Mapping the Mega Paleodrainage Basin Using Shuttle Radar Topography Mission in Eastern Sahara and Its Impact on the New Development Projects in Southern Egypt

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Abstract In the current study, the shuttle radar topography mission (SRTM) data, with ~90 m horizontal resolution, were used to delineate the paleodrainage system and their mega basin extent in the East Sahara area. One mega-drainage basin has been detected, covering an area of 256 000 km². It is classified into two sub mega basins. The Uweinite sub mega basin, which is composed of four main tributaries, collected water from a vast catchment region and drained eastward from the north, west, and southwest, starting at highland areas. The first subwatershed basin is in the northern plateau, south of the Abu-Balas area, with a total catchment area of 25 045 km². The second subwatershed is in the Gilf Kebir plateau and has a total catchment area of 38 257 km². The third subwatershed drains from the Uweinite highlands and has a catchment area of 46 154 km². The fourth subwatershed, which is known in literature as Wadi Mokhtafi in its upper reach and Wadi Arid in its lower reach, drains the northwestern highlands of Sudan and has a total catchment area of 28 653 km². The Tushka sub mega basin includes one watershed that drains from the northeast highlands of Sudan and has a total catchment area of 63 019 km². The Uweinite and Tushka sub mega basins are joined together to the North of the Tushka depression, which drains northward toward the Kharga depression. This study indicates that the Eastern Sahara Mega Basin is a closed hydrological system independent of the other drainage systems, such as the Nile hydrosystem and the Qena Valley system. The present research illustrates the capability of the SRTM data in mapping the paleochannel networks, as well as estimate the catchment area and direction of the water flow. Finally, the study reveals that the four areas could be potentially used for different reclamation activities due to the ground water accumulations possibilities.

Keywords GIS; paleodrainages; SRTM; hydro-tools; groundwater potentiality

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Introduction

The area of the present study represents a part of a large flat sandy sheet region in Eastern Sahara. It is located in southwest Egypt and northwest Sudan (Fig. 1). This region called the Great Selima sand sheet and is located west and northwest of the Selima Oasis in northwestern Sudan (Fig. 2). In Fig. 2, the East Uweinate Project is located utilizes groundwater (Nu-
bian Aquifer) for agricultural farms as well as Selima Oasis located on the east south of East Uweinate Project. The outline of Eastern Sahara Mega Basin is shown in a green color. Also, Tushka Project located to the East of Tushka Lakes (using water from Lake Nasser). The Selima Oasis was a stop station for salt merchants (camel caravan) from Sudan to the Nile Valley in southern Egypt.

Fig. 1 The location of the Eastern Sahara Mega Basin within southwestern Egypt and northwester Sudan

Fig. 2 Landsat ETM+ mosaic images of the East Sahara area showing flat terrain covered by a sand sheet (white circle) where the paleochannels are hidden beneath

The sand sheet is centered at latitude 22° N (Egypt-Sudan border) and covers an area of ~259 000 km² (Fig. 2)[1]. It forms the core of the eastern Sahara of North Africa. The Eastern Sahara area is one of the driest and most uninhabited places on Earth. However, in the past few decades, the Egyptian government has established a development project called East Uweinate Project. This project area appears as a green island in the middle of the great sand sheet. It relies on the groundwater extracted from the Nubian Aquifer System (Fig. 2). Another project is located to the east of New Lakes of Sahara called the Tushka Project, and it depends on the water delivered through artificial canals from the Lake Nasser (Fig. 2).

The area surround Selima Oasis is challenging from a hydrological point of view. Here, large numbers of channel courses are buried under an extensive blanket of Aeolian deposits. This is clearly true in the area surrounding the East Uweinate Project, where no surface drainage networks are visible in multispectral satellite images (ETM+ mosaic Fig. 2). These channels are impossible to identify in the field or by using optical images, because they are buried under the sand sheet. For that reason, the use of radar images is the only practical way to map such buried channels. The reason for that is due to the capability of radar waves to penetrate the dry sand surface and unveil the subsurface features.

Radar images have been previously used by several authors to map and identify paleochannels, as well as their flow directions based on visual interpretation and manual digitization techniques[2,3,4]. This introduces human bias, and there are no estimates of the area of land area that drains water into these paleochannels. The buried channels were detected in part of the study area in northwestern Sudan using radar images[5]. This study was the first spectacular attempt to use the first Shuttle Imaging Radar (SAR-A) mission of 1981. However, this study was unable to determine the flow direction of these channels. On the other hand, the first attempt to use SRTM data to map the basin areas, the paleochannel and the flow direction in the Eastern Sahara region was developed in 2007[6]. This study was only for a part of the East Sahara Mega Basin. It was illustrated that where the Selima sand sheet lies, there is an internal closed basin, which receives water from the surrounding highlands[3]. Based on Radar SIR-C images and (1 km) USGS Global Topography (GTOPO30) digital elevation model (DEM), it was suggested that an inland drainage basin drains northeasterly from northwestern Sudan toward the Kharga depression[4]. From the aforementioned discussion, it is apparent that the flow
direction of the whole Mega East Sahara channels is still controversial and needs further study, especially with the availability of a new source of space data (SRTM) at a global scale.

The current study aimed to 1) map the drainage network pattern of the whole Eastern Sahara Mega Basin, 2) determine the flow direction of the main channel, 3) find the relationship between different sub-basins with each other, 4) identify the most suitable areas for the groundwater potentiality in the region that could be promising areas for agricultural activities, and 5) evaluate the sustainable development in the East Uweinite Project due to its location in relation to the East Sahara Mega Basin.

1 Data used

Shuttle Radar Topography Mission (SRTM) elevation data are used, which are distributed by the USGS EROS Data Center (EDC), on a near-global scale as part of an international project by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). These data are obtained with the radar C-band and sampled at 3 arc-second or ~90 m spatial resolution. The SRTM consisted of a specially modified radar system that flew on board the Space Shuttle Endeavour during an 11-day mission in February 2000, in order to gather topographic (elevation) data of the Earth's surface. The STRM data were used to image the paleochannels and not the surface of the sand sheet. This is due to the penetration capabilities of radar signals (50 cm for C-band (λ = 5.7 cm)).

Landsat ETM+ data was used to outline the surface features of East Sahara region. Landsat ETM+ is a multispectral remote sensing data that has four bands in the visible and near infrared (VNIR) regions of the electromagnetic spectrum with 30 m spatial resolution (visible blue = band 1; visible green = band 2; visible red = band 3; and NIR = band 4), two bands in the Shortwave Infrared (SWIR) region with 30 m spatial resolution (bands 5 and 7), and one band in the Thermal Infrared (TIR) region with 90 m spatial resolution (band 6). The Landsat ETM+ mosaic with 30 m pixel resolution is used for visual interpretation of the surface features.

2 Methodology and results

The Arc Hydro tool of ESRI ArcGIS 9.2 has been used to create a basis for obtaining a deeper understanding of the drainage and watershed systems of the East Sahara region. These tools are a set of utilities developed on top of the Arc Hydro data model operating in the ArcGIS environment. Some of the functions require the spatial and 3D Analyst extensions. Terrain preprocessing has been used in processing and creating the watershed basin of the study area. The purpose of terrain preprocessing is to perform an initial analysis of the terrain and to prepare the dataset for further processing. The SRTM data (digital elevation model) of the study area is used as input for terrain preprocessing. The following functions, in order, are involved in terrain preprocessing including the following:

(1) The Fill Sinks function fills sinks in a DEM grid. Sinks are formed if a cell is surrounded by higher elevation cells; the water is trapped in that cell and cannot flow. The Fill Sinks function modifies the elevation value to eliminate these problems. The function takes as input SRTM data. The function produces as output a grid ‘Hydro DEM,’ where no sinks exist. This is to ensure hydraulic connectivity within the watershed to be delineated; all the identified pits in the resulting DEM are filled (assuming no internal drainage). These pits are artifacts in the East Sahara area[6]. Filling the pits is one of the most complex steps in the drainage extraction process. It requires a substantial amount of iteration, as removing one pit may create another one.

(2) The Flow Direction function takes ‘Hydro DEM’ data previously prepared as input and computes the corresponding flow direction grid. The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell, using the 8-flow direction algorithm of Jensen and Domingue[7], which is widely used in literatures[8,9] and implemented in the used ESRI Arc-Hydro tool in ArcGIS v.9.2.

(3) Once the direction of the flow out of each cell is resolved, it is possible, through the calculation of the flow accumulation grid, to delineate the drainage network of the study area. The Flow Accumulation function takes a flow direction grid as input and com-
puotes the associated flow accumulation grid that contains the accumulated number of cells upstream of a cell, for each cell in the input grid.

(4) The Stream Definition function takes a flow accumulation grid as input and creates a Stream Grid for a user-defined threshold. The stream grid will have a value of “1” for all the cells in the input grid that have a value greater than the given threshold. All other cells in the Stream Grid contain no data. In the current study, three thresholds have been used including 1 000, 300, and 100 to create the main buried streams and other small streams for the whole watershed of East Sahara Mega Basin (Fig. 3). In Fig. 3, the main buried channels are in white (for Threshold 1 000), the sub-main buried channels are in orange (for 300 threshold), and the small drainage networks in are black (for 100 threshold). On the east south side, there are the adjacent Nile system drainages.

Fig. 3  Drainage network with different threshold extracted from the 90 m x-y resolution SRTM DEMs

(5) The Catchment Grid Delineation function creates a grid in which each cell carries a value (grid code), indicating to which catchment does the cell belong to. The value corresponds to the value carried by the stream segment that drains that area, which is defined in the stream segment link grid. The Catchment Polygon Processing function takes as input a catchment grid and converts it into a catchment polygon feature class. The adjacent cells in the grid that have the same grid code are combined into a single area, whose boundary is vectorized.

(6) The Adjoint Catchment Processing function generates the aggregated upstream catchments from the “Catchment” feature class (Fig. 4). In Fig. 4, the outlet of the mega basin ends at Kharga depression. The yellow color shows the water conduit flow.

(7) Stream links, where streams join together, were calculated. This is followed by the interactive selection of outlet cells, where main channels join the mainstream trunk. Outlet points were utilized in the derivation of the watershed of East Sahara Mega Basin and its associated main subwatersheds.

Fig. 4  Eastern Sahara Mega Basin divided into 5 large subbasins (I, II, III, IV, and V) and small basins (A, B, C, D, E, F, and G)

In the past, it was impossible to recognize the watershed extent because of the areal extent of the area, the huge amount of the sand cover, and so on. Different studies tried to extract some segments of the mainstream using radar images; however, no estimation for the catchment areas were calculated entirely[6]. The current research attempts to map the whole watersheds of the Eastern Sahara, which represents one of the mega watersheds in Egypt. It also provides the complete drainage map of the area (Fig. 3 and Fig. 4). The derived mega drainage basin is called Eastern Sahara watershed.

The Sahara drainage system is one of the largest known basins in Egypt after the Nile River system. This mega basin would have collected rainwater in the form of runoff from an area of 256 000 km², during previous humid phases. There is evidence of large stores of fresh groundwater located in the Eastern Sahara that lies hidden beneath the sands of Egypt and Sudan[3,10]. The Nubian Aquifer system has an enormous groundwater mass that should contain the largest reservoir in the entire area of the Sahara where the
East Sahara Basin covers large part of it\textsuperscript{[11]}. Drainages in the east Sahara region were formed during Tertiary times\textsuperscript{[12]}.

The East Sahara hydrosystem model consists of two main basins, the Uweinate and Tushka Basins. (1) The Uweinate sub mega basin is composed of four main tributaries that would have collected water from a vast catchment region and drained eastward from the north, west, and southwest, starting in highland areas (Fig. 3 and Fig. 4).

a) The first subwatershed basin (I in Fig. 3 and Fig. 4) is located in the north, which emerges from the northern plateau, south of the Abu-Balas area, and of relatively moderate elevation (400 m asl). It trends due south with a total main channel length of 243.3 km and a total catchment area of 25 045 km\(^2\).

b) The second subwatershed (II in Fig. 3 and Fig. 4) emerges from the Gilf Kebir plateau (about 1 000 m asl) and flows easterly with a total main channel length of 699.6 km and a total catchment area of 38 257 km\(^2\).

c) The third and largest subwatershed (III in Fig. 3 and Fig. 4) drains from the Uweinate highlands (800 m asl). It flows northeasterly with a total main channels length of 859.11 km and a catchment area of 46 154 km\(^2\).

d) The fourth subwatershed (IV in Fig. 3 and Fig. 4), which is known in literature as Wadi Mokhtafi in its upper reach and Wadi Arid in its lower reach, drains the northwestern highlands of Sudan (about 600 m asl). It runs northeasterly with a total main channel length of 534.6 km and a total catchment area of 28 653 km\(^2\). It was suggested that its main channel follows a dominant NE (Gulf of Aqaba) trend and its linearity, particularly in its lower reach, suggests structural control\textsuperscript{[6]}.

(2) The Tushka sub mega basin drains from the northeast highlands of Sudan (about 600 m asl) and runs northeasterly with a total main channel length of 724.1 km and a total catchment area of 63 019 km\(^2\) (V in Fig. 3 and Fig. 4). It has two main channels that join together and follow the depressions in the area where it moves through the Nabta depression then Tushka depressions from south to north. After that, it joins the main stream of Uweinate Basin to form one main stream moving toward El Kharga depression.

3 Validation of the SRTM data

To test the reliability of the channel courses derived from the SRTM data, it is important to raise a question as to whether the SRTM is capable of imaging paleodrainages. The answer to this question depends on the depth of penetration of the microwave signal, which is proportional to its wavelength ($\lambda$). The maximum depth of subsurface imaging is 30 cm for X band ($\lambda = 3$ cm), 50 cm for C band ($\lambda = 5.7$ cm) and 200 cm for L band ($\lambda = 23.5$ cm)\textsuperscript{[13]}. Generally, the SRTM and Radarsat-1 are using microwave signals of the same wavelength (5.7 cm), and it would be expected, under the same environmental conditions, that SRTM signals would penetrate the desert sand layer and image the buried channels, in just the same way the signals of Radarsat-1 do. To illustrate this, the drainage channels detected by both techniques are compared (Fig. 5)\textsuperscript{[6]}. Channels of a small part of the watershed to validate against those imaged by Radarsat have been used\textsuperscript{[6]}. They concluded that there is an excellent agreement between the SRTM-derived drainage networks and those revealed in a Radarsat image (Fig. 5(a)). They used a large threshold value to delineate only the main large channels and avoid very small and dense branches that might crowd the resultant drainage basin map (Fig. 5(b)).

![Fig. 5](image-url)
4 Discussions

4.1 Surface water-groundwater Interaction in the area

The last time when any standing body of water existing in the Sahara desert was 6000 years ago during the last intermittence of wet and dry periods in the Holocene leading to the emergence of the Sahara desert to dominate northern Africa\textsuperscript{[14,15]}. The Eastern Sahara watershed (described in the present study), the Bir Kiseiba paleodrainage\textsuperscript{[16]}, the Kufra paleochannel\textsuperscript{[17]}, and the Nubian paleolake\textsuperscript{[18,19]} must have played a significant role in recharging the groundwater reservoirs in the eastern part of the Great Sahara.

Inspection of the Landsat ETM+ mosaic of the study area indicates that there is no sign of the existence of the drainage network (Fig. 2). The area appears as a featureless plain where the sand cover masks the delineated subwatersheds. These results have been verified by the gradient calculations from the SRTM. The central area in the mega basin is located along the hydrologic gradient, with relatively gentle slope (ranges from 0.02° to 0.04°). The low slope values imply low runoff velocity and thus favoring infiltration conditions during past pluvial eras (long periods of steady and seasonal rainfall). Accordingly, this area and its vicinity would represent locations with high groundwater potential. This results are verified by the studies in the central portion of the study area, where several exposures of late Pleistocene lacustrine and near-shore sediments associated with Early to Mid-Paleolithic archeological sit, at Bir-Tarfawi and Bir-Sahara\textsuperscript{[20]} (Fig. 4). These lake deposits extend for approximately 35–40 km from east to west and may be considered as one of the largest playas in Egypt\textsuperscript{[21]}. These lacustrine deposits, which today stand 2–3 m above the surrounding surface, together with the numerous truncated spring-vents of more than 50 m in diameter\textsuperscript{[20]}, all testify to the presence of lakes in this particular location of the study area.

On the other hand, the surface topography of the East Sahara watershed is remarkably flat. This may be partly ascribed to the work of the five tributaries of the Uweinat and Tushka watersheds. The obvious flatness of the surface, which is covered by the Great Selima sand sheet, could be an indication of the basin's old stage of development. In this old stage, the five tributaries would have paved the surrounding surface by developing wide floodplains. During this stage, the basin normally receives water from many tributaries and increases in size and sediment load. Accordingly, the region beneath the sand cover are expected to be rich in alluvial deposits as well as subsurface water that would have seeped into the underlying sandstone rocks during the active periods of the mega basin.

4.2 Groundwater potentiality for reclamation

With the aid of the SRTM data, the first complete drainage map of the eastern Sahara region has been generated. The extent of the Eastern Sahara Mega Basin adds a new perspective on the early wet phases that affected the eastern part of the Great Sahara of North Africa and emphasizes that its landscape was originally produced by fluvial action. The existence of the vast Quaternary sand sheet within the study area indicates that the sand is of a fluvial origin\textsuperscript{[22]}, and the low lying areas must have hosted great volumes of surface water during the wet climate conditions\textsuperscript{[10]}. Much of the water would have percolated into the underlying rocks feeding the groundwater aquifers.

The present work found that there are four feasible areas for groundwater exploration and exploitation. These areas are delineated within the course of the present research study using multispectral data and hydrogeological findings from SRTM data. One of these areas has already been utilized for several years now in the biggest reclamation project in Egypt. The other three areas might be candidates for future reclamation activities as well. In the following part, a brief description of these areas will be discussed (Fig. 6):

(1) The first area extends from East El-Uweinate to beyond the Egyptian-Sudanese border line. This area underlies a part of Selima sand sheet area in Sudan. Within this area, dense networks of drainage channels were discovered below the thin veneer of sand sheet. Main drainage channels are oriented in NE direction (Fig. 6). These facts suggest active fluvial recharge of the underlying Nubian Sandstone layers during the past pluvial periods. If groundwater potential can be
proven in a reasonable quality and quantity from the underground aquifer in the above mentioned area, then a new land reclamation project may be established either within the Egyptian side only or as a joint venture land reclamation project between Egypt and Sudan.

Fig. 6 The best potential locations for groundwater accumulations and reclamation activities

(2) The second area extends between the East El Uweinat and El Gilf Kebir/Uweinate highlands (Fig. 6). A 3D perspective view using ETM+ draped over the Radar data (SRTM) proved the occurrence of some deltaic fans at the outlet of drainage systems (Fig. 7(a) and (b)). These fans concentrated in the outlets of the major Wadis of the Gilf Kbeer and Uweinate highlands. The geological observations as detected from well logs drilled in the area indicate that the thickness of the Nubian Sandstone aquifer increases toward the west. Accordingly, the area underlying the discovered alluvial fans may be feasible for groundwater exploration and possible exploitation.

Fig. 7 (a) Fan location in relation to main drainage channels, (b) 3D perspective model showing the possible location of the fans in front of Gilf Kabier and Uweinate highland.

(3) The third area is located between Darb El Arbaein and Tushka-Nabta depressions. Dense drainage channels are detected in this area oriented in SW-NE direction, taking the same orientation of the fault system in the area (Fig. 6). No hydrogeological information is available at present time; however, the basement rocks are expected to be shallower in this area than the western areas. This area is very important in connection with land reclamation activity as it connects Darb El Arbaein with East El-Uweinat and Dakhla Oasis.

(4) The fourth area is called the East Uweinat Project where the Egyptian government was involved in major development in which an irrigational-agricultural developmental project is underway to appear in the East Uweinat area (Fig. 6, 7(a) and 7(b)). This plan is independent on the Lake Nasser Project, which in turn depends on the groundwater extracted from the Nubian aquifer system. From radar imagery and previous groundwater investigation results, it was easy to characterize the Nubian aquifer in the East El-Uweinat area of the Misaha graben of southwest Egypt. The Nubian aquifer system is considered to be unconfined whereby groundwater resides in sandstone rocks that uncomfortably overlie basement rocks and are covered by Quaternary deposits. The surface of the area surround East Uweinat Project, which represent part of the Selima sand sheet is covered by flat to undulating sand and gravel surfaces. It is a natural vegetation-free and dissected by some isolated of low dunes and nearly imperceptible giant ripples [23]. The east Uweinat area is located within the three basins (II, III, and IV) (Fig. 4). Finally, the future proposed areas may require geophysical investigation to help in evaluating the geometry of the groundwater aquifer.

5 Conclusion

The practical role of SRTM data utilization to impact groundwater resource management decisions in the Western desert of Egypt has been investigated. The focus of the research is to confirm the ability of SRTM data to penetrate through the veneer of desert sand to image sand covered courses of wadis and river beds, to delineate underlying geological diver-
sity, to understand the Paleo-channel distribution, and to improve the interpretative capabilities of SRTM data with respect to paleodrainage direction definition. The present study demonstrates the penetration capability of the SRTM in mapping paleodrainage systems in sandy desert regions even in areas of low topographic variations. These data proved to be powerful for mapping watersheds of continental scale and, thus, may be of great assistance in reconstructing the paleohydrology of desert regions worldwide.

The SRTM data show that the Tushka depression and the Nubta depression are located along the main channel of Tushka Basin. However, the Kharga depression is located north of the outlet of the Eastern Sahara Mega Basin. The study shows that the main water collector for the Tushka Basin is Tushka depression, , for the Uweinat Basin is the East Uweinat area, and, finally, for the Eastern Sahara Mega Basin is the Kharga depression.

The results of the present research show that the east Sahara watershed is an independent hydrological system that does not relate to the Chad Basin\textsuperscript{[2]}, the Nile hydrosystem\textsuperscript{[24]}, or to the Qena Basin\textsuperscript{[12]}. Rather, this system collects water from only its northern, western, and southern highlands. Being surrounded by highlands (water divide line) from the three directions might indicate that the groundwater of the Eastern Sahara Basin is not related in origin to the groundwater elsewhere in the eastern Sahara. On the other hand, the study shows that the main outlet of this basin into Kharga Oasis and the Tushka depression is isolated from the Uweinat Basin, where both basins are joined together at Darb El Arbaein area and follow toward the Kharga Oasis. The data also concluded that according to the geology, geomorphology, and drainage analysis data extracted from the SRTM, there are four possible areas that have a good chance for groundwater accumulations. One of these areas represents the East Uweinat Project for agricultural activities.

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Notes to Contributors

Contributions are welcomed on one of the following subjects or in related areas:

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★ Geo-surveying
★ Photogrammetry
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