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Climate change impact and runoff harvesting in arid regions

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Abstract The most significant large-scale environmental challenge that many countries, especially in the arid and semi-arid regions of the world, will face in the middle and long-term are water scarcity problems, which are attributed to climate change impacts such as temperature increase, abundance of high solar radiation, and aridity in addition to population pressure. In many countries, current water resources use already exceeds sustainable and renewable supply. Various methodologies are suggested to increase the sources of water supply, among which one of the alternatives is rainwater and runoff harvesting (ROH). Water scarcity and additional stress are among the most specific problems in arid and semi-arid regions, where vegetation cover is very weak under extensive solar irradiation effects with high evaporation rates. Present global warming, climate change impacts, and their future patterns are expected to cause increase in the evapotranspiration rates and hence reduction in the groundwater recharges. Under such circumstances, any simple but effective water storage augmentation facility as the artificial groundwater recharge gains vital importance for sustainability of water supply and survivals in desert ecosystems. Although intensive and frequent rainfall events are rare they generate significant surface water flow during occasional floods and especially flash floods with huge amounts of surface water. It is, therefore, necessary to enhance artificial groundwater recharge from consequent frequent runoffs through suitable hydraulic structures. This paper aims at assessing the importance of ROH systems for domestic supply in arid regions with specific reference to the Kingdom of Saudi Arabia. For this purpose, it presents ROH from the surface flows in depressions of Quaternary wadi deposits in arid and semi-arid regions.

Keywords Aridity · Geology · Groundwater · Harvesting · Pipes · Quaternary deposits · Rainfall · Recharge · Runoff · Wadi

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Introduction

The Third and Fourth Intergovernmental Panel on Climate Change reports in 2001 and 2007 on climate change draw attention to the fact that completely unambiguous detection and attribution of climate change had already occurred, the "balance of evidence suggests a discernible human influence on global climate" (Santer et al. 2006; Kundzewicz et al. 2007). Climate change is expected to affect water availability and distribution implying infrastructure, and systems to manage water and especially groundwater resources. Global water resources will exhibit different spatial and time distributions. On this ground, rainfall frequency and intensity increases are expected at different place in the Arabian Peninsula (AP). Some areas will start to suffer from desertification, lack of rainfall, or flooding; but on the other hand, today, some arid-zones should change into more humid zones with significant groundwater recharges. There is no sufficient literature about how different climate changes may affect the infrastructure and complex systems built to manage water resources. At the same time, significant knowledge gaps remain and far more research is needed. Priorities and directions for future work should come from water managers and planners as well as from the more traditional academic and scientific research community (Şen 2008a).

Climate change also affects the water availability in terms of quantity and quality, which are reflected in the supply and demand patterns of water resources management. The relationship between groundwater recharge and climate change is significant for subsurface groundwater storage enhancements and increments. Among the most important questions are how do water and agriculture interact; how can they be managed sustainably? For this purpose, the following points must be taken into close consideration.

1. What are the current and future needs for irrigation water under a changing climate?
2. How can suitable locations for groundwater recharge (natural or artificial) through runoff harvesting (ROH) be determined?
3. How can various options in order to reduce the water demand and the risks associated with water distribution be managed?
4. How can the risk of water scarcity be best addressed in regionally integrated land and water managements?

The global climate change impacts are the most effective events with respect to sustainable water supply. The AP including the Kingdom of Saudi Arabia (KSA) and alike arid areas have one of the lowest per capita water availability worldwide. Due to recent urbanization and industrial developments, these areas experience rising water demands, while available water gradually decreases. One of the very early climate impact change study in the region is due to Nasrallah and Balling (1996) who provided the analysis of recent climatic changes in the AP. Climate scenarios for the AP based on general circulation (climate) models predict regional rainfall variability with slightly increasing trends at many sites (First Climate Change Report of KSA 2005). It is, therefore, of prime importance in arid regions to prepare for future climate impact mitigation and adaptation concerning groundwater resources and their natural and artificial recharge possibilities. Hence, construction of small water-harvesting structures across wadis is gaining importance in recent years. As for water resources and impact of climate change, Al Zawad (2008) presented a detailed study based on a software named "Providing Regional Climates for Impacts Studies" which is developed by the Hadley Center in England to produce high-resolution climate scenarios. His report mentions about a mean increase of 4.2°C of the daily surface mean temperature over KSA that is apparent for A2 scenario while it is 3.0°C for B2 scenario. The change values for precipitation, evaporation, runoff, and winds for A2 scenario were 37.1 mm/year, 20.8 mm/year, 1.1 mm/year, and 0.01 m/s, respectively. A slight decrease of the mean surface wind speeds of 0.1 m/s was registered by B2 scenario. The mean precipitation change for B2 scenario was 9.8 mm/year which is 23% of the present value and about half of A2 percentage increase (41% of the present). The mean evaporation for B2 was 48.9 mm/year and the runoff was 0.5 mm/year which is 79% of the present, but much less than the corresponding percentage increases for A2 (226% of the present). On the other hand, the study by Dennis (2009) presented some potential security and sustainability implications of climate change on the Persian Gulf countries. The challenges range from food provision to a growing population, to alternative energy generation in a context of growing demand and diminishing oil reserves in some of these countries. ElNesr et al. (2010) investigated temperature trends and distribution in the AP. They concluded that KSA as well as the AP are suffering from a considerable warming temperature trend, which is an important issue to be considered for rural development and water resources management. Recently, the study by Almazroui (2011) examined the sensitivity of the regional climate model (RegCM3) for simulation of intense rainfall events over the AP by considering domain size, boundary location, forcing fields, and resolution.

Currently, there is no standard approach adaptation to facilitate ROH designs. This paper provides available ROH standard design techniques after each storm rainfall for artificial groundwater recharge possibility. It is also among the main purposes of this paper to review possible ROH facilities, to propose a systematic procedure for identification of suitable locations, and to provide comparative discussion for their application in the field with possible application in the KSA as a representative of arid regions.

Arabian Peninsula geological features

Groundwater resources are attracting an ever-increasing interest due to scarcity of good quality subsurface water and growing need of water for domestic, agricultural, and industrial uses under the increasing impacts of the climate change future patterns. Especially in arid regions, groundwater resources are highly demanded. The possibility of increasing frequency and intensity of rainfall over the AP provides a significant opportunity to replenish groundwater resources through ROH provided that rational and systematic planning, construction, operation, and maintenance of harvesting structures are effectively put into action. Hence, water scarcity can be sorted out to certain extent by ROH into potential aquifers. In Quaternary wadi deposits, availability of groundwater is of limited extent. Occurrence of groundwater in such deposits is essentially confined greatly to porous horizons that are underlain by weathered and subsequent fractured zones. Efficient management and planning of groundwater in these areas are of utmost importance.

It is a well-established fact that geological setup of an area plays a vital role in the distribution and occurrence of groundwater (Krishnamurthy and Srinivas 1995). In the AP, Quaternary wadi fills are structurally controlled and the materials are mainly sheet wash from the plateau area and pediplains. They consist of alluvial along the various streams of the watershed. This geomorphic unit acts as good prospective zone for groundwater development. Eroded pediplains are seen along the stream channels of high- and low-lying areas. Highly fractured, weathered, and dissected plateau units show lateral formation, which covers most of the wadis. Pediments have generally low permeability, poor infiltration rate, and are around the dissected plateau regions, high elevations, and water divide areas with irregular shapes and sizes (Al-Sayari and Zötl 1978). Especially, in the western regions of the AP, Tertiary basalt flows cover wadis leading to buried channels. They are formed due to coalescence of buried pediments having thick overburden of weathered materials. They have high porosity, permeability, and infiltration rate and their groundwater prospects are of moderate to good potential.

A lineament is defined as a large-scale linear structural feature, which may represent deep seated faults, master fractures and joints sets, drainage lines, and boundary lines of different rock formations. Lineaments provide the pathways for groundwater movement and are hydro-geologically very important (Sankar 2002). They are important in rocks where secondary permeability features (fractures) play significant role for natural groundwater recharge movement and availability.

On the other hand, geomorphology of an area is one of the most important features in the groundwater prospect and potential assessment. It controls the subsurface movement of groundwater and also surface water through dissections, depressions, wadi channels, and faults.

Pipe-born supply of water is not available in many poor rural areas of the AP, but their only source of water is from shallow groundwater storages in Quaternary alluvial deposits, which may not be sustainable throughout the year. It is, therefore, very suitable to install convenient and innovative ROH structures at potential locations or groundwater enhancement in the form of artificial groundwater recharge after each storm rainfall event, which provides an opportunity for self-reliance in nearby communities. Since some of the storm rainfall over the AP has high rainfall rates, ROH hydraulic structure construction is an ideal way to promote self-sufficiency in these rural communities, especially during period of scarcity and dry season, which may last for many months.

It is possible to combine a range of culturally appropriate ROH technologies together with a local water action plan as a drought model in arid regions. The ROH initiative in the AP as it is among the purposes of this paper tries to form part of a global sustainable development initiative with the following objectives.

1. To prove that the ROH, if planned and organized in an efficient way provides additional subsurface groundwater storage in support of additional water supply for drought-prone areas or in arid regions such as the AP,
2. Reduction of flood risks at the downstream of the concerned wadi,
3. To conserve on-site potable water use,
4. To meet local stormwater management requirements to protect surface water quality and to minimize flooding in the Quaternary alluvial channels,
5. To enrich unconfined aquifers in the Quaternary deposits by recharging the unsaturated zone.

Kingdom of Saudi Arabia

In the KSA, the groundwater storages can be viewed in two broad categories as areally extensive and interconnected granular medium (Quaternary deposits) of sedimentary rocks and the fractured medium. The former covers very extensive areas including the whole of eastern provinces, which constitutes the two thirds of the country and the dissected wadi course alluvium sediments on the western parts made up of igneous rock bases and metamorphic rocks with volcanic intrusions. The groundwater recharge is more on the sedimentary rocks but the recharge rate is smaller than the fractured aquifers, which have very small areal coverage.

The first groundwater recharge study within the KSA is made by Dincer et al. (1974) who concluded that for recharge to occur in the sand dunes, the rainfall amount should be over 50 mm. This conclusion is obtained after the stable isotopes study on groundwater samples collected from the area. Caro and Eagleson (1981) applied a water balance approach for groundwater recharge estimation in the central AP with values ranging from 10 to 24 mm and from 1 to 6 mm, respectively. Ghurm and Basmaci (1983) stated that the groundwater recharge in the upstream of wadis may reach up to 41%. Al-Kabir (1985) noted that deuterium excess of groundwater samples collected from wadis showed recharge from high-intensity summer rainfalls. Abdulrazzak et al. (1989) used water balance approach to one of the wadis in the southwestern region of Saudi Arabia and they estimated that only 3% of the rainfall occurs as runoff out of which 75% contributes towards groundwater. Bazuhair and Wood (1996) used chlorine balance method for groundwater recharge estimations in the wadi aquifers within the western region of the KSA. This methodology is further developed by Subyani and Şen (2006). Geological outcrops are also related to groundwater recharge calculations by Subyani and Şen (1991).

Groundwater recharge estimation from ROH is one of the most significant hydrological component calculations especially in arid regions such as the KSA where the spatial and temporal rainfall variations are sporadic and irregular. The rapid agricultural, rural, and industrial trends in the KSA have changed drastically the groundwater storage and exploitation. Consequently, due to groundwater abstraction in excess of recharge gave ways for groundwater piezometer falls in many parts of the KSA. This led to excessive costs in water pumping in addition to reduction in the rate of abstraction. If proper groundwater managements are not planned by taking into consideration the recharge possibilities and ROH, then the groundwater storages may be depleted in several years. It is, therefore, very necessary to have reliable groundwater recharge rate estimations in order to delineate the recharge and injection (recharge) well-field areas, to control regional groundwater movement, and to keep a balance between the abstraction for water demand and water availability. The following points indicate types of information expected as relevant to water resources in the KSA.

1. Future climate change scenario predictions by taking into consideration the local temporal and spatial data variability,
2. Future water availability, supply, and demand based on the relevant climate scenarios,
3. Future regional database development on water resources including extreme events (droughts and floods),
4. Assessments of combined effects of future land use, climate change, and variability on water resources,
5. Information on frequencies and effects of climatologic and hydrological extreme events,
6. Identification of ROH locations depending on the future climate change scenarios together with the local geological, geomorphologic, and demographical features.

Runoff Harvesting

ROH is a means of rainwater collection for water supply in arid and semi-arid regions of the world by means of suitable water structure setup on Quaternary alluvium channel rainwater for groundwater storage recharge on the one hand during medium ranges of water scarcity and direct water haulage on the other hand from the surface reservoir during short-term scarcity by means of water transportation through tankers to adjacent areas especially for agricultural activities. ROH technique can be adapted in arid and semi-arid countries in order to provide an innovative solution to water shortages. The following points are important for rainwater and subsequent ROH in arid regions.

1. Supplemental water source for sustainable agricultural production, livestock, and small-scale settlement water demand,
2. Enhancement in water resources through ROH encourages local inhabitants to continue their activities without temporary or continuous migrations,
3. It also helps nearby towns and villages for population reduction or sustenance. It is also necessary that these local settlements do not accept additional migration,
4. Traditional settlement and agricultural activity locations indicate possible revival of lands for water related areas. It is also useful to benefit from the expert view of local settlers,
5. ROH helps strategically to reduce the additional water stress at settlement areas,
6. Rainfall and subsequent ROH help to improve the groundwater quality also.

A cost-effective technique might be very efficient in comparison to large-scale infrastructural project. ROH represents a viable solution for poor water-scarce communities and countries to advance their attainment of the United Nations Millennium Development Goals on water, sanitation, and poverty alleviation. Especially in desert areas of the world, the ROH aims to provide a sustainable freshwater source for rural communities through a number of innovative strategies designed to promote traditional ROH technologies. It is possible to develop culturally appropriate ROH technologies for rural village communities in semi-arid and drought-affected regions of the world.

Initially, the ROH starts as a small-scale project by constructing a basic rainwater reservoir and even helps to provide water delivery via tankers to several nearby drought-affected communities over the next few years after each storm rainfall event.

The main purpose of the ROH is to provide a sustainable source of water for agriculture to guarantee reliable production of local food, to improve community health (by reducing the level of water borne diseases), to stimulate sustainable economic growth through a revival of the water dependant agricultural industries, to improve local environment especially in terms of groundwater recharge in arid regions, and to protect biodiversity.

ROH should also address the following three significant points in determining the size of the surface ponds.

1. To conserve or capture as much water volume as possible. This follows the traditional use for ROH and is met by on balancing water demand with supply. Conservation of water is achieved simply by utilizing

harvest waters for uses that would otherwise be supplied by potable water.
2. To drain this volume into subsurface permeable geological layers as fast as possible.
3. To reduce the risk of flood danger at the downstream areas. This requires an innovative use for ROH and stormwater management. It is realized only if the collection and storage components are large enough to capture that part of the storm that would otherwise be treated by stormwater treatment and detention devices.

Effectively meeting stormwater management obligations through an appropriately sized ROH system leads to the development of a financial benefit, which equals the costs of construction facilities to meet local stormwater management requirements for flood control and groundwater recharge amounts.

ROH has existed as a water supply source technique since circa 1500 B.C. (Hunt et al. 2006). The most basic systems as they can be applied in wadis of arid regions require identification of a potential surface water impoundment and groundwater recharge possibility location by considering the following items.

1. An effective catchments area for surface water concentration and conservation in surface ponds,
2. Construction of a pond or a small dam or aqums (earth-filled surface barriers along the potential location across the surface flow direction),
3. An efficient surface water and groundwater recharge conveyance system such as surface depressions, excavations, wells, vertical pipes, or surface water injection into porous and permeable subsurface strata,
4. Piezometer locations at a set of downstream points and their proper design for groundwater level measurements.

Since ROH water is naturally soft (with its electric conductivity, EC<200 ppm), it often does not meet drinking water standards (Meera 2006). In order to serve as a potable water source, some level of treatment or better mixture with groundwater must be affected (Şen et al. 2003; As-Sefry et al. 2005).

Recharge potential and ROH

Groundwater is the major freshwater source especially for arid and semi-arid regions, but unfortunately there has been very little attention or study on the potential climate change effects on these freshwater resources (IPCC 2007). Most of the works are concentrated on humid regions. Aquifers in arid and semi-arid regions are replenished by floods at possible recharge outcrop areas through fractured and fissured rocks, solution cavities in dolomite or limestone geological setups, as well as through main stream channels and depressions of Quaternary alluvium deposits (wadis). At convenient places along the main channel, engineering infrastructures such as levees, dikes, successive small-scale groundwater recharge dams, and artificial depression ponds may be constructed for groundwater recharge augmentation. Especially, ponds help ROH for runoff conservation after each storm rainfall event.

The unconfined or shallow aquifers that are in contact with present-day hydrological cycle will be affected by climate change and they are also suitable geological formations for ROH possibilities. On the other hand, deep and especially confined aquifers are not in contact with the present day hydrological cycle and consequently their effect from climate change is virtually negligible. They include fossil groundwater storages, which are not replenishable.

Groundwater recharge and ROH have a random behavior depending on the sporadic, irregular, chaotic, and complex features of storm rainfall occurrences, geological layer composition, and geomorphologic features. Although it is rather complex for control, it controls the spatial and temporal groundwater recharge in nature. In areas of perennial surface water flow, there are continuous infiltration and consequent groundwater recharge along the main flow channel in all seasons and especially in summer. In arid regions, such as the KSA, the recharge possibilities are available in an intermitted manner due to occasional storm rainfall occurrences and their ephemeral streams for some seasons. Recharge is irregular and occurs during periods of intense rainfalls, which is mainly during the winter season in the northern hemisphere. Otherwise, the rainfall only wets the top soil of the unsaturated zone without any water reaching the groundwater storage. ROH enhances groundwater recharge facilities especially in arid regions.

Although ROH is an old technique, but due to water scarcity, stress, and climate change impacts, its use is resurfacing in the modern times as one of the simplest adaptation methodology in arid and semi-arid regions. Their use exists since time immemorial for collecting and storing from rainfall, rainwater, and runoff. In the past, ROH techniques are used mainly for different purposes including watering, agriculture, husbandry, and even drinking. There are five major benefits from their use in recent years, which are,

1. To support water stress,
2. To reduce water scarcity effects,
3. To provide additional water supply at lower costs,
4. To improve water quality by artificial mixture,
5. To relieve the climate impact to a certain extent.

The most convenient way of ROH in arid and semi-arid regions is the collection of surface water at convenient places for various uses as,

1. Direct and local use,
2. Long distance transfers in arid regions,
3. Most significantly to enhance groundwater recharge.

In its simplest form in arid climates, rain ponds for ROH are often used to store water during the rainy season for use during drier periods. ROH ponds may have a reasonable initial cost. ROH water is valuable due to its purity, softness, nearly neutral pH, and intact from disinfection by-products, salts, minerals, and other natural and man-made contaminants. Additionally, rainfall water fed agricultural products provide the best quality of vegetables and crops.

Archeological evidence attests to the capture of rainwater as far back as 4,000 years ago, and the concept of rainwater harvesting in China may date back 6,000 years. Ruins of cisterns built as early as 2000 B. C. for storing runoff from hillsides for agricultural and domestic purposes are still standing in Istanbul, Turkey (Şen 1998). Advantages and benefits of ROH are numerous (Krishna 2003).

1. The water is almost free of charge and the only cost is for collection and use.
2. The end use of ROH water is located close to the source, eliminating the need for complex and costly distribution systems.
3. ROH provides a water source when groundwater is unacceptable or unavailable, or it can augment limited groundwater supplies.
4. Almost zero hardness of ROH water helps to prevent scale on appliances, extending their use. It also eliminates the need for a water softener and the salts added during the softening process.
5. ROH is sodium-free, important for persons on low-sodium diets,
6. ROH water is superior for landscape irrigation.
7. ROH reduces flow to stormwater drains and also reduces non-point source pollution.
8. ROH helps utilities reduce the summer demand peak and delay expansion of existing water treatment plants.
9. ROH reduces consumers' utility bills.

ROH provides water conservation in groundwater storages through a pit or recharge pond in order to support the water supply during non-rainy season, without endangering the environment conditions. Such ponds with their various dimensions, depending upon physiographic and hydrogeological conditions allow percolation and recharge to groundwater. Accomplishment of a successful ROH enquires the following prerequisites:

1. Determination of recharge point locations,
2. Identification of surface and sub-surface hydrological properties of potential locations,
3. Environmental and social responsibilities of local settlers.

The selection of recharge points depends on the identification of permeable zones along the wadis. In case of no sufficiently permeable zone, the groundwater cannot move from one place to other and the water would come up through the recharge point and reach the surface, which is not desirable in arid and semi-arid regions because they will be lost due to evaporation. In such cases, it is necessary to make additional subsurface permeability augmentation operations similar to what have been used in the past as kanats (Şen 1995).

In general, engineers and common people alike start to think of large water structures such as dams, derivation tunnels, canals, pipes, etc. for water storage and transportation in addition to groundwater abstraction during drought periods; but unfortunately, ROH, groundwater recharge by injection wells, or by any means after each storm rainfall is not a common thought among the researchers, planners, administrators, and people alike. However, such water structures are available and constructible in cases of water availability and settlement localities that can support its construction and maintenance. Unfortunately in many parts of the world, most often the people are not able to access to such water structures and therefore they have to depend on local water resources, which are the groundwater storages in many cases. However, exploitation of groundwater is easy by drilling or digging wells but after some time, due to poor recharge, the groundwater levels fall rapidly, which brings with it additional problems such as the extra energy request, groundwater quality variations, and most dangerously mining of groundwater storages and hindering the sustainability. It is, therefore, necessary to enhance by any means the groundwater resources; and the most simple but effective means is the ROH, which has been in use since time immemorial. Perhaps, present-day technological developments pushed the ROH as an inefficient way of water harvesting, but it is one of the most effective means for groundwater enhancement especially in arid regions where there are occasional storm rainfall occurrences and depending on the surface features also flash floods, which are potential water resources for dry regions. ROH application does not require high-economical investments and at its simples case it can be achieved by locally available means provided that there is a good intention for its application. Especially at places where water is inextricably linked to poverty, such simple but efficient and effective approaches provide solutions for relevance of some water problems. In some countries, the recharge of groundwater is supplemented from the river flows and likewise wadi flows after each storm rainfall provide some significant amount of water and its impoundment into the groundwater aquifers gives opportunity for groundwater exploitation during drought periods. It is well-known that with ROH, even the poor can have water because rain falls everywhere. ROH applications in practice can be categorized as follows:

1. Natural or artificial depression storages depending on the geological stratigraphic composition of the area and surrounding areas, where depression possibilities are possible,
2. Artificial recharge of groundwater water after each storm rainfall,
3. Stream improvements within settlement areas and to let the surface water to convenient depressions instead of their forever loss in the seas or deserts.

At some places, it is possible to collect about 25% of the overall water demand from simple storages through ROH. Women are more active in ROH by tanks because they have the main responsibility for household activities. ROH helps to ensure environmental sustainability according to integrated principles of sustainable development into country policies, programs, and reverse loss of environmental resources.

Systematic ROH work

An effective planning, design, operation, and maintenance of an ROH work need two phases for the successful completion of overall procedure. These are preliminary and detailed office work and field study in the proposed study area for the implementation of ROH structure. Figure 1 presents the necessary steps and flow diagram for office work and it is self explanatory. Relevant maps (geographic, geologic, structural geologic, subsurface geologic, topographic, etc.) are necessary for preliminary concentration on the potential locations. In the mean time, satellite images and remote sense facilities are also very supportive documents in such a preliminary identification. Isohyetal rainfall maps in terms of single storm rainfall occurrences provide very useful information as for the most potential location for ROH location together with the availability of all the previously mentioned maps.

All these preparations provide information base for the problem diagnosis, which help to have an expert view about the preliminary recommendations, approximate location identification, and first lay out for possible well locations

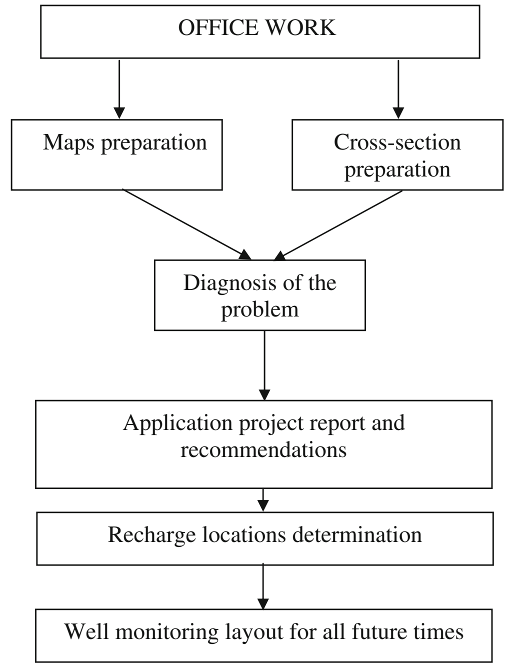

Fig. 1 Office work flow diagram

(piezometer or observation wells) for future monitoring. Based on such information ensemble, the experts are ready for better precision improvement by setting out to field trips of several times with adaptive treatment of collected information with office work fundamentals. Figure 2 indicates various meaningful steps for field work in the form of flow chart. The major work lies within the field trips, because now the actual and factual information and test of preliminary information from the office work are under treatment. The most suitable location for ROH is decided with many

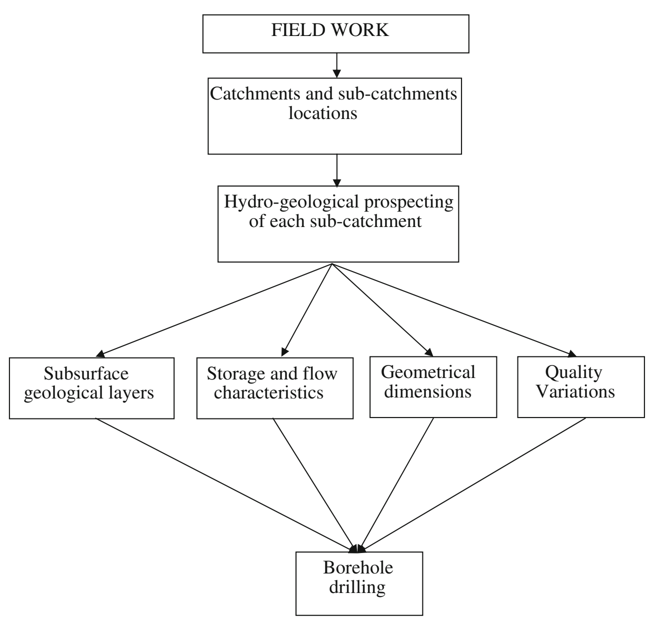

Fig. 2 Field work flow diagram

consultations among different but concerned specialists leading to a common consensus. Subsequently, the major catchments and its branches are identified leading to the rainfall-runoff calculations in wadis (Sen 2008b).

Application

The application of all the phases and steps mentioned in the previous section are applied at Al-Ghat Dam, which is situated in the Riyadh (capital of the KSA) region (about 220 km north of Riyadh). It is an earthen dam having a length of 250 m and a height of 11 m. The storage capacity of the reservoir is about 1.0×10^6 m^3 and the dam was built with the purpose of groundwater recharge. The catchments area is about 43 km^2, the perimeter is approximately 40 km, and the total stream length is about 82 km. After the impoundment of surface water behind the constructed small dam, vertical pipe feeders are located for ROH into the subsurface quaternary deposit deposits (Fig. 3). It shows the location of feeder pipes for speeding up the groundwater recharge into the aquifer beneath the location and then onwards subsurface flow towards the downstream of the wadi. A flood came in December 2006 and filled the pond as shown in the figure. The people in the surrounding communities started to haul water directly from the pond by trucks for at least 7 months. In the mean time, groundwater recharge continued to take place in an augmentative manner in the subsurface towards the downstream localities, where again local settlers could abstract groundwater through their large diameter wells. Water vendors normally sell water in remote areas for a very high price, but even with an average price of 6 Saudi Riyals per cubic meter, the savings of the local residents from only one flood in one location is about 1.5 million Saudi Riyals. It is interesting to mention here that the estimated cost of the construction of the pond at is about 2 million Saudi Riyals. The application of the recharge pipes (feeder pipes) at Al-Ghat Dam has resulted in speeding the recharge to groundwater in the area downstream of the dam

A major flood in April 2008 completely filled Al-Ghat Dam. It took only 11 days to convey almost all the impounded water behind the dam into subsurface through the aforementioned design of a set of recharge pipes. Otherwise, the water used to stay in the dam for many weeks or months before the installation of the recharge pipes. Another flood came in November 2008 and measurements of water level and quality in a farm downstream of Al-Ghat Dam showed substantial improvements in groundwater level and quality. The water level had risen by 11.6 m in one of the downstream wells 14 days after the beginning of the artificial recharge process and the total dissolved salts have decreased from 2,752 to 1,536 ppm.

Hence, ROH possibility provides additional groundwater source into already available aquifer domain and such structures are expected to increase in the arid regions of the world for groundwater augmentation especially with the effect of climate change impacts in the AP. Although annual average precipitation predictions have decreasing trend in the Mediterranean region and northern parts of the AP by 10–20%, increasing rainfall trends are expected at 10% and 30% in the southwestern part of Saudi Arabia, Yemen, United Arab Emirates, and Oman (IPCC 2007). It is possible to conclude from these figures that the central AP will also experience rainfall increases due to climate change but at lesser percentages. In general, the AP will have increasing rainfall trends from north to the south and from the Red Sea in the west to the Arabian Gulf at the east. Such a rainfall pattern is plausible because due to temperature increases all over the AP, higher evaporation rates from the surrounding surface waters (Red Sea in the west, Arabian Sea in the south and Arabian Gulf in the east) will penetrate the AP and most often orographic and occasional convective rainfall occurrences will take place depending on the locations and seasons of the year. As for the AP, monsoonal air movements and their penetrations must also be taken into consideration especially for the eastern and southern parts of the AP. All these explanations imply flood and flash flood expectation frequency and

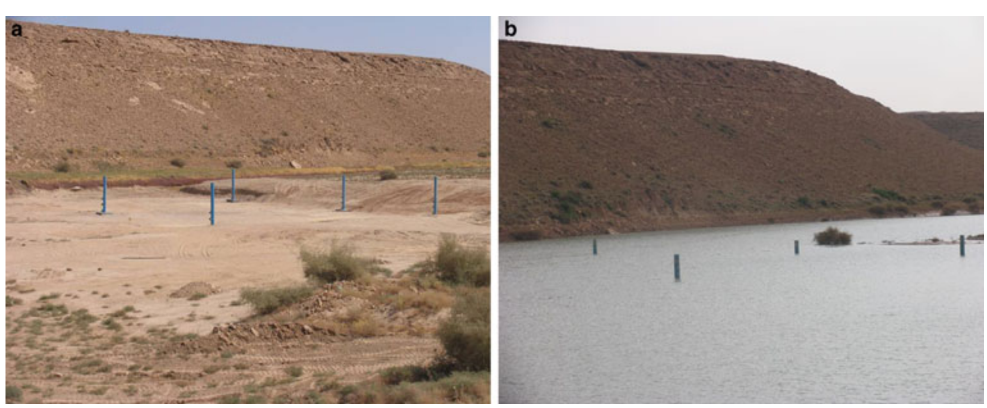

Fig. 3 Ghat site **a** before the storm rainfall and **b** after the storm rainfall

magnitude increases, which justify construction of ROH structures at convenient locations for groundwater recharge.

Conclusions

Arid and semi-arid regions of the world are in need of additional water resources for water supply and irrigation (food production) activities. Each country tries to be self-sufficient and dependent on national water resources and hence various structural plans and designs are implemented for water resources capacity increment. The only natural source in arid and semi-arid regions is the groundwater storages in confined and unconfined aquifers. Especially, Quaternary deposits in wadis are the most suitable groundwater recharge locations, because after each rainfall surface water occurs as runoff, which should be rendered into beneficial uses prior it's lost in deserts due to extremely dry conditions and high evaporation rates. Many climate change scenarios indicate that the rainfall occurrence frequency and magnitude are expected to increase in the future and hence accordingly similar increases are also expected in the flood and flash flood occurrences. For this purpose, the necessary procedures in their detailed steps are presented for ROH. The application of ROH methodology to an area near Riyadh, Saudi Arabia is implemented under the guidelines presented in this paper. It is hoped that the similar procedure will be useful at some other parts of the world for groundwater storage augmentations after each storm rainfall and subsequent runoff occurrences.

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