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Water Harvesting for Improving Rainwater Use Efficiency Using GIS: A Case Study, Tigris River Basin, Iraq

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Abstract

The distribution of rainfall in dry areas, such as Iraq, is extremely erratic. The rainfall is mostly limited to occasional, intense, and unpredictable storms with high surface runoff and uncontrolled gullies and rills flowing on soils with low infiltration rates, and then it is collected at the end in wadis. Thus, most of the rainwater is lost as evaporation if not harvested. The objectives of this work were to explore the promising water harvesting areas of the Tigris River Basin (TRB), evaluate the amount of harvested rainwater from the river basin in Iraq, and then how to improve rainwater use efficiency. The GIS technique was utilized to examine the hydrological characteristics of the basin and locate the rainwater harvesting sites. The volumes of the harvested water (runoff) were assessed utilizing the SCS-CN method. The results showed that about 70% of the river basin inside Iraq is suitable for rainwater harvesting with a total annual runoff of 324 BCM. The results demonstrated that the harvested rainwater use efficiency ratio increases with the increasing amount of the used water or the relative water protectivity per unit area. The paper presented some suggestions and recommendations for improving rainwater use efficiency in the catchments of the TRB within Iraq.

Keywords: Geographic Information System, Rainwater Use Efficiency, Tigris River Basin, Water Harvesting.

1. Introduction

Since Mesopotamian (now Iraq) first successful efforts to control the flow of water a thousand years ago, a rich history of hydraulics has evolved in Iraq, the home of two tributaries, the Tigris and Euphrates rivers, i.e., the largest streams in western Asia. Nevertheless, Iraq is located in the lower part of the basin of its rivers. Thus, Iraq is suffering from a severe scarcity of water resources attributed to the limited water level in the Tigris and Euphrates rivers resulting from water impounding in the watersheds of the basin of the two rivers. In addition, Iraq is now experiencing long periods of drought attributed to climate change; thus, water shortage problems have become extremely severe [1]-[7]. As a consequence, it is estimated that about 55% of the agricultural lands in Iraq are threatened by desertification, and 15% (27 million dunams) are under desertification [8],[9]. Moreover, the rainfall distribution in Iraq is characterized as extremely erratic, mostly limited, occasional, intense, and erratic storms with high surface runoff and uncontrolled flow of gullies and rills on soils of low infiltration rates. Thus, the rainfall is lost by evaporation from the soil or from the runoff that is collected in wadis if not harvested. At present, annually Iraq is losing about 8 BCM of its water by evaporation [8]. As a consequence, desertification, land erosion in some parts, and severe water stress occur in regions of high drainage rates. Thus, there is a need for innovative solutions to reduce degradation and improve the productivity of rural areas. Moreover, the absence of suitable development plans has resulted in minimizing the development of the existing system. Consequently, low land productivity makes rural people seek alternative opportunities for income-earning elsewhere. The problem of migration from these areas can cause social pressure and added economic costs in urban regions. The challenge here is to enhance productivity per unit of water in these areas, which suffer from limited water, through the improved management of natural resources in all their available forms [10]. At present, more than 75% of the total usage of water worldwide is consumed by the agriculture sector. Water would further be reallocated from other sectors due to the rapid population growth. Moreover, capturing new water in the area is now considered a limited opportunity. Historically, the water sources in Iraq, and since the Mesopotamian civilization, have largely depended on the water of the Tigris and the Euphrates Rivers. The area of inland water in Iraq covers about 924 km^2 of the area of Iraq, which is about 438,320 km^2 [2],[5],[11]. The construction of several dams and water structures the upstream of Tigris and Euphrates rivers, such as in Turkey and Iran, significantly changed the flow of these rivers inside Iraq, where more than 75% of the Iraqi water flows from outside the borders, and the Tigris and Euphrates Rivers flowrates were estimated to continuously decline, and they will be expected to be dry by the mid of this century [2],[12]. The flow regimes in the basins have faced large pressure resulting from the operation of large-scale projects for irrigation in the river systems. In addition to the overexploitation of the current resources of groundwater, where extraction exceeds the recharge rate in many cases, few resources of renewable groundwater remain untapped. The current demand in Iraq ranges between 66.8 and 77 BCM, while the supply is predicted to be about 18 BCM [2],[13]. The topography of Iraq is a large basin that contains the Mesopotamian plain of the Tigris and Euphrates. Therefore, the area can be considered a large pan to harvest rainwater to be used to avoid the deficit in water resources in the area, since periodic droughts will impact the water supply for all sectors in the future. Moreover, the Middle East, particularly Iraq, is experiencing periods of drought due to climate change in addition to high population growth; these factors make the problems of water scarcity more severe.

Tigris River is one of the longest rivers in the Middle East, with a length of more than 1800 km [5],[14]. It is one of the main sources of water in the Tigris-Euphrates River system. The Tigris River is the lifeblood of about 25 million inhabitants in the river basin. The Tigris has four basin riparian countries, which are Turkey, Syria, Iran, and Iraq [5],[12]. Tigris water has been altered by large water development projects in all these riparian countries with no basin-wide agreement in place. The crises in water resources have been the subject of many studies due to the relation of water to people's lives in the area, municipal uses, agriculture, and industry. Several small field-scale studies within the Tigris River Basin (TRB) have been provided recently using rainfall-runoff models for different weather events and climate change over long periods and used in water shortage times (e.g., [15],[16]). Another benchmark work was Al-Kakey et al. [17], which identified the possible runoff harvesting sites in the Hami Qeshan Watershed, North of Iraq. The work employed a criterion of 10 integrated data with approaches of Multi-Criteria Decision Analysis (MCDA) for the identification of the runoff harvesting sites within the GIS environment to enhance water management. The work suggested 10 locations of runoff harvesting in the watershed. Yousuf et al. [18] described water management in the north of Iraq based on collected data. The work included a critical analysis of the recent case and represents the introductory steps suggested and needed for implementing a new principle integrated with the European Union (EU) in Iraq that aims to improve the quantitative and ecological status of water. One of these recommendations is to collect and save rainwater for agricultural purposes and reserve renewable groundwater under climate change. Al-Ansari et al. [19] viewed and discussed the difficulties facing Iraq in water resources, and suggested recommendations for managing water in Iraq. The work evaluated water harvesting and treated wastewater as a new source of water. The work used non-conventional methods to enhance water resources and sanitation; the work showed that water harvesting techniques are efficient and low-cost.

A catchment may be defined as a portion of the land surface that gathers runoff and directs it towards the lowest downstream point called a catchment outlet [20],[21]. The runoff concentrated by a catchment (i.e., catchment outlet) connects with another larger catchment or flows to the ocean [22]. The term catchment commonly refers to both watershed and basin. In general, the term watershed refers to a small catchment (e.g., stream watershed), whereas the basin term is used for large catchments such as river basins [23]. Watersheds can be described and managed using hydrological and physical features using new technology such as the Geographic Information System (GIS) technique, and then applied to many studies such as water harvesting and environmental studies [16],[24],[25]. There is an increase in the applications of GIS and Remote Sensing RS in engineering fields worldwide since there is a need for planning and maintenance of hydraulic structures and analysis such as water resources (e.g., stormwater management, hydrology, and hydraulics) [14],[26]. Moreover, GIS techniques have been integrated with remote sensing applications, which are used for exploring characteristics of watersheds in many studies. Saedi and Al-Obaidi [27] used Remote Sensing RS data (30 m resolution DEM) and GIS techniques to examine the morphometrics of the basin of the Euphrates River in Iraq. They found that several sub-basins with different characteristics shaped the river basin. The work concluded that the basin has low vegetation cover, low groundwater flow, and also high runoff and sediment. Also, the work found that the shape of the drainage in the basin varied from dendritic in the southwest to parallel in the northeast, and this may be attributed to the fact that the study area is controlled by hydraulic structures. The work also concluded that the basin has low land cover, and, as a consequence, it has a high discharge of water and sediments. Also, Aziz et al. [28] presented a work that used GIS tools together with the generation of data about flow in sub-basins and morphometric parameters for watershed delineation, water harvesting, and water management in the Diyala River basin, Iraq. Several sub-basins with different stream orders were delineated, and the drainage density was also determined in the basin. The work selected water harvesting sites with low cost and less time. Akinwumiju and Olorunfemi [29] assessed morphometric parameters of Osun Basin, Nigeria, to evaluate the infiltration rate using data from SPOT DEM and ArcGIS. The work stated that the infiltration rate is low to moderate, as runoff takes a short time to enter the drainage channels. The work also stated that a high percentage of rainfall feeds the river draining the basin due to the low infiltration rate, with the partially structurally controlled drainage lines of the basin. Only 25% of the farmland of Iraq uses river water, and the rest 75% of the area depends on groundwater resources, this reflects the value of groundwater for the economy, in particular for the supply of drinking water and irrigation [30],[31], and thus hydrogeological investigations were conducted recently, for example, the hydrogeological project in Northern Iraq and wells investigations in the southwestern desert of Iraq [32]. The total yearly estimated amount of groundwater that is suitable for domestic and agricultural use is 12.6 B m^3, and about 20% of this amount has been exploited [30]. To supply municipal uses and provide for agricultural purposes, many wells were dug in Iraq. Some of these wells are shallow, 100 m deep, while the deepest wells reached 1600 m near Mosul city north of the study area [33].

Rainwater harvesting (RWH) is a mechanism of capturing water from the catchment to improve water for certain areas [34]. Water harvesting makes the water further available for domestic, municipal, agricultural, livestock, etc. Moreover, water harvesting controls runoff and results in increased rainwater productivity, controlled soil erosion, and reduced the impact of drought [19],[35],[36]. Zakaria et al. [37] estimated volumes of harvested runoff for the Koysinjaq area in northern Iraq (2002-2011) using the technique of rainwater harvesting using the method of Soil Conservation Service Curve Number (SCS-CN). The work showed that the volume of the runoff ranged from 14.83×10^6 to 80.77×10^6 m^3 from the whole study area of the sub-basins. This means that the technique of RWH (Macro) may be considered a source of water provision for reducing the problem of water scarcity. Rahi and Abudi [38] studied some of the rainwater harvesting techniques that can be recommended for Iraq, such as wells, trenches, contour bands, and rooftops. The work concluded that these techniques are suitable to meet hydrological, geological, topographical, and economic requirements. Omar et al. [39] presented a work to determine the amount of runoff in the basin of the Greater Zab, one of the tributaries of the Tigris River, using GIS techniques. They examined the adequacy of the basin for appropriate rainwater harvesting. The SCS-CN method was used to calculate the runoff in the river basin. The results showed that the estimated annual depth of the runoff in the basin was 60.1 mm, and more than 50 % of the basin area is suitable for rainwater harvesting, with considerable potential for rainwater harvesting if locations are identified properly in the basin. The proper design and operation of the water harvesting systems help to achieve rainwater use efficiency (rainwater availability) for different sectors, e.g., domestic and agriculture [35],[36]. Recently, rainwater harvesting has become the subject of many studies; e.g., Buraihi and Shariff [40] presented a work about rainwater harvesting in Kirkuk City, Iraq, using the Multi-Criteria Decision Analysis (MCDA) method. The work produced a potential map of rainwater harvesting sites, e.g., farm ponds, by evaluating features of some parameters integrated with GIS. The results showed that there are three suitable zones for rainwater harvesting: low, moderate, and high. In particular, about 3.7% of the area is good for farm ponds and 4% for check dams. Another work by Ali [41] also used the MCA method integrated with the GIS to generate a layout of rainwater harvesting sites in Badrah City, Wasit, Iraq. The sites of water harvesting were located based on precipitation, topography, and location, and thus, the basin was characterized by three zones of suitability: low (35%), moderate (27%), and high (2%), respectively. Ibrahim et al. [42] estimated the runoff amount to be stored in harvesting sites such as small dams using GIS and RS and by applying the Multi-Criteria Evaluation (MCE) and using tools of runoff rate, stream order, topography, land use, and soil. The work showed that the highly suitable sites are about 15% of the area, 21% are moderately suitable sites, and 51% are unsuitable (poor) for rainwater harvesting.

The rainfall data are essential to evaluate hydraulic events (runoff) and provide water harvesting techniques in future planning for catching the water for several sectors such as agricultural and municipal uses in the study area. Rainwater harvesting (RWH) makes water more available in dry conditions, reduces the impact of drought, and increases rainwater productivity through a controlled concentration of runoff into target areas. Therefore, the desired objectives of this work were to investigate the water harvesting areas of the Tigris River Basin (TRB) to improve rainwater use efficiency in Iraq and conduct hydrological investigations about the water resources of the TRB in Iraq, i.e., to investigate different water harvesting sites that are suitable for Iraq to collect and efficiently utilize rainwater runoff in productive and sustainable systems. More specifically, the objectives of the proposed work were to investigate the Tigris River Basin using hydrological, geological, and remote sensing aspects, and to improve rainwater use efficiency for water harvesting in the TRB in Iraq. Further, identification of future flow predictions at the river forecast points is required to extract more watersheds and stream networks and then to manage the water of the river basin. Therefore, improving water resources management and then offsetting variability with increasing demand and climate change requires high water control, and this can be achieved using improved water-harvesting techniques with high efficiency; these issues go beyond the scope of this work, and they will be the future focus of this work when more data become available.

2. The Study Area

The study area represents the catchment area of the Tigris River Basin (TRB). Fig. 1 shows the study area of the Tigris River Basin (TRB). It extends over four riparian countries and lies between latitudes (39° 0′ 0″ to 49° 0′ 0″) and longitudes (38° 0′ 0″ to 31° 0′ 0″). The Tigris River is shared by four riparian countries: Turkey, Syria, Iran, and Iraq. The water of the river originates from precipitation in the Armenian Highlands and tributaries in the Zagros Mountains in Turkey, Iran, and Iraq. The river basin is the residence of about 24 million people in all riparian countries, of which more than 78% live in Iraq [43].

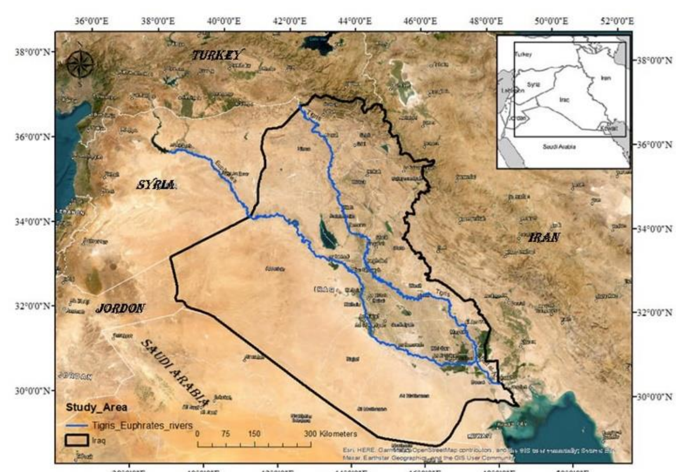

Figure 1. Location map of the study area and Tigris River.

The course of the river is generated by the joining of two main tributaries, the Batman and the Botan, in the Taurus Mountains, Turkey [5]. The river starts from Turkey, the upstream of the basin, from the north and flows southeast in a short reach through the borders of Syria and Turkey, and then it enters Iraq and flows for about 1,350 km. The outlet of the basin is the Mesopotamian marshes or the Shatt al-Arab, which is considered the lower part of the Tigris River Basin. The tributaries of the Tigris are shared by either Iraq and Turkey or Iran and Iraq. In Iraq, below Baghdad, the river flows in a low-slope land for 350 km, where the river is fed by inflow water from the Diyala River and several wadis before the confluence with the Euphrates to form the Shatt al-Arab in the south of Iraq [44].

The climate of the study area varies from semi-humid in the north to semi-arid in the south. The average annual rainfall of the basin varied between 400 mm and 600 mm. In particular, for the basin in Iraq, in most of upper Mesopotamia the rainfall amount is more than 250 mm/yr; from Mosul in the north down to Baghdad at the border between upper and lower Mesopotamia, the rainfall ranges from 400 to 150 mm/yr, while in the lower Mesopotamia, the annual precipitation decreases to 140 mm at the Shatt al-Arab region [45]. It mostly occurs during five months from November to April, and snowfall occurs from January to March in the mountain regions. The climate in the headwaters characterizes the hydrology of the river. The riparian contributions are estimated at 40-65% of the annual discharge of the river from Turkey, 10- 40% from Iraq, while between 5% and 25% of the river flow comes from Iranian tributaries. There is no significant discharge that contributes to the river flow in the Syrian section [44]. The mean annual flow rate of the river at Mosul station (north of Iraq) for 30 years was 20 BCM and at Kut station (middle of Iraq) was 25.7 BCM. The maximum annual flood discharge recorded at Mosul in 1969 was 43.1×10^9 m^3 and 59.2×10^9 m^3 at Kut in 1946 [46].

3. Methodology

The scope of this work employed two parts of the methodology. In the first part, the work distinguished a DEM map for catchments of the Tigris River Basin (TRB) to locate suitable rainwater harvesting sites using the GIS technique. In the second part, the work used a runoff model to estimate the runoff from the rainwater harvesting sites based on the Soil Conservation Service Curve Number (SCS-CN) method. The workflow employed in the methodology of the work is described mainly by the data collection, preparation, analysis, and design. The two main parts of the workflow used are illustrated as follows.

3.1 First Part: Identifying the Suitable Sites of the Drainage Area using GIS Techniques

The main purpose here is to identify suitable rainwater harvesting sites for the river basin within Iraq. This involves watershed delineation and stream network characteristics using GIS techniques based on the Digital Elevation Model (DEM) using the Arc-Hydro v.10.8 tools. The objectives are to download geospatial information and then extract the data for the study area. The extraction of the basin area was generated using advanced geological processing techniques in ArcGIS. The Arc-Hydro analysis was implemented to provide data on flow and watershed characteristics. These data are necessary for the representation of catchments and drainage lines from selected sites that are required in network analysis. This required the delineation of stream catchments and watersheds, evaluation and examination of drainage areas and stream properties, creating slope maps, and determining an average slope for the study area. The watershed function also allows for the delineation of catchments upstream of distinct connection segments in the stream network. The methodology consists of several essential stages: flow direction, flow accumulation, stream definition, catchment, Terrain preprocessing, catchment grid delineation, drainage line processing, adjoint catchment processing, drainage point processing, longest flow path for the catchment, longest flow path for the adjoint catchment, and slope. Using drainage lines gives the ability to extract river information (like flow length) from the attribute table. Based on the site location, it is required to export the data related to that watershed. Extract the study area information, like the area, from the attribute table. Records include the total length and number of stream connection segments in the study area. The tool Drainage Points Processing assigns an outlet in each stream segment based on flow accumulation and catchment layers. The outlet positions based on this tool computation may be different than USGS locations, but keep in mind there are several factors to establish a hydro station, like construction in a river system (like a bridge, reservoir, etc.), so the USGS outlet should be far away from them to measure accurate flow rates. The tool of the longest flow path for the catchment gives information that can be used for time of concentration estimation and other properties. The tool of the longest path of flow for the adjoint catchment creates the longest path of flow for the entire watershed system. The adjoint catchment processing calculates the physical parameters of each sub-watershed. It also provides the number of sub-watersheds in an entire watershed system. Based on the basin watershed processing, this basin has several sub-watersheds. Based on the slope map, the average slope for the entire watershed is extracted. Then the watershed area and flow length are delineated in the watershed system based on a Hydro DEM. Based on the above GIS methodology part, the rainwater harvesting sites were located and identified in each sub-basin represented by characterized sub-watersheds. The contributing sub-watersheds of the rainwater-harvested sites were also delineated. The output of this part was used as input data for the second part of the conceptual methodology.

3.2 Second Part: Rainwater Harvesting Estimation

The second part of this work involves estimating the runoff from rainwater harvesting (RWH) using a runoff model involving the implementation of the method of Soil Conservation Service Curve Number (SCS-CN). Using soil and climate data, including rainfall and soil texture data, extract the Hydrological Soil Group HSG from the data. By comparing data on HSG and data on land use and land cover LULC, the Curve Number CN was adjusted under antecedent soil moisture conditions (AMCs) for the sub-watershed of the rainwater harvested site that was estimated in Part I. Finally, rainwater harvesting calculation using the SCS-CN method is proceeding to estimate the runoff of the sites of rainwater harvesting. The governing equations of the model were solved using a code written in MATLAB version R.2018. Finally, the harvested rainwater (runoff) is used to compute the water use efficiency in the watershed area within the irrigation network. The workflow in Fig. 2 illustrates the steps followed for the calculations in the work.

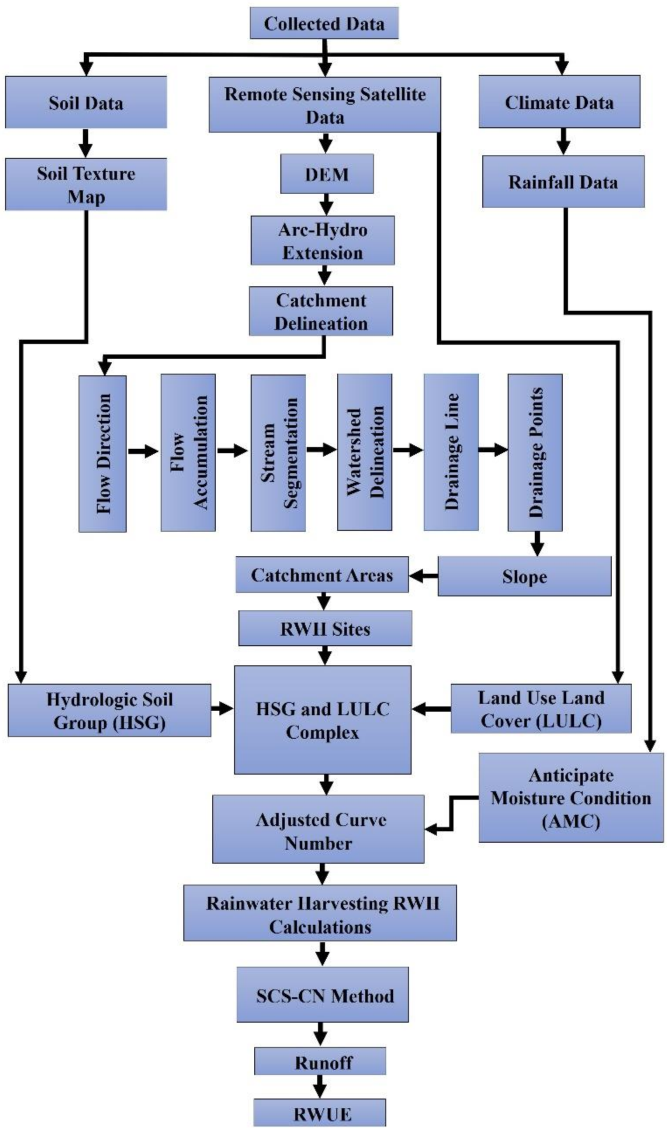

Figure 2. The employed methodology in the work.

4. Results Analysis

In this work, the Tigris River basin is divided into four distinct sub-basins: Upper, High, Middle, and Lower. The basin/watershed extraction method is shown in Figs. 3 to Fig. 6. The process begins by manipulating the flow direction raster data and ends by generating a watershed boundary.

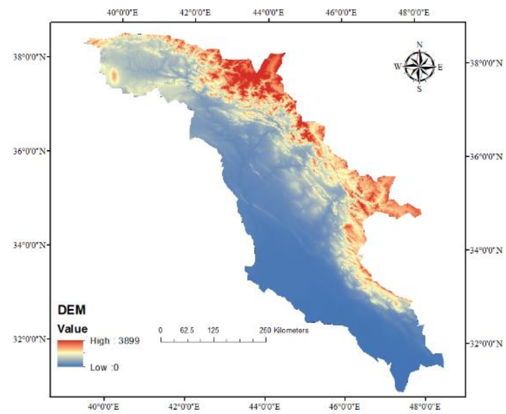

Figure 3. DEM map of the study area.

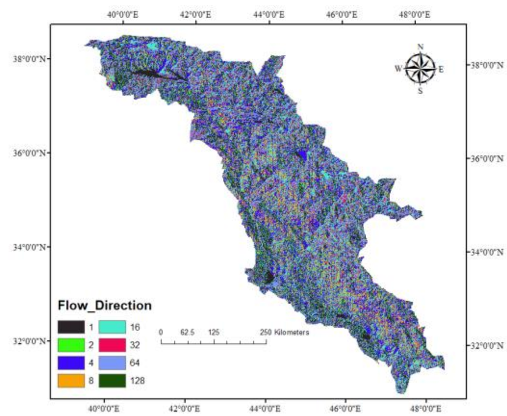

Figure 4. Flow direction of Tigris River Basin.

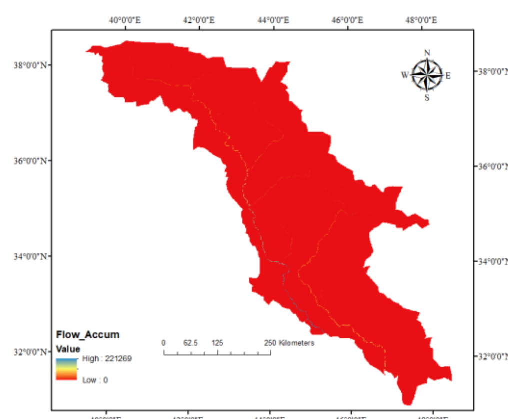

Figure 5. Flow accumulation of the Tigris River Basin.

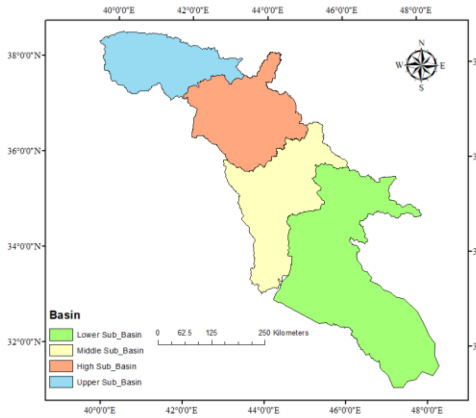

Figure 6. Drainage basins of the Tigris River Basin.

Fig. 7 provides the location of the river sub-basins overlapped in the study area of Iraq. Fig. 8 shows the distribution ratio of the catchment area of the TRB inside and outside Iraq. Two of these sub-basins are shared with two riparian countries; the Upper sub-basin is shared between Turkey and Iraq, and the Lower sub-basin is shared between Iraq and Iran. Table 1 shows the catchment areas of the sub-basins inside and outside Iraq. The Upper sub-basin is totally outside Iraq, 68 % of the High sub-basin is inside Iraq, 92 % of the Middle sub-basin is inside Iraq, and 58.7% of the Lower sub-basin is inside Iraq. The total area of the river basin is 216141.53 km^2, and about 84 % of the basin lies inside Iraq.

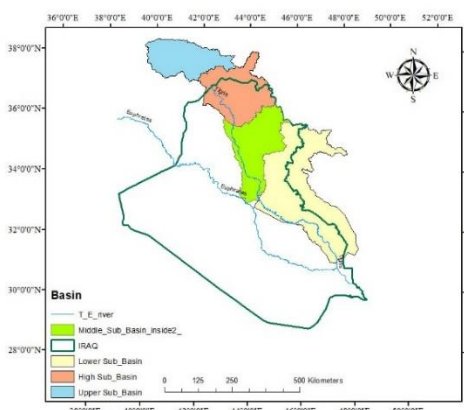

Figure 7. Location of Tigris River Basin in Iraq.

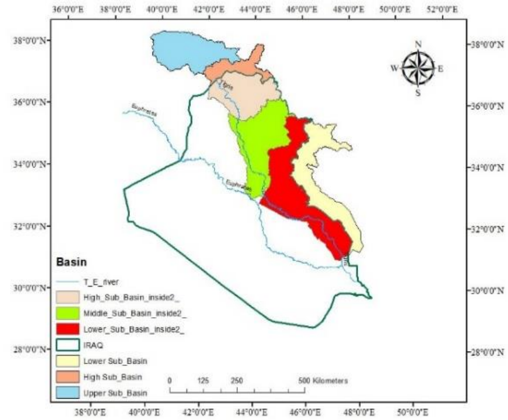

Figure 8. Distribution of the drainage area ratio of the TRB in Iraq.

Table 1. The catchment area of the sub-basins of the Tigris River (km^2).

Sub-basin	Total area (km^2)	Inside Iraq (km^2)	Outside Iraq (km^2)
Upper	32779.75	----	32779.75
High	43912.91	29988.40	13924.50
Middle	46754.60	43079.20	3675.40
Lower	92694.27	54405.24	38289.04
Summation	216141.53	183361.78	32779.75

Fig. 9 shows the stream features within the river basin, where the distribution of streams seems uniform over the whole area of the basin in all sub-basins. The black points represent the outlets of the sub-basins. The results clearly showed that the size of the sub-basins increases downstream of the river, and this is due to the decrease in the slope of the catchment downstream.

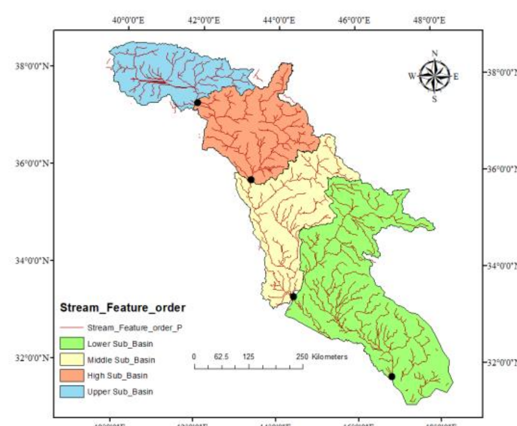

Figure 9. Stream features and order of the Tigris River Basin.

4.1 The Upper Tigris River Sub-basin

The Upper Tigris River sub-basin is considered the main source of the Tigris River basin, with a drainage area of 32779.75 km2, and lies totally outside Iraq. This sub-basin contributes 40-65% of the annual flow rate of the river [5]. The upper basin is wet in comparison with the other areas of the Tigris drainage basin inside Iraq. The annual precipitation ranges from 1000 mm in the southwest of the basin to 600 mm in the northeast, close to the borders of Iraq and Turkey. The seasons of this sub-basin are characterized by two faces: wet and dry. The rainy season spans from September to June, and about 70 % of the rainfall comes during this time [44]. The dry season runs from July to August. The mean monthly precipitation in the wet season is between 10 and 80 mm. In the upper basin, topography is highly varied in elevation and ranges from lowlands to mountains. The rainfall amount increases with increasing altitude due to decreasing temperature. Temperatures in this sub-basin vary from -35°C in the wet season to 40°C in the dry season. Fig. 10 shows the location of the Upper Tigris River sub-basin in the study area. The transboundary upper sub-basin is common between Turkey and Syria, and it is at longitudes 39° E and 44° E, latitudes 36° N and –39° N, as shown in Fig. 10. Fig. 11 indicates the DEM map of the Upper Tigris River sub-basin. There is a large variation in topography within the basin, with a 30 m horizontal resolution in the elevation grid. The elevation ranges from 400 m to more than 3480 m above sea level.

Basin characteristics and some useful indices (morphometric analysis) were assessed using measurement tools in Arc-GIS 10.8, such as the area, length, perimeter (outer boundary of drainage basin) of the basin, topography, stream order in sub-basins, stream number (total number of stream parts), and stream frequency. Create a map using Arch-GIS- for each sub-basin involving drainage points; drainage lines; and the longest flow paths. The results illustrated that the total number of streams in the Upper Tigris River sub-basin is 118, the Hierarchical rank is 4, the basin perimeter, i.e., the outer boundary of the basin in km, equals 1073.67 km, and the basin ratio is 0.03. Stream frequency (Fs), which is the proportion of the total number of streams to the basin area, equals 0.004. The hydrological characteristic of this basin is also represented by the flow direction. The main flow direction of this basin can be categorized into two aspects, one west-east and the other east-west. The black dot represents the main outlet of the catchment. It is clear from the results that this outlet is located close to the Ilisu Dam, Turkey, which was constructed in 2010 with a total capacity of 10.41 BCM for hydropower and irrigation purposes. Moreover, the Southeastern Anatolia Project (GAP) in Turkey has 22 dam projects that made the water shortage in the river basin more severe; in particular, one of these dam projects is the Ilisu Dam located near Ilisu, i.e., 65 km from the border of Syrian-Turkish and close to Iraq. The dam height is 135 m, with a reservoir size of 10.41 BCM, a hydropower of 1200 MW, and an expected power generation of 3,800 GWh/yr.

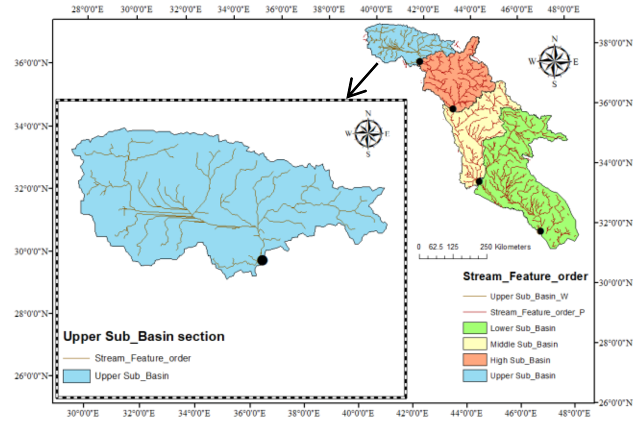

Figure 10. Location of the Upper Tigris River sub-basin.

There is a lack of hydrogeological data in the area located on the Iraqi-Turkish border in the basin. However, previous works stated that there is a hydraulic connection between the two riparian countries, with water discharging toward Iraq and entering Iraq via outcropping aquifers. A previous work also mentioned that when the river moves along Syria's north-east borders, a chance of an inflow of groundwater occurs in the area from the unconsolidated aquifer. The springs in the catchment are exploited and used before they meet the river, with no groundwater in the Syrian basin.

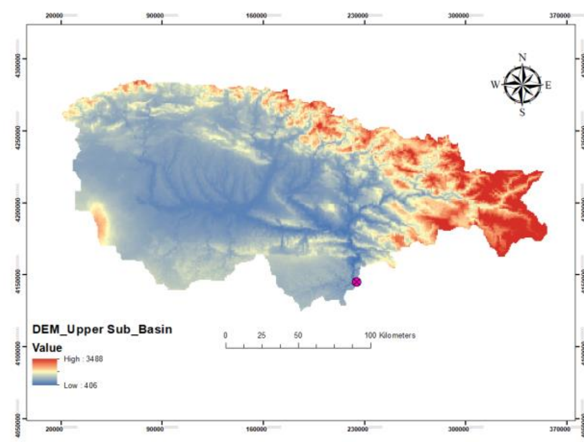

Figure 11. DEM of the elevation of the Upper Tigris River sub-basin.

Fig. 12 shows watershed outlet points represented by the drainage points (red points) in each stream segment (blue lines) based on flow accumulation and catchment layers. The results concluded that the intensity of the drainage points is high in the central part of the catchment of this sub-basin. These points can represent the possible sites for rainwater harvesting in the basin. Stream orders are presented in Fig. 13.

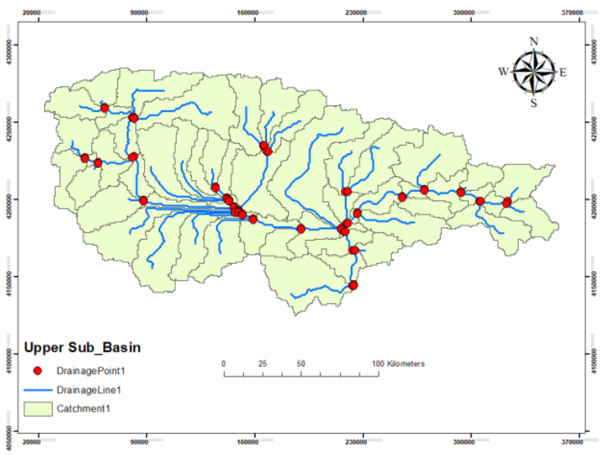

Figure 12. Drainage points in the Upper Tigris River sub-basin.

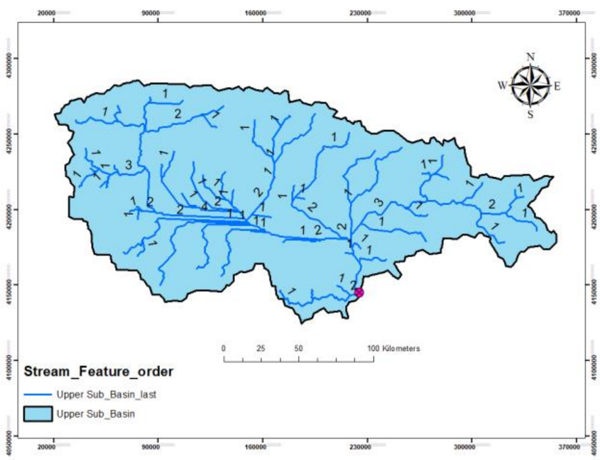

Figure 13. Stream orders of the Upper Tigris River sub-basin.

4.2 The High Tigris River Sub-basin

The High Tigris River sub-basin (i.e., sub-basin II) is located in the most northern region of Iraq, and it is considered one of the most important sub-basins for water resources in Iraq. This basin is presented in brown color in Fig. 4, which also shows that about 70% of this sub-basin is located inside the Iraq boundary.

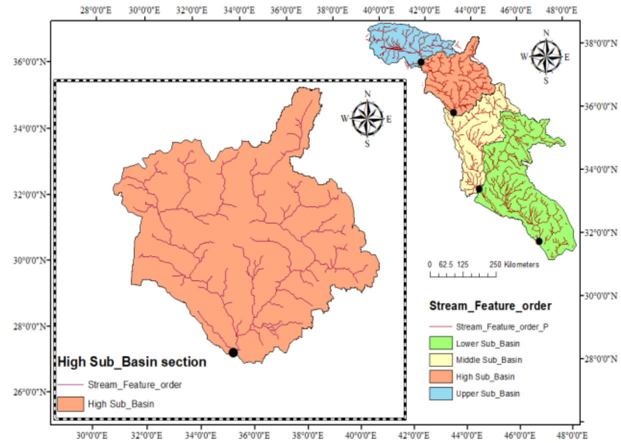

Figure 14. Location of the High Tigris River sub-basin.

The drainage area of the basin covers about 43912.907 km^2, where 70% lies outside Iraq and 30% inside Iraq. The topography ranges from 172 m to more than 3895 m msl, as shown in Fig. 15. Fig. 16 shows watersheds and drainage points (the red points) of the High Tigris River sub-basin. The drainage points are highly distributed in the sub-basin with two main rows. This gives this sub-basin a high degree of control in the management of water harvesting. Stream orders in the High Tigris River sub-basin are presented in Fig. 17. The results showed that the total number of streams in this sub-basin is 151. The Hierarchical rank is 5, the basin perimeter equals 1362.3 km, and the basin ratio is 0.032. The stream frequency (Fs) of the basin is equal to 0.0035. The results also showed that the flow direction in the catchment of this basin is, in general, from north to southeast. The distribution of the drainage basin area of the High sub-basin between the riparian areas is shown in Fig. 18. The green area indicates the part of the sub-basin that lies inside Iraq. Most of the sub-basin area lies inside the Iraq region.

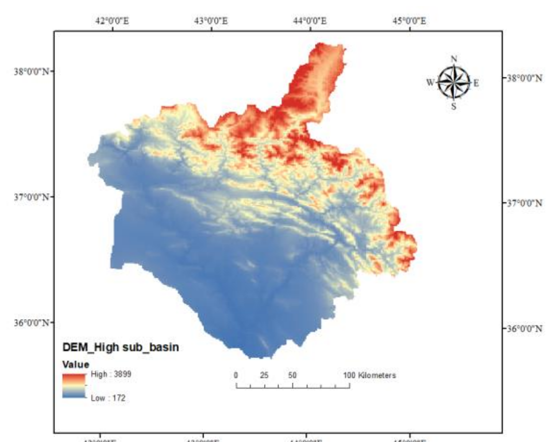

Figure 15. DEM of the elevation map of the High Tigris River sub-basin.

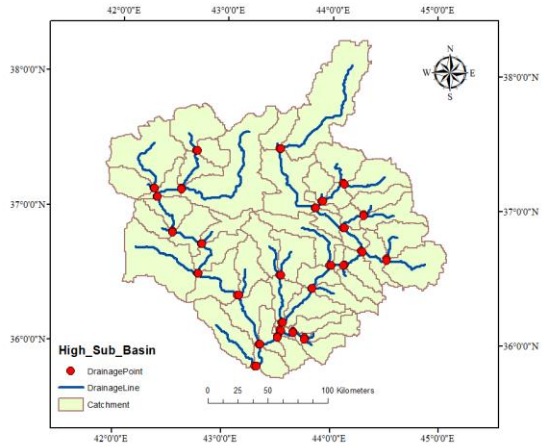

Figure 16. Watersheds and drainage points of the High Tigris River sub-basin.

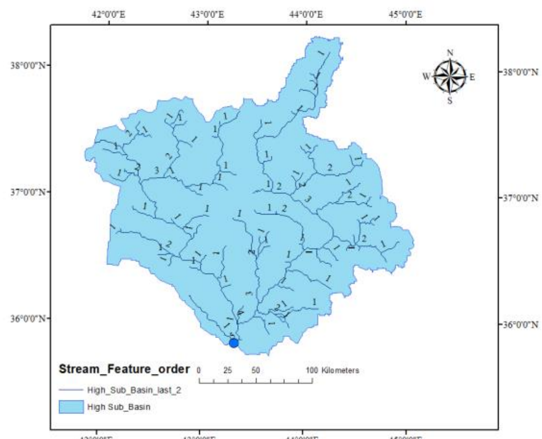

Figure 17. Stream orders feature in the High Tigris River sub-basin.

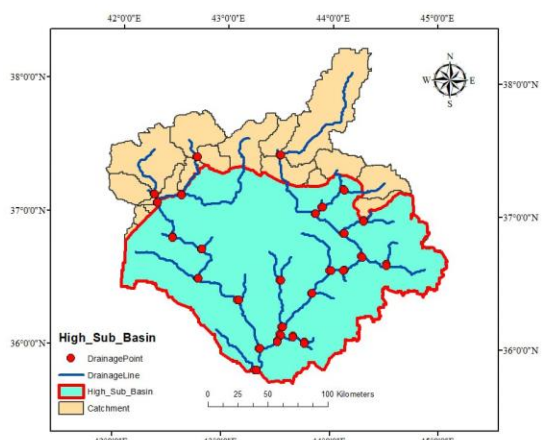

Figure 18. Distribution area of the drainage basin of the High Tigris River sub-basin between the riparian countries.

4.3 Middle Tigris River Sub-basin (Iraqi Tigris River Sub-basin)

The Middle sub-basin is also considered an important sub-basin of the Tigris River basin area for water resources in Iraq. The catchment area of the basin covers about 46754.602 km^2, where 92% is within Iraq and 8% outside of Iraq. The altitude ranges from 30 m msl to more than 3550 m. The processing of the calculations of the sub-basin is presented in Figs. 19 to 22. The results showed that the total number of streams in this sub-basin is 145. The Hierarchical rank is 5, the basin perimeter equals 15754.7 km, and the basin ratio is 0.0029 stream frequency (Fs) of the basin is equal to 0.0031. The hydrological characteristic of this basin is also represented by the flow direction. The main flow direction of this basin is from northeast to southwest, as shown in Fig. 22.

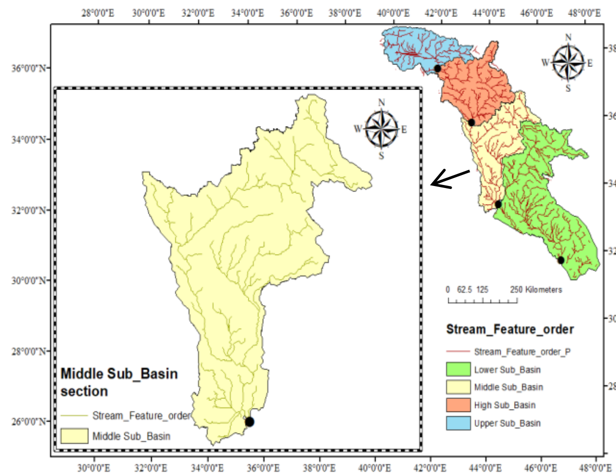

Figure 19. Location of the Middle Tigris River sub-basin.

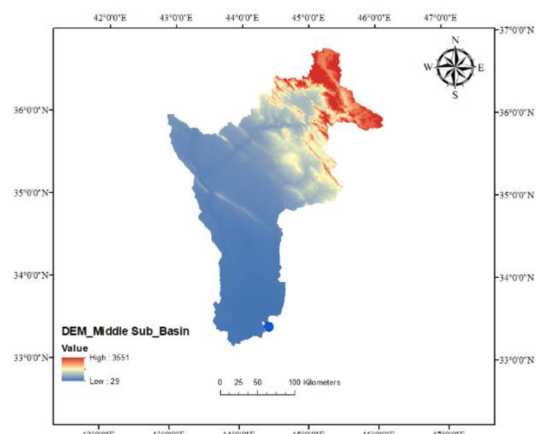

Figure 20. DEM of the elevation map of the Middle Tigris River sub-basin.

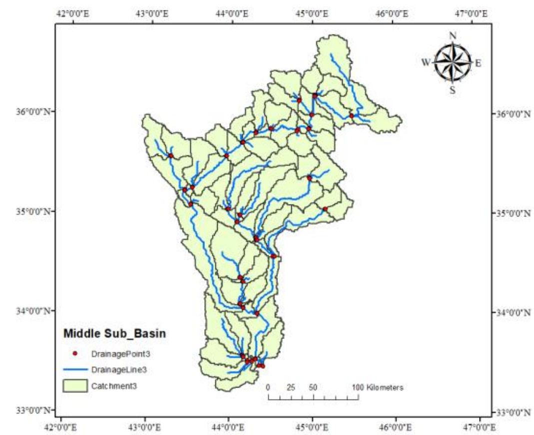

Figure 21. Watersheds and drainage points of the Middle Tigris River sub-basin.

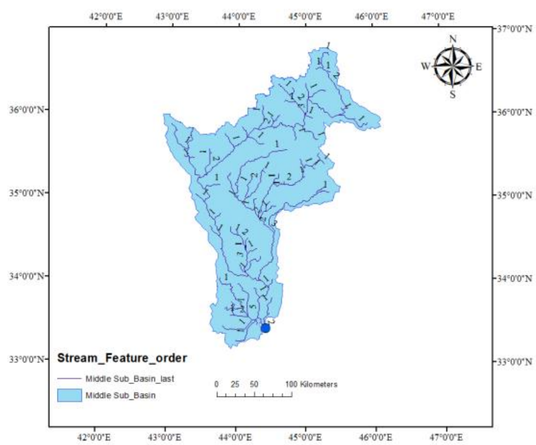

Figure 22. Distribution of stream orders of the Middle Tigris River sub-basin.

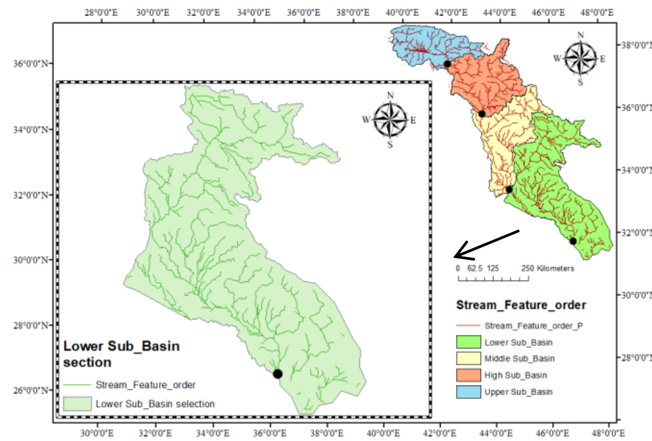

Figure 23. Location of the Lower Tigris River sub-basin.

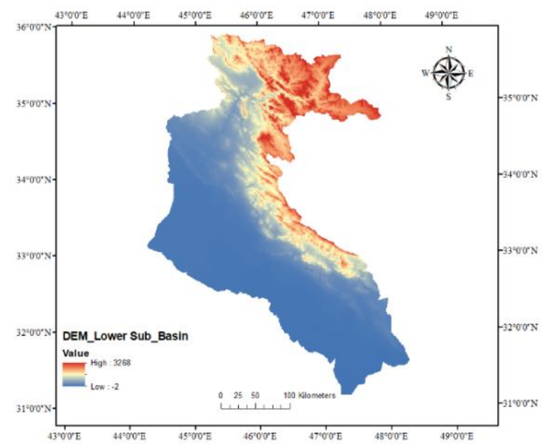

Figure 24. DEM of the elevation map of the Middle Tigris River sub-basin.

4.4 Lower Tigris River Sub-basin

The catchment area of the Lower Tigris River sub-basin covers 92694.27 km^2, which is considered the largest sub-basin that lies inside Iraq, as shown in Fig. 23. About 60% of the drainage area lies inside Iraq while 40% lies outside (Iran). The topography ranges from 3268 m to about -2 m msl, as shown in Fig. 24.

Figs. 24 to Fig. 27 illustrate the steps of the calculations of the results of the sub-basin. The results showed that the total number of streams in this sub-basin is 267. The Hierarchical rank is 5; the basin perimeter, i.e., the outer boundary of the drainage basin (km), equals 2160 km; the basin ratio is 0.049; and the stream frequency (Fs) of the basin is equal to 0.0028. The main flow direction of this basin can be categorized into two directions: one from northeast to southeast and the other from northwest to south.

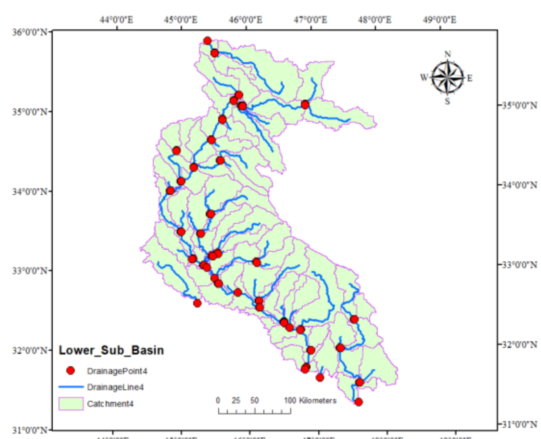

Figure 25. Watersheds and drainage points of the Middle Tigris River sub-basin.

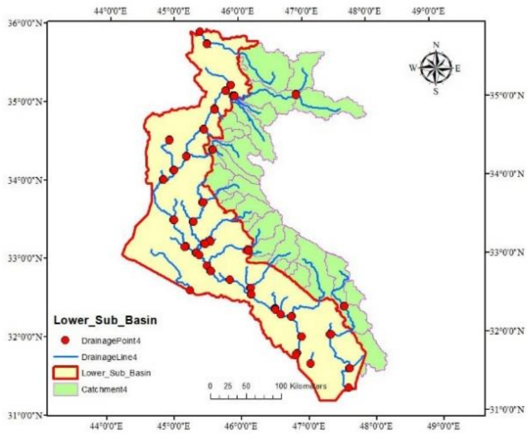

Figure 26. Distribution area of the drainage basin of the Lower Tigris River sub-basin between the riparian countries.

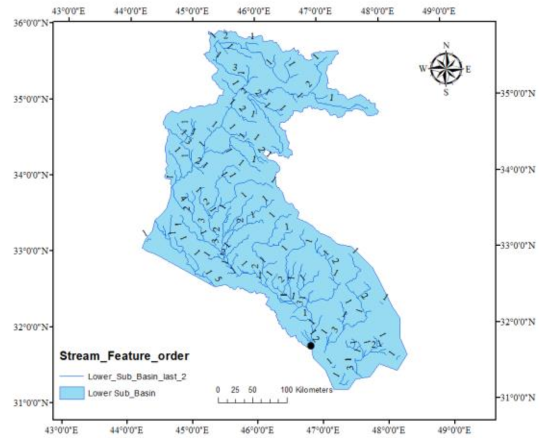

Figure 27. Distribution of stream orders of the Lower Tigris River sub-basin.

Table 2 summarizes the results of the hydrological characteristics of the sub-basins, including area, basin perimeter, elevation, basin ratio, and stream number. The work results were in agreement with the investigation of previous benchmark studies about the characteristics of some catchments in the studied basin (e.g., [28],[34],[40]).

Table 2. Summary of the hydrological characteristics of sub-basins.

Sub-basin	Basin Area (km^2)	Basin Perimeter (km)	Max Elv. (m)	Min Elv. (m)	Basin Ratio	Stream Number
Upper	32779.74	1073.67	3488	406	0.03	118
High	43912.9	1362.3	3899	172	0.032	151
Middle	46754.6	15754.7	3551	29	0.0029	145
Lower	92694.27	2160	3268	-2	0.049	267

5. The Main Infrastructures in the Iraqi Watershed of the Tigris River Basin

The northern and northeast region of Iraq covers parts of the three Tigris River sub-basins, High, Middle, and Lower. This region has several infrastructures of the tributaries and effluents of the Tigris River. It is essential to study this region intensively, with each sub-basin that it contains. Thus, an extensive investigation of this catchment is covered by this work, which is required to identify and locate the sites of rainwater harvesting. Studying this catchment can be implemented in two parts: surface water and subsurface water, as follows.

5.1. Hydrological Characteristics

The mountainous region of north and north-east Iraq receives more than 700 mm of rain yearly [47]. The catchment area lies between longitude 42-46 and latitude 35-37, as shown in Fig. 28. It is located in a dry area (Iraq) which is highly erratic in the distribution of precipitation both within and between years. The distribution of rainfall over the drainage area ranges from 100 mm/yr in the south of the catchment area to 1000 mm/year in the mountains area, and the mean average rainfall over the study area based on available data of 46 years is 600 mm, the rainy season occurs between October to May of the year, the average temperature for this period is 21 C^o, the annual evaporation of the study area ranges between 1400 to 1900 mm [2]. Most of the limited rainfall comes in sporadic, intense, and unpredictable storms with high intensities and short duration. Most precipitation occurs between October and May months of the year, and usually in bursts. Moreover, the land cover in the study area is moderate, usually on soils with low infiltration rates, resulting in runoff and uncontrolled water flow in the rill and gully. The Zagros Mountains, located in northern and northeastern Iraq, characterize the landscape of the north of Iraq with a wide flat area dissected by a complex fluvial network. The wide floodplains show a well-developed hydrological network belonging to the Tigris River catchment.

The Tigris River is one of the main sources of water in Iraq. The total catchment of the Tigris River is about 180,000 km^2. It crosses the borders of Iraq from the northeast toward the southwest. Tigris River is also fed within the High sub-basin by numerous watercourses following from the mountains. Tigris River has six tributaries, one on the left bank following down from the Zagros Mountains, one in Turkey, and five tributaries within Iraq, four in the north of Iraq (the High sub-basin area), and one close to the river outlet (south of Iraq). The tributaries of the Tigris lie mostly inside the catchment area. These tributaries, from upstream to downstream, are the Feesh

Khabour, Greater Zab, Lesser Zab, Adhaim, Diyala River, and Tib and Dwairej. The tributaries that join the Tigris River in Iraq are the Feesh Khabour, Greater Zab, Lesser Zab, Adhaim, and Diyala. Inside Iraq, the catchment area of the sub-basins includes four watersheds: the Greater Zab watershed, the Lesser Zab watershed, the Adhaim watershed, and the Diyala watershed. The Greater Zab tributary, the largest tributary, is common between Turkey and Iraq. It starts in Turkey and supplies the Tigris River with 12.7 Bm^3 of flow yearly. Turkey uses a large part of the Greater Zab waters before it enters Iraq. The Lesser Zab is common between Iran and Iraq; it arises in Iran close to the border of Iraq. The Lesser Zab contributes 249 m^3/s to the Tigris River from its mean annual flow of 7.8 Bm^3. These two tributaries are considered the most significant contributors of flow to the river. The only tributary not shared by the Tigris is Adhaim, which is a sporadic stream with a drainage area of 13,000 km^2 in Iraq. This tributary shows flash flooding and generates about 0.79 Bm^3 annually and supplies the Tigris. The Diyala is a shared tributary by Iran and Iraq; this river also crosses the border between Iraq and Iran for more than 30 km. This tributary lies in the third sub-basin, i.e., the Middle Tigris River sub-basin. The mean annual flow of Diyala is 4.6 Bm^3 and supplies the Tigris 15 km to the south of Baghdad city. The Diyala River is regulated by five dams, with two dams lying inside Iran and the other three dams in the Iraqi basin. For the lower part of the Tigris River basin south of Iraq, i.e., the lower Tigris River sub-basin, the river has two tributaries, which are the Tib and Dwairej tributaries; these rivers flow between Iran and Iraq [25]. The mean annual flow of each one is ~1 Bm^3. The Dwairej joins the Tigris in Amara city, southern Iraq.

The mean flow of the Tigris River is about 400 m^3/s and reaches 80,000 m^3/s during the spring season of the year. More than 67% of the water of the Tigris is sourced from outside. The natural flow regimes of the streams have been controlled by human activities. The hydraulic structures within the area of northern Iraq are the Mosul Dam on the Tigris River, the Dukan Dam, the Derbendikhan Dam, the Adhaim Dam, the Makhool Dam, and the Hamreen Dam. The Mosul Dam is a rockfill dam that was constructed in 1986 about 50 km north of Mosul city with a storage capacity of 11.11 Bm^3, which is the largest dam in Iraq; the reservoir of the dam is about 380 km^2. The live storage of the dam reservoir is 8.16 Bm^3, and the dead storage is 2.95 Bm^3. The discharge of the spillway is about 5730 m^3/s at an elevation of 330 m msl and about 10300 m^3/s at an elevation of 335.8 msl, and reaches 12600 m^3/s at an elevation of 338 m msl. The Dukan Dam was built on the Lesser Zab, and it was constructed in 1959 and is considered the oldest dam in Iraq. The dam was constructed for water storage, irrigation, and electric power. The maximum discharge of the dam is 4300 m^3/s. Dukan Lake is a reservoir constructed by the dam that extends for about 270 km^2. The Duhok dam on the Duhok River, constructed in 1988, with live storage of about 47.51 Mm^3 and dead storage of 4.39 Mm^3, is constructed for irrigation purposes using a pipeline system. Dibis Dam is a regulator dam constructed in 1965 to divert water from the Lesser Zab to agriculture projects in Kirkuk City. The discharge through the spillway of the dam reaches 4000 m^3/s. Darbandkhan Dam was constructed on the Diyalla River in 1956 for irrigation, flood protection, and electric purposes in addition to tourist purposes. The dam reservoir collects water from a catchment with an area of 17850 km^2. The total storage of the dam is 3 Bm^3, and the volume of the reservoir is 113 km^3. The maximum discharge from the dam spillway is 11400 m^3/sec. Adhaim Dam on Adhaim River, 133 km north of Baghdad city, was constructed in 1999 for purposes of irrigation and power generation with a storage capacity of about 1.5 Bm^3. Hamreen Dam on the Diyala River in north-east Iraq, about 120 km north-east of Baghdad, was built in 1981 for flood control and irrigation, besides power generation for 0.25 million hectares of agriculture. The dam storage capacity is about 2.06 Bm^3, with an area of the lake of the dam of about 340 km^2, a live storage of 2.04 Bm^3 with 104 m elevation, and the maximum discharge from the spillway of the dam is about 6800 m^3/s with 107.5 m of elevation. Also, there is a suggested dam on the Tigris River called Makhool Dam, which lies below the lowest tributary of the Tigris River. Work on this dam started in 2000, but it was not finished and work stopped in 2003; it was supposed to start again in 2022. The purposes of dam construction are flood control, power generation, and agriculture. The storage capacity of the dam will be 13 Bm^3. Samara small Dam on the Tigris River was constructed in 1955 for irrigation, flood protection, and electricity, the storage capacity of the dam is 150 Mm^3 but filled with sediment, the dam has 17 gates that can pass 700 m^3/s downstream of the Tigris River and 36 gates pass 9000 m^3/s into Thirthar canal. Then, the Tigris River runs onto a wide, low-slope, dry, and poorly drained floodplain for several hundred kilometers and merges with the Euphrates River to form the Shatt Al-Arab River in southeastern Iraq. The basin of the Tigris River dominates the northern part of Iraq, and the rest of the country is restricted by the water of the two rivers. The Tigris River water was extensively exploited for irrigation of the lower Mesopotamian Plain since the earliest civilization.

The precipitation in the basin is highly erratic over time. Most of the limited rainfall comes in sporadic, intense, and unpredictable storms. Therefore, the second objective of this work was to analyze the hydrological characteristics of any storms that may happen within the study area by studying the hydrological features using the GIS technique. To carry out this study, data are required for a DEM (Digital Elevation Model) and rainfall data. The DEM map (30 m resolution) for the whole study area was downloaded from the USGS website, along with the shapefile of the study area, using the ArcGIS 10.8 platform. For the rainfall data, gage stations are based on analysis of the precipitation in the region, i.e., Iraq, for a time period of 46 years using the Iraqi Meteorological Organization and Seismology (unpublished data). Catchment areas are calculated for the study area in this catchment, and it showed that there are between four and five distinct areas for the whole watershed. This is attributed to the topographic nature of the region; there are mountains and hilly areas in the north and low plains in the south. After analysis of the catchment areas, it can be concluded that the catchment area contributes to the runoff into different hydro edges, and there is no common outlet for the watershed. This helps to reduce the flood risk of any storm within the area and then good management of the watershed. The topographic map created in this work shows that the contour map varies between 2550 m in the north and 150 in the south. Also, the flow direction was calculated and it was noticed that the flow direction is a radial flow for the entire study area and is attributed to the topographic nature as shown in Fig. 28. Also, the other features such as drainage points and drainage lines, which are necessary for irrigation and drainage system design and flood protection structures, and identify the sites of rainwater harvesting were calculated. Also, in this work, the longest flow path of the catchments was estimated, as shown in Fig. 29. Its length is about 300 km, and it lies near the middle of the watershed. Determination of the longest flow path is necessary in the hydrological investigations of watersheds, in particular in channel flood routing and for hydrograph analysis, for example, estimating the synthetic hydrograph for the storm. Water harvesting is a technique used to capture and store water in a reservoir; it is essential to determine the best site of a reservoir to capture much water. It was noted that the best location of such a reservoir is at the end of the longest path. In conclusion, more data and information are needed to do the hydrological analyses using GIS.

The wadis in the study area of north Iraq drain the rainfall quickly into the streams, thus restricting the recharge of groundwater aquifers. However, the short precipitation bursts decrease the losses of evaporation from the rainfall. The average annual evaporation is 2500-3000 mm, of which about 20% of this amount occurs in July and August. The density of the drainage reflects the hydrological properties of the basin also the nature of aquifers in the region.

In this work, some of the hydrological indices are determined by using geometry and measurement tools in ArcGIS. These indices are the area, length, perimeter, and topography. From these parameters, some morphometric parameters that can be estimated for the basin of the study area were implemented using ArcGIS v.10.8 software. Drainage density is the proportion between the total stream length of all orders (km) and the basin area (km^2). The area of the basin represents the area where water drains into a combined stream and is estimated by reverse ridges. The discharge of the channel is the volume of the stream valleys that drain the accumulated water. It increases with increasing stream order. Low drainage density promotes high infiltration, whereas high drainage density means slight/low permeable subsurface materials and poor land cover. This indicates good discharge or runoff of water and sediment. If drainage density < 0.6, it is low; if drainage density is between 0.6-0.9, it is average; and if drainage density > 0.9, it is high. The relief factor of the basin is the difference between the highest point and the lowest point in the basin. This factor is essential in understanding the erosion of the watersheds. The max relief factor of the basin is 2100. The relief ratio, or what is called channel gradient, identifies the average slope of the basin, measures the flow rate intensity, and then the erosion and sedimentation of the streams. The relief ratio is the ratio between the maximum basin relief to the maximum basin length (i.e., the line that represents the axis of the basin). The relief ratio indicates the average slope of the basin, which was found equal to 10.75. The relative relief ratio represents the ratio between the maximum relief of the basin and the basin perimeter. The relative relief ratio is 0.38. This means the drainage volume of the basin is high with a moderate slope for flow. The relief index (km) is the proportion between the area of the basin to the length of the basin, and it was found equal to 32 km.

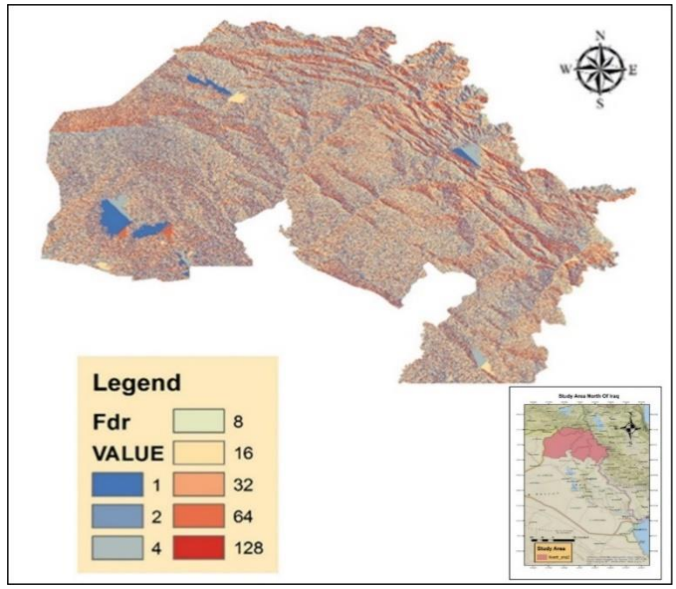

Figure 28. Flow directions of the Tigris River catchment in the north of Iraq.

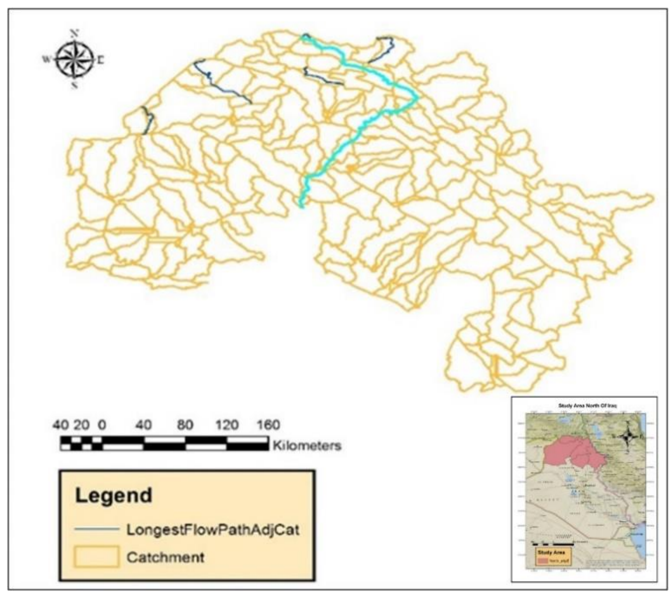

Figure 29. The longest flow path of the Tigris River catchment in the North of Iraq.

5.2. Rainwater Groundwater Investigation of the Watershed of Tigris River in North Iraq

From the geological aspect, the study area of the basin witnessed dramatic (tectonic) activities in the period between the Cambrian and Quaternary (geological time scale), leading to two major types of stability. The catchment (north and northeast of Iraq) is located in an unstable part, which is divided into three subzones that increase the amount of deformation from southwest to northwest: foothill, high folded zone, and truss zone. For example, the Arbil area is located in the foothill zone. Geological formation refers to the lagoon where there is carbonate rock [48]. The mountain belt dominates the north and northeast parts of the area, with an elevation greater than 1500 m MSL. The basin is mainly connected to the groundwater. Thus, the amount and distribution of rainfall in the area affect groundwater level fluctuations, where the shape of the earth is related to climate and runoff. Groundwater resources from direct rainfall are important, especially when limited water is available. The water table in the area ranges between 20 and 30 m below the surface. For water quality, the mountainous region of the area is characterized by freshwater where the salinity is less than 1 g/L, whereas in the rest of the region, irrigation water reaches greater than 3 g/L. The hydraulic conductivity of most areas of this watershed lies between 3-7.5 m/day and decreases to less than 3 m/day in the west of the Tigris River. This part focuses on groundwater investigations that are connected with some tools of GIS to get the relationship between geological features and groundwater quality. The process of this part is done in three steps: collecting information and data, interpolating the dataset, and deterministic analysis. The methodology of hydrogeological investigations on any catchment area depends on the available data. In catchments where data are scarce (e.g., mountain areas) the hydrogeological studies are approximate and often based on geological analogs. Thus, some statistical analyses are needed in some areas where sufficient hydrogeological and hydrochemical data from drilled and hand-dug wells are available. The dataset was collected from the Iraqi Methodological Organization and the Seismology Research Institute, which deals with water investigation in the northern part of Iraq, which is the most important hydrogeological unit of the whole of Iraq. This information includes 1000 wells in the study area north of Iraq, including 15% of well samples distributed in the Erbil area. Fig. 30 shows a sample of local wells distributed within the study area in the north of Iraq. Due to the topography and complexity of the structures (see Section 5.1) of the area in northern and eastern Iraq, the regional flow direction of the groundwater in this area is generally to the southwest and south towards the Tigris River and its tributaries [49].

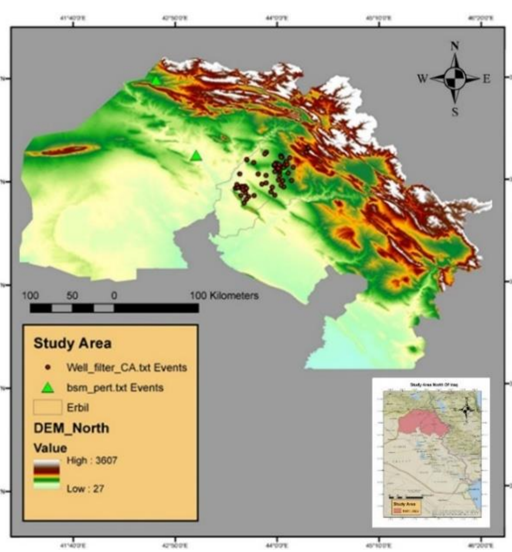

Figure 30. Location of a sample of local wells in the north of Iraq.

The rainwater harvesting system is an effective source of groundwater when the capacity of the reservoir is less than the collected runoff volume. When reservoirs are about to be empty, the groundwater may be an effective support system for the supplemental irrigation associated with rainwater harvesting (RWH). This issue may help to solve the stifling water crisis in Iraq. Thus, rainwater harvesting is one of the solutions to confront the current water scarcity problem in Iraq.

6. Rainwater Harvesting and Rainwater Use Efficiency

6.1. Rainwater Harvesting (RWH)

The runoff is estimated by simulating the sub-basin as a hydrologic system, as illustrated in Fig. 31. In this simulation, the system event is input from precipitation (rainfall and snowmelt) and output from infiltration, evaporation, interception, and surface wetting. The net above the basin surface exceeds a depth d. The water above the box of depth ds is runoff q.

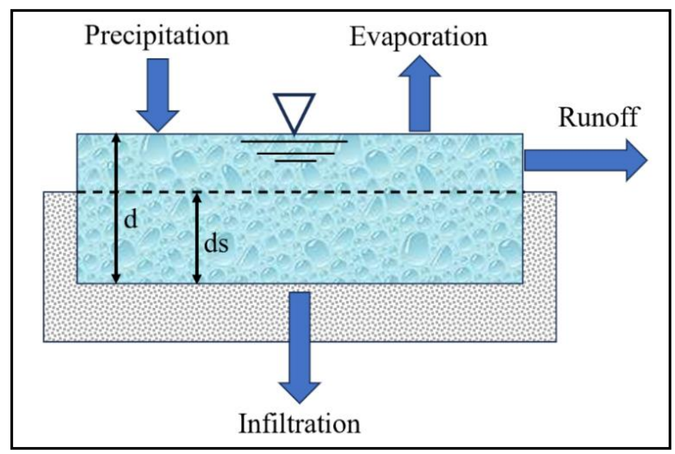

Figure 31. The storage model of a sub-basin.

From the mass conservation applied over the sub-basin, as described in (1):

$$\frac{\Delta d}{\Delta t} = P - E - f - q \qquad (1)$$

where P is the precipitation (m/s/area); E is the evaporation rate (m/s/area); f infiltration rate (m/s/area); q is the runoff rate (m/s/area); Δd change in water depth; and Δt the change in time (s). Assuming uniform flow, the volume of runoff flow rate Q (m^3/s) is estimated using the Manning equation for an open channel of width W (m), and depth (d–ds), as expressed in (2):

$$Q = \frac{1}{n} A\, R_h^{2/3} S^{1/2} \qquad (2)$$

where n is the coefficient of roughness; S is the average sub-basin slope (channel slope) (m/m); A is the cross-sectional area of the sub-basin (m^2); and Rh is the hydraulic radius (m). Since $W > d$, then $A = W(d{-}dS)$ and Rh = $d{-}d$s. To get the runoff q, equation (2) is divided by A, as shown in (3):

$$q = \frac{1}{nA} W S^{1/2} (d - ds)^{5/3} \qquad (3)$$

Substituting (3) into (1) gets (4):

$$\frac{\Delta d}{\Delta t} = P - E - f - \beta(d - ds)^{5/3} \tag{4}$$

where β is $\frac{1}{nA} W S^{1/2}$. For given values of *P, E, f, ds,* and β, the value of the depth *d* is solved numerically over the time step *Δt.* Then values of *q* can be computed using Equation (3). Equation 4 is only valid when $d > ds$. Runoff *q* is zero when $d <= ds$. To solve the governing system of equations numerically, the model code was written using MATLAB version R.2018. The harvested rainwater can be stored in ponds by check dams or weirs and farm ponds. It is proposed that these ponds be placed close to the drainage points at the end of streams in the catchment area of the sub-basin. The most used water harvesting structures for water harvesting and soil conservation are the check dams; they are also suitable for lower-order streams [50]. The harvested water is then proposed to be used with high efficiency, where about 75% of this water goes to the agriculture sector, and the rest goes to municipal uses.

The distribution of rainfall over the drainage area ranges from 100 mm/yr in the south of the catchment area to 1000 mm/year in the northern region (mountain area), and the mean annual rainfall over the study area, according to the available data of 46 years, is 600 mm. Fig. 32 shows the geographical location of rainfall stations in Iraq with the mean annual precipitation data over 46 years [51]. The red circles represent the locations of the rain gauge stations. The mean annual values of the precipitation recorded at the stations are shown in the attribute table, as shown in Fig. 32.

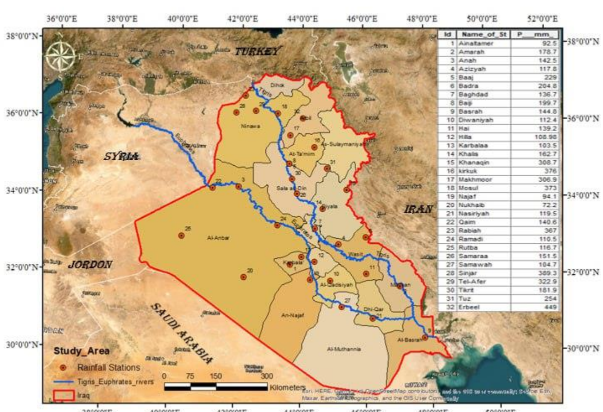

Figure 32. Location map of Meteorological stations in Iraq.

In this work, one of the objectives was to improve the rainwater use efficiency of the harvested water that goes to the agricultural part because the rationalization of water use in municipal usage is relatively low, especially in emerging countries such as Iraq. The runoff is estimated via the Soil Conservation Service-Curve Number (SCS-CN) method. The SCS-CN is an approach applied to assess the surface runoff from catchments after a rainfall event [52]. The curve number CN indicates the relation between land cover and the hydrologic soil group HSG. The value of CN is dependent on several factors, e.g., type and texture of soil, land use and land cover, and antecedent moisture conditions (AMC) [52]-[54]. The depth of the runoff is estimated using (5) as follows:

$$Q_{CN} = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{5}$$

where $Q_{CN} = 0$ if $P <= 0.2S$; *S* represents the maximum soil retention (mm) and is computed using (6) as follows:

$$S = 25.4(\frac{1000}{CN} - 10) \tag{6}$$

Curve number CN was computed assuming normal moisture conditions. Curve numbers were weighted for the watershed area by applying (7) as follows:

$$CN_{wt} = \frac{\sum CN_i \times A_i}{A_t} \tag{7}$$

where CN_{wt} is the weighted CN; CN_i is the curve number associated with the land use; A_i is the area beyond the curve number and land use; and A_t is the total area. Then the volume of the runoff *V* is estimated using (8) as follows:

$$V = Q_{CN} \times A_t \tag{8}$$

The curve number CN reflects watershed runoff potential. The CN is given in tabular form provided by TR-55 and hydrology texts, represented by land use and land cover LULC, HSG, watershed wetness, and surface cover conditions. Based on the SCS classification of soil. There are more than 4000 types of soils grouped into four classes of HSG based on runoff potential A, B, C, and D [55]. Table 3 shows the characteristics of the soil associated with the hydrologic soil groups [55].

Table 3. Soil characteristics of hydrologic soil groups [55].

HSG	Description
A	Soils of high infiltration rates and low runoff potential; e.g., deep sand; deep loess; aggregated silts.
B	Soils of moderate infiltration rates when thoroughly wetted and moderately well to well-drained soils; e.g., shallow loess; or sandy loam.
C	Soils of slow infiltration rates when thoroughly wetted, soils of moderate to fine texture; e.g., clay loams, shallow sandy loam; soils low in organic content; soils usually high in clay.
D	Soils of low infiltration rates and high runoff potential; e.g., soils that swell significantly when wet; heavy plastic clays; and certain saline soils.

The data on the hydrologic soil group (HSG) of the study area were provided from the Geomorphological map of Iraq, State Establishment of Geological Survey and Mining (GeoSURV) in 1988 [56], as shown in Fig. 33. Table 4 illustrates the values of CN for the different land use treatments and hydrological conditions. The runoff volume is significantly affected by antecedent soil moisture conditions (AMCs). The SCS developed three conditions of AMCs labeled I, II, and III. The conditions of soil with these types are: Condition I represents dry soil but higher than the wilting level; Condition II is average condition; Condition III is saturated soil by heavy or light rainfall occurring within the last 5 days with low temperatures.

In this work, the Curve number CN was computed assuming normal moisture conditions, i.e., antecedent moisture condition (AMC II). The details about the HSG were given in the country soil survey or soil characteristics [55].

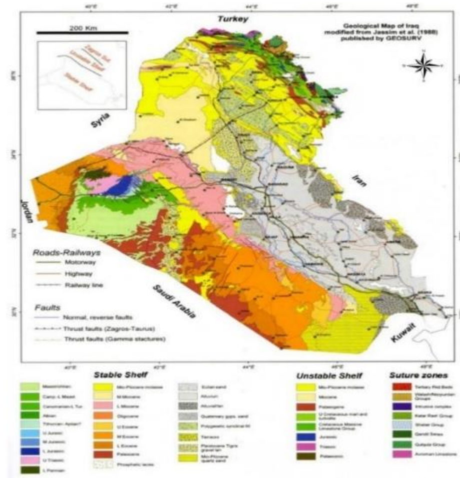

Figure 33. Geomorphological map of Iraq [56].

Table 4. Average runoff Curve number for different LULC and HSG [57].

		Curve Numbers CN for Hydrologic Soil Group Classification (HSG)			
		A	**B**	**C**	**D**
Open Space					
Poor Condition (grass cover < 50%)		68	79	86	89
Fair Condition (grass cover 50-75%)		49	69	79	84
Good Condition (grass cover > 75%)		39	61	74	80
Impervious areas (paved parking lots, roofs, etc.)		98	98	98	98
Streets and Roads					
Paved with curbs and storm sewers		98	98	98	98
Paved with open ditches		83	89	92	93
Gravel		76	85	89	91
Dirt		72	82	87	89
	Average % impervious				
Urban Land Use					
Comm and Business	85	89	92	94	95
Industrial	72	81	88	91	93
Row houses, Townhouses, and Residential Homes with lot size 1/8 Acre or less	65	77	85	90	92
Residential: average lot size					
1/4 Acre	38	61	75	83	87
1/3 Acre	30	57	72	81	86
1/2 Acre	25	54	70	80	85
1 Acre	20	51	68	79	84
2 Acres	12	46	65	77	82
Developing urban areas, newly graded, no grass cover		77	86	91	94
Pasture					
Poor		68	79	86	89
Fair		49	69	79	84
Good		39	61	74	80
Woods					
Poor Condition		57	73	82	86
Fair Condition		43	65	76	82
Good Condition		32	58	65	78
	Hydrologic Condition				
Row Crops					
Straight row	Poor	72	81	88	91
	Good	67	78	85	89
Contoured	Poor	70	79	84	88
	Good	65	75	80	82
Contoured and Terraced	Poor	66	74	80	82
	Good	62	71	78	81

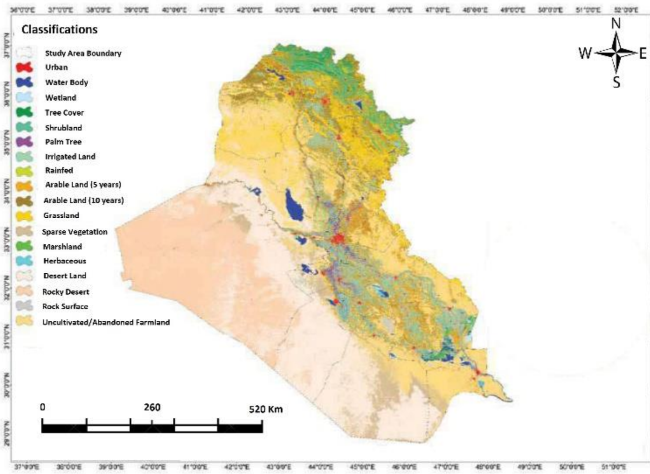

Figure 34. Distribution of LULC for Iraq in 2023 [58].

The land use and land cover LULC data maps were provided from benchmark references [58]. Fig. 34 illustrates the LULC map of the study area in 2022 [58].

The hydrological characteristics of the Tigris River sub-basins and some useful indices (morphometric analysis) were assessed to examine the sub-basins for rainwater harvesting. The main points of water harvesting sites in each sub-basin inside Iraq were identified and located to store the harvested water by providing good information about the catchment, and then they were used to determine the locations of water harvesting dams in the valleys located in the Tigris River Basin. The proposed rainwater harvesting sites for each sub-basin within the Iraqi Tigris River basin cover most of the area of the catchment with a high degree of distribution. Catchment areas for each suitable RWH site were identified as shown in Figs. 35 to Fig. 37. Also, the mean monthly runoff of the catchments was estimated for each RWH site. The captured volume of the runoff in RWH sites can be used in the design of the structure of the RWH at these sites. For the High Tigris River sub-basin, it was found that about 83% of the basin area is suitable for RWH sites. For the Middle Tigris River sub-basin, it was found that about 69% of the basin area is suitable for RWH sites. For the Lower Tigris River sub-basin, it was found that 63% of the basin area is suitable for RWH sites. In general, about 70% of the river basin area inside Iraq seems to be suitable for rainwater harvesting. This can be attributed to the topography of the basin, where the slope of the land decreases towards the downstream of the river, and the river has high sinuosity south of Baghdad city, close to the center of Iraq.

Tables 5, 6, and 7 show the results of the monthly runoff volume of the harvested rainwater from the Iraqi Tigris River sub-basins (inside Iraq). The hydrological soil group HSG is classified according to the SCS-CN method and coincides with maps of LULC and geomorphology of Iraq; P here is the monthly average precipitation at the site (mm); Ia is taken equal to 0.2S (mm). Iraq is considered a poorly rain-gauged watershed, as shown in Fig. 32. Thus, for the sites that lie between the rain gauge stations, the value of average rainfall was estimated using average precipitation methods over an area, such as the Average Arithmetic method, Isohyetal method, Thiessen method, or Interpolation method.

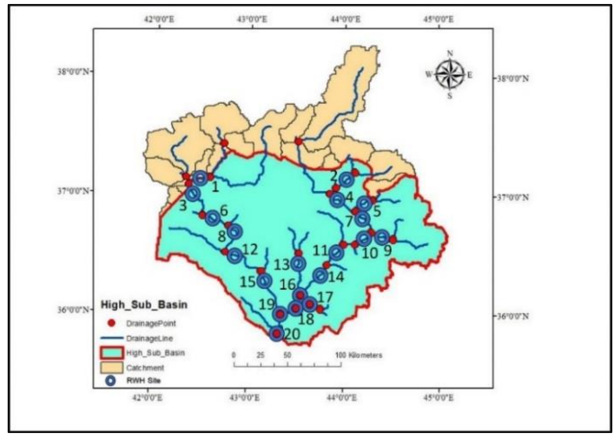

Figure 35. The proposed rainwater harvesting sites in the High Tigris River sub-basin.

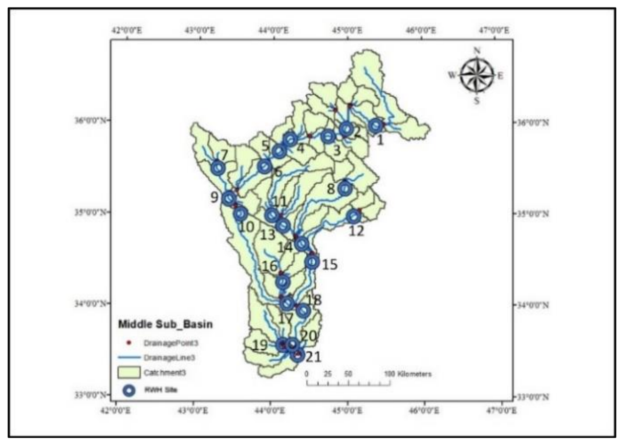

Figure 36. The proposed rainwater harvesting sites in the Middle Tigris River sub-basin.

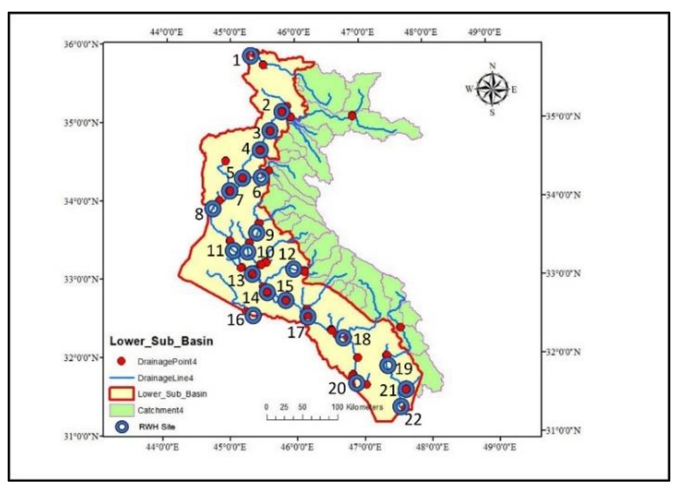

Figure 37. The proposed rainwater harvesting sites in the Lower Tigris River sub-basin.

Table 8 shows the annual harvested runoff of the three sub-basins. In the calculations, based on the used data, the rainy season of the year consists of 8 to 9 months (September to May; except the months of June, July, and August). A total annual runoff volume of 324 BCM was estimated as a result of collected runoff from the sub-basins during the rainfall season. The results were in agreement with the investigations of previous benchmark studies about the runoff amount from some sub-catchments in the river basin (e.g., [34],[39]).

Table 5. Runoff volume of the harvested rainwater from the High Tigris River sub-basin inside Iraq.

Site No.	HSG	CN_i	P (mm)	A_i (km^2)	S_i (mm)	Ia_i (mm)	Qi (mm)	V_i (m^3)
H1	D	98	600	4913.5	5.184	1.037	593.824	2917754561
H2	D	98	900	1842	5.184	1.037	893.809	1646396751
H3	C	79	580	2271	67.519	13.504	506.168	1149506621
H4	D	89	870	5217	31.394	6.279	833.429	4347999652
H5	C	74	864	1289.5	89.243	17.849	765.423	987012369
H6	C	79	500	1141.9	67.519	13.504	427.206	487826412
H7	C	91	420	1105	25.121	5.024	391.289	432374184
H8	B	65	400	615	136.770	27.354	272.597	167647216
H9	B	61	800	2209.5	162.394	32.479	633.487	1399689659
H10	C	86	700	982	41.349	8.270	652.714	640964803
H11	A	67	630	1474	125.105	25.021	501.312	738934001
H12	D	93	264	3314.4	19.118	3.824	242.367	803300354
H13	A	57	644	2454.6	191.614	38.323	460.114	1129395843
H14	B	92	520	738	22.087	4.4174	494.403	364869387
H15	D	84	440	1280	48.381	9.676	386.833	495145657
H16	A	57	456	1107.6	191.614	38.323	286.323	317131619
H17	A	57	558	982.3	191.614	38.323	379.682	372961503
H18	D	86	433	883.8	41.349	8.270	387.050	342074537
H19	A	49	410	1105.7	264.36	52.874	205.214	226905323
H20	D	84	386	1596.1	48.381	9.676	333.454	532226335

Table 6. Runoff volume of the harvested rainwater from the Middle Tigris River sub-basin inside Iraq.

Site No.	HSG	CN_i	Pi (mm)	A_i (km^2)	S_i (mm)	Ia_i (mm)	Qi (mm)	V_i (m^3)
M1	A	39	800	2949	397.282	79.456	464.458	1369686650
M2	D	82	700	2946.6	55.756	11.151	637.268	1877773022
M3	D	89	680	738	31.393	6.279	643.726	475069631
M4	C	79	523	860	67.519	13.504	449.878	386894992
M5	B	73	430	983	93.945	18.789	334.737	329046459
M6	A	39	300	982.7	397.282	79.456	78.727	77364888.9
M7	D	86	260	1351.3	41.349	8.270	216.215	292171417
M8	A	49	500	860.8	264.367	52.874	280.989	241875550
M9	A	57	180	2579	191.614	38.323	60.225	155319987
M10	A	82	167	982.1	55.756	11.152	114.784	112729311
M11	A	57	223	2088	191.614	38.323	90.636	189248711
M12	B	82	510	860	55.756	11.151	448.698	385880290
M13	C	76	267	983	80.211	16.042	190.175	186941759
M14	C	82	164	2334	55.756	11.151	111.995	261396849
M15	B	73	156	369	93.945	18.789	81.447	30053737.3
M16	B	69	147	1843	114.116	22.823	64.710	119260193
M17	B	61	143	2457	162.394	32.479	44.757	109968981
M18	B	74	156	492	89.243	17.849	83.933	41294788
M19	A	77	146	3315.6	75.870	15.174	82.805	274547690
M20	C	85	153	1475	44.824	8.965	109.850	162028939
M21	B	90	162	737	28.223	5.645	132.449	97614584.2

Table 7. Runoff volume of the harvested rainwater from the Lower Tigris River sub-basin inside Iraq.

Site No.	HSG	CN_i	P (mm)	A_i (km^2)	S_i (mm)	Ia_i (mm)	Qi (mm)	V_i (m^3)
L1	D	80	910	3436.7	63.5	12.7	837.997	2.88E+09
L2	D	84	813	8226.5	48.381	9.676	757.691	6.233E+09
L3	C	82	732	1597.2	55.756	11.152	669.096	1.069E+09
L4	B	73	669	1720	93.945	18.789	568.126	977176318
L5	A	32	264	1228	539.750	107.950	34.998	42977534
L6	A	57	348	2333.6	191.614	38.323	191.306	446431422
L7	C	74	153	1473	89.243	17.849	81.4008	119903301
L8	C	74	147	1105.7	89.243	17.849	76.376	84448771
L9	B	73	152	3070.3	93.945	18.789	78.119	239848052
L10	D	86	156	2457	41.349	8.270	115.424	283596236
L11	C	74	158	1228	89.243	17.849	85.627	105150118
L12	D	65	154	737.6	136.769	27.354	60.890	44912143
L13	C	82	149	4053	55.756	11.151	98.150	397801270
L14	D	86	151	1473.8	41.349	8.270	110.669	163104554
L15	C	82	155	982.1	55.756	11.1512	103.667	101811522
L16	D	86	148	2947.6	41.349	8.270	107.823	317819878
L17	C	91	161	3192	25.121	5.024	134.340	428811986
L18	D	82	164	6874.4	55.756	11.152	111.995	769899956
L19	C	82	158	4296.7	55.756	11.152	106.437	457325926
L20	C	82	150	2455.5	55.756	11.152	99.067	243259806
L21	D	86	157	1228.2	41.349	8.270	116.376	142933263
L22	C	76	149	2209.6	80.21	16.042	82.929	183239481

Table 8. Summary of the annual harvested runoff in the sub-basins.

Basin	Catchment Area (km^2)	CN_{wt}	Monthly Runoff Volume (BCM)	Annual Runoff Volume (BCM)
High sub-basin	36522.9	81	18.4	165.6
Middle sub-basin	32186.1	69	7.2	57.6
Lower sub-basin	58326.5	79	12.6	100.8
Total	127035.5		38.2	324

6.2. Rainwater Use Efficiency (RWUE)

There are several terms to express water use efficiency. One of these terms is rainwater use efficiency RWUE which is defined as the efficient use of water through issue under rainfed conditions. It also indicates the water productivity of treatment under rainfed conditions with no irrigation to the crop. The harvested rainwater use efficiency RWUE is the augmentation of the crop yield (Y) per unit of harvested rainwater for supplemental irrigation, i.e., rainwater productivity ($kg.m^{-3}$) [42],[59],[60], as expressed in (9).

$$HRWUE = \frac{Y}{HRW} \tag{9}$$

where Y is the rainwater productivity or grain yield of marketable crops in the agricultural sector ($kg.m^{-3}$); and HRW is the harvested rainwater (rainfall).

Due to a lack of adequate data about productivity per unit area under ideal conditions, this work used what is called relative water use efficiency, which represents the ratio between the actual water use efficiency and the optimum water use efficiency [61], as shown in (10) as follows:

$$WUEr = \frac{WUEa}{WUEm} \tag{10}$$

where WUEa is the water use efficiency under actual conditions ($kg.ha^{-1}.mm^{-1}$); WUEm represents the water use efficiency under optimum conditions ($kg.ha^{-1}.mm^{-1}$).

The results showed that the water use efficiency per unit harvested water (WUEr) decreases with the increasing amount of the used water or the relative water protectivity Yr, which is the ratio between the actual yield Ya to the maximum Ym (i.e., Ya/Ym), as shown in Fig. 38. The results shown in Fig. 38 are presented based on collected data on the amount of water and crop yield per unit of water, i.e., rainwater productivity [61]. To enhance the credibility of the correlation, the presentation of results included statistical measures of fit (the black line), where the relation showed good agreement.

Rainwater harvesting is a time-tested, sustainable solution and technique that includes collecting and storing rainwater to supplement surface and groundwater and has been used in diverse applications, including agriculture and domestic use. This ancient technology has seen renewed interest in recent years due to its attractive environmental, economic, and social benefits. Rainwater harvesting is a sustainable solution for water resources; it plays an essential role in alleviating the challenges of water scarcity, especially in regions grappling with issues related to water availability and equitable distribution, such as Iraq. The choice of rainwater and floodwater harvesting technology depends on several variables, including:

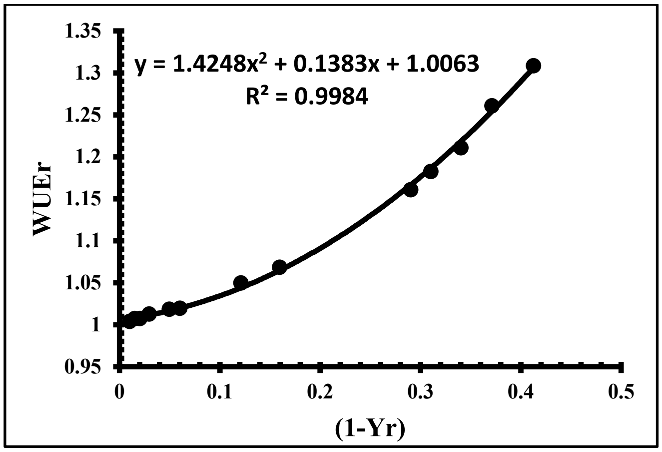

Figure 38. The relation between the relative water protectivity and the WUEr.

1. Environmental conditions (rainfall intensity, availability of water resources, quality of rainwater, distribution of seasons);
2. Technical factors (available space, intended use, tank capacity, system use, local regulations, efficient system design, stringent maintenance protocols, and vigilant water quality management);
3. Economic factors (budget, construction cost, system operating cost, maintenance) and policies and regulations in the region; and
4. Community acceptance and participation are also key factors to avoid abandoning the system after it is established.

The water harvesting technique makes the water more available to consumers in dry conditions, i.e., it is one of the efficient methods that can be used for water conservation, flood regulation, and improving the hydrological cycle on Earth. It controls the runoff into target areas, increases water availability for irrigation, reduces erosion, reduces the impact of drought, and increases rainwater productivity. The proposed rainwater harvesting sites for each sub-basin within the Iraqi Tigris River Basin (TRB) cover most of the area of the catchment with a high degree of distribution. This work suggested that the rainwater harvested was used under the promotion of rationalization of water consumption.

7. Conclusions

This work investigated the rainwater harvesting areas of the Tigris River Basin (TRB) in Iraq, evaluated the amount of water that can be harvested from the river basin, and then proposed some suggestions and recommendations for improving rainwater use efficiency in the Iraqi watersheds in particular. The paper utilized GIS techniques to examine the hydrological characteristics of the TRB and identify and locate the rainwater harvesting sites in the TRB in Iraq. The volumes of the harvested water (runoff) were assessed utilizing the SCS-CN method. The harvested rainwater (runoff) is used to evaluate the water use efficiency in the watershed area within the irrigation network. The main findings of the paper indicated that the drainage basin of the Tigris River was shaped by four distinguished sub-basins, namely the Upper sub-basin, High sub-basin, Middle sub-basin, and Lower sub-basin, with a total area of 216,141 km^2. The Iraqi sub-basins shared with the Tigris River Basin are three sub-basins: the High sub-basin, the Middle sub-basin, and the Lower sub-basin. The results showed that the Iraqi sub-basins are highly suitable areas for rainwater harvesting (RWH) sites, where more than 83% of the High sub-basin area is suitable for rainwater harvesting sites, 69% of the Middle sub-basin area is suitable for RWH sites, and about 63% of the Lower sub-basin area is suitable for RWH sites. The annual harvested runoff results in the sub-basins inside Iraq, High, Middle, and Lower, were 165.6 BCM, 57.6 BCM, and 100.8 BCM, respectively. The expected quantity of annual runoff from the whole Tigris River basin, i.e., the harvested rainfall, in Iraq was 324 BCM. The harvested rainwater use efficiency ratio increases with the increasing amount of the used water or the relative water protectivity per unit area.

The integration between technology and water policy can enhance opportunities for the smallholders in the sub-basins to improve water productivity under dry conditions by adapting to the deficit in water resources and sustaining a water balance for agriculture and the environment. This work confronts some limitations that need to be addressed. One of these limitations is that the use of the SCS-CN method is based on some assumptions and simplifications. Also, the paper did not account for the effects of climate change and changes in land use and land cover, which significantly impact the hydrological features of the basin over time. Thus, future work should address these limitations and incorporate more advanced methods to improve the accuracy of the runoff estimation and assess the impact of changing environmental conditions on water resources in the study area. Moreover, the future work beyond this work's objectives to improve water resources management and offset variability with increasing demand and climate change requires high water control, and this can be achieved using improved water-harvesting techniques with high efficiency; these will be the future face of this work when more data become available. More specifically, the proposed recommendations for future work to develop the present work will focus on some issues such as ameliorating methodologies for the identification of water-harvesting sites for various environments; methodologies for planning and implementing such techniques at studied watersheds for supplying sustainable sources of water from rainfall and run-off for the economic aspect of crops and important plants; and techniques for optimal use of the harvested water in the catchments.

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Nomenclature

A	cross-section area of the sub-basin, km^2
a	actual conditions, (-)
Ai	area beyond land use, km^2
At	total area, km^2
CN	curve number, (-)
CNi	curve number for land use, (-)
CNwt	weighted curve number over the area, (-)
d	water depth, m
ds	water depth above the box, m
E	evaporation, $m.sec^{-1}. km^{-2}$
f	infiltration rate, $m.sec^{-1}. km^{-2}$
HRW	harvested rainwater, m
i	land use type, (-)
n	coefficient of roughness, (-)
p	precipitation, mm
q	runoff rate per unit area, $m.sec^{-1}. km^{-2}$
Q	runoff flowrate, $m^3.sec^{-1}$
Qi	depth of runoff at site i, mm
Rh	hydraulic radius, m
RWUE	rainwater use efficiency, $kg.ha^{-1}.mm^{-1}$
s	slope of the sub-basin, $m.m^{-1}$
S	maximum soil retention, mm
t	time, sec
V	volume of the runoff, m^3
Vi	volume of the runoff at site i, m^3
wt	weighted value, (-)
WUEa	actual water use efficiency, $kg.ha^{-1}.mm^{-1}$
WUEm	optimum water use efficiency, $kg.ha^{-1}.mm^{-1}$
WUEr	relative water use efficiency, (-)
Y	water productivity or grain yield, $kg.m^{-3}$
Ya	actual water productivity or grain yield, $kg.m^{-3}$
Ym	optimum water productivity or grain yield, $kg.m^{-3}$
Yr	relative water productivity or grain yield, (-)
Δd	change in water depth, m
Δt	time interval, sec

Conflict of interest

The authors confirm that the publication of this article causes no conflict of interest.

Author Contribution Statement

Basim M. Al-Zaidi: Proposed the work idea, conceptualization, methodology, modeling, coding, running of the simulation, supervising the findings and results of the work, and reaching conclusions for the work.

Mohammed H. AL-Umar: Conducted GIS work computations, data collection, analysis, and results and discussion.

Mourtadha Sarhan Sachit: Prepared data curation, analysis, review, and discussion.

All authors discussed the results and contributed to the final version of the manuscript.

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