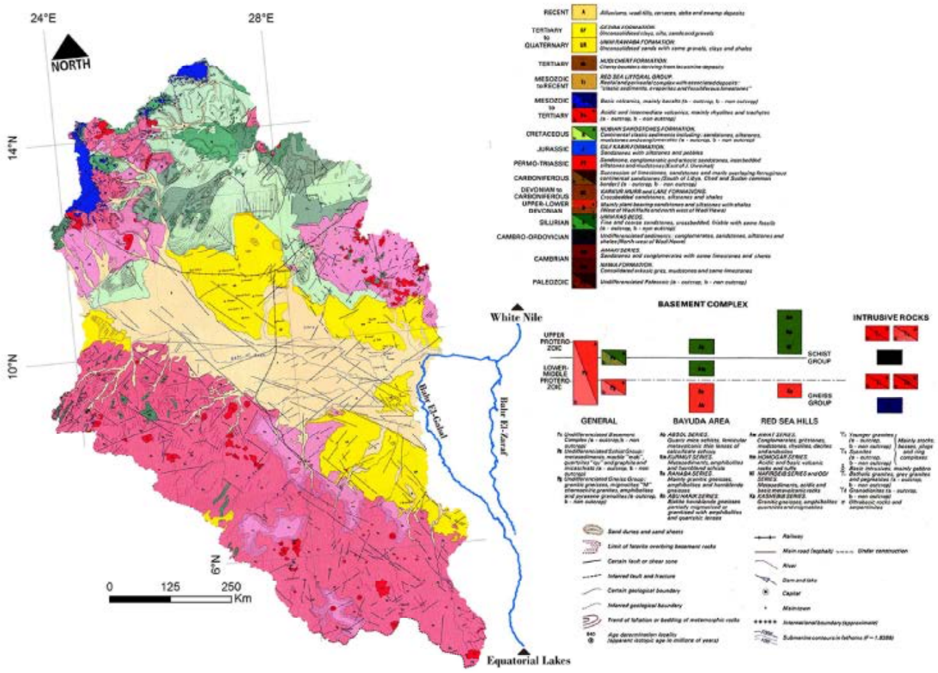

Fig. 3: Geologic map of Bahr El-Ghazal Basin (AfterGMRD Khartoum – Sudan, 1981, Scale 1:2,000,000).

west Gondwana. This CARS has later been developed as a shear reactivation along the Central African Shear Zone (CASZ), which has led to the development of parallel and sub parallel half grabens of predominantly NW–SE orientation in the central and southern Sudan craton area [22] (Figure 2). The Muglad rift basin is one of those half grabens [22-24]. It trends northwest–southeast for most of its length (Figure 2) and becomes more complex towards its northwestern end [25]. It occupies an area of more than 100,000 km^2 and contains thick interbedded sequence of claystones and sandstones above the basement. Sediments within the Muglad basin are composed mainly of thick fluvial and lacustrine deposits of non-marine origin [22]. The geological map over Bahr El-Ghazal catchment (Figure 3) clearly shows that the recent Quaternary deposits are mantling the basin surface and they are entirely bounded by faults of the rift system (Figure 2 and Figure 3). The abandoned Quaternary outcrops on surrounding Tertiary deposits could either indicate recent tectonic activities, or relate to the paleo-levels of the swamps occupying the trough. The channels are of well-defined banks in the upstream areas, which are carved in the underlying basement rocks.While the lower reaches of the channels are not only of ill-defined boundaries, but also of complex braided pattern before entering the swamps. That is why the use of Shuttle Radar Topography Mission (SRTM) satellite images and topographic maps as well as the historical field surveyed data in previous researchhave proven successful to map the drainage channels in headwater areas, but failed to agree on the existing hydrological patterns in the trough area [19, 26, 27]. Therefore, It is quite clear that the interaction of hydrological processes and the morphotectonic setting of Muglad basin controls the temporal changes of the river channels, the distribution of swamp areas and the dynamics of related land-cover features.

MATERIAL AND METHODS

The SRTM DEM with 90 m resolution [28] is used to extract different geomorphological parameters of drainage basins, including drainage networks, catchment divides, slope gradient and aspect and upstream flow contributing areas, following the standard algorithms embedded into Arc Hydro Tools add-in for ArcGIS 10.1 software. The available Landsat multi-temporal images have been downloaded from the USGS website (http://glovis.usgs.gov/) and processed to monitor and assess the land-cover changes, particularly for the regions of Sudd Trough (Figure 2). The channel networks derived from the SRTM DEM were compared with their counterparts on the satellite images, firstly; to make sure they are accurate so consequent analyses are reliable. Secondly;to determine the spatial extent and longitudinal profiles of the channels in the proximity of the swamps and its downstream, in order to examine the feasibility of selecting alternative routes to bypass the swamps with least cost.

The detailed hydrological analysis of the SRTM data is as follow: First, the DEM is pre-processed; missing data are filled by local interpolation and then compiled into a mosaic covering the area of interest. The processing of a DEM to produce hydrologically correct and connected drainage networks requires that sinks be first removed [29-31]. This can easily be achieved by filling all the sinks to the level of the next lowest cell of the perimeter. Sink filling is an iterative technique. A given sink is filled to reach the nearest lowest elevation, the boundaries of the filled area may then be part of new sinks, which then need to be filled and this process is repeated until all the pits are removed [32]. True sinks or closed depressions are thought to be rare on natural surfaces and restricted to particular geomorphological environments such as karst topography or endoreic basins. However, in the study area, natural sinks are not uncommon, so they were excluded from the sink-filling process. Once a hydrologically connected DEM is produced by sink removal, flow direction is calculated using the D8 algorithm in ARC-Info (ESRI, Redlands, California, USA). This layer is used to calculate a grid of flow accumulation.Finally, thresholding is applied to extract upslope contributing areas for all the drainage channels in the DEM [30]. The resulting drainage networks and associated sub-catchments were then overlaid on top of the multi-spectral satellite images (both Landsat and google earth images) to check that they correspond to visible wadis and streams.

RESULTS AND DISCUSSION

Water resources management depends on how we understand the hydrological processes and the availability of the relevant distributed data for the drainage basins. Water resources management projects at a given location may adversely affect neighboring areas because of the lack of full understanding of the nature of the catchment hydrology or the reliance on inaccurate data or models. Therefore, understanding the geology and geomorphology for drainage basins may help improve the hydrological studies, as they will contribute toward optimizing site selection for certain development projects (e.g. diversion or bypassing channels, dams, etc.). Results from our examination of the SRTM data and those obtained from the optical satellite images revealed that the streams currently accommodates the surface flowof rainfall water (we will refer to it as active streams/channels) did not change from those extracted from the SRTM data in the upstream of Bahr El-Ghazal catchment. On the other hand, these natural streams increase in complexity and deviates from those extracted from the SRTM data as we move towards the eastern most

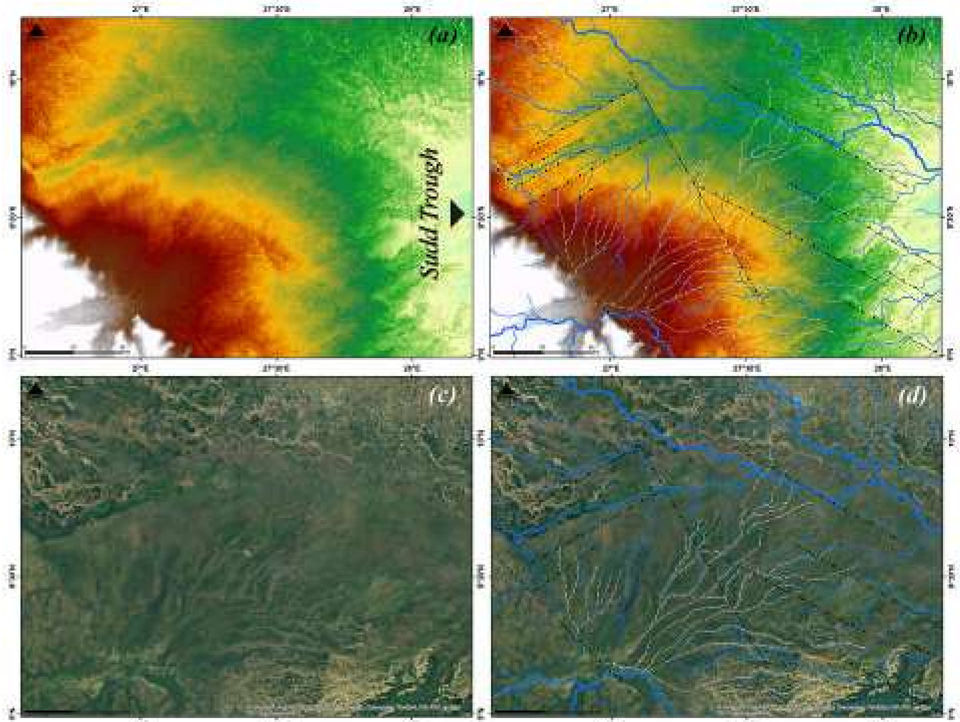

Fig. 4: SRTM data and multi-spectral satellite images show the increasing complexity of the drainage network as we move towards the Sudd Trough. (a) Digital elevation model (elevation range from 399-519 m above sea level) extracted from SRTM data, (b) structural interpretation of the SRTM data with the current stream network (blue lines) and abandoned stream network (white lines) interpreted from the satellite image in (c) and (d).

part of the catchment, particularly at the swamps area of the Sudd Trough (Figure 4) as well as the south eastern part of Muglad rift's shoulder (similar observations have been reported by Butcher, [33]; JIT, [34]; Howell *et al*., [35]. Such complexity has been described by Woodward [36] to be due to the high discharge rates in early Holocene. Petersen *et al*. [19] studied the morphology of the whole Sudd area (Figure 1) using SRTM, Landsat and historical field surveyed data. In his study, the SRTM data has proven successful in both the qualitative and quantitative analysis of the region, except for the Sudd Trough region, where he described the SRTM data to be irrelevant. Petersen *et al*. [19] result is based on the discrepancy of the historical land survey pointscollected by Hurst [26] in the Sudd Trough from theelevation values extracted from the SRTM data with double the expected error calculated by Rodriguez *et al*. [27] for the region. In addition, the historical land surveyed data didn't confirm the presence of the Sudd Trough indicated by the SRTM data (Figure 5). The presence of the Sudd Trough has been successfully verified using a DEM extracted from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) stereo-pairs [19]. Regardless of the similar results obtained from the SRTM and ASTER DEMs for the area as well as the geological and geophysical studies revealing the presence of the Muglad rift basin [22, 23, 24, 37], Petersen *et al*. [19] rushed into the conclusion that the SRTM data cannot be suitable for providing elevation data for this area.Interpretation of lineaments extracted from the SRTM data show coherence with almost all the published geological maps of the area as well as other rift basins related studiesthat indicates the presence of a conjugate system of faults trending mainly NE, ENE, WNW and NW (Figure 3) [38-40] (Figure 4a&b). Close examination of the streams revealed that such trends controls most of the currently active ones (streams that accommodate the water flow towards the downstream) (Figure 4c&d). Another set of dry channels have been observed (Figure 6). Such channels appear to be older than the current ones and does not seem to be affected much by the above-mentioned structural trends (Figure 4). They intersects the active channels in random manner and some of them become active (by receiving water) during rainy seasons.Detailed examination of the high resolution satellite imagery (from google earth) of the Sudd Trough

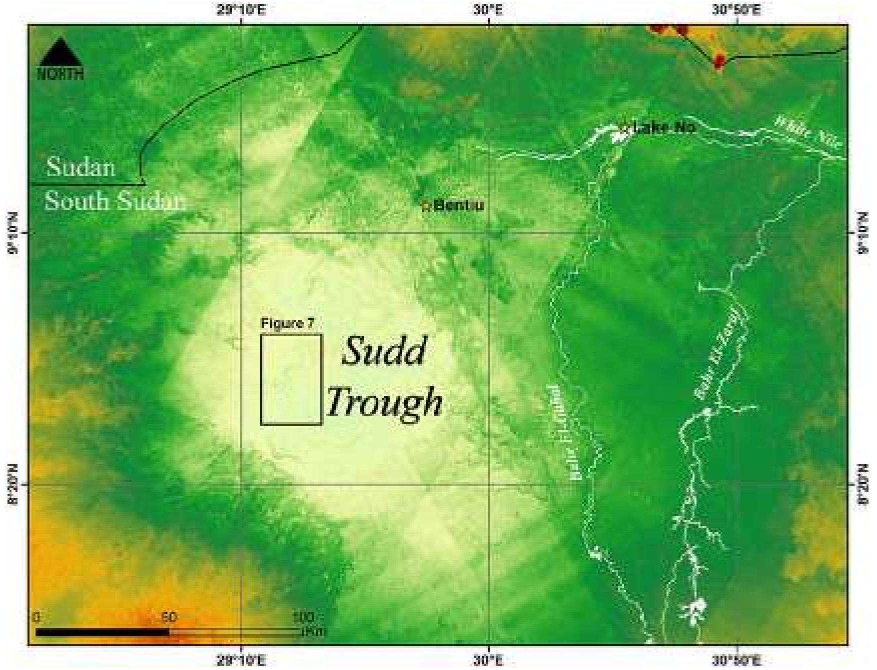

Fig. 5: SRTM data showing the location and extent of the Sudd Trough.

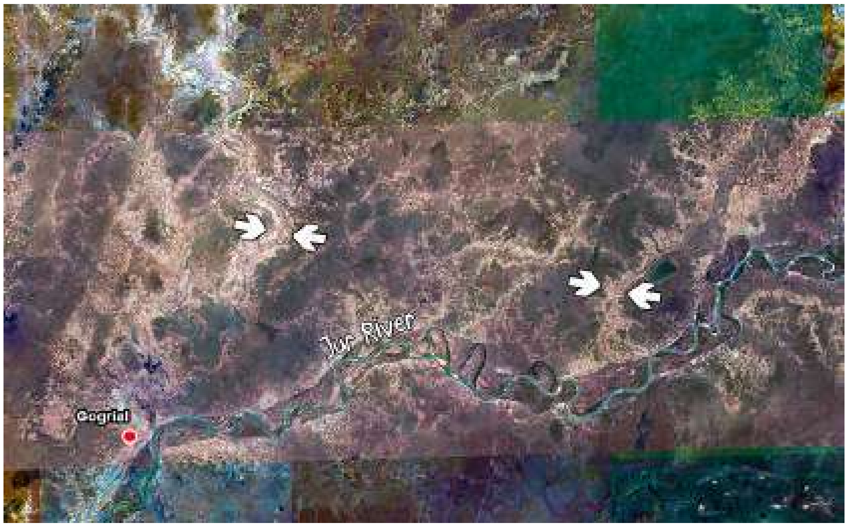

Fig. 6: A high resolution satellite image (from google earth – acquired in 26/01/2004 and 22/11/2004) showing the active course of the Jur River flowing towards the Sudd Trough. White arrows indicate the location of the old barren channels.

revealed a new set of structures, trending mainly N,NNE and NNW and affects the active streams as well. These structural trends can be seen mostly within the Sudd Trough and is quite noticeable bounding the “Buhayrat Abu Shanab”, a small lake, to its east and accumulating water at the downthrown block of it (Figure 7). All the previously discussed structural trends controls the water motion by forcing it to flow towards the Sudd Trough and does not allow any discharge out of the basin to the main Nile stream (White Nile at Lake No) except by the overflow process during flood seasons (adding 0.5 billion m^3 to Lake No every year) while for the remaining parts of the year, water is usually consumed in the Sudd region (through evaporation and subsurface percolation). In addition and according to locals, a reverse flow at Lake No towards the Sudd region may occur consuming huge volumes of White Nile water [14, 15].

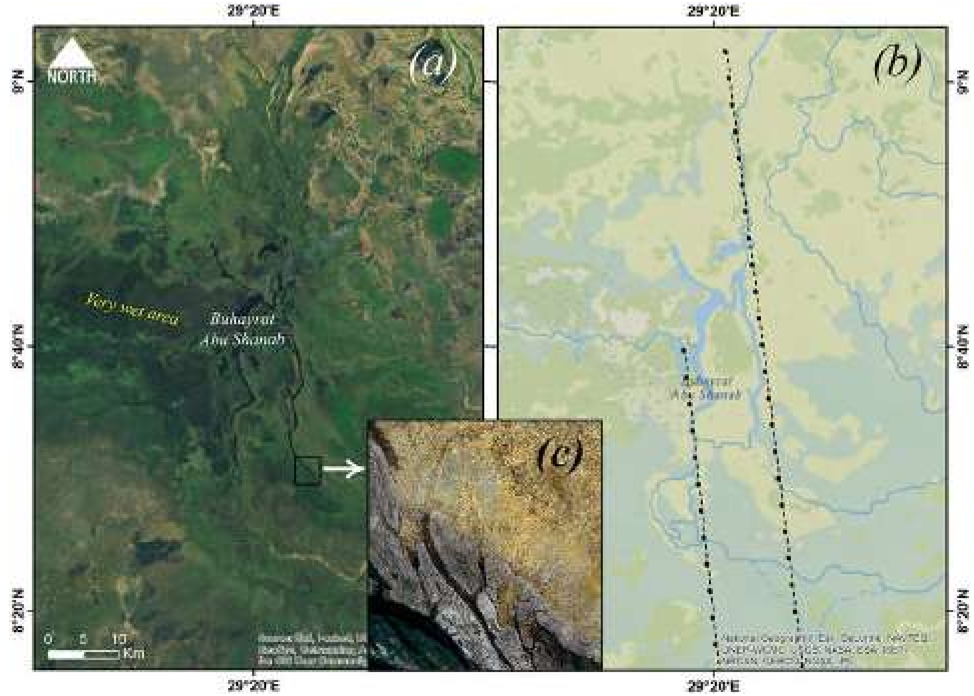

Fig. 7: (a) Satellite image showing the "Buhayrat Abu Shanab" lake with the clear N-S structure pattern that bounds it. Also note the dark green tone of the area to the west of the lake indicating increased wetness due to blocking of flow.(b) interpretation map of the satellite image. (c) a very high resolution satellite image (from google earth – acquired in 28/03/2004) showing the dry uplifted streams vs active streams in the downthrown side of the fault.

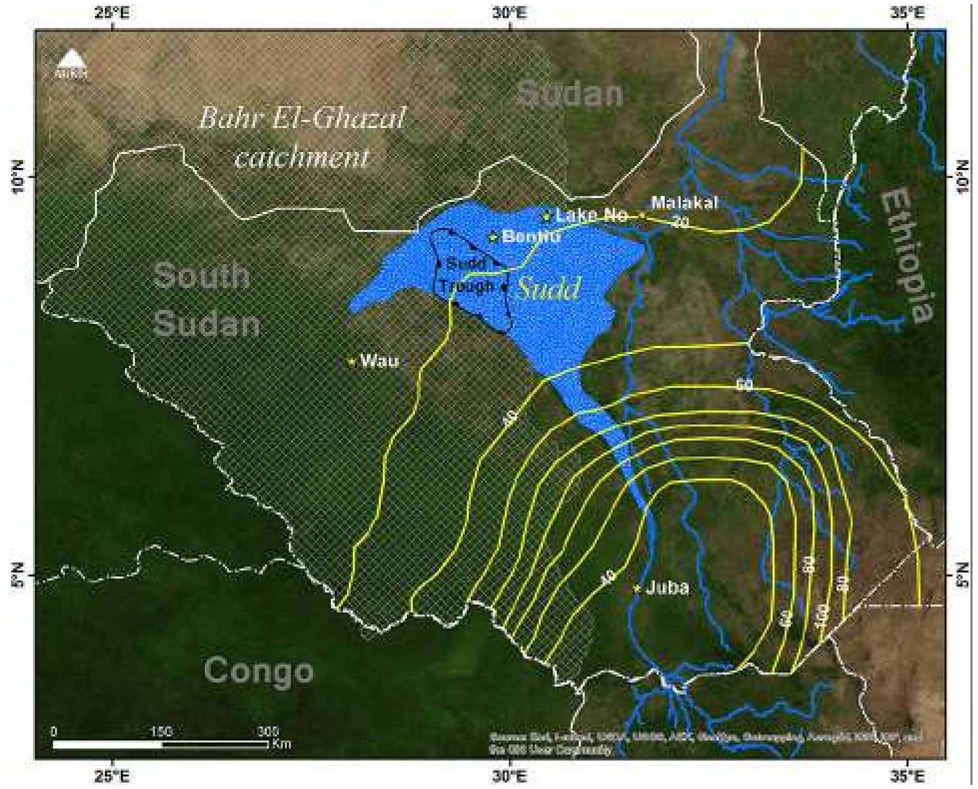

Fig. 8: Peak ground acceleration for 50 years return period of Abdalla *et al*.(1996),(represented by red line contours).

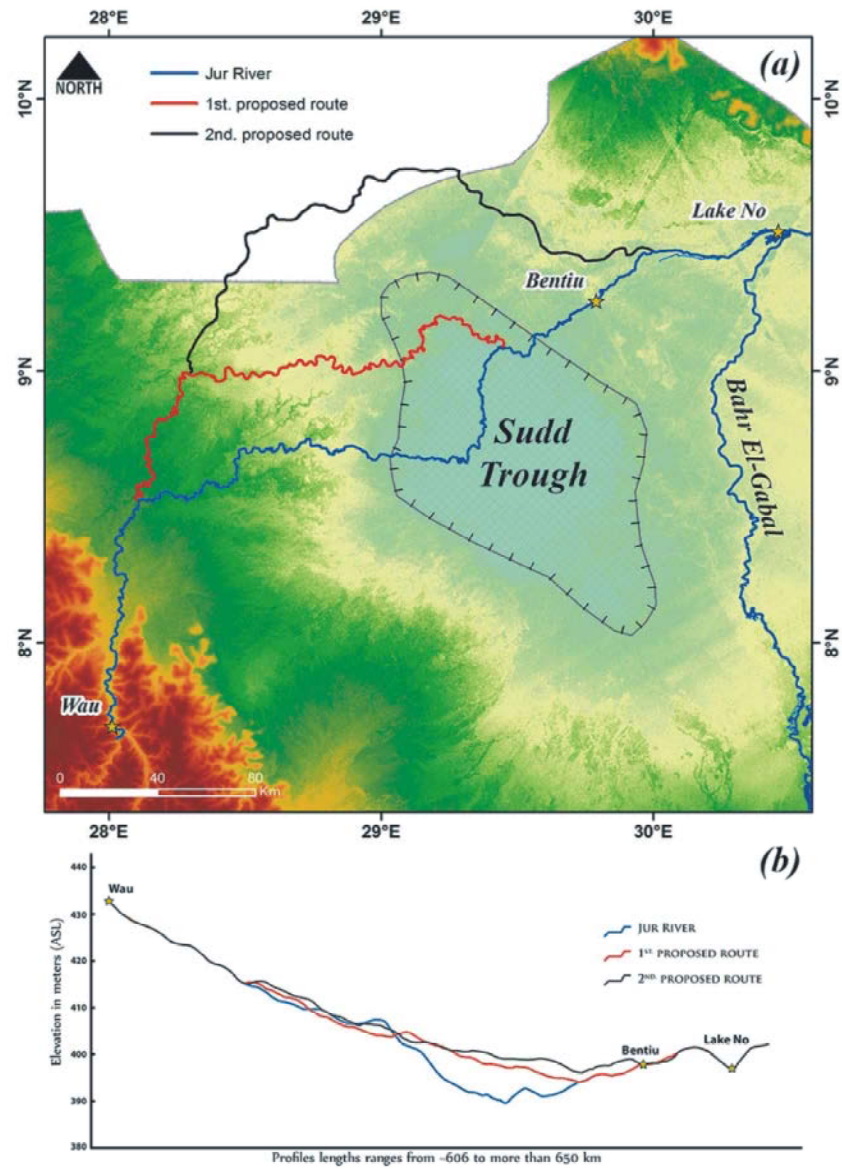

Fig. 9: (a) A map showing the location of the Jur river between Wau City and Lake No and the proposed routes away from the Sudd Trough, while (b) is the elevation profiles of the river course as well as the proposed routes (Jur River segment length = ~607 km, 1st. route segment = ~637 km and 2nd. route segment = ~700 km).

Nearly all the previously discussed structures are very hard to observe in the field within the Sudd Trough. This is usually due to the type of Quaternary deposits [14, 18, 19], vegetation cover as well as the swampy nature of the region. Interestingly, the earthquake data analysis made by Abdalla *et al*. [41] indicate that the eastern Part of South Sudan is seismically active with a peak ground acceleration (PCA) ranges from 20 cm/sec^{2}near "Lake No" to ~60 cm/sec^2 near the southern border of South Sudan, at a 50 years return period (Figure 8). Although the seismic hazard of Abdalla *et al*. [41] seems to be related to the East African Rift System, he indicated that there is no need to rush into such interpretation since the relationship between faults, rifts and earthquakes in Sudan are not well established.

Observations discussed above suggest thata tectonicactivity within the Sudd Trough took place sometime during the Holocene. The discrepancy of the historical land survey pointscollected in 1933 from theelevation values extracted from the SRTM dataacquired in the early 2000s could be an indication of such activity, taking in consideration the tectonic setting/history of the region as well as the calculated error of the SRTM data of Rodriguez *et al*. [27]. The observed and/or interpreted structural trends from multispectral satellite images and SRTM DEMs in addition to the complexity of the stream network and the flow direction change of the most active (and most recent) streams towards the Sudd Trough favors a subsiding type of activity (Figure 6). The calculated PCA of the regionmade byAbdalla *et al*. [41] support the presence of such activityand giving a hint that it is probably active until the present day. Such activity makes the area so sensitive when planning for major hydrological projects. It is worth noting that further studies are required to confirm such activity especially after the installment of theJuba's seismograph station (by The Department of Earth Science, University of Bergen in Juba, South Sudan)in early 2009 for earthquake hazard monitoring. This station is the most closest station to the study area that is currently collecting valuable information on local earthquakes in the region. New ground surveying measurements are required. LiDAR scanning of the region is also proposedin places where land surveying is inaccessible.

The development of Bahr El-Ghazal catchment has been progressively advised directly before the independence of the of South Sudan state. Directly after the independence, the development of the catchment became a must since there are no much transportation facilities to link the western part of the country to the main River Nile channel.A hydropower dam project at Wau city at the upstream of the Jur River along with the associateddredging of the Jur/Bahr El-Ghazal Riverschannel from Wau city downstreamto Lake No have been announced in September 2011 (Figure 9a) by water resources minister of South Sudan. Thechannel to be dredged from Wau city to Lake No is planned to be used as a seasonal navigational route (because of the seasonal flow of the river) since the road network at this part of the country is underdeveloped. Closer look at the river course from Wau city to Lake No we can see that the river will cross the Sudd Trough for a length of about 180 km. The topography of the river course indicates that it will require an extensive yet costlydredging process. That if successful, will be threatened by the active subsidence in the region, once verified. Results from our study indicate that flow from the upstream of the Jur River can be conveyed into one of the previously discussed paleo- channels, thus controlling the flow directions before reaching the Sudd Trough. Flow diversion can be easily achieved by constructing divergent dikes on the main course of Jur channel bed. The newly conveyed channel will not only minimize the cost of the project but will also guarantee a full year navigational route towards the main Nile Stream (at the White Nile). In addition, a dramatic increase in water discharge from the catchment will be obtained. Our rough calculations of the annual increase in the water budget at Lake No is at least four to five times of its current state. Two proposed routes have been illustrated by connecting both the active and barren channels to follow the topographic gradient around the Sudd Trough (Figure 9a&b). This gradient in topography will naturally carve the paleo-channels, with minimum man-made dredging work to be done at locations where divergent dikes are proposed.

CONCLUSION

The proposed water balance projects of Bahr El-Ghazal catchment requires the collection of relevant rainfall, runoff, detailed topographic surveys along the proposed stretches and detailed geo-technical studies of the sediments and tectonic activities that may affect the capacities of storage and transmitting flows within the catchment. The role of the technical issues in portraying and modeling the flow patterns of the area cannot be neglected. This is why understanding the geologic and geomorphologic settings and evolutionof such a complex catchment along with the different associated aspects of the hydrological processing is crucial for such development projects. The Jurassic to Quaternary evolution of the Bahr El-Ghazal catchment is proven to be tectonically controlled. The Holocene activity of the eastern most part of the catchment, particularly at the Sudd Trough,can be attributed to the East African Rift System but further studies are still required to verify the hypothesis. Observations from SRTM and multi-spectral satellite images suggest a recent tectonic subsidence resulted in forcing the flow towards the Sudd Trough through the formation of new stream banks. Our evaluation of the recently proposed development projects at the river of Jur suggest that by conveying the flow of the Jur River through some of the old/abandoned channels,that flow around the Sudd Trough region, we will not only enhance results planned from the development projects but we will also increase the water budget of the catchment at Lake No. Taking into consideration the type of water revenue calculations made for the Jonglei Canal, our rough estimate for water revenue from the catchment after the construction of the proposed route is at least four to five times of its current amount.Further measurements and studies must be carried out for accurate calculations and modeling.

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