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Integrated management of surface water and groundwater to mitigate flood risks and water scarcity in arid and semi-arid regions

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Abstract

Water scarcity in arid and semi-arid regions represents a significant obstruction to social and economic development. Also, flood hazards affect the life of many people in these areas. This study aims to develop a new model for integrated management of surface water and groundwater, which involves rainwater harvesting and recharge to groundwater aquifers. Integrated hydrological models, including geographic information system (GIS), watershed modelling system (WMS) and groundwater modelling system (GMS) were used. This research provides an integrated vision for exploiting the rainwater in Wadi Watier, South Sinai, Egypt and shows new insights on how to protect these areas from flood risks and store water to solve the water scarcity in this region. Based on physical properties of sub-basins and soil properties, fourteen dams were suggested and designed to protect the study area from flood risks; five dams were used for storage and nine dams for groundwater recharge. The results showed that the dams could collect about 160.72 million m^3 of rainwater which can be stored or recharged into groundwater aquifers. This will increase the national income and provide stability for residents in these areas that suffer from water shortage. Decision-makers can use these models for sustainable flood management in similar areas.

KEYWORDS

flood risks management, groundwater recharge, rainwater harvesting, water resources management

1 | INTRODUCTION

Arid and semi-arid regions are suffering from water scarcity, and hence the management of the available water resources is essential for these areas. These areas are characterised by high evaporation rates and percolation of surface water to the subsurface environment. Flash floods in such areas are characterised by high velocity and low duration with sharp discharge peaks. Large sediment loads may be carried by floods, which threaten fields and settlements in the valleys and even people who live there. This requires the determination of quantity and direction and locations of floods by deriving rainfall-runoff relationship, which is an essential aspect of hydrologic practice to determine the availability of water resources and to design flood mitigation (Parmar et al., 2016).

Sinai Peninsula, Egypt is an example of such arid regions suffering from water scarcity. This area mainly depends on rainwater and groundwater as primary sources for drinking and irrigation water. Flash floods cause environmental problems in such areas, mainly because floodwater is not exploited due to lack of planning for its collection and use as part of a proper water resources management plan. Rainwater harvesting (RWH) and recharge could help in sustainable development in these areas.

RWH techniques are used for converting barren desert lands into productive, fertile ones and have been used to recharge groundwater in different regions of the world. Adhams, Jahan, Mazumder, Hossain, and Haque (2010) studied the groundwater recharge potential in Barind Tract, Northwest Bangladesh, based on GIS and remote sensing (RS) techniques. Ismail et al. (2010) showed the capabilities of GIS techniques for mapping groundwater recharge zones in the Maknassy basin, Tunisia, while Greskowiak et al. (2005) studied the spatial and temporal distribution of the redox reactions to develop an artificial recharge pond near Lake Tegel, Germany. Jasrotia, Kumar, and Saraf (2007) used integrated RS and GIS techniques to provide a platform for the analysis of multidisciplinary data and decision making for artificial recharge to groundwater. Other researchers used different methods for water harvesting in arid and semi-arid regions. For example, Tammam, Gaber, and Bakr (2017) studied water harvesting in Saint Catherine area in South Sinai using small capacity reservoirs, which are a natural lake in the top of the mountains.

Some studies used neural networks to monitor the groundwater levels in different locations of the world. Gholami, Chau, Fadaee, Torkaman, and Ghaffari (2015) simulated groundwater level oscillations using neural networks. In another study, Taormina, Chau, and Sethi (2012) developed an application of feedforward neural networks model for long-period simulations of hourly groundwater levels in a coastal unconfined aquifer in Italy. The established model was able to propagate water level disparities after initialising the model with groundwater elevations detected at a given time. More recently, Mosavi, Ozturk, and Chau (2018) presented state of the art machine learning (ML) models in flood forecast and provided vision into the most appropriate models. Recently, Liu et al. (2020) used storm flood disaster (SFD) risk zoning technique for investigating the potential impact of SFD. The statistics about natural, social, and risk related to SFD were collated. The results indicated that the disaster risk is mainly affected by hazard factors, catastrophic intensity, population density, as well as economic development in the affected area.

Integration of surface water and groundwater simultaneously is an important research topic. Castle et al. (2014) evaluated the effect of conjunctive surface water and groundwater use for water availability in the Colorado River Basin. Scanlon, Reedy, Faunt, Pool, and Uhlman (2016) discussed the possibility of using groundwater reservoirs to better adapt to climate extremes in California's Central Valley and central Arizona. Fuchs, Carroll, and King (2018) quantified the resilience of the agricultural system that depends on the conjunctive use of surface and groundwater in Rincon Valley, USA, while Nikoo, Karimi, Kerachian, Poorsepahy-Samian, and Daneshmand (2013) developed optimal operation scheduling rules for a reservoir-river-groundwater joint system through data mining. Tian et al. (2018) investigated the impact of reservoir operation on the water cycle and evaluated the effect of the joint operation of surface water and groundwater reservoirs in arid regions through an integrated modelling approach. Ebrahim, Villholth, and Boulos (2019) used remote sensing and a 3D dynamic model to study rainfall-runoff relation in the Hout catchment, South Africa. The results indicated that a delicate human-natural system has highly variable recharge and is propagating through variable pumping to even more variable storage, making the combined system vulnerable to climate and anthropogenic changes.

Several studies were carried out in arid and semi-arid regions for groundwater management. Mohamed, Al-Suweidi, Ebraheem, and Al Mulla (2015) discussed different scenarios for sustainable management of groundwater in the Northeastern United Arab Emirates. El Arabi (2012) found the artificial recharge into groundwater aquifers using treated wastewater is promising. Another study in Egypt by Elewa, Qaddah, and Elfeel (2012) used RS and GIS-based modelling for determining potential sites for runoff water harvesting in Sinai. The study classified Sinai into four classes that graded from high to moderate, low and very low for RWH. The promising watersheds were decided as Sidr, Feran, Alaawag, and Watir, which is the area being studied in this paper. They recommended these basins could be investigated at a detail with larger scale to determine the appropriate locations for implementing the RWH structures and techniques.

A number of studies have been conducted for flood prediction and mitigation in different Wadies in Sinai Peninsula, Egypt. Fathy, Abd-Elhamid, and Negm (2020) presented a method for predicting the runoff volume in Wadi Sudr, Sinai, Egypt, using GIS and hydrological models and discussed ways of mitigating flood hazards in this area using small dams and open channels. In another study, Abbas, Carling, Jansen, and Al-Saqarat (2020) used flood discharge modelling and field measurements to estimate the total flood volume, duration, infiltration rate, and transmission losses in Wadi Umm Sidr, Egypt. They presented recommendations for flood protection of the Red sea coastal infrastructure. Also, Yousif and Hussien (2020) used geophysical data, remote sensing, and field investigations to mitigate the flash flood risks in Sharm El Sheikh, Egypt. They proposed the use of culverts to protect roads and sites for groundwater exploration.

Some studies provided new approaches to estimate the runoff in arid regions, such as Masoud, Schneider, and El Osta (2013), who used the Gerinne model based on paleo-flood measurements to estimate the runoff and groundwater recharge at El Hawashyia basin and Ghazala sub-basin, Egypt based on two computer programs: Stormwater Management and Design Aid. The results showed that El Hawashyia basin produces a discharge volume of 10.2×10^6 m^3 and Ghazala sub-basin 3.16×10^6 m^3. In another study, Masoud, Schumann, and Abdel Mogheeth (2013) used the finite element groundwater model FEFLOW to estimate groundwater recharge to the Nubian Sandstone aquifer and its impact on the present development in southwest Egypt. More recently, Abdeldayem et al. (2020) studied flash flood risk mitigation in a Founa Village, Egypt, using an artificial infiltration-pond. They substituted the low-permeability silty sand in the pond area with a high-permeability one, which enhanced the water harvesting and reduced the direct evaporation.

Models integration could help in flood risk analysis and groundwater recharge modelling. Basahi, Masoud, and Zaidi (2016) used the integration of morphometric parameters, geo-informatics, and hydrological models to assess the flash flood risks in Wadi Halyah, Saudi Arabia. They used different models, including ASTER, DEM, and GIS in the study. The runoff ranged from 26.7×10^6 to 111.4×10^6 m^3. In another study, Elfeki, Masoud, and Niyazi (2017) presented an approach for evaluating flood hazardous in Wadi Fatimah, Saudi Arabia. The approach included different statistical analyses, geological and geomorphologic analyses, land use and land cover analyses, and delineation of the inundation area in the presence and absence of dams. The results showed that the presence of a dam reduced the inundation depth by 10%, and the reduction in the inundation area was about 25%. Recently, Masoud, Basahi, and Zaidi (2019) assessed the potential of artificial groundwater recharge through the estimation of permeability values from infiltration and aquifer tests in unconsolidated alluvial formations in Wadi Baysh in southwestern Saudi Arabia. The results showed that Wadi Baysh catchment has good potential for groundwater recharge.

From the above studies and others, there is a great need for a proper plan for flood mitigation in Wadi Watier, Egypt and similar arid areas. There is also a need to use water from flash floods water to help develop these regions that already suffer from water scarcity. Therefore, the main purpose of this study is to develop an integrated model that involves flood risk management, rainwater harvesting and recharge to groundwater aquifers at Wadi Watier, South Sinai, Egypt. The integrated model includes a geographic information system (GIS), watershed modelling system (WMS) and groundwater modelling system (GMS). The work also aims to determine the amount of water and site of collection, and decides which portion will be used for water storage or recharge into the groundwater aquifers. Building new dams in the study area was proposed to protect it from flood risks and store rainfall water. The proposed surface water/groundwater model should be of interest for water resources managers and flood mitigation planners in Egypt, and similar parts of the world, to help develop such areas.

2 | STUDY AREA AND DATA USED

2.1 | Description of the study area

Wadi Watier is one of the largest Wadis in the Sinai Peninsula, Egypt, and was selected as the study area (Figure 1). The total area of the Wadi is about (351,1I7) km^2, and is located between 28°48′ to 29°33′ N and 33°50′ to 34°50′ E. Previous studies focusing on this Wadi showed that RWH is promising there, and there is a potential that large amounts of water can be collected and stored, but a detailed investigation is required (e.g., Elewa et al., 2012). Similarly, the results of Al Zayed, Ribbe, and Al Salhi (2013), which were based on physical, environmental, and social aspects where they interviewed the local residents there, showed a promising potential for water harvesting in some areas of the Wadi with estimated 0.24, 0.45 and 2.7 million m^3 that could be harvested respectively for 2, 3 and 25 year return periods.

Wadi Watier flows into the Aqaba Gulf, and its mouth ends at Nuweiba city, Sinai Peninsula. Nuweiba port is located close to Nuweiba city, one of the most important intra-Arab trade axes. The international road linking Ahmed Hamdi tunnel and the Nuweiba port passes through Wadi Watier and is parallel to the Aqaba Golf coast. This road is risky due to the frequent occurrence of floods that destroys some parts of the road. Data from the digital elevation model indicated varying ground surface levels, ranging from 1,500 m above mean sea level to the lowest level at the delta of the valley that flows into the

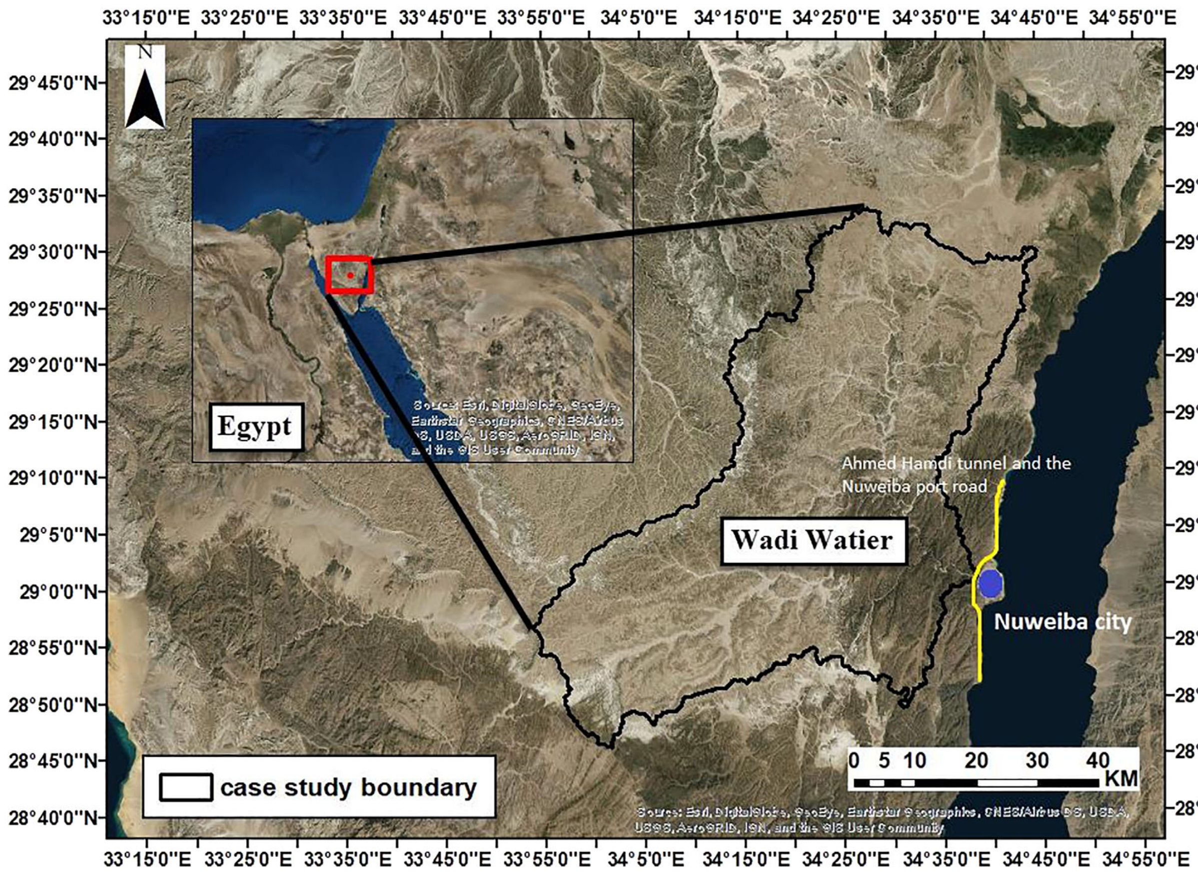


FIGURE 1 Location map of Wadi Watier

Gulf of Aqaba. There is a variation in the slope of the ground level of Wadi Watier that reaches 90% in most areas due to the very steep mountainous nature (WRRI, 2012). The watershed boundaries and main streams of the Wadi are shown in Figure 2a. The figure indicates that Wadi Watier has a good drainage system that will convey runoff water quickly. The Wadi consists of several sub-basins that have different areas and slopes. The main sub-basins in Wadi Watier are shown in Figure 2b; it is divided into 16 basins.

2.2 | Topographic data

Digital elevation models (DEM) represent the elevation distribution around the study area in a grid format. DEM can be used to derive the natural flow paths and the corresponding catchment boundaries of a given area. In the current study, 30 m resolution maps were used. DEM, and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) model of the study area, were derived and presented in Figure 3a, which shows the ground elevations in the study area. It can be seen that Wadi Watier has a steep slope in the western part, a flatter slope in the eastern part and medium slope in the middle part. This indicates that there is a variety of runoff characteristics along the Wadi.

2.3 | Geological data

From the geological perspective, calcareous rocks cover most of the area of the drainage basin. These rocks are significantly affected by the presence of some cracks and joints, which in turn affects surface water infiltration to groundwater. In addition, there are sandstone deposits characterised by medium to high water infiltration. Finally, the east and south-east of the valley are characterised by high rigidity, which increases the runoff rate and decreases the infiltration. The soil type in Wadi Watier varies between igneous rock, limestone, falcons, sandstone and Wadi deposits. Igneous rock represents 25% of the total area, which indicates good capability in harvesting a large quantity of rainwater. Limestone represents 60%, Wadi deposits 12%, and Falcons 3%. Figure 3b shows the geological map of Wadi Watier. Figure 4 presents the longitudinal profile of the Wadi's ground layer, which shows the aquifer depth to receive

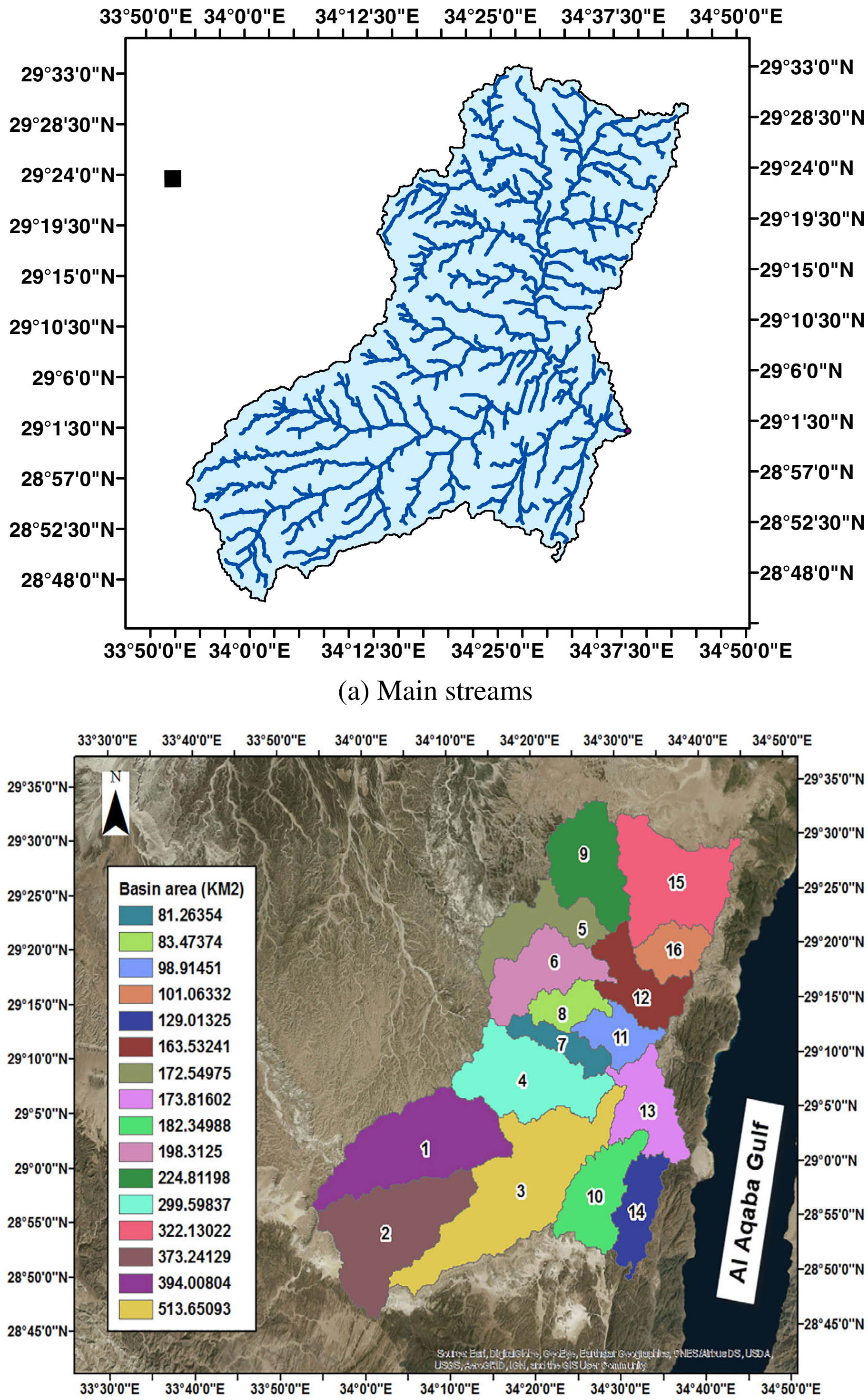
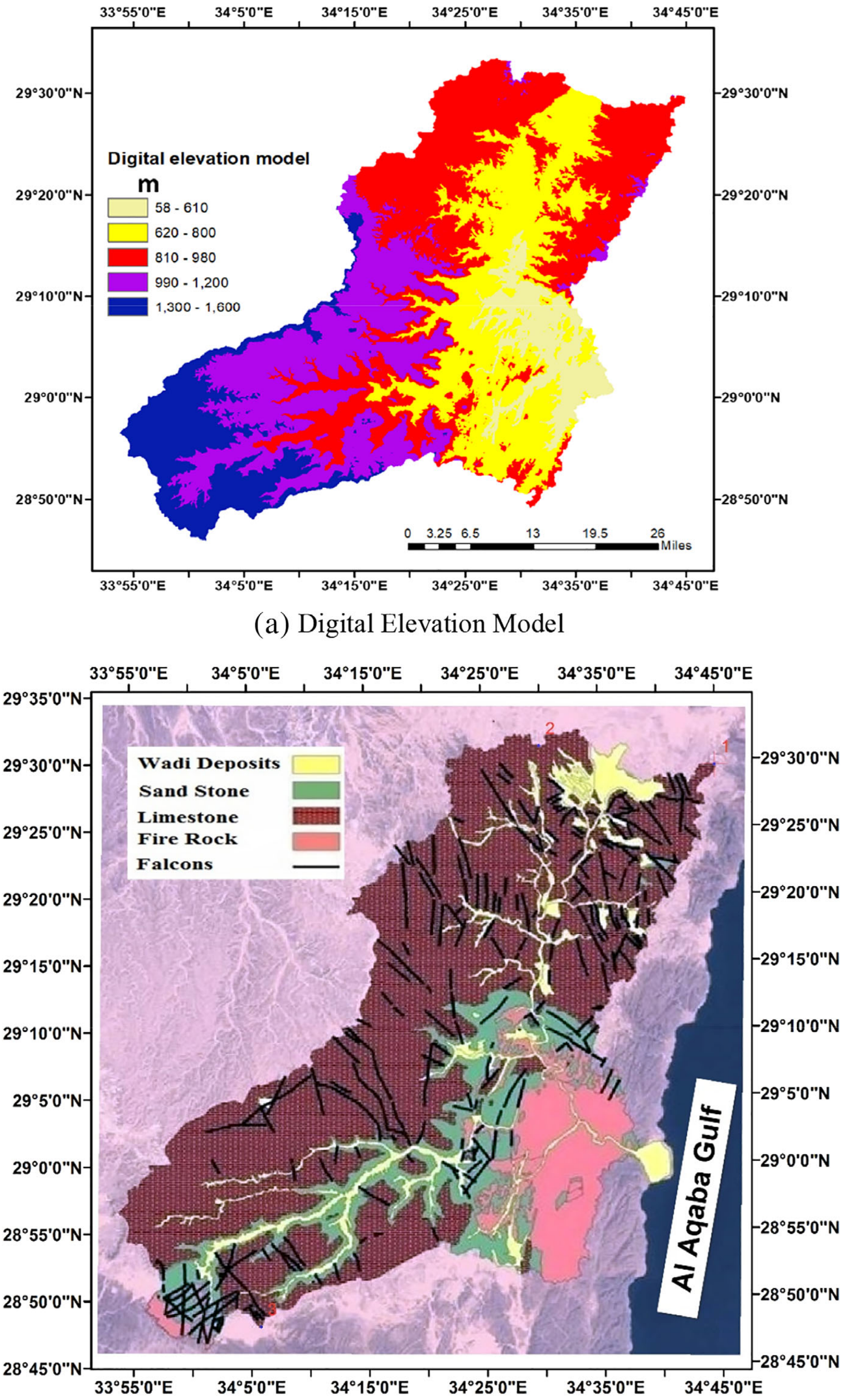


FIGURE 2 Main streams and sub-basins of Wadi Watier

detention water. The depth of aquifer reaches up to 100 m, which may lead to saltwater intrusion from the seaside. The initial water level was 50.00 m AMSL (WRRI, 2012).

The study area of Wadi Watier is divided into 16 sub-basins (Figure 2b). Geomorphical properties of each sub-basin, including area, slope and elevation, are determined using WMS and are presented in Table 1. The sub-basin areas ranged from 80 to 400 km^2. It is noticed that there is a steep slope in sub-basins 14, 13, 7, 4, 10, 11 and 8, which indicates a significant probability of a flash flood in this area. According to Table 1, the maximum stream length (length from remote point to sub-basin outlet) ranged from 23 to 76 km, which affects the time of



(a) Digital Elevation Model

(b) Geological map

FIGURE 3 Geological map and Digital Elevation Model of Wadi Watier

concentration and the peak discharge value. The shape factor (the perimeter of sub-basin divided by the square root of its area) was also calculated and ranged from 1.4 to 6.2. In general, there is an adverse relationship between shape factor and peak discharge so this parameter is vital for hydrology engineers. Sinuosity (the ratio of the length along the curve) and distance (straight line) is also calculated and found to be 1.07–17.5. Also this parameter has an adverse relationship with peak discharge. Based on the soil type and land use of the Wadi, the Curve Number (CN) of sub-basins was calculated according to the geological formation and land use of site area. The CN values ranged from 78 to 87.

2.4 | Hydrological data

Saint Catherine rain gauge station is the nearest rain gauge station for the study area and is located at 50 km from the site. The coordinates of this station are 28°18.931′ N, 34°2.343′ E. The daily rainfall data of this station for 26 years from 1990 to 2016 (which was available for us) were collected, annual rainfall depth ranged from 4 mm to 25 mm. Statistical analysis was done by Hyfran using the Gumbel method to determine the depth of rainfall for different years which fitted the measured data well and predicted the future data with a confidence of 95%. The depth of rainfall at different return periods was calculated and presented in Table 2. After the depth of rainfall is calculated, the bell method was used to estimate the intensity duration frequency (IDF) curve of the study area, as shown in Figure 5.

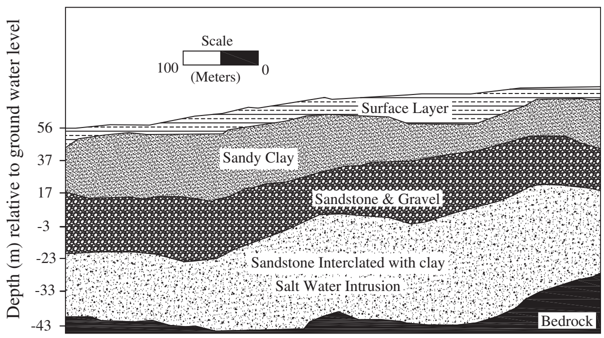


FIGURE 4 Geological cross section of Wadi Watier (modified after, WRRI, 2012)

3 | METHODOLOGY

The required data have been collected from different resources, including digital elevation models (DEM), satellite images, geological data, geographic information system (GIS), and remote sensing (RS). Field data such as topographic and hydrological data have also been collected for the study area. DEM is used to derive the natural flow paths and the corresponding catchment boundaries for the study area. Rainwater harvesting and groundwater recharge studies require integration between a number of models such as Hyfran, GIS, WMS and GMS.

Hyfran allows fitting several statistical distributions to a data sample. The software is conceived to simplify tasks linked to the fitting of statistical distribution to a random sample. These tasks are grouped into two categories, including data acquisition and statistical characteristics study of a random sample, and fitting one or several statistical formulae from results analysis. This program is suitable for fitting rainfall data and predicting the rainfall depth for different return periods. GIS is a system for management, analysis and display of geographic

TABLE 1 Geomorphic properties of sub-basins

Basin name	A (km^2)	S (m/m)	MSD (m)	MSS (m/m)	SF	SI	MBE	CN
1	394.01	0.134	47,706.70	0.015	3.84	1.17	1,136.10	83
2	373.24	0.127	41,322.00	0.017	2.66	1.22	1,211.75	81
3	513.65	0.156	76,884.76	0.015	6.21	1.31	967.18	80
4	299.60	0.169	41,829.41	0.024	3.16	1.28	947.08	78
5	172.55	0.072	42,773.63	0.015	4.00	1.52	900.61	83
6	198.31	0.118	37,963.04	0.017	3.22	1.40	902.81	82
7	81.26	0.163	26,929.09	0.023	5.31	1.15	809.37	79
8	83.47	0.141	24,365.41	0.020	3.14	1.38	866.13	79
9	224.81	0.076	39,328.58	0.008	2.28	1.55	862.55	82
10	182.35	0.200	31,306.67	0.030	3.51	1.11	711.00	78
11	98.91	0.164	23,186.30	0.021	1.47	1.75	682.70	80
12	163.53	0.134	25,831.23	0.017	1.44	1.50	784.26	82
13	173.82	0.266	34,597.67	0.028	2.75	1.51	528.65	85
14	129.01	0.166	28,104.25	0.029	4.12	1.07	679.20	87
15	322.13	0.059	38,628.99	0.007	2.37	1.29	831.56	79
16	101.06	0.108	20,925.25	0.016	2.28	1.19	844.54	78

Abbreviations: A, basin area; CN, curve number; MBE, mean basin elevation; MSD, max stream distant; MSS, max stream slope; S, basin slop; SF, shape factor; SI, sinuosity.

Return period (years)	2 Y	5 Y	10 Y	25 Y	50 Y	100 Y
Maximum 24 hr rainfall (mm)	7.16	14.64	25.14	51.37	70.15	98.20

TABLE 2 Depth of rainfall at different return periods

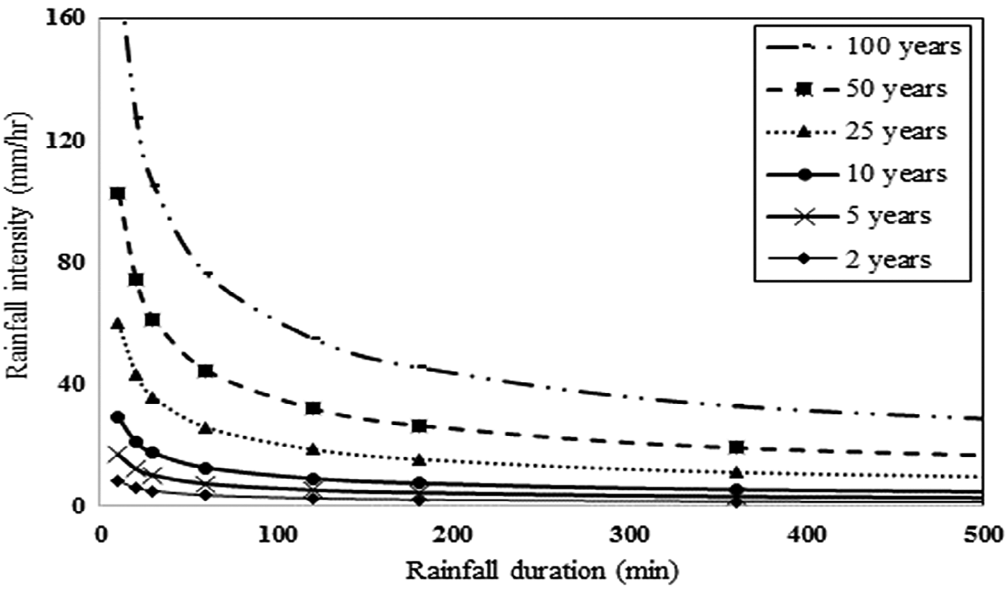


FIGURE 5 IDF curve of the study area

information. It includes a set of comprehensive tools for working with geographic data. WMS is comprehensive graphical modelling for all phases of watershed hydrology and hydraulics. It has powerful tools to automate modelling processes such as automated basin delineation, geometric parameter calculations, GIS overlay computations, Curve Number (CN), rainfall depth, roughness coefficients, etc. GMS is a model for groundwater flow and contaminant transport in porous media. It uses MODFLOW to determine groundwater flow, groundwater change levels due to various conditions such as pumping wells, suction wells and rainfall recharges. In the current study, these models are integrated to study rainwater harvesting and groundwater recharge, as shown in the flow chart of Figure 6. The figures summarise the input, processing, output, and interaction between the different models.

3.1 | Surface runoff estimation

For runoff hydrograph computation, different equations can be used, and we used the Soil Conservation Service (SCS) method in this study due to its high accuracy (Chow, Maidment, & Mays, 1988). SCS utilises geological information to assign a unique curve number (CN) coefficient value for each area that will be further used to estimate the surface runoff depth and the peak discharge magnitude. The equation can be described as:

$$Q=\frac{(P-0.20S)^2}{P+0.80S} \quad (1)$$

where Q is the depth of direct runoff (mm), P is the depth of precipitation for a specific return period (mm), and S is the maximum potential retention (mm) and can be calculated from the following equation:

$$S=25.40\left(\frac{1000}{CN}-1\right)\text{mm and } 0<\text{CN}\leq 100 \quad (2)$$

Tables that provide values of CN are presented in several publications (e.g., Sen, 2008). The curve number CN depends on soil type and land use.

The time of concentration (T_c) is considered an important factor in flood assessment since it is the time required by runoff to travel from the most distant point to the basin's outlet point. A number of formulas can be used for computing T_c such as Kirpich equation (Chow et al., 1988), which is described as following:

$$T_c=0.0195\ L^{0.775}S^{-0.385} \quad (3)$$

where T_c is the time of concentration (min), L is the catchment main stream length (m), and S is the main stream slope (m/m).

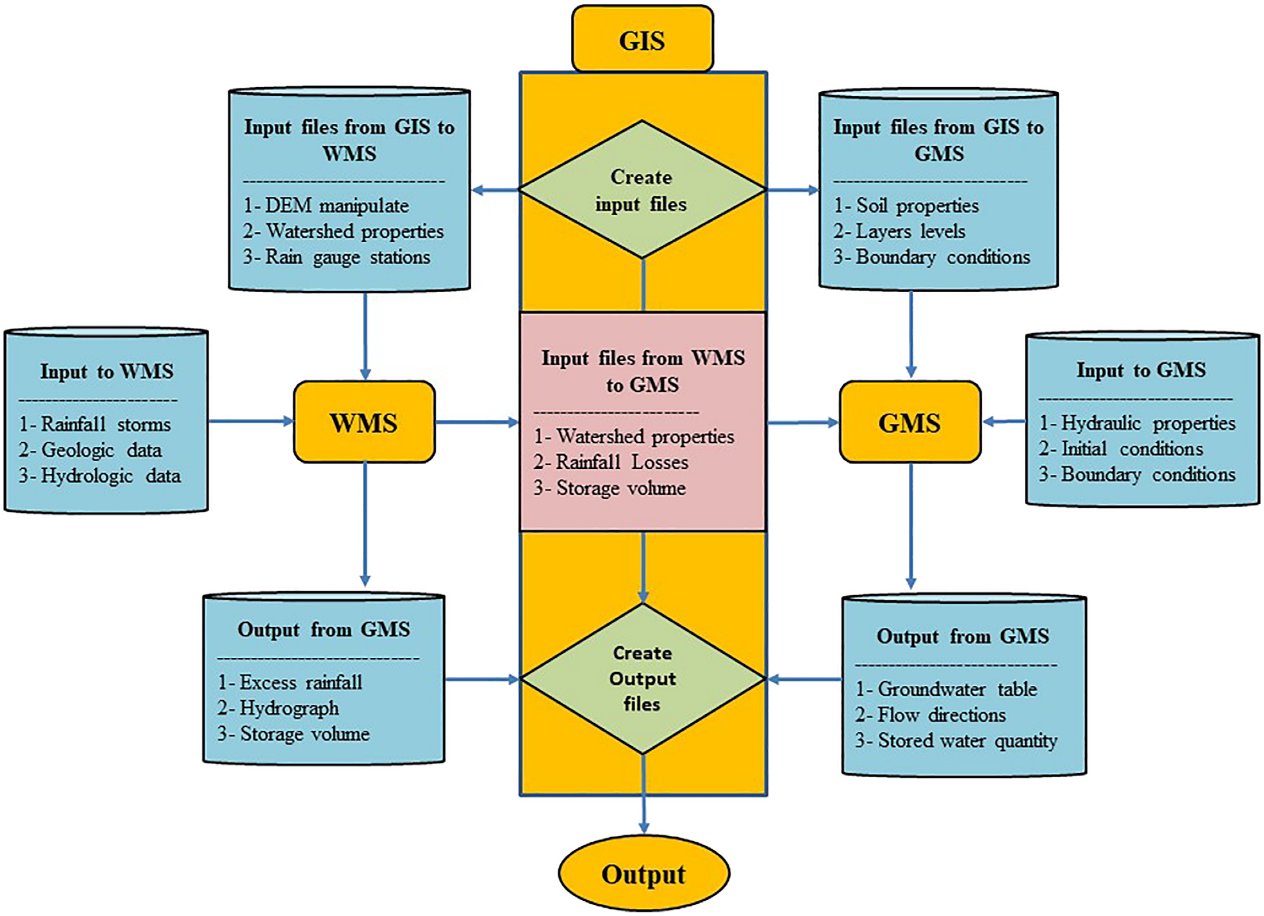


FIGURE 6 Flow chart of the integrated models

3.2 | Groundwater flow model

A three-dimensional GMS computer program was used for groundwater simulation. The governing equation can be written as Jasrotia et al. (2007).

$$\frac{\partial}{\partial x}\left(T\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial Z}\left(T\frac{\partial h}{\partial Z}\right)=S\frac{\partial h}{\partial t}+Q \tag{4}$$

where T is the aquifer transmissivity (m^2/day), h is the hydraulic head (m), S is the aquifer storage coefficient, t is the time (day), Q is the net groundwater flux per unit area (m^3/day/m).

4 | RESULTS

4.1 | Protection of flood risks

As noted above, Wadi Watier has been exposed to many floods that affect people and many international roads in the area. The WMS model was used for delineation of the study area with its 16 sub-basins to identify the main streams, drainage paths, flow directions and quantities of water. The risky locations have also been detected to protect such areas from flood risk. In two sub-basins (13 and 14), the flow is sheet flow and can go directly to the Aqaba Gulf. However, 14 sub-basins require the construction of dams for both protection and storage of water. The locations of 14 dams have been selected, as presented in Table 3, to protect the area from flood risk and store water to be subsequently used for different purposes. Design of dams is discussed in Section 4.2.

4.2 | Rainwater harvesting and storage

Dam locations in the different sub-basins, and their type either to collect or store rainwater is presented in Figure 7a. Recharge dam (1) type in the figure refers to recharge using the ponds, while recharge dam (2) type uses deep wells. The location of recharge wells is shown in Figure 7b. The locations of dams and wells were selected based on the soil properties (Figure 4) such that storage dams were selected at low permeability soil (e.g., igneous rock and lime stone) and recharge dams

TABLE 3 Proposed locations of dams. Recharge (1) means recharge pond, and recharge (2) refers to recharge by deep wells (see Figure 7a)

DAM no.	Coordinates		Type
	X	*Y*	
1	648,924	3,245,332.704	Storage
2	648,869.543	3,245,538.564	Recharge (1)
3	644,651.576	3,248,256.292	Storage
4	644,410	3,248,073.826	Storage
5	645,795.856	3,239,379.685	Storage
6	651,677	3,214,399.44	Recharge (2)
7	619,239.559	3,204,940.39	Recharge (1)
8	625,463.593	3,209,923.177	Recharge (1)
9	646,957.851	3,222,156	Recharge (2)
10	644,730.843	3,223,713.182	Recharge (1)
11	644,239.741	3,225,594	Recharge (1)
12	644,816.31	3,233,650	Recharge (2)
13	645,887.08	3,235,797	Storage
14	644,544	3,225,486.965	Recharge (1)

were selected at areas of high permeability soil (e.g., Wadi deposit). Five dams were used for storage and nine for recharging the aquifer with depth wells.

Figure 8 presents the storage curve of four of the dams (dam 1, dam 4, dam 6, and dam 13) that have different storage capacity, as an example for the 14 dams. The curves of the other dams are not shown here for brevity purposes. The storage curves are used to determine the volume of storage at different water levels. The storage elevation curves of all the 14 dams together indicate that the collected amounts of water is 160.72 million m^3. The dams showed distinctly different water storage owing to the different topography, which affects the peak discharge and soil characteristics. Another reason is because steep slope has a greater peak discharge than flat slope. For example, dam 9 can store ~25.2 million m^3 of water due to low levels of land in front of the dam while dam 1 can only store ~4.57 million m^3 of water. This is due to the fact that dam 1 is built over high land level. Other dams showed different storages, such as dam 12 that had only storage of 3.93 million m^3; these different storages are mainly because of the above reasons.

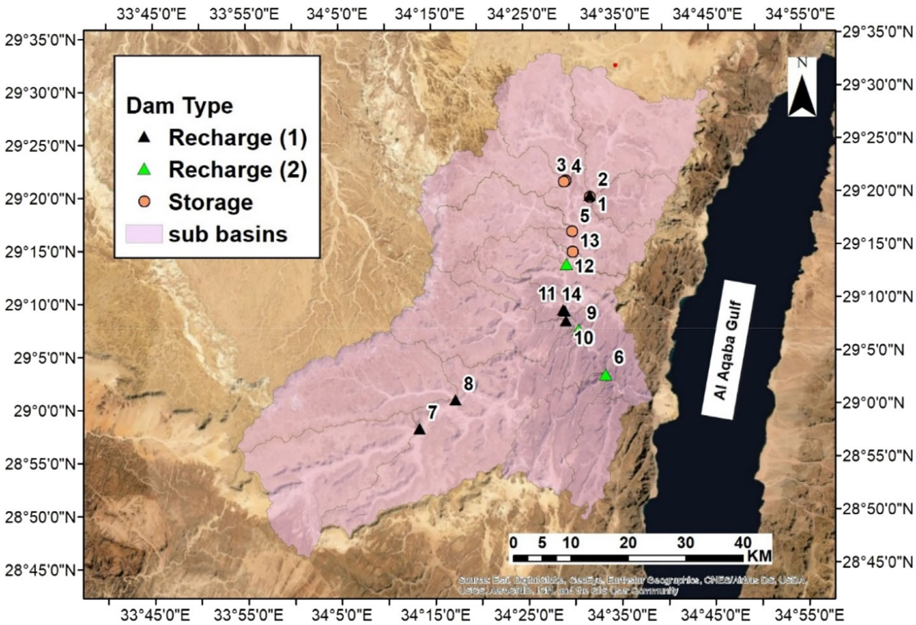
Khattab (1991) presented empirical dimensions of a dam body such as the minimum top width is 6 m, dam height is determined from the storage curve with minimum free board equals to 1 m and upstream and downstream slopes are 3:1 and 2.1 respectively. Also the core dimensions were determined with top width of 2 m and side slopes 1.5:1. Table 4 presents the storage volume upstream of each dam at different return periods used in dams design. The design parameters of each dam are presented in Table 5, and a typical cross section of Dam 1 is shown in Figure 9. The construction costs of dams have been roughly estimated following Abdel-Fattah, Kantoush, Saber, and Sumi (2020) who developed an approach for flood mitigation in Wadi Abadi in the Eastern Desert of Egypt. They compared the construction of three dams with one large dam to protect the area from flood risks. The cost of dam construction reached $12,108.33 per meter length for dams of height from 10 to 17 m and length from 600 to 1,200 m. The current case study has similar conditions and this cost can be used here. Following this cost estimate, the cost of Dam 1 is about $4.843 million US dollars (about 3.6 million sterling pounds) for storage volume of 4.57×10^6 m^3.

4.3 | Groundwater recharge

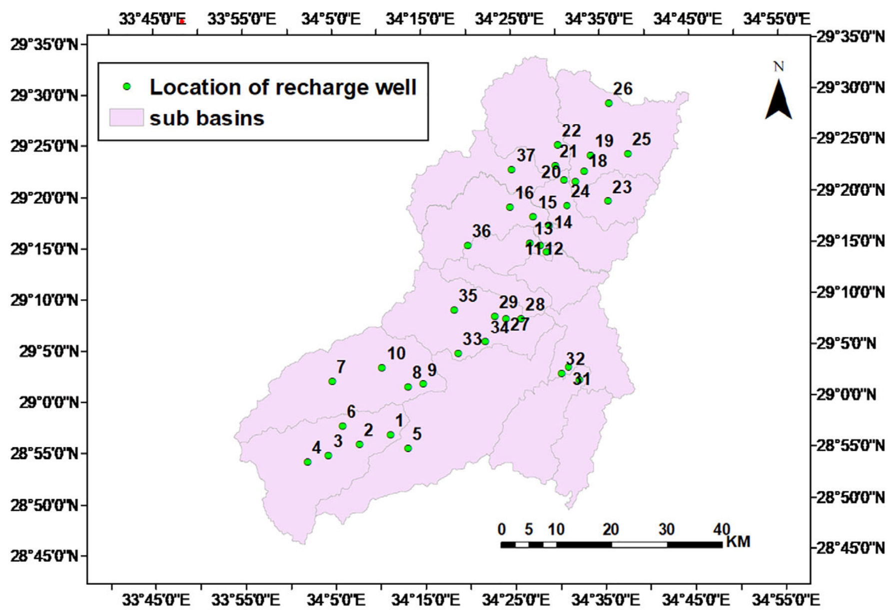
The numerical model GMS was used to determine the flow directions and quantity of water that can be stored into the aquifer. The model domain was subdivided into 200 rows and 200 columns with cell dimensions (0.4 × 0.4) km as shown in Figure 10a. The simulated area was divided into three layers. Cross-sections in X-direction from east to west and Y-direction from the north to the south are shown in Figure 10b,c. The thickness of the aquifer layers varied between 50 m at the south to 200 m at the north. Figure 10d shows the 3-D domain and grid for the study area. The boundary conditions are set as constant head with zero value along the shoreline at the eastern south boundary (Gulf of Aqaba). The south was bounded by constant head of 43 m below mean sea level. The west boundary was left free for the groundwater direction perpendicular to the shoreline. The initial values of the hydraulic parameters of the aquifer in the study area are presented in Table 6, and were used as input data to the model. These data were estimated according to soil type. Recharge to the aquifer is calculated according to soil infiltration process from the WMS output ($q = 0.001$ m/day).

Groundwater recharge was done through recharge wells by injecting the harvested water into aquifers. The data of these wells are listed in Table 7 and their locations are shown in Figure 7b. The locations of these wells were selected according to the soil type of the upper part of the aquifer. The use of recharge wells was restricted to areas where the upper part of the aquifer has a low permeability soil (such as an igneous rock layer, see Figure 4) in which the water infiltration will be very slow and hence much evaporation will take place. For areas where the top layer has high permeability soil, there was

FIGURE 7 Distribution map of proposed 14 dams on the sub-basins and recharge wells. Recharge (1) means recharge pond, and recharge (2) refers to recharge by deep wells



(a) Recharge dams



(b) Recharge wells

no need for recharge wells as the surface runoff water will easily infiltrate to the groundwater. The recharge wells consisted of 10 gravel wells with 1 m diameter. The infiltration rate of the gravel was taken between 50 and 75 m/day.

As expected, the recharged freshwater increased the storage of the groundwater reservoir in the region. The initial groundwater level in the study area is shown in Figure 11a and the new levels after recharge are shown in Figure 11b. The figure reveals that the groundwater levels have increased in the aquifer up to over 50 m of water head in some regions in the northern part of the basin. This demonstrates the benefit of storing and pumping the water into the aquifer, which can then be used for agricultural and other purposes. This will undoubtedly help in the development of these arid areas and fill some of their water needs wherein they already suffer from water shortage.

5 | DISCUSSION

The study presented a comprehensive analysis of protection from flood risks, a rainwater harvesting process, and

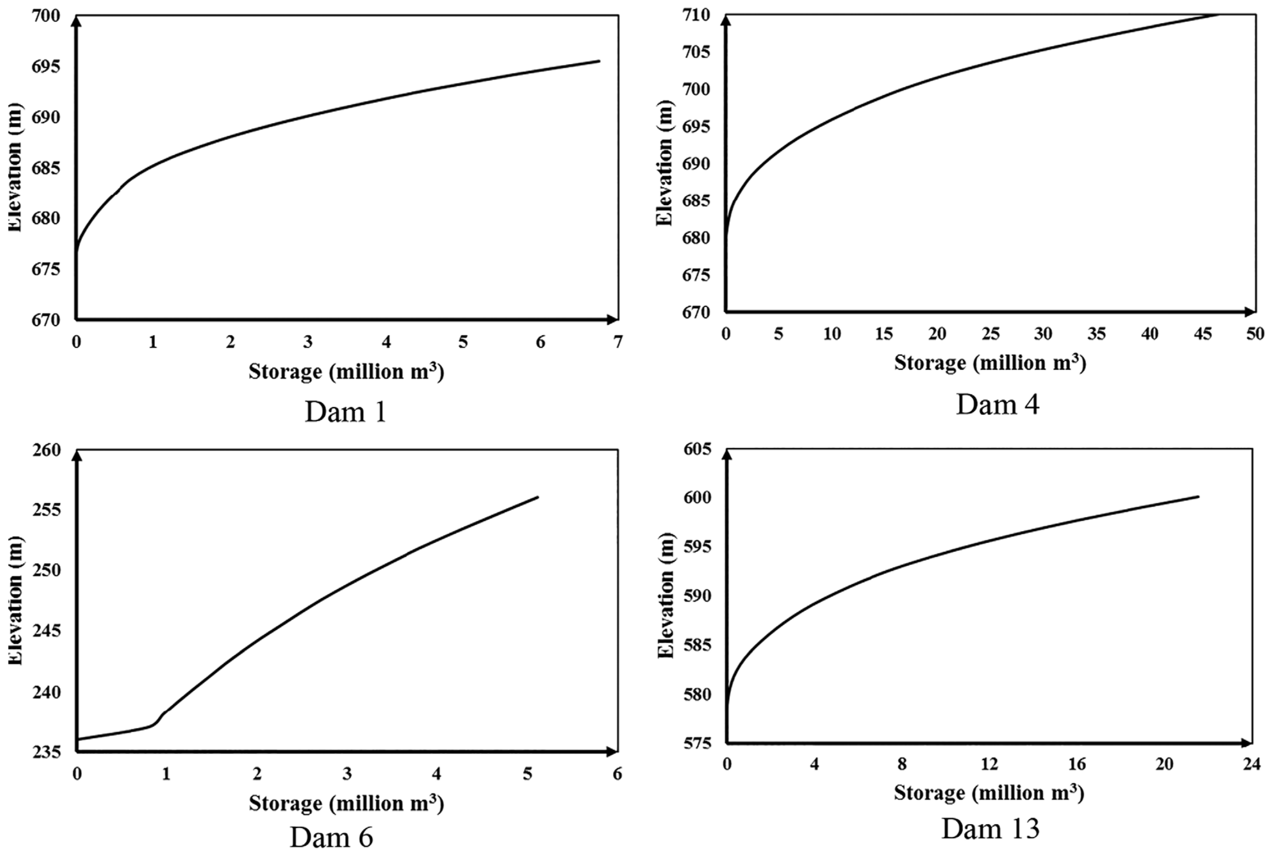


FIGURE 8 Storage curve of Dams 1, 4, 6, 13 (only four dams are shown for brevity purposes)

TABLE 4 Flow and storage volume of sub-basins

BASIN name	Q10 (m^3/s)	Q25 (m^3/s)	Q50 (m^3/s)	Q100 (m^3/s)	V10 (10^6 m^3)	V25 (10^6 m^3)	V50 (10^6 m^3)	V100 (10^6 m^3)
1	33.98	221.39	405.26	715.12	1.28	7.11	12.58	21.72
2	22.88	182.13	348.38	635.23	0.90	5.87	10.74	19.05
3	21.01	169.89	327.07	602.19	1.05	7.52	14.02	25.20
4	10.13	116.63	238.91	459.88	0.42	3.78	7.32	13.55
5	13.04	82.2	149.84	263.85	0.56	3.11	5.51	9.51
6	15.1	109.69	205.86	368.84	0.56	3.34	6.02	10.52
7	4	44.68	90.59	171.74	0.14	1.11	2.10	3.83
8	4.13	46.11	93.43	177.41	0.14	1.14	2.16	3.93
9	14.89	103.61	193.07	345.44	0.63	3.79	6.82	11.93
10	6.97	88.56	183.69	356.12	0.26	2.30	4.46	8.25
11	6.55	66.41	131.82	245.15	0.20	1.45	2.70	4.85
12	15.35	119.01	225.32	405.1	0.46	2.76	4.96	8.68
13	31.86	187.59	331.16	566.53	0.75	3.58	6.14	10.32
14	32.78	161.58	247.04	454.51	0.72	3.03	5.02	8.24
15	7.77	83.86	169.31	321	0.55	4.36	8.29	15.13
16	3.89	49.64	103.12	199.62	0.14	1.28	2.47	4.57

Note: Q10 and V10 mean flow rate and volume for return period of 10 years.

TABLE 5 Design parameters of Dams

Dam no	Basin no	Volume of water stored (10^6 m^3)	Length of dam (m)	Top width (m)	Upstream slope width (m)	Downstream slope width (m)	Core top width (m)	Core bottom width (m)	Upstream water depth (m)	Free board height (m)	Core height (m)
		V	L	B2	B1	B3	B4	B5	H1	H2	H3
1	16	4.57	400	6	57	38	2	52.25	17	2	16.75
2	15	15.13	450	10	43.5	29	2	40.25	13	1.5	12.75
3	9	11.93	700	12	78	52	2	73.25	24	2	23.75
4	5	9.51	200	10	37.5	25	2	34.25	11	1.5	10.75
5	6	10.52	500	12	66	44	2	61.25	20	2	19.75
6	10	8.25	750	12	66	44	2	61.25	20	2	19.75
7	2	19.05	1,100	12	51	34	2	46.25	15	2	14.75
8	1	21.72	1,200	12	60	40	2	55.25	18	2	17.75
9	3	25.20	900	12	51	34	2	46.25	15	2	14.75
10	4	13.55	900	12	66	44	2	61.25	20	2	19.75
11	7	3.83	200	10	25.5	17	2	22.25	7	1.5	6.75
12	8	3.93	450	10	34.5	23	2	31.25	10	1.5	9.75
13	12	8.68	1,000	10	34.5	23	2	31.25	10	1.5	9.75
14	11	4.85	200	10	34.5	23	2	31.25	10	1.5	9.75

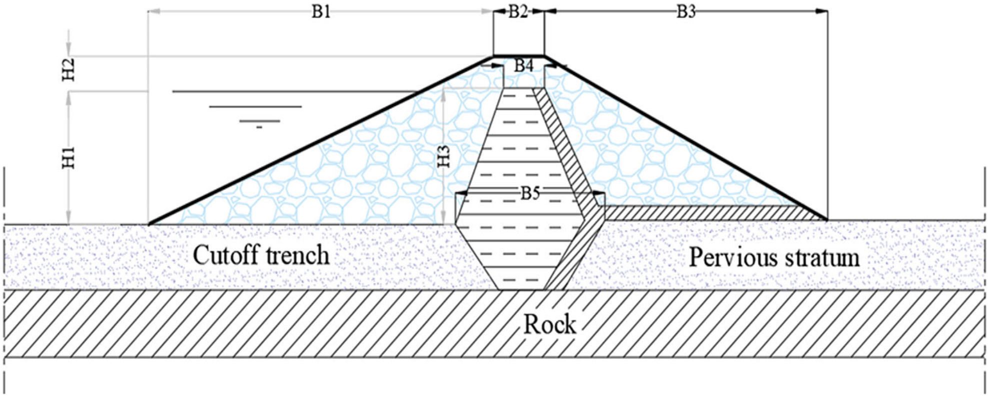


FIGURE 9 Typical cross section of Dam 1

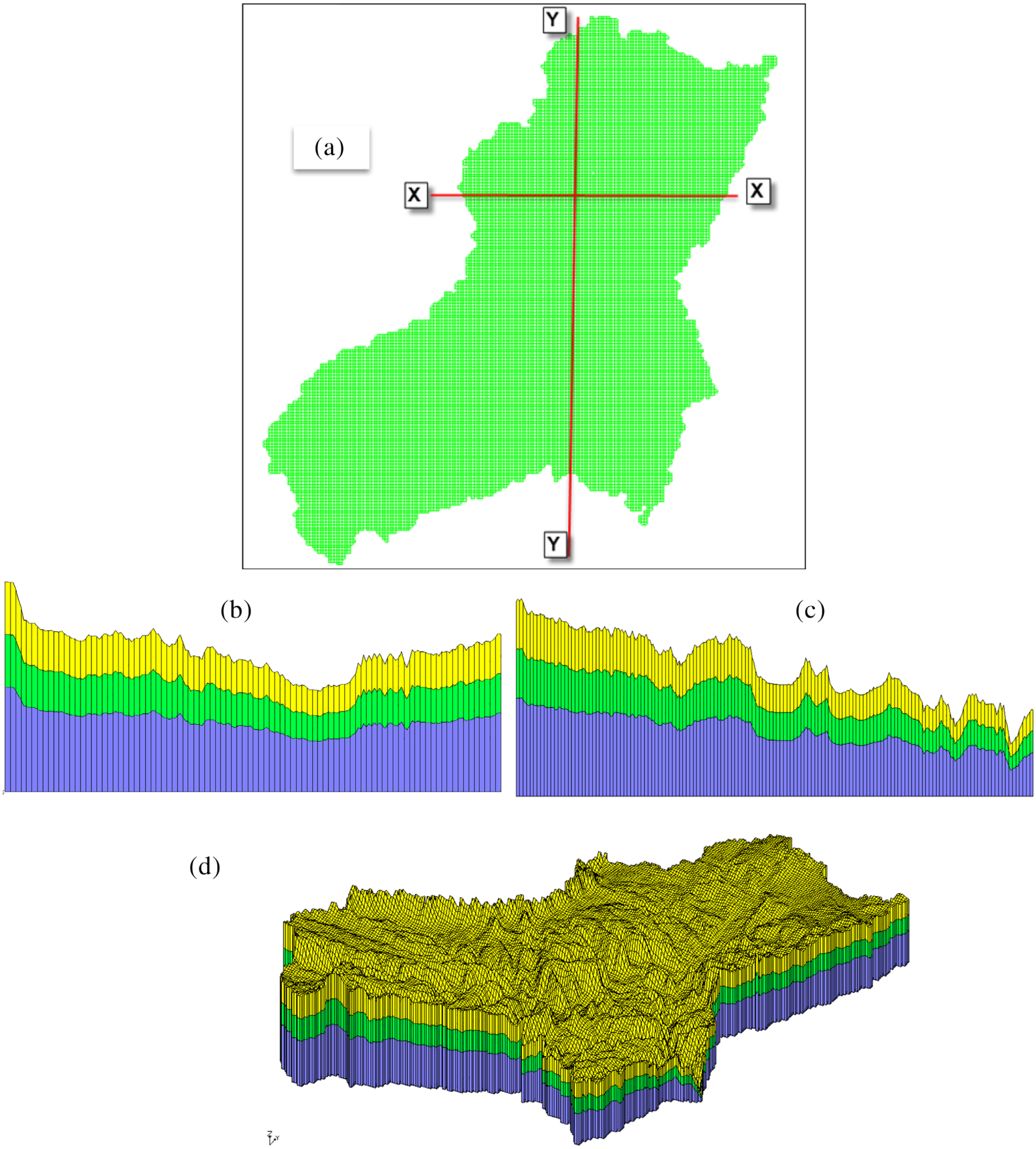


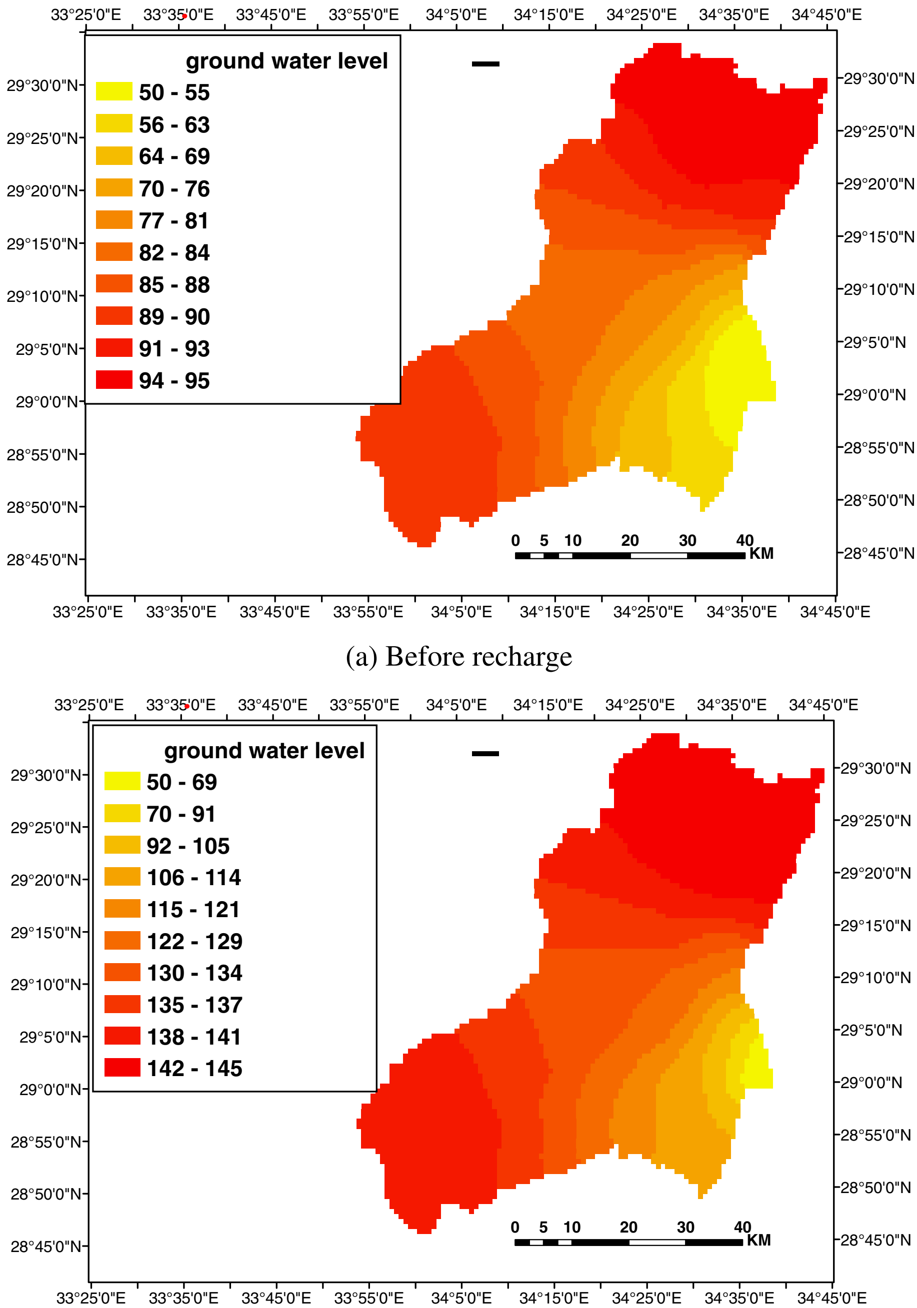
FIGURE 10 Model geometry of the study area created by GMS. (a) Plan view, (b) horizontal cross section (X-X), (c) vertical cross section (Y-Y), and (d) 3-D domain

TABLE 6 Hydraulic properties of aquifer

	Horizontal hydraulic conductivity K_h (m/day)	Vertical hydraulic conductivity K_V (m/day)	Storage coefficient S (m/m)	Specific yield S_y (1/m)	Effective porosity n (m/m)
Layer_1	25–100	2.5–10	2.00×10^{-3}	0.18	25
Layer_2	50–100	5.0–10	3.00×10^{-3}	0.25	35
Layer_3	35–100	3.5–10	2.50×10^{-3}	0.20	30

TABLE 7 Recharge wells data. All wells have a 1 m diameter

Well no.	X (m)	Y (m)	Ground level	Q (m^3/day)	Depth (m)
1	615,806.465	3,202,308.2	837.6	4,000	200
2	610,184.058	3,200,654.551	896.6	4,000	200
3	604,495.505	3,198,670.172	958.3	4,000	200
4	600,711.956	3,197,479.544	1,008.8	4,000	200
5	618,915.325	3,199,913.716	860	4,000	200
6	607,061.968	3,203,935.391	1,106.6	4,000	200
7	605,156.965	3,211,978.74	1,085.1	4,000	200
8	618,915.325	3,211,026.238	799.1	4,000	200
9	621,666.998	3,211,449.572	775.7	4,000	200
10	614,258.649	3,214,412.912	958.6	4,000	200
11	643,938.344	3,235,369.276	561.4	4,000	200
12	642,714.644	3,236,460.685	595.6	4,000	200
13	640,895.63	3,236,923.707	616.2	4,000	200
14	644,374.908	3,240,105.328	572.8	4,000	200
15	641,517.402	3,241,745.747	723.1	4,000	200
16	637,336.977	3,243,386.167	681.4	4,000	200
17	649,137.417	3,247,954.649	650.6	4,000	200
18	650,764.608	3,249,899.34	676.3	4,000	200
19	651,875.86	3,252,717.158	683.7	4,000	200
20	647,113.35	3,248,232.462	642.2	4,000	200
21	645,446.472	3,250,812.154	678.9	4,000	200
22	645,962.411	3,254,661.85	710.4	4,000	200
23	655,103.783	3,244,498.522	751.6	4,000	200
24	647,589.601	3,243,704.77	629.9	4,000	200
25	658,649.207	3,253,018.122	751	4,000	200
26	655,262.533	3,262,262.683	738.9	4,000	200
27	636,624.805	3,223,318.143	613.2	4,000	50
28	639,336.79	3,223,318.143	575.6	4,000	50
29	634,574.28	3,223,715.019	621.2	4,000	50
30	649,893.686	3,212,218.85	276	4,000	50
31	647,909.307	3,214,600.105	619.1	4,000	50
32	646,639.304	3,213,409.477	776.3	4,000	50
33	627,992.757	3,216,954.901	1,057.8	4,000	50
34	632,914.017	3,219,177.405	986.3	4,000	50
35	627,199.005	3,224,892.417	981	4,000	50
36	629,686.093	3,236,581.732	953.5	4,000	200
37	637,639.484	3,250,218.384	715.7	4,000	200



(a) Before recharge

(b) After recharge

FIGURE 11 Groundwater levels in the aquifer

linking it to recharging groundwater aquifers using different hydrological models as part of a flood mitigation plan in Wadi Watier. The results presented herein builds on previous investigation by Elewa et al. (2012) that divided Sinai to four categories according to runoff water harvesting. Wadi Watier was one of the areas the study found has potential of high harvesting of runoff water. The need for integrated studies, like the one presented here, was also one of the main findings of Abdel-Fattah, Kantoush, and Sumi (2015) who investigated the flash floods of 2010, and 2014 in Wadi Abadi in Sinai Peninsula, Egypt.

For flood risk management, the study area was divided to 16 sub-basins, two of which do not need dams while fourteen dams have been proposed and designed to protect the area and to store water. Five dams are used for storage and nine dams are used for groundwater recharge using ponds and deep wells. The proposed dams are capable of protecting the area from flood risks and storing a large amount of water that can be used in the development of the area. The estimated water to be stored is 160.72 million m^3 from for the 100 year return period. Recharging groundwater to the groundwater aquifer in the study area has raised the water level by 50 m.

Also, the proposed water management solution can help reduce groundwater contamination by saline water. An extra advantage of the raised groundwater level that comes as a consequence of the recharge wells is that it protects the aquifer from saltwater intrusion through the repulsion of the saline wedge, as demonstrated in many studies (e.g., Abdoulhalik & Ahmed, 2018; Robinson, Ahmed, & Hamill, 2016). These studies and others demonstrated that even small increases in the groundwater levels have significant effects in repulsing the saline water contamination.

The limitation of this study is the shortage of some field data such as the piezometric head, recent data of rainfall and geological data of all layers of the case study in addition to the tidal effects of seawater on groundwater recharge. Also, cost–benefit analysis and visibility study of the recommended protection measures require more details, and more analysis will be considered in future studies.

6 | CONCLUSIONS

The economic growth in arid and semi-arid regions is always impacted by water scarcity. Therefore, innovative approaches for developing integrated surface-water/groundwater models that help in water resources planning and management are of great importance for sustainable development in these areas. Innovative ways for the capture, storage and use of rainwater will lead to more sustainable and profitable crop production. This paper presents a case study for Wadi Watier, south Sinai, Egypt for rainwater harvesting and recharge to groundwater to mitigate flood risks and water scarcity. The results are mapped using GIS and WMS with the production of a series of maps. Hydrological analyses using WMS was carried out in order to develop the drainage networks and to estimate the runoff parameters that are used to calculate the flood hydrographs depending on existing rainfall/runoff data. The hydrological analyses and mitigation strategies for Wadi Watier were presented. The study area was subdivided into 16 sub-basins, and the characteristics of each basin were determined using WMS. The boundary, delineation, drainage paths, mainstream and flood estimation locations of each sub-basin are also determined. Based on the flow direction and magnitude, locations of 14 dams were selected to protect the study area from flood risks and to store floodwater. Based on the soil properties in each sub-basin, five dams were used for storage and nine dams for groundwater recharge. The results showed that applying the water harvesting technique can collect large amounts of water about 160.72 million m^3) from the fourteen dams. Also, these dams help protect the area from flood risks. The collected water can be used for domestic and agricultural purposes. This will increase the national income and provide stability for residents in these areas. This study offers some solutions to authorities and decision-makers in these areas that help in the sustainable management of water resources. The study provides a good example to be applied in Egypt and other parts of the world.

DATA AVAILABILITY STATEMENT

Data will be provided when requested.

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