Assessing basin blue-green available water components under different management and climate scenarios using SWAT

[Short title: Assessing basin blue-green available water components]

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- Using SWAT model, the proposed methodology is capable to 1) assess spatial and temporal variations of blue and green available water components within an integrated framework and 2) evaluate impacts of climate and management scenarios on available water.
- Application of the modelling setup for the case study showed very applicable information for management of its water resources, such as sensibility of the basin's green and blue water to climate variability/change or how the exploitation of its major dam has changed blue water.

Abstract
Because the pattern of climate and water demand varies, available water (AW) must be determined to facilitate policymaking and to prepare for sustainable use of water resources. This study investigated the components of basin water availability using a comprehensive water balance framework based on SWAT model. The resulting system is capable of supporting systematic presentation of the current status and past trends in the components of AW, presentation of interlinkages of blue and green water components, assessment of measures on AW at farm and basin scales, spatial and temporal variations of AW components under different water policies and climate scenarios and evaluation of water shortage. To explore this methodology, the system was applied to the Tashk-Bakhtegan basin (Iran). The results for the historical period showed wide ranges for the blue water components, which was 113 mm on average. While it was 48.2 mm for green water components. Similarly, blue water was more sensitive than green water to the future annual precipitation variations. Evaluation of the construction of the Durodzan dam (the basin's major water storage facility) showed that it has drastic impact on the spatial blue AW components. Such that they are increased in the adjacent subbasin up to 97% and reduced to half the status quo in the downstream subbasins. The basin has also experienced 30% increase in its cropped areas between 1987 and 2015 that has resulted 1500 MCM water shortage in the current condition. Considering the framework as a relatively easy-to-use tools with readily available data, is strongly recommended for other regions.

Kewords: Available water, green-blue components, integrated framework, SWAT model, Tashk-Bakhtegan Basin

1. Introduction

It is a widely believed that the sustainability of freshwater supplies is affected by increases in water demand and ongoing changes in climatic conditions. Management decisions pertaining to sustainable water require accurate understanding and updated information about available water (AW) (Padowski & Jawitz, 2012; Koshida *et al.,* 2015). Various definitions of AW have been offered in the literature. In general, it is the amount of fresh (often blue) water that is available for human consumption. AW encompasses the dynamic cycle of rainfall and hydrological responses as well as different management measures like agriculture practices and engineered infrastructure (storage or diversion of water) that eventuality effect temporal and spatial variations in accessible water (Rijsberman, 2006; Tidwell *et al.,* 2012; Raeisi et al., 2019).

Component proxies have been also formulated that can provide insight into specific aspects of AW (Tidwell *et al.,* 2012). The concept of blue and green water resources can be helpful, too that was first proposed by Falkenmark (2006). Blue water is the sum of river discharge and deep aquifer recharge (surface runoff and groundwater formed by precipitation) and also can include temporary storage in lakes and reservoirs. Green water includes green water flow (actual evapotranspiration) and green water storage (soil moisture content) (Falkenmark & Rockstrom, 2004; Schuol *et al.,* 2008). Studies have reported that blue and green water resources change in response to human activity, which can alter water cycle dynamics and the proportion of blue and green water in a river basin (Faramarzi *et al.,* 2009; Pokhrel *et al.,* 2012; Porkka *et al.,* 2016). An increase in green water shortage may cause an increase in irrigation demand (blue water). Because irrigation is mainly derived from blue water resources, this can increase evapotranspiration and decrease streamflow (Veettil & Mishra, 2018). Appendix A lists the AW definitions of different proxies classified according to blue water (BW) and green water (GW) components. Eventually, using these concepts, unused blue/green AW or even pressure on them can be detected for new development or mitigation measures (Tidwell et al., 2016, 2018). Considering the table, it is seen that AW have been considered from different aspects using green and blue water resources.

Additionally, the focus of some researches has been on hydrological cycles and "renewable water" as the difference between the received precipitation and evaporation (FAO, 2003). From this perspective, the European Environmental Agency considers freshwater resources as river flow, and water storage as snow and in glaciers (EEA, 2009). This approach assesses the basin hydrological response to climate and land conditions (Jaramillo & Destouni, 2014). In fact, researchers who follow a renewable water approach consider water resources that have not yet been exploited as being available, regardless of the feasibility of use. For green water, not all renewable AW can be provided for use. Unused evaporation and soil retention in excess of plant uptake ability are portions of AW that cannot be counted on as useful.

A deficiency in previous approaches is that technical limitation and environmental restrictions on the use of water resources mean that not all resources could or should be considered to meet water demand. In light of such limitations, another approach has been developed in which available water is examined more closely in terms of "exploitable or utilizable water" resources. FAO Report 23 on Country Water Resources is an example in which "use and exploitation" has been substituted for "water offer". However, a limitation of this method is its lack of widespread use at basin scale and failure to consider non-renewable groundwater (FAO, 2003). Furthermore, the role of return flows in surface-groundwater interactions and consequently on AW (i.e. blue water yield) are crucial (Ahmadzadeh et al., 2015; Raeisi et al., 2019).

Stored blue AW also requires consideration. In many basins today, infrastructures such as dams, flood control and hydropower production (Vörösmarty & Sahagian, 2000) as well as change-release scheduling to reduce the effect of drought (Padowski & Jawitz, 2012; Wanders & Wada, 2015) can affect hydrological systems and increase storage capacity (AghaKouchak *et al.,* 2016). However, most studies have focused only on surface water resources because there are often no accurate estimates of groundwater recharge rates (Xu & Wu, 2017). “Green water storage” also should be considered for its role in rainfed crop production and ecosystem services (Schuol *et al.,* 2008).

From green water resources perspective, it includes both flows from cropland and permanent pastureland. However, not all “utilizable green” AW will be used productively. Productive green water flow components (transpiration) also could be considered as “manageable green” AW. The difference between manageable green water and green water availability represents the potential for improving green water productivity (Rockström *et al.,* 2009).

The aforementioned components are not only affected by human activities. Moreover, it is of key importance to understand the influence of climatic variability and change on AW (Gohar & Cashman, 2016; Mishra *et al*., 2017). Both result changes in available freshwater resource distribution in spatial and temporal dimensions.

In order to consider the dependence of dynamic water resources on natural features and human factors, integrated/procced-based conceptual hydrological models that facilitate assessment of water availability are required to enable policymakers and administrators to make robust decisions under uncertain future conditions. Such models can be used to estimate the temporal-spatial variation of blue and green water resources with a clearer physical mechanism (Schuol *et al.,* 2008; Zhang *et al.,* 2012). At the same time, it would be possible to assess the impacts of different scenarios, a capability that cannot be achieved by relying on databases alone.

It has been demonstrated that the soil and water assessment tool (SWAT) model)Arnold *et al.,* 1998) can simulate most processes related to hydrology, climate, and water and agricultural management (Arabi et al., 2008). This model has widespread applications and has been proven to be effective for studying hydrological impacts globally (Gassman *et al.,* 2007; Jayakrishnan et al., 2005; Krysanova & White, 2015). It can be used to calculate water balance on different scales. The SWAT model has been used to quantify the available water (green and blue) resources at continent scale for Africa (Schuol *et al.,* 2008) and Europe (Abbaspour *et al*., 2015) and at basin scale in China (Zhang *et al.,* 2012) and Brazil (Rodrigues *et al.,* 2014).

This study aims to evaluate green and blue available water components in an integrated framework, with four main objectives: 1) How SWAT hydrological model can be effectively adopted to simulate green and blue water dynamics components and their interlinkages; 2) How the implication of such green and blue water assessment can contribute to provide useful information for the planning and management at basin scale; 3) How dynamics of available water- temporally and spatially, can be applied to address human and climate impacts on AW and 4) How future climate scenario analysis can be applied for evaluation of AW components.

2. Material and methods

2.1. Study area and data

Tashk-Bakhtegan basin was selected as the study area for this research. This basin is located on the central plateau of Iran and encompasses 27500 km^2 at 29°N and 31°20'N longitude and 51°50'E and 54°40'E latitude (Figure 1). The average annual rainfall in the basin is 150 to 645 mm. Precipitation falls mainly in winter and the highest rainfall sums are recorded in the northwest. The major river in the basin originates from the Zagros Mountains and flows into Tashk and Bakhtegan lakes at southern end of the basin.

The land cover in the basin includes pastoral land (62%) and agricultural land (27%). The total irrigated area under cultivation in the cropped and horticultural lands of this basin is approximately 400,000 hectares and most of the basin water resources have been allocated to agriculture. The construction of dams on streams has facilitated withdrawal of stored surface water for agricultural use. However, about 80% of the withdrawal in the basin is from groundwater resources to meet irrigated farming needs (Ministry of Energy, 2018). Such consumption has seriously reduced runoff, which is evidenced by the drying up of many natural lakes in the basin. Another issue is also expand of the agriculture areas. A comparison of the basin's land use between 1987 and 2015 shows 30% increase in cultivated lands (Farrokhnia et al., 2020).

Table 1 shows the provided data and respective sources for the case study. It includes hydro-climate, agriculture management, and the hydro-structure data as well as spatial remote sensing (e.g. DEM, soil and land use) information. Also, the location of the selected meteorological and discharge stations are shown in Figure 1.

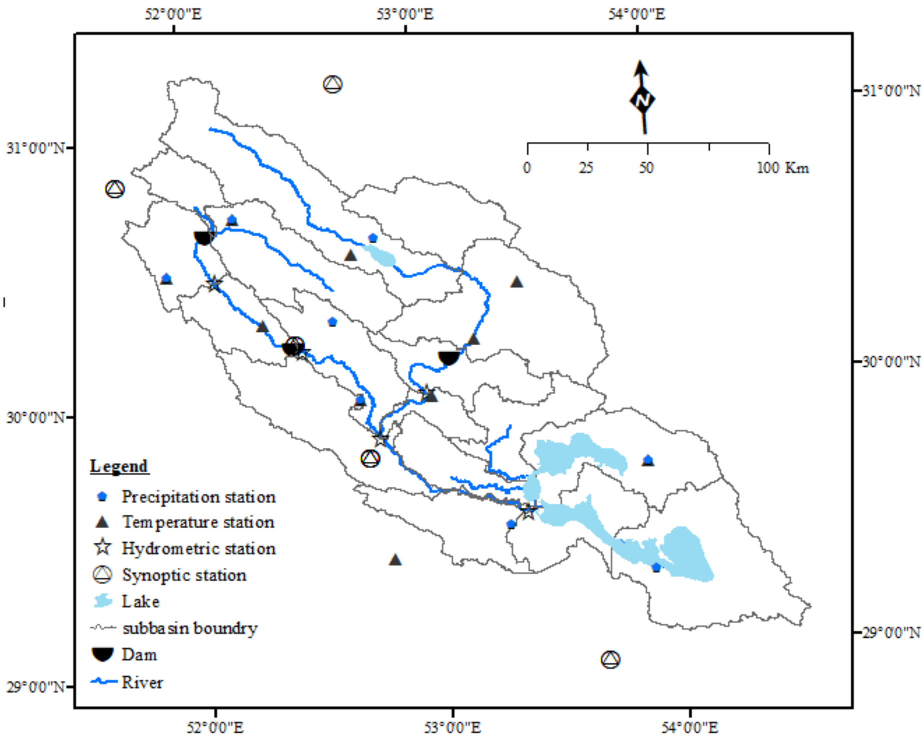


Figure 1. Location of the Tashk-Bakhtegan basin, and measured stations

2.2. Conceptual framework

Figure 2 is a conceptual framework for available water with the details considered in this study. The AW includes both green and blue water resources. Renewable blue water has been calculated as the sum of runoff and recharge to the aquifer. The blue water yield is amount of water from runoff and the return flow from the aquifer as well as the subsurface flow. Blue water is stored in surface reservoirs (natural or structural) and underground aquifers.

Because blue water flow is outflow from streams, in a closed basin, this has no value. If a water transfer plan is in place, these resources will be added to or deducted from the blue water flow. Loss caused by evaporation from the blue water bodies is inevitable.

The available green water resources are similarly divided. Renewable green water resources are calculated as the sum of actual evapotranspiration and the soil moisture content. The utilizable green water can be calculated by deducting the evaporation and soil retention from agricultural and pastoral lands. Where there is irrigation, these new resources also will be considered to be utilizable green water resources. After subtracting the amount of evaporation, the utilizable green water resources can be divided into two parts: green water storage (moisture stored in the root zone) and manageable green water (outflow through transpiration).

Table 1 Data description and sources

Hydrometric stations	River	Latitude	Longitude	Type and source of data
Chamriz	Kor	30.46°N	52.10°E	Daily time series of flow measurements obtained from the Ministry of Energy
Sad doroudzan	Kor	30.20°N	52.44°E	
Dashtbal	Sivand	30.01°N	52.98°E	
Polkhan	Kor	29.85°N	52.77°E	
Kharame	Kor	29.57°N	53.34°E	
Synoptic stations				
Yasouj		30.85°N	51.73°E	Time series observations of meteorological variables obtained from the National Meteorological Organization
Abadeh		31.18°N	52.67°E	
Doroudzan		30.20°N	52.44°E	
Zarghan		29.76°N	52.70°E	
Fasa		29.01°N	53.68°E	
Precipitation gaging stations				
Sedeh		30.71°N	52.16°E	Daily time series of precipitation observed by the Ministry of Energy
Jamal-beyg		30.61°N	52.82°E	
Choobkhole		30.53°N	51.88°E	
Pole-khan		29.86°N	52.76°E	
Kharame		29.52°N	53.31°E	
Jahan-abad		29.70°N	53.85°E	
Sahl-abad		29.25°N	53.89°E	
Reservoir				
Mola-sadra		30.64°N	52.08°E	Time series of released flows obtained from The Ministry of Energy
Doroudzan		30.21°N	52.42°E	
Sivand		30.14°N	53.09°E	

Geographic spatial information			
	Type	**Description**	**Reference/Source of information**
Digital Elevation Model (DEM)	Raster map	30m×30m	30m×30m obtained from Aster; https://asterweb.jpl.nasa.gov/gdem.asp
Soil map	Raster map	10km×10km	FAO–UNESCO global soil map http://www.fao.org/nr/land/soils/ digital-soil-map-of-the-world/en/
Land use	Raster map		1988 & 2015 land uses using Landsat images (Farrokhnia et al., 2020)
Cultivation activities include (cropping pattern, Planting, irrigation, harvest, …)	Information	Include dates, time table, values, …	Delavar et al. (2020)

2.3. SWAT model

The SWAT model is a process-based hydrological model was used that can accommodate various hydrological components and spatial and temporal distribution of the blue and green water content in the basin. In the model, the hydrological cycle is simulated based on the water balance equation (Neitsch *et al.,* 2011):

$$SW_t = SW_0 + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right)_t \quad (1)$$

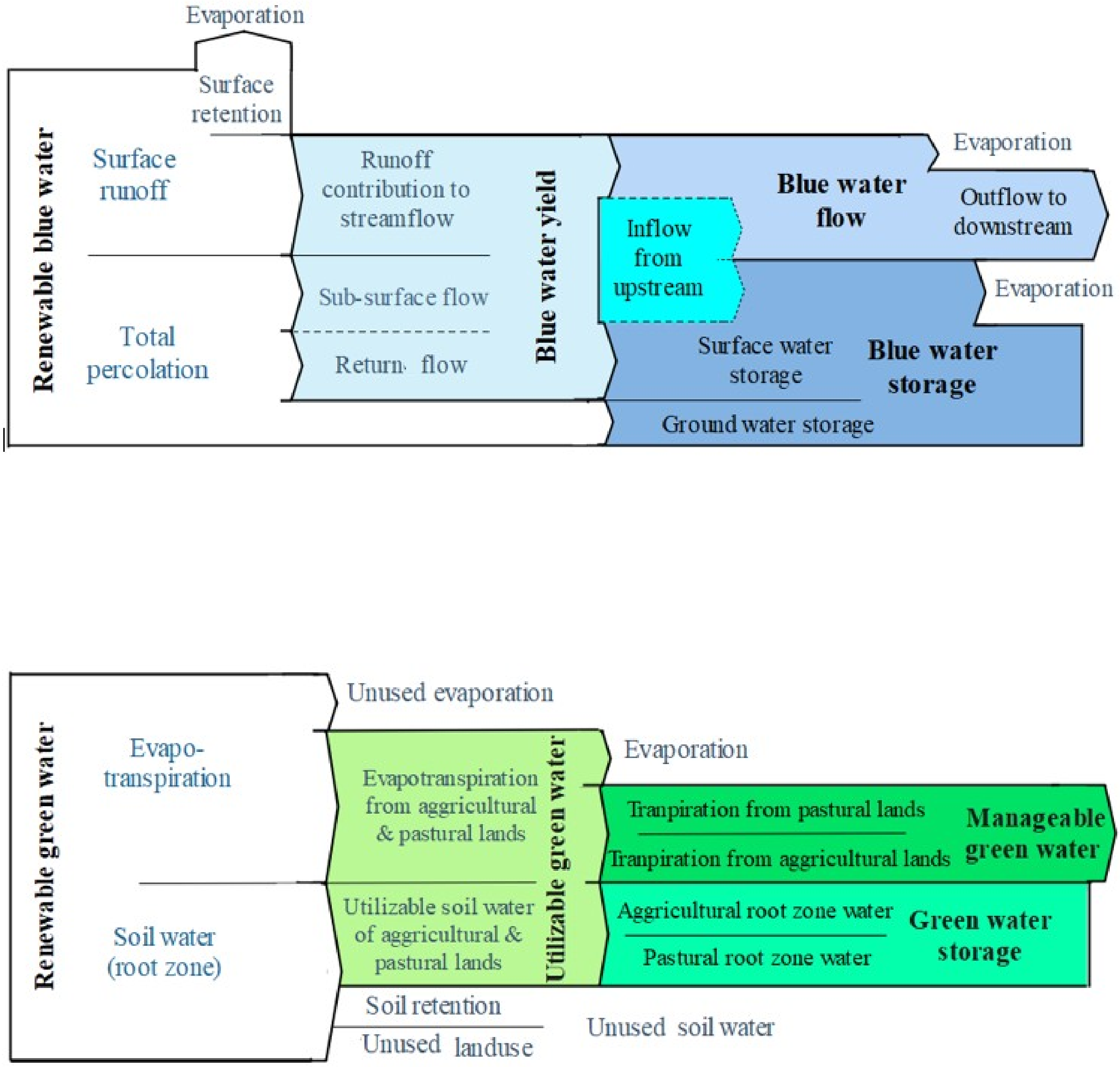


Figure 2. Conceptual model of available blue and green water components

where SW_t is the final soil water content (mm); SW_0 is the previous soil water content (mm); t is the step of time (day); R_{day}, Q_{surf} and E_a are the amount of precipitation, surface runoff, and evaporation on day i (mm), respectively; W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm), and Q_{gw} is the return flow on day i (mm).

ArcSWAT (2012) was selected for the model setup based on a monthly time step. It requires digital elevation, land use, and soil maps as well as meteorological information for hydrological modelling. These spatial layers were used to delineate the basin and divide it into multiple sub-basins. Each sub-basin was further partitioned into combined land use, soil, and management units, called hydrologic response units (HRUs). For this study, it is divided into 17 sub-basins and 403 HRUs. After the formation of the basin structure, information about water management and use, reservoir operation, and agricultural practice (e.g. crop pattern, planting calendar, irrigation source and scheduling) of the different areas were introduced to the model. Four major crops were considered as proxies for rainfed agricultural land (wheat, grapes, almonds, figs) and five major crops as proxies for irrigated land (wheat, rice, beans, sunflowers, almonds). The sources of these data and information are illustrated in Table 1.

Simulation of the hydrological processes was based on the water balance at each HRU. After the simulations were performed at the HRU level, they were aggregated and summarized at the sub-basin level. A detailed explanation of SWAT computational equations can be found in Neitsch *et al.* (2011).

2.3.1. Available water computation using SWAT model

The model consists of a system of relationships describing the basic principles of water balance in the aeration zone of the soil, including the effect of vegetation cover, and in the groundwater. The hydrologic fluxes used to quantify water availability were runoff, groundwater, evapotranspiration, sub-surface flow, and streamflow. Water storage includes soil moisture, groundwater storage (shallow and deep aquifers), surface reservoirs, and natural lakes. The components of the AW of the basin were extracted from different model outputs. Figure 3 summarizes the variables of each AW component according to the conceptual model. Information about the specific outputs of the model were used to quantify the simulated hydrological processes.

2.3.2. Blue water estimation

To represent the available blue water using different approaches, different water resource components were selected. The computational relationships used in each approach are discussed below. From a water-offer perspective, AW is actually the renewable water resources of the basin. These are designated as renewable because they occur every year in the natural cycle of precipitation before external factors resulting from human interference and harvesting affect them. Surface runoff and recharge to the aquifer at each HRU were used to calculate the renewable blue water. These variables were aggregated for each sub-basin using the mean annual values. Renewable blue water can be calculated as:

$$BAW_R = Q_r + Q_l + Q_g \quad (2)$$

where BAW_R is the renewable blue water, Q_r is the average annual amount of surface runoff, Q_l is the lateral (sub-surface) flow, and Q_g is the groundwater recharge.

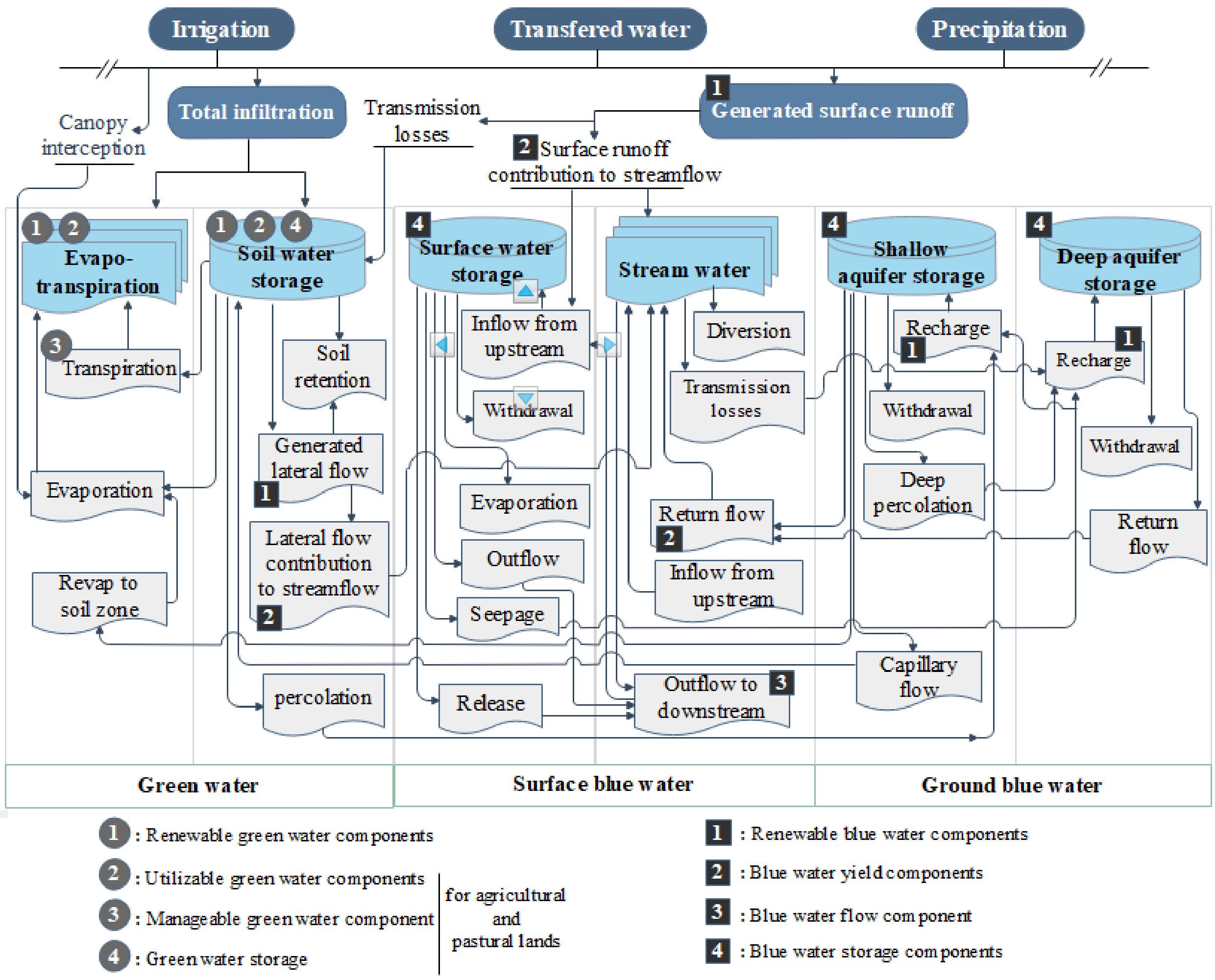


Figure 3. Flowchart of the model structure to retrieve components of available water

The water yield-based approach involves return flow. Blue water yield is considered to be accessible water because inevitable losses (including evaporation and transmission) have been included in the calculation. The amount of runoff in the HRUs reaching the streams of the sub-basin (Q_r¿ forms the basis of local available water. The calculated lateral (subsurface) flow in the time step join it and the interaction of local flow and groundwater is used to calculate the return flow. Blue water yield can be calculated as:

$$BAW_Y = WYLD = Q_r + Q_{lat} + Q_{gw} - T_{loss} \quad (3)$$

where BAW_Y is natural water yield, Q_{lat} is subsurface lateral flow, Q_{gw} is groundwater participation in surface flow or return flow, and T_{loss} is transmission loss. Blue water yield can be obtained from the model outputs directly as water yield at the outlet point of each sub-basin.

Another approach was used to determine the water resources ready for new development. Here, surface flow from each sub-basin be ignored. This value may be released due to environmental considerations or downstream water rights. This available blue water can be called developable water because, if there were no plans for use or downstream rights, it can be used in the sub-basin for future water use and development.

The outflow consists of local water yield and upstream inflow to each sub-basin. This is routed along the stream and finally arrives at the sub-basin outlet. The variable travel time method was used to simulate the channel routing process. In this method, in addition to input from upstream, the effects of existing water withdrawals, imports, and storage infrastructures is included in the model calculations. Ultimately, only a fraction of the stream flow of each sub-basin reaches its outlet and is calculated (as net sub-basin outflow) and reported as water resources provided for new development. Blue water flow is calculated as:

$$BAW_f = V_q \quad (4)$$

where BAW_f is blue water flow and V_q is the average volume of outflow from sub-basin streams. This value can be calculated from model output files using the outflow variable at each sub-basin. The net values are calculated as the difference between the inlet and outlet flows of the sub-basins.

Another perspective for determining stored water takes into account the amount of water stored in natural and structural reservoirs. These resources can be called manageable or exploitable water as they are net resources which can exploited directly and are routinely used for different allocations. These resources are provided by local water yield and inflow to each sub-basin from upstream and net groundwater recharge. Water resources stored in the sub-basin depends on the reservoir capacity and/or operation. Blue water storage can be calculated as:

$$BAW_s = V_v + V_g \quad (5)$$

where BAW_s is blue water storage, V_v and V_g are the average volume of water stored at the surface and in underground reservoirs, respectively. The groundwater storage value is the difference between recharge and discharge (i.e. net change) at each time step.

The amount of available water calculated in this research (Equations (2) to (5)) at each simulation time-step are presented as equivalent water heights (relative to area) for the basin in order to obtain a better understanding of the amount of water resources available.

2.3.3. Green water estimation

The available green water components were calculated *in situ* at the HRU level as the sum of the soil moisture and evapotranspiration values simulated by the model. The Hargreaves method (Hargreaves *et al.,* 1985) was used to estimate potential evapotranspiration. Once the total potential evapotranspiration had been determined, SWAT first evaporated any rainfall intercepted by the plant canopy. The remaining evaporative water demand was partitioned between the vegetation and soil.

In the Hargreaves method for SWAT, transpiration is calculated as a function of the plant leaf area index. The actual amount of transpiration may decrease from a lack of AW in the soil. When the water content of the soil is below field capacity (*FC*), the evaporative demand for soil decreases to the wilting point (*WP*). The *FC* and permanent *WP* are the amount of water held in the soil at a tension of 0.033 and 1.5 MPa, respectively. This is considered to be the available waster for plant extraction (*AWC*). Water in excess of FC is available for percolation or lateral flow as:

$$AWC = FC - \wp \tag{6}$$

The *WP* per soil layer is calculated as:

$$\wp_{ly} = 0.4 \times \frac{m_c \times \rho_b}{100} \tag{7}$$

$$\varnothing_{soil} = 1 - \frac{\rho_b}{\rho_s} \tag{8}$$

where $\varnothing_{soil}$ is the porosity expressed as a fraction of the total soil volume, m_c is the clay content of the soil,ρ_b is the bulk density (Mg m^{-3}), and ρ_s is the particle density (Mg m^{-3}). Details about how these processes are simulated can be found in the SWAT User Manual.

To define the basin green water resources, the renewable green water resources were calculated from the sum of natural evapotranspiration and soil moisture storage. These values were aggregated and reported at the sub-basin/basin level. Evapotranspiration was calculated as the accumulated flow through the plants to the air by time-step (one month). However, only the soil moisture content in the root zone layer of the soil was used, as water use often occurs at this depth. This value was calculated at the end of each time step as:

$$GAW_R = ET_t + SW_t \quad (9)$$

where GAW_R is the renewable green water, ET_t is the average annual amount of evapotranspiration, and SW_t is the soil water in root depth. That portion of the green water resources was denoted as the utilizable green water resources. These resources are the amount of evapotranspiration and root zone soil moisture in agricultural and pastoral lands that can lead to economically efficient vegetable consumption as:

$$GAW_u = ET_u + SW_u \quad (10)$$

where GAW_u is the utilizable green water and ET_u and SW_u are the average annual amount of utilizable evapotranspiration and soil water, respectively, that occur in agricultural and pastoral lands.

The utilizable green water resources consist of stored green water and manageable, or output, green water. The soil moisture in the root zone in agricultural and pastoral lands are denoted as green water storage (GAW_s¿. The actual transpiration from agricultural and pastoral lands (T_m) is denoted as manageable green water (GAW_m) as:

$$GAW_s = SW_u \quad (11)$$

$$GAW_m = T_m \quad (12)$$

2.4. Evaluation of water availability under climate scenarios

As climate change projections themselves are uncertain, a range of possibilities for plausible future changes as model outputs were investigated for different combinations of precipitation and temperature change rather than for a historical period. In the assessment, the effects of meteorological variables were taken into account and the other variables were considered constant.

The sensitivity of an AW type to climate change can be considered as the proportional change of simulated BW and GW availability in different hypothetical states compared to the no-change state for precipitation and temperature. Sensitivity can be calculated as:

$$\Delta AW(\%) = \frac{AW_{\Delta P,\Delta T} - AW_{0,0}}{AW_{0,0}} \times 100 \quad (13)$$

where ΔAW is the response of AW to precipitation and temperature change, ΔP and ΔT are hypothetical precipitation and temperature changes, respectively, $AW_{\Delta P,\Delta T}$is the AW under hypothetical climate change scenarios, $AW_{0,0}$ is the AW under the no-change scenario for precipitation and temperature. Here, AW is any component of available blue or green water.

2.5. Modelling scenarios to estimate AW

To estimate different components of AW, it is required to run the model within different management scenarios with respect to the objective of study. For this, they are as follows:

Actual conditions (AC)

This scenario simulates the current agriculture management including dams operations, irrigation management, planting, harvesting, fertilizer and etc. (Table 1). The area under cultivation and irrigation schedules were also held constant to allow investigation of only the effects of climate on available water.

No withdrawal (NW)

The no-withdrawal scenario assumes no human water management; thus, the effects of infrastructures (dam structure and operation) were excluded. This approach runs without irrigation withdrawal to exclude the effect of water abstraction. In this scenario, water resources equilibrium over the study period was determined by groundwater calibration.

Automatic irrigation (AI)

Irrigation influences discharge into streams and transpiration from irrigated crops. In this scenario, all of the basin water management and dams operated such that all crop water requirements were fulfilled by auto irrigation and unlimited water resources. This AI calculates maximum plant transpiration and soil evaporation as explained by Neitsch *et al.* (2011).

2.6. Evaluation of water shortage

In order to investigate water shortage, the relationship presented in the research (Boulay et al., 2018) is used. In this regard, the difference between available water and water demand is calculated:

$$WSh = AW - D \qquad (14)$$

where *WSh* is water shortage, *AW* is available water (exploitable or renewable water) and *D* is water demand, respectively. The method is very flexible and can be calculated at unit area, subbasin and basin levels as well as daily, monthly and yearly time scales. To estimate *AW* and *D,* the modelling setup needs to be run for NW and AI scenarios. It is worth mentioning that many other water indices can be applies with respect to the different AW components.

3. Results and discussion

3.1. Model calibration and validation

The SWAT needed further calibration and validation. For this aim, we applied a "multi-variable & multi-site calibration". Since, the conventional reliance on hydrometric data is insufficient. To obtain the best model outputs, it is important to estimate the robust model parameters. For this, the SWAT-CUP tool developed by Abbaspour *et al.* (2008) was applied for parameter sensitivity analysis and calibration. A description of SWAT-CUP can be found in Abbaspour (2012). The Sequential Uncertainty Fitting algorithm (SUFI-2), a semi-automatic inverse modelling procedure in SWAT-CUP, was selected to analyse the many parameters in the smallest number of model runs.

Because the model cannot simulate groundwater volume and water table fluctuations, these were performed in a relative manner to ensure calibration of the groundwater parameters and volume of groundwater storage. The model is able to estimate the amount of recharge to the aquifer; therefore, groundwater storage has been expressed as net aquifer change. The parameters were selected and calibrated such that the long-term change in groundwater under natural conditions and without human intervention (NW scenario) would be approximately zero. In the long run, surface water and groundwater interaction were in equilibrium. Additionally, the Tashk-Bakhtegan Lake's volume and crop yields are other information that are considered for this step. Figure 4 diagrams the steps in this process.

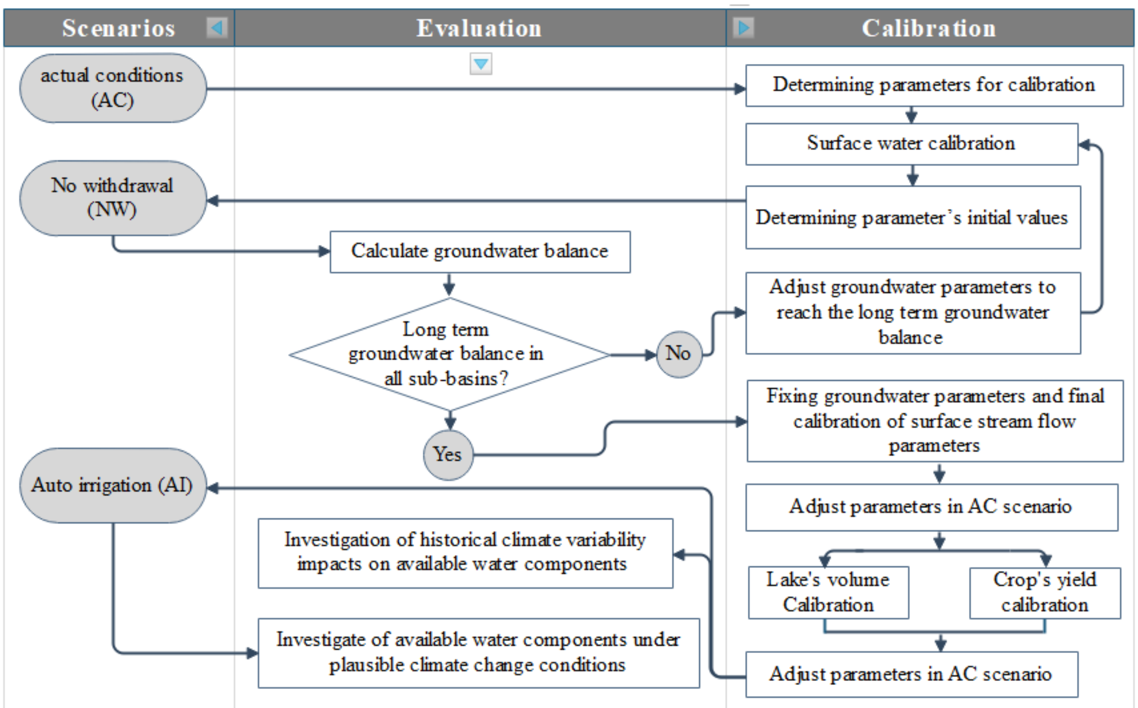


Figure 4. Framework for the model calibration and validation process

Furthermore, first year of the study period was chosen for warm-up. The 20-year period from 1986 to 2005 was considered for calibration and the remaining years for validation of the model. To compare the ability of SWAT to reproduce streamflow and observations, the performance criteria of the mean and standard deviation of simulations, coefficient of determination (R^2), Nash Sutcliffe efficiency (E), P-factor, and R-factor were used. The calibration and validation results are presented in Table 2. The table shows the values of R^2 and NS are generally more than 0.5, which indicate an acceptable model performance for stream flow simulation in the calibration and validation periods.

Table 2 Monthly stream-flow calibration and validation results

Calibration period: 2006-2015								
R-factor	P-factor	NS	R^2	Sim. SD	Obs. SD	Sim. mean	Obs. mean	Station
0.28	0.55	0.75	0.78	30.9	31.1	25.3	29.0	Chamriz
0.1	0.97	0.98	0.98	25.4	25.2	16.0	16.1	Doroudzan
0.37	0.62	0.69	0.71	5.8	7.4	4.0	4.8	Dashtbal
0.28	0.63	0.71	0.78	30.4	41.0	25.5	35.1	Polkhan
0.40	0.40	0.53	0.55	15.7	21.3	11.7	14.9	Kharame
Validation period: 2006-2015								
0.85	0.63	0.64	0.76	10.7	11.6	10	13.5	Chamriz
0.19	0.98	0.99	0.99	11.6	11.6	7.3	7.4	Doroudzan
2.2	0.30	0.31	0.37	0.9	0.5	0.8	0.3	Dashtbal
0.85	0.76	0.81	0.82	10.4	11.5	8.1	7.5	Polkhan
1.22	0.26	0.26	0.39	3.6	3.4	3.8	1.1	Kharame

As stated before, to ensure the calibration results, model simulation of the crop yield and volume of basin lakes was examined using limited observational data the results are shown in Table 3 and Figure 5. It was concluded that the performance of the model was satisfactory and the calibrated model was able to replicate the watershed hydrology of the Tashk-Bakhtegan basin.

Table 3 Model crop yield simulation for observed data (second crop planted after winter wheat harvest)

Irrigated crops				Rainfed crops			
Ave. crop yield (ton/ha)		Irrigated land (%)	Crop	Ave. crop yield (ton/ha)		Rainfed land (%)	Crop
Sim.	Obs.			Sim.	Obs.		
1.9	1.8	30	almonds	0.4	0.55	30	almonds
4.4	4.6	70	*winter wheat	1.16	1.12	40	winter wheat
Percentage of winter wheat area				2.1	2.8	15	grapes
1.7	1.5	30	sunflowers	2.1	2.2	15	figs
2.7	2.4	20	beans				
3.6	4.1	50	rice				

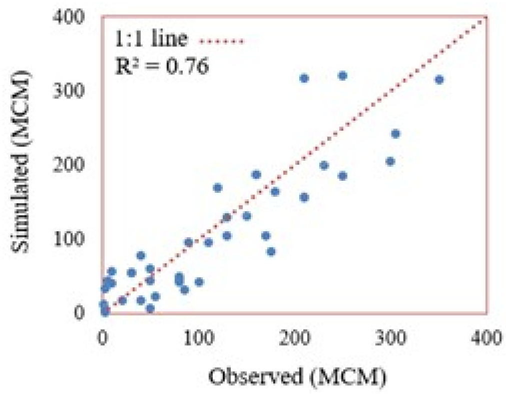


Figure 5. Observed vs. simulated lake water volume

3.2. AW assessment under management and climate scenarios

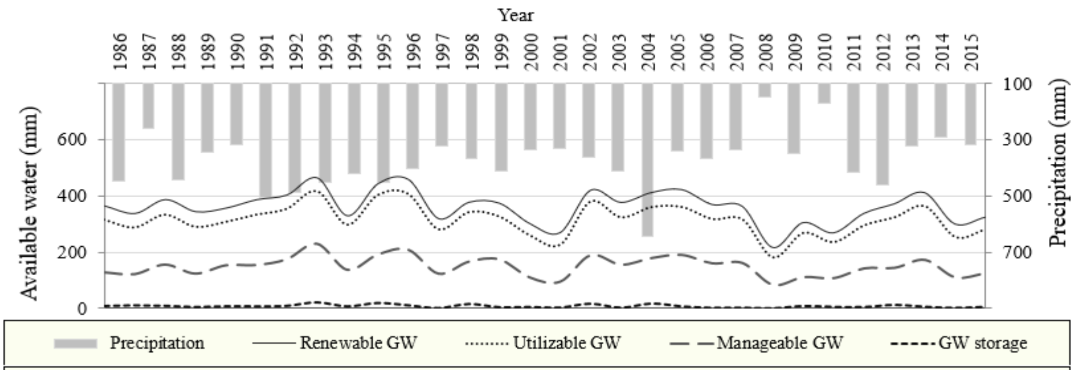
This section explores the modeling setup's capabilities for analyzing AW components. For this purpose, we first present historical situation of AW in the basin. Then, role of the Droudzan dam on spatial variation of AW will be assessed. Impact of the development in agriculture lands from 1987 to 2015 on the basin's water shortage is the next issue. Finally, the basin's AW will evaluated under different climate scenarios. It is also worth mentioning, the framework is very flexible and using the management options of SWAT model, many other scenarios can also be implemented and evaluated.

3.2.1. AW assessment during historical period

This section explores the modelling setup's capabilities for analysing AW status through the Tashk-Bakhtegan basin.

Figure 6 shows the annual variation in basin green water and demonstrates the rapid reaction between the green water and rainfall. The figure also shows that, regardless of the quantity, the trends for renewable, utilizable, and manageable green water were the same in the simulation period. The greatest and smallest changes from the average values were related to green water storage (about 190%) and renewable green water (about 40%), respectively.

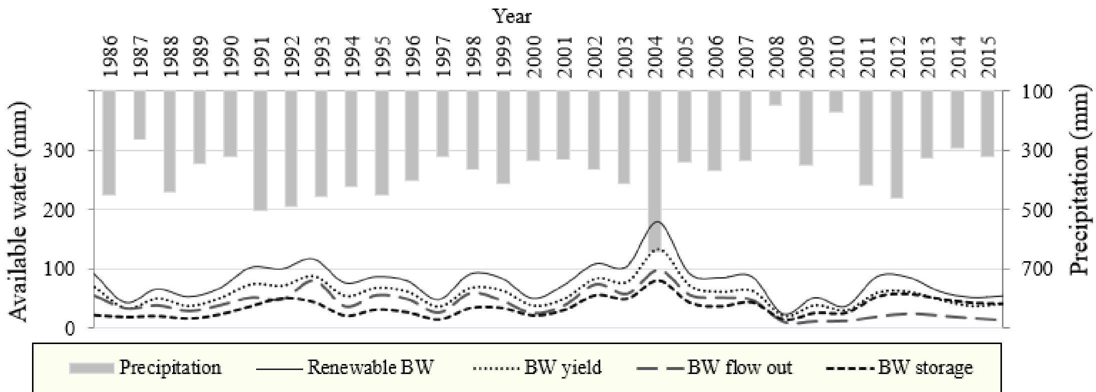
Figure 7 shows the estimated available blue water components across the entire simulation period on an annual basis. As seen, there was a difference in the amounts of the calculated available blue water components. Also, the trend of change between the components of the blue water differed. It can be seen that, in years with low precipitation (e.g. 2008), the estimated values of the available blue water components were similar, but in a year with high precipitation (e.g. 2004), the renewable water value diverged significantly from the rest.



	Precipitation	Renewable GW	Utilizable GW	Manageable GW	GW storage
Mean (mm	374	361	314	149	8
Max (mm)	645	466	415	231	23
Min (mm)	149	217	182	89	1

Figure 6. Annual value available green water over time (years)

Renewable water showed the greatest range of fluctuation, from 23 mm in 2008 to 179 mm in 2004. These values were 20 to 133 mm for blue water yield. Because, aside from the base flow reaction, initial evaporation and infiltration losses have been incorporated into blue water yield calculations, the response was lower. In other blue AW components, the blue water flow was 10 to 97 mm and the blue water storage ranged from 14 to 80 mm. One reason for the difference in high boundary values in the available blue water components could be the estimation method used. Renewable blue water and blue water yield are less dependent upon basin features, more affected by climate, and are not necessarily combined with hydrological features (e.g. streams and reservoirs).



	Precipitation	Renewable BW	BW yield	BW flow out	BW storage
Mean (mm) :	374	77	57	40	35
Max (mm) :	645	179	133	97	80
Min (mm) :	149	23	20	10	14

Figure 7. Annual values available blue water over time (years).

Figures 6 and 7 show that annual rainfall had different effects on the AW components. For example, the ratio of the highest to lowest renewable blue water was 9.8 and for the blue water flow was 4.8. The changes in basin AW were studied during dry and humid years to further investigate the effects of climate variability. Statistics for three years were selected from years with maximum precipitation and three from years with minimum precipitation. In Figure 8, the high rainfall years are denoted by dark bars and the low rainfall years by dashed bars. The green and blue water components for these years were compared with the mean period shown in Figure 8. It is clear that the green water was less susceptible to changes in annual precipitation. Also, the reaction of blue water to the high rainfall years was more severe, while the reaction of green water to the low rainfall years was more severe. Among the AW components of blue and green water, blue water storage and green water storage, respectively, were most affected by changes in precipitation changes.

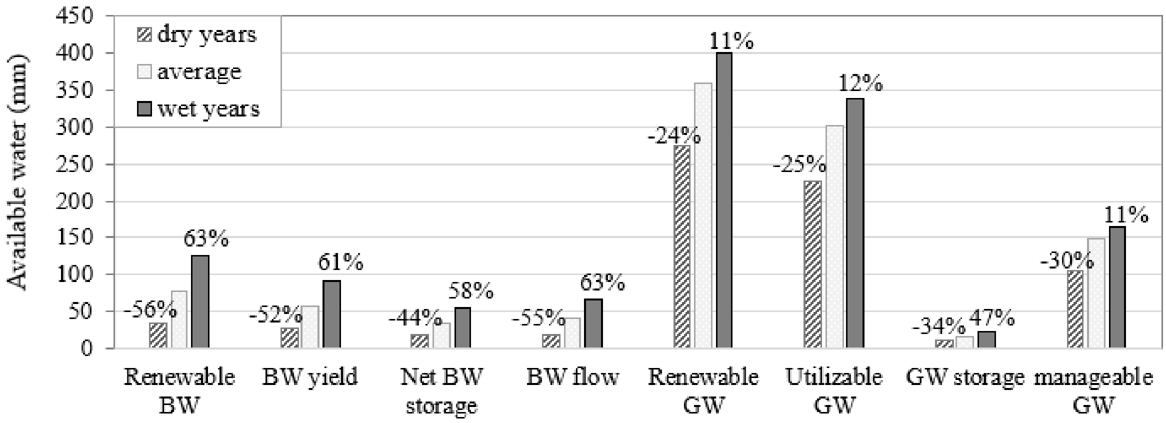


Figure 8. Available BW and GW in wet and dry years compared with average years

3.2.2. AW change under dam construction

Using the applied methodology and considering "renewable water" and "exploitable water", impact of the Dorudzan dam on AW are evaluated. The results showed no significant impact of this infrastructure on AW at basin level. But, when the assessments were made at the sub-basin scale, the changes in "exploitable water" were significant. Figure 9 shows this issue and how it is changed due to construction of the dam as the main storage facility in the basin. It is seen that the dam has increased AW in respected subbasin up to 97%, while it is substantially reduced at the downstream subbasins, where the Task-Bakhtegan wetland is located.

3.2.3. Effect of land use changes on water shortage

The impact of land use changes on AW components is important. The SWAT model is also capable to handle such as an issue (Wang et al., 2014). As stated before, comparison of the 1987 and 2015 land uses of the basin shows about 30% increase in the agricultural lands. The effect of such a change on the basin's water shortage is evaluated in this section. For this aim, the modelling setup was run using the two land uses under AI and AC scenarios to calculate

WSh (in Eq. 14) at the basin level and monthly time scale. The results showed (Figure 10) that the 30% increase in agricultural land has caused significant changes in water shortages. The basin was almost in equilibrium in 1987, while the results shows about 1500 MCM water shortage (algebraic sum of the monthly water shortages in Figure 10). As expected, *WHs* is more pronounced between April and September that is the cropping season. It is noteworthy that the order of the months has changed in terms of water shortage that can be attributed to the change in basin's cropping pattern (e.g. expansion of rice cultivation). As mentioned before, due to the evaluations at basin scale, he results for exploitable and renewable AW are not much significant.

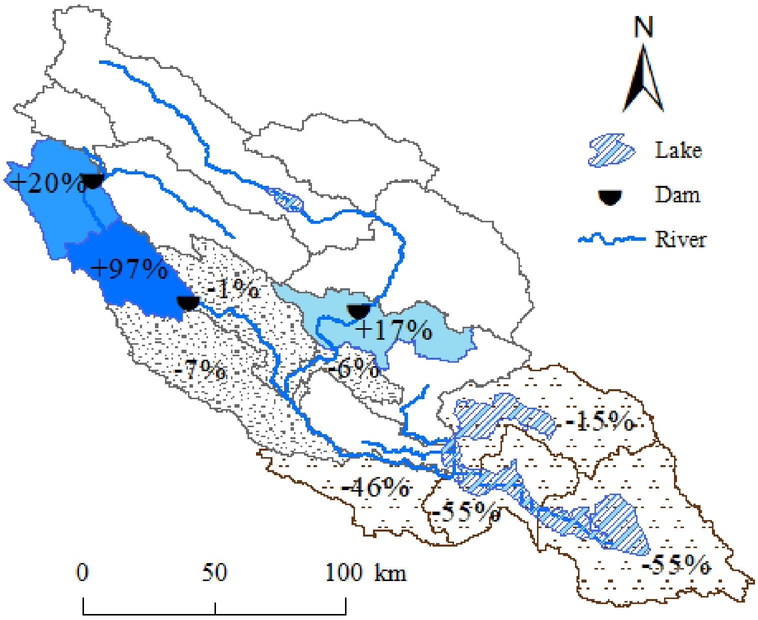


Figure 9. Spatial effect of dams on exploitable available water at sub-basins scale

3.2.4. Effect of plausible climate change on available water components

Figure 11 shows the results of sensitivity assessment of AW components using a range of climatic scenarios. Using the basin's climate change study by Massah et al. (2020), It was assumed that changes in precipitation ranged from -30% to 20% and the temperature changes ranged from -0.5 to +2 °C.

As seen in the figure, blue water was more sensitive to precipitation change than green water. A 20% increase in precipitation increased renewable blue water 35% and renewable green water 8%. Green water showed a slightly greater response to reduced precipitation. Green water storage was the component most sensitive to changes in precipitation.

The response of blue water to precipitation was nonlinear. The gradient of the iso-magnitude lines for AW increased as the precipitation increased. The local water-offer approach was less sensitive to precipitation changes than exploitable water. In this scenario, blue water storage was calculated as net change between time steps. The greatest change with a change in precipitation occurred in blue water storage, where the reaction to increased precipitation was more pronounced than to a decrease in precipitation.

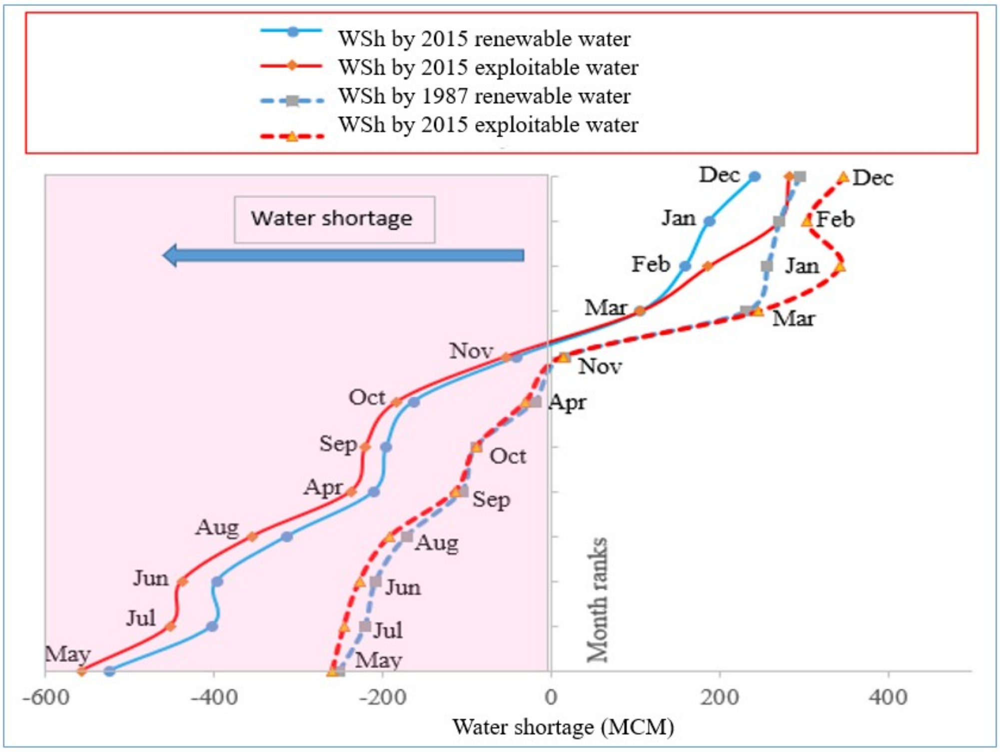


Figure 10. Comparison of the 1987 and 2015 Tashk-Bakhtegan basin's monthly water shortage

Air temperature was also an important factor affecting green water. As expected, an increase in temperature decreased the available blue water and green water storage. However, evapotranspiration increased to a lesser extent under warmer conditions. These results can be used to improve scientific understanding of the evolution of blue and green water resources as affected by climate change in the basins and is especially necessary for sustainable water use in arid and semi-arid regions.

4. Conclusions

This research focused on an integrated framework to evaluate AW and its components. The effort builds on an inclusive approach of available water modelling using SWAT model. The most important concerns regarding the methodology and modelling setup are as follows:

- Systematic presentation of the current status and past trends in the components of AW as well as future situation under different climate and management scenarios;

- Presentation of interlinkages of blue and green water components;

- Spatial variation of AW components under different water policies at basin and subbasin scales;

- Evaluation of measures on AW components at farm and basin scales for realistic results,

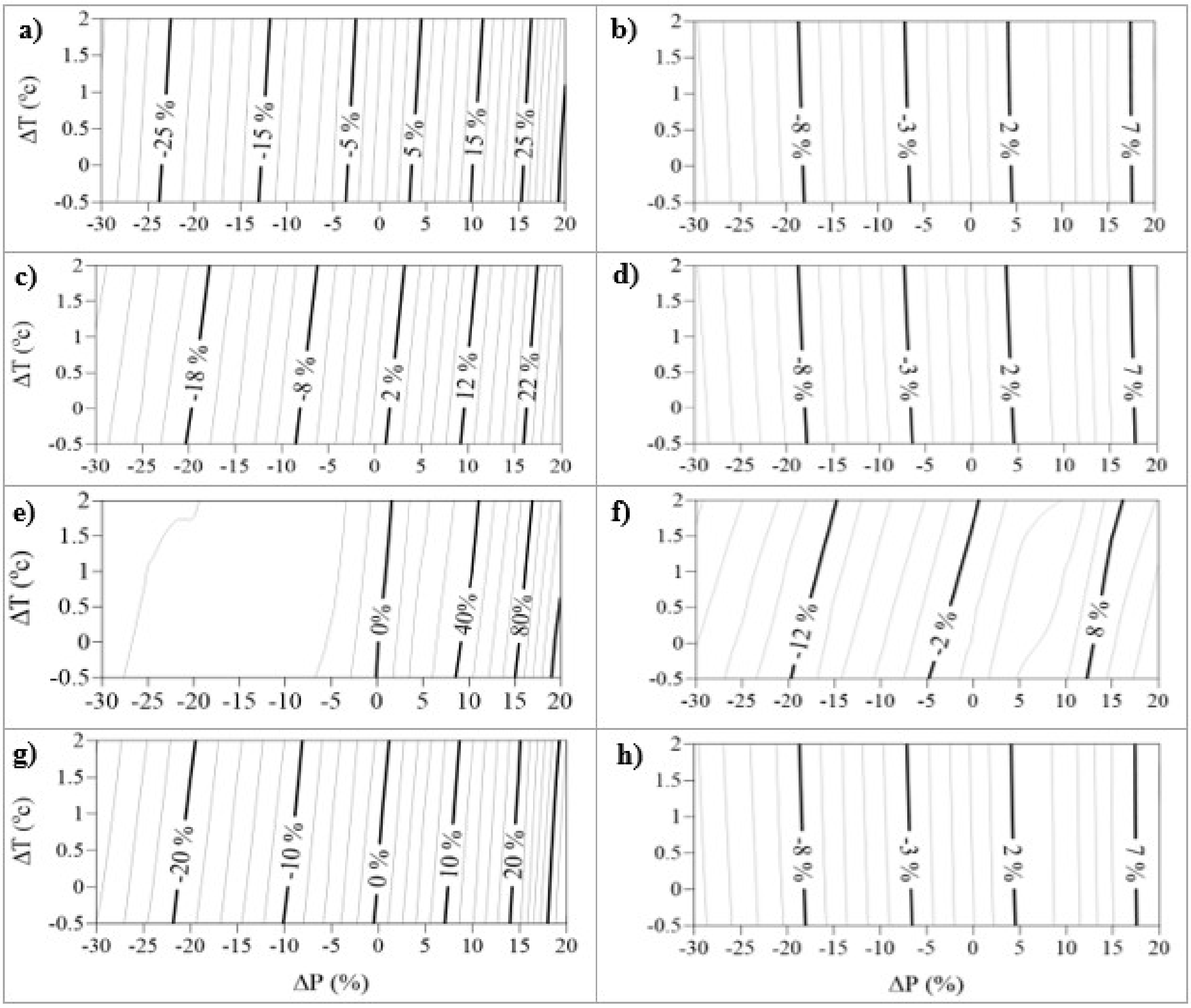


Figure 11. Sensitivity of AW components to plausible climate change: (a) renewable blue water; (b) renewable green water; (c) blue water yield; (d) utilizable green water; (e) net blue water storage; (f) green water storage; (g) blue water flow; (h) manageable green water.

- Temporal pattern of AW components at daily, monthly and yearly time scales;

- Possibility to show spatial and temporal status of water shortage.

To show the capability of the methodology, Tashk-Bkhtegan basin is applied. Here are some of the remarks:

- Using the historical information of basin (1986-2015), the components of AW for a set of dry and wet years were computed and compared. The results showed wide ranges for the blue water components, which was 113 mm on average. While it was 48.2 mm for green water components. Similarly, blue water was more sensitive than green water to the future annual precipitation variability.

- Evaluation of the construction of the Durodzan dam showed that it has drastic impact on the spatial blue AW components. Such that they are increased in the adjacent subbasin up to 97% and reduced to half the status quo in the downstream subbasins. Thus, the modelling setup provides relevant information for the future operation of dam, possible changes in the environment flows and even the expected social consequences (e.g. upstream-downstream conflicts).

- The basin has experienced 30% increase in its cropped areas between 1987 and 2015. As a result, it has significantly increased the different between available water and demand. In another word, while the basin was almost in equilibrium situation in 1987, it is facing with 1500 MCM water shortage in current condition.

- The proposed modelling framework can provide relevant information on AW as well as the potential influence of anthropogenic and climate variables. This methodology is very applicable where different polices/measures; like watershed management, agriculture water saving and environment water supply need to be evaluated in an integrated framework and their effects and side-effects should be considered. Finally, it is an easy-to-use tools with readily available data in order to facilitate water availability assessment and is strongly recommended for other regions.

5. Data availability statement

These data were derived from the following resources available in the public domain:

- Digital Elevation Model (DEM). 30m×30m. obtained from Aster. https://asterweb.jpl.nasa.gov/gdem.asp

- Soil map. 10km×10km. FAO–UNESCO global soil map. http://www.fao.org/nr/land/soils/digital-soil-map-of-the-world/en/

References

Abbaspour, K. C., 2008. SWAT calibration and uncertainty programs. A User Manual. Eawag Zurich, Switzerland, 20.

Abbaspour, K.C., 2012. SWAT-CUP 2012: SWAT calibration and uncertainty programs - a user manual. Eawag: Swiss Federal Institute Science and Technology

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, Srinivasan, R., Yang, H. and Kløve, B., 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. Journal of Hydrology, 524, pp.733-752.

AghaKouchak, A., Mehran, A., and Mazdiyasni, O., 2016. Socioeconomic Drought in a Changing

Climate: Modeling and Management. In *EGU General Assembly Conference Abstracts*, , 14075.

Ahmadzadeh, H., Morid, S., Delavar, M., and Srinivasan, R., 2015.Using the SWAT Model to Assess the Impacts of Changing Irrigation from Surface to Pressurized Systems on Water Productivity and Water Saving in the Zarrineh Rud Catchment. *Agricultural Water Management*. http://dx.doi.org/10.1016/j.agwat.2015.10.026.

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T. and Siebert, S., 2003. Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions. Hydrological Sciences Journal, 48(3), pp.339-348.

Arabi, M.; Frankenberger, J.R.; Engel, B.A.; Arnold, J.G., 2008. Representation of agricultural conservation practices with SWAT. Hydrol. Process, 22, 3042–3055

Arnold, J G., Srinivasan, R., Muttiah R S., and Williams J R., 1998. Large Area Hydrologic Modeling and Assesment Part I: Model Development. *JAWRA Journal of the American Water Resources Association* 34(1): 73–89.

Boulay, A.M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A.V. and Ridoutt, B., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). The International Journal of Life Cycle Assessment, 23(2), pp.368-378.

Delavar, M. Abbasi, H., Morid., R., Mahmoudi, Y. Mehrazar, A. (2020) Modeling Water and Agricultural Resource Systems under the Impact of Climate Change within Pilot Area (Tashk-Bakhtegan Basin), National Strategies for Water Sector in Adaptation to Climate Change. Ministry of Energy Vol. 6 (In Farsi).

Döll, P., Kaspar, F. and Lehner, B., 2003. A global hydrological model for deriving water availability indicators: model tuning and validation. Journal of Hydrology, 270(1-2), pp.105-134.

Falkenmark, M., and Rockström, J., 2004. *Balancing Water for Humans and Nature: The New Approach in Ecohydrology*. Earthscan.

Falkenmark., 2006. The New Blue and Green Water Paradigm: Breaking New Ground for Water Resources Planning and Management. *Journal of Water Resources Planning and Management* 132(3): 129–32. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:3(129).

FAO., 2003. Review of World Water Resources by Country: 2. Concepts and Definitions. : 124. http://www.fao.org/docrep/005/y4473e/y4473e06.htm.

Faramarzi, M., Abbaspour, K.C., Lu, W., Fennell, J., Zehnder, A.J. and Goss, G.G., 2017. Uncertainty based assessment of dynamic freshwater scarcity in semi-arid watersheds of Alberta, Canada. Journal of Hydrology: Regional Studies, 9, pp.48-68.

Farrokhnia, A. Imani, S. Kardam Moghadam, H. Sheshangosht, S. (2020) Collecting Basic Information (Tashk-Bakhtegan Basin), National Strategies for Water Sector in Adaptation to Climate Change. Ministry of Energy Vol. 3 (In Farsi).

Gassman, P W., Reyes, M R., Green, C H., and Arnold, J G., 2007. The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. *Transactions of the ASABE* 50(4): 1211–50.

Gohar, A.A. and Cashman, A., 2016. A methodology to assess the impact of climate variability and change on water resources, food security and economic welfare. Agricultural Systems, 147, pp.51-64.

Hargreaves, G. H., & Samani, Z. A., 1985. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture, 1(2), 96-99.

Jaramillo, F., and Destouni, G., 2014. Developing Water Change Spectra and Distinguishing Change Drivers Worldwide. *Geophysical Research Letters* 41(23): 8377–86.

Jayakrishnan, R. Srinivasan, R., Santhi, C. Arnold JG. (2005) Advances in the application of the SWAT model for water resources management. Hydrological Processes: An International Journal 19 (3), 749-762

Karimi, P., W. G.M. Bastiaanssen, and D. Molden., 2013. Water Accounting Plus (WA+) - A Water Accounting Procedure for Complex River Basins Based on Satellite Measurements. *Hydrology and Earth System Sciences* 17(7): 2459–72.

Koshida, G., Cohen, S., & Mortsch, L., 2015. Climate and water availability indicators in Canada:

Challenges and a way forward. Part I–Indicators. Canadian Water Resources Journal/Revue canadienne des ressources hydriques, 40(2), 133-145.
Krysanova, V. and White, M., 2015. Advances in water resources assessment with SWAT—an overview. Hydrological Sciences Journal, 60(5), pp.771-783.
Massah A.R., Alimohamadi H., and Toufigh T., 2020. Emergence of Climate Change Impacts in Past Periods and Generation of Climate Change Scenarios for Future Periods (Tashk-Bakhtegan Basin), National Strategies for Water Sector in Adaptation to Climate Change. Ministry of Energy Vol (5) (In Farsi).
Ministry of Energy, 2018. Updating the comprehensive water plan of Maharloo-Bakhtegan. Jamab Consulting Engineers (In Persian).
Mishra, S., Mishra, D., & Santra, G. H., 2017. Adaptive boosting of weak regressors for forecasting of crop production considering climatic variability: An empirical assessment. Journal of King Saud University-Computer and Information Sciences.
Neitsch, S.L., Arnold, J.G., J.R Kiniry, and Williams, J.R., 2011. Soil & Water Assessment Tool Theoretical Documentation Version 2009. Texas Water Resources Institute: 1–647.
Padowski, J. C., & Jawitz, J. W., 2012. Water availability and vulnerability of 225 large cities in the United States. Water Resources Research, 48(12).
Pokhrel, Y. N., Hanasaki, N., Yeh, P. J., Yamada, T. J., Kanae, S., & Oki, T., 2012. Model estimates of sea-level change due to anthropogenic impacts on terrestrial water storage. Nature Geoscience, 5(6), 389-392.
Porkka, M., Gerten, D., Schaphoff, S., Siebert, S. and Kummu, M., 2016. Causes and trends of water scarcity in food production. Environmental research letters, 11(1), p.015001.
Raeisi, L. G., Morid, S., Delavar, M., & Srinivasan, R., 2019. Effect and side-effect assessment of different agricultural water saving measures in an integrated framework. Agricultural Water Management, 223, 105685.
Rijsberman, F. R., 2006. Water scarcity: fact or fiction?. Agricultural water management, 80(1-3), 5-22.
Rockstrom, J., Karlberg, L., Hoff, H., Rost, S. and Gerten, D., 2009. Future water availability for global food production: The potential of green water for increasing resilience to global change. Water Resources Research.
Rodrigues, D.B., Gupta, H.V. and Mendiondo, E.M., 2014. A blue/green water‐based accounting framework for assessment of water security. Water Resources Research, 50(9), pp.7187-7205.
Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J. and Schaphoff, S., 2008. Agricultural green and blue water consumption and its influence on the global water system. Water Resources Research, 44(9).
Schuol, J., Abbaspour, K.C., Yang, H., Srinivasan, R. and Zehnder, A.J., 2008. Modeling blue and green water availability in Africa. Water Resources Research, 44(7).
Tidwell, V.C., Kobos, P.H., Malczynski, L.A., Klise, G. and Castillo, C.R., 2012. Exploring the water-thermoelectric power nexus. Journal of Water Resources Planning and Management, 138(5), pp.491-501.
Tidwell, V.C., Bailey, M., Zemlick, K.M. and Moreland, B.D., 2016. Water supply as a constraint on transmission expansion planning in the Western interconnection. Environmental Research Letters, 11(12), p.124001.
Tidwell, V.C., Moreland, B.D., Shaneyfelt, C.R. and Kobos, P., 2018. Mapping water availability, cost and projected consumptive use in the eastern United States with comparisons to the west. Environmental Research Letters, 13(1), p.014023.
Veettil, A. V., & Mishra, A. K., 2018. Potential influence of climate and anthropogenic variables on water security using blue and green water scarcity, Falkenmark index, and freshwater provision indicator. Journal of Environmental Management, 228, 346-362.
Vörösmarty, C. J., & Sahagian, D., 2000. Anthropogenic disturbance of the terrestrial water cycle. Bioscience, 50(9), 753-765.
Wang G, Yang H, Wang L, Xu Z, Xue B (2014) Using the SWAT model to assess impacts of land use changes on runoff generation in headwaters. Hydrol Process 28: 1032–1042
Wanders, N, and Wada, Y., 2015. Human and Climate Impacts on the 21st Century Hydrological

Drought. Journal of Hydrology 526: 208–20. https://doi.org/10.1016/j.jhydrol.2014.10.047.
Water resources across Europe-confronting water scarcity and drought. European Environmental Agency EEA Report series. N. 2/2009. ISSN 1725-9177
Weib, M. and Alcamo, J., 2011. A systematic approach to assessing the sensitivity and vulnerability of water availability to climate change in Europe. Water Resources Research 47.
Xu, H. and Wu, M.M., 2017. Water availability indices–a literature review (No. ANL/ESD-17/5). Argonne National Lab.(ANL), Argonne, IL (United States).
Zang, C.F., Liu, J., Van Der Velde, M. and Kraxner, F., 2012. Assessment of spatial and temporal patterns of green and blue water flows in inland river basins in Northwest China. Hydrology & Earth System Sciences Discussions, 9(3).

Appendix A:
Available water classification

AW component	Definition	Reference
Renewable BW	Sum of surface runoff and recharge to aquifer	FAO (2003); Falkenmark & Rockstrom (2006)
	Runoff in rivers and aquifers (only renewable fraction) and temporary storage in lakes and reservoirs	Porkka *et al.* (2016)
BW yield	Total river discharge, which is the sum of surface runoff and groundwater recharge	Alcamo *et al.* (2003, 2010)
	Annual renewable discharge available assuming the amount of water that can be used	Döll *et al.* (2003); Weib & Alcamo (2011)
BW storage	The proportion of runoff water that can be sustainably withdrawn given the sum of blue water available in the rivers, stored in lakes and reservoirs, and in groundwater	Rost *et al.* (2008)
BW outflow	Total additional water demand that a basin can support above current use	Tidwell *et al*. (2016)
	The supply of water in excess of that currently allocated for consumption in a particular basin, which is the amount of water available for new development	Tidwell *et al.* (2018)
Renewable GW	Actual evapotranspiration and soil water	School *et al.* (2008); Falkenmark & Rockstrom (2006); Karimi et al. 2013
Utilizable GW	Green water availability: evapotranspiration from cropland during growing periods and 1/3 of evapotranspiration from grazing land	Porkka *et al*. (2016)
	Productive evapotranspiration and accessible stored soil water for plants at root zone depth in agricultural and pastoral lands	Current article
GW storage	Accessible stored soil water for plants at root zone depth in agricultural and pastoral lands	Current article
Manageable GW	Productive green water flow (transpiration), including green water flows from both cropland and permanent pastureland	Rockström *et al*. (2009)