



Flash Flood Management and Harvesting Via Groundwater Recharging in Wadi Systems: An Integrative Approach of Remote Sensing and Direct Current Resistivity Techniques

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Abstract

An integrated approach is carried out to study the hydrogeological conditions in wadi systems. In this chapter, the use of remote sensing and direct current (DC) resistivity techniques was considered to manage the flash flood and explore groundwater in desert lands. As case studies, two wadis at the Eastern and Western Deserts, Egypt, are presented to show the efficiency of using the suggested integrated study. Based on satellite images, remote sensing (RS) and geographic information system (GIS) techniques are used to identify the regional geology, geomorphological features, lineaments, and active channels regarding flash flood events in desert lands. Consequently, a hydrograph and runoff modeling can be estimated for wadi systems. Furthermore, the calculated flash flood total discharges and the storage capacity of existing mitigation measures can be recognized. From a geophysical point of view, the DC resistivity method can be applied to identify the subsurface layer distributions, image the near-surface lateral heterogeneities, subsurface structures, and potential groundwater zones. Based on geophysical data inversion results, this chapter shows that it is possible to recognize sites for successful dam construction and groundwater

bearing zones exploration. Accordingly, the results of these case studies represent the importance of the integrated approach for the flash flood hazards management and its harvesting.

Keywords

Remote sensing • GIS • DC resistivity • ERT • Flood hazards mitigation • Groundwater exploration

1 Introduction

The flood is a water overflow that usually submerges dry-lands in wadi systems. After heavy rainfall, large water volumes are discharged in dry riverbeds. Further, the flood hazards refer to a phenomenon causing societal damage from the natural environment. Accordingly, flash flood hazards assessment is a key component of natural risk management. The natural hazards can be considered within a hydro-meteorological and geological frame, where floods, earthquakes, landslides, storms, volcanoes, droughts, and tsunamis are the major types (Alcantara-Ayala 2002; Youssef et al. 2009). Such natural hazards occur worldwide, but their environmental impact is greater in developing countries regarding geographic location and existence of different types of social, cultural, and economic vulnerabilities. Additionally, limited water resources and increasing population in such countries increase the freshwater demand for sustainable development.

It is worth mentioning that the sustainable development in the arid and semi-arid region depends mainly on groundwater exploration and utilizing the available water resources for favoring human demands. Specifically, the flash flood water can be considered as an important source for renewal water resources in desert lands to meet a part of water demand for sustainable development. There are many authors who investigated the groundwater recharge and

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rainfall-runoff processes for wadi systems applying hydrogeological models (e.g. Gheith and Sultan 2002) and flash flood modeling approaches (e.g. El Bastawesy et al. 2009) using geographic information system (GIS), remote sensing (RS), and digital elevation models (DEM). Against the ongoing climate change, runoff water harvesting is considered as a supplementary action worldwide for (i) flash flood hazards management and (ii) water resources development.

RS has become an important tool for collecting multi-temporal, spatially extensive, and cost-effective data. Satellite RS offers a chance for more systematic analysis and better inspection of various geomorphologic units. Further, GIS is a powerful tool for analysis and integrating multi-thematic layers. GIS provides an excellent tool for integrating the information on the controlling parameters. Accordingly, RS and GIS become very important techniques for hydrogeological investigations (e.g. Tweed et al. 2007; webhelp.esri.com/arcgisDesktop/9.1/index.cfm?...An%20overview%).

In general, the electrical geophysical methods are not routinely integrated with RS datasets. Direct current (DC) resistivity method is one of the most popular electrical methods for groundwater exploration and geoenvironmental investigations (e.g. Al-Manmi and Rauf 2016; Attwa et al. 2009). In high conductive soils, penetration depth and resolution of DC resistivity method are less than that of resistive medium and resistivity imaging under conductive soils. They can be quite challenging if not impractically used (Attwa and Günther 2013; Reynolds 2011). Consequently, DC resistivity method, especially when combined with RS and GIS, can be capable of categorizing and characterizing areas prone to geohazards.

Recently, Egypt faces several flash flood events in the coastal areas and the Nile wadi system. The total economic damage was estimated at about 1.2 billion USD/year from 1975–2014. From the inspection of downstream features in Egypt, it can be noticed that the wadis discharge the floodwater into coast areas (Red sea Wadis, e.g., W. Ambagi and W. Safaga) and/or Nile plateaus (Eastern desert (ED) wadis, e.g., W. Atfih and W. Abadi). On the other hand, Nile water is currently insufficient especially after the establishment of large-scale land reclamation projects in desert fringes around the Nile valley. Consequently, the development and management of groundwater and floodwater have recently become extremely important. As a consequence, the mitigation of flash flood hazards and effective use of floodwater for groundwater recharge become vital and urgent.

With the aim to mitigate the flash flood hazards, this chapter attempts to present an integrative approach of GIS, RS, and DC resistivity data to manage the flash flood in wadi system. Furthermore, this approach aims to assess the water resources in arid and semi-arid areas making recommendations concerning sustainable development. Here, two case

studies will be presented in two wadis in Egypt in which we used an amazing integrative approach for the investigation and management of flash floods.

2 Methods

This section presents an overview of the methods used to achieve the objective of this chapter based on the methodology shown in Fig. 1. The present integration strategy aims to combine geological, hydrogeological, and geophysical data in order to evaluate the hydrogeological conditions and to manage the flash flood hazards wadi systems. The suggested strategy depends on using the surface geological data as a key while interpreting geophysical data which assess many geological controls that enhance subsurface modeling and reduce the geological uncertainty. The integration strategy workflow is summarized in Fig. 1.

2.1 GIS and Remote Sensing

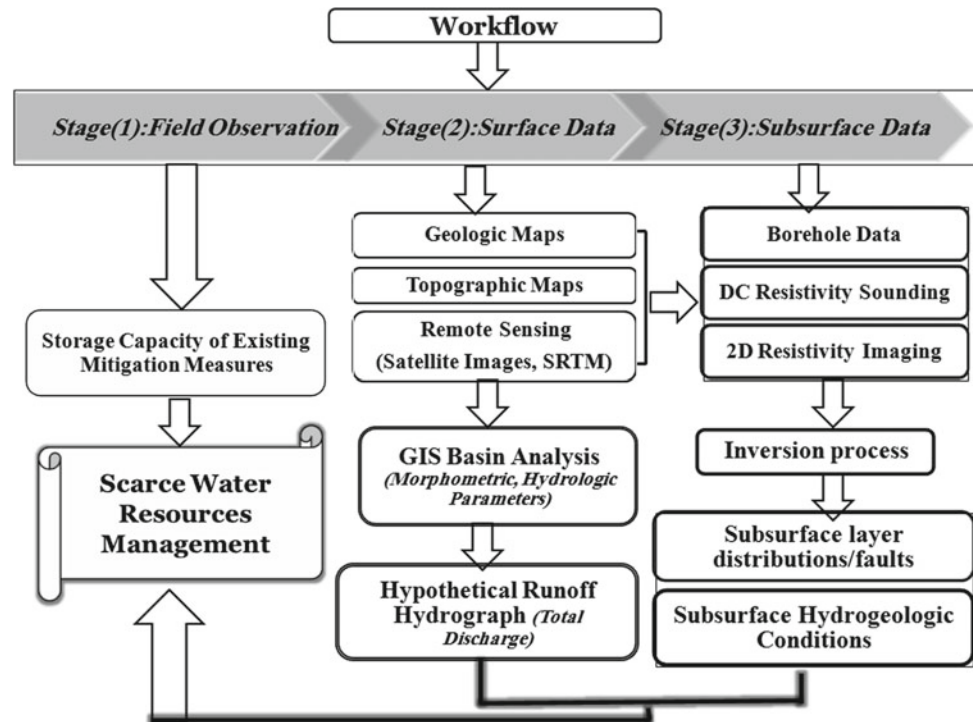
Recently, the water resources and flash flood hazards management is carried out using GIS and RS techniques. In the present integrative methodology, GIS, RS, and DC resistivity collected data were integrated to assess the hydrogeological conditions in arid and semi-arid areas (e.g., wadis). The GIS and RS are applied to construct the hydrological model according to four steps.

2.1.1 A Digital Elevation Model (DEM)

DEM is a digital file of terrain elevations or a terrain's surface 3D representation created from ground elevation data usually for a planet including Earth (Fig. 2). A DEM can be shown in the form of a raster (a squares grid) of a continuous surface where each cell value in the raster represents elevation. DEMs are constructed using RS techniques and land surveying. DEMs are used in GIS and are the basis for digitally relief maps production. Shuttle Radar Topography Mission (SRTM images) which is produced in 2003 with a spatial resolution of 90 m is used. To get accurate results from the surface analysis, the data must have been projected.

In general, the constructed DEMs are processed using ArcGIS software to fix a few errors. The grid involves little errors because of anomalies values which usually represent either sinks or peaks (maybe dams and wells or pits). A cell with indeterminate drainage direction, where no surrounding cells are lower, is known as a sink. On the other hand, a cell where no neighboring cells are higher is known as a peak. These errors are often as a result of data resolution, missing or insufficient data, or elevations rounding to the nearest integer value. Furthermore, sinks lead to stop the drainage

Fig. 1 Workflow of an integrated approach for hydrogeological assessment and flash flood management in wadi systems



network, separate a part of the basin (Attwa et al. 2014), and finally give undependable results while flow directions calculation. Therefore, filling sinks should be applied to guarantee accurate delineation of watersheds and streams. The tool can be applied to remove peaks, i.e., cells with an elevation greater than would be expected. Because sinks and peaks are filled, others can be formed at the boundaries of the filled areas, which are removed in the next iteration.

2.1.2 Flow Direction Determination

The flow direction is circumscribed by the direction of flow from each cell in the raster to its neighbor of the steepest downslope or its maximum drop. This can be calculated as follows:

$$\text{Maximum Drop} = \frac{\text{Change_In_Z} - \text{Value}}{\text{Distance}} * 100$$

The distance is delineated between cells' centers; therefore, if the two cells are orthogonal, the distance between the two of them is 90 m. If the two cells are diagonal, the distance between the two of them is about 127 m. This suggests that each extracted stream will be ≥ 90 m in case of using one cell as a threshold for delineation of the stream.

The approach of the D-8 flow model (Tarboton 2000) has been used to get the direction of flow out of each cell where eight output directions are valid; flow could pass through the eight bordering cells. When the steepest descent direction is found, the output pixel is coded with the value characterizing that direction (Fig. 3).

2.1.3 Calculating Flow Accumulation and Delineating Watersheds

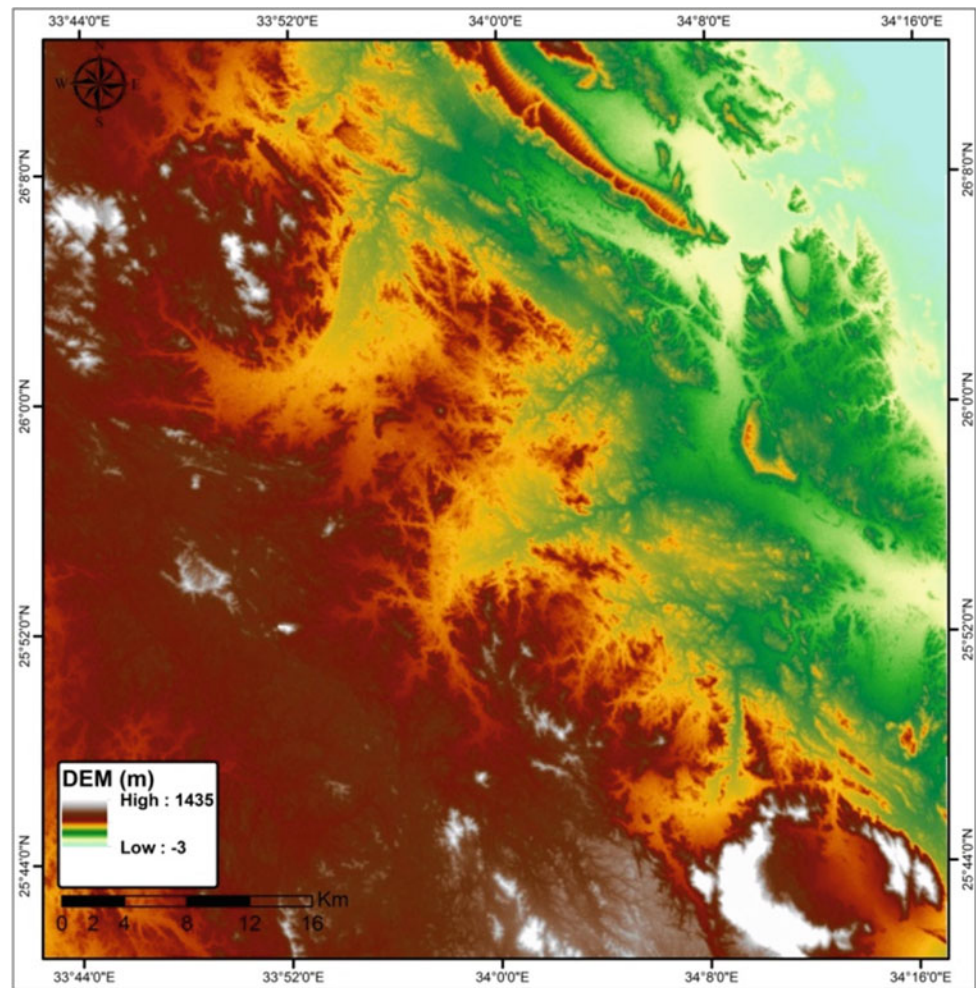
The flow accumulation is calculated as the accumulated weight of the whole cells flowing into each downslope cell. The cell value of the output raster represents the cells' number flowing into each cell. Cells with 0 value of flow accumulation are considered restricted topographic highs and can be used for identifying ridges; the higher the flow accumulation of the cells, the more the concentration of the flow in these areas. Therefore, the main channels can be identified. In the following graphic, the image placed in the bottom left direction shows the travel direction from each cell and the image placed in the bottom right direction shows the cells' number of this flow into each cell.

Watershed delineation means creating a boundary that represents the contributing area for a particular control point or outlet. For example, the value of the outlet point of a watershed located in the central Eastern desert, west Red Sea coast, and Al-Quseir city has been determined, and the boundary of it is delineated (Fig. 4). The pixel value (flow accumulation) of this point is 16979 representing the number of cells contributing to the watershed.

2.1.4 Extracting Stream Networks, Orders, and Automatic Vectorization

In this step, stream networks have been detected by applying a value of threshold to the output of the flow accumulation process using these null tool. Then, the stream link tool has been applied to assign distinctive values to all the links in a

Fig. 2 Digital elevation model (DEM) in meters (an example)

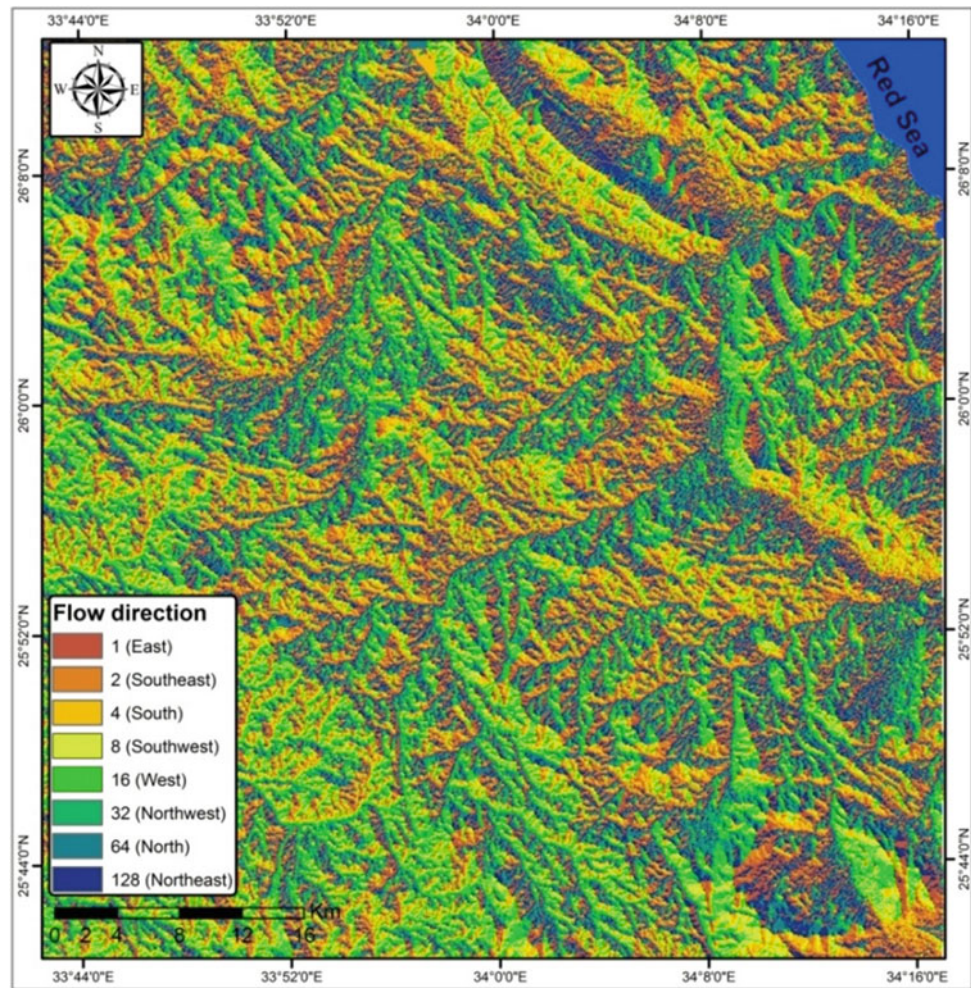


linear network of a raster between intersections where links are the stream channel segments linking two consecutive junctions, the outlet and a junction, or the drainage divide and a junction. Stream ordering is a technique to derive main stream channel and its tributaries. The stream order tool has two methods you can use to assign orders. There are two methods to assign the stream order proposed by (Jenson and Domingue 1988; StrahlerAN 1957).

Flow length is known as the length of the longest overland flow path within a given basin to the upstream or the downstream direction. It can also be defined as the weighted distance along the flow path for each cell. In GIS, the flow length can be determined by the summation of the progressive distances along the flow path from each pixel center-to-center from the designated pixel to the outlet one (<https://www.slideshare.net/BUGINGOAnnie/exercise-advanced-gisandhydrology>). The tool can be used to create distance–area diagrams of hypothetical rainfall and runoff events using the weight raster as impedance to movement downslope. Once the flow direction for each cell is obtained,

the grid of flow direction is reclassified to get the flow length through each cell. The moment that both the flow velocities and lengths are determined for each cell, the travel time of the flow in each cell is acquired by dividing the length by the flow velocity estimated for each cell using the Manning equation (El Bastawesy et al. 2009). Once the velocity and the length of the flow within each cell are estimated, the travel time for each cell in the catchment is possible to be estimated. The flow length function in ArcInfo can determine the accumulated downstream flowlength. In this time grid, each one of the cells possesses a value that represents the time needed (in seconds) for the surface runoff generating within or transferred to each cell to arrive at the basin outlet. Therefore, the watershed can be divided into several time–area zones (in hours) detached by isochrones. Transmission loss, eliminations because of storage or loss along the flow path, are neglected, and the surface runoff created from any time–area zone will arrive at the catchment outlet in a certain time (ShreveRL 1966). The runoff will pursue the same paths with the same velocity despite surplus rainfall depth.

Fig. 3 Flow direction distribution (an example)



2.2 DC Resistivity Method

DC resistivity method is one of the oldest geophysical survey techniques used until today. It aims to determine the distribution of subsurface's resistivity based on the principle of applying electric current to the earth through two electrodes and measuring the potential difference between two or more other electrodes (Fig. 5). The true resistivity of the subsurface can be estimated from these measurements.

The electrical resistivity of a geological formation is a physical characteristic depending on the flow of electric current in the formation. Subsurface resistivity is related to several geological parameters and varies with these parameters such as the texture of the rock, nature of mineralization, and conductivity of electrolyte contained within the rock. Further, resistivity not only changes from formation to formation but even within a particular formation (Maidment 1993). Accordingly, there are a few parameters that influence the ground resistivity such as mineral and fluid content, porosity, and the degree of water saturation in the rock. These parameters make the resistivity method an ideal

technique for geotechnical, archeological, environmental, and hydrogeological investigations (e.g., Sharma 1997; Attwa and Günther 2012; Attwa and El-Shinawi 2017).

DC resistivity measurements involve four active electrodes (stainless steel bar). These electrodes are planted into the ground. Two current electrodes (A and B) are used to inject an electrical current into the ground (earth), Fig. 5. We measure the ability of that material to resist the current (I) by recording the resulting voltage difference (ΔV) at two points on the ground surface measured by two potential electrodes (M and N), shown in Fig. 5. The potential difference is then given by

$$\rho_a = K \left(\frac{\Delta V}{I} \right)$$

where K is the geometrical factor having the dimension of length (m), which depends on the arrangement of the four electrodes.

If the ground is heterogeneous, the resistivity is called the apparent resistivity. The apparent resistivity (ρ_a) depends on

Fig. 4 Flow accumulation and basin boundary after watershed delineation (an example)

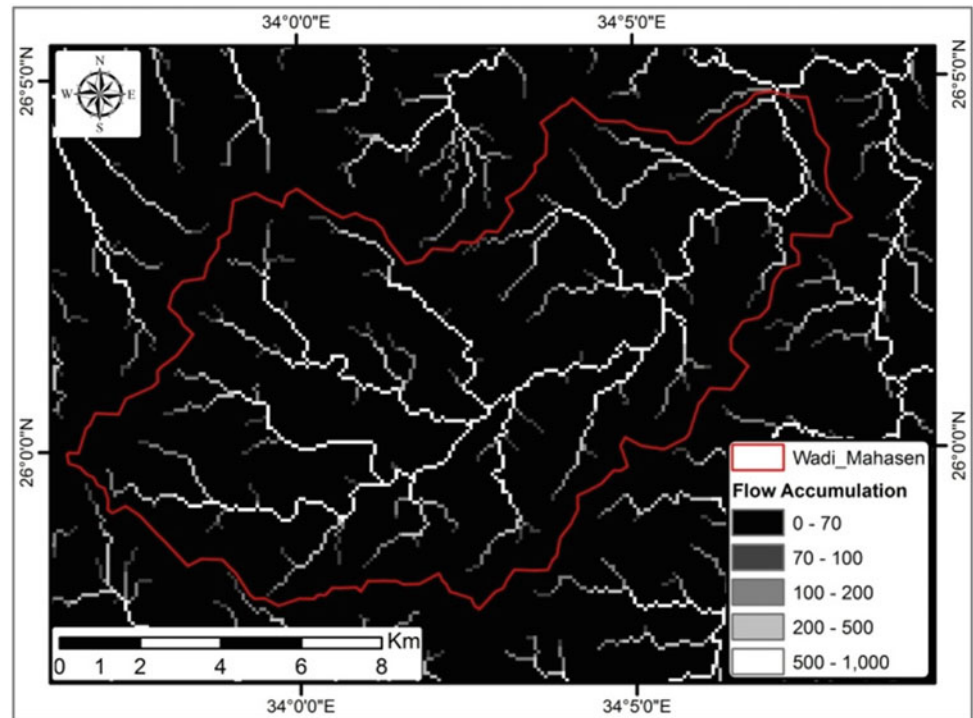
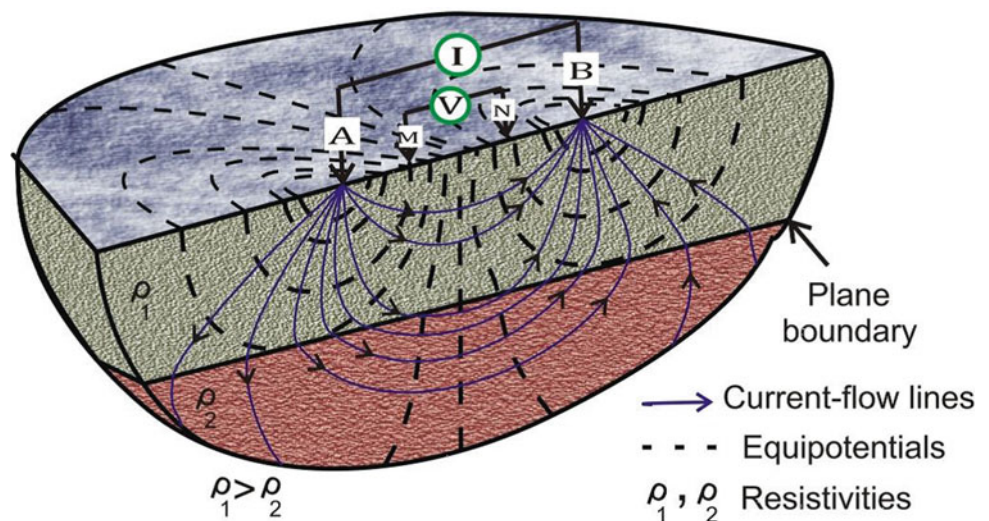


Fig. 5 Principle of resistivity measurements with a four-electrode configuration (modified after, Attwa and Henaish 2018)



the element geometry and resistivity constituting the given geologic medium.

The ground resistivity variation scan causes divergences in the current flow and the measured voltage differences. As its origin, DC resistivity method is known as resistivity sounding. This is a one-dimensional (1D) survey where only vertical changes are taken into account. For lateral heterogeneity imaging, 2D-electrical resistivity tomography (ERT) survey can be carried out using different configurations of electrodes on the ground surfaces. There are frequent

configurations/ arrangements for placing the potential and current electrodes. Some of the common electrode arrays for geologic studies are Schlumberger (SC), Wenner (MN), dipole-dipole (DD), and pole-dipole (PD) arrays (Fig. 6).

In desert lands, the condition of measurements is extremely difficult in most locations; this difficulty can be attributed to the ground resistance contact and inhomogeneities of the ground surface layer, which composed of dry loose sands mixed with gravel, large boulders, and rock fragments Fig. 7. To overcome the high resistance, digging a

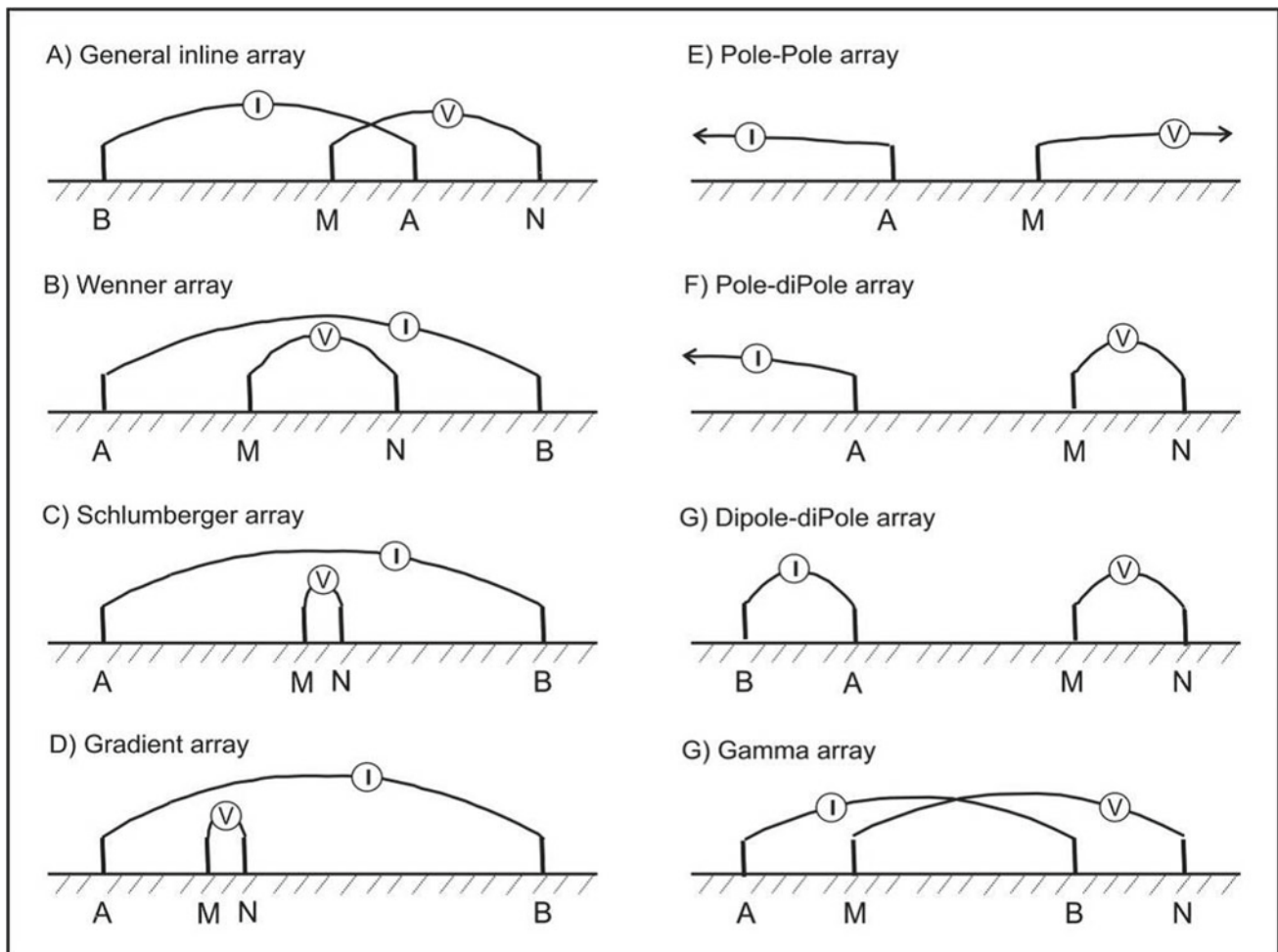
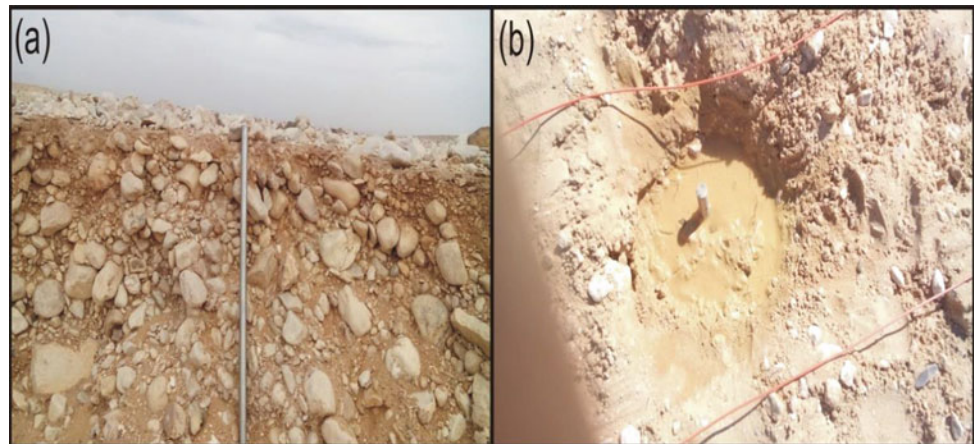


Fig. 6 Some of the most commonly used electrode configurations. The letters A and B denote the current electrodes and the letters M and N denote the potential electrodes

Fig. 7 The difficult conditions due to the resistance contact and inhomogeneity of the surface cover. **a** Surface cover composed of gravel, large boulders, and rock fragments. **b** Cone-shaped hole is filled by bentonite



hole for each electrode and adding water in the hole were performed or two electrodes can be set in parallel at each point to decrease this value. However, in most cases with

difficult conditions, we dug a cone-shaped hole with a depth of 50 cm and fill it by drilling mud (bentonite) and then adding water after plugging electrode.

3 Case Studies

3.1 Mahasen Basin, Eastern Desert, Egypt

Here, Mahasen watershed is represented as a case study for proving the present approach. Mahasen watershed is situated in the central Eastern desert as a subbasin contributing to Al-Ambagi basin which is draining directly in Al- Quseir city located on the Red Sea coast (see Fig. 8). Geologically, basement rocks are the prevailing rock units in this basin except for the very small area of Quseir formation and Quaternary deposits (see Fig. 8). This characteristic enhances the composition of flash floods. After the watershed delineation, the hydrologic layers (DEM-fill-flow direction, flow accumulation flow length, drainage network, and time-

area zones) of that basin were extracted following the previously mentioned methodology. Figure 9 shows some of these hydrological parameters (flow direction and length).

The time-area zone is calculated for Mahasen watershed in order to estimate the runoff hydrograph (i.e., flash flood discharge curve) that is acquired depending on an effective hypothetical 10 mm rainfall event (El Bastawesy et al. 2009), Fig. 10. The total discharge of Mahasen watershed has been determined (1427868 m^3) which needs to be managed. Water resources management can be achieved by dam construction in a site promoting groundwater harvesting.

The resistivity measurements were carried out along the main wadi bed where the stream density is high to explore alluvium thickness, saturation, and depth of the basement

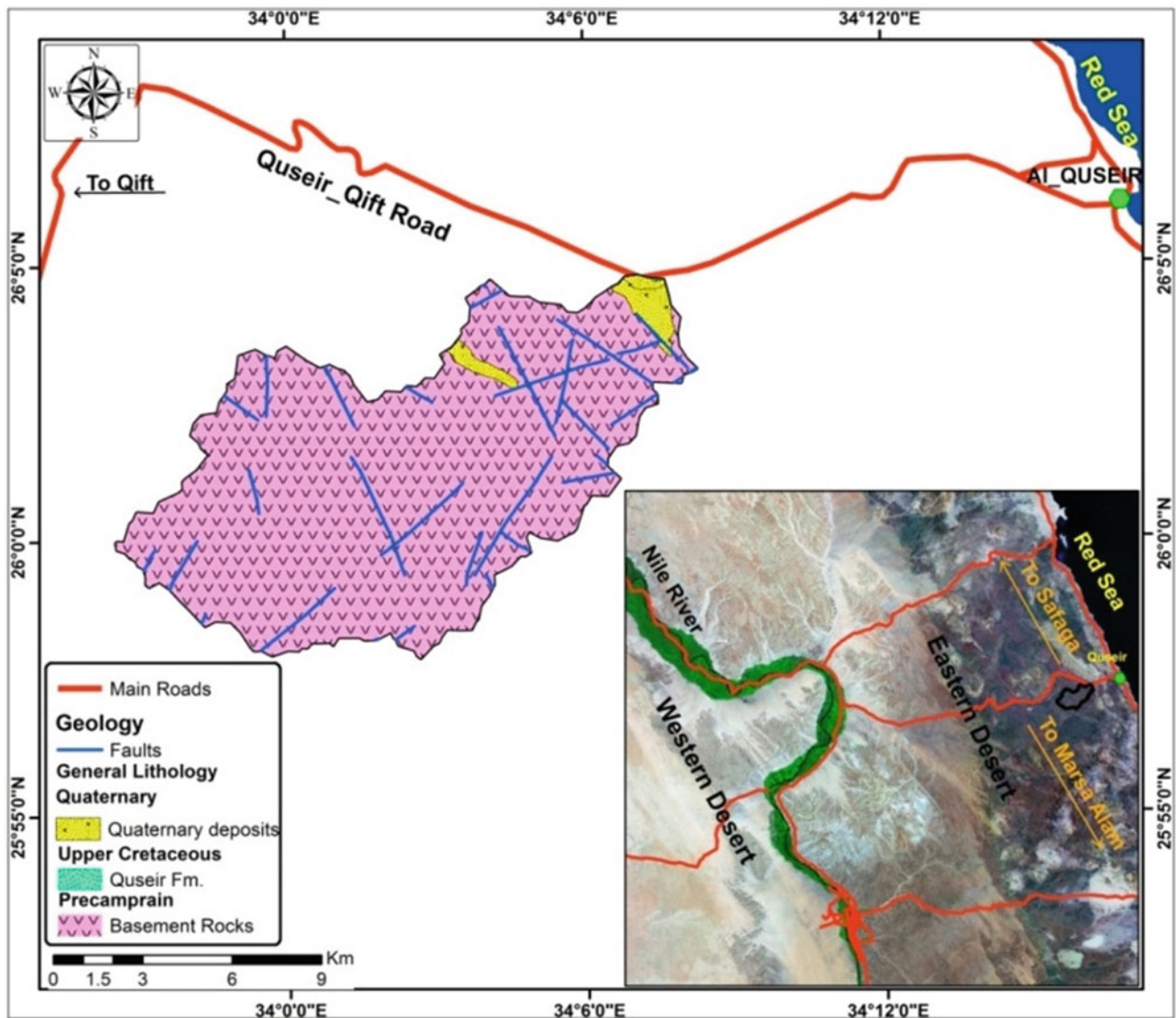


Fig. 8 Location map of Mahasen watershed

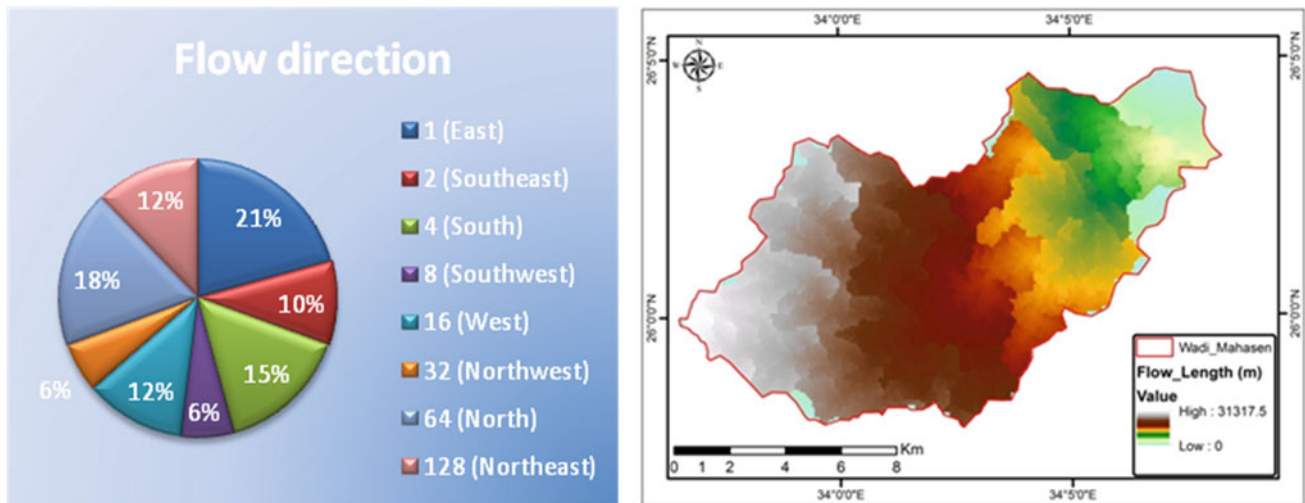


Fig. 9 (left) Flow direction and its distribution and (right) flow length in meters of Mahasen basin

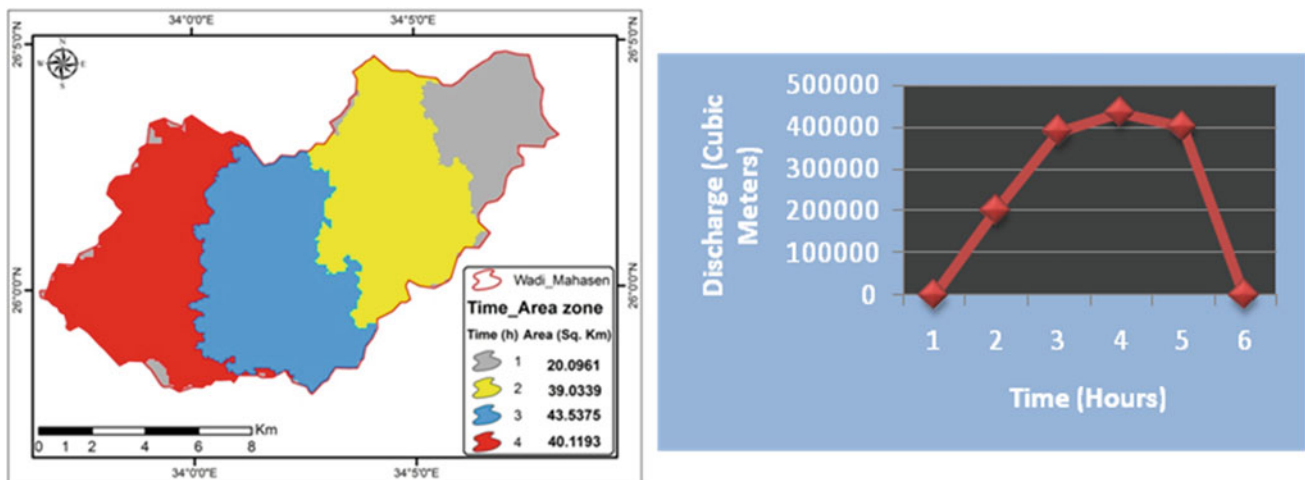


Fig. 10 (left) Time–area zones and (right) hypothetical runoff hydrograph of Mahasin basin

rocks. The inversion result of the 2D profile (i.e., 2D-ERT) showing the subsurface geology and inferred faults is shown in Fig. 11. After the 2D profile had been interpreted, it was found the same location of the profile is an optimum site for constructing a dam as a tool for scarce water management because of the chance given to the runoff water to be recharged and also the underground structure location managing the movement of the groundwater. Furthermore, the great thickness of sediments located between the two basement blocks is very useful for runoff recharge. The recommended dam should be constructed by special dimensions to control more than the entire runoff from the whole catchment. The proposed dam will be expected to exceed the needed total storage capacity as it will control about 2.6 million cubic meters.

3.2 Wadi Esna, Western Desert, Egypt

Wadi Esna watershed is represented as a second case study for proving the present approach. The investigated area is located on the west bank of the River Nile, west Esna city. It situated within the transitional zone between the western desert and the Nile valley; it is bounded from the west by Limestone Eocene plateau and from the east by the river Nile. The surface land of the area is characterized by a change of terrains and elevations. The average ground elevation varies from about 69 m above mean sea level (AMSL) in the eastern part to about 606 m AMSL in the western part.

In the present case study, morphometric analysis of the Esna basin (Fig. 12), based on several drainage parameters

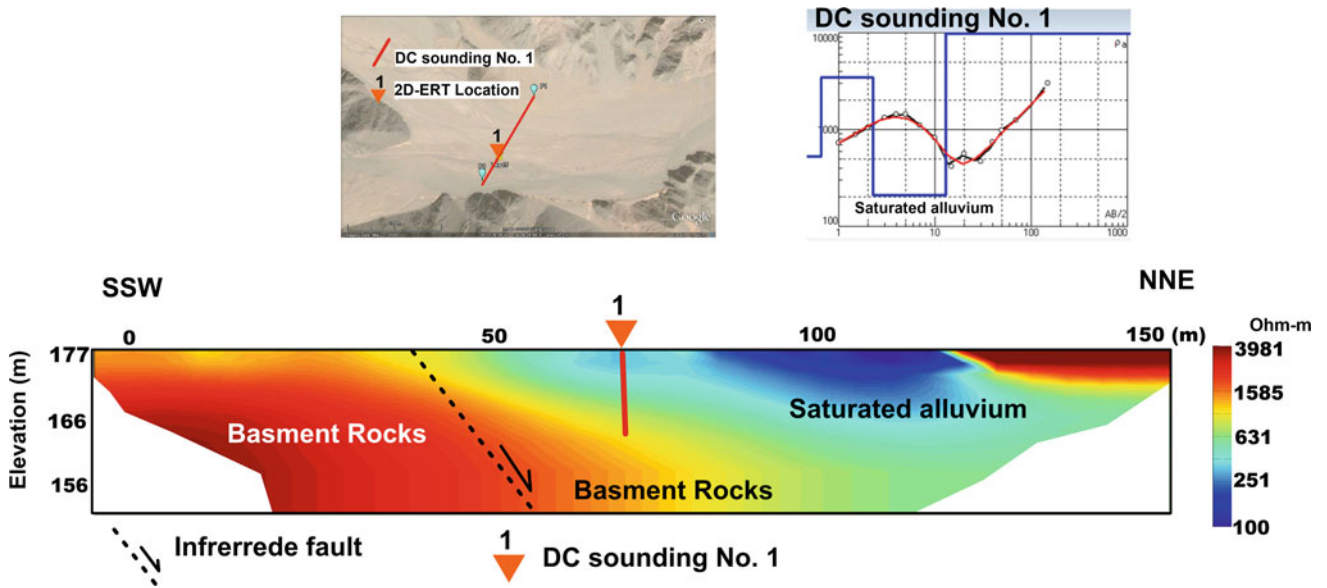


Fig. 11 DC soundings inversion results and 2D-ERT carried out at Mahasin basin showing the subsurface geology and inferred fault

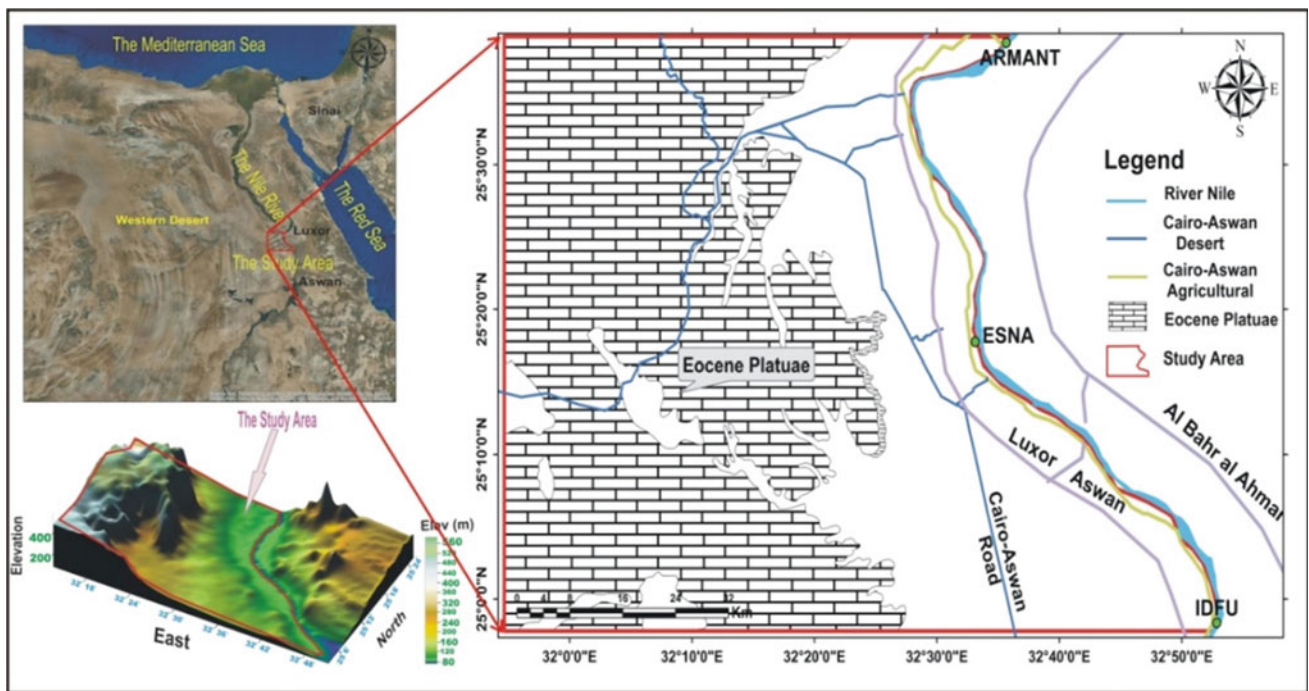


Fig. 12 Location map of Esna, Western Desert, Egypt

applying RS satellite data and latest GIS techniques for drainage analysis, has been represented. It is observed that the present wadi can be classified into six basins (Fig. 13). Detailed morphometric analysis of all basins indicates dendritic to sub-dendritic drainage forms, which indicate homogenous lithology and variations of R_b values among the basins related to the difference in elevation and geometric development. The maximum frequency of stream order is

noticed in the case of first-order streams and then for the second order. Accordingly, it is observed that there are stream order increases as the stream frequency decreases and vice versa.

Runoff, especially flash flood is a real danger for the development in these areas, and is considered being the main reason to lose large quantities of freshwater besides the destruction of life stocks and infrastructure in the desert.

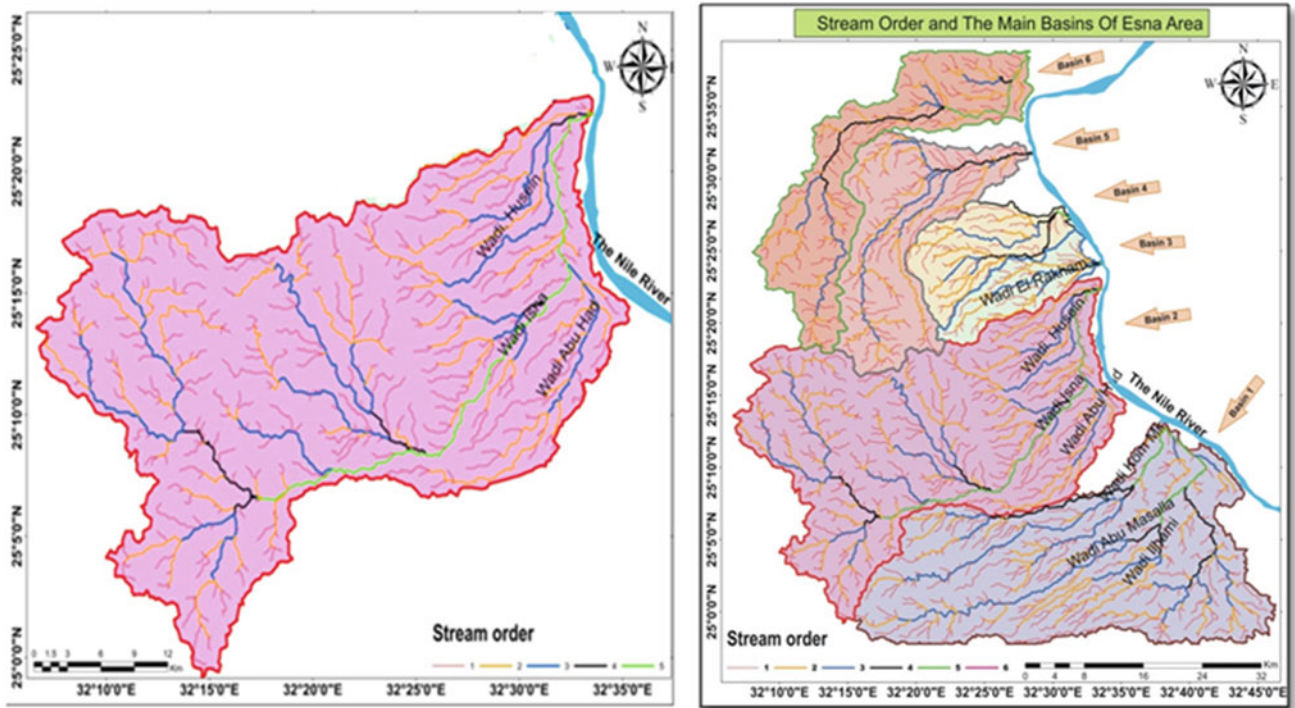


Fig. 13 Drainage network map of main basins at Esna basin, Western Desert, Egypt

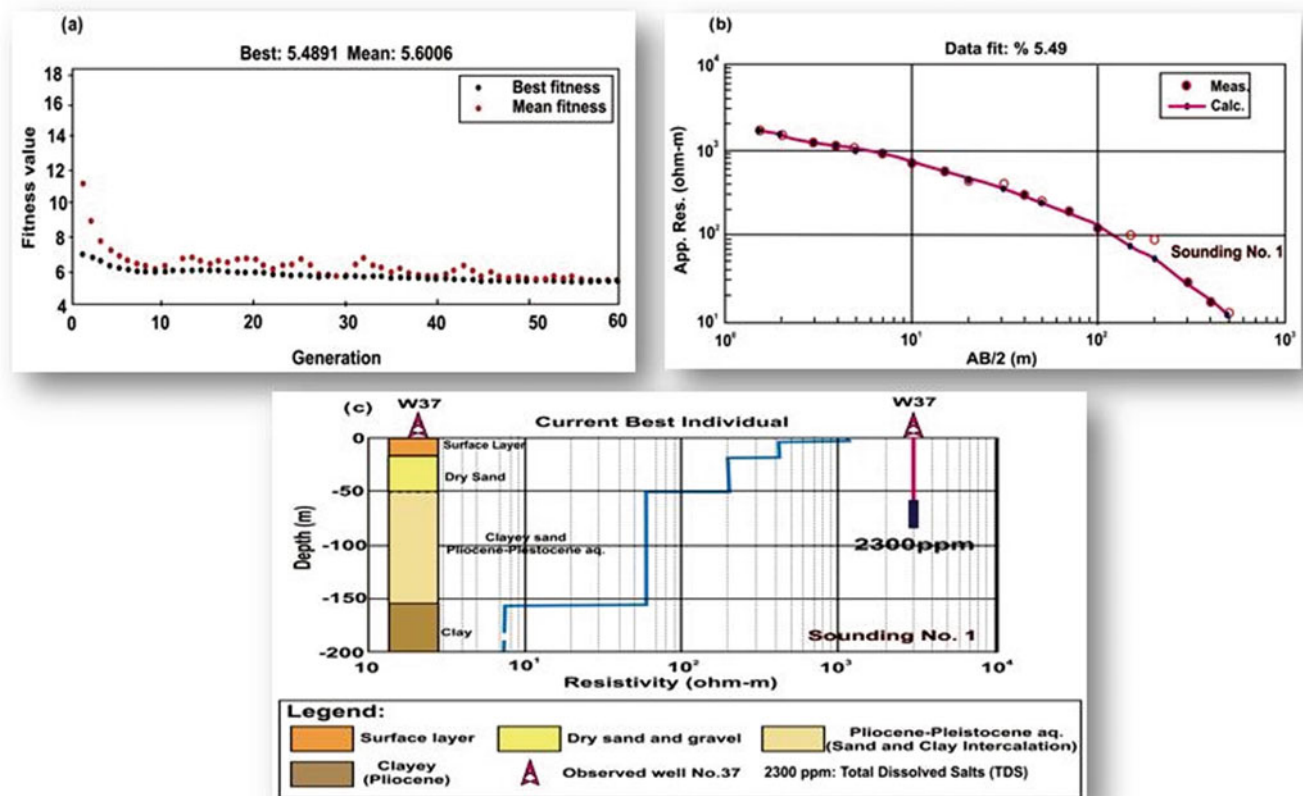


Fig. 14 The inversion results of DC resistivity soundings using a genetic algorithm (GA); a Variations of mean and best misfit versus generation, b a comparison between the measured and calculated data at the best misfit value, c a comparison between the model response and borehole information

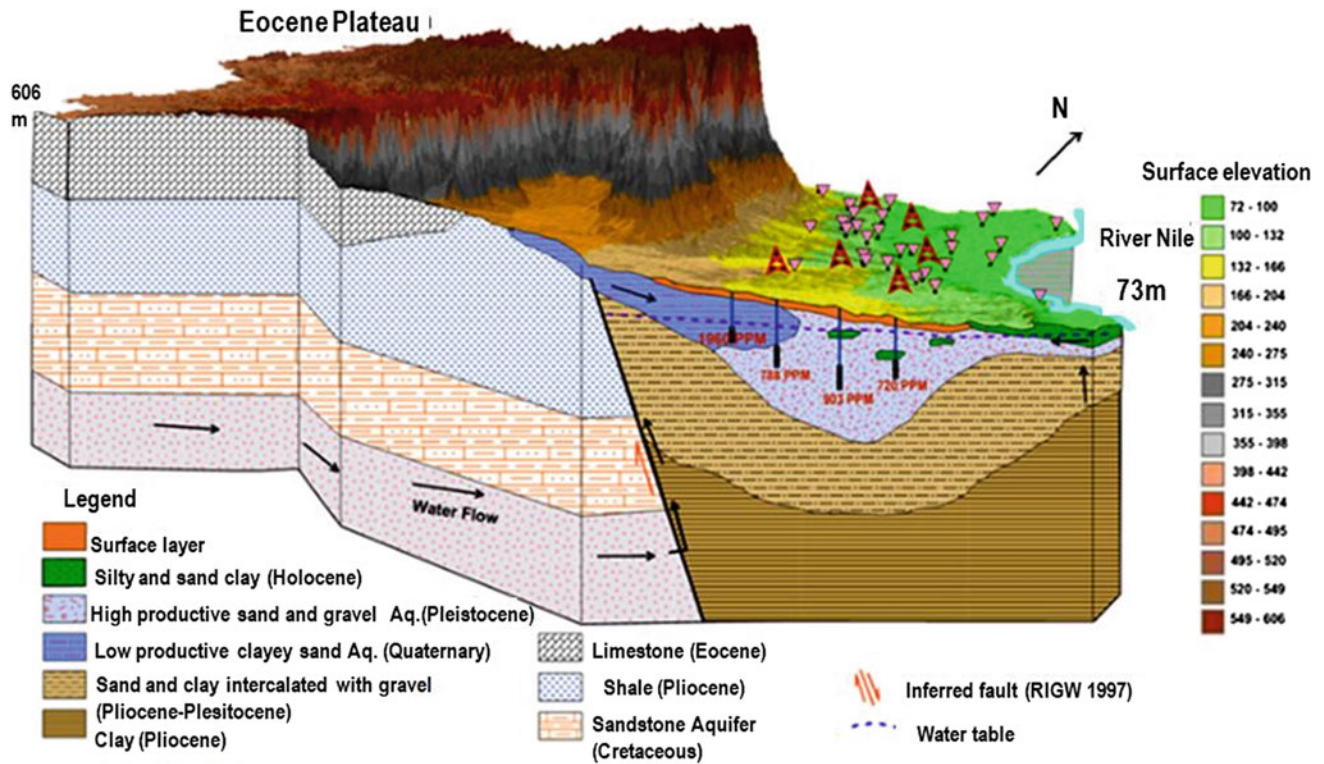


Fig. 15 3D visualized model showing the subsurface layers distribution and hydrogeological conditions at Esna basin, Western Desert, Egypt

Runoff measured in the study area requires sufficient data about climate conditions such as rainfall, evaporation, infiltration, and transpiration. Also, geomorphological and geological setting is needed as well as data with regard to flash flood, i.e., gauge height, if available, water quantity, velocity, and the time which is running until reaching the estuary coast by a flash flood. The rational equation can be used to estimate surface runoff in the study area:

$$V = R * C * A * P$$

$$R = 1.05 - 0.0053\sqrt{A}$$

where V is the surface runoff volume, P is the total rainfall depth, C is runoff coefficient, A is the basin area upstream the point of interest, and R is the reduction factor that depends on basin area (Seidel and Lange 2007). The runoff volume values according to rational equation range from 30549.4 m³/h in basin no.2 to 6571.5 m³/h in basin No.3 (Fig. 13).

The all previous results of morphometric analysis and the runoff volume together make the basin number 2 have high priority for water flooding potentiality. Consequently, high chance for runoff water harvesting and increasing groundwater recharge possibilities. So, we select these basins to carry out the geoelectrical study (i.e., DC resistivity measurements). Figure 14 shows an example of the measured

DCR resistivity soundings with its interpretation. Furthermore, correlation between the interpreted resistivity layers of the selected DC resistivity sounding (No. 1) and the given borehole applying a non-conventional inversion scheme (i.e., a genetic algorithm, GA) is presented in Fig. 14.

DC resistivity measurements were carried out in the form of DC resistivity soundings (i.e., 1D). The inversion process of DC resistivity soundings was carried out using non-conventional inversion method (genetic algorithm), (e.g., Reynolds 2011; Attwa et al. 2016), Fig. 13. Based on the inversion results of DC soundings, 3D visualized model (Fig. 15) was constructed to show the subsurface layers distribution and hydrogeological conditions along wadi Esna.

4 Conclusions and Recommendations

In desert lands, flash flood management and groundwater resources assessment are urgently required. In this book chapter, an integrative approach of RS and DC resistivity data was discussed. As case studies, the efficiency of this approach was presented at two wadis from Egypt. This approach illustrated and proved how efficient was the integration between the RS, GIS, and DC resistivity techniques for scarce water resources management in wadi systems. The

proposed approach was useful not only for the mitigation of flash flood hazards but also for replenishing aquifers in an attempt to urban development even in small scales. RS and GIS techniques can be applied to delineate the basin of a high chance for runoff water harvesting and groundwater recharge possibilities. On the other hand, the DC resistivity method can be used to delineate/image the subsurface layer distributions and aquifers extension. Accordingly, the successful applications of the present integrative approach open the way for sustainable development in wadi systems by decision-makers to (i) overcome water scarcity problem and (ii) reduce the flash flood hazards.

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