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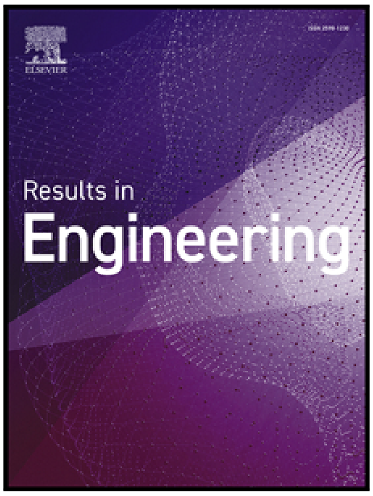

Sustainability through Integrated Hydrological-Hydraulic Modelling for Rainwater Harvesting in Arid Regions: A Case Study of Ali Al-Gharbi, Southern Iraq

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Highlights (for review)

- The research topic holds significant practical relevance in water resources management, flood control, and rainfall harvesting, especially in dry and semi-arid locations like the Ali al-Gharbi area in southern Iraq.
- The watershed site has not undergone prior investigation, and not all facts about the area are accessible.
- Integrating hydrological modelling with hydraulic modelling (HEC-HMS, Geo-HMS, GIS, HEC-RAS) and remote sensing data constitutes a contemporary methodology. The CSI approach was employed for validation due to insufficient data.
- It is proposed to transport the collected water to the Tigris River, located near the research area, through a gated canal to prevent flooding.

Sustainability through Integrated Hydrological-Hydraulic Modelling for Rainwater Harvesting in Arid Regions: A Case Study of Ali Al-Gharbi, Southern Iraq

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Abstract. Transforming hydrological risks into regulated water resources is essential for sustainability in arid and semi-arid areas. This study proposes an integrated hydrological and hydraulic modelling framework for rainwater collecting in the Ali Al-Gharbi watershed, southern Iraq (Area: 2945.33 km²). The study uses Geospatial Analysis (GIS), Sentinel-2 imagery, and FAO-HWSD soil data to identify a high runoff potential, as indicated by Curve Number (CN) values ranging from 71 to 100, driven by dominant agricultural land use (94.05%) and low-infiltration soil types (B and C). Hydrological modelling using HEC-HMS, validated against historical events with high accuracy metrics (CSI = 89.0%, HR = 98.2%), predicted a peak discharge of 489.7 m³/s and a total harvestable runoff volume of 144.4 million m³ during the extreme April 2019 event. To handle this output, a 1.759 km gravity-driven connection canal was designed using HEC-RAS and optimised with a bed slope of 0.0017 to reduce elevation from 8.0 m to 5.0 m without mechanical pumping. It has the unusual potential to serve as a "linear reservoir" for temporary storage, filling the gap between intermittent rainfall and seasonal irrigation requirements. The design includes a terminal regulator and four radial gates, which convert the canal into a linear reservoir for seasonal storage and flood backflow protection. The findings show that this integrated HEC-HMS/RAS strategy offers a cost-effective, long-term infrastructure model for transforming damaging flash floods into strategic water security in data-poor, semi-arid locations.

Keywords: Sustainability; Rainwater Harvesting; Flood Simulation; Hydraulic Modelling; HEC-HMS/HEC-RAS.

1 Introduction

Due to factors such as climate change, population growth, and poor water management, the already limited freshwater supplies in arid and semi-arid countries are being further stressed, intensifying water scarcity [1]. Annual precipitation averages less than 150 mm in southern Iraq, including the Al-Gharbi area of Maysan Governorate. Rainfall is concentrated in just a few months, from November to March, according to [2]. Despite the area's dryness, flash floods, the result of intense, brief rainfall, may occur from time to time, causing damage to infrastructure and leading to losses and soil erosion [3]. In a remarkable turn of events, these frequent floods are a huge unutilized water resource that may be captured by strategically placing rainwater harvesting (RWH) measures. Appropriate RWH infrastructure could boost soil moisture retention and groundwater recharge by as much as 30% [4], researchers in southern Tunisia found. In drylands, where surface and groundwater resources are either limited or heavily used, RWH has been known for a long time as an effective method for water security [5]. Capturing, concentrating, and storing storm runoff for agricultural, residential, or groundwater recharge uses are the goals of RWH systems in dry climates. These systems can take several forms, including micro-catchments, contour ridges, check dams, and infiltration channels [6]. This, in turn, improved plant cover and cereal yields in arid regions [7]. A similar example may be seen in Morocco's semi-arid wadis, where built water-harvesting basins have served to both reduce the risk of flash floods and provide seasonal water sources for irrigation and grazing [8]. Recent studies [9] confirm the efficiency of using open-source data in hydrological modeling of data-poor areas. The results demonstrated the possibility of achieving a correlation coefficient (R^2) of up to 0.84 when calibrating models using remote sensing data, which supports this study's methodology of relying on Sentinel-2 data to estimate basin characteristics with high accuracy.

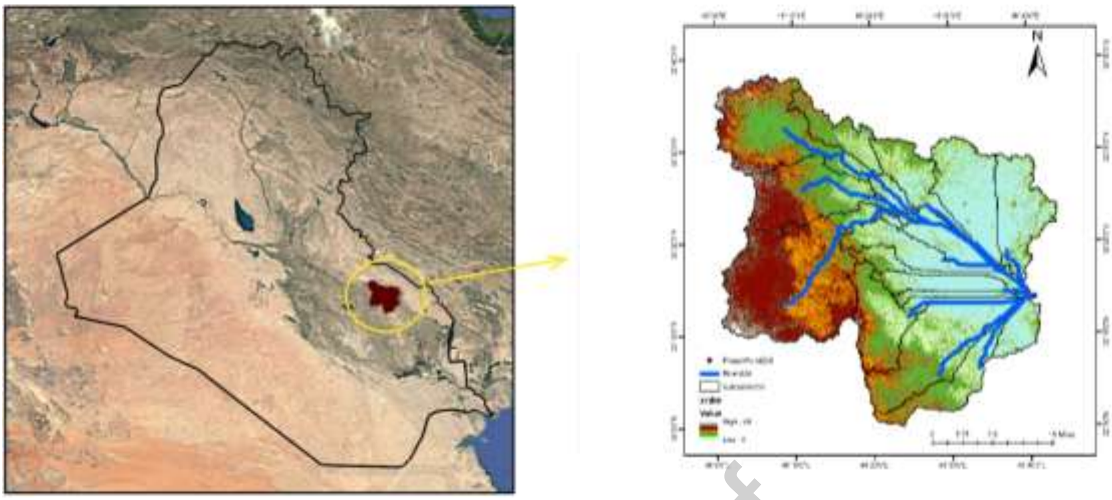
In conjunction with hydrological modelling, these tools allow planners to optimize structure location, evaluate post-harvest hydrological reactions, and assess potential harvestable quantities [10]. In this regard, integrated strategies for managing valleys in Egypt have been proposed, relying on remote sensing technologies and mathematical modeling to design a system that includes check and retention dams and artificial lakes, which contributes to reducing flood risks and transforming them into a sustainable water source for irrigation and replenishing groundwater reservoirs [11]. The broader concept of "flood as a

resource" is being adopted by MENA nations that are grappling with chronic water scarcity, and this approach is consistent with it [12].
The development of effective RWH infrastructure relies heavily on accurate hydrological and hydraulic modelling. As a result of its simplicity and reliance on land use and soil data, the Soil Conservation Service Curve Number (SCS-CN) method has become the norm for runoff estimation in ungauged or data-scarce dry basins [13]. It is also connected with GIS. The Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS) offers a versatile framework for modelling rainfall-runoff processes at the watershed scale with the use of synthetic or historical storm events, after the volume and timing of runoff have been determined [14]. Scientific results [15] have shown that integrating morphometric modelling with SCS-CN and HEC software provides high accuracy in predicting flood risks. The model successfully simulated flood events with a 92% match between simulated and observed flooded areas, thus enhancing confidence in using this technical integration for designing mitigation structures.
Yet infrastructure planning cannot be adequately accomplished with hydrological modelling on its own. The use of hydrodynamic models is essential for assessing flood levels, channel capacities, and flow dynamics. Using the two-dimensional (2D) module of the HEC-RAS (River Analysis System) model, which is especially useful in the flat, complicated terrains typical of southern Iraq, high-resolution simulations of overland flow, flood extent, depth, and velocity are possible [16, 17]. New features in HEC-RAS 6.x make it easy to connect with HEC-HMS outputs, which means you can simulate flooding from rainfall all the way to the end [18]. When it comes to forecasting flood behaviour in low-slope basins that have not been gauged, 2D HEC-RAS performs far better than 1D models, according to studies conducted in Kazakhstan [19] and India [20]. Regarding gently sloping terrain, studies by [21] indicated that the use of HEC-RAS 2D based on high-resolution DEM data enabled the identification of hazard zones with exceptional accuracy, achieving a success rate of approximately 88% in determining flood depths and runoff velocities compared to field measurements. This justifies our reliance on 2D modeling for the Ali Al-Gharbi area.
Both the flood risk assessment and the design of dual-purpose infrastructure that integrates water harvesting and flood prevention have been greatly improved by integrating HEC-HMS and HEC-RAS. In southern Iraq, an area that experiences high water stress and periodic floods, no integrated research has yet addressed the transformation of flash flood runoff into a regulated artificial river system. This is despite these improvements. There is an extreme absence of current infrastructure, and planning is still quite reactive [22].
Although recent research [23] has successfully reduced hydraulic uncertainties in flood maps by 15% through the integration of advanced GIS techniques, the need remains for innovative active diversion structures. This study proposes a hydraulically controlled channel designed not only to reduce peak flooding but also to restore an effective water supply in a chronically water-stressed environment by proposing utilizing rainwater for storage during rainy seasons or flood years and releasing it during the summer or dry season. As a result of this research, we propose constructing a channel to divert the collected water and release it into the Tigris River via a regulator.
The novelty of this study lies in its presentation of an integrated engineering framework that transcends mere 'flood risk characterization' to 'active structural management' through the development of a hydraulically controlled channel that functions as a linear reservoir system. Due to severe water scarcity and massive flooding in regions already struggling with chronic water stress, this study is critically needed in southern Iraq. Recent studies [21] demonstrated that the integrated methodology combining HEC-HMS and HEC-RAS 2D effectively simulates gently sloping terrain; it was selected for this task. The relationship between radial gates and peak flows can be accurately modelled in this way. Accordingly, this research aims to bridge the scientific and practical gap by constructing this channel in the Ali al-Gharbi district, serving as a viable model for managing non-conventional water resources and aligning with the Iraqi National Water Strategy (2023-2035).

2. Material and Methods

2.1. Study Area

The research area was chosen as the northern part of the Ali Al Gharbi district in Iraq, located between the northern and southern administrations of Maysan and Wasit. The basin is located between 32°00' and 32°38' North and 46°00' and 46°45' East. The watershed is 505.84 km long and covers an area of 2945.33 km² (see Fig. 1).



a) b)

Figure 1: Study area position, a) Iraqi map; b) Location of the study watershed

The heavy rainfall caused a tremendous rise in the amount of water that flowed from the Al-Kut barrage to the Maysan Governorate through the Al-Musandaq Escape. To deal with these risks, the officials are opening flood escapes along the river's edges to protect farmlands, starting in the Ali Al-Gharbi district and going all the way to Al-Amara city in the Maysan Governorate. However, two problems have arisen [25]. The first step is picking the right spot for the flood escape. The second factor is the extent of flooding and damage, which directly correlates with the size of the flooding. The damage happens when water drains into a huge pool [26].

2.2. Data Collection and Preparation

2.2.1. Rainfall Data

The Maysan Governorate has a dry to semi-arid climate, which means that summers are quite hot, winters are mild, and there is not much rain each year [27]. The meteorological data were obtained from the Ali Al-Gharbi station from the Iraqi Agrometeorological Center from March 1 to May 31, 2019, as shown in Fig.2. The significant floods of 2019, which this paper examines, illustrate the region's remarkable climatic variability. The Iraqi Ministry of Water Resources says that the research location gets about 103 mm of rain each year [28].

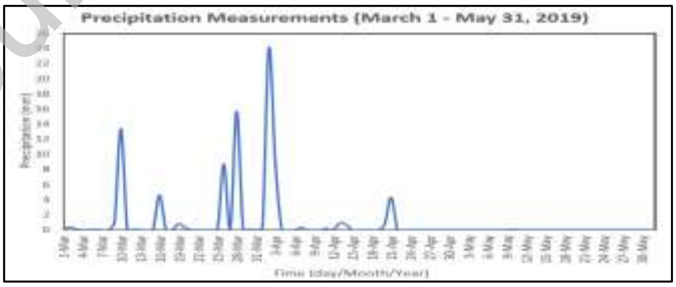


Figure 2: Daily rainfall data for Ali Al-Gharbi station from March to May 2019 [28]

To provide a deeper understanding of the extreme climatic conditions that accompanied this event, Figures 3 and 4 illustrate the daily variations in temperature and relative humidity.

Figure 3: Daily temperature data for Ali Al-Gharbi station from March to May 2019 [28]

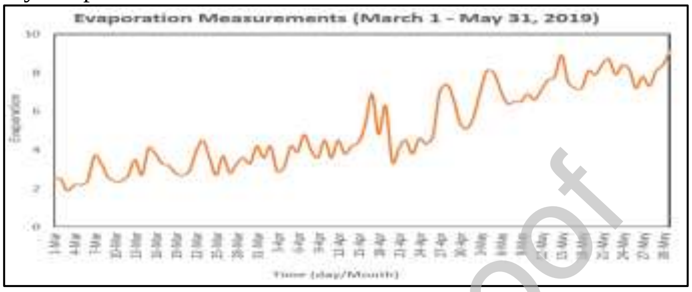


Figure 4: Daily evaporation data for Ali Al-Gharbi station from March to May 2019[28]

A gradual increase in temperature coincided with high specific humidity levels, creating an ideal environment for the formation of cumulonimbus clouds. This resulted in high-intensity rainfall over short periods, explaining the significant shift in the region's hydrological patterns and traditional IDF curves.

2.2.2. Topographic Data

The US Geological Survey (USGS) website (https://earthexplorer.usgs.gov/) has a Digital Elevation Model (DEM) that may be used to find the slope, gradient, drainage pattern, and basins. To commence the geometric correction, the Datum WGS 1984 (Zone 38) Universal Transverse Mercator (UTM) data processing systems were projected onto the DEM with a horizontal spatial resolution of 30 m. The Shuttle Radar Topography Mission's Digital Elevation Model (SRTM) was made public, mosaiced, and analyzed at a horizontal spatial resolution of 1 arc-second (30 meters) between March 1 and May 31, 2019, the time of the flood research [29].

2.3. Generation and Calculation of Curve Numbers

With the Arc Hydro tools and Hec-GeoHMS in ArcGIS (v 10.7.1), the CN is generated by integrating the DEM with land use/cover (LULC) data and utilizing the Sentinel-2 Land Cover Explorer (https://livingatlas.arcgis.com/landcoverexplorer) to produce a comprehensive watershed-wide land use map based on ESRI's 10-meter-resolution LULC cover data from the 2019-2020 flood research period. The "Reclassify" function of ArcGIS Spatial Analyst condensed the original classification into five categories: water, urban areas, forest, bare soil, and agriculture. Thereafter, the HWSD algorithm was employed to correlate and authenticate the soil texture data. The FAO Harmonized World Soil Database (HWSD v1.2) (https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en) supplied the soil data for the research area. The soil shapefile was clipped to the watershed boundary, reprojected to UTM Zone 38N, and converted to raster format using ArcGIS tools. By using HWSD, significant data regarding the soil attribute table can be obtained, including the fractions of clay, silt, sand, and gravel; pH; texture class; predominant soil group; and soil unit designation [30]. The USDA-SCS methodology [31] utilized these physical characteristics to categorize soils into Hydrologic Soil Groups (HSGs A–D) and the CN table. ArcGIS determines the CN by applying union processing properties to a certain land and hydrological soil group. The identification of CN is accomplished by the approach depicted in Fig. 3, as cited in [29].

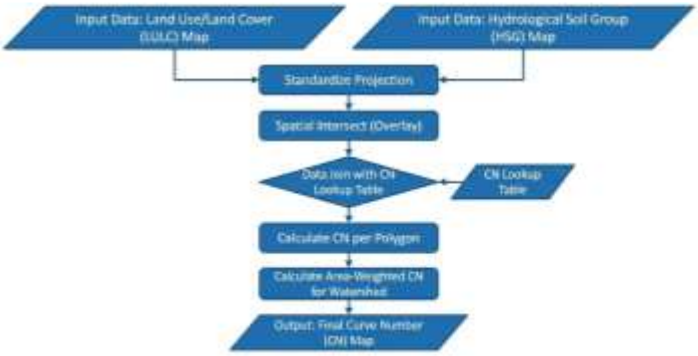


Figure 3: Flowchart diagram for the project

2.4. Hydrological Modelling Using HEC-HMS and Configuration

After determining the CN, the proportion of impervious surfaces, and the initial evaluation of the period of concentration, utilizing ArcGIS 10.7.1. It was also utilized to ascertain hydrologic attributes such as reaches, junctions, and outlet locations. The calculated parameters have been exported, encompassing the lengths, slopes, and elevations of the rivers, as a Basin Model file (BASIN.XML) for prompt utilization by HEC-HMS. HEC-HMS is a semi-distributed, physically based framework utilized to simulate rainfall-runoff dynamics using three months of continuous precipitation data. Part one of the model is the Basin Model, which shows the landscape and watershed; part two is the Meteorological Model, which shows the patterns and losses of precipitation; part three is the Time Series Manager; and part four is the Control Specifications.

The HEC-HMS Technical Reference Manual [14] states that the SCS-CN method was used to estimate losses, the SCS Unit Hydrograph was employed to transform excess precipitation into direct runoff [32,33], and the Muskingum routing technique was implemented to model channel flow. This method is particularly beneficial for basins such as Ali Al-Gharbi that are deficient in data.

2.5. Sensitivity Analysis in HEC-HMS

Within the HEC-HMS modelling system, a sensitivity analysis was done to determine how much of an effect important hydrologic factors had on simulated runoff response outputs. These outputs were then used as boundary conditions for the hydraulic simulations in HEC-RAS. CN, time of concentration (Tc), lag time, and Muskingum routing coefficients (K and X) were some of the most important inputs that the analysis looked at. Each parameter can be changed in a way that makes sense in the real world (±10% to ±30% of baseline values), while keeping all the other inputs the same [30]. The goal was not to recalibrate the model but to find out which parameters have the most influence on model output.

2.6. Hydraulic Modelling Using HEC-RAS 2D

The HEC-RAS at the Hydrologic Engineering Center models two-dimensional unsteady flow by solving the depth-averaged shallow water equations. These equations describe how fluids move when hydrostatic pressure is spread out, and there aren't any noticeable vertical accelerations compared to gravity [35].

Before it can run HEC-RAS 2D on your computer, you must first create a grid of grid cells that include height and roughness data for the area. Regular rectangular grids are typical; however, irregular geometries can be accommodated by using unstructured triangular pieces around the edges [36]. The typical grid resolution for floodplain studies ranges from 5 to 30 meters. The grid needs to be fast to compute and accurate to the terrain, depending on the complexity of the terrain and the flow characteristics you want to monitor [37]. Errors in the terrain have a direct impact on the simulated water surface levels and the extent of floods, which is why a high-accuracy DEM is very necessary [38]. As land cover and usage classes affect the distribution of Manning's n values, it can be inferred that flow resistance is present. These figures account for differences in vegetation, urbanisation, and loam, among other topographical characteristics [39].

Physical conditions must be in agreement with the predicted scenario in order for HEC-RAS to implement its border conditions, which impose hydraulic constraints at the domain boundaries. Inflow hydrographs, which show the flow of water over time, are commonly used to establish boundaries upstream. The downstream limitations are established by analyzing stage hydrographs, rating curves, or channel features to determine the normal/critical depth assumptions [36]. A combination of finite-difference and finite-volume approaches is used to block the transfer of mass and momentum between cells in the solution. The Courant-Friedrichs-Lewy (CFL) condition uses adaptive temporal stepping to keep the numerical stability:

$$\Delta t \leq \frac{\Delta x}{|u| + \sqrt{gh}} \qquad (1)$$

According to [3], the cell's properties are represented by Δx, the calculation's time step is u, and the flow velocity is g and h. Because of this restriction, the amount of time required to calculate is directly impacted by the need for smaller time steps to achieve quicker speeds or better spatial resolutions.

2.7. Model verification

Model verification combines quantitative and qualitative methods to evaluate the dependability of simulations. When there is a dearth of in situ discharge or stage data, it is useful to compare the extents of simulated floods to those in field observations or satellite photographs (like Sentinel-2) [3]. When assessing the degree of geographical agreement between actual and anticipated floods, categorical measures like the Critical Success Index (CSI), Hit Rate (HR), and False Alarm Ratio (FAR) are frequently used in the hydrological and remote sensing fields [36]. To put it into action, you'll need to use ArcGIS's Raster Calculator tool to convert the flood map retrieved from satellites and the 2D output from HEC-RAS's vector polygons into binary raster layers. In these layers, water pixels will be set to 255 and non-water pixels to 0. Next, we can calculate CSI by:

$$\mathrm{CSI} = \frac{\mathrm{Hits}}{\mathrm{Hits} + \mathrm{Misses} + \mathrm{False\ Alarms}} \qquad (2)$$

Cells that were correctly projected to be flooded are shown as hits, whereas cells that were seen but not modelled as misses, and cells that were modelled but not seen as false alarms are shown as misses. A CSI score of 0 indicates no talent, and a score of 1 indicates perfect agreement. It is common practice to accept values above 0.85 when doing practical flood modelling [40]. To overcome the limitations of one-dimensional methods, the two-dimensional modelling framework allows for continuous hydraulic representation over floodplains, independent of predefined cross-sections and flow routes. Flood risk assessment in geometrically complicated terrains can be improved with this capacity because it allows for the precise simulation of complex hydrodynamic processes, such as flow separation around barriers, overland routing across heterogeneous surfaces, and transitory storage in topographic depressions [41]. Typically, GIS settings are utilized to analyze hydraulic outputs spatially and create inundation maps. These maps display water depth, speed, and area, and they aid in integrated flood risk management and water harvesting planning [39].

2.8. Hydraulic Modeling of Excavated Diversion Channels for Rainwater Harvesting Using HEC-RAS

One major method of managing water resources in semi-arid regions is to combine hydraulic models with rainwater-gathering technology. Intentionally building diversion channels in places with inadequate natural drainage connectivity to perennial rivers is one engineering solution for increasing runoff conveyance and maximising water-collecting capacity. In order to study the geographical features and their vicinity to the Tigris River, researchers went on a field trip to the study area in the Ali Al-Gharbi District of the northern Maysan Governorate. As seen in Fig. 4, the drone used during the tour actually captured aerial photographs.

Figure 4: The research region's terrain (February 2026)

In order to analyse unstable 2D flow, a comprehensive hydraulic modelling framework was built using HEC-RAS version 6.0. As demonstrated in Figure 5, ArcGIS was used to analyse a high-resolution DEM having a spatial resolution of 30 m. The results along the proposed channel alignment include watershed borders, stream networks, and cross-sectional geometries generated at 50 m intervals [42].

a) b)

Figure 5: a) Image from Google Earth, b) cross-sectional geometry for the proposed channel

The results of a comprehensive topographical cross-section profile generated by the Global Mapper program are displayed in Fig. 6, and this is the value used to calculate the channel's bed slope of 0.0017. The chosen outlet points of the study region and the adjacent bank of the Tigris River are both covered by this profile

Figure 6: Detailed terrain cross-section profile from the watershed outlet to the Tigris River, generated via Global Mapper.

Fig. 7 shows where the watershed's outlet point is and how far away it is from the Tigris River.

Figure 7: The watershed region in Ali Al-Gharbi district, Maysan governate, Iraq

HEC-RAS Mapper's terrain modification has been used to replicate channel excavation via high topographic features that naturally separate the watershed from the river system next to it [43]. To help with hydraulic parameterization, soil hydraulic qualities were put into groups based on the USDA Hydrologic Soil Groups.

3. Results

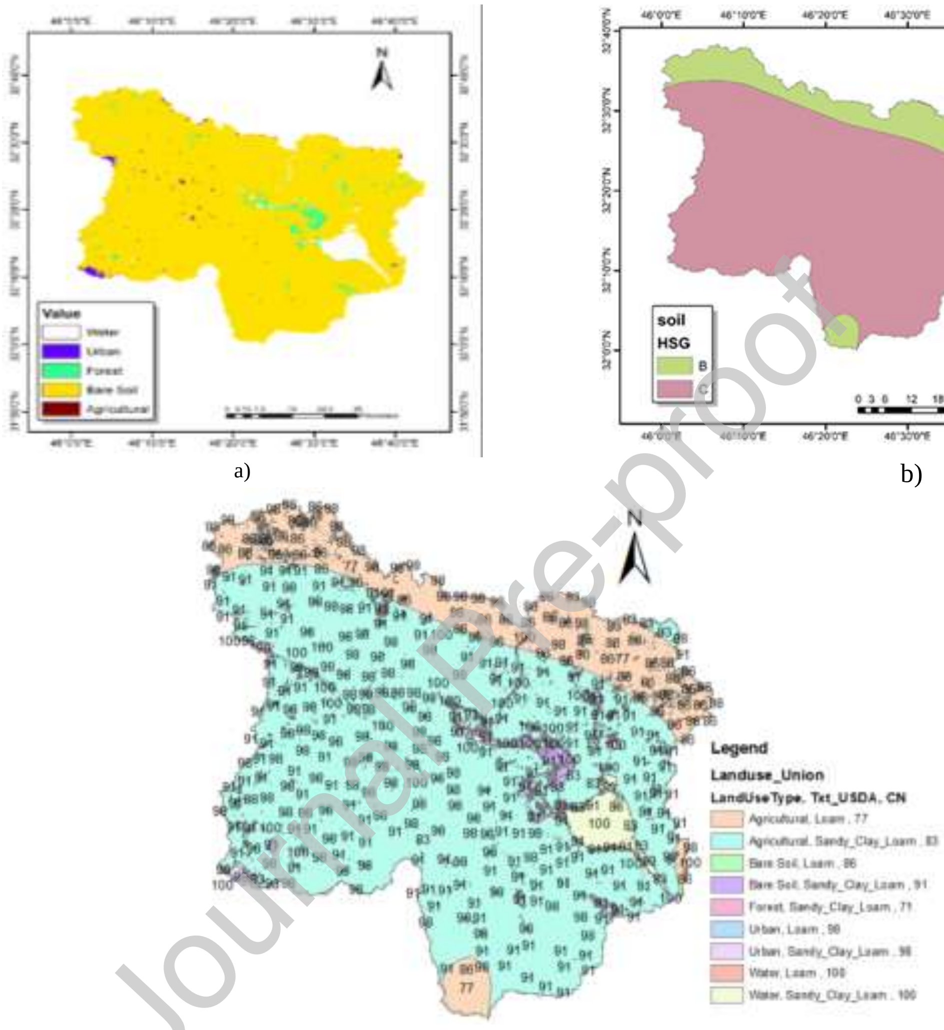
3.1. Land Use, Soil Characteristics, and Curve Number Derivation

The characteristics of the soil significantly influence the hydrology of a watershed, with the predominant types in the research region being groups B (3.8–7.6 mm/hr infiltration) and C (1.3–3.8 mm/hr), as categorized by the USDA. The groups exhibited sandy clay loam (91.56%) and loam (8.44%) textures. These soils are moderately restrictive, and with 94.05% of the land area used for crops, rangelands, and inundated vegetation, they exhibit poor water absorption, increasing the likelihood of runoff. These findings were further supported by the same region, as mentioned in [44]. Table 1 show the LULC details.

Table 1: LULC percentages

No.	Type	Percentage (%)
1	Agricultural	94.05%
2	Water	2.64%
3	Bare Soil	2.54%
4	Urban	0.77%
5	Forest	0.01%

A wide range of CN values (71–100) demonstrated the interplay between various soil types and land cover types. There were two primary values displayed on the CN map: 77 for arable land (which made up 94.05% of the basin) and 100 for bodies of water (which made up 2.64% of the basin) as shown in Fig. 8. When the CN value is high, water has a hard time flowing across urban, saturated, or otherwise irregular surfaces. A rapid increase in runoff generation is the primary goal of the watershed's hydrological response due to the absence of forest cover, which is typically associated with low CN values. This is an important factor to think about when designing a rainwater harvesting system in this semi-arid area.



a) b) c)

Figure 8:CN map from a) LULC; b) soil type; c) combination of LULC, soil type and CN

3.2. HEC- HMs Modelling and Sensitivity Analysis

Hydrological simulations conducted using the HEC-HMS model produced a peak discharge of 489.7 m³/s at the basin outlet, and the total surface runoff amounted to 144.4 million m³ and a peak flow of 489.7 m³/s. Fig. 9 shows HEC-HMS watershed subbasins. The results represent the subbasins' hydrological response to meteorological data acquired throughout the study period. These amounts are strategically important because the area is arid and has few water resources.

Figure 9: HEC-HMS watershed subbasins

A sensitivity analysis was performed on essential HEC-HMS parameters to assess their influence on hydrological response. This test omitted CN, although it is widely recognized as a significant factor in calculating runoff. The investigated parameters—impervious %, duration of concentration (Tc), initial abstraction (Ia), Muskingum K, and Muskingum X—have varying degrees of impact, as shown in Table2.

Table 2 Summary of Parameter Sensitivity in HEC-HMS

Parameter/Variable	Functional Definition	Sensitivity Level	Direction of Impact on Outputs	Range/Quantitative Note	Hydrological Interpretation
Initial Abstraction (Ia)	Water retention by ground surface before runoff begins	Low	Minor percentage changes	±32% to 48% of default values	Low initial values do not negatively impact; changes dynamically with simulation time
Impervious Surface Ratio	Indicator of urban expansion and built-up area extent	Low	Limited impact regardless of level	Depends on accuracy of default values	Model relies on other parameters to produce realistic results
Time of Concentration (Tc)	Time duration for water to flow from the most remote point to the outlet	High	Inverse relationship: Shorter Tc → Higher runoff; Longer Tc → Lower runoff	Significant changes in peak discharge and volume	Shorter supply periods generate higher runoff volumes and vice versa
Muskingum Coefficients (K, X)	Control the timing and velocity of water flow through river channels	High	Direct impact on timing and magnitude of peak flow	Change >13% clearly affects results	Directly affect the velocity of hydraulic wave in the channel

CN was not included in the sensitivity analysis because it is a fixed GIS-derived input based on the type of soil and land use, not a parameter that can be adjusted. Parameters with a high sensitivity (Time of Concentration, Muskingum K and X) were calibrated first because of the impact they had on peak discharge and hydrograph timing, while parameters with a low sensitivity (Initial Abstraction within 0.1S-0.3S, Impervious Surface Ratio) were only adjusted after the fact. By avoiding overfitting to seemingly insignificant changes in parameters, this targeted approach guarantees calibration based on physical data.

3.3. HEC-RAS Model Structuring for Water Resource Estimation

The hydraulic simulation used a flow hydrograph as a boundary condition and flow that changed over time from March 1 to May 31, 2019. This process has been done by making the DEM in RAS Mapper. In RAS Mapper, the shapefile of the reaches was imported from HEC-HMS, and the cross-sections were created and modified to match the shapes and areas of the sections in reality. (see Fig. 10).

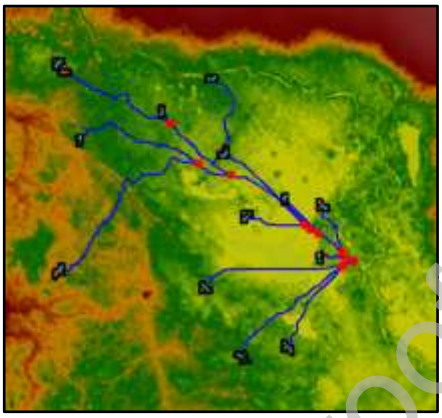


Figure 10: Created the Ras Mapper terrain, river reaches, and cross sections

Collecting elevation data at each cross-section made it feasible to accurately figure out how deep the floods were in the study area. This task was done using a two-dimensional (2D) modelling method, and the size of the computerized grid was chosen to find a good compromise between the speed of the HEC-RAS run and accuracy.

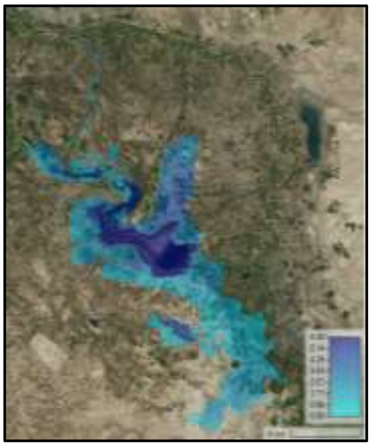
The hydraulic model began with NASA's Earth Observing System LULC data integrated into RAS Mapper as a geographic layer. The land use map used to give hydraulic roughness characteristics was created via raster data processing and sorting. Each pixel or grid cell in this layer represents a land cover and needs the correct Manning's roughness coefficient to predict water flow. The land cover data only reveals how different surfaces are distributed, not the hydraulic features the model needs. Thus, a reference database showing Manning's N value for each land use type was needed. This is given in Table 3 below.

Table 3 Manning coefficient values

ID	Name	Mannings N
2	Developed - High Intensity	0.13
4	Developed - Low Intensity	0.04
5	Developed - Open Space	0.15
1/0	No Data / Unclassified	0.15
11	Mixed Forest	0.2
7	Pasture-Hay	0.28
8	Grassland-Herbaceous	0.24

3.4. HEC-RAS Model Calibration and Validation to Ensure Accuracy of Storage Capacity Estimates

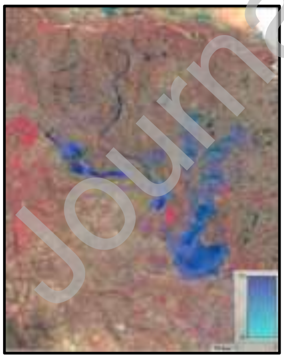
The CSI was employed to juxtapose the flood map results with the actual satellite image captured on April 2, 2019 (https://earthmap.org/compare.html?geoJson/), as illustrated in Fig. 11. When evaluated against flood extents ascertained by satellite during the previous storm, the model performed exceptionally well, with a CSI of 82.43%, HR was 93.89%, and FAR was 12.89%. The model was validated by adding these verified and corrected parameters into Flood, which occurred previously. This ensured the model's trustworthiness after calibration by adjusting some critical hydrological parameters based on the previous sensitivity analysis, resulting in accurate convergence between simulation and actual conditions.


(a)

(b)

Figure 11: (a): hydraulic modelling of flood water depth using HEC-RAS (b): actual satellite image at the same time (April 2, 2019)

The model was validated by including these verified and corrected parameters in the flood on November 27, 2018 (https://earthobservatory.nasa.gov/images/144308/floods-swamp-iraq) as shown in Fig. 12, and after the calibration steps were complete, the model's dependability was ensured by altering some of the most sensitive hydrological parameters in accordance with the sensitivity analysis and achieving precise convergence. Comparing simulated and satellite-derived flooding, CSI = 89.0%, HR = 98.2%, and FAR = 9.5% were discovered.




(a) **(b)**

Figure 12: a) Hydraulic modelling flood water depth using HEC-RAS, 2D, b) actual satellite image at the same time (November 27, 2018)

To enhance the scientific reliability of the aforementioned results, the modeling outputs in this study were compared with recent global studies conducted in basins with similar characteristics. The model validation accuracy in our study (CSI = 89.0%) is consistent with the results reported by [15] and [21], who achieved concordance rates ranging from 88% to 92% using HEC-HMS and HEC-RAS 2D integration. Furthermore, the calculated surface runoff volume (144.4 million m³) and peak discharge (489.7 m³/s) reflect a logical hydrological response consistent with the findings of [9] in semi-arid environments, where their results showed that basins with high CN values generate sharp peak flows and a rapid response. Additionally, the study by [45] confirms this. Reliance on morphometric and spatial analysis is the most accurate method for estimating runoff risks in unmeasured basins, which supports the validity of the figures presented and confirms the accuracy of storage capacity estimates before proceeding to canal design.

3.5. Technical Design Specifications and Hydraulic Performance

Sustainable development must prioritise the adoption of resilient water management methods in light of the growing water scarcity and the rising frequency of droughts. This idea presents a methodical strategy for collecting water to guarantee a steady supply for both agricultural and household needs. Building a water-moving canal with a sluice gate and a direct connection to the Tigris River is the main objective of this project.

The ability to precisely control water flow and to store and reroute water during peak flow periods for usage during drought circumstances is made possible by this regulatory structure. Building this link is crucial to the project's goal of making the most of the Tigris River's assets. The river's resources become more valuable, durable, and resistant to climate change as a result of this.

A comprehensive survey was carried out in the study area to confirm the method's practical feasibility. The true course of the river was located and studied during the site visit. Important topographical and hydrological characteristics could be located in this way. We meticulously tracked and documented any potential obstacles, including land use restrictions, accessibility issues, and existing infrastructure. Assuming meticulous engineering design and consideration of environmental concerns, the preliminary analysis also demonstrated that the proposed link between the harvesting canal and the Tigris River could technically be constructed. To go from project planning to detailed design and implementation, these field observations are crucial.

Meanwhile, Fig. 13 displays the proposed channel’s position, that extend from the Watershed Outlet point to where it meets the Tigris River.

Figure 13: illustrates the location of the proposed channel confluence with the Tigris River

This introduction presents the basic idea and strategic goals that will guide the channel's technology design. HEC-HMS simulations and HEC-RAS hydraulic modelling yielded the following findings for the conveyance system from the watershed outlet to the river destination over a distance of 1.759 km, as shown in Fig. 14:

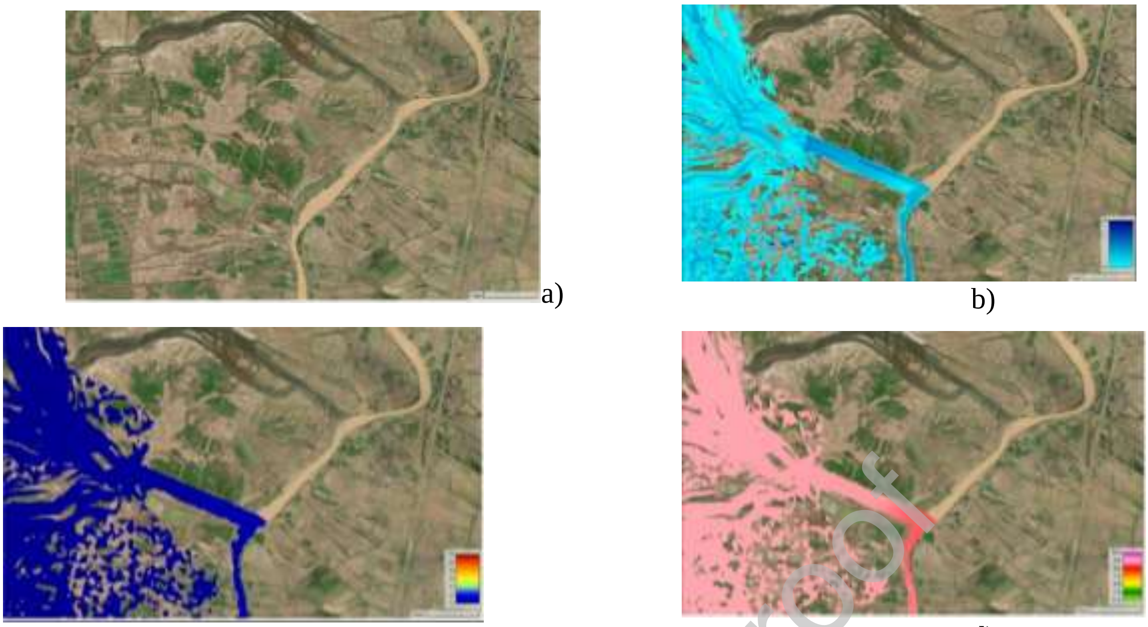


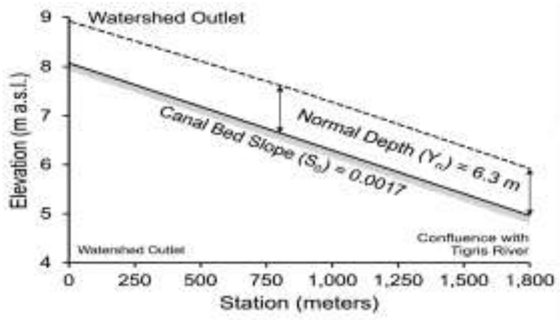
Figure 14: Flood simulation using HEC-RAS software, where a) is the location of the proposed channel before the flood, b) is the flood depth (m), c is the flood velocity (m3/s), and c) is the water sea elevation (m)

- **Channel Geometry Specifications**

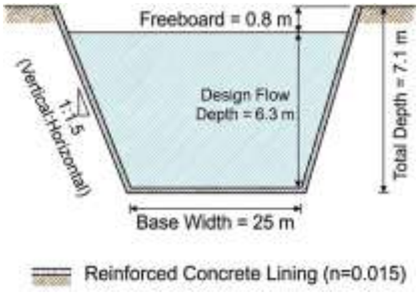
According to the soil texture analysis, the discharge point soil is sandy clay loam. Following the roughness coefficient guidelines in [38], the terminal regulator structure is lined with reinforced concrete (Manning's n = 0.015) to protect the gate foundation and ensure precise flow control with a smooth hydraulic boundary. To achieve a peak discharge of 489.7 m^3/s with the lowest excavation and land acquisition expenses, economic optimization research advises a 25 m channel bed width. A 1:1.5 (H: V) side slope ratio is ideal for wet soil stability [38]. The average depth, or design flow depth, was determined to be 6.3 meters by the HEC-RAS steady flow analysis, which utilized Manning's equation. H is 7.1 meters when hydraulic uncertainty, wave movement, and wind setting are taken into consideration.

- **Hydraulic Performance Parameters**

An elevation decline from 8.0 m to 5.0 m over a channel length of 1.759 km was indicated by a high-resolution DEM analysis, which was used to compute a design bed slope of 0.0017 [38]. As a result, less digging is needed while gravity flow is optimized. Following the guidelines laid out by the USBR Concrete Lining Standards and acceptable velocity tables, the design flow velocity can be anywhere from 2.0 to 2.5 m/s. While silt deposition and plant growth are restricted at 2.0 m/s, the concrete lining is protected against erosion and cavitation at 2.5 m/s [38]. The subcritical flow regime (Froude Number $Fr < 1$) must be maintained throughout the channel reach to keep the flow parameters consistent and controlled, prevent hydraulic jumps in the conveyance system, and permit successful gate operation and flow measurements through HEC-RAS profile computations, as shown in Fig. 15.



a) Longitudinal Profile of proposed canal



b) Cross-Section of typical canal

Figure 15: Technical Specifications for the Proposed Canal

- **Terminal Regulator Structure**

Due to their excellent sealing capabilities, a record of reliable flood control, and accurate flow regulation, radial gates are suitable for large discharge applications [46]. All or some of the four gates can be opened at will, providing operational flexibility; during maintenance, there is redundancy; modular flow control is possible; and risk can be distributed over numerous independent units based on hydraulic distribution analysis. To ensure structural viability and a head loss of less than 0.3 m, the 5.0 m (width) × 4.5 m (height) dimensions can allow 122.4 m^3/s per gate ($Q_{aeak}/4$), according to the HEC-RAS gate flow equations and orifice flow theory. The depth of the design flows up with the height of the gate [38]. Construct three intermediate piers made of reinforced concrete, each 1.5 meters wide. Fig. 16 shows a schematic that is not scaled.

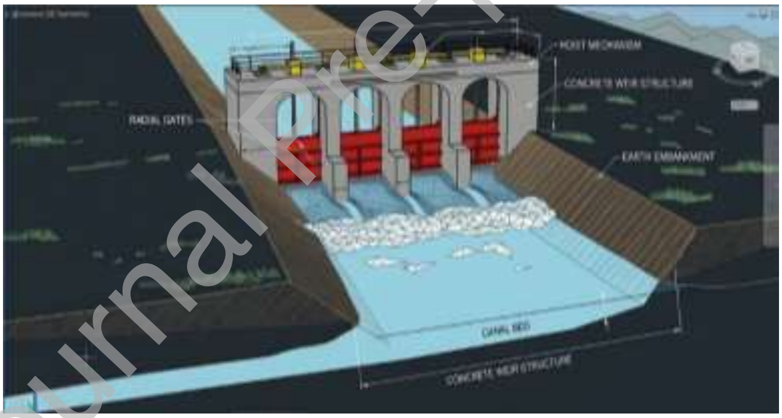


Figure 16: A diagram of the outlet-excavated canal with gates to the Tigris River

4. Discussion

A comprehensive framework for hydrological and hydraulic modelling of a semi-arid watershed in Iraq was successfully constructed in this study using ArcGIS, HEC-HMS, and HEC-RAS. The definition of a 2,945.33 km² basin, along with a spatial analysis of soil and land use characteristics, created a strong base for modelling rainfall-runoff processes and flood dynamics. The fact that sandy clay loam (68.32%) and loam (31.68%) soils are the most common and that a lot of land is used for farming (94.05%) means that the CN values range from 71 to 100, which means that runoff can happen at a moderate to extremely high pace. This research shows that the watershed is prone to flash flooding with heavy rain, which is an important factor to think about when managing risk in areas with little data.

The SCS-CN rainfall-runoff method in HEC-HMS did a good job of simulating how the hydrology of a basin would respond, with the total surface runoff amounting to 144.4 million m³ for the modelled period. Sensitivity analysis showed that the CN and Initial Abstraction (Ia) had the biggest effect on runoff volume, especially when the flow was high. Muskingum coefficients (K, X), lag time, impervious area %, and time of concentration (Tc) were less influential. Prioritising model calibration in additional ungauged basins can be informed by this order of how parameters impact each other. When tested, the results show that the model accurately approximates the patterns of actual floods, and an evaluation of flood risk in areas with few ground-based monitoring systems can benefit from this combination of sensitivity and precision. There is a place for improvement by incorporating additional topographic data or using ensemble modelling techniques.

The proposed 1.759 km diversion canal utilizes a gravity-fed system, providing an effective hydraulic method for converting potential flooding into a sustainable water resource. The design eliminates the need for pumping stations and provides a peak flow of up to 489.7 m^3/s for the Tigris River, significantly reducing energy consumption and operational expenses. The bottom slope is 0.0017 m (a drop from 8.0 m to 5.0 m). A flow regulator with four radial gates at the downstream end safeguards the neighbouring areas and the canal by carefully regulating flow and preventing backflow floods during high river levels. Transforming the canal into a 'linear reservoir' increases operational flexibility by allowing for temporary water storage during peak periods and bridging the gap between intermittent rainfall and seasonal irrigation requirements. This method is appropriate for semi-arid environments, as it reduces evaporation losses compared to big reservoirs while providing a rapid water supply. Furthermore, selective lining is a cost-effective approach for minimising building costs while maintaining structural integrity. To ensure structural integrity, this technique calls for leaving some earthen areas unlined in the canal's main section and repairing them with concrete at the outflow.

Consistent with current scientific thinking, this study's findings highlight the importance of mathematical modelling and geomorphological features in water management. When we compare our results to those of [45], we see that morphometric and spatial analysis is the best method for discovering the best channel route in unmeasured basins by identifying places that could have substantial runoff, as was shown in the Ali Al-Gharbi Basin. In addition, our findings support the idea that structural solutions (like channels) and flow control are the most effective ways to drastically decrease flood volume, especially in places where rainfall patterns vary sharply. This is in line with previous research [47], which used PCSWMM modelling for urban flood management. This means that the 'link channel' design that has been suggested is an eco-friendly option that satisfies modern global norms.

5. Conclusion

The results of this study show that semi-arid areas can greatly benefit from integrated hydrological-hydraulic modelling and focused infrastructure designs when it comes to managing their water resources. The results show that rainwater harvesting systems do more than just reduce the likelihood of flooding; they also recharge aquifers, guarantee irrigation supplies, and enhance environmental flows downstream even when drought is present. In order to guarantee adaptive management resilience in the face of growing climatic variability, the study stresses that these projects can only be technically successful with supportive institutional frameworks, active community involvement, and persistent oversight.

6. Limitations and Future Research

To improve the precision and thoroughness of the findings, future research should address the following limitations, notwithstanding the study's contributions:

- Simulation timeframe: Future research should broaden the modelling period to incorporate interannual climatic variability, since the present simulation is only valid for certain time periods.
- The changing climate: Incorporating future climate change scenarios and projections allows us to investigate how these changes could affect infrastructure design and flood patterns.
- Pragmatically speaking: To make sure the suggested water harvesting buildings are realistic, future studies need to examine their socioeconomic feasibility more thoroughly.
- Condition of the water supply: In order to perform thorough evaluations of the transportation of pollutants during peak floods, it is crucial to include water quality modelling modules.
- Insufficient data: Better model calibration will result from more precise field data, the study did a great job of identifying areas with limited data.

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CRediT authorship contribution statement

Mays Ibrahim Alsaidi: Conceptualization, methodology, software, formal analysis, investigation, data curation, writing – original draft.

Ahmed Naseh Ahmed Hamdan: Supervision, validation, project administration.

Dina Ali Yaseen: Supervision, validation, project administration.

Declaration of competing interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request

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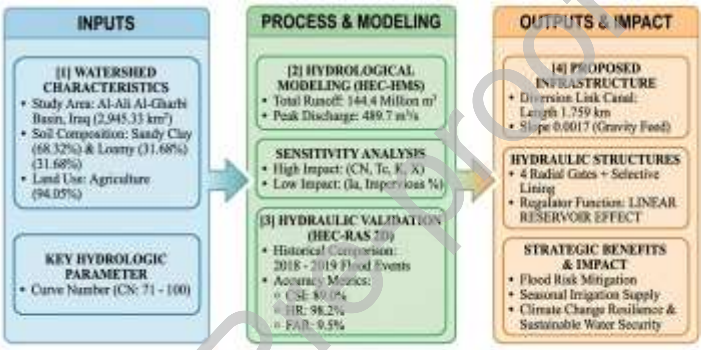
Graphical Abstract: Flowchart of the Integrated Hydrological-Hydraulic Framework



Declaration of Interest Statement

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.