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Potential assessment of runoff harvesting in rock outcrop catchments (Case study: Qohestan park watershed, Qaen, Southern Khorasan, Iran)

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Abstract

Valuable studies have been conducted in recent years to collect water from impermeable urban levels in some parts of the country. Nevertheless, the background of the studies in this field has been poor in south Khorasan province, Iran. This study aims to help urban planners and managers to recognize the potential of water harvesting. The purpose of this study is to identify and prioritize the sub-catchment covered by the rock outcrops playing an important role in runoff production. This work was carried out via the modeling of runoff by empirical methods and the SWMM model in Qaen urban watershed. Accordingly, it is possible to determine the amount of water available for supplemental irrigation of the urban green space and thereby provide a suitable extension pattern for similar areas. The irrigation in the urban park is done by well, which is a major problem for Qaen, as an arid area. About 54% (248.4 ha) of the basin surface has been populated by the 90% rock outcrops that has high runoff potential and can be useful in planning in terms of high potential of runoff production. Considering the existing facilities and the number of park trees, an approach is needed. The water shortage for supplemental irrigation of this park will compensate, if only 10% of the annual runoff equivalent to 11800 m3 can be harvested and stored during the months with no precipitation.

Keywords: Qaen, Rock outcrop, Runoff, Supplemental irrigation, SWMM.

1- Introduction

During this century, water shortage would be one of the major threats to humanity (Prinz, 2001). In arid regions of the world, the water quantity in rivers and groundwater will not be sufficient to meet the needs of agriculture and urban areas; thus we will easily find the value of some traditional irrigation by re-evaluating them in the future (Prinz, 2000). As a solution in recent decades, most of countries around the world have turned their attention to updating some of the sustainable approaches based on indigenous knowledge and public participation. Rainwater harvesting is one of the most prominent water resources management techniques to deal with dehydration in arid and semi-arid regions that is rapidly developing (Prinz, 1999). Water harvesting methods can be divided into three groups: rainwater harvesting, flood exploitation and underground and sedimentary dams (UNEP, 1983). Rainwater harvesting and flood spreading provide the opportunity to increase the efficiency of rangeland and agricultural land by reducing water stress. It can also assist forestry and gardening projects. The establishment of vegetation in turn will prevent the desertification of lands. There are several methods that are relatively inexpensive and can be a good alternative to areas that do not have access to the usual water resources or are not cost effective to use. Unlike pump-based systems, the water extraction method is predominantly gross and easier to maintain (Hadson, 1987). Rainwater harvesting is a simple and low cost technique that capture, store and reuse rainwater. It requires minimum specific expertise and knowledge, as well (Worm & van Hattum, 2006). For millennia, people in Tamil Nadu have used rainwater harvesting tanks to capture, store, and deliver water-related services to local villagers. Tanks were small reservoirs primarily used for crop irrigation, and a central driver of early settlement patterns across South India (Kajisa et al.2007). A successful method of controlling storm water should include (1) controlling the volume of runoff, (2) controlling the peak flow rates, and (3) reducing pollutants while restoring the natural hydrologic cycle (Pennsylvania Storm Water Best Management Practices Manual, 2007). Rainwater Harvesting (RWH) can be applied as one of the best climate adaptation strategy for water management, as well (Julius at el, 2013).Climate variables, especially precipitation and temperature, have both direct and indirect impacts on agriculture and on the rest of the productive sectors. This, in turn, affects economic growth and the livelihoods of mainly the poorest populations (Wu Rs et al. 2018). The use of rainwater storage systems is not a new concept. In ancient times, it was customary to state the capacity of rainwater reservoirs in days' consumption Many semi-empirical relations are available for this purpose. (Qinwen,et al 2019).All surface and subsurface water resources are replenished by precipitation (dew, hail, rain, and snow), with rainfall being the main source and major component of the hydrological cycle. Thus, rainwater harvesting systems entailing carefully harvesting, storing, and transporting rainwater are suitable solutions for water supply as long as rain falls on earth. Besides its direct use, rainwater can be infiltrating into the subsurface when and where it falls, thereby increasing aquifer recharge while minimizing soil erosion and limiting floods (Qinwen Qiet al., 2019).

Complementary irrigation using runoff is one of the strategies reducing the risk factor in the country and has more stability in crop yield in arid and semi-arid regions (Tajbakhsh.M et al., 2012). One of the suitable areas for water extraction in dry areas is rock outcrops. Although rock outcrops absorb a significant portion of rainwater through their crevices; however, the use of these geomorphologic facies in some parts of the world, including in Kenya, as a system of rainwater harvesting has been highly regarded, as in the Kitui region alone, 400 reservoirs of runoff from rock outcrops have been constructed and exploited (Peterson, 2006). There are various tools and models to identify the potential of runoff generation from urban watersheds, including the hydrological simulation model like SWMM. The SWMM was developed in 1969-1979 and is one of the earliest models of quantity and quality of urban runoff modeling that analyzes urban runoff problems (Metcalf & Eddy, 1971). The SWMM is one of the most widely used models for simulating the quantity and quality of urban watersheds (Vasililus & Rizwan, 1997).

Valuable studies have been conducted in recent years to collect water from impermeable urban surfaces in some parts of the country. However, unfortunately, the background of studies in this field has been poor in South Khorasan. This study aims to help urban planners and managers to recognize the potential of water harvesting. The purpose of this study is to identify and prioritize sub catchments of rock mass zones playing an important role in runoff production and modeling runoff by empirical methods and SWMM model in Qayen urban watershed. Accordingly, it is possible to determine the amount of water available for supplemental irrigation of the urban green space and thereby provide a suitable extension pattern for similar areas.

2- Materials and methods

Study area

The Qohestan park in Qaen, located at 59◦ 10' E and 32◦ 40' N in the south of the city, covers about 80 hectares of 138 hectares of urban green space, . The park has an area of 117 hectares, of which 80 hectares is green space (Farahmand. 2002). The average annual rainfall is 158.95 mm with maximum and average relative humidity of 65% in February and 35% in June. The maximum 24-hour rainfall is 40 mm with maximum monthly evaporation (July) of 450 mm (Hataminezhad. H, 2001).

The upstream watershed area is 460 hectares with a watershed length of 3343 m; its average height is 1855 m, and the average slope is 41.1 %. The rainy season in Qayen starts from November and continues until June. The massive lime with a limited amount of green Marl, Sandstone, and Conglomerate are the main units of the watershed geological structures.

3- Methodology

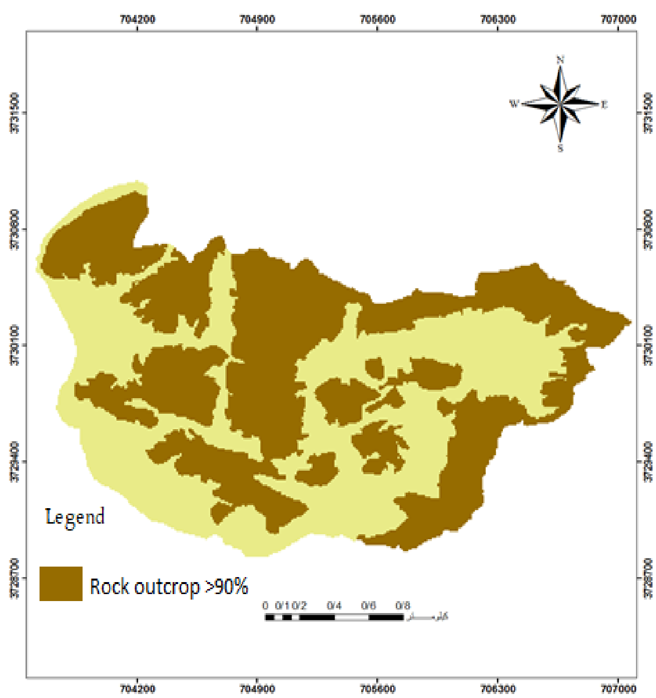

Fig. 1- Rock outcrops (brown polygons) vs. soil surfaces (beige polygons)

Runoff estimation using experimental approach

To prepare the geomorphological map, the required maps including topography, lithology, aerial and satellite images were used. To detect the geomorphologic facies within each geological unit, the dominant morphs were homogenized as a homogeneous polygon with respect to field surveys and the use of slope map and satellite imagery in Google Earth environment. Then the surfaces with more than 90% of the rock cover was separated from the corresponding map (Figure 1) and determined as the work units. Due to the conditions in the area and the runoff coefficient of the units, the watershed surfaces with the rock outcrops higher than 90% have the highest runoff coefficient and the lowest water absorption due to high slope and the hydrological group D. The average runoff coefficient was calculated to be 0.5 in this area (Mahdavi,M,1994).

The precipitation data of the reference stations available in the region for 4 months from June to September, introduced as the months with supplementary irrigation, were employed in this study.

There are various experimental methods for calculating runoff such as runoff coefficients, Koutagne, Icar, Barlow and Justin, which the last one was employed in this work. In Justin formula (equation 1), which is currently one of the most commonly used methods in estimating annual runoff, besides the precipitation, the slope of the basin as a function of the watershed area (equation 2) and the evaporation represented by temperature, may impact on annual discharge (Dezab Consultant Engineers Co, 2003), as follows:

$$R=K\, S^{0.155} \frac{P^2}{1.8T+32} \quad (1)$$

$$S=\frac{H_{max}-H_{min}}{\sqrt{A}} \quad (2)$$

Where, R is “the annual runoff height” (cm), P is “the annual rainfall height” (cm), S is “the slope of the basin” (m/m), T is “the average of the temperature” (◦C), A is “the watershed area” (km^2), k is “the Justin coefficient”, H_{min} is “the minimum height of the basin” (Km) and

H_{max} is "the maximum height of the basin" (Km) (Alizadeh, 2004).

The accuracy of the runoff estimation depends on the accuracy of Justin coefficient. The initial value for K is suggested as 0.284; however there is a different K coefficient in Justin model depending on different climatic conditions. For this reason, the amount of this coefficient will be calibrated in two ways, i.e. point and regional with the information of hydrometric stations in the area (Alizadeh, 2004).

Physical modeling using SWMM

The SWMM is physical-based software consisting of various hydrological and hydraulic models for dynamic rainfall-runoff simulation that is able to simulate qualitatively and quantitatively runoff in the form of both event-based and continuous runs. SWMM is able to study and simulate different hydrological processes involved in the production of urban runoff (Gironás, J et al., 2009). The SWMM as a dynamic model for rainfall-runoff simulation is used for event-based or continuous simulation of the quantity and quality of runoff in urban areas (Gironas et al., 2010). In this method, the output hydrograph of the watershed is simulated using meteorological information and physical characteristics of the basin and its drainage network (Rosman & Supply, 2006). The most important application of SWMM model in this project is to calculate the volume of runoff from the rock outcrop sub-watersheds in both event-based and continuous forms.

4- Results and discussion

From past to present, the people of arid and semi-arid areas have been paying close attention to the management of their habitat for survival, sustainability, and stabilization of land ownership, for many years relying on indigenous knowledge in a variety of ways. In addition to water issues, property stabilization, sustainable production, soil conservation and land creation have a special importance for these people. Supplemental irrigation is meant to allocate one or two irrigation intervals in agriculture. In fact, complementary irrigation is a type of irrigation aimed at improving water use efficiency (Emdadi. R&Ghalebi.s,2011).

Rock outcrops

This facies covers most of the southern steep area of the basin. Due to the presence of lime layers in rock outcrops and the amount of soils with very low depth, the sedimentary material is less than 20%. Overall, about 54% of the watershed area has more than 90% rock fragments that have high runoff potential and can be useful in planning in terms of water harvesting (Figure 2). Based on the permeability investigation of lithological structures and field studies; the geological formations of the watershed are divided into four categories: high, medium, low, and very low. The major part of the basin is made of rock outcrops with high runoff potential that increases the possibility of flash floods. A low percentage of runoff volume has infiltrated in the shallow aquifer.

Runoff estimation

In this study, the K value of the Justin approach was calibrated regionally. The value of each parameter is subdivided into sub catchments in the table (1).

Table (1) indicates that precipitation and temperature are considered as direct factors in the amount of the runoff and the area is as an indirect factor in the calculations. Therefore, the higher average slope in the small catchments results into a higher runoff.

The annual runoff volume for the sub-basins Q1 to Q4 is 73476.24 m3, 1839.72 m3, 25597.73 m3, and 11468.9 m3, respectively. In the sub-basin Q1, there are some embankment dams with rainfed farming with an area of 10000 m2 which store a runoff volume of 10,000 m3. The rest of the runoff flows to the Q1 outlet, leaving the runoff in the Q2, Q3 and Q4 sub-basins. All runoff in the form of floods leave the basin. By harvesting this volume of runoff, the problem of water deficit can be solved in the Qohestan park of Qayen.

In order to run SWMM model, the study area was divided into 15 sub-watersheds(Figure

3). The number of canals and nodes were twenty-four and six outlets were determined for the runoff measurement. The storm event on February 1st, 2010 has also been used to evaluate runoff production.

According to table (2), about 30.19% of the total volume of precipitation is infiltrated, 65.34% is transformed to runoff and flow through the canals and the rest is trapped by surface depressions.

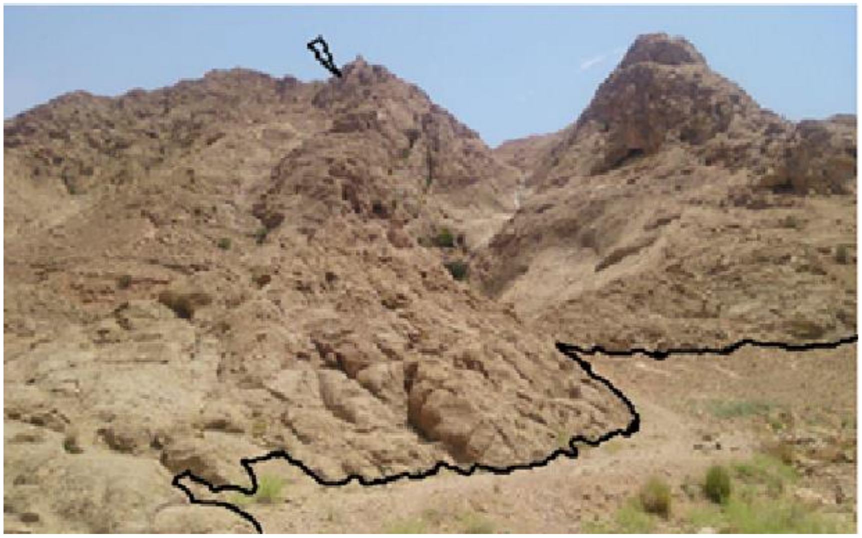

Fig. 2- Rock outcrops with higher than 90% of massive lime structures

Table 1- The runoff parameters, used for K Justin calibration through regional approach

Sub catchment	A	H_{max}	H_{min}	S	R	T	P	K
Q_1	2.4	2000	1580	0.27	3.06	12.08	202.48	0.49
Q_2	0.751	1730	1520	0.24	2.45	13.07	185.65	
Q_3	0.977	1800	1520	2.28	2.62	12.86	189.22	
Q_4	0.462	1710	1490	0.32	2.48	13.22	183.1	

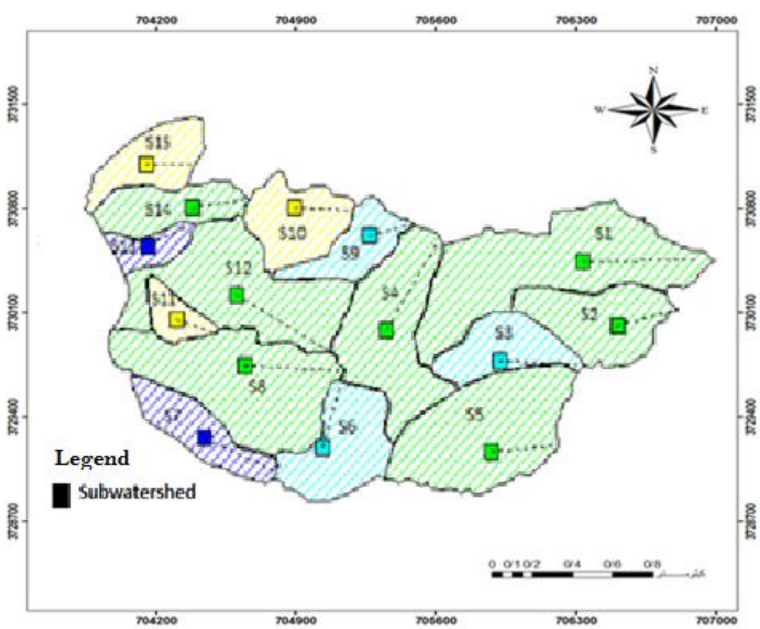

Fig.3- The subwatersheds, delineated by the SWMM model

Table 2- SWMM results in different sub catchments

Sub-basin	Total precipitation (mm)	Total infiltration (mm)	Total runoff depth (mm)	Total runoff volume (million liters)	Maximum runoff (m3 / s)	Runoff coefficient
S_1	10.50	3.21	6.81	4.53	0.76	0.694
S_2	10.50	2.67	7.29	2.06	0.33	0.694
S_3	10.50	3.87	6.29	1.29	0.23	0.599
S_4	10.50	3.27	6.77	3.01	0.51	0.655
S_5	10.50	3.18	6.85	3.57	0.60	0.653
S_6	10.50	3.91	6.25	1.76	0.32	0.596
S_7	10.50	6.50	3.99	0.74	0.13	0.380
S_8	10.50	3.01	6.99	3.95	0.65	0.665
S_9	10.50	4.50	5.78	0.91	0.17	0.550
S_{10}	10.50	1.66	8.23	1.84	0.27	0.783
S_{11}	10.50	2.24	7.64	3.92	0.60	0728
S_{12}	10.50	3.06	7.00	0.57	0.09	0.667
S_{13}	10.50	5.42	5.00	0.41	0.08	0.476
S_{14}	10.50	2.84	7.16	1.38	0.22	0.682
S_{15}	10.50	1.60	8.19	1.53	0.22	0.780

The sub catchment S1 has the highest flooding potential and the sub-catchments S8, S5, S11, S4, S2, S6, S10, S3, S14, S15, S9, S7, S12 and S13, respectively are in next orders. The runoff transfer system of this catchment is discharged at six separated points, the runoff from the main channels being discharged out of the catchment with a total volume of 26427 m3. These results are consistent with the annual runoff obtained by the Justin equation. By harvesting this amount of runoff and storing it, all plants and trees can be irrigated during dry seasons in Qohestan park. Depending on the existing facilities and equipment and the number of trees in the park, if 10% of the annual runoff volume can be extracted and stored during dry seasons, supplementary irrigation can be fulfilled. These results confirmed the studies of Tajbakhsh**.** M.et al (2012) and Qinwen,Q et.al (2019).

5- Conclusion

In this study, annual runoff volume was estimated using Justin empirical approach and

SWMM model. In Justin model, the runoff volume of the sub-watersheds is 73476.24 m3, 18395.72 m3, 25597.73 m3 11468.9 m3, respectively. In the sub-basin Q1, there are some embankment dams with rainfed farming with an area of 10000 m2 which store a runoff volume of 10,000 m3. The rest of the runoff flows to the Q1 outlet, leaving the runoff in the Q2, Q3 and Q4 sub-basins. The total volume of annual runoff produced in the basin is 118938.59 m3. According to the results of the SWMM model, about 30.19% of the total volume of precipitation is infiltrated, 65.34% is transformed to runoff and flow through the canals and the rest is trapped by surface depressions. The volume of the produced runoff by the storm event on February 1st, 2010 is 26427 m3, which is consistent with the annual runoff estimated by Justin equation. Considering the existing facilities and the number of park trees, a runoff harvesting approach is needed. The water shortage for supplemental irrigation of this park will be compensated, if only 10% of the annual runoff equivalent to 11800 m3 can be harvested and stored during the months with no precipitation.

6- Conflicts of Interest

No potential conflict of interest was reported by the authors.

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