



# Water resource management for improved crop cultivation and productivity with hydraulic engineering solution in arid northern Afghanistan

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Received: 6 October 2021 / Accepted: 29 November 2022 / Published online: 30 December 2022  
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## Abstract

This study is presenting a multidisciplinary approach for mitigations of water resources in the irrigation, water supply, energy, and flood protection using hydrological model coupled with multi-criteria decision analysis (MCDA). The study area is originated in the northern Afghanistan with serious water issues. Soil and Water Assessment Tool (SWAT) was adopted for the hydrological modelling. The model was calibrated and validated using monthly streamflow from 2010 to 2018. The current irrigation state of the watershed was revised based on the crop water requirements and land area to address water shortages. The investigations lead to an engineering-based solution (dam construction) to regulate and control the streamflow, especially during winter and flood season. Analytical hierarchy process (AHP) based on expert's opinions were used to determine suitable dam site locations. Then, the dam was added to the SWAT model for dam's impact assessment. The dam reservoir capacity (197,900,938 m<sup>3</sup>), dam storage area (748 ha), dam height (69 m), electricity generation (Ave = 25.4 MW, Min = 16.23 MW, Max = 66.5 MW), and flood protection ability were estimated. Finally, cost–benefit analysis (CBA) was conducted to ensure the project feasibility. The CBA proves the feasibility and applicability of proposal. The surplus water can address the water shortages with an extra capacity of irrigating 17,180.5 ha or provision of water supply for the Mazar-i-Sharif city (the fourth biggest city in the Afghanistan). These findings can be used as guidance for the decision-makers in the BRB for the future development of water resource management strategies.

**Keywords** Irrigation scheme · Dam · SWAT · AHP · Groundwater · Balkhab River

## Introduction

Water resources management has direct impact on the economic development and human activity through history. During the past century, the plant population grew rapidly with increased human consumption of natural resources. In this century, water consumption growth was two times larger than population growth and caused every continent to experience water scarcity (United Nation 2020). Seckler et al. (1999) approaches in 118 countries from 1990 to 2025 show that a quarter of the global population and a third of the population in developing countries will suffer from severe water scarcity in the next century. In particular, arid and semi-arid regions with sparse precipitation are more vulnerable to water scarcity issues. Recent studies showed an increase in drought severity in Afghanistan, Central Asia, and Iran, which are dominated by arid and semi-arid climates (Li et al. 2017; Qutbudin et al. 2019; Ta et al. 2018; Zoljoodi and Didevarasl 2013). Therefore, proper management practice

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for the water resources is essential for those regions to ensure the economic development and access to the safe, healthy, and sustainable sources of water.

Afghanistan's economy highly depends on agricultural activity. This sector makes 18.6% of the gross domestic product (GDP) and directly or indirectly impacts 80% of the total population's livelihood in rural areas (Mahmoodi 2008; NSIA 2019). The surface water is the country's most important source of irrigation and provide 86% of irrigation water demand (Rout 2008). A traditional operation system is used for irrigation water management in the country by the water users headed by *mirabs* (Viala 2003). *Mirab*, a combined Arabic and Persian word, means watermaster, and this term is used widely in Iran and Central Asia. The traditional *mirab* system mainly manages the water allocation in the main, secondary, and tertiary canals, and they do not have the support of the higher institution at the village or provincial level (Ward et al. 2013). The decision on the main canal's water allocation was made by the River Basin Authority, managed by Ministry of Energy and Water. Salman et al. (2017) highlighted the issue of uneven water allocation among water users where the upstream users receive more water than the downstream in Afghanistan, especially during the low flow period. Despite less precipitation in the country still, there is a huge capacity of unused water resources. Decades of war and conflict collapsed Afghanistan's irrigation infrastructures. Country has  $7.9 \times 10^6$  ha of arable land, and in 1980,  $3.3 \times 10^6$  ha of land was cultivated. During year 2008, just  $1.8 \times 10^6$  ha of those arable land were cultivated (Mahmoodi 2008). The current irrigation challenges in Afghanistan can be categorized into two major issues: (1) lack of hydraulics structures and (2) water resource management issue. To overcome the current problems, Afghanistan needs put both into consideration. Hard approaches include the rehabilitation of the existing infrastructure and the construction of new irrigation structures with improved efficiency can address the first issue. On the other hand, soft approaches refer to policy development for water resource management should be considered for water management and decision on infrastructure construction.

The Soil and Water Assessment Tool (SWAT) is a useful tool for performing irrigation and chemical yield assessments in watersheds. Scholars have used the SWAT model to investigate different scenarios in irrigation water management and worldwide agricultural practice. Many scholars successfully used SWAT for runoff and sediment modelling (Dhami et al. 2018; Himanshu et al. 2017), management of the chemical yield and sediment (Himanshu et al. 2019), assessing the impact of alternative agriculture management projects (Ullrich and Volk 2009), drought in catchment scale based on evapotranspiration (Dash et al. 2021), impact of using technological upgrades and innovation to increase the water productivity (Huang and Li 2010), estimation of crop

water productivity (Faramarzi et al. 2010), assessing different management practices, and finding the optimum solutions (Huang and Li 2010; Panagopoulos et al. 2014). The literature proves SWAT is a reasonable tool for assessing different irrigation water management policies and proposals before implementation and finding their impacts. The current study aims to assess the optimal locations of hydraulic dams using multi-criteria decision analysis and to assess the impact of proposed dam construction over the study region on water resources management, especially for downstream agricultural water usage using SWAT.

The study adopts analytical hierarchy process (AHP) under multi-criteria decision analysis (MCDA) to decide the optimal dam site location. AHP is widely used to solve a broad range of multi-criteria decision-making problems to calculate the weight of every criterion (Cabrera and Lee 2019; Tuy et al. 2022). AHP has been used in dam site suitability (Noori et al. 2019; Shao et al. 2020). Noori et al. (2019) used the dam site suitability analysis to find a suitable site for dam location in northern Iraq to reduce the impact of climate change and long-term drought caused water shortage and water issues in the study region. Another study used the dam suitability stream model (DSSM) coupled with AHP to give weight to the input parameter in the northern Pakistan (Shao et al. 2020). Identifying the criteria and their importance for the dam site suitability varies from study to study (Karakuş and Yıldız 2022; Noori et al. 2019; Raaj et al. 2022; Shao et al. 2020).

The main aim of this study is to present a sustainable engineering-based solution for the water resource management in a less developed watershed using the hydrological models coupled with MCDA. This study adapts a multidisciplinary approach for mitigating irrigation water resource management, overcoming water supply issues, flood risk reduction, sustainable energy generation, and CBA for the dam construction. The findings in this study could help the decision-makers for further decisions on water resources in the basin. This paper adopts the SWAT modelling of the basin adopts from a previous study by Hussainzada and Lee (2021). Also, it contains the dam site suitability analysis using AHP, and proposes an engineering-based solution by adding a hydraulics structure and revising the irrigation scheme adopted from the study of Hussainzada and Lee (2022). Furthermore, this paper developed the CBA for the proposed scenario.

## Materials

### Study area

The current study originated in northern Afghanistan in a semi-arid climate. Afghanistan is officially divided into five

major basins: the Harirod Murghab, Kabul (Indus), Helmand, Amu Darya, and Northern River basins (Fig. 1a). The study area is the Balkhab River basin (BRB) (Fig. 1b) in the Northern River basin (NRB) of Afghanistan, with an elevation range from 202 to 4616 m. Five hydrometrological stations are installed in the entire basin and record discharge and other climatic parameters (Fig. 1c). The average annual precipitation in this basin is 247 mm based on the data provided by the Ministry of Energy and Water (MEW) between 2010 and 2018. Most of the water resources in the basin are consumed by the agriculture sector for irrigation of 296,744 ha of land. The irrigation water is distributed through 101 irrigation canals and three regulator dams. Based on the investigations in the current research, 11 downstream canals of BRB face severe water shortages for irrigation of farm products, especially during the low flow period. Please refer to Table 1 for the details of 11 subbasin canals. Based on the recorded discharge in the most downstream station, an annual average discharge of  $1657 \times 10^6 \text{ m}^3$  passed this section of river from 2010 to 2018.

**Datasets**

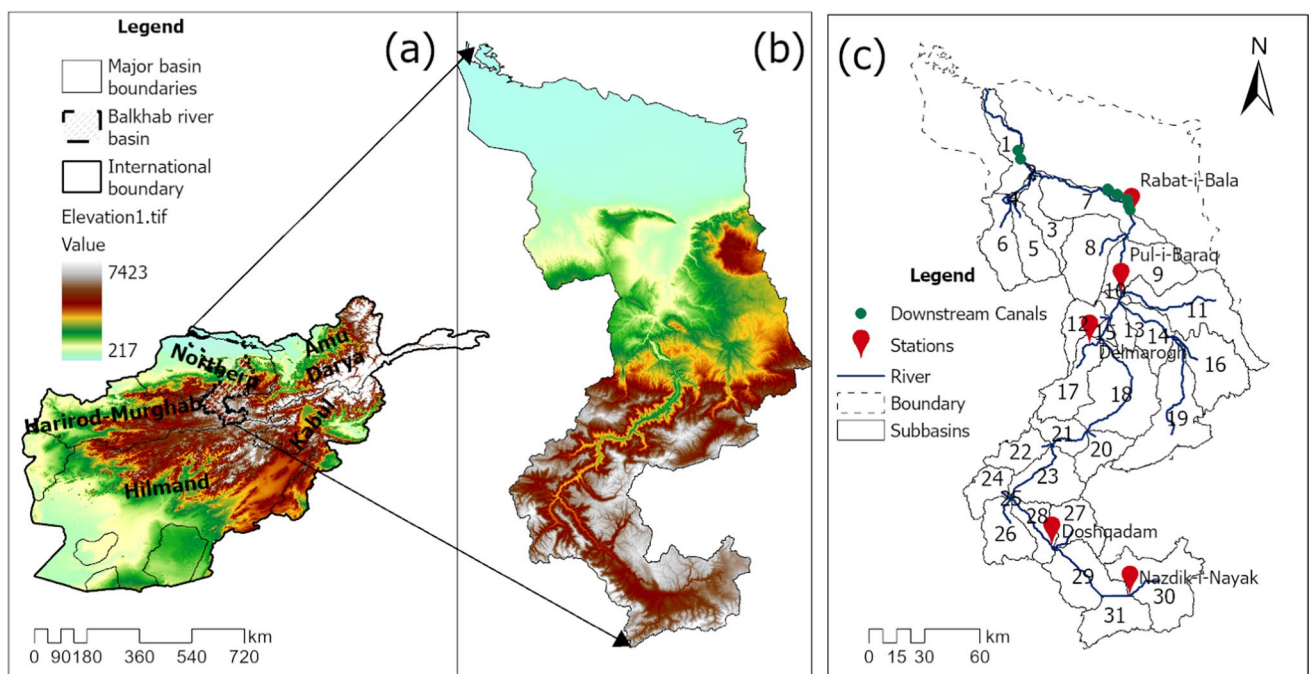
In this study, the SWAT model was used to model the hydrological regime for the study region. The inputs for modelling purposes are climatic data precipitation, relative humidity, maximum temperature, minimum temperature, solar radiation, and wind speed. Also, the digital elevation model

**Table 1** Irrigation land area and water rights for the 11 downstream irrigation canals (NRBA 2019)

No	Canal name	Irrigation land area (ha)	Water allocation (%)
1	Imam Sahib	7741.9	3.80
2	Nahar-i-Shahi	14,005.2	10.66
3	Sia Gird	7702.0	2.85
4	Balkh	8086.6	1.33
5	Moshtaq	9207.1	3.98
6	Chemtal	8003.4	3.12
7	Abdullah	22,866.3	13.32
8	Dawlat Abad	38,728.2	14.27
9	Char Bolak	36,078.3	14.27
10	Fayaz Abad	17,180.5	11.42
11	Aqcha	88,706.0	20.94
Total		258,305.5	100*

\* The water allocation percentage is based on the available stream flow passing Rabat-i-Bala stations

(DEM), land cover, soil type, and canal water allocation were fed to the model. Finally, monthly average discharge was used for model validation purposes. Daily weather data for the maximum temperature, minimum temperatures, precipitation, relative humidity, and river discharge were collected from a hydrometrological station installed in the basin (Figure S1). The solar radiation and wind speed



**Fig. 1** Map of the study area: **a** Afghanistan map showing the five major basins and elevation, **b** Balkhab River basin (BRB) with the Balkhab River, five hydrometeorological stations, and eleven irrigation canal downstream

were retrieved from the NASA Prediction of World Energy Resources in the same coordinates of hydrometeorological stations. Table 2 depicts the summary of the dataset used for the current research.

DEMs were obtained from the ALOS PALASAR Radiometric Terrain Correction (RT1) dataset provided by the Alaska Satellite Facility Distributed Archive Data Center (ASF DAAC) with a spatial resolution of 12.5 m. The land-cover map used for the current study is from the FAO Agricultural Market Information Services System in association with the Ministry of Agriculture, Irrigation, and Livestock, Islamic Republic of Afghanistan (FAO 2016). A proper soil type map does not exist in many parts of the world, but the global soil type maps of Harmonized World Soil Database (HWSD\_v121) and FAO/UNESCO soil map of the world can be used as a substitute (Abbaspour et al. 2019). The FAO/UNESCO soil map of the world with corresponding data was used as input for the SWAT model. This soil map was developed from the World Inventory of Soil Emissions (WISE) database by statistical analysis 4353 soil profiles in the inventory, which was developed at the International Soil References and Information Centre (ISRIC) to provide geographical descriptions of soil factors that influence global change (Batjes 1997). Doe (1962) provided further information and a description of the world's FAO/UNESCO soil map. Meanwhile, a huge portion of the streamflow in BRB is consumed by the agriculture sector. The water allocation to the canals and geographical coordinates for the canal intake are included in the SWAT model from official reports by NRB (NRBA 2019, pp. 24–26).

### Seasonal crop cultivation

Based on the Hussainzada and Lee (2022), the common crop types in northern Afghanistan are wheat, cotton, barley, rice, maize, pulses, vetches, potato, clover, oil seed,

lucerne, vegetables, melons, and opium poppy. In order to synchronize between water delivery patterns and crop life cycle, a proper understanding of crop calendar information is necessary (Murthy et al. 1998). Cropping calendar and crop water requirement can lead us to an accurate estimation of irrigation water demand in the basin on a monthly basis. Afghanistan's irrigation data are scarce and limited for scientific studies. The current study adopted crop water requirements from a recent published study in Khost Province, southern Afghanistan (Wali et al. 2019). Wali et al. (2019) used remote sensing techniques to estimate crop water requirements for 2017. The weather conditions in Khost Province with mean annual temperature 10.4 °C and the mean annual precipitation 188 mm are similar to BRB climate conditions. The crop water requirements from Wali et al. (2019) in different months are summarized in Table S1 in Supplementary material.

### Current irrigation status

The water allocation to the main canals is decided by the local government and managed through irrigation canals by *mirabs*. The data for water allocation to the main canals are collected from the official NRB report (NRBA 2019). However, there is an exception for water allocation to downstream canals due to water scarcity issues during the year. Water allocation amounts for the 11 downstream irrigation canals (Table 1) are based on the available water in the main river. The water allocation of 11 downstream canals (Table 1) were decided based on tax payments and the agricultural land area in each region (G. Sakhi, personal communication, November 2, 2020). The water rights for the 11 canals in the percentage of available water in the main river based on the records in the Rabat-i-Bala (Table 1).

**Table 2** Summary of the datasets used in the SWAT modelling

Datasets	Temporal resolution	Spatial resolution	Source
Precipitation, maximum and minimum temperatures, relative humidity	Daily	–	Ministry of Energy and Water (MEW), Islamic Republic of Afghanistan (Feb-2019)
Solar radiation and wind speed	Daily	–	NASA Prediction of Worldwide Energy Resources ( <a href="https://power.larc.nasa.gov/">https://power.larc.nasa.gov/</a> )
Monthly average discharge	Monthly	–	Ministry of Energy and Water (MEW), Islamic Republic of Afghanistan
Irrigation canal discharge	–	–	Northern River Basin authority (NRBA)
Digital elevation model	–	12.5 m	ALOS PLASAR ( <a href="https://search.asf.alaska.edu/#/">https://search.asf.alaska.edu/#/</a> )
Soil type map	–	–	FAO/UNESCO soil map of the world
Land-cover map	–	–	Ministry of Agriculture, Irrigation, and Live stocks (MAIL), Islamic Republic of Afghanistan

## Methodology

### Irrigation scenario

In this study, a detailed investigation of the current irrigation scheme was conducted, and the irrigation water management was revised as a new irrigation scenario based on land area, crop water requirement, and crop type. The crop type was determined based on the national agriculture profile from 2016 to 2018, and the agricultural land area was consider based on NRB official reports. Per the NSIA (2019), the main cultivated different crops (and associated cultivation areas) are wheat (60.0%), rice (3.3%), barley (3.3%), maize (3.6%), pulses (2.3%), vegetable (4.3%), potato (1%), onion (0.3%), fruits (9.3%), almond (0.6%), oil seed (2.6%), and others (9.4%). The new irrigation scenario proposed by the current study is wheat (65%), rice (5%), maize (5%), pluses (4%), spring vegetables (5%), summer vegetables (4%), and orchards (12%) for entire BRB downstream. In addition, based on the crop water requirements for different crop types (Table S1) and the specified irrigation area for each crop (Table 3), the monthly water requirement for 1 ha of agricultural land is estimated as shown in Table 3.

Table 3 summarizes the water consumption of a single hectare of agricultural land if it is cultivated as the proposed crop type percentage scenario. Estimations show that for irrigation of unit area of land in BRB 4559.5 m<sup>3</sup>/ha/year of water is required. Table 4 shows the current irrigation water allocation and proposed scenario water allocation for 11 downstream canals. The cell with the white background is the water allocation to each canal based on the newly proposed scenario, while the cell with the grey background in Table 4 shows the current water allocation to the canals by NRB. The proposed irrigation scenario is based on the storing water during the winter and high flow behind the storage dam and use it during low flow period with high irrigation water consumption.

### SWAT model set-up with a proposed dam

The SWAT is a semi-distributed physical model capable of predicting the impact of water management, agriculture chemical yield, and sediment in the large watershed on different timescales (Arnold et al. 1998; Duan et al. 2018; Grusson et al. 2015). The model inputs are precipitation, relative humidity, temperature, wind speed, and solar radiation, on a daily basis. The model is capable of computing the output on the temporal resolution of the daily, monthly, or annual timescale. SWAT is widely used for water resource assessment (Guiamel and Lee 2020),

**Table 3** Estimation of monthly irrigation water consumption for 1 ha of agricultural land in BRB downstream adopted from (Hussainzada and Lee 2022)

Crop type	Area (%)	Monthly crop water requirement (m <sup>3</sup> /ha/mon)											
		January	February	March	April	May	June	July	August	September	October	November	December
Wheat	65	213.9	339	514.2	828.75	610.4	76.95	85.5	77.4	61.9	31.3	59	111.2
Rice	5				27.85		42.4	74.95	60.15	18.8			
Maize	5				11		39.52	59.28	26.72	0			
Pulses	4				6.44		49	53.8	42.04	2.32			
Summer vegetables	4				35.08								
Spring vegetables	5		8.4	25.05	58.2	46.8	166	147.1	57.5				
Orchards	12			57	130.8	163.6	373.8	440.8	353.4	140	31.3	59	111.2
<b>Total</b>	<b>100</b>	<b>213.9</b>	<b>348</b>	<b>569.2</b>	<b>1017.8</b>	<b>901.1</b>	<b>373.8</b>	<b>440.8</b>	<b>353.4</b>	<b>140</b>	<b>31.3</b>	<b>59</b>	<b>111.2</b>

**Table 4** Monthly required water allocations for the 11 downstream irrigation canals and required water allocation based on the purposed irrigation scheme scenario

No	Canal name	Irrigation land (ha)	Required canal water allocation (m <sup>3</sup> /s)											
			January	February	March	April	May	June	July	August	September	October	November	December
1	Imam Sahib	7741.9	0.74	1.34	1.97	3.65	3.13	1.34	1.53	1.23	0.50	0.11	0.21	0.39
			<b>1.37</b>	<b>1.47</b>	<b>1.92</b>	<b>3.51</b>	<b>4.30</b>	<b>2.46</b>	<b>1.64</b>	<b>1.24</b>	<b>1.22</b>	<b>1.28</b>	<b>1.39</b>	<b>1.37</b>
2	Nahar-i-Shahi	14,005.2	1.34	2.42	3.57	6.60	5.65	2.42	2.77	2.22	0.91	0.20	0.38	0.70
			<b>3.84</b>	<b>4.12</b>	<b>5.39</b>	<b>9.84</b>	<b>12.05</b>	<b>6.91</b>	<b>4.59</b>	<b>3.47</b>	<b>3.41</b>	<b>3.60</b>	<b>3.91</b>	<b>3.85</b>
3	Sia Gird	7702.0	0.74	1.33	1.96	3.63	3.11	1.33	1.52	1.22	0.50	0.11	0.21	0.38
			<b>1.03</b>	<b>1.10</b>	<b>1.44</b>	<b>2.63</b>	<b>3.22</b>	<b>1.85</b>	<b>1.23</b>	<b>0.93</b>	<b>0.91</b>	<b>0.96</b>	<b>1.05</b>	<b>1.03</b>
4	Balkh	8086.6	0.77	1.40	2.06	3.81	3.26	1.40	1.60	1.28	0.52	0.11	0.22	0.40
			<b>0.48</b>	<b>0.51</b>	<b>0.67</b>	<b>1.23</b>	<b>1.50</b>	<b>0.86</b>	<b>0.57</b>	<b>0.43</b>	<b>0.43</b>	<b>0.45</b>	<b>0.49</b>	<b>0.48</b>
5	Moshtaq	9207.1	0.88	1.59	2.35	4.34	3.72	1.59	1.82	1.46	0.60	0.13	0.25	0.46
			<b>1.43</b>	<b>1.54</b>	<b>2.01</b>	<b>3.67</b>	<b>4.50</b>	<b>2.58</b>	<b>1.71</b>	<b>1.29</b>	<b>1.27</b>	<b>1.35</b>	<b>1.46</b>	<b>1.44</b>
6	Chemtal	8003.4	0.77	1.38	2.04	3.77	3.23	1.39	1.58	1.27	0.52	0.11	0.22	0.40
			<b>1.12</b>	<b>1.21</b>	<b>1.58</b>	<b>2.88</b>	<b>3.53</b>	<b>2.02</b>	<b>1.34</b>	<b>1.01</b>	<b>1.00</b>	<b>1.05</b>	<b>1.14</b>	<b>1.13</b>
7	Abdullah	22,866.3	2.19	3.95	5.83	10.77	9.23	3.96	4.52	3.62	1.48	0.32	0.62	1.14
			<b>4.80</b>	<b>5.15</b>	<b>6.73</b>	<b>12.29</b>	<b>15.06</b>	<b>8.63</b>	<b>5.74</b>	<b>4.33</b>	<b>4.26</b>	<b>4.50</b>	<b>4.88</b>	<b>4.82</b>
8	Dawlat Abad	38,728.2	3.71	6.69	9.88	18.25	15.64	6.70	7.65	6.13	2.51	0.54	1.06	1.93
			<b>5.14</b>	<b>5.52</b>	<b>7.21</b>	<b>13.17</b>	<b>16.13</b>	<b>9.25</b>	<b>6.15</b>	<b>4.64</b>	<b>4.56</b>	<b>4.82</b>	<b>5.23</b>	<b>5.16</b>
9	Char Bolak	36,078.3	3.46	6.23	9.20	17.00	14.57	6.24	7.13	5.71	2.34	0.51	0.99	1.80
			<b>5.14</b>	<b>5.52</b>	<b>7.21</b>	<b>13.17</b>	<b>16.13</b>	<b>9.25</b>	<b>6.15</b>	<b>4.64</b>	<b>4.56</b>	<b>4.82</b>	<b>5.23</b>	<b>5.16</b>
10	Fayaz Abad	17,180.5	1.65	2.97	4.38	8.10	6.94	2.97	3.39	2.72	1.11	0.24	0.47	0.86
			<b>4.11</b>	<b>4.42</b>	<b>5.77</b>	<b>10.54</b>	<b>12.91</b>	<b>7.40</b>	<b>4.92</b>	<b>3.71</b>	<b>3.65</b>	<b>3.86</b>	<b>4.19</b>	<b>4.13</b>
11	Aqcha	88,706.0	8.50	15.31	22.62	41.80	35.81	15.35	17.52	14.05	5.75	1.24	2.42	4.42
			<b>7.54</b>	<b>8.10</b>	<b>10.58</b>	<b>19.33</b>	<b>23.67</b>	<b>13.57</b>	<b>9.02</b>	<b>6.81</b>	<b>6.70</b>	<b>7.08</b>	<b>7.68</b>	<b>7.57</b>
<b>Total</b>		258,305.5	24.75	44.59	65.87	121.71	104.28	44.70	51.01	40.90	16.74	3.62	7.06	12.87
			<b>36.00</b>	<b>38.66</b>	<b>50.51</b>	<b>92.26</b>	<b>113.00</b>	<b>64.78</b>	<b>43.06</b>	<b>32.50</b>	<b>31.97</b>	<b>33.77</b>	<b>36.65</b>	<b>36.14</b>

The cell with white background shows the water requirement for new irrigation scheme included 20% loss of water in the irrigation system while the cell with bold values shows the current water allocation by BRB

evaluations of non-point source pollution, and climate change in relation to water supplies and watersheds (Adu and Kumarasamy 2018; Reddy 2019). The model predicts surface runoff based on a water balance equation (Eq. 1).

$$SW_t = SW + \sum_{i=1}^t (R_i - Q_i - ET_i - P_i - QR_i) \quad (1)$$

where  $SW_t$  and  $SW$  are the respective final and initial soil water contents at time  $t$ , respectively;  $R$ ,  $Q$ ,  $ET$ ,  $P$ , and  $QR$  are daily precipitation, runoff, evapotranspiration, percolation, and the return flow, respectively; and all units are mm of  $H_2O$ .

The major procedure for the SWAT hydrological model set-up and sustainable water resource management using AHP for decision-making over BRB watershed is shown in Fig. 2.

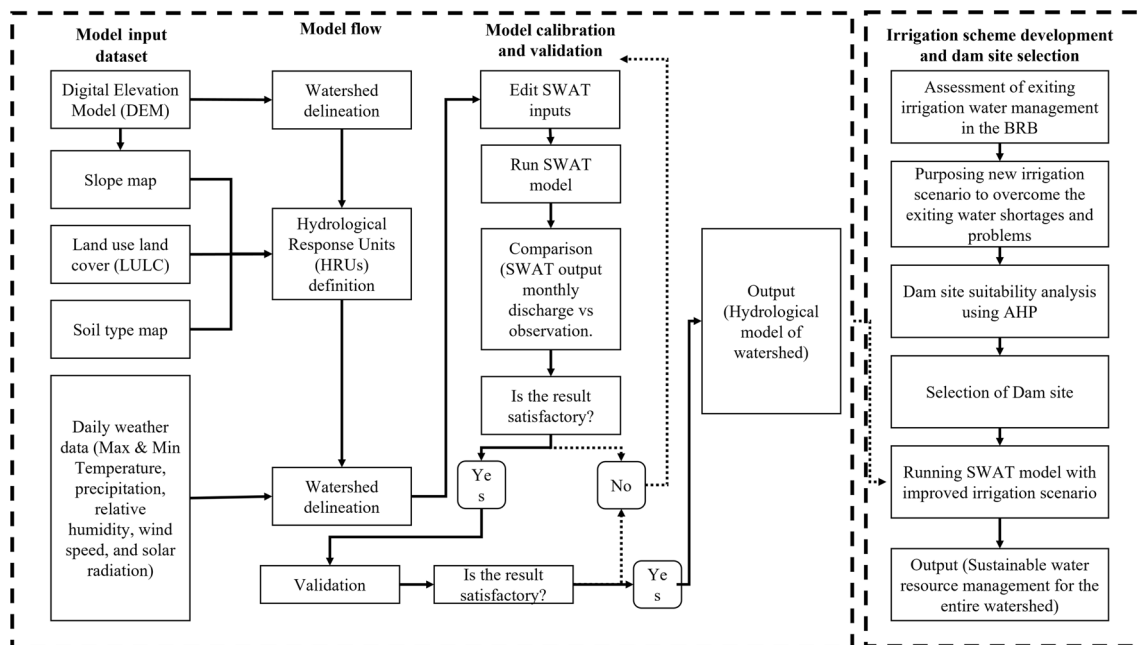
**Step 1.** Watershed delineation: The SWAT in ArcGIS Desktop interface was used for stream flow simulation. In this step, the watershed was divided into smaller 31 subbasins with DEM as a input to the model.

**Step 2.** Hydrological response units (HRUs) definition: Land use–land cover, soil type, and slope maps were used to divide the 31 subbasins to smaller units with homogeneous characteristics. In this

step, the 31 subbasins were divided into 1,532 HRUs.

**Step 3.** Creating input tables: The weather data were entered as the input data for the streamflow simulation into model database from 2010 to 2018 with daily resolutions.

**Step 4.** Calibration and validation: Parameter optimization was performed for the SWAT model using the SWAT Calibration and Uncertainty Procedure (SWAT-CUP) v5.2.1 (Abbaspour 2007) and the Sequential Uncertainty Fitting Algorithm (SUFIA2) for model calibration and uncertainty analysis. The SUFIA2 details were presented by Homan et al. (2011) and Abbaspour (2007). The model was run for the entire BRB within three-time periods; three years warmup period (2010–2012), three-year calibration period (2013–2015), and two-year and nine-month validation period from January 2016 to September 2018. The model calibration and validation were based on the monthly average streamflow observations recorded on the subbasins 7, 10, 28, and 30 on the Rabat-i-Bala, Pul-i-Baraq, Doshqadam, and Nazdik-i-Nayak stations respectively. The SWAT hydrological model of BRB used for testing the improved irrigation scenario purposed in the current study. The SWAT hydrological model of BRB is adopted from a



**Fig. 2** Methodological flow chart for hydrological modelling with SWAT and sustainable water resource management and dam site suitability analysis using AHP

previous study over BRB from Hussainzada and Lee (2021).

### Dam suitability assessment using analytical hierarchy process (AHP)

Dam suitable sites is the primary water resource management strategy (Karakuş and Yıldız 2022). A quantitative assessment for Dam site selection depends on multiple criteria, such as soil type (*S*), drainage (*D*), slope (*Sl*), elevation (*E*), and land use–land cover (*LULC*). Furthermore, in this study, appropriate areas of the dam site were identified using GIS and AHP under the multi-criteria decision analysis (MCDA). The list of criteria was preselected by the author’s decision. The level of importance of each criterion was identified using expert opinions. The questionnaire was sent to 13 experts in the field via email and 10 of them were used as the source for ranking the criteria and three of them were inconsistent. Below is the list of criteria and its description. Natural break method was adopted for the classification of the criterion to very low, low, medium, high, and very high suitable for dam construction, and the result is given in Table 5.

- **Soil:** Soil type and hydrological soil classification are significant factors in determining an area's water holding and infiltration characteristics (Cabrera and Lee 2018). The harmonized world soil database was used for this purpose.
- **Discharge:** The amount of water flow in the river (m<sup>3</sup>/s). The river discharge comes from the precipitation, snow-melt, and groundwater flow in the Basin (Hussainzada and Lee 2021).
- **Slope:** When the slope increases, the flow velocity will also increase. A rise in the gradient lowers infiltration but increases surface runoff; as a result, in areas with a lower gradient, a large volume of water gets stagnant, resulting in flooding (Lei et al. 2020).
- **Elevation:** The movement of the overflow direction and the depth of the water level are controlled by the elevation (Al-Ruzouq et al. 2019).

- **Land Use and Land Cover:** The built-up area and agricultural lands are less desirable for the dam construction while the barren land has higher desirability because of the land price.

The pairwise comparison matrix is the first step in the AHP method. Each criterion was compared to another criterion from the 1–9 scale from Saaty (1980). In this paper, we adjusted the scale from one to five based on the number of criteria of the study. The second step is the normalization, where each value in the comparison matrix (*C<sub>ij</sub>*) is divided by the sum of column in the pairwise comparison matrix to get the normalized value (*X<sub>ij</sub>*) (Eq. 2).

$$X_{ij} = C_{ij} / \sum_{i=1}^n C_{ij} \tag{2}$$

The next step is to generate the weight of each criterion (*W<sub>ij</sub>*) by dividing the normalized value (*X<sub>ij</sub>*) by the number of criterion (*n*) (Eq. 3).

$$W_{ij} = \sum_{i=1}^n X_{ij} / n \tag{3}$$

The consistency ratio is the last part in the AHP procedure with three subcomponents. The first subcomponent is to determine the consistency measure (*CM*). *CM* can be derived by multiplying the pairwise matrix with the weight (*W<sub>ij</sub>*), and the result is divided by the weighted sum vector with the criterion weight. Next, the consistency index (*CI*) is calculated using Eq. 4, where the  $\lambda_{max}$  is the average of the *CM* and *n* is the number of criteria. Finally, the consistency ratio (*CR*) is derived using Eq. 5, where the value of the relative index (*RI*) is defined in the relative index table of Prof. Saaty (1980).

$$CI = (\lambda \max - n) / (n - 1) \tag{4}$$

$$CR = CI / RI \tag{5}$$

**Table 5** Summary of the criteria classification used for the AHP

Criteria	Classification [suitability level]				
	Very low [1]	Low [2]	Moderate [3]	High [4]	Very high [5]
Elevation (m)	3054–4621	2255–3054	1439–2255	706–1439	241–706
Discharge (m <sup>3</sup> /s)	0.03–0.61	0.62–2.59	2.60–5.11	5.12–19.89	19.90–50.18
Slope (deg)	39.30– 83	26.64–39.30	16.24–26.63	7.4–16.24	0.1–7.5
LULC	Built-up	Agriculture	Forest	Water Bodies	Barren Land
Soil	-	Rock outcrops (RK)	Coarse and rocky soil (LP)	Sandy clay loam (AR)	Silt loam (CL)



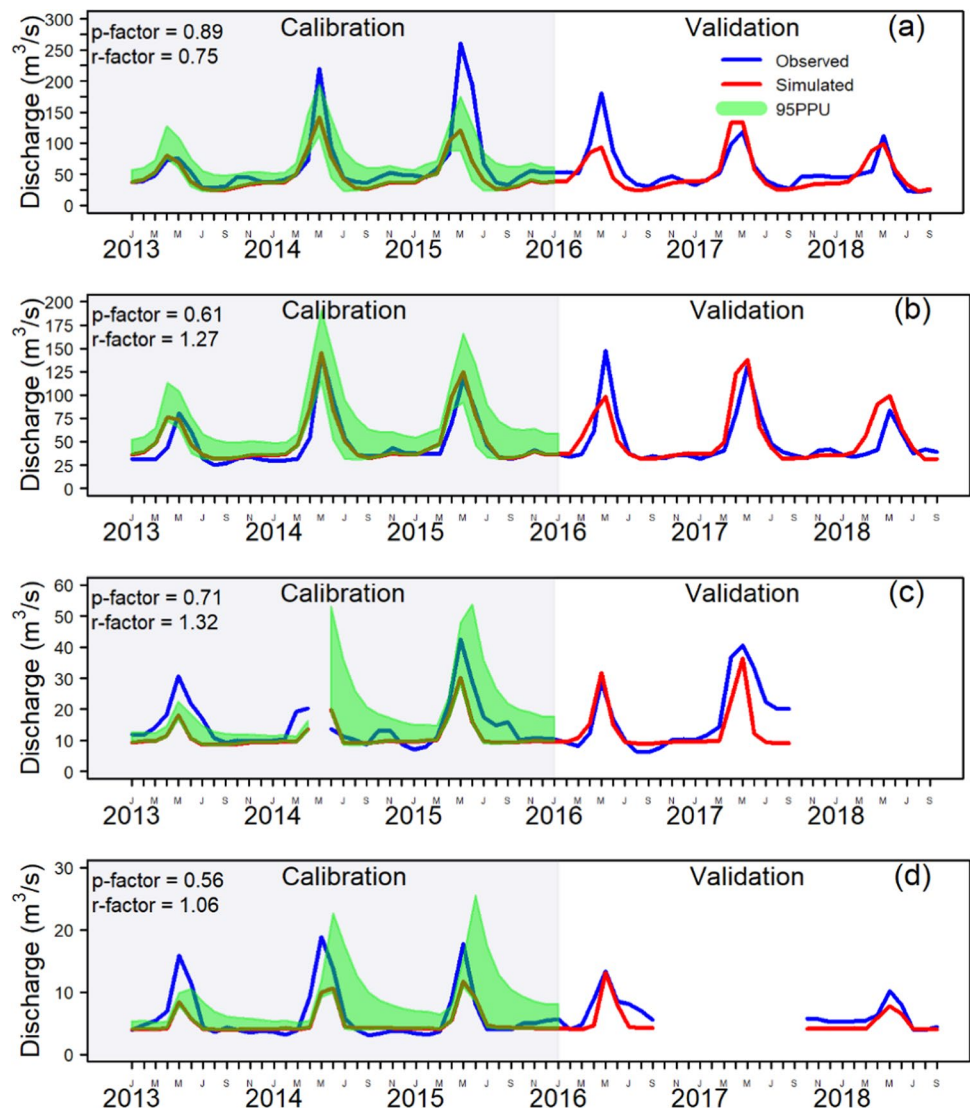
## Results

### SWAT model calibration and validation

The SWAT model was set up using ArcGIS Desktop as the platform with three years of warmup period, three years for calibration, and two years and nine months for the validation from January 2010 to September 2018 using SWAT-CUP. Firstly, the model was calibrated using an elevation band; secondly, the snow parameters were calibrated; then, the most sensitive parameters were selected for the calibration. Seven parameters were found to be the most sensitive parameters, namely threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), groundwater “revap” coefficient (GW\_REVAP), groundwater delay (GW\_DELAY), available water capacity for the soil layer (SOL\_AWC), SCS runoff

curve number (CN2), soil evaporation compensation factor (ESCO), and saturated hydraulics conductivity (SOL\_K). The river discharge baseflow is affected by seepage and spring water discharge, especially during the dry season between July to September. Since there was no record of the river discharge, the point-source station discharge records were used to estimate the contribution of groundwater and spring to the flow. The hydrograph in Fig. 3 shows the comparison between model output and monthly observations for river discharge in the four stations in sub-basins 7, 10, 28, and 30 (Fig. 1c). The model performance was assessed using the coefficient of determination ( $R^2$ ), Nash–Sutcliffe efficiency (NSE) (Nash and Sutcliffe 1970), and per cent BIAS (PBAIS) (Gupta et al. 1999) in the four stations from upstream to downstream in the BRB. The SWAT modelling results exhibit a good agreement with the station’s monthly discharges. Statistics for model performance are summarized in Table 6. The model is

**Fig. 3** Comparisons between the observed and simulated monthly discharge in **a** subbasin 7 [Rabat-i-Bala], **b** subbasin 10 [Pul-i-Baraq], **c** subbasin 28 [Doshqadam], and **d** subbasin 30 [Nazdik-i-Nayak] for calibration and validation period



**Table 6** Summary of statistical indicators for model performance

Subbasin	Calibration			Validation		
	R <sup>2</sup>	NSE	PBIAS	R <sup>2</sup>	NSE	PBIAS
7	0.70	0.52	23.4	0.63	0.58	10.7
10	0.86	0.83	-8.5	0.66	0.61	-4.6
28	0.67	0.40	23.4	0.58	0.47	20.2
30	0.80	0.57	17.5	0.76	0.43	20.2

**Table 7** Pairwise comparison matrix for dam suitable assessment based on the expert’s opinion

CRITERIA	D	S	SL	E	LULC
Discharge (D)	1.00	2.00	2.00	2.00	2.00
Soil (S)	0.49	1.00	2.00	2.00	2.00
Slope (SL)	0.53	0.64	1.00	2.00	2.00
Elevation(E)	0.40	0.55	0.50	1.00	2.00
LULC	0.48	0.45	0.44	0.47	1.00
Sum	2.90	4.69	5.40	7.78	9.72

adopted from Hussainzada and Lee (2021). Please refer to Hussainzada and Lee (2021) for more details on the process and result for calibration and validation.

**Site identification using AHP**

This section presents the result of the AHP expert opinion in determining the suitable dam site location. Moreover, Table 7 shows the pairwise comparison matrix for the aggregate results from the consistent responses. Table 8 shows the normalized information with the column (Weight) containing the relative importance weights of every criterion. This study’s *RI* and  $\lambda_{max}$  values are 1.12 and 5.15, respectively. Moreover, the *CR* value is 0.033, indicating a level of coherence in comparing each criterion. Finally, the suitability index (*SI*) using GIS and remote sensing technology was calculated on Eq. 6. This equation is derived from the AHP weights, as shown in Table 8.

$$SI = D \times 0.33 + S \times 0.23 + SL \times 0.20 + E \times 0.14 + LULC \times 0.10 \tag{6}$$

**Table 8** Matrix normalization with the weights and consistency measure (CM)

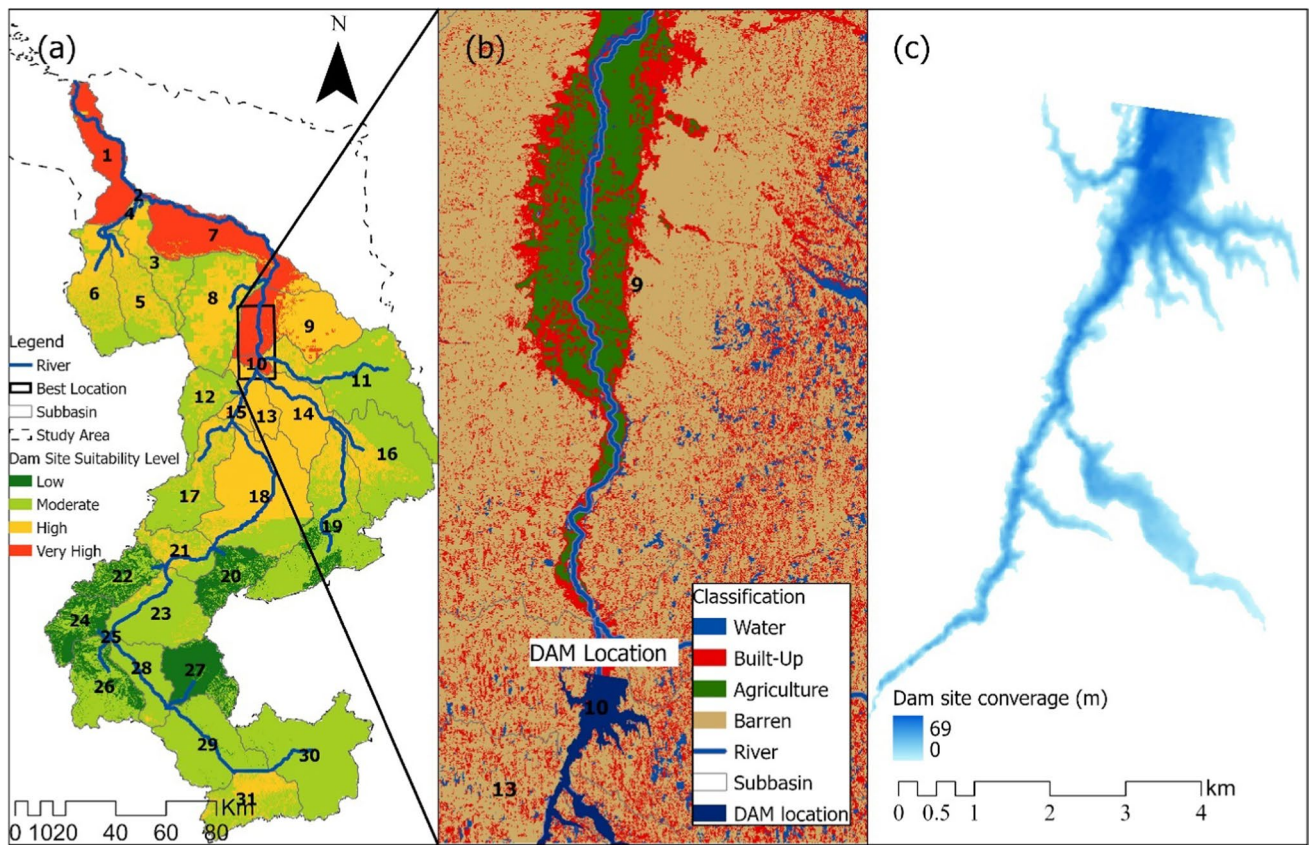
CRITERIA	D	S	SL	E	LULC	CM	Weight
Discharge (D)	0.35	0.44	0.35	0.32	0.22	5.20	0.33
Soil (S)	0.17	0.21	0.29	0.24	0.23	5.20	0.23
Slope (SL)	0.18	0.14	0.19	0.25	0.23	5.17	0.20
Elevation(E)	0.14	0.12	0.09	0.13	0.22	5.12	0.14
LULC	0.16	0.10	0.08	0.06	0.10	5.10	0.10
Sum	1.00	1.00	1.00	1.00	1.00	-	1.00

The output of the AHP process for the dam site suitability analysis is shown in Fig. 4. In Fig. 4a, based on the specified criteria and its importance, the suitable area for dam construction is dedicated by red colour. The subbasins 10, 9, 7, and 1 are found to be most suitable for dam construction. The authors tentatively select subbasin 10 as the best location for dam construction. The reason behind this selection is that BRB is mountainous in the southern part, and most of its flat area is in the northern part of BRB, where suitable lands for the agriculture exist. Selection of dam in the most upstream gives more chance for land development in the dam downstream. Figure 4b is LULC prepared using the Landsat 8 level 1 imagery for more detail of the area and location of the dam. The author decides to locate dam in the southern part where the agricultural land and built-up are in minimum and most of the surface coverage is barren land to reduce the land cost for the dam construction project. As shown in Fig. 4c, the dam located in subbasin 10 with an estimated height of 69 m of water can store 197,900,938 m<sup>3</sup> of water and will submerge an area of approximately 748 ha and a length of 1600 m. The mentioned capacity is chosen because the water shortage for irrigation water supply happens in three consecutive months February, March, and April. The total difference between supply and required water for the current conditions estimated to be 131,820,480 m<sup>3</sup>. The extra storage is considered to be used for flood control and storage of surplus water.

**Water resource management**

**Irrigation water management**

As per Hussainzada and Lee (2022), the irrigation water allocation in the BRB is determined based on the tax and



**Fig. 4** Dam site suitability map using AHP: **a** dam site suitability level map on the subbasins level, **b** land-use/land-cover map created using Landsat 8 satellite images using support vector machine, **c** spatial extension of water in case of dam construction in subbasin 10

agricultural land and available water in the river for each month. (Refer to Table 1 for the percentage of water allocation to each canal in the BRB downstream.) The comparison between the current and proposed irrigation scenarios in Hussainzada and Lee (2022) shows that the BRB downstream farmers face water shortages during February, March, April, July, and August and extra water in other months than the irrigation consumption. The most significant water shortage happens during the three consecutive months in February, March, and April with shortage of 138, 820, 480 m<sup>3</sup> for irrigation. The annual average flow in subbasin 10 was estimated as 1.578 × 10<sup>9</sup> m<sup>3</sup> by the SWAT model from 2013 to 2018. Additionally, the irrigation water requirement in the BRB was estimated to be 1.395 × 10<sup>9</sup> m<sup>3</sup> including 20% loss in the irrigation channels (Hussainzada and Lee 2022). The dam can regulate the water flow for entire year to fill the gap between the consumption and natural flow in the river.

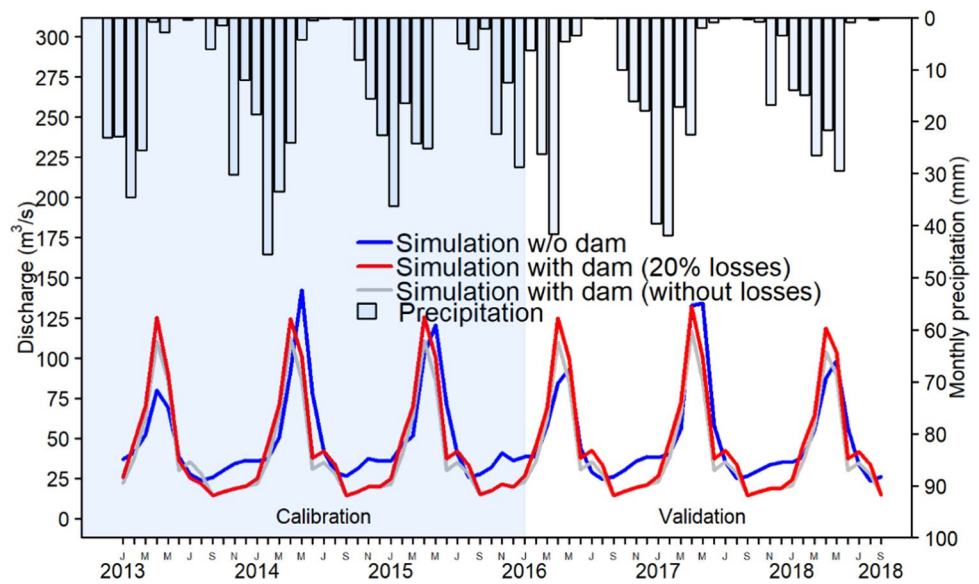
Figure 5 illustrates the hydrograph in the subbasin 7 under three different conditions: (1) the blue line represent the river flow in the subbasin 7 in the current condition, (2) the red line shows the controlled river flow by dam constructed in the subbasin 10 and release water based on the existing crop water requirements plus 20% possible water

loss in the irrigation canals and releasing of a minimum 20 m<sup>3</sup>/s during non-irrigation months to maintain the downstream ecosystems, and (3) grey line represent the ideal case of no water loss in the irrigation canals. The calculation based on Table 4 and considering the scenario of releasing at least 20 m<sup>3</sup>/s of water during the non-irrigation period shows that the Balkhab River owns a surplus water of approximately 84 × 10<sup>6</sup> m<sup>3</sup>. As a possible scenario, the surplus water can be used for the irrigation of 17,180.5 ha of new arable land in the BRB (Hussainzada and Lee 2022).

### Hydroelectricity generation

The dam can be used for multiple purposes. Energy generation is one of the possible surplus uses of the dam. A Dam with 69 m head and annual flow of 1.578 × 10<sup>9</sup> m<sup>3</sup> has a theoretical capacity of generating 25.4 MW or 87, 840 MWh of energy based on Eq. 7 if we consider the annual average flow from the dam. Considering the dam outflow schedule in Table 4, the minimum and maximum discharge are 131 m<sup>3</sup>/s and 31.97 m<sup>3</sup>/s which can generate 66.5 MW and 16.23 MW respectively. As per Ahady et al. (2022), the residential energy consumption in Mazar-i-Sharif, Afghanistan

**Fig. 5** Resulting hydrographs from subbasin 7 with (red) and without (blue) dam inclusion in subbasin 10



is 236,526.3 kWh for cooling, heating, lightening, and domestic hot water usage. The population of Mazar-i-Sharif is 584,886 (NISA, 2020). The generation from the dam is 37 times bigger than the demand for the Mazar-i-Sharif which is one of five big cities in Afghanistan.

$$P = g \times H \times Q \times \text{Efficiency} \quad (7)$$

where the  $P$  is power generated in KW,  $g$  is the gravitational acceleration ( $9.81 \text{ m/s}^2$ ),  $H$  is effective head (m),  $Q$  is the amount of water flow ( $\text{m}^3/\text{s}$ ), and efficiency is how well the turbine and generator convert the power of falling water into electric power. The average flow from dam is  $50.04 \text{ m}^3/\text{s}$ , and the efficiency of the turbine and generator are between 95 and 75% where to be in safe side the lower range were included in the estimation.

### Water supply

The river has a surplus flow of  $84 \times 10^6 \text{ m}^3$  flow after irrigation of the existing lands. In this study, the urban population living in BRB are targeted as the consumer of the water supply system. The urban population in the BRB was reported at 584,886, and the population growth rate was reported at 2.14% (NISA 2020). If we consider the geometric population growth in Eq. 8, the projected population of BRB in 50 years will be 1,686,024. Afghanistan Ministry of Urban Development and Land determined the per capita demand for water supply as 140 l/day/person. The estimation shows that 86,155,856  $\text{m}^3$  is sufficient for the water consumption of the urban population in 2070. The surplus water in the BRB is almost sufficient for a water supply project with 50-year life span.

$$P_t = P_0(1 + r)^n \quad (8)$$

where  $P_t$  is the projected population at time  $t$ ,  $P_0$  is the initial population,  $r$  is the population growth rate, and  $n$  is the number of years for the future projection.

### Flood control

The Balkhab River experiences the highest flow in May ( $113 \text{ m}^3/\text{s}$ ) due to rapid snowmelt and rainfall (Hussainzada and Lee 2022). The driest month in the basin is September, with an average total monthly flow of  $31.97 \text{ m}^3/\text{s}$ . The most extreme flood events were recorded ( $1190 \text{ m}^3/\text{s}$ ) in the Rabat-i-Bala station during May 2014 (Figure S1), and the accumulated volume of water within a day was 102 million  $\text{m}^3$ . The capacity of the dam is approximately 192 million  $\text{m}^3$ . Therefore, the volume of water in the extreme event is only 53% of the dam's capacity. Then, add the 84 million  $\text{m}^3$  as surplus water based on the result in Sect. 4.3.1. The total volume of water is 196 million  $\text{m}^3$ . Thus, the overflow is only 4 million  $\text{m}^3$  which the dam outflow rate can handle. The dam can control the water flow during extreme scenarios and reduce the damage downstream.

### Cost-benefit analysis (CBA)

An estimation of the costs and benefits of the dam is presented in Table 9. The construction cost was estimated based on similar dams constructed in Afghanistan. In western Afghanistan, the Salma dam construction was finished in 2016 with a capacity of 640 million  $\text{m}^3$ , and electricity generation of 42 MW costs 290 million USD (BBC 2016). Comparing the Salma dam reservoir capacity and electricity generation capacity BRB dam is almost one-third in size

**Table 9** CBA results for the dam construction with an effective life span of 50 years

Cost		
No	Description	Amount (USD)
1	Construction	89,600,000
2	Operation and Maintenance (2.5% of construction costs)	2,241,846
3	Land Acquisition	3,550,889
	<b>Total</b>	<b>95,392,735</b>
Benefit		
6	Hydroelectric Energy	623,011,200
7	Irrigation Water	226,826,994
8	Municipal and Industrial Water Supply	11,165,798
9	Reduction of Flood Losses	79,411,764
10	Fishery and Recreational Benefits from Reservoirs	7,570,500
	<b>Total<sup>1</sup></b>	<b>721,159,262</b>
	<b>Total<sup>2</sup></b>	<b>936,820,458</b>

The decision-makers should consider using surplus water for the irrigation or water supply. Total<sup>1</sup> is the benefits for the developing water supply system case and total<sup>2</sup> is the benefit in case of agricultural land development

and will roughly cost 89.6 million USD. The operation and maintenance of the dam will cost 1.5–2.5% construction cost (Paul Lako, Giorgio Simbolotti, 2010). The price for a single hectare of land was determined based on the interview with local people to be 10,130 USD/ha in subbasin 10.

On the other hand, the electricity price is 0.056 USD/kWh. The price for the agricultural products were estimated based on the market price in Afghanistan, and the agriculture products were estimated based on the yield of agriculture products per hectare of land. The average revenue of 20% was consider as farmer profits. The municipal and industrial water supply price is currently 0.36 USD/m<sup>3</sup>. There is no record for the flood damage in region scales. However, the annual flood damage in Afghanistan estimates at 54 million USD, and we consider the flood damage as total damage divided by the number of provinces times 50 years. The revenue for the fishery was compared with the Darunta dam located in eastern Afghanistan.

## Discussion

### Economical impact of dam reservoir

Most BRB residents rely on the agriculture sector and agriculture activities. Farming is one of the low-income activities in the country. The agriculture sector makes up 18.6% of the country's GDP, while 80% of the population is directly or indirectly engaged in agricultural activities (Hussainzada and Lee 2021). Farmers lose their agricultural products near harvesting time due to lack of water, or they do not cultivate the total capacity of their land

from the beginning. The severe water shortages made the farmers move to the big city and engaged labour work for their livelihood. The construction of the BRB dam can improve the farmers' economic condition. The adequacy of water can let the farmers shift to more profitable products and use the full capacity of their land. Regulation of the water under a controlled hydraulics structure can encourage the farmers and investors to invest more in the agriculture sector. Currently, farmers use traditional agricultural techniques for farming and irrigation. Cheap manpower is being used instead of agricultural machinery, and the most used irrigation system are earth open channels and surface irrigation. A more stable water source can change the agriculture sector to more mechanized modern techniques and increase product yields.

The cost and benefit analysis shows that the dam construction is economically feasible. The dam's construction can affect the resident's daily life by providing sustainable irrigation and water supply. A sustainable source of irrigation can improve the farmers' economic status and prevent them from migrating to the urban area by increasing the incomes from the agriculture sector. The power generation from the dam can provide the energy source to the resident and in case of connection to the power grid for the neighbouring provinces. Energy generation alone can provide enough revenue to cover the costs of the dam. Besides, dam construction can substantially reduce the flood risk downstream, causing the fatality and loss of agricultural products, livestock, and residents' shelter. In addition, the resident can benefit from the improvement in the fishery and recreational activities in the dam site and neighbourhood.

## Downstream water resource development

Proper water resource management in the basin with limited amounts of water is essential for the sustainable development and improvement of the residents' livelihoods. The scholars used a similar approach for water resource management also. For example, Talebi et al. (2019) used the SWAT model analytical network process (ANP) to determine the suitable location of underground dams for subsurface flow in Iran. Another study evaluates the rainwater harvesting system using the SWAT model and MCDA in Iran (Doulabian et al. 2021). In this study, the SWAT was used as a tool to simulate the streamflow and test the proposed solution. In the current study, SWAT modelling was coupled with MCDA to solve the irrigation water management issues at the basin level.

On the other hand, the dam can be used for power generation. Afghanistan installed capacity during 2020 was 1030.87 GWh, while the country imports from neighbouring countries was 5151.87 GWh. The construction of the multi-purpose dam can fulfil the country's energy requirements and improve the country's economy through job creation and power independence. As it is already discussed in Sect. 4.3.2, the capacity of power generation from the dam is 37 times bigger than the demand in the urban area located in the BRB.

The BRB residents rely on groundwater for their water supply. They use shallow to deep wells to extract the water for domestic usage. The high demands in recent decades caused groundwater degradation and groundwater table reduction, especially in the populated urban area. It is possible for the local government to use the irrigation surplus water for the water supply consumption of the urban area. The estimation in Sect. 4.3.3 shows that the Balkhab River can provide the domestic water demand for population until 2070. However, more detailed studies are required for the water quality and project feasibility.

The construction of the dam will reduce the risk of flooding in the downstream and lessen the lost in the agriculture products, livestock, and reduce casualties. BBR will directly benefit from the dam by increasing agricultural products, stable water supply sources, renewable energy production, and downstream flood control. Indirectly, the construction of dams will create lots of jobs in construction, operation, and maintenance. The other benefits from the dam construction are the increase in food security for the country, providing more income for local communities from recreational activities, fishery, and reduction in CO<sub>2</sub> emission.

## Conclusions

This study presents a package for water resource management in the less developed basin. The study contents start with hydrological modelling in the basin and

a consequence of other studies for sustainable water resources management in the basin with low precipitation and limited water resources. The basin's hydrological model is used to determine the basin's hydrologic regime and find the strong and weak points of the stream flow. Consequently, current water management practices in the basin were analysed to find the gaps in the management. After identifying the problems and evaluating the resources, engineering-based solutions were proposed and tested in the basin using the hydrological models already prepared. After testing the proposed mitigation, further detailed studies were conducted to develop the possible management practices for the existing resources.

AHP was used to determine the suitable site for dam construction. Then, the dam reservoir capacity (192 millionm<sup>3</sup>) and height (69 m) were measured using remote sensing techniques. The mitigation scenarios to overcome water shortages were estimated, and possible usage for the surplus water (84 millionm<sup>3</sup>) was proposed in the current study. The surplus water can be used for electricity generation, domestic water supply, and agriculture land development. Finally, a CBA was included in determining the feasibility of implementation for the proposed solutions.

The outcomes of the current study could be used for the primary investigations in the basins with limited water resources which faced the water shortage for irrigation activities. Specifically, the content of the current study could be used as the starting point for the decision-makers in developing the BRB. The outcomes show that not only the BRB owns a sufficient amount of water resources for current activities but also there is a potential of further development in case of proper management of existing resources.

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1007/s13201-022-01850-w>.

**Acknowledgements** The first author is supported by the Project for the Promotion and Enhancement of the Afghan Capacity for Effective Development (PEACE), JICA, Japan. The authors would like to thank the members of Coastal Hazard and Energy System Science (CHESS Lab), Hiroshima University for their kind support and feedbacks for improving the content, especially Mr. Chisale Sylvester William.

**Author's contributions** WH, JSC and ATS were involved in conceptualization, methodology, software, data curation, writing and preparing the original draft, visualization, and investigation. HSL was responsible for supervision, conceptualization, methodology, investigation, and writing, reviewing, and editing.

**Funding** The first author is supported by the Afghan PEACE programme of the Japan International Cooperation Agency (JICA), Japan.

**Data availability** Available upon requests.

**Code availability** Not applicable.

## Declarations

**Conflict of interests** The authors declare that they have no conflict of interest.

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