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Water harvesting: Groundwater storage reservoir in Wadi Ishe, Jordan

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Wadi Ishe pilot project is a trial project set to illustrate the recharge of runoff and storage in an artificial groundwater reservoir to minimize evaporation losses and as a substitute of water supply for rural arid areas that could be used for stock watering and some agricultural activities. The HEC-Hydrologic modeling System was used to estimate the runoff potential. The model in the research will provide possibilities for the simulation of precipitation-runoff procedures. The hydrographs shows a 10 years return period with a total yearly precipitation of 44 mm and total loss of 35.3 mm gave a total runoff of 8.7 mm. The total precipitation volume for the years 2000-2010 within the catchment area was approximately 36.14 Mm³. Designed to intercept the groundwater flow in connection with a flood in the Wadi Ishe basin, an underground dam was constructed from the base of the wadi channel all the way up to the surface (about 3 m height). A well was incorporated upstream of the barrier to extract the stored water from the underground reservoir. The porosity of the refilled reservoir test section was calculated to be 20-23%. The annual storage of the subsurface reservoir is approximately around 300 m³/year, where there is an average of 5 annual rain events in that area. In the catchment area another 11 potential sites were identified using the site selection criteria that was developed. Those sites once implemented using this technique would make a clear difference in water availability and enhance development around Wadi Madoneh. With this study the in different regions of the world already applied technique of groundwater dams could be first time also effectively implemented in small arid wadi catchments by using an adapted improved new technology by combining harvesting and artificial recharge effects.

Key words: Groundwater reservoir, Jordan, rainfall-runoff model, surface runoff Wadi Ishe, water harvesting.

INTRODUCTION

Jordan is a parched nation with inadequate resources of freshwater. The water accessibility is categorized as 'very low' on the Index of Water Stress. The over-all resources of renewable freshwater in Jordan are approximated at 850 Mm³/year or 167 m³/capita/year (MWI, 2004). The Kingdom of Jordan is confronting a constant inequity between the aggregate water demand and the available source of freshwater within sector. It is expected that by 2020, the total demand for water will increase to 1,685 Mm³.

Only around 2.2% of Jordan's land receives an average annual precipitation of more than 250 mm; 29.1%

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receives less than 100 mm (Jordan Department of Statistics, 2000). In addition to climatic conditions, social and economic factors, which includes water price combined with agricultural policies, which focus on an increase and intensification of agricultural production, influence the development of land use and water consumption. The increasing pressures on the available water resources in Jordan represent a challenge for scientists, engineers and policy makers involved in the development sector in different fields that are dependent upon the water resources availability (Talozzi, 2007).

The purpose of the research is to demonstrate, that within arid to semiarid areas the temporarily existing groundwater flow in the alluvial fillings of small wadi channels can be used for water harvesting. Practices of run-off harvesting regarding freshwater increase had been experienced in dry areas since 4000 BC (Prinz, 1996; Botha and Anderson, 2007). Rainwater harvesting can be termed as the various methods that are deployed for the storage and collection of runoff from rainwater for agricultural and domestic uses (Sánchez et al., 2015).

Groundwater recharge development (including practices of artificial recharge and water harvesting) is seldom practiced in arid environments (Dillon et al., 2010). Valley alluvium offers an ideal water storage medium in various areas globally. It generally forms high permeable aquifers, which includes a high rate of porosity for water storage. Alluvium mainly consists of coarser materials, such as sand, gravel etc deposited by streams and rivers in valleys frequently eroded in hard or dense rock sequences and later filled up by the alluvial deposits in periods of accumulation. In case of an impervious surrounding hard rock the alluvial channel can be easily dammed up with a clay barrier across the alluvial channel (Prinz, 2002; Raju et al., 2006), so that the section upstream of such an artificial dam might serve as an underground reservoir. The advantage of this kind of underground storage is that the water in the underground is protected from the high evaporation loss compared to surface reservoirs (Van Haveren et al., 1987). Another advantage is that the groundwater flow generally does not contain high sediment load, while storage of flood water in surface reservoirs cause high sedimentation rates, this is especially the case in arid areas.

A subsurface dam is built below the level of ground surface, which prevents discharge of the natural groundwater from the section above the dam (Onder and Yilmaz, 2005; Suk, 2012). Subsurface dams are generally constructed at a location, where an aquifer is widely distributed with permeable alluvium sediments. Loss due to evaporation is considered negligible in groundwater dams, which is an important factor in semi-arid regions (Hanson and Nilsson, 1986).

Onder and Yilmaz (2005) summarized the advantages of groundwater dams in comparison to surface dams, which includes:

1) It has a longer lifespan.
2) The ground above the stored water can be used.
3) Stored groundwater with a constant temperature and better quality can be obtained throughout the year.
4) It is easy to be constructed.
5) The groundwater can be used effectively.
6) Sustainable development of water resources can be achieved.

Various groundwater dams have been constructed in Europe, Asia, Africa and America (Foster and Tuinhof, 2004; Raju et al., 2006). According to Schumacher (1973), masses of villagers of the emerging nations, can relish from the available systematic knowledge on self-help approaches of water storage, low-cost, transport, and protection. Synthetic aquifers formed by edifice of barrier dams with the hand tools, community labor assistance, local materials, and represent an applicable technology for the availability of high-quality water to small populations within region suffering from arid (van Haveren, 2004). In Korea, six groundwater dams have been constructed and are in operation, their storage capacity ranges from 16,000-43,000 m³ and were mainly developed for agricultural use (Suk, 2012).

In Kenya, sub-surface water dams are constructed for stock watering and irrigation with height 2-5 m, and width of 30 m (Barron et al., 2003). In his findings, Suk (2012) found that thickness of the alluvial layer affects the storage capacity largely. He also concluded that geological conditions such as distribution of alluvial zone were more important factors than an efficient groundwater dam construction. In Malibogazi, Turkey, the groundwater dam of storage capacity of 55,000 m³ increased the groundwater level about 2 m. Particularly, groundwater amount has been augmented to 6,500-7,000 m³ within the dam reservoirs (Apaydin 2009).

Groundwater harvesting with underground storage has not been realized in Jordan. For the demonstration of this option especially for groundwater flows in small valleys, the valley called: Wadi Ishe project was initiated and performed. This pilot project is a trial project for the illustration of the reimbursements of runoff storage in sedimentary aquifer channels by subsurface dam as a supernumerary water supply for Jordan rural arid areas. With growing water demand and water scarcity coupled with flood hazards due high intensity and abrupt rainfall events, groundwater reservoirs can be an option for water harvesting connected with artificial recharge and in mitigating flood negative effects in Wadi Ishe basin.

DESCRIPTION OF WADI ISHE SITE

Location and catchment

Wadi Ishe site known also as Wadi Madoneh is approximately 9 km south of the city of Zarqa. Zarqa governorate is approximately 15 km east of Amman

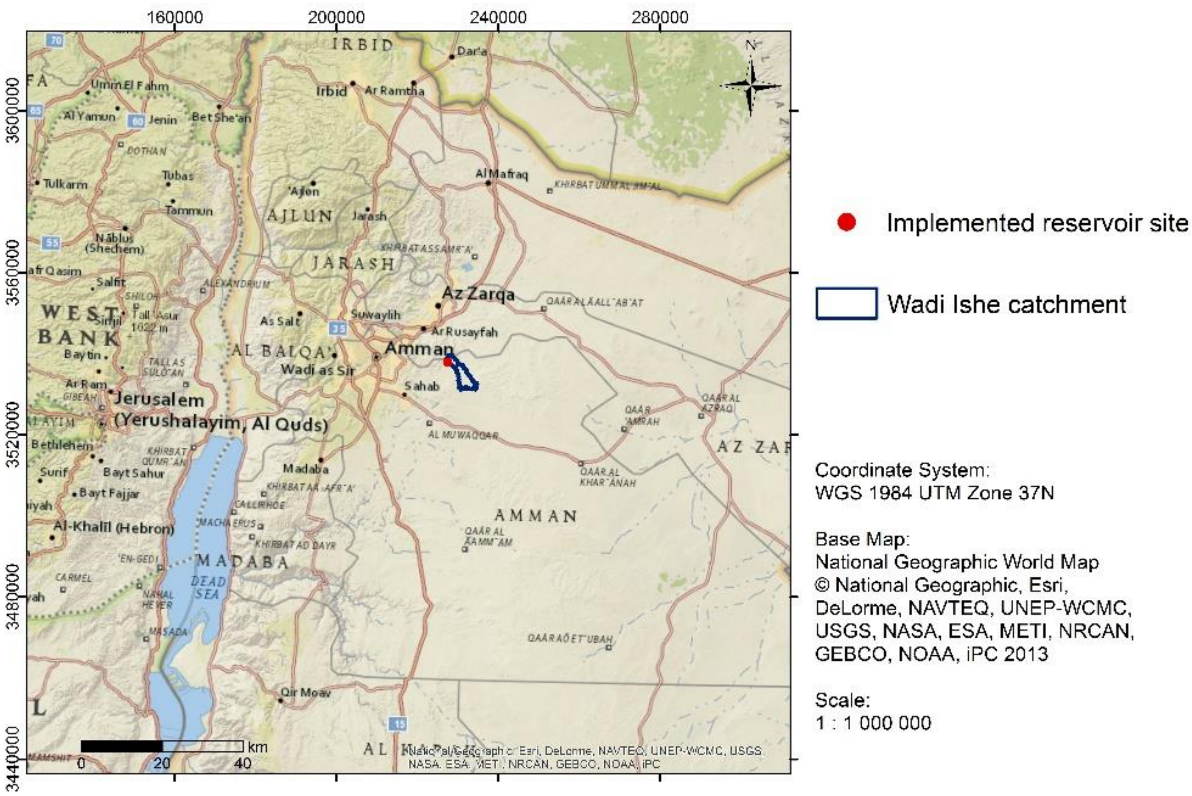

Figure 1. Location of Wadi Ishe Groundwater reservoir.

(Figure 1). Wadi Ishe watershed is located within the upper reaches of the Zarqa drainage river system. Land use approximately in Wadi Ishe pilot site is largely unclassified due to lack of survey. However, in the upstream areas there are some cultivated areas. The area at the outflow point of the watershed is undeveloped and uninhabited. There are small houses and small farms within a radius of 7 km from the general site area. Some grazing activities are around the catchment area. Wadi Ishe catchment has been classified as bush land/range land. Some industries like battery recycling plant and a sulfo-chemical plant is located downstream around 10 km of the site. Wadi Ishe area can be classified as an undulating to hilly area (Qaisi, 2008). The bed elevations ranges between 700 m to 725 m above sea level, and hill top elevations are between 950 m - 975 m above sea level. Archetypally, groundwater storage technologies are used, when the topographical gradient of the riverbed is between 0.2 and 4%. The general topography becomes hilly towards the northern downstream. From wadi bed, the topography rises steeply over a short distance and slopes range up to gradients of 25%.

Geology of Wadi Ishe

The outcropping rocks belong to the Upper Cretaceous, which is subdivided into two major groups: the lower part is the Ajlun Group and the upper part is the Belqa Group. The Ajloun group overlies the Kurnub Sandstone of the Lower Cretaceous. Thick carbonate sediments (limestone, dolomite and marl) form the pre-dominant lithology and the thickness of the whole group reaches about 600 m (Abed, 1982).

The upper most formation of the Ajloun group is the Wadis Sir Limestone, which is outcropping in the northern part of Wadi Ishe (Figure 2).

For the geological description in general: Al (Alluvium) and s (sand/ soil) are of Holocene age and Pl (fluviatile and lacustrine gravels) is of Pleistocene age. WSL (Wadi as Sir Limestone) belongs to Ajloun Group, while the others (ASL, MCM, URC, and WG) belong to the Belqa Group. The bedding of the Cretaceous sediments is dipping slightly to east and southeast. The underground dam and reservoir is located in the small outcropping zone of the relative impermeable Umm Ghudran marls.

The parent rocks and the morphology closely control the soil formations in the Wadi Ishe catchment in general with thickness of 0.5-1.5 m thick. Soils surrounding the groundwater reservoir consist mainly of in situ weathered and dissected silicified limestone, in places where the Wadi Umm Ghudran marls outcropping the soil is enriched with marly and clayey material. The grain sizes on the surfaces are sandy to gravely, towards the depth

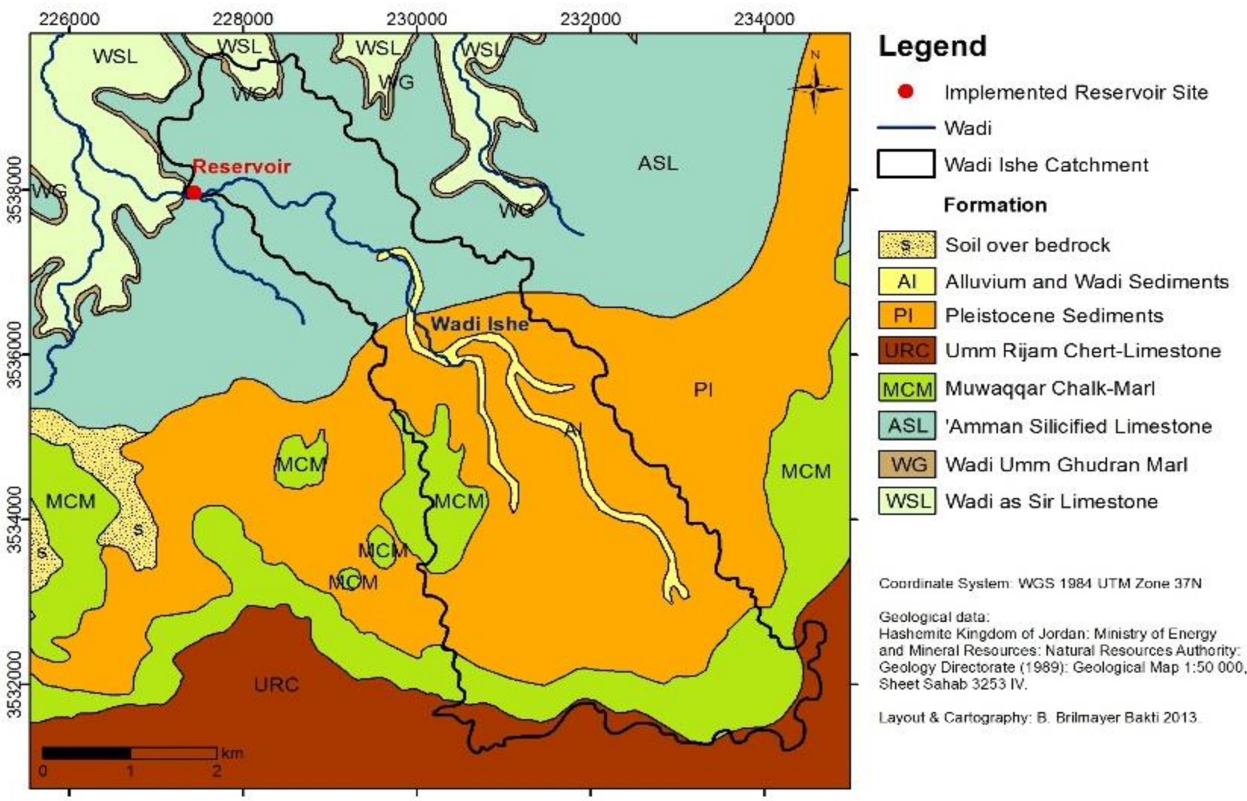

Figure 2. Geological map of Wadi Ishe catchment with location of the groundwater reservoir. (Jordan Ministry of Energy and Mineral Resources, Natural Resources Authority, 2013)

unweathered coarse pebbles predominating. In the southern part of the catchment, where steep slopes dominating the soil general consists mainly of coarse talus material.

SURFACE RUNOFF AND RAINFALL-RUNOFF MODELS

HEC-HMS model

The climate of Wadi Ishe area is described by mild winters and hot summers. The data is precipitation for the recent 10 years - from 2000 to 2010, water years designate that, the average precipitation in the year is approximately upstream basin and the pilot site, ranges between 120 to 150 mm. The average potential evaporation that has been observed annually is approximately 1,075 mm. The real evaporation losses are about 90% of the precipitation leaving only 10% for runoff most of which in connection with flash floods.

In Wadi Ishe pilot site, a hydrologic model was established in order to evaluate the runoff potential by means of the Hydrologic Modeling System of the Hydrologic Engineering Center (HEC, 1998). The model of HEC-HMS offers various options for simulating precipitation-runoff procedures. For HEC-HMS model, the following data are required:

1) The Catchment and its sub-basins parameters, which includes area, slope and main channel length.
2) The hydrologic modeling methods including rainfall losses, excess rainfall calculating method, and the runoff hydrograph development method. There are more than one option for the calculation depending on the available data, in our case we used the Curve Number method to calculate rainfall losses and excess and the SCS Unit Hydrograph method to develop the runoff hydrograph.
3) Design storm depth, where historical daily rainfall data for stations in the study area are used to find the depth of the design daily storm.

Soil conservation service curve number loss technique

The purpose of the loss method within HEC-HMS was to determine how much of the rainfall would eventually become runoff. The soil Conservation Service, CN (Curve Number), and NRCS (National Resource conservation Service) method relied on the relationship between hydrologic soil type and land cover to determine how

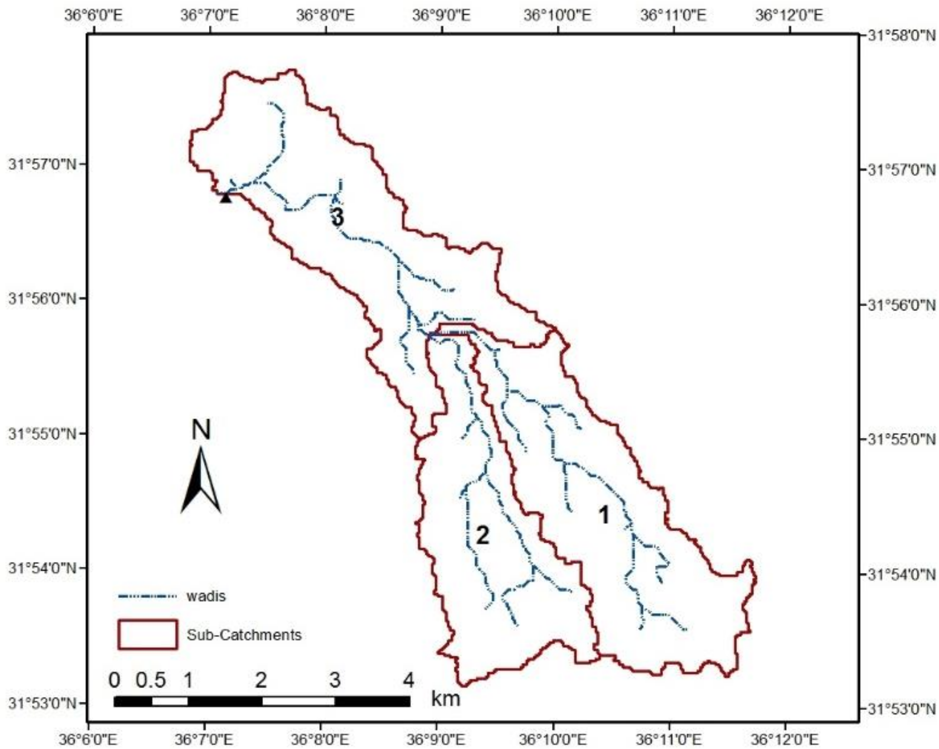

Figure 3. Wadi Ishe catchment and its sub-basins.

much of the rainfall would become runoff. The CN values used for this study were taken from (Hammouri and EL-Naqa, 2007) as 78.

CN values ranged from a maximum of 100 for water bodies, to a minimum of 30 for permeable soils with maximum infiltration rates (Feldman 2000).

One of the benefits, which led to the selection of this method, is an established mean for determining precipitation excess. The simplicity and predictability of this method were also considerations leading to its selection. Perhaps the most important features of this method were the easily grasped environmental inputs needed to perform the calculations.

Runoff hydrograph

In areas with no runoff hydrograph records, the SCS developed standard Unit Hydrograph is applicable for most rural areas. The SCS Unit Hydrograph (UH) method is used to simulate the sub-basins runoff hydrographs and the catchment's outflow Hydrograph. For this method, the lag time is calculated using the following SCS equations (HEC, 2005).

$$t_c = 0.136\ L^{0.8}\left(\frac{1000}{CN} - 9\right)^{0.7} S^{-0.5} \tag{4}$$

$$t_L = 0.6\, t_c \tag{5}$$

Where:

t_c = concentration time (maximum travel time), this is the time a water parcel takes to travel from hydraulically supreme distant part of the watershed to the outlet.

t_L = lag time (min), distance from the center excess rainfall mass to the peak discharge

L = main wadi length (m),

CN = Curve Number,

S = Sub-basin slope (%).

For this run-off analysis, the catchment, which has an area of 22.256 km^2, was divided into three sub-basins as presented in (Figures 3 and 4). The main model parameters for the three sub-basins are specified in Table 1, whereby the lag time and initial abstraction is calculated using the equations above.

Design storm

The 24-h, 10-years return period storm is used to model the catchment's outflow. For modeling, the storm three different databases were used. The first estimation storm is derived using daily rainfall records from both stations

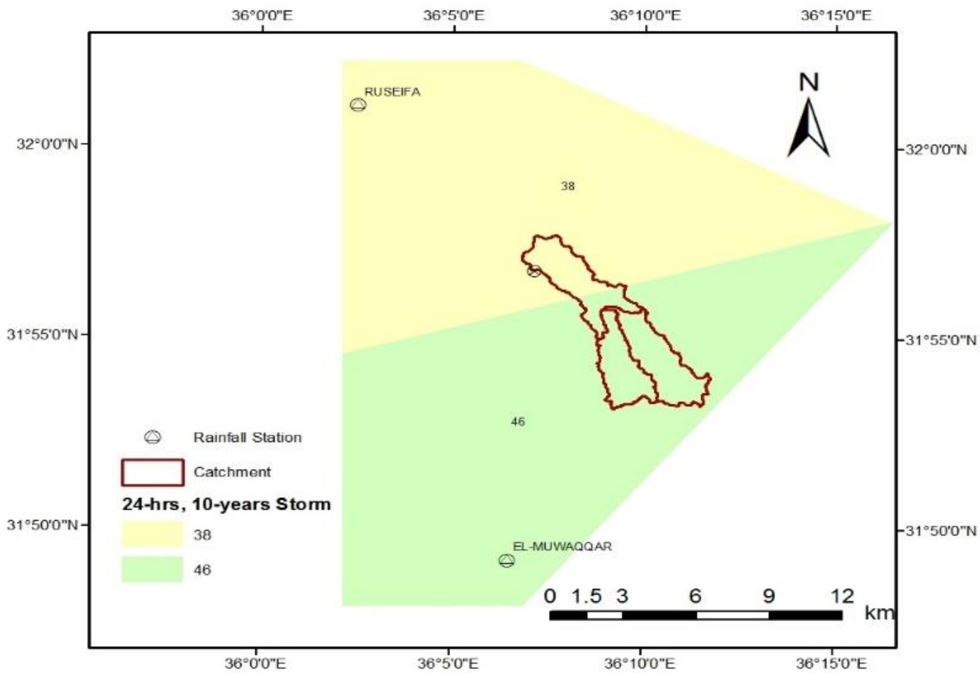

Figure 4. Location of Mwaqqar and Rusaifah stations for average rainfall.

Table 1. Main model parameters for the sub-basins using SCS method.

Sub-Basin	Area (km^2)	Slope (%)	Main Wadi Length (km)	Initial Abstraction (mm)	Lag Time (min)
1	7.954	1.26	6.623	14.3	212
2	6.176	2.25	5.305	14.3	133
3	8.126	1.58	5.315	14.3	159
Catchment area	**22.256**				

Ruseifa and El-Muwaqqar (Figure 4) for the years 2000 to 2010. The data were analyzed using Extreme Value distribution and the 10 years return period daily (24-h) storms are calculated for both stations. The daily rainfall storm for the catchment is calculated using simple interpolation between the two stations. The other two estimations were taken from Sajdi and Partners (2011) and from Hammouri and El-Naqa (2007) who determined these values for similar areas.

To refine the rainfall-runoff simulation, the unit hydrograph duration is designated as small as possible. The catchment physical parameters of the catchment determine the time of concentration as in Equation 4 above. SCS suggested an equation to approximate the UH duration (D) as:

$$D = 0.133\ tc \qquad (6)$$

The duration D is then approximated to the closest 0.5 h to ease the simulation calculations. The daily rainfall storm, which has 24 h duration, will be used with the D-hrs UH to calculate the runoff hydrograph of this storm. The simulation process requires the storm duration(s) to be the same as the UH duration. For that purposes, the SCS developed a continuous distribution curve for the 24-h storm that can be used to find partial storms of any duration of the 24 h. There are three curves Type I, Type II and Type III. SCS Type II storm is the average curve where Type I and III are for dry and wet. In this simulation, Type II will be used to find the D-hrs storms depths. Table 2, lists the 24 h, 10-years storms used in the modeling and the reference for these storms.

Modeling results

The catchment is modeled using the three storm depths and the peak discharge and outflow volume is tabulated in Table 3. The outflow hydrograph for the catchment using the 44.0 mm storm is mentioned in (Figure 5).

Table 2. The 24 h, 10-years storms used in the modeling of Wadi Ishe catchment and the reference for these storms.

Rainfall depth estimation reference	Storm depth (mm)
From daily rainfall of two stations	44.00
Consulting Engineering Center (1998)	45.60
Hammouri and El -Naqa (2007)	42.58

Table 3. Storm depth evaluation for Wadi Ishe and the resulting peak discharge and outflow volume by using the HEC-HMS model (Feldman, 2000).

Storm depth (mm)	Peak discharge (m^3/s)	Outflow volume (m^3)
44.00	5.7	193,300
45.60	6.2	210,300
42.58	5.2	177,800

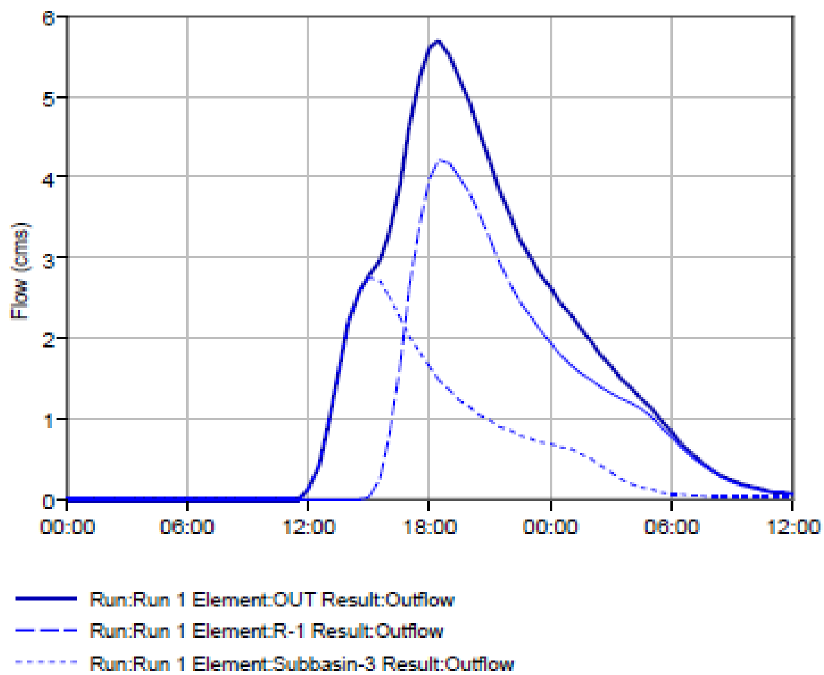

Figure 5. Hydrograph for Wadi Ishe basin for a 24-h storm 10 years return period and its sub basins.

The purpose of using HEC-HMS model is to discover the potential of surface water for subsurface groundwater storage in Wadi Ishe catchment basin. However, the study area is an ungauged basin, thereto HEC-HMS model with GIS were deployed in order to simulate rainfall-runoff using SCS curve number. The results of the hydrographs for the 10 years return period with a total yearly precipitation of 44 mm and total loss of 35.3 mm gave a total runoff of 8.7 mm. The total precipitation volume for the years 2000-2010 within the catchment area was approximately 36.14 Mm³. For the years 2000 – 2010, the total rainfall for El Muwaqqar Station was 1647.4 mm. Only 29 storms during this period exceeded the initial abstraction of 14.3 mm and resulted in runoff as shown in Table 4. The total rainfall depth for these storms was 689.8 mm, which forms about 41.9% of the total rainfall in the same period. Each one of these storms is modeled using HEC-HMS. The total runoff depth for the years 2000 – 2010 was 52.71 mm that is approximately 3.2% of the total rainfall and near 7.6% of the total storms

Table 4. Storms recorded in El-Muwaqqer Station that are greater than the initial abstraction of 14.3 mm and the generated rainfall excess and runoff coefficients for these storms:

Storm depth (mm)	Rainfall losses (mm)	Excess rainfall (mm)	Storm runoff coefficient (%)
45.0	35.79	9.21	20.5
44.0	35.30	8.70	19.8
38.8	32.56	6.24	16.1
37.0	31.54	5.46	14.8
34.5	30.06	4.44	12.9
33.0	29.13	3.87	11.7
32.0	28.49	3.51	11.0
30.0	27.18	2.82	9.4
26.8	24.94	1.86	6.9
24.0	22.84	1.16	4.8
24.0	22.84	1.16	4.8
24.0	22.84	1.16	4.8
22.5	21.66	0.84	3.7
20.0	19.58	0.42	2.1
20.0	19.58	0.42	2.1
18.8	18.53	0.27	1.4
18.7	18.45	0.25	1.3
18.0	17.82	0.18	1.0
18.0	17.82	0.18	1.0
18.0	17.82	0.18	1.0
17.0	16.90	0.10	0.6
17.0	16.90	0.10	0.6
16.4	16.34	0.06	0.4
16.0	15.96	0.04	0.2
15.7	15.67	0.03	0.2
15.6	15.58	0.02	0.1
15.0	14.99	0.01	0.1
15.0	14.99	0.01	0.1
15.0	14.99	0.01	0.1
742	2527	915	

over the initial abstraction.

For Wadi Ishe catchment that has an area of 22.256 km2, it received about 36.66 Mm^3 of rainfall during the years 2000 – 2010, only 3.2% of that was generated as runoff (about 1.17 Mm^3).

According to the reservoir geometry, evaluation weighting has been carried out to the three reservoir volume sections. Out of volume weighting, the porosity for all the reservoir volume was calculated to be 20 -23 % .Whereas out of the total volume of the reservoir of 945 m^3, the total water volume available to be stored within this reservoir is around 300 m^3.

In Figure 5, the first line (small dash) presents the contribution of the upper two sub-basins to the main outlet, the second line (large dash) presents the lower sub-basin to the main outlet and the third line (solid one) presents the outflow discharge resulted from the whole catchment, which is the summation of the two dashed line.

WADI ISHE GROUNDWATER HARVESTING

Site selection and Wadi alluvials

The catchment of Wadi Ishe is mainly comprised of limestone, which shows temperate to high permeability due to joints and karstification. A reservoir in a wadi channel above such rocks will cause a fast seeping of the water from the alluvial filling of the wadi downwards into the permeable rocks with further discharge. The only option for an underground reservoir in the Wadi Ishe was the small outcropping zone of the Umm Ghudran Marls, which are intercalated in the limestone-dominated sequence. This part of the Wadi Ishe was selected for the test site to build an underground dam.

Figure 6. Trench in the Wadi Ishe showing the upper part of the wadi filling: unsorted gravels with high content of sand and silt material.

Direct site investigation started with small trenches to explore the thickness and properties of the alluvial deposits in the former wadi channel. The filling of the erosional wadi channel consists of the following sediments:

1) The first 1.5 -1.8 m are formed by a red-brownish layer of poorly organized gravels with high content of sandy silty material in between (Figure 6). The gravels with sizes of 30 to 150 mm are slightly rounded due to longer transport ways, but include also pebbles and boulders up to 500 mm, which are obviously washed in from the near slope scree. The whole layer is very loose and unconsolidated and probably deposited by flash floods. The material is highly permeable, though the total porosity is rather small due to the high amount of intercalated fine material.

2) The top layer is partly underlaid by a yellow-orange firm layer of clayey marly material, which was obviously deposited in a small irregular basin under slow water condition. The thickness is varying between 0.0 and 0.7 m.

3) Below the clay layer or directly below the top gravel layer follows a 1.0 -1.3 m of a more compacted layer of

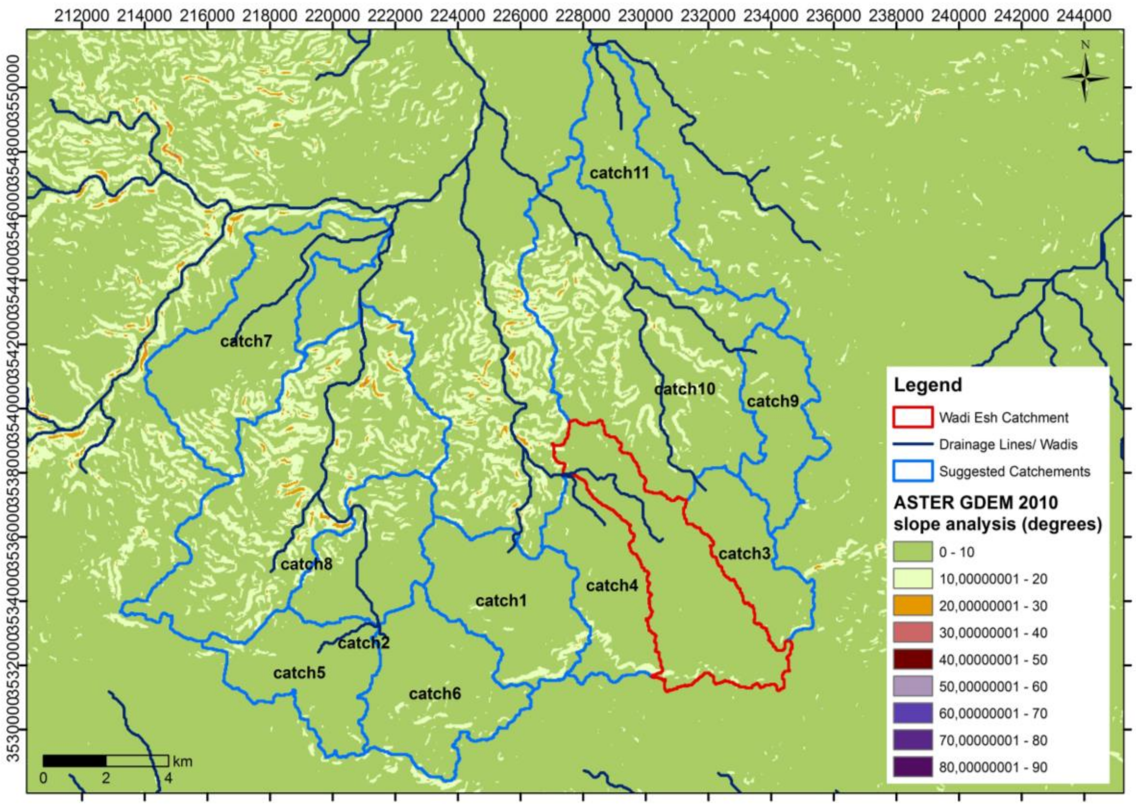

Figure 7. Suggested outscaling implementation sites for Wadi Madoneh to apply subsurface storage. Slope analysis map.

light creamy color. It consists of adjusted bladed small limestone pebbles of 20 to 50 mm. These limestone pebbles are interbedded in partly sandy or more silt-clayey material, which might have been deposited under intermittent slow flow conditions. Due to later calcite precipitation between the grains, it formed a compact and indurate sequence with rather lower permeability.

4) The base of the alluvial sequence is formed partly by lighter colored very compact and hard layer. The light color and the white parts suggest high lime contents and lime cementation, which could be a cemented lime accumulation layer (duricrust). In other places, even larger limestone blocks partly embedded in weathered marly material indicate the beginning of the slightly loosened sequence of bedrock.

Finally, a section of the wadi channel of about 90 m length was selected and excavated 4m wide and 3m deep. The trench across the course of the wadis dispelled the young wadi sediments completely. The marly rock layers on the ground as well as both sides of the original erosion channel were exposed in the trench. Originally, it was planned to excavate only a wider cross trench for the construction of the groundwater dam. Due to the high content of silty and clayey material in the gravelly sandy wadi filling with its low porosity the whole distance of the wadi channel over 90 m was excavated. The sandy and clayey material was separated and the gravel and boulders used to refill the trench in order to get a higher storage volume in this section of the wadi channel.

Through the implementation of wadi Ishe pilot site, the site selection criteria were developed. The suitability of an underground dam is highly site-specific and depends on aquifer properties, hydrological conditions and geological setting of the basin. A thorough hydro geological investigation coupled with model analysis is therefore done for Wadi Ishe site and as decision support document. The maps shown in Figures 7 and 8 show potentials sites for implementation. Sites were selected depending on the geological and hydrological criteria. Eleven other sites are investigated for outscaling at the Wadi Madoneh catchment (Table 5).

However, a potentiality map can be produced for other catchments and at the country scale to help as policy document.

Construction of the dam

For the dam site, the downstream end of 90 m long trench was selected. There and across to the channel the

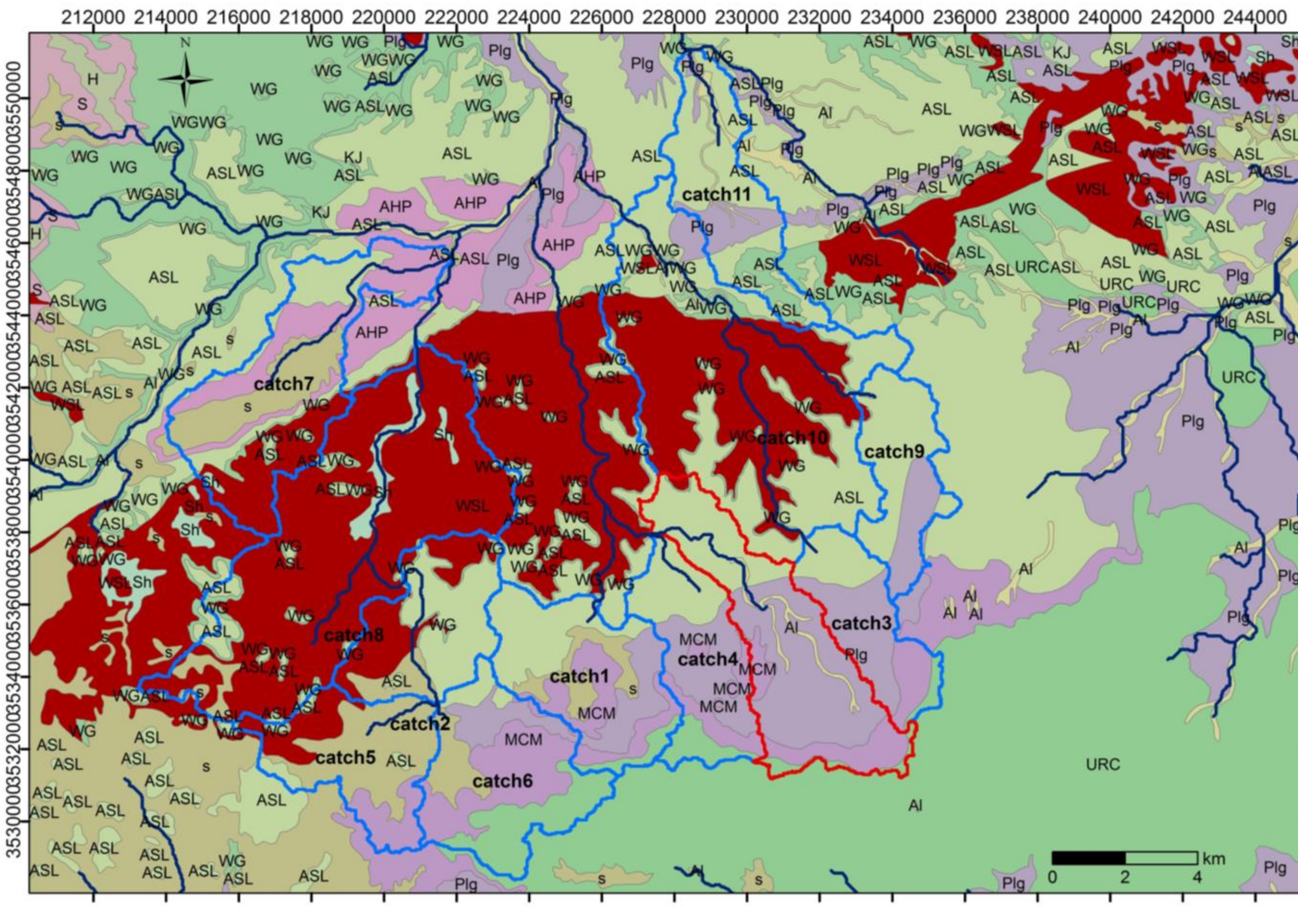

Figure 8. Geological map for Wadi Madoneh indicating the suggested 11 catchments.

Table 5. Suggested catchments with codes, area and geological formations.

FID	OID	Shape length	Shape area	HydroID	Name	Area catchment (km²)	Geological formation within catchment area
1	0	26659.7198	17640983.7	1792	Catch1	17.64098371	ASL,s,MCM,Plg,URC,WG
2	0	51160.9928	47363935.4	1794	Catch2	47.36393537	ASL,s,MCM,Plg,URC,WG,WSL
3	0	21992.81	10684131.9	1796	Catch3	10.68413189	ASL,MCM,Plg,URC
4	0	26309.7014	13523194.3	1798	Catch4	13.52319432	ASL,MCM,Plg,URC
5	0	26776.3916	14351856.9	1800	Catch5	14.35185692	ASL,s,MCM,Plg,WG,WSL
6	0	28993.1742	18580248	1801	Catch6	18.58024803	ASL,s,MCM,Plg,URC
7	0	39785.4024	24281344.3	1802	Catch7	24.28134425	ASL,s,AHP,Al,WG,WSL
8	0	71578.7215	92428205	1803	Catch8	92.42820496	ASL,s,MCM,Plg,URC,WG,WSL,Sh
9	0	26251.3644	10712207.7	1805	Catch9	10.71220768	ASL,s,MCM,Plg,WG,WSL
10	0	65628.4127	67112308.3	1807	Catch10	67.11230827	ASL,s,MCM,Plg,URC,WG,WSL,Al
11	0	30276.574	14214030.1	1809	Catch11	14.21403009	ASL,Al,Plg,WG,WSL

alluvial sediments were completely removed so that the marly bedrocks were forming the frame. The dam was constructed in a three layer core dam (Figure 9) (Nilson, 1988; Onder and Yilmaz, 2005). The downstream side is naturally formed by the original undisturbed alluvium (Figure 9) then follows a 1 m thick section of unsorted material excavated from the trench (B), the core of the dam is formed by a compacted benthonite layer (C) and the upstream cover of the core (B) consists once again of 1 m refilled alluvial material.

Benthonite is a type of clay fundamentally composed of crystalline smectite minerals commonly known as

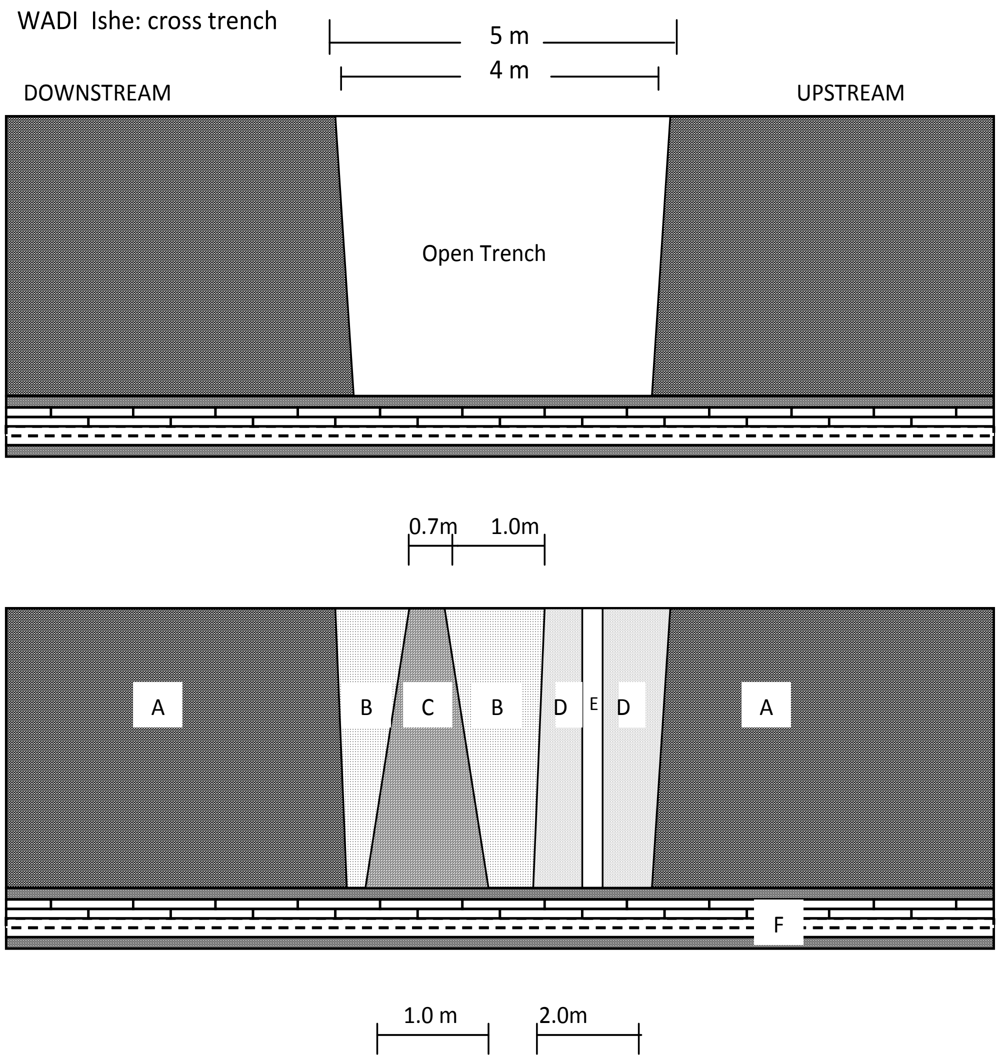

Figure 9. Cross section of Wadi Ishe groundwater dam with material filling sequence. A: Natural wadi filling (gravels, sands, silts), B: Refilled wadi sediment, C: Clay sealing (Benthonite), D: Washed out/ sieved gravels, E: Observation and pump well with protection shelter (perforated pipe: diameter about 300 mm), F: bed rocks (marls with some limestone layers).

montmorillonite. It is molded from modification of glassy igneous material either tuff or volcanic ash (Mahasneh, 2012). The used material was resourced from a site near Al Azraq basin, where volcanic material was deposited in lakes with shallow water in the Plio-Pleistocene time. Upstream of the dam a 2.0 to 2.5 m wide sheet (D) with washed or sieved gravel and ballast material (with high porosity and good permeability). In this gravel layer, a perforated well pipe of 30,5 cm was installed (Figures 9 and 10). The incorporation of the materials B, C and D was concurrently done in from the bottom upwards in layers of 0.5 to 0.7 m where the individual layers, in particular the clay, should be moist and installed compressed.

After the completion of the construction of the groundwater dam, the filling of the trench as well as the assembly of certain measurement devices, the wadi course was completely restored, profiled, and planned so that no bar would obstruct the surface flow conditions specifically an occurrence of a rare flash flood under arid conditions (Figure 9). It is expected that the normal minor runoffs after rare rain events or perhaps stronger flash floods will already cause infiltration in the underground further upstream and generate a certain groundwater discharge in the alluvial filling of the wadi channel. The underground dam will keep this groundwater flow back and the water will be stored in the immediate upstream part of the dam. The advantage compared with the storage of surface runoff is that groundwater flow continues over a longer period, while surface runoff may stop after rain events in arid areas only after one or few days. On the other hand, there would be no concern

Figure 10. Left side: excavation of the 90 m long trench along the old wadi channel. Right side: the restored wadi section: below the front part is the now covered groundwater dam, behind the observation and pumping well and in the background the refilled wadi section used as groundwater reservoir. The picture shows the rebuilt wadi section after the first flood event.

regarding the increased amounts of sediments the surface runoff usually transport in arid areas after rain events.

Water harvesting in the subsurface reservoir

Due to the dry periods and the absence of rainy events that persevered throughout this pilot project, an artificial recharge experimental test was performed which started in April 2013. The experiment involved feeding 13 m^3 of water via the observation well into the reservoir for two hours continuously under constant water head. Divers and deep-meter recorded the buildup con of depletion and recovery. The results of the measurement indicated that the static water level increased from 1.85 to 1.25 m bgl (metres below ground level).

A feeding section of 118 m^3 was calculated using the reservoir geometry by multiplying the 32 cm water depth (according to the built up cone of the divers) by the structure length of 90 m multiplied by the 4 m width of the wadi. The percent void volume of 11% within this section was then calculated by dividing the 13 m^3 total water volume by the 118 m^3 feeding section. This is now used as the average representative porosity of the entire section. The cross section of the reservoir structure shows that the upper part of the structure is more porous than the lower part according to the fine materials included.

The test results were based on the reservoir volume of 945 m^3, which is the trapezoidal cross section 10.5 m^2 multiplied by the wadi 90 m length. Knowing that the static water level was measured by the diver's m-scop was found 1.85 m bgl, thus we can consider that the saturated section from 1.85 to 3.00 m depth making the volume about 330 m^3 (3.15×1.15×90) m^3 considering the ratio of 1/3 from the total structure volume. The 13 m^3 of water was added to the reservoir over two hours and interspersed by 15 minutes recovery measurements. After 48 h, the test was concluded and the new static water level was measured at 1.25 m. This however, indicates that the saturated zone increased by 0.60 m (1.85-1.25) m according to the final water level. Moreover, the level was measured after 72 h and found to be at 153 m bgl, this value shows that the saturated zone increased by 0.32 m due to the supplementary water.

Whereas the water volume is 13 m^3 that distributed within 118.05 $m^3$of the reservoir section volume. The void volume within this section is estimated to be 13 m^3 / 118.05 which is equivalent to the porosity of this section and equals to 0.11.

The diver measurements and the manuals (m- scop) reading during the pumping indicated that the bottom section dropped from a depth of 1.45 m bgl to a depth of 1.15 m bgl which we consider as less permeable with low porosity. The middle section, the section from 1.15 to 0.85 m bgl, was medium permeable with medium porosity, while the upper section from 0.65 m bgl up to the ground surface was very permeable with high porosity.

Considering the reservoir geometry, evaluation weighting has been carried out on the three reservoir layers. Out of volume weighting, the porosity for the whole reservoir volume is calculated to be 20-23%, while the porosity of the section 1.85-1.53 was low at 11%, and the upper section (1.53-0) porosity was high. The average for the reservoir is around 20-23%.

Pursuant to the total volume of the reservoir is 945 m^3 makes the total water volume available to be stored within this 90 m long reservoir around 217.35 m^3 (Figure 11).

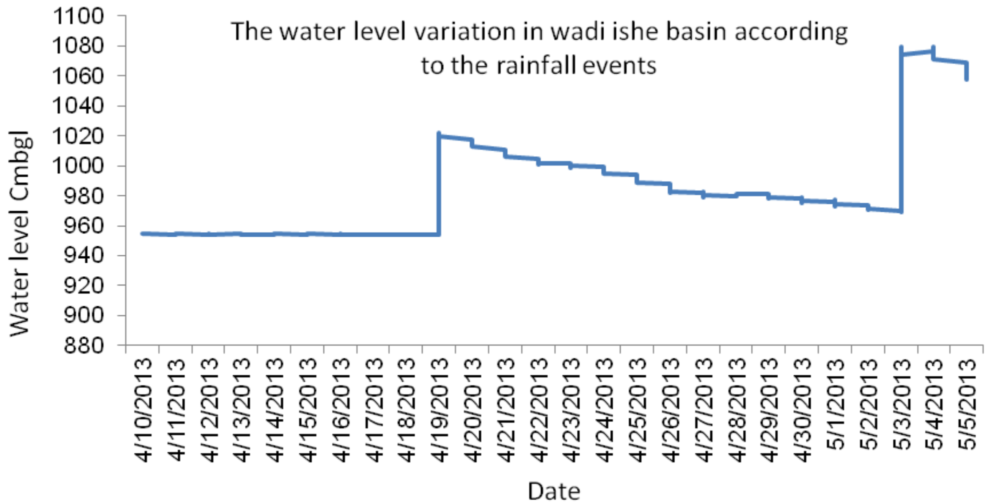

Figure 11. The water level variation in Wadi Ishe basin.

In April-May 2013, the diver was installed at 165cm from the well surface while the static water level in the monitoring well was at 125 cm from the surface Figure 9. The diver readings between the 10^{th} and the 19^{th} of April 2013 showed minor variation in the water level. This variation was measured at 3-6 mm, which is considered a stable water budget in the structure. On 19 April, the water level increased up 66.7 cm from 125 cm to 58.3 cm. Considering a basin volume of 126.66 m^3 at 125 cm elevation and a volume of 272.73 m^3 at 58.3 cm elevation, the distributed water volume would be 146.07 m^3. Given the structure porosity of 23%, the water stored during this rainy event at this elevation would be around 33.6 m^3.

Moreover, during the period between the 19^{th} of April and 3^{rd} of May the water elevation dropped to 111.3 cm, that is, around 53 cm in value, obviously due to certain leakage effects in the upper more pervious layer. This means a loss of 17 m^3 according to seepage. Another rain event came on 3 May and caused an increase of 65 m^3 of storage according to the diver readings. We conclude that up to early May 2013 the total water volume stored in the subsurface reservoir is around 99.5 m^3. Earlier on 19^{th} of April 2013 the water level in the observation well increased from 125 to 58 cm bgl, which was caused by a rainfall event - refer to Fig.11. The water volume that was stored in this section of the basin due to this rain event is equivalent to 24.8 m^3. Indeed, this result matches the calculation of the basin geometry and the pumping test findings. On 3 May 2013, another rain event took place, which resulted in 39 m^3 of water volume storage. The diver records indicated the seepage factor of around 1 m/day. The annual storage of the subsurface reservoir is estimated to be at least around 300 m^3/year where the average annual rain events in that area are normally 5 evens.

CONCLUSIONS

The research has proposed the methods of groundwater storage with underground dams in arid and semi-arid countries such as Jordan proposes an attractive solution for water shortage challenges and to minimize the evaporation losses. Despite of recent dry climatic conditions, there are frequently small and shallow wadi channels filled up with alluvial sediments depending on the geomorphologic and climatic history of the landscape. Even under high arid conditions, there are always few precipitation events, which are concerned with short-term flash floods, causing also groundwater flows in the alluvial channels. While the surface runoff of the flash floods is strongly loaded with sediments and only of very short duration, the accompanying groundwater flow is filtrated and continuing over several days. Harvesting of this groundwater can be reached easily by the construction of an underground dam sealing the whole sediment filled wadi channel.

The experiments in Wadi Ishe is considered as an adaptation measure for climate change, it illustrates that adequate water harvesting can be achieved even with small yearly precipitation rates down to 150 mm. Once those small structures are integrated in a catchment management plan, they would affect the water availability in arid areas at the macro catchment level. Besides, water stored in such underground reservoirs could be used for grazing, stock watering or irrigation purposes.

The total amount of storable water depends on the cross section of the alluvial channels and the gradient, so that even longer section of the upstream channel can be used for the underground reservoir. Precondition for the effectivity in the design is of course a certain water tightness of the rocks in which the wadi channel is incised.

Clayey or Marley sediment rocks most of the metamorphic and igneous rocks form a good base for the required impermeability.

Moreover, the concept of storing water and the development of groundwater basin in subsurface terrain have relatively limited environmental and social impacts and present a promising potential specifically in the developing countries of Africa and Asia.

Conflict of Interests

The authors have not declared any conflict of interests.

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