RESEARCH ARTICLE-CIVIL ENGINEERING

Feasibility Assessment and Environmental Benefits of Developing Rainwater Retention Ponds Across Najran Valley

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Abstract

Water resources in arid and semi-arid regions are constrained by several critical problems, including scarcity of water resources and extensive use of groundwater. Climate change and population growth will certainly result in a decline in water tables and degradation of groundwater quality. The purpose of this study is to create rainwater retention ponds in the Najran Valley located at the southern border of Saudi Arabia. Over the past decade, various researchers have reported a sharp decrease in the availability of water in the area. In addition to urban sprawl, excessive groundwater extraction is the primary cause of the decrease. Even though the valley receives a sufficient amount of rainfall throughout the year, there is no adequate rainwater management system in place. As a result of this combined water management issue, the authorities are seeking additional water storage options in addition to the Najran dam reservoir. To evaluate the flood characteristics of the region, an extensive GIS-based hydrological study is conducted. To estimate flood volumes, the critical flood-prone areas are identified and their catchments are calculated. To store rainwater generated by these catchments during rainfall events, a variety of suitable locations have been proposed for retention ponds. The construction of retention ponds would have numerous environmental benefits in addition to solving the problem of water scarcity. As a result of the study, the authorities will be able to implement a management strategy that maximizes the use of the region's water resources.

Keywords Flood risk assessment · Retention ponds · Surface runoff · Hydrological modeling · GIS

Abbreviations

CN	Curve number
DEM	Digital elevation model
DTM	Digital terrain model
DW	Diffusion wave
IDF	Water distribution network
IWRM	Integrated water resources Mgmt.
KW	Kinematic wave
SCS	Soil conservation service
SRTM	Shuttle radar topography mission
SWE	Shallow water equations
d	Water depth for SWE
f	Coriolis parameter for SWE
h	Water level for SWE
I_a	Initial abstraction
L	Length of drainage basin (km)
P	Accumulated depth of rainfall (mm)
q	Source flow for SWE
R	Depth of runoff (mm)
S	Function of CN value (mm)
S_B	Slope of drainage basin (m/m)
S_o	Bed slope variation for SWE
T_C	Time of concentration (min.)
u, v	Average velocities of flow

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1 Introduction

Water is the most vital resource of life. Although water scarcity is becoming a widespread risk, flooding has been a catastrophic problem facing humanity since ever. Since major segments of human societies settle near rivers and streams as water is required for life but on the other hand these areas are flood-prone, the need for flood modeling to approach safe protection and water management is essential. One of such flood risk areas of the Kingdom of Saudi Arabia is Najran region which is located in the southwest of the country and extends between longitude 43° 47' E and latitude 17° 19' N. The topography of this region varies between relatively flat areas to the east and mountainous areas along the southern and northwestern borders. Although the topography of this region extends around large numbers of valleys, it does not have a comprehensive flood protection or rainwater harvesting strategy available. Also, there is a lack of hydrology assessments and urban stormwater master plans for the area [1].

In the recent past, a lot of issues related to water resources in Najran have been reported. Although Najran is being supplied with water from one of the huge dams of Saudi Arabia, the requirement of the population exceeds the water storage capacity of the Najran Dam [2]. The water resources are being depleted day by day. The main reason for this water depletion is reported to be excessive groundwater extraction, abrupt urban development, and the lack of water management as well [3–5]. Although the region gets a sufficient amount of rainfall, the excessive amount of water goes down the Najran River as waste, because there are no water storage facilities. If such facilities are created and an additional amount of water can be stored other than the Najran Dam reservoir, the problem of water resources in Najran can be resolved to a large extent.

There are several types of rainwater harvesting systems used in the world which can be categorized into three categories according to their scale and size; household-scale harvesting systems [6]. First on the list are household harvesting systems, which include rooftops, green roofs, and surface area harvesting systems. In this system, rainwater is collected and stored in a small tank so that it can be directly used for domestic activities such as irrigation and flushing [7]. There are several advantages to these systems, including their relatively low cost and ease of installation. However, Saudi Arabian landowners are less motivated to install such a system due to the dry climate, as an adequate quantity of rainwater cannot be harvested and cannot satisfy the watering needs of a household. The second category is neighborhood-scale systems, such as cistern systems, trenches, permeable pavements, driveways, or patios. These systems are more expensive than the first ones and require a higher level of maintenance and operation, making them inapplicable to Saudi Arabian neighborhoods. The third type is the city-scale harvesting systems, which include retention ponds and dams. In arid climates where seasonal flooding is common, such as in the Najran region, this system can be an effective solution. Stormwater management, irrigation, and groundwater recharge are necessary elements of constructing retention ponds. Further, it can play an important role in achieving integrated water resources management (IWRM) in Najran City [8].

1.1 Urban Flood Modeling Methodologies

Since the analysis and design related to flood risk assessment and hydrological studies rely heavily on water flow modeling, the following section shall discuss various parameters involved in the process including overland flow mathematical approaches, common hydrodynamic approximations, and model type classifications found in the literature. Various approaches are presently available for flood modeling, characterized by their dimensionality or how they link different dimensionalities. The flood modeling application can be sufficiently covered using 1D, 1D + , 1D/2D, and 2D methodologies.

1D models are based on integrating the Navier–Stokes equations over the cross-sectional area of flow, which drives what is so-called the Saint–Venant or shallow water equations (SWE), as shown in Fig. 1a. This set of equations can be used in the full hydrodynamic form or by implementing an approximation of either kinematic wave (KW) or diffusive wave (DW). Due to the derivation assumptions of Saint–Venant equations, they can only be implemented where water direction movement is aligned to the center line of the river channel [9]. However, their use is now extended to model flow in compound channels but with two limitations, namely that: 1) floodplain flow is assumed to be in one direction parallel to the main channel, which often is not the case, and 2) in situations where large variations in velocity magnitude exist across the floodplain, the predicted cross-sectional averaged velocity has a less tangible physical meaning [10].

1D + models involve a 1D approach to model the main channel flow only, and floodplains are modeled as storage cells defined through a water level and volume relationship. The flow exchange between both channel flow and storage cell is modeled using discharge relationships which are often called spill units or spill links. This also can be used to link storage cells to each other. The water level in each storage cell is computed using volume conservation. However, no momentum conservation is included in flood plains [11].

On the other hand, 2D models are a simplified version of the 2D shallow water equations (SWE) resulting in the kinematic wave (KW) and diffusion wave (DW) approximations. Moreover, they implement a structured grid digital elevation model (DEM) and 1D simplified representation of
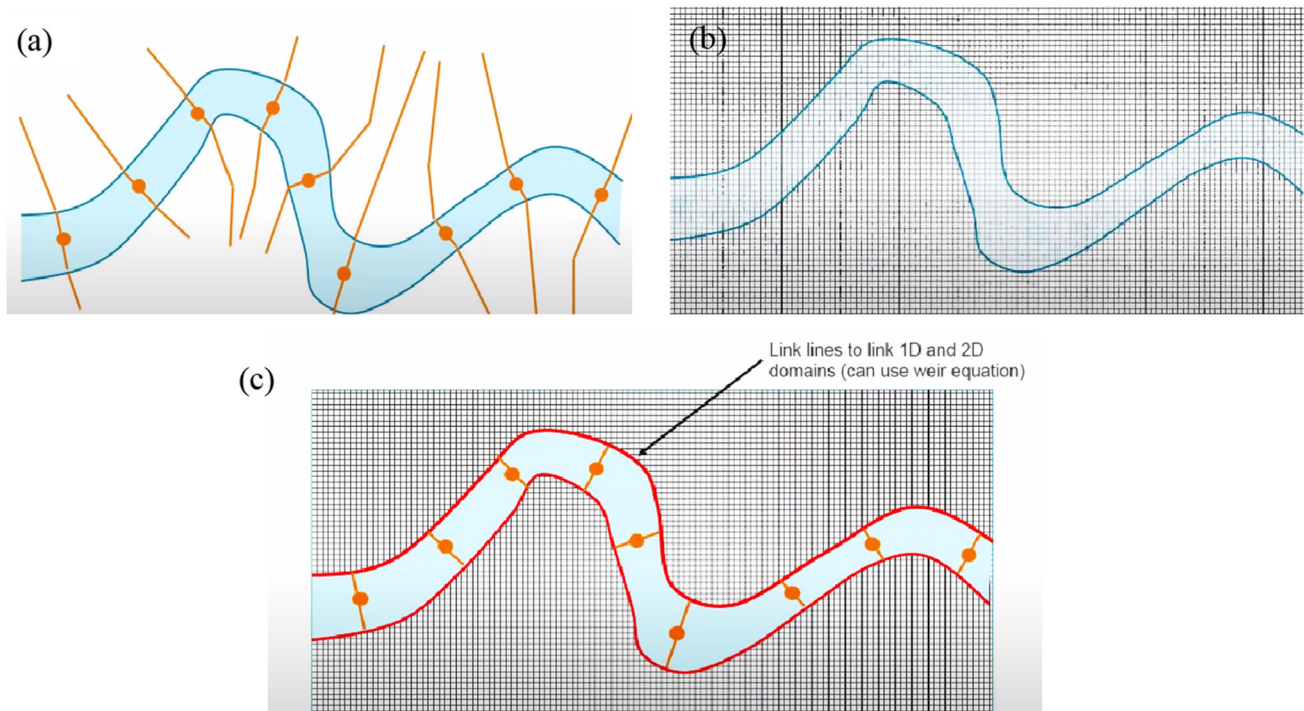
Fig. 1 Flood modeling approaches: **a** 1D Cross-sectional, **b** 2D Grid, and **c** Linked 1D/2D

the flow between the raster DEM cells, as shown in Fig. 1b. Similar to the 1D + approach, no momentum conservation is included in the 2D floodplain simulation. Later, 2D models implement the full hydrodynamic equations resulting in momentum conservation. Néelz and Pender [10] presented a comparison of different modeling approaches and expected generated outputs along with possible applications. They also showed a sample of commonly used modeling packages with expected computational time overhead.

1D and 1D + models are commonly used for sewer and river analysis. According to Leandro et al. [12], when the overland flow paths can be identified, 1D surface models are robust with a major computational time saving. Another composite concept of 1D/2D modeling also exists, where the urban surface is treated as a network of open channels and ponds as DEM including the topographical details, while the drainage network, the pipes, and the streets are modeled with a set of 1D equations, as shown in Fig. 1c. This concept portrays the real flood inundation extent and velocity. This modeling approach is a computational time saver and produces comparative results to a full 2D system.

On the other hand, various wave models are also found in the literature used by many researchers based on the characteristics of their scenario. A dynamic wave model includes all terms of the reduced Saint–Venant equations allowing for the modeling of full transient phenomenon. The full hydrodynamic models are commonly used for 1D modeling; however, only a few 2D models apply the full equation. The main

reason is due to the significant computational time requirements, though it is essential to apply the full hydrodynamic equations in some applications, e.g., dam break analysis and complex topography [9].

Then, a non-convective acceleration wave model drops the convective acceleration term in the Saint–Venant equations. Such models have recently been used in urban flood modeling due to the assumption that flood inundation is a slow, shallow phenomenon; hence, the convective acceleration term can be assumed to be small compared to other terms. The convective acceleration terms are described as the reason for the oscillatory behavior of the equations [13]. Accordingly, the non-convective acceleration models benefit from an increase in stability while keeping the ability to propagate along two characteristic directions. Along similar lines, the non-local acceleration wave model drops the local acceleration term. This approximation is preferable for flows where inertia terms are dominant [14].

One of the most commonly used wave models is the diffusive wave model. This type of model drops both the local and the convective acceleration terms and can only propagate in one set of characteristics in the same direction of the flow; hence, it can be reduced to a single convective-diffusion equation. The model can produce both the backwater effect and transport of pollutants due to its mechanism of wave translation and diffusion. It is recommended for low Froude number conditions [15]. Similarly, a kinematic wave model considers only the pressure and gravity terms. In such a case, both the

pressure and acceleration terms become small compared to bed and friction slope terms, and friction and bed slopes are approximately in balance. The model cannot produce backwater effects as the wave can only propagate downstream [14].

1.2 Related Studies in Various Regions and Saudi Arabia

There is an increase in the use of retention ponds in arid regions including Saudi Arabia as a method for managing stormwater, preventing floods, and harvesting valuable water resources. There has been a significant increase in the number of scientific papers published in the last few years (2017–2023) that explore the performance and design considerations for retention ponds in various regions of the world. Although there is a large amount of published work available on scientific platforms, a few major works are being presented here.

Staccione et al. performed a feasibility study to assess the creation of retention ponds for agriculture in northern Italy. They found sufficient potential for water storage by using this method that may enhance the agricultural production of the area [16]. In a recent study, Birkinshaw and Krivtsov studied the effect of retention ponds on the flood characteristics in the Braid Burn catchment in Scotland [17]. They found a sufficient reduction in the flood volumes due to the construction of retention basins. In a similar study performed for the Odaw river basin, Ghana, and hilly areas of Hungary and Slovenia, significant comparative results were obtained [18, 19]. Table 1 presents a summary of related works that focus on the development and optimization of retention ponds in various regions of Saudi Arabia.

In Saudi Arabia, retention ponds are a promising way to manage stormwater to combat flooding, water scarcity, and pollution. However, ensuring optimal performance and minimizing environmental impacts requires careful design, implementation, and maintenance. For long-term sustainability, design guidelines need to be refined, pond configurations must be optimized for specific needs, and management strategies must be developed.

2 Methodology of Research and Analysis Options

This section presents the methods that are to be used in the hydrological analysis of the watershed catchments of the Najran region, as well as defines the hydrological parameters that are to be used in the models. For the majority of the urbanized area, a 2D or 1D/2D hydrodynamic model is implemented using the digital terrain models (DTM). The

drainage basin response is calculated for the design rainfall values changing spatially and temporally to achieve the best possible representation of water runoff processes in the drainage basins and presents the results of the hydrological analysis of the Najran region. Figure 2 shows the procedure followed for the analysis to achieve the objectives of the research.

2.1 Study Area Characteristics

Najran region can be divided into three major geographical regions. The first region consists of the flat area which lies in the middle of Najran in the form of valleys. The valley areas lie between 1200 to 1350 m above mean sea level (MSL). The second region consists of the mountainous area which is in the north, the west, and the south of the Najran city. Many of the mountains are famous for good quality granite rocks, where this stone is quarried and supplied to a large part of the country to be used as a building material. Some of them are higher than 1900 m above MSL. The third region consists of deserts and sandy soil which lies in the east of the city. This region is extremely rich in subsurface oil and lies between 1100 to 1200 m above MSL [1]. All three major regions are identified in the satellite image of the Najran Valley shown in Fig. 3a and the elevation contour map shown in Fig. 3b.

As far as the climate of the Najran region is concerned, it stands as an epitome of a subtropical desert climate, falling under the Köppen climate classification 'BWh' [26]. Throughout the year, temperatures vary substantially, with as low as 8 °C to as high as 40 °C during the summer as shown in Fig. 4. The summer in Najran stretches from June through August with temperatures above 37 °C on average, while winter shows up between December and February, with average lows of 12 °C to just 9 °C [2].

The region receives very little precipitation with rainfall levels ranging from 1 to 18 mm spread over the year, as shown in Fig. 5a. The rainfall does not show a consistent pattern, resonating with the unpredictability of desert climate. The months of March to May and August witness high rains, while other months hardly receive any rainfall [2].

Table 2 shows the Intensity–Duration–Frequency (IDF) chart for the Najran region based on the past 50-year (1970–2020) precipitation data, as shown in Fig. 5b. IDF chart is developed by considering a storm return period of 5, 10, 25, 50, and 100 years corresponding to a range of rainfall intensities.

Average monthly data for a few other climatic variables for the Najran region are shown in Table 3, showing variations in the wind speed, relative humidity, and the corresponding air temperature for the region.

Table 1 Related Studies for Saudi Arabian Valleys

Valley name	Scope of Study	Description	References
Wadi Rumah	Water Quality	This study found that the quality of water is "very good" for irrigation, "fair" for livestock drinking, and "marginal" for fisheries and recreation. In the wet period, the quality of water is marginal for all uses. Water quality management requires effective monitoring of effluent and river waters	[20]
Wadi Al Rimah	Hydrologic Performance	There is an opportunity to control floods upstream of Buraidah and to recharge the main aquifer through the outcropping of the Al Saq aquifer, which is being aggressively pumped. Since the main 2 channels in the downstream catchment reach about 1.6 km on average and the surrounding rock shoulders are 19 m higher than the channel bed, the construction of the proposed dam is quite feasible	[21]
Wadi Najran	Flood Management	This study identifies flood-risk zones using flash flood mapping. According to SPOT, 25% of the population living in 17 zones has low flooding risk, 50% lives in 23 zones have moderate flooding risk, 9% live in 17 zones and 16% live in 11 zones with very high flood risk	[22]
Wadi Fatimah	Groundwater	This study evaluates groundwater evolution and vulnerability from a hydrogeological and hydrochemical standpoint. Wadi Fatimah basin quaternary aquifers are primarily recharged by rainwater, with a small contribution from the Red Sea. Water resources of the Wadi Fatimah basin are being threatened by agricultural practices, shallow water levels, and deep sandy soils, as well as climate change	[23]
Six valleys in the Central region	Environmental Concerns	This study investigated heavy metal pollution in Saudi Arabia. In six polluted valleys, they measured concentrations of Mn, Fe, Ni, Cu, Zn, Cd, and Pb in roots, rhizomes, stems, and leaves. Heavy metal contamination was found in the valleys. The arid climate makes recreational facilities scarce in big cities, so remediation is urgent	[24]
Wadi Al Baida	Water Storage	This study describes the feasibility of creating water storage facilities for irrigation in the underdeveloped areas of Wadi Al Baida. Detailed runoff analysis is performed and the proposed location of storage facilities has been identified	[25]

2.2 Modeling Tools Used for the Research

The hydrological modeling depends on simulating the relationship between the rainfall, runoff, and flow. Accordingly, the hydrological modeling depends on the infiltration coefficients such as the runoff coefficient, curve number (CN), or initial abstraction. All these coefficients depend on the soil's physical and hydraulic properties and land uses. Several mathematical models could be used to determine the resulting discharges [28].

The ArcGIS is a comprehensive graphical modeling environment for all phases of watershed hydrology and hydraulics. The software provides tools to automate basins and sub-basins delineation using digital elevation models (DEM) generated based on topographic maps or any other related sources such as aerial maps and SRTM 30 m. It can analyze watershed characteristics and geometric parameters such as catchment areas, stream lengths and slopes, and terrain elevations. It is also used to simulate precipitation-runoff processes in a watershed. The software features a completely integrated work environment including a database, data entry utilities, computation engine, and results reporting tools.

A graphical user interface allows the user seamless movement between the different parts of the software. ArcScene, another linked module of ArcGIS, is also utilized for better understanding and visualization of watershed catchments and flood maps [29].

The characteristics of the watershed catchment areas contributing to the primary drainage basin including the time of concentration, the soil types, the nature of the vegetation cover, and the different patterns of land use for each catchment area are of great importance in the hydrological analysis process. The calculation methods of various variables and mathematical models used for the research are described below.

2.3 SCS-Curve Number Values for Najran

This is a widely used method to estimate surface runoff and determine the hydrographs and peak flows of floodwater after deducting the different losses of rainwater falling on the drainage basin. The method does not only depend on rainfall values but also the characteristics of the drainage basin, its soil moisture content, soil type, initial losses, and land
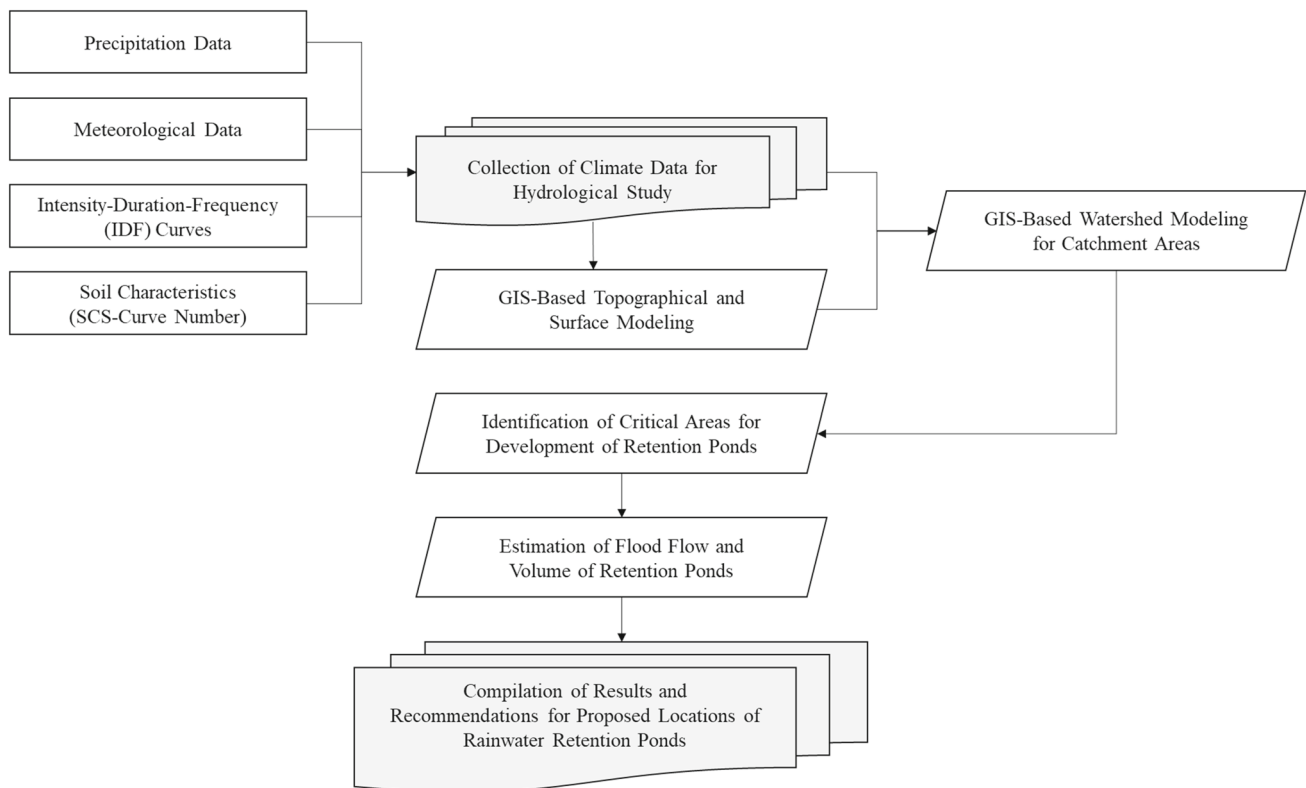
Fig. 2 Research methodology flow chart

use/land cover as well. These losses are expressed by a factor called runoff curve number (CN). This number typically ranges from 25 for low runoff depressions to 98 for paved impervious areas [28].

The characteristics and structure of drainage basins directly affect the relationship between the amount of rainfall on the basin and the amount of surface runoff resulting from these precipitation values. In the soil conservation service curve number (SCS-CN) method, the soil is classified into four main categories according to the value of the infiltration rate through its granules. The first category A includes sandy soils or gravel which have low runoff potential and high infiltration rates even when thoroughly wet. The surface runoff over drainage basins of such soils is very weak. The second category B includes medium sandy, sandy loam, and medium and moderately coarse soil, characterized by medium to high infiltration rates in case of soil saturation. Surface runoff over drainage basins consisting of such soils ranges between weak and average. Then, category C includes clay loam soil having a thick surface layer. It does not contain a high percentage of organic matter and its grains are fine to moderately fine. This soil is characterized by medium to low infiltration rates and runoff over drainage basins consisting of such soils is between medium and high. Finally, category D includes clay soil with high swelling potential, shallow soil followed by an impervious layer or soil where the level of groundwater

is always high, characterized by very low infiltration rates. This soil group has a high runoff potential [28].

Runoff depth (R) for any type of soil is estimated for the unit area above the surface of the drainage basins using the following relation.

$$R = \frac{(P - I_a)^2}{(P - I_a) + S} \quad (1)$$

where R is the accumulated depth of runoff (mm), P is the accumulated depth of rainfall (mm), and the value of S is a function of the CN value (mm) as given by the following equation.

$$S = 254\left(\frac{100}{CN} - 1\right) \quad (2)$$

The initial abstraction (I_a) in Eq. 1 can be expressed as follows:

$$I_a = 0.2S \quad (3)$$

Substituting in Eq. 1, the runoff depth (R) can be expressed on the unit area by the following relation:

$$R = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (4)$$

Fig. 3 **a** Satellite image and **b** Elevation contour plan with marked boundary of study area
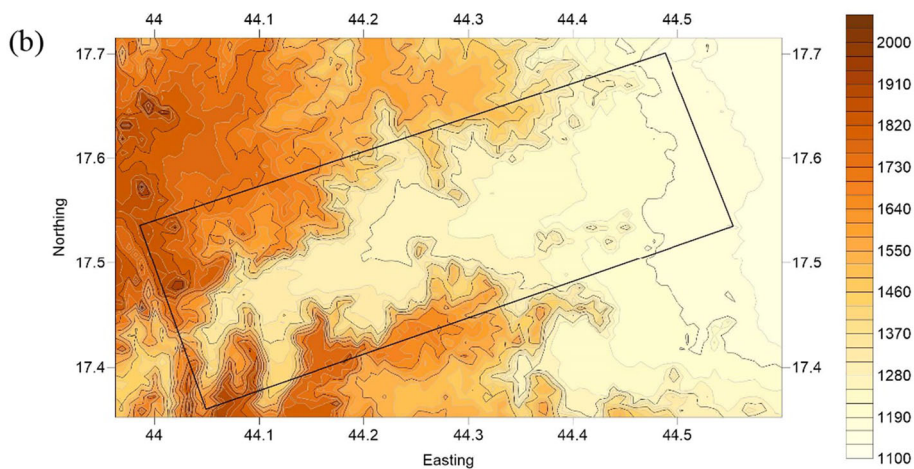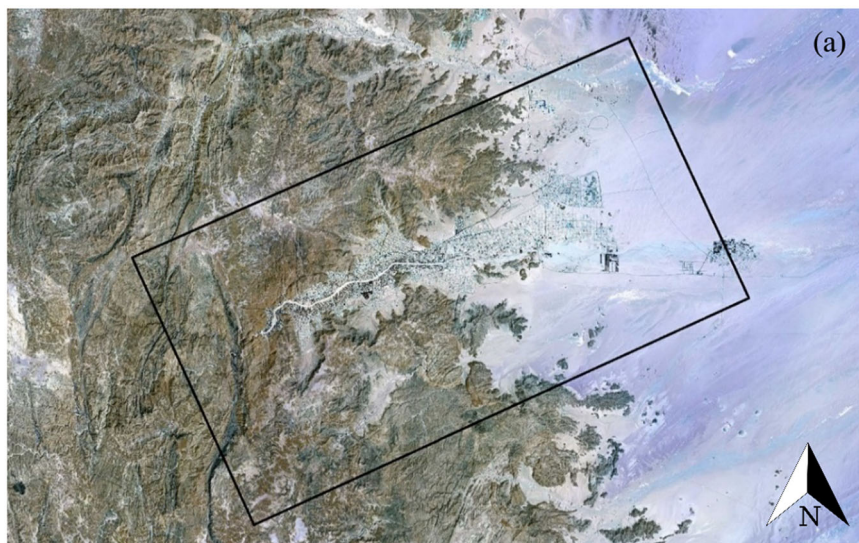

Fig. 4 Average monthly maximum and minimum temperatures for Najran Valley [27]
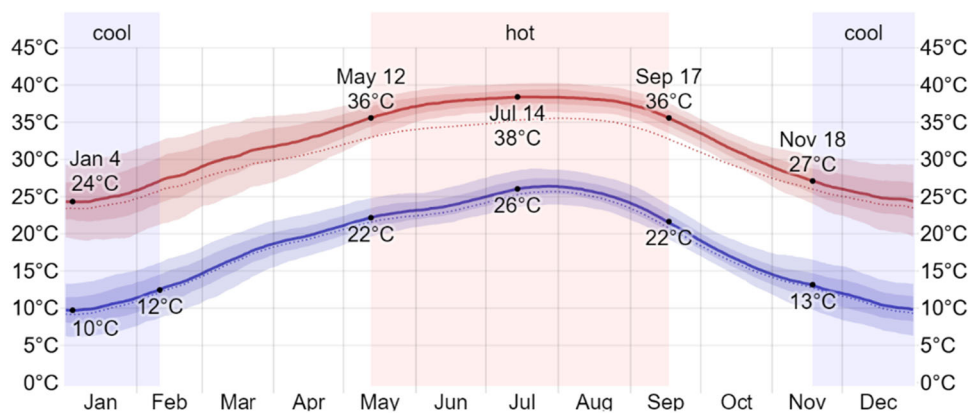
Fig. 5 a Annual max. daily rainfall and **b** average monthly rainfall for Najran Valley 1970–2020 [27]
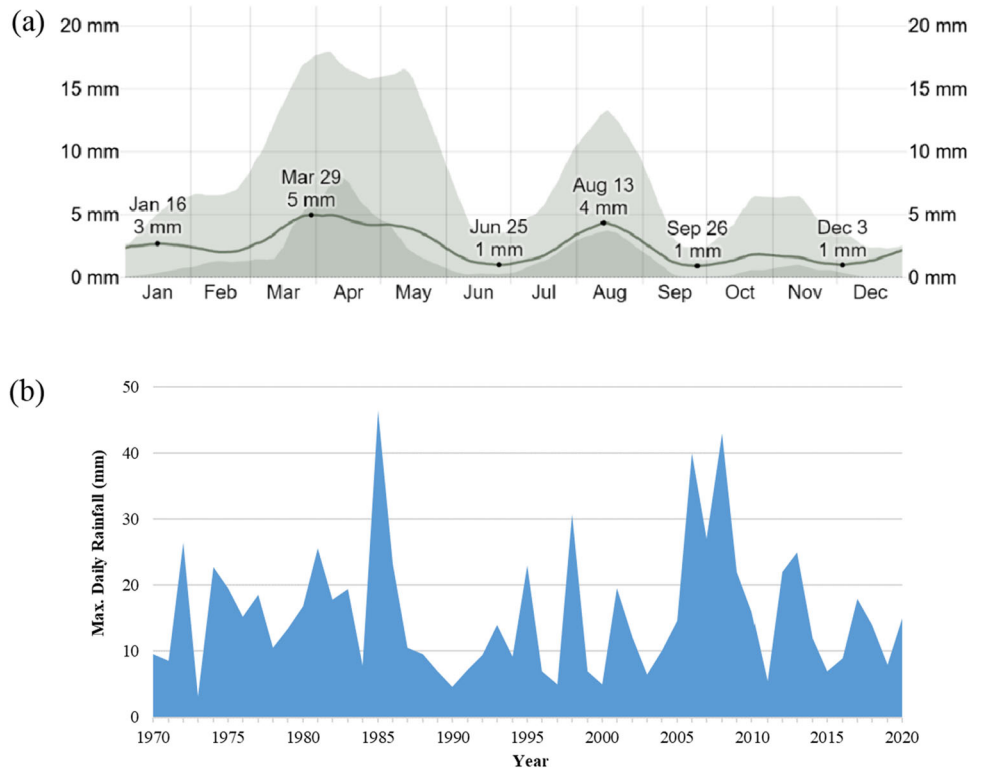

Table 2 Intensity–Duration–Frequency Chart for Najran Region [27]

Storm return period	Rainfall Intensity (mm/hr)							
	15 min	30 min	1 h	2 h	3 h	6 h	12 h	24 h
5 year	112.9	72.6	43.3	24.4	17.2	9.3	5.0	2.7
10 year	138.0	88.7	52.9	29.8	21.0	11.3	6.1	3.3
25 year	169.8	109.1	65.1	36.7	25.8	13.9	7.5	4.1
50 year	193.1	124.2	74.0	41.8	29.4	15.8	8.5	4.7
100 year	216.7	139.3	83.0	46.8	32.9	17.8	9.6	5.2

Table 3 Average Monthly Climatic Values for Najran for Duration 1970–2020, [27]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg. daily rainfall (mm)	2.9	2.2	4.3	5.0	4.0	1.3	1.8	4.2	1.2	1.6	1.5	1.4
Wind speed (m/s)	2.9	3.3	3.4	3.2	3.3	3.5	4.1	3.7	3.6	3.5	3.0	2.8
Relative humidity (%)	42	34	32	30	21	16	17	19	19	25	33	41
Air temperature (^{o}C)	17	20	23	26	29	31	33	31	29	24	21	18

The most predominant factors in estimating the value of CN are the soil type and land use. Through the capabilities of the spatial analyst extension of the ArcGIS and using the land use and soil type aided by the Curve Numbers lookup tables, the CN values for the catchments are determined for the Najran region.

3 Time of Concentration for Surface Runoff

Time of concentration is the time duration from the beginning of the rainfall event to the time when water from the furthest point in the catchment reaches the point under consideration. There are several equations to calculate the time of concentration of a specific drainage basin, but Kirpich's equation is considered to be the most reliable and accurate to

date. The equation used to calculate the time of concentration is as follows [30].

$$T_c = 0.06628 \left(\frac{60L^{0.77}}{S_B^{0.385}} \right) \qquad (5)$$

where T_c is the time of concentration (min.), L is the horizontally projected length of the drainage basin along the main watercourse (km), and S_B is the slope of the drainage basin (m/m).

The time of concentration affects the shape of the flood hydrograph. It is also directly used in rainfall-runoff transformation methods including the SCS-CN method which is adopted in this study. Several other equations are also used in the various references such as the Izzard equation, the kinematic wave, and the equation of the lag time of the SCS. Kirpich developed his equation by using information from SCS-CN for seven catchment basins in Tennessee State of the USA which are characterized by clear drainage channels and steep slopes of 3 to 10% [30]. This equation is commonly used in valleys in arid areas where there is poor vegetation [31]. It has also been used in many studies of valleys in Saudi Arabia. Also, the Kirpich method calculates the time of concentration closer to the actual measured data than any other method [32, 33]. As suggested by the Code of Practice of the Saudi Ministry of Transport and Ministry of Communications and the Saudi Authority for Industrial Cities and Technology Zones (MODON), Kirpich's equation is sufficiently reliable to calculate the time of concentration [34].

4 Shallow Water Equations

As discussed in Sect. 1, the flow of water in 2D space may be described by the shallow water equations (SWE) or the Saint–Venant equations, which represent mass and momentum conservation and can be derived by water depth averaging the Navier–Stokes equations in the vertical direction. The SWE consists of one conservation of mass equation called the continuity equation and two conservation of momentum equations for the two orthogonal directions x and y [9].

The continuity equation for the 2D overland flow is formulated as below:

$$q = \frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} \qquad (6)$$

The momentum equations in the x and y directions are formulated as below:

In x-direction,

$$\frac{\partial (hu)}{\partial t} + \frac{\partial \left(hu^2 + \frac{1}{2}gh^2 \right)}{\partial x} + \frac{\partial (huv)}{\partial y}$$
$$+ gh \left(-S_{ox} + f \frac{u\sqrt{u^2 + v^2}}{4gh} \right) = 0 \qquad (7)$$

In y-direction,

$$\frac{\partial (hv)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial \left(hv^2 + \frac{1}{2}gh^2 \right)}{\partial y}$$
$$+ gh \left(-S_{oy} + f \frac{u\sqrt{u^2 + v^2}}{4gh} \right) = 0 \qquad (8)$$

where x and y are the two space dimensions, t is the time, h is the water level referred to in some datum, u and v are the average velocities in x and y directions, respectively, d is the water depth, g is the acceleration due to gravity, S_{ox} and S_{oy} are the bed slope variations in x and y directions, respectively, f defines the Coriolis parameter, and q is the source flow or sink per unit area [35, 36]. Equations 6, 7, and 8 are used to obtain the flow accumulation and watershed maps by the ArcGIS software package.

5 Results and Discussion

5.1 Pour Point Analysis and Identification of Catchment Areas

The primary catchments and their characteristics are determined using digital elevation models (DEM). Several catchment areas are identified for the valleys that pass through the study area. During the analysis, a 30-m accuracy Shuttle Radar Topography Mission (SRTM) DEM along with a 4-m DEM are used to determine the primary catchments and watersheds affecting the study area. The DEM images are obtained from the United States Geological Survey Earth Explorer website where the data is available for free download for educational or research purposes [37]. Terrain processing is the first stage of the analysis on ArcGIS software. It is used to check the obtained digital elevation model (DEM) through the terrain processing tools. The DEM obtained from USGS for Najran Valley is shown in Fig. 6.

The primary and secondary drainage systems of the basin area are determined to identify the sub-basins and the downstream discharge point associated with each of them. The sinks are filled which obstructs water flow between points in the digital elevation model, causing water flow to stop at a cell called a pour point with lower elevations than all its
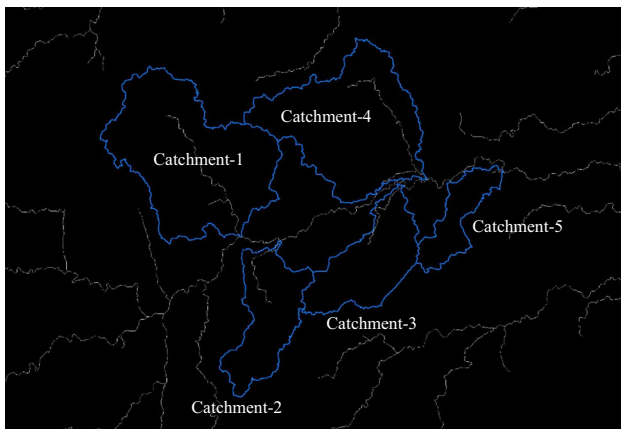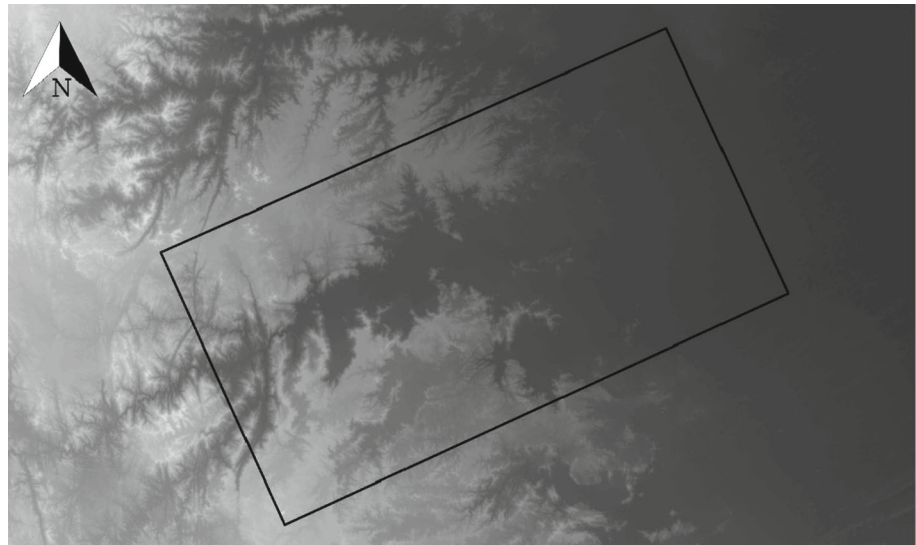
Fig. 7 Flow accumulation map with major catchment areas

surrounding cells. The sinks are raised and a new layer is created. By using this new layer, the flow direction is computed for the grid. The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell. The flow direction tool determines the direction in which water will flow from each cell to its adjacent cells by comparing the height of the cell with neighboring cell levels and determining the steepest slope to which water flows from the original and subtracted directions. It converts the DEM file to a raster file with each cell containing the flow direction value. The flow direction raster is then used to calculate the flow accumulation for the catchment areas that contain the accumulated number of cells upstream of a certain pour point cell. The flow accumulation map generated from ArcGIS for Najran Valley is shown in Fig. 7. The tributaries from the major catchment areas are also shown which are discharging in the Najran Valley River.

After creating the flow accumulation plan, a threshold is defined for each watershed catchment area with the minimum number of cells or the area from which a water stream is defined as one path, thus determining the drainage network from the flow accumulation automatically. ArcGIS then creates a grid of stream segments that have a unique identification. Either a segment may be a head segment, or it may be defined as a segment between two segment junctions. All the cells in a particular segment have the same grid code that is specific to that segment. Tributaries are generated giving each tributary an identification number with all its hydrological characteristics.

The software package converts the drainage basins of each extension from grid to polygons and extracts a map for each basin as per the initial inputs of the step that preceded it. The watershed catchment area map for the identified five major catchments in Najran Valley is shown in Fig. 8.

Based on the above analysis, the catchment area features along with their topographical characteristics including the area and length of the streams are estimated and further analysis for the proposed location of retention ponds is performed.

6 Proposed Location of Retention Ponds

The identification of critical locations in the Najran region and related characteristics of retention ponds are classified into five categories based on their priority starting from high priority (A) to low priority (E). The priority of locations is classified based on the hazard rating and importance of each location. The flood map for storm events of 100 years was developed for the current situation in Najran, as presented in Fig. 9. Flood inundation maps were also created for different

Fig. 8 Watershed catchment area map for Najran Valley showing major catchments
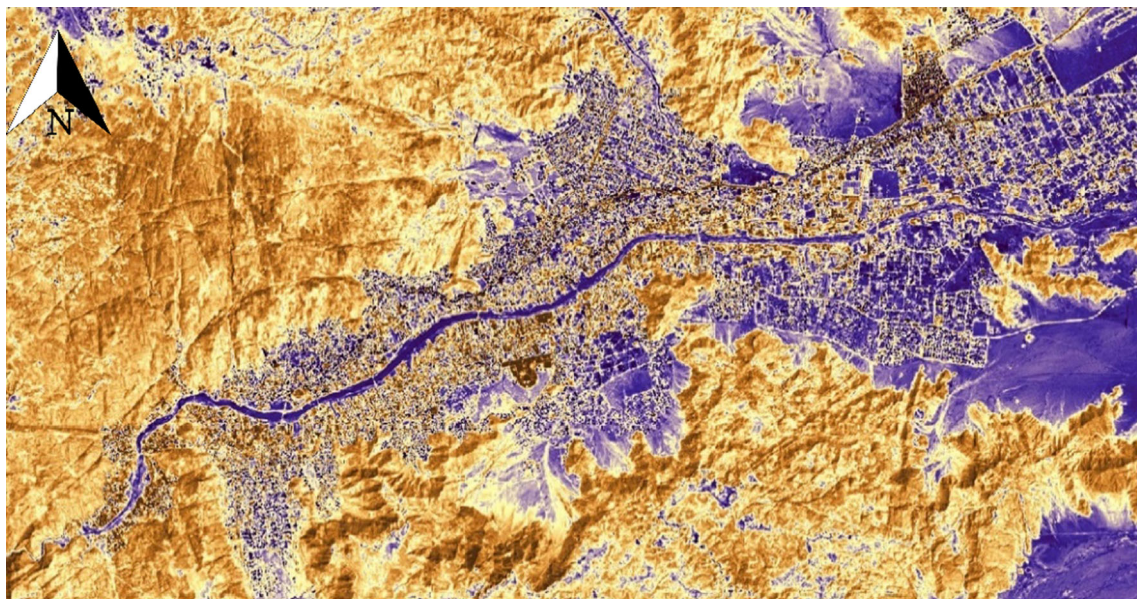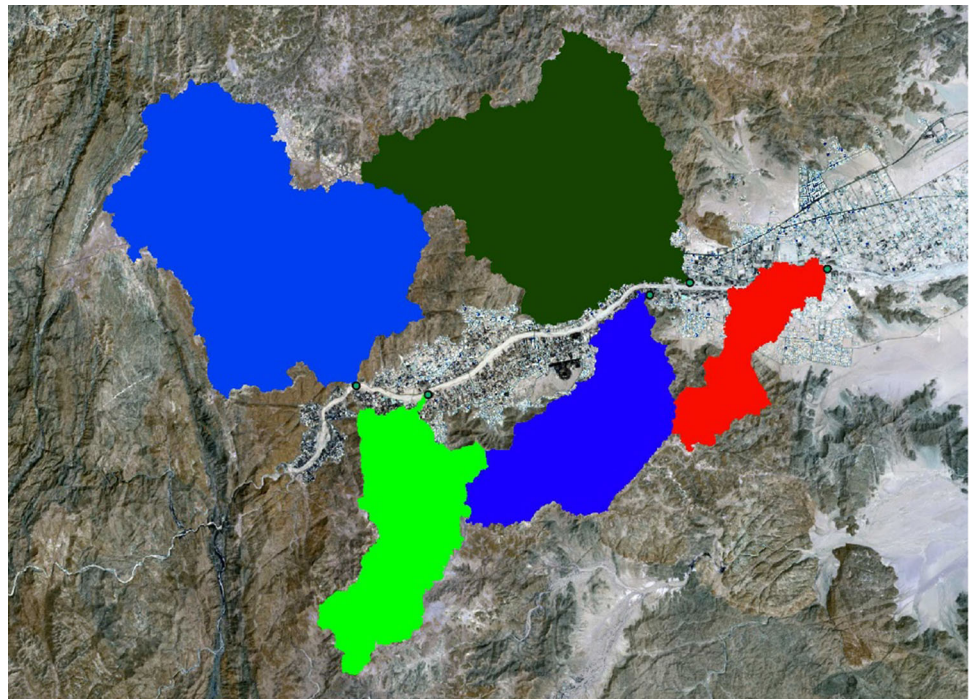

Fig. 9 Flood map of Najran Valley for 100-year storm return period showing flood-prone areas
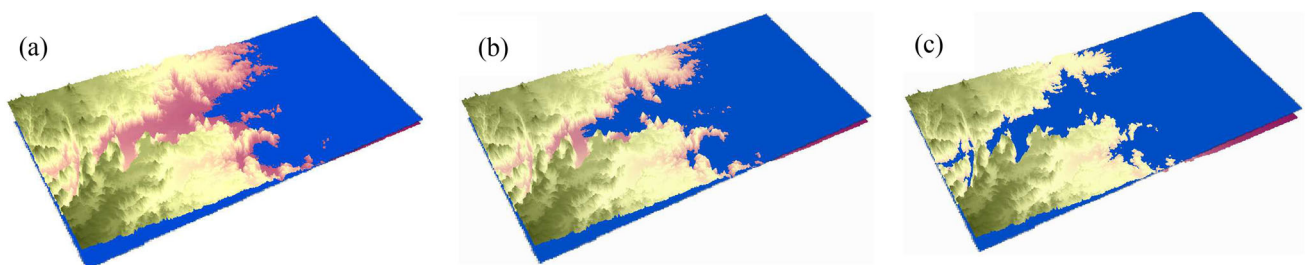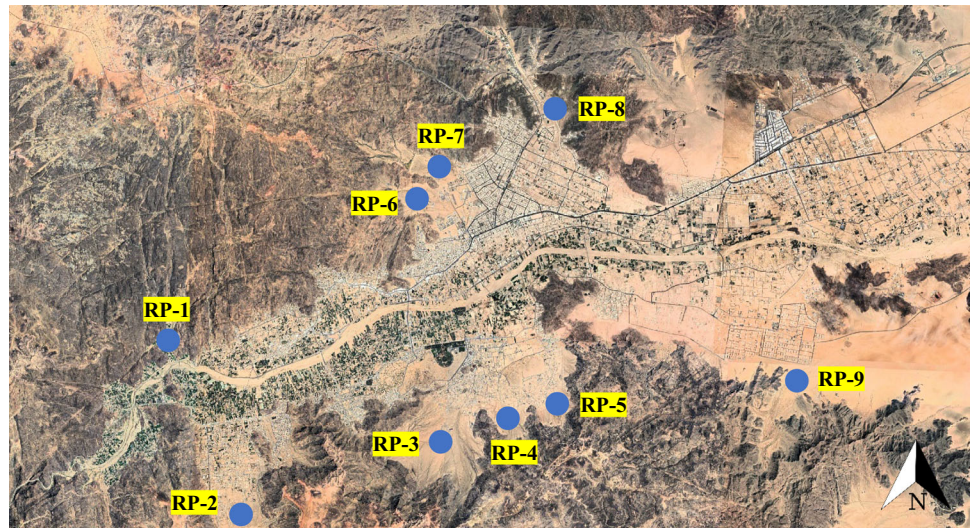

(a) (b) (c)

Fig. 10 Flood inundation maps of Najran Valley for MSL **a** 1150, **b** 1300, and, **c** 1450

Fig. 11 Location of proposed retention ponds in Najran Valley

elevations to validate the critical locations of water ponding in the valley. The flood inundation maps are shown in Fig. 10.

Based on the soil characteristics of the Najran Valley and surrounding areas shedding water into the Najran River, an SCS-CN value of 85 was used [28]. After the analysis, Catchment No. 1 is found to be the largest catchment that flows toward the Najran valley with an area of $211.9 \, km^2$. The accumulated volume of water at the lowest point is calculated as 1.18 McM, proving to be one of the best locations for creating a retention pond, hence referred to as RP-1, as shown in Fig. 11. RP-2 is proposed to be located a bit downstream of RP-1, with an estimated water volume of 0.47 McM. RP-2 shall cover a watershed area of $79.86 \, km^2$ from Catchment No. 2 as shown in Fig. 7.

For Catchment No. 3, three separate locations of retention ponds are proposed based on the topography of the area. Retention ponds RP-3, RP-4, and RP-5 are proposed to accumulate a rainwater volume of 0.09, 0.17, and 0.23 McM, respectively. Similarly, RP-6, RP-7, and RP-8 are proposed for Catchment No. 4 accumulating rainwater volumes of 0.2, 0.29, and 0.58 McM, respectively, as shown in Table 4. Finally, for Catchment No. 5, one retention pond RP-9 is proposed having a water volume of 0.24 McM. The location of all the proposed retention ponds is shown in Fig. 11 with their exact coordinates presented in Table 4. It can be seen that the proposed retention ponds can store a huge amount of water accumulating to 3.45 McM at various locations in Najran Valley. Also, Catchment No. 1 contains the longest stream length of 23.73 km.

Based on the results of the expected volume of water for each location of retention ponds, the detailed design of the reservoir can be done as an extension of this research. However, the average depth of the ponds may be kept within a range of 1 to 4 m. The duration of water storage is generally for the whole season. The excess amount of water is allowed

to be disposed of with the help of an overflow outlet to the nearby river, which in this scenario is the Najran River. Water loss through seepage in the bed of the retention ponds should be prevented with the usage of PVC membranes or any other waterproofing alternative.

7 Environmental and Design Requirements of Retention Ponds

The success of retention ponds depends on both environmental factors and design considerations. The key environmental factors in constructing the retention ponds are rainfall patterns, temperature fluctuations, and evaporation rates. These factors can influence the volume and quality of water in the retention ponds. Therefore, the local climate of Najran is crucial to account for expected water levels and potential droughts in the area. Another important factor is identifying runoff water quality including the nature of pollutants and sediment concentration in the collected water. This is necessary for designing effective treatment mechanisms within the retention pond [38]. It is often recommended that the retention pond integrates harmoniously with the existing ecosystem and does not harm sensitive species. Ultimately, to make sure that environmental protection measures are taking place, it is important to adhere to international and local environmental regulations [39, 40].

In addition to this, there are many key design features as well that must be taken into account when designing a retention pond. A few of these are discussed below.

1. Catchment Area: The size and depth of the catchment area, along with rainfall intensity, and desired retention time are the first steps to making the verdict on the feasibility of constructing a retention pond [41].

Table 4 Location and Hydrological Characteristics of Proposed Retention Ponds in Najran Valley

Catchment no	Catchment area (km^2)	Pond No	Location coordinates	Max. length of stream (km)	Retention pond capacity (McM)
C-1	211.9	RP-1	17° 29′ 06″ N 44° 05′ 01″ E	23.73	1.18
C-2	79.86	RP-2	17° 25′ 34″ N 44° 07′ 00″ E	16.69	0.47
C-3	84.97	RP-3	17° 27′ 14″ N 44° 12′ 14″ E	3.21	0.09
		RP-4	17° 27′ 54″ N 44° 14′ 04″ E	4.59	0.17
		RP-5	17° 28′ 12″ N 44° 15′ 10″ E	7.21	0.23
C-4	181.76	RP-6	17° 33′ 11″ N 44° 11′ 20″ E	6.93	0.2
		RP-7	17° 33′ 58″ N 44° 11′ 38″ E	11.27	0.29
		RP-8	17° 35′ 36″ N 44° 14′ 37″ E	17.54	0.58
C-5	40.29	RP-9	17° 28′ 56″ N 44° 21′ 24″ E	13.18	0.24

2. Bed Material and Site Conditions: The material used for the bed of retention ponds (e.g., sand, clay, and geo-membrane) and site conditions are also important aspects of the design. The material is required to be less porous or completely waterproof to avoid any loss of water through seepage and to maintain the water quality [42].

3. Inlet and Outlet Structures: The dimensions and shape of inlet and outlet structures help control water flow in and out of the pond, influencing retention time and preventing flooding. Design should consider potential debris accumulation and ease of maintenance [43].

4. Vegetation: Plants can protect the banks of the pond, prevent erosion, and serve as a filter for pollutants. The presence of submerged or emergent plants can enhance the quality of water and provide a healthy habitat for aquatic organisms [44].

5. Safety: Ensuring that fencing, signage, and access points are in place to prevent accidents, especially concerning ponds with larger depths [45].

6. Aesthetics: Ponds can be designed in a manner that complements the natural landscape and is visually appealing. Also, they can be used as a central point for recreational activities [46].

8 Conclusions

Retention ponds are a versatile and cost-effective stormwater management solution that can offer several benefits when they are adopted. A comprehensive hydrological analysis of the Najran region shows that there is sufficient potential for the development of retention ponds across the valley and a suitable amount of rainwater can be stored during storm events, which can later be used for agricultural or domestic use. A total of five primary catchment areas are identified shedding their runoff into the Najran River. After studying topography and various hydrological design parameters, nine locations are proposed as suitable locations for the development of retention ponds. The capacity of these retention ponds is estimated to be 3.45 McM every year which is a substantial amount of water the region can have as a storage in addition to the Najran dam reservoir. In addition, the proposed retention ponds for the Najran region may offer the following environmental benefits in the future.

1. Retention ponds shall help in the reduction of dust storms in the Najran valley by trapping dust particles in the air. This shall improve air quality in the area and shall reduce the risk of respiratory problems.

2. Retention ponds shall help protect infrastructure, such as roads, bridges, and buildings of the Najran region, from the damage caused by flooding.

3. Retention ponds are a proven method of conserving water resources by storing stormwater runoff. As Najran Valley consists of huge agricultural lands, the stored water in the retention ponds can be supplied to the nearby farms in the dry season as per the requirement of irrigation. Also, the stored water can be supplied to the nearby residential communities for domestic use.

The study also presents a huge scope of expanding the research for future researchers related to a similar field. The hydraulic and structural design of the retention ponds may be proposed based on the results obtained in this research. Moreover, water management studies can further be updated for the Najran region using the hydrological analysis presented in this study.

Data Availability Statement The datasets generated and analyzed during the research are available with the corresponding author and can be furnished upon request.

Declarations

Conflict of interest There is no conflict of interest to declare.

References

1. UNHSP: Najran City Profile, Future Saudi Cities Program, Ministry of Municipal and Rural Affairs and United Nations Human Settlements Program, ISBN: 978–603–8279–32–8 (2019)

2. Alyami, S.H.; Alqahtany, A.; Ghanim, A.A.; Elkhrachy, I.; Alrawaf, T.I.; Jamil, R.; Aldossary, N.A.: Water resources depletion and its consequences on agricultural activities in Najran Valley. Sustainability **11**, 122 (2022)

3. Al-Ghobari, H. M.: The effect of chemical application and excessive extraction of water resources on groundwater quality and environment in Saudi Arabia Najran Region as study case. In: Proceedings of International Conference of Water, Energy and Environment – ICWEE-'2011, Sharjah, UAE, pp. 57–63 (2011)

4. Ghanim, A.A.: Water resources crisis in Saudi Arabia, challenges and possible management options: an analytic review. Int. J. Environ. Ecol. Eng. **13**(2), 51–56 (2019)

5. Youssef, A.M.; Sabtan, A.A.; Maerz, N.H.; Zabramawi, Y.A.: Earth fissures in Wadi Najran, Kingdom of Saudi Arabia. Nat. Hazards **71**(3), 2013–2027 (2014)

6. Zhong, Q.; Tong, D.; Crosson, C.; Zhang, Y.: A GIS-based approach to assessing the capacity of rainwater harvesting for addressing outdoor irrigation. Landsc. Urban Plan. **223**, 104416 (2022)

7. Jamil, R.: Reduction in Fresh Water Consumption by Grey Water Reuse for Flushing and Irrigation: A Case Study of a Multistorey

8. Carollo, M.; Butera, I.; Revelli, R.: Water savings and urban storm water management: Evaluation of the potentiality of rainwater harvesting systems from the building to the city scale. PLoS ONE **17**(11), e0278107 (2022)

9. Chaudhry, M. H.: Open-Channel Flow, ISBN: 978–3–030–96449–8 (2022)

10. Néelz, S., Pender, G.: Desktop review of 2D hydraulic modelling packages, Science Report SC080035. Joint Defra/Environment Agency Flood and Coastal Erosion—Risk Management R&D Program. ISBN: 978–1–84911–079–2 (2009)

11. Evans, E.P.; Wicks, J.M.; Whitlow, C.D.; Ramsbottom, D.M.: The evolution of a river modelling system. Proc. Inst. Civil Engineers Water Manage. **160**(1), 3–13 (2007)

12. Leandro, J.; Chen, A.S.; Djordjević, S.; Savić, D.A.: Comparison of 1D/1D and 1D/2D coupled (sewer/surface) hydraulic models for urban flood simulation. J. Hydraul. Eng. **135**(6), 495–504 (2009)

13. Aronica, G.T.; Lanza, L.G.: Drainage efficiency in urban areas: a case study. Hydrol. Process. **19**(5), 1105–1119 (2005)

14. Seyoum, S.D.: Framework for Dynamic Modelling of Urban Floods at Different Topographical Resolutions. TU Delft University, CRC Press (2013)

15. USACE: Engineering and Design: River Hydraulics, US Army Corps of Engineers, Engineer Manual CECW-EH-Y 1110–2–1416 (1993)

16. Staccione, A.; Broccoli, D.; Mazzoli, P.; Bagli, S.; Mysiak, J.: Natural water retention ponds for water management in agriculture: A potential scenario in Northern Italy. J. Environ. Manage. **292**, 11249 (2021)

17. Birkinshaw, S.J.; Krivtsov, B.: Evaluating the effect of the location and design of retention ponds on flooding in a Peri-Urban River catchment. Land **11**, 1368 (2022)

18. Acheampong, J.N.; Gyamfi, C.; Arthur, E.: Impacts of retention basins on downstream flood peak attenuation in the Odaw river basin, Ghana. J. Hydrol. Regional Stud. **47**, 101364 (2023)

19. Ferk, M.; Ciglič, R.; Komac, B.; Lóczy, D.: Management of small retention ponds and their impact on flood hazard prevention in the Slovenske Gorice Hills. Acta Geogr. Slov. **60**(1), 107–126 (2020)

20. Al-Hetari, M.; Haider, H.; Ghumman, A.R.; Al-Salamah, I.S.; Thabit, H.; Shafiquzzaman, M.: Development of a water quality management model for dry rivers in arid regions: application on Wadi Rumah, Saudi Arabia. Ecosyst. Sustain. **9**, 0001 (2023)

21. El Bastawesy, M.; Al Ghamdi, K.: Assessment and management of the flash floods in Al Qaseem Area, Kingdom of Saudi Arabia. Int. J. Water Resources Arid Environ. **2**(3), 146–157 (2013)

22. Elkhrachy, I.: Flash flood hazard mapping using satellite images and GIS tools: a case study of Najran City, Kingdom of Saudi Arabia (KSA). Egypt. J. Remote Sens. Space Sci. **18**(2), 261–278 (2015)

23. El Osta, M.; Niyazi, B.; Masoud, M.: Groundwater evolution and vulnerability in semi-arid regions using modeling and GIS tools for sustainable development: Case study of Wadi Fatimah,Saudi Arabia. Environ. Earth Sci. **81**(9), 248 (2022)

24. Al-Homaidan, A.A.; Al-Otaibi, T.G.; El-Sheikh, M.A.; Al-Ghanayem, A.A.; Ameen, F.: Accumulation of heavy metals in a macrophyte Phragmites australis: Implications to phytoremediation in the Arabian Peninsula wadis. Environ. Monit. Assess. **192**, 1–10 (2020)

25. Jamil, R.: GIS-based watershed analysis for water storage facilities in underdeveloped areas: case of a Gravity Hill in Saudi Arabia, Chapter 7, Handbook of Research on Driving Transformational Change in the Digital Built Environment, pp. 164–178 (2021)

26. Cui, D.; Liang, S.; Waang, D.: Observed and projected changes in global climate zones based on Köppen climate classification. WIREs Clim. Change **12**(3), e701 (2021)

27. MEWA: The General Authority of Meteorology and Environmental Protection, Ministry of Environment Water and Agriculture, Saudi Arabia (2023)

28. < https://www.mewa.gov.sa/en/InformationCenter/OpenData/Pages/Home.aspx >

29. NEH: Hydrology, Section 4. United States Soil Conservation Service, University of Minnesota, National Engineering Handbook (1983)

30. Gorr, W. L.; Kurland, K. S.: GIS Tutorial for ArcGIS Desktop 10.8, Environmental System Research Institute (ESRI), ISBN: 9781589486140 (2020)

31. Kirpich, Z.P.: Time of concentration of small agricultural watersheds. Civ. Eng. **10**(6), 362 (1940)

32. Wheater, H.; Al-Weshah, R.: Hydrology of Wadi Systems, IHP Regional Network on Wadi hydrology in the Arab Region. IHP-V UNESCO, Technical Documents in Hydrology, No. 55 (2002)

33. El-Hames, A.S.; Al-Wagdany, A.S.: Reconstruction of flood characteristics in urbanized arid regions: case study of the flood of 25 November 2009 in Jeddah, Saudi Arabia. Hydrol. Sci. J. **57**(3), 507–516 (2012)

34. Hagras, M.A.; Elmoustafa, A.M.; Kotb, A.: Flood plain mitigation in arid regions case study: South of Al-Kharj city, Saudi Arabia. Int. J. Recent Res. Appl. Stud. **16**, 147–157 (2013)

35. MOC: General Specifications for Road and Bridge Construction, Ministry of Communications, Saudi Authority for Industrial Cities and Technology Zones (MODON) (1998)

36. < https://www.modon.gov.sa/en/Systems/Pages/StandardsGuide.aspx >

37. Garcia-Navarro, P.; Brufau, P.: Numerical methods for the shallow water equations: 2D approach, Chapter 20. In: River Basin Modeling for Flood Risk Mitigation, pp. 409–428 ISBN: 9781439824702 (2005)

38. Garcia-Navarro, P.; Burguete, J, Numerical methods for the shallow water equations: 1D approach, Chapter 19. River Basin Modeling for Flood Risk Mitigation, pp. 387–408 ISBN: 9781439824702 (2005)

39. USGS: United States Geological Survey Earth Explorer, < https://earthexplorer.usgs.gov/ > (2023)

40. Janke, B.D.; Finlay, J.C.; Taguchi, V.J.; Gulliver, J.S.: Hydrologic processes regulate nutrient retention in stormwater detention ponds. Sci. Total. Environ. **823**, 153722 (2022)

41. Keyvanfar, A.; Shafaghat, A.; Ismail, N.; Mohamad, S.; Ahmad, H.: Multifunctional retention pond for stormwater management: A decision-support model using Analytical Network Process (ANP) and Global Sensitivity Analysis (GSA). Ecol. Ind. **124**, 107317 (2021)

42. Valenca, R.; Garcia, L.; Espinosa, C.; Flor, D.; Mohanty, S.K.: Can water composition and weather factors predict fecal indicator bacteria removal in retention ponds in variable weather conditions? Sci. Total. Environ. **838**(3), 156410 (2022)

43. Egemose, S.; Sønderup, M.J.; Grudinina, A.; Hansen, A.S.; Flindt, M.R.: Heavy metal composition in stormwater and retention in ponds dependent on pond age, design and catchment type. Environ. Technol. **36**(8), 959–969 (2015)

44. Thiel, R.; Giroud, J.P.: Important considerations for leakage control of exposed geomembrane-lined ponds. In: Proceedings of the 13th International Waste Management and Landfill Symposium, Santa Margherita di Pula, Cagliari, Italy, pp. 3–7 (2011)

45. Dodd, J.C.: Elements of pond design and construction. Handbook of Microalgal Mass Culture, CRC Press, pp. 265–284, ISBN: 9780203712405 (2017)

46. Hamer, A.J.; Smith, P.J.; McDonnell, M.J.: The importance of habitat design and aquatic connectivity in amphibian use of urban stormwater retention ponds. Urban Ecosystems **15**, 451–471 (2012)

47. Kinas, H.; Sinnatamby, N.; Randall, L.; Jordan-McLachlan, S.: Operational beneficial management practices to support urban wetland biodiversity in the City of Calgary. https://rockies.ca/ (2023)

48. Hill, M.J.; Greaves, H.M.; Sayer, C.D.; Hassall, C.; Milin, M.; Milner, V.S.; Marazzi, L.; Hall, R.; Harper, L.R.; Thornhill, I.; Walton, R.: Pond ecology and conservation: research priorities and knowledge gaps. Ecosphere **12**(12), e03853 (2021)