NEW APPROACH FOR GROUND GEOPHYSICS IN THE DEVELOPMENT OF GROUNDWATER IN THE BASEMENT TERRAINS (A case study from south Sinai, Egypt)

E. H. Shendi & A. A. Abouelmagd
Department of Geology, Faculty of Science, Suez Canal University, Ismailia.

ABSTRACT: In areas covered by the basement rocks, the groundwater aquifers are very limited in both lateral and vertical extensions relying mainly on the surface irregularities in the buried basement rocks. These negative irregularities (i.e. depressions) can be artificially recharged through construction of surface dams to mitigate flash floods during the periods of heavy rains and facilitate the downward percolation of surface water. Ground geophysics, especially magnetic and electrical resistivity sounding methods, has a great role in delineating those depressions, which are suitable for storing of groundwater and hence controlling the construction of surface dams.

Three sites in the basement terrains in south Sinai have been selected as a case study. These sites, which are located in Wadi El-Sheikh; Wadi Sahab and Wadi Solaf, have risky flooding probabilities as deduced from the previous hydrogeological studies. Ground magnetic and geoelectric sounding measurements have been carried out in order to detect the depressions in the buried basement rocks and recommend the suitable sites to construct surface dams even if these depressions are dry. Results of these measurements have detected a number of depressions where there is a great thickness of alluvial deposits and weathered basement rocks, which are suitable for storing of ground water. Accordingly, surface dams should be designed and constructed at these sites and a system of wells should be drilled to consume the ground water storage.

1. INTRODUCTION

The concept of using ground geophysics in the development of ground water in the basement terrains is relatively new. It was always used to use geophysical methods for ground water exploration rather than development. In the present study it is attempted to apply some effective ground geophysical methods along some wadis running through basement terrains, in the light of the available geological and hydrogeological information, in order to detect the subsurface basins, which are responsible for groundwater accumulation. These basins will be recharged mainly by water of flash floods after constructing some kinds of surface dams. The hydrogeological studies must be carried out first in order to let us know the areas, which are suffering from flash floods and thereafter the ground geophysics will give us an answer about the presence of subsurface basins.

Three sites in the basement terrains in south Sinai have been selected as a case study. These sites, which are located in Wadi El-Sheikh; Wadi Sahab and Wadi Solaf (Fig.1), have risky flooding probabilities as deduced from the previous hydrogeological investigations.

2. OCCURRENCES OF GROUNDWATER IN THE BASEMENT TERRAINS

It is much better to start this study by giving a brief information about the mode of occurrence of groundwater in an area covered by basement terrains. The basement rocks include metamorphic, volcanic and granitic varieties that are invaded by acidic and basic dykes as well as dissected by narrow deep drainage lines. These rocks are generally impermeable except through fractures such as faults, joints and shear zones, which represent the conduits of water flow. Joint porosity may be as large as 2% of the total rock volume and the porosity of the weathered igneous and metamorphic rocks may exceed 10% (El-Rayes 1992). The groundwater in the basement rocks occurs mainly in fissures, joints and along the fault planes. Also, the variation of the rock types in the basement terrains is considered as one of the important factors that are possibly controlling the groundwater occurrences. The basic rock are weathered at greater depths than the acidic rocks. The fine-grained igneous rocks are more fractured than the coarse grained rocks. The weathering of these rock varieties tends to increase the secondary porosity and the permeability of their aquifers. Dyke swarms of different compositions traverse the basement rocks and play a great role in the occurrence of groundwater. Positive features cause irregularities in the basement relief underlying the alluvial deposits. The basic dykes are highly affected by the weathering processes resulting in clayey materials, which act as aquifers with low horizontal permeability. However, granitic rocks in arid regions are usually overlain by a variable thickness of weathered granite, which is produced by in-situ weathering of granitic rocks (Acworth 1987). These weathered basement rocks grade into solid unfractured rocks over several tens of meters (Fig.2). Hydrogeologically, the weathered basement rocks have high porosity and contain a significant amount of water, but because of their relatively high clay content, they have low permeability.
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Figure 1. Location map of the studied sites.

The bedrock on the other hand is fresh but frequently fractured, which gives it a high permeability. Because of the fractures do not constitute a significant volume of the rock; fractured basement has a low porosity. For this reason a good borehole is the one which has the following characteristics:

a- It penetrates a large thickness of weathered basement rocks.

b- It intersects fractures in the underlying solid basement rocks where the fractures provide the rapid transport mechanism from the reservoir and hence the high yield. However, boreholes, which intersect fractures but are not overlain by thick saturated weathered basement, can’t be expected to provide high yields in the long term. Boreholes, which penetrate saturated weathered basement but don’t find fractures in the solid basement bedrock are likely to provide sufficient yield for a hand pump only (Barker 2001). However, closely spaced joints and fractures in the solid basement facilitate the downward migration of water which increases the weathering process. For this reason it is better to choose sites for constructing surface dams at points where the bedrock occurs at great depths.

The Quaternary alluvial deposits, which are filling the wadi floors in the basement terrains with variable thicknesses and textures, constitute an important aquifer for ground water (Fig.2). They are composed of rock fragments, sand, gravel and boulders that derived mainly from disintegration of the basement rocks. Their thicknesses depend on the surface irregularities of the underlying basement rocks and they are recharged mainly from the following sources:

1- The percolation of rainfall and surface run off water.

2- The lateral inflow from the joints of the surrounding basement rocks.

On the other hand, fault zones represent weak zones in the basement rocks and form good environments for storing of ground water (Fig.2). Some of them are filled with porous materials, which may be the products of faulting process, such as the kaolinitized materials and gouges, or may be of fracture filling origin.

3. FLASH FLOODS IN THE BASEMENT TERRAINS

A considerable part of the rainwater in the basement terrains is stored in the fractures and joints of the outcropping rocks either in the form of water or snow. When the temperature goes up, this snow will melt and flow through the connected fractures from different directions to cause flash floods. These floods are frequently occurred in the basement terrains in arid
regions such as south Sinai causing severe damage to the human utilities in the low lands. If there is some kind of surface dams to control these floods, most of the water will percolate the alluvial deposits and feeds the groundwater or even stored in the dry subsurface reservoirs. This is the main target of the present study, which is using ground geophysical measurements to locate the subsurface reservoirs, which are responsible to store floodwater if surface dams are constructed. The most appropriate ground geophysical methods in this case include:

1. The magnetic method is mainly used to determine the depth to the solid basement rocks and hence the total thickness of the overlying alluvial deposits and the weathered basement. This can be achieved depending on the great variation in the magnetic susceptibility between these deposits and the basement rocks.

2. The vertical electrical soundings (VES) can be successfully used to determine the total thickness of both the alluvial deposits and the weathered basement depending on the great variation in their electrical resistivities.

Figure 2. Schematic diagram showing the occurrences of groundwater in the basement terrains.

4. CASE STUDY FROM SOUTH SINAI

Three sites in the basement terrains of south Sinai have been considered in this study. These sites are located in Wadi El-Sheikh, Wadi Sahab and Wadi Solaf (Fig.1) and depend mainly on the groundwater as the only source for drinking and domestic purposes. The vulnerable selection of these three sites is based on several logical reasons such as the accessibility and the high population of Bedouins. In the last few years, the groundwater decreased to serious levels. At the same time, the area is suffering annually from flash floods where huge amounts of surface water couldn’t be used by local inhabitants besides the severe damage effects on the local human utilities. On the other hand the tourism activities in south Sinai are growing rapidly, which need more water. Accordingly, the development of groundwater is essential to continue life and human activities in this remote and attractive area. From the hydrogeological standpoint, several geophysical studies have been done nearby the investigated sites (e.g. Wachs et al.,1979; El-Shazly et al., 1985; Shendi, 1989; Hosney, 1991 and Shendi, 1992). In general, most of these studies have been carried out for exploration of the groundwater and locating sites for drilling water wells. But, almost no geophysical studies have been carried out for the
purpose of groundwater development. For that, this study is intending to apply different ground geophysical methods in order to acquire all the necessary and required information for suggesting groundwater development scheme in the three sites.

Granitic rocks, which are invaded by dykes of different composition, mainly cover the studied sites. These rocks are faulted and jointed with various intensities, forming relatively small hills with highly weathered surfaces. The main courses of the wadis are filled by Quaternary alluvial deposits, which are composed of gravel, sand and silt (El-Shamy et.al. 1989 & El-Etr et.al. 1995). Previous hydrogeological studies on the investigated sites and surroundings indicated that this area receives a huge quantity of rainfall annually which may reach up to 72.3 million cubic meter (i.e. 40mm/year). Up to 64% of this water flows as seepage through the aquifers due to their short duration and heavy showers (Gerish et.al. 2001).

5. GEOPHYSICAL FIELD DATA ACQUISITION

Geophysical fieldwork has been carried out by using magnetic measurements and geoelectric soundings. The main purpose of these measurements is detecting the depressions in the buried basement bedrock, which contain a great thickness of alluvial deposits and weathered basement rocks that are suitable for storing the flood water. The obtained geophysical results will enable us to select the most reasonable locations for applying the artificial recharge design and constructing the suitable surface and sub-surface dams that contribute in the downward infiltration to the groundwater aquifers.

Three magnetic profiles were carried out to determine the depth to the solid and unweathered basement bedrocks. On the other hand, fifteen vertical electrical soundings (VES) were measured using Schlumberger electrode configuration with a maximum current electrode (AB) spacing of 400 m. This spreading is long enough to penetrate the underlying weathered basement rocks for a few tens of meters. In the following, a detailed description of each of the geophysical measurements is given:

5.1. Magnetic Profiling

It is well knowing that the magnetic method gives good results where there is a clear difference in the magnetic susceptibility between the examined rocks or deposits. In the present study, the alluvial deposits, which are filling the floor of the selected wadis, have extremely lower susceptibility than the underlying fresh basement bedrock. This makes the magnetic method has a considerable importance in this study to map the lateral irregularities in the buried basement bedrocks.

Three magnetic profiles have been recorded in the three studied wadis, which are: profile A-A’ runs along the downstream part of W. El-Sheikh at the location of Sahab well with a length of about 4Km, while the profile B-B’ covers a length of about 2Km along the downstream part of W. Sahab, which is perpendicular to profile A-A’. Whereas, the profile C-C’ runs along the upstream part of W. Solaf with a length of about 5Km (Fig.3).

Digital fluxgate magnetometer (MFD-4) was used in this study to record the vertical component of the earth’s magnetic field at stations every 50m along the examined profiles, which was reduced to 20m nearby water wells, where detailed information are needed. The accuracy of this device is 5 gammas if it is hand held and 1 gamma when it is used with the tripod. The field measurements were corrected due to the effect of the diurnal variations in the earth’s magnetic field by repeating readings at a base station every one-hour during the day time.

5.2. Vertical Electrical Sounding (VES)

In arid regions the VES technique is commonly used for groundwater exploration in order to detect the vertical distribution of the electrical resistivities of the different lithologic units and their thicknesses. This technique works well if these resistivities are clearly different. In the basement terrains, such as in the present study, there is a great difference in the electrical resistivity between the alluvial deposits and the underlying basement bedrock even if there is not ground water (Shendi et.al 1997 & 1999). Accordingly, the VES technique can be successfully used to determine the depth to the basement bedrocks and hence the great thickness of the alluvial deposits and the weathered basement (i.e. basins). In this study, the VES technique was used in cooperation with the magnetic profiling in order to delineate the subsurface basins, which are reasonable to store the percolated floodwaters if appropriate surface dams have been constructed above these basins.

In the studied wadis, the VES locations were controlled by the results of the magnetic profiling. They have distributed to cover all the magnetic lows (i.e. the expected depression in the buried basement bedrock). Fifteen soundings have been executed in the three studied wadis (Fig.3). Besides four soundings have been measured nearly four water wells, distributed around the investigated sites and have nearly the same geological and hydrogeological conditions as those sites. The results of these soundings have guided us during the interpretation of the other fifteen soundings. Schlumberger electrode array has been used with a maximum electrical electrode distance (i.e. AB distance) of 400m. Resistivity and self-potential unit (RSP-6) was used to collect the field data. This device has been designed to measure the ∆V/I ratio, which is multiplied by the configuration factor to produce the apparent resistivity value for each electrode spacing.
6. PROCESSING OF THE GEOPHYSICAL FIELD DATA

6.1. Magnetic Profiling
The recorded magnetic data have been corrected due to the effect of the daily variations in the earth’s magnetic field by repeating readings at a base station every one-hour during the day time. These corrected values were then represented in the form of profiles and smoothed by applying the three-point weighted average technique to remove the sharp peaks due to the near surface inhomogeneity. The regional magnetic effect has also been removed by the graphical technique where the undisturbed ends of the profile were connected. A number of anomalies could be detected along each magnetic profile which were used to determine the depth to the solid and fresh basement rocks by applying different graphical techniques such as Peter’s half slope (1949) and tangent method (Logatchev, 1968).

6.2. Vertical Electrical Soundings (VES)
In the studied wadis the VES data were automatically interpreted using the following softwares:
i- ATO (Zohdy 1989) which is an interactive software giving the number of subsurface geoelectrical units, their resistivities and thicknesses.
ii- RESIST (Valpen, 1988) which needs an initial models consisting of a number of layers, their thicknesses and their resistivities. The ATO’s results were used to suggest these models, which were subjected to a number of iterations in order to achieve the best fitting with the field curve.

Figure 3. Locations of the magnetic profiles and geoelectric soundings.
Results of the automatic analysis were then used to construct a number of geo-electric cross sections and pseudosections along the studied sites.

7. INTERPRETATION OF THE GEOPHYSICAL FIELD MEASUREMENTS

The smoothed magnetic profiles show alternative high and low anomalies reflecting irregularities on the buried basement surface and lateral lithologic variations in the basement bed rocks producing lateral differences in their magnetic susceptibility. Along the magnetic profile A-A’ (Wadi El-Sheikh), the average estimated depth to the fresh basement bedrock ranges between 27 to 104 meters (Fig. 5a & c). A great depression is noticed between stations 30 & 70 where Sahab water well is located just above the center of this depression, which is characterized by a great thickness of alluvial deposits and weathered basement rocks. This noticeable depression is resulted due to deep fault crossing W. Sahab and more or less perpendicular to W. El-Sheikh. Whereas the estimated depth to the fresh basement bedrock along profile B- B’ (Wadi Sahab) ranges between 31 to 164 meters (Fig.6a & c). On the other hand, Two considerable depressions could be detected along the profile C-C’ (Wadi Solaf). The first and great one occurs in the area between stations 55 & 75 with an average depth of about 164 meters. The second and shallow one is located in the area between stations 15 & 35 with an average depth of about 80 meters (Fig.7a & c). The first depression is resulted from the intersection of two wadis namely, Wadi El-Furia and W. Rofaiyed at the upstream part of Wadi Solaf. Only one shallow dug well is located near station 85 and unfortunately it is away from the first depression by about 300 meters. So, its wrong location gave low yield of water.

Furthermore, all the remarkable detected depressions on the examined profiles are of great importance as groundwater collectors in the proposed artificial recharge design, which satisfies our aim from applying the magnetic measurements.

The geoelectrical soundings in this study have been started by executing and interpreting a number of soundings near four common productive wells in the investigated area. Their results will be discussed in the following section in order to be familiar with the resistivities of the different geoelectric units which are characterizing the basement terrains.

7.1. Resistivity Spectrum in the Basement Terrains of the Study Area

Four soundings have been measured nearby some of the known water wells in the study area namely, Haroun, Zeituna, El-Watia and Sahab wells. This is usually done to get more information about the electrical resistivity of the subsurface sediments either dry or water saturated in an attempt to deduce a geoelectric spectrum of the area. This spectrum could then be successfully used as a guide in the interpretation of the other VES’es in the three sites.

Figure (4) shows the VES’es which have been measured besides the concerned water wells and the results of their interpretation. It could be concluded that the obtained VES curves are of HA types (ρ₁>ρ₂<ρ₃<ρ₄). The surficial layer, which is dry and composed of a mixture of alluvial deposits and rock fragments, is characterized by relatively high resistivity values ranging between 522 & 1161 Ωm.

The same high resistivity values, but sometimes higher, are recorded at greater depths which represent the basement bed rocks. The top part of these rocks is weathered, highly fractured and may constitute a part of the groundwater aquifer. This part is characterized by resistivity values range between 581 & 2898 Ωm. Whereas the lower part of the basement bed rocks is massive, less fractured and may constitute subsurface damming for vertical percolation of groundwater. This part is characterized by very high resistivity values which may exceed several thousands of Ohmm. In between the surfacial alluvial deposits and the deep solid basement rocks there is a relatively low resistivity layer, which is composed of alluvial deposits and highly weathered and fractured basement rocks and sometimes saturated with groundwater. This layer has a resistivity ranging between 162 & 2898 Ωm and constitutes the main groundwater aquifer in the study area. All these results are listed in (Table. 1).

Now, we are going to interpret the data of the other fifteen soundings in the light of the resistivity spectrum. The obtained VES curves of these soundings represent mulitlayer types, which consist of four-layers. The common type of these curves is HA-types (ρ₁>ρ₂<ρ₃<ρ₄).

Apparent resistivity sections were constructed, along the studied sites, by plotting the apparent resistivity values as observed along the vertical lines located just beneath the sounding stations. These sections will illustrate the lateral and vertical distribution of the apparent resistivities at different current electrode spacing (Zohdy et al., 1974, Ramananah et al., 1982 and Shendi, 1992). General inspection of these sections along the studied sites will be described as follows:

a- Section (A-A’), which is located along the downstream part of Wadi El-Sheikh at the location of Sahab well, includes VES’es from 1 to 6 (Fig.5b). This section reveals that high resistivity values are recorded at short current electrode distances, reflecting dry and compacted alluvial deposits at shallow depths. On the other hand, a relatively low apparent resistivity zone appears in the area between VES’es 1 and 4 at intermediate depths.
Table 1. Resistivity spectrum of the study area.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Resistivity range (Ωm)</th>
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</thead>
<tbody>
<tr>
<td>1-Alluvium, rock fragments and granitic boulders (Dry)</td>
<td>522 – 1161</td>
</tr>
<tr>
<td>2-Alluvial deposits (saturated to dry)</td>
<td>162 – 413</td>
</tr>
<tr>
<td>3-Weathered &amp; fractured basement rocks (saturated to dry)</td>
<td>581 – 2898</td>
</tr>
<tr>
<td>4-Massive basement rocks (Dry)</td>
<td>&gt; 4000</td>
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Figure 5. Magnetic profiling (a), Pseudo electric section (b) and geolectric section (c) of profile (A-A').
Figure 6. Magnetic profiling (a), Pseudo electric section (b) and geoelectric section (c) of profile (B-B’).
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Figure 7. Magnetic profiling (a), Pseudo electric section (b) and geoelectric section (c) of profile (C-C').
The apparent resistivity values along this zone reach as low as $300 \, \Omega \cdot m$, which may be interpreted as compacted unsaturated alluvial deposits that may reach to an occurrence of groundwater at its bottom part. This interpretation is confirmed by the presence of Sahab water well which is located at VES 3. However, the concave shape of the contour lines below the low resistivity zone at VES’es 1, 2 and 3 may reflect depressions in the buried basement bed rock (i.e. great thickness of the alluvial deposits). Whereas, the convex pattern of the contour lines below the other VES’es along profile (A-A’) may indicate an uplifting in the basement rocks and hence a low thickness of alluvial deposits. This uplifting can act as a subsurface barrier for a lateral flow of groundwater and increases the probability of storing the groundwater below VES’es 1 & 3. Accordingly, the area between VES 1 and VES 3 is recommended for constructing surface dams to increase the chance of applying the artificial recharge.

b- Nearly the same conditions exist along the profile (B-B’) with depressions below VES’es 8 & 10 which are considered good sites for artificial recharge design (Fig.6b). This section extends along the downstream part of Wadi Sahab, including VES’es from 7 to 10 plus VES 3 at Sahab well, from the profile A-A’. The apparent resistivity is high and nearly the same at short electrode spacing, reflecting homogeneity and dryness of the surficial alluvial layer. It decreases gradually with depth, then increase at long electrode spacings reflecting a low resistivity zone in between the shallow dry alluvial deposits and the deep hard basement rocks. The subsurface depression, which was discovered along the previous profile A-A’, is continuing along profile B-B’ until VES no. 10. This means that the intersection of Wadi Sahab and Wadi El-Sheikh at this site represents very suitable conditions for storing groundwater if surface dams are constructed to control the flood water in this area.

c- The apparent resistivity section (C-C’) extends along the upstream part of Wadi Solaf and includes five VES’es (Fig.7b). A relatively low apparent resistivity zone appears along this section at intermediate depths indicating the presence of unsaturated alluvial deposits. However, the pattern of the contour lines at long current electrode distances indicates the existence of a depression (i.e. great thickness of alluvial deposits) in the basement bedrock below VES’es 1, 3 & 4 which is reasonable for artificial recharge design. The importance of VES 3 comes from its location at the intersection of two wadis which are Wadi El-Furia and Wadi Rofaiyed.

However, the geoelectric sections which have been constructed along the examined profile A-A’, B-B’ and C-C’ (Figs. 5c, 6c & 7c) show the following geoelectric layers:

1- The top soil layer, which consists of dry fine sand, granitic pebbles and silt particles, has relatively high true resistivity values ranging between $440 - 2651 \, \Omega \cdot m$

2- The second geoelectric layer corresponds to the unsaturated alluvium with intermediate true resistivity, ranging between $150$ and $570 \, \Omega \cdot m$. This considerable variation in the resistivity values may be due to the degree of water saturation and/or lithological changes.

3- The third geoelectric layer represents the weathered and fractured top part of the buried basement rocks, which has an electrical resistivity ranging between $450 - 922 \, \Omega \cdot m$. This great variation in the resistivity may be due to the degree of water saturation according to the degree of weathering and fracturing of the basement rocks. Accordingly, the alluvial deposits in combined the weathered basement rocks constitute the groundwater aquifer which is reasonable to store groundwater in considerable quantities.

4- The bottom geoelectric layer represents the solid granitic rocks, which has an electrical resistivity more than $4000 \, \Omega \cdot m$ and it can act as a sub-surface barrier for any vertical percolation of groundwater.

The above results could conclude that the great thickness of alluvial deposits along with the weathered basement rocks could constitute suitable sites for storing the groundwater if surface management of flood water was achieved. Furthermore, it is noticed that the results of the VES’es which have been carried out along the studied profiles give an indication of the presence of the water-bearing horizon (de-saturated bed) at depths ranging from 10 to 20 meters. But, the drilling results did not obtain groundwater from this horizon where the groundwater usually occurs at a depth starting from, at least, 30 meter. This desaturated horizon is attributed to flash flood and rainfall waters which penetrate the alluvial deposits. This water didn’t have enough time to reach to the main water aquifer which indicates that a large quantity of surface flooding water doesn’t consume properly and the idea of constructing surface dams to facilitate the artificial recharge in the study area is worthy to be considered.

**CONCLUSION**

In this study, it was attempted to use ground geophysical measurements in order to develop the groundwater occurrences in the basement terrains. The wadis in the basement terrains are commonly suffering from flash floods, which usually produce, sever damage to the human utilities. If the flooding water could be controlled by surface dams and allowed to be stored in the subsurface aquifers, there will be a chance to develop the groundwater resources in these arid terrains. The detection of the subsurface aquifers, which will be suitable reservoirs for storing flooding water, is an ideal job for ground geophysical measurements including magnetic and vertical electrical sounding. Three wadis, namely W. El-Sheikh; W. Sahab & W. Solaf in the basement terrains of south Sinai, have been selected for carrying out ground geophysical measurements. The selection of these wadis based on several important reasons such
as the accessibility and the high population of Bedouins as well as the results of the previous hydrogeological studies that proved that these wadis are highly flooded sites. The ground geophysical measurements, in these wadis, have detected several shallow and deep aquifers, which are reasonable for storing of groundwater if surface dams are constructed to control the surface runoff of the flooding water.

RECOMMENDATIONS
1- Magnetic and vertical electrical soundings can be successfully used not only for locating water well sites in the basement terrains but also for controlling flash floods in order to avoid their damage and to develop groundwater quantity.
2- It is highly recommended to precede the geophysical measurements by hydrogeological investigation in order to decide the wadis which are suffering from flash floods.
3- It is highly recommended to apply this study as soon as possible in the basement areas of south Sinai such as Saint Katherine, Wadi Watir, Wadi Kid and Sharm El-Sheikh in order to control the flash floods which cause severe damage to the human utilities and use their runoff water to develop the groundwater resources.

REFERENCES

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