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Integration of GIS, Remote Sensing and Hydrologic Modeling for Proper Rainwater Harvesting Evaluation, East El-Fashn Area, Egypt

Hakeem Musaed[1,2] *Khaled Gemail[3] Sayed Bedair[4] Ahmed Mosa[5] and Mohamed El Alfy[1]

[1] Geology Department, Faculty of Science, Mansoura University, Mansoura 35511, Egypt.

[2]Department of Geological Engineering, Faculty of Oil and Minerals, University of Shabwah, Shabwah, Yemen.

[3] Environmental Geophysics Lab (ZEGL) at Geology Department, Faculty of Science, Zagazig University, 44519 Zagazig, Egypt.

[4] The Research Institute for Groundwater (RIGW), Ministry of Water Resources & Irrigation, Kanater Khairia, Egypt.

[5]Department of Soils, Faculty of Agriculture, Mansoura University, Mansoura 35516, Egypt.

** Correspondence: hakeem21112@gmail.com; Tel.: 00201119101981*

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Abstract: GIS and remote sensing are integrated with hydrological modeling to evaluate ideal sites for rainwater harvesting and groundwater recharge east El-Fashn area. The El-Fashn basin was separated into 36 sub-basins of the 4th order. The hydrological model highlighted the southeastern portion of the study zone as having the highst precipitation rates and, the steepest slopes. The Analytic Hierarchy Process was employed to locate the optimal Rainwater Harvesting (RWH) sites, considering different factors such as; slope, land use/land cover, lineament density, average daily precipitation, and stream order. Among the tested criteria, ground surface slope, land cover and raifall emerged as the most influential factors in locating the suitable RWH sites. Five potential locations for constructing low dams were proposed to reduce flood hazard and leverage rainfall harvesting opportunities in the study zone. The results indicate that rainwater harvesting and groundwater replenishment are significant in the southeast and northeast areas, while recharge with Nile River water is dominant in the west. The reaserch findings and applied craiterias can be informed in larger-scale water resource management strategies and apply to similar conditions in various regions**.**

keywords: Arid areas, Rainfall-Runoff modelling, Rainwater harvesting, Groundwater recharge

1.Introduction

Egypt, situated in the eastern portion of the Great Sahara, is renowned as the driest region on Earth [1]. Consequently, the country faces a severe water scarcity issue, necessitating urgent exploration of new water sources and implementation of effective management practices to mitigate the crisis to some extent [2]. Egypt relies on a variety of surface water resources, such as the River Nile, precipitation, and flash floods. Among these, the River Nile holds paramount importance, constituting approximately 97% of the country's renewable water resources. Moreover, Egypt possesses substantial groundwater sources, including the Nile Valley and Delta aquifer, the Nubian Sandstone aquifer, Moghra, the fractured limestone aquifer in the Eastern and Western Deserts, and the Sinai Peninsula [3].

The Eastern Desert, covering around 22% of Egypt's territories, hosts significant groundwater reserves, making it crucial to conduct a comprehensive and efficient assessment of these resources [4]. The groundwater resources in the Eastern Desert are constrained and predominantly exist in shallow alluvial and fracture zone aquifers, which also include sandstone and fractured carbonate aquifers [5].

Flash floods represent a critical water source in such regions; however, only a minor fraction of this water manages to infiltrate the ground and recharge the groundwater reservoirs [6,7]. Rainwater harvesting (RWH) dates back to 3000 BC and was widely practiced. Twentieth-century technological advancements led to a decline in RWH, but recent years have seen a resurgence of interest due to population growth, climate change, and dwindling water supplies [8].

Current study conducted in the eastern region of El-Fashn city used various data sources, including DEM, remote sensing and rainfall-runoff data. These data were essential for rainfall-runoff modeling and identifying suitable locations for rainwater harvesting (RWH) using the Analytic Hierarchy Process (AHP) method. The aim to assess the most suatable locations for raiwater havesting and groundwater reachrge study area.

2. Study Area

The research location is situated in the southeastern portion of the El-Fashn City, within the latitudinal range of 28° 42' N to 28° 54' N, and the longitudinal range of 30° 26' E to 31° 10' E (**Error! Reference source not found.**). The study area covers approximately 245.38 km^2, with a length of approximately 25.33 km and an average width of about 9.69 km. The elevation ranges from 30 meters (asl) in the zone near the Nile River (western portion) to 310m in the southeastern portion, near to the mountains (Figure 1). The research site is located in the arid area in the east of the desert, known for its scorching summers, where temperatures can reach up to 40°C, and chilly winters with smallest temperatures nearing 0 °C. Evaporation vary throughout the year Varying from 5 mm/day the winter to 12.4 mm/day in the summer [9]. The study area is characterized by a sequence of Tertiary and Quaternary sedimentary rocks. The El-Fashn Formation is formed of chalky limestone with flint nodules, measuring 80m to 135m in thickness, as observed in the Jabal Abyad region [10]. The Qarara Formation describes the limestone successions (170m) prominently visible east of Maghagha in Gabal Qarara [11].

3. Materials and methods

The methodology utilizes rainfall-runoff modeling, employing a spatio-temporal lumped approach for calculate runoff sizes in each sub-basins and determine suitable sites for rainwater harvesting. The remote sensing (RS), rainfall-runoff data and digital elevation model (DEM) were used. Various programs were utilized, including ENVI 4.5, WMS 11.1, ERDAS Imagine 2015, ArcGIS 10.2, PCI-Geomatics 2015, HyfranPlus, RockWorks 16 and HEC-HMS 4.5. Meteorological data on daily rainfall for the period from 1979 to 2014 were sourced from the Directorate General of Meteorology (DGM). This study focused on analyzing the Temporal-spatial distribution of rainfall in every sub-basin using adjacent gridded data. To evaluate extreme precipitation events, we considered five hypothetical design storms with recurrence intervals of 5 to 100 years. Employing statistical frequency examination, we identified values of max 24-hr rainfall to each return period. The Log-Pearson type 3 technique based on moments (BOB) was employed. STRM with 30 resoltion was used.

Multi-spectral satellite images (Landsat-8) with spatial resolutions 30 m and 15 m (for multi-spectral, panchromatic, respectively), were utilized. Composite bands, principle component and band ratios were conducted to identify land-use classes and curve number (CN). After the initial unsupervised classification, a supervised classification approach was implemented [12].

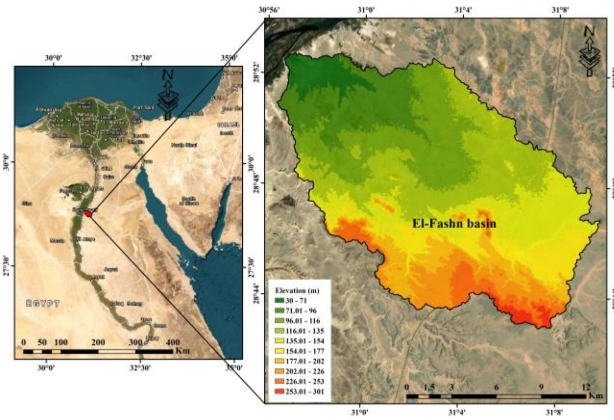

Figure 1: Study area Location.

HEC-HMS was utilized for conducting the rainfall and runoff modeling, software, specifically designed for simulating rainfall-runoff processes in watershed systems[13]. In the process of rainfall-runoff modeling, diverse datasets including soil typ, meteorological data, land-use and DEM are incorporated. SCS-CN technique was employed for this purpose. This technique uses Equations

$$CN_W = \frac{\Sigma CNi * Ai}{At} \quad (1)$$

$$S = \left(\frac{100}{CNw}\right) - 10 \quad (2)$$

$$Q = \frac{(p-0.25)^2}{(p+0.8S)} \, for \, Q > 0.2S: else \, Q = 0 \quad (3)$$

$$Ia = 0.2S \quad (4)$$

$$Tc = \frac{5}{3} + T \quad (5)$$

$$Tp = \frac{\Delta D}{2} + TL \quad (6)$$

The equation involves several variables, such as CNw representing the weight of CN, CNi denoting the CN of the same value in a sub-basin, Ai representing the area of CNi in the sub-basin (in km^2), and At signifying the total area of the sub-basin (in km^2). Additionally, S is the potential maximum soil moisture retention depth, Ia stands for the initial abstraction loss depth, Q represents the direct runoff depth over the entire sub-basin for any return period, and P signifies the precipitation depth for a 24-hour period storm for each return period in the each sub-basin. Furthermore, Tc and TL represent the time concentration and lag time (in hours) for each sub-basin, respectively. Furthermore, ΔD stands for the period time for rainfall, and Tp represents the time to peak (in hours)[14].

The methods employed to identify suitable locations for rainwater harvesting (RWH) involved RS, GIS, and various analytical methods. The (AHP) method was utilized. To identify suitable locations for rainwater harvesting (RWH), various factors were considered, including stream order, land-cover, slope, average rainfall, and lineaments density. Every of these data groups was subdivided into classes then assigned specific ranks that influence RWH decisions. The relative important of diverse criteria was defined based on previous studies [15]. Each layer is assigned a rating rank based on its significance [16] for each criterion.

Next, a diagonal matrix is created for pairwise comparison, and relative weights are determined by normalizing the rows and columns of the diagonal matrices used for pairwise comparison. The division of every element in every column is computed by summing up that column. Values of eigenvectors from matrices are obtained by calculating an average of normalization matrix. The AHP-GIS multi-criteria model was utilized to create the final map of suitable rainwater harvesting (RWH) locations. This process involved overlaying the reclassified weighted raster, which resulted in dividing the raster into five categories: excellent; very good; moderate; poor; and unsuitable for RWH [17,18].

4. Results and Discussion

The El-Fashn basin covering an area of 245.39 km^2 is subdivided into 36 sub-basins with 4^{th} order (**Figure 2**). The study area exhibits composite and interconnected patterns indicating the morphotectonic evolution of the drainage system. The WMS 11.0 and Arc Hydro 10.2 package are utilized to compute various morphometric parameters (Table 1). The El-Fashn basin is characterized by its elongated shape, measuring 25.33 km in length and with a maximum width of 9.69 km.

The Nu values for the main basin amount to 3736, while the 4^{th} order Sub-basins range from 18 to 135 (sub-basins No. 33 and 22, respectively) with through a mean of 60.03 and a standard deviation of 29.02 (Table 1). he substantial increase in the number of streams can be attributed to the limited permeability and penetration capacity of the ground's surface. The WMRb value for the large basin is 4.71, while for the 4^{th} order sub-basins, it ranges from 2.49 to 6.14 (specifically, sub-basins No. 33 and 10, respectively), with an average of 4.35 and a standard deviation of 0.80 (Table 1). Higher Rb values indicate mountainous regions with elongated basin shapes and low susceptibility to flooding. Conversely, smaller Rb values suggest circular basin shapes, which are more prone to rapid hydrographic high peak flooding and are more vulnerable to floods. The main basin has an Lb value of 25 km, while for the 4^{th} order sub-basins, it ranges from 1 to 6 kilometers (specifically, sub-basins No. 33 and 7, respectively), with an average of 3.76 km and a standard deviation of 1.29 (Table1). Long sub-basin has longer flood travel time than short sub-basin, but it's more favorable for groundwater recharge. The MFD value for the main basin is 35872.7 m, while for 4^{th} order sub-basins, it ranges from 1333.93 to 9014.79 meters (specifically, sub-basins No. 13 and No. 27, respectively), with a mean of 4275.31 m and a standard deviation of 1726.70 (Table 1). High values correspond to the length of the longest waterway from basin outflow to upper boundary. The main basin has an area of 245.38 km^2, while the 4th order Sub-basins range from 0.74 to 8.66 km^2 (specifically, Sub-basins No. 33 and No. 22, respectively), with a mean of 3.88 km^2 ,and a standard deviation of 1.94 (Table 1). According to Horton (1945), the sub-basins were classified as small basins. The value of Dd for the large basin is 4.98 km/km^2, whereas for the 4th order sub-basins, it ranges from 4.10 to 7.91 km/km^2 (specifically, sub-basins No. 2 and 33, respectively), with a mean of 6.56 km/km^2, and a standard deviation of 0.73 (Table 1). High drainage density indicates higher runoff potential while low values imply surface fractured rocks. The main basin has a basin slope value of 0.0515, while for the 4th order sub-basins, it ranges from 0.03 to 0.13 (specifically, sub-basins No. 13 and 5, respectively), with an average of 0.06 and a standard deviation of 0.03 (Table 1). Basins with gentle slopes experience longer concentration times, minimal runoff, and smaller peaks in the hydrograph. In contrast, sub-basins with sharp slopes have greater runoff, shorter concentration times, and higher peaks in the hydrograph.

Table 1: Descriptive Statistics of morphometric parameters for 36 Sub-basins in the study area.

Parameters	Min	Max	Mean	S. D.
Nu	18.00	135.00	60.03	29.02
WMRb	2.49	6.14	4.35	0.80
Lb	1.40	6.55	3.76	1.29
MFD	1333.93	9014.79	4275.31	1726.7
A	0.74	8.66	3.88	1.94
Dd	4.10	7.91	6.56	0.73
BS	0.03	0.13	0.06	0.03

Total Stream Number (Nu), ,Weighted Mean bifurcation ratio (WMRb), Basin length (Lb) in Km, Maximum flow distance (MFD) in Meters, Basin area (A) in Km^2, Drainage density (Dd) in (km/km^2) and Basin slope (BS) and

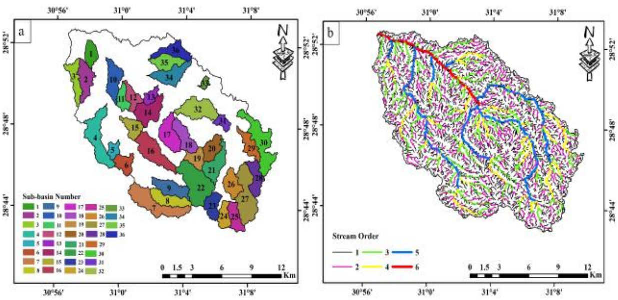

Figure 2: (a) watershed; (b) stream order.

4.1 Rainfall–Runoff Modeling

Five synthetic storm scenarios were generated for rainfall events with recurrence periods of 5, 10, 25, 50, and 100 years. The maximum 24-hour precipitation values for these recurrence periods vary from 1 to 55 mm/year. The curves relating the reoccurrence period to the historical 24-hour precipitation depth were computed with a 95% confidence level (**Figure 3**).

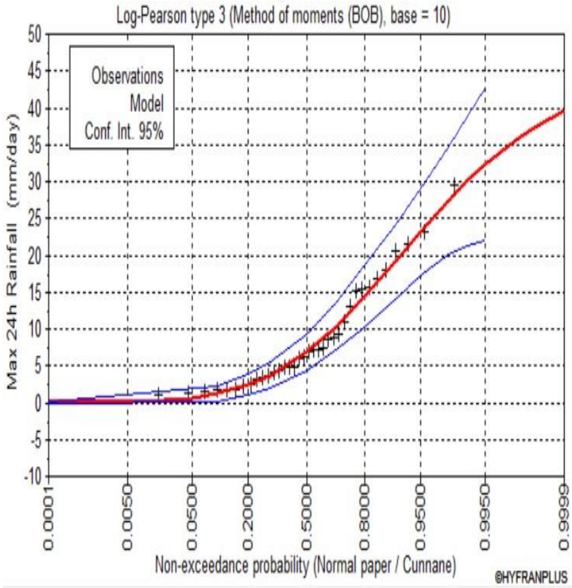

Figure 3: The max 24 hours precipitation data for the analysis of precipitation data.

Spatial analysis shows that the northeast parts of the El-Fashn basins have the highest precipitation depths. The spatial values of the Curve number (CN) were obtained for each pixel using the land use map and the spatial composite tool in ArcMap. A supervised classification was performed using Landsat 8 data. The Curve number (CN) values were assigned as follows: 55 for vegetation (green color), 60 for sand (blue color), 61 for recent alluvial (yellow color), 69 for old alluvial (Cretan Blue), and 89 for limestone (red color) (Figure 4a). To validate these CN values, various methods were utilized, including the Google Earth program, map of geology, Band Ratios (7/5, 3/2, 4/5), and principle components analysis (1, 4, 3) (Figure 4 b, c, and d).

Sub-basin 6 recorded the highest peak discharge value, ranging from 2.7 m^3/s (5-year period) to 8.6 m^3/s (100-year period) (**Error! Reference source not found.** and Figure5a). For the large El-Fashn basin, the peak runoff discharge varied from 4.20 m^3/s to 18 m^3/s, with a total volume runoff of 207800 m3 to

992300 m^3 (5 and 100-year stages, respectively) (Figure5b). The presence of extensive limestone rock formations significantly affects hydrological conditions, leading to reduced infiltration rates and increased runoff, resulting in frequent and intense flooding events. This poses risks to urban and agricultural areas. To mitigate these risks, the construction of low dams in suitable locations is recommended for protection purposes. In regions with alluvium sedemints and gradual slopes, rainfall harvesting can be employed to recharge the groundwater or for direct utilization in local and agricultural practices. In this section, the Analytic Hierarchy Process (AHP) was used as a Multi-Criteria Decision Analysis Tool to identify suitable locations for rainwater harvesting (RWH).

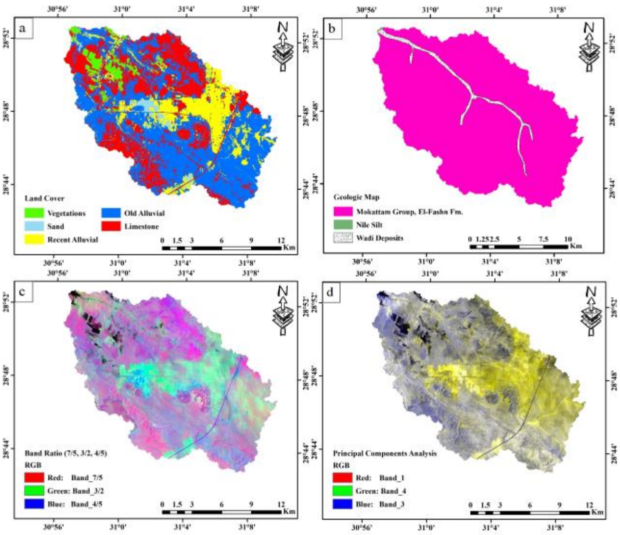

Figure 4: To validate the Curve Number (CN) map.

Five layers of information, including slope, land-cover, lineament density map, average rainfall and stream order were utilized. Each layer was classified and reclassified into different classes with specific weights assigned to them based on their relative importance (Table and Figure).

In this basin, the northeastern and southeastern regions receive high rainfall (**Figure** c) and have steep slopes, contributing to a well-developed hydrological network. On the contrary, the central portions of the basin feature mild slopes and receive lower precipitation. Despite this, the main stream flows through this area, making it suitable for rainwater harvesting. Throughout the basin, there are scattered areas with low potential for rainwater harvesting, characterized by steep slopes and comparatively less rainfall compared to other regions. Among the various factors considered, the ground surface slope plays a significant role in determining suitable areas for rainwater harvesting, overshadowing other criteria. Five potential dam construction sites have been identified to establish suitable dam reservoirs (**Figure**). The identification of these sites primarily depends on factors such as the terrain, average precipitation rates, and the economic importance of each area.

Table 2: Peak discharge (m^3/s), for every Sub-basin , and every return period.

Basin No	Return Period (Year)				
	5	**10**	**25**	**50**	**100**
1	0.3	0.4	0.5	0.7	0.8
2	1.8	2.2	2.5	4	4.9
3	1.3	1.9	2.7	3.5	4.3
4	1.2	1.7	2.3	3	3.8
5	1.4	1.9	2.9	3.7	4.6
6	2.7	3.9	5.8	7.2	8.6
7	0.8	1.1	1.5	1.9	2.4
8	0.7	0.9	1.3	1.6	2
9	0.2	0.3	0.4	0.5	0.7
10	0.4	0.5	0.7	0.8	1
11	0.5	0.7	1	1.3	1.6
12	0.6	0.8	1.1	1.5	1.9
13	0.3	0.4	0.6	0.8	0.9
14	0.2	0.3	0.4	0.4	0.5
15	0.2	0.3	0.4	0.4	0.5
16	0.4	0.5	0.7	0.8	1.1
17	0.2	0.2	0.3	0.3	0.4
18	0.3	0.4	0.5	0.6	0.8
19	1.7	2.4	3.2	4	4.8
20	0.3	0.4	0.5	0.7	0.8
21	0.1	0.2	0.2	0.3	0.3
22	0.5	0.7	1	1.1	1.4
23	0.7	1	1.3	1.6	2
24	0.7	1	1.3	1.6	1.9
25	0.2	0.3	0.4	0.4	0.5
26	0.2	0.2	0.3	0.4	0.4
27	0.3	0.5	0.6	0.7	0.9
28	0.1	0.2	0.2	0.3	0.3
29	0.1	0.1	0.2	0.2	0.3
30	0.4	0.5	0.7	0.8	1
31	0.1	0.1	0.1	0.1	0.2
32	0.5	0.7	0.9	1.1	1.3
33	0.4	0.5	0.7	0.8	1
34	0.7	1	1.5	1.9	2.4
35	0.9	1.3	1.8	2.3	2.7
36	1.2	1.7	2.4	3	3.6
Main basin	4.20	5.90	8.50	12.50	18.00

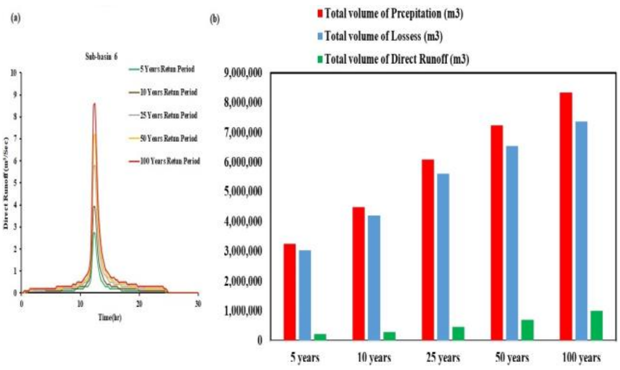

Figure5: (a) Hydrograph curves; (b) Histogram for the large basin.

Table 3: Normalized matrix

Criteria	Eigenvalues
Land cover	0.209
Slope	0.473
Rainfall	0.186
Lineaments	0.070
Stream order	0.060

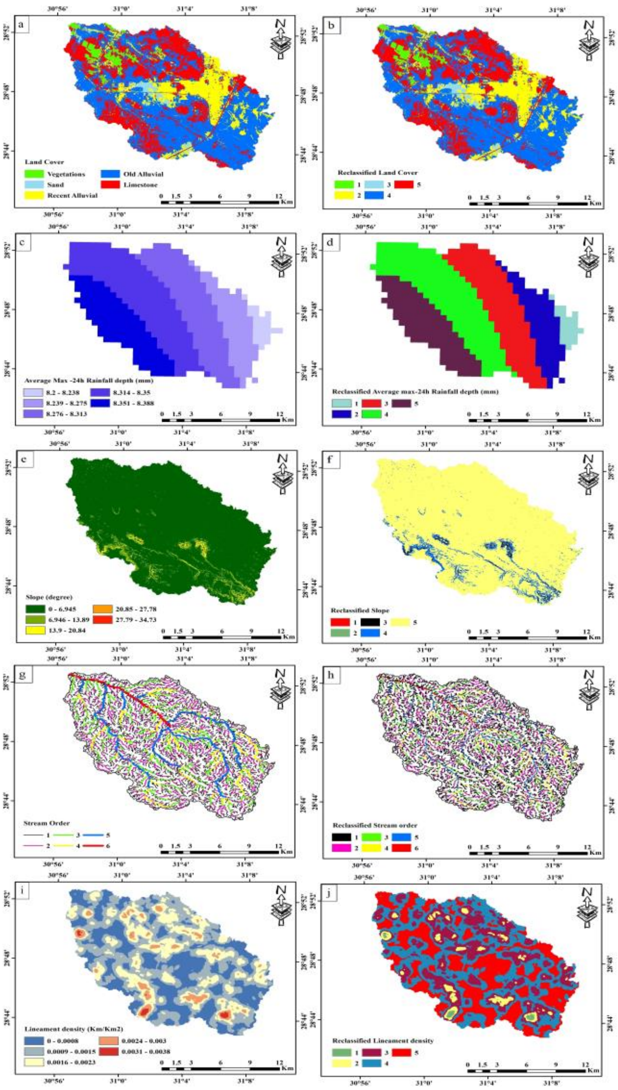

Figure 6: Maps depicting the criteria for the Analytic Hierarchy Process (AHP) related to rainwater harvesting in the El-Fashn basin.

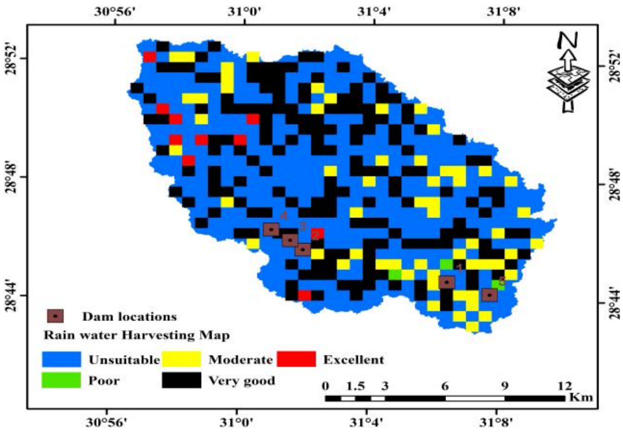

Figure7: Rainwater harvesting map and dam locations.

5- Conclusion

GIS and remote sensing intigrated with hydrological modeling were employed to assess the most suatable locations for rainwater havesting and groundwater reachrge in east El-Fashn area. The El-Fashn basin subdivided into 36 sub-basins with 4th order. The hydrologic model indicates the southeastern portion of region experiences, high precipitation rates and steep slopes. Sub-basin No. 6 registers the highest peak discharge (2.7-8.6 m^3/s (5-100 year periodreturn periods; respectively). For the large El-Fashn basin, the peak runoff discharge varied from 4.20 m^3/s to 18 m^3/s, with a total volume runoff of 207800 to 992300 m^3 (5-100-year periods, respectively). Analytic Hierarchy Process (AHP) is used to map optimal Rainwater Harvesting (RWH) sites. The used criteria included slope, land-use/land-cover, lineament density, average daily precipitation and stream order. Ground surface slope had the most significant influence in identifying the suitable RWH sites. Consequently, five potential locations for low dams were suggested to mitigate flooding vulnerability and capitalize on rainwater harvesting opportunities in the current study.

Based on the results, rainwater harvesting, and recharge of groundwater dominate in the southeast and northeast areas, while the Nile River recharge dominates in the western part. These results could be applied to regional-scale water resource management and may have relevance in similar conditions across various regions.

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