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ORIGINAL ARTICLE

Developing a water budget for the Amman-Zarqa basin using water accounting plus and the pixel-based soil water balance model

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Abstract
Water resources assessments are essential for effective planning in water-scarce regions such as Jordan. Such assessments require sufficient data in space and time. The WaPOR-based Water Accounting Plus (WA+) framework is relevant as it integrates remote sensing data and the Pixel-Based Soil Water Balance model to simulate a basin's water balance. However, since it relies on remote sensing, this framework only tracks water consumption in irrigated agriculture and does not consider non-irrigation water use and its return flow. This paper modifies the WaPOR-based WA+framework to include non-irrigation manmade consumption and its return flows. The modified framework provides a more comprehensive water budget for the Amman-Zarqa (AZ) basin, presented in a modified WA+resource base sheet for 2018 through 2021. The results show that water availability in the AZ basin is highly responsive to precipitation changes. Average precipitation was approximately 926 Mm^3/year between 2018 and 2020, corresponding to an average available water of 485 Mm^3/year. However, a reduction in average precipitation by 28% in 2021 corresponded to a reduction in available water to 243 Mm^3/year. Nevertheless, substantial groundwater outflows to neighbouring basins may indicate that available water is being overestimated. Manmade consumption increased by 18% from 2018 to 2021, and the total demand exceeded the available supply by 150%. This underscores the pressing need to investigate supply augmentation and conservation methods. Future studies could focus on improving the representation of groundwater dynamics in the modified framework by improving groundwater dynamics in PixSWAB and testing the modified framework with other remote sensing datasets.

Keywords Jordan · Water scarcity · Water balance · Remote sensing · River basin planning

Introduction

Jordan faces severe water scarcity due to low and erratic rainfall, rapid population growth, and continuously increasing water demand (MWI 2023a). According to Jordan's Ministry of Water and Irrigation (MWI), the availability of renewable freshwater resources stands at an average of 61 m^3/capita/year, and it is projected to decline to 35 m^3/capita/year by 2040 due to climate change and population growth (MWI 2023a).

Managing water resources effectively in water-scarce environments necessitates comprehensive assessments of water availability and utilization in space and time (Cosgrove and Loucks 2015; Loucks and van Beek 2017). These assessments are essential for short and long-term water resources planning (Moyers et al. 2023).

Recognizing this need, the MWI develops the national water budgets for Jordan annually, utilizing data from ground observations and expert input (e.g., MWI 2023b).

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These budgets include two main components: 1) the hydrological balance for the country's fifteen surface water basins, including information on precipitation, evaporation, runoff, and recharge, and 2) water usage across different sectors, classified by water source and use type (see Annex 1 for the methodology behind Jordan's annual water budgets).

Previous research has identified several issues regarding the quality of the national water budgets. For example, data from meteorological stations used to calculate the hydrological balance are often insufficient in terms of both spatial and temporal coverage. Additionally, recharge and evaporation data are not consistently available and are often estimated using long-term averages and expert opinion (Ta'ani 2017). Water use in irrigation is frequently underestimated due to unauthorized abstractions (Al Kuisi and El-Naqa 2013; Al-Kharabsheh 2020). Moreover, the hydrological balance is reported at the basin scale, while water use is documented at an administrative scale. This discrepancy in the spatial scale complicates water assessments, typically undertaken at the basin scale.

Addressing these challenges requires a more refined water accounting approach (Al-Shibli et al. 2017). Among the available water accounting methods, Water Accounting Plus (WA +), jointly developed collaboratively by IHE Delft, IWMI, and FAO, employs open-access remote sensing data to describe water resources in river basins with limited data availability. This information assists basin managers in creating six standardized sheets (resource base, evapotranspiration, agricultural services, utilized flow, surface water, and groundwater) supported by graphs, maps, and tables (Karimi et al. 2013).

The WA + framework tracks blue and green evapotranspiration. Therefore, it is often integrated with models for splitting blue and green evapotranspiration. Examples of these models include hydrological models such as the Spatial Tools for River Basin Environmental Analysis and Management (STREAM) (Kiptala et al. 2014), pixel-based soil water balance models (FAO and IHE Delft 2019; Poortinga et al. 2017), and crop models (Chukalla et al. 2015). These models also provide other input data to the WA + framework (e.g., surface water outflow) in basins with limited ground data. In a few instances, WA + was implemented using only the outputs from hydrological models such as the Soil and Water Assessment Tool (SWAT) to undertake WA + assessments in small sub-basins where the spatial resolution of remote sensing data is not sufficient (Delavar et al. 2020, 2022).

A recent adaptation of WA + is the rapid WaPOR-based WA + framework (FAO and IHE Delft 2020). This framework utilizes the FAO's WAter Productivity through Open access of Remotely sensed derived data (WaPOR) level 2 data on evapotranspiration and precipitation. The framework provides essential Python tools for collecting and processing WaPOR data alongside a Pixel-Based Soil Water Balance model (PixSWAB) to split evapotranspiration into its blue and green components and quantify water flows that are otherwise challenging to measure, such as runoff and deep percolation. These tools and the PixSWAB model are available through open access on GitHub (WAPORWA). The outputs from this framework can be presented in the WA + resource base sheet, which delineates the water balance in river basins, including inflows, outflows across various land use classes and storage change. This approach was applied to develop rapid water accounts in the Jordan, Awash, Nile, Niger, and Litani river basins, highlighting the value of remote sensing and simulated fluxes for water resource assessments in areas with limited meteorological data (FAO and IHE Delft 2019, 2020a, 2020b, 2020c).

As it relies on remote sensing, the WaPOR-based WA + framework is helpful to quantify water consumption from irrigation. However, it does not account for non-irrigation water consumption, constituting a significant portion of total water use in Jordan (MWI 2019, 2022).

Therefore, this study modifies the WaPOR-based WA framework by integrating non-irrigation manmade consumption and its return flow to report a comprehensive water budget of the Amman-Zarqa (AZ) basin in Jordan. This modification is achieved by incorporating ground observations of non-irrigation water use and return flow with the remote sensing and simulation-based fluxes typically applied in the WaPOR-based WA + framework. The outputs of the water budget are presented in a modified version of the WA + resource base sheet, along with indicators useful for basin management.

Materials and methods

Study area

The Amman-Zarqa (AZ) basin was chosen as a case study due to its societal, economic, and agricultural significance for Jordan. It accommodates over 60% of Jordan's population, 80% of its industries, and key agricultural activities. Additionally, it provides water for irrigation in the greater Jordan Valley[1] (Al-Omari et al. 2013). The basin covers an area of approximately 4100 km^2, with 93% in Jordan and 7% in Syria (Fig. 1). Annual precipitation ranges from 50 mm/year in the east to more than 500 mm/year in the northwest near Ajloun and southwest of Amman. These variations, primarily due to topographic influences, result in a long-term average annual precipitation of 782 Mm^3/year (MWI 2023b).

[1] Treated wastewater generated in the AZ basin is transferred to the Jordan Valley for irrigation.

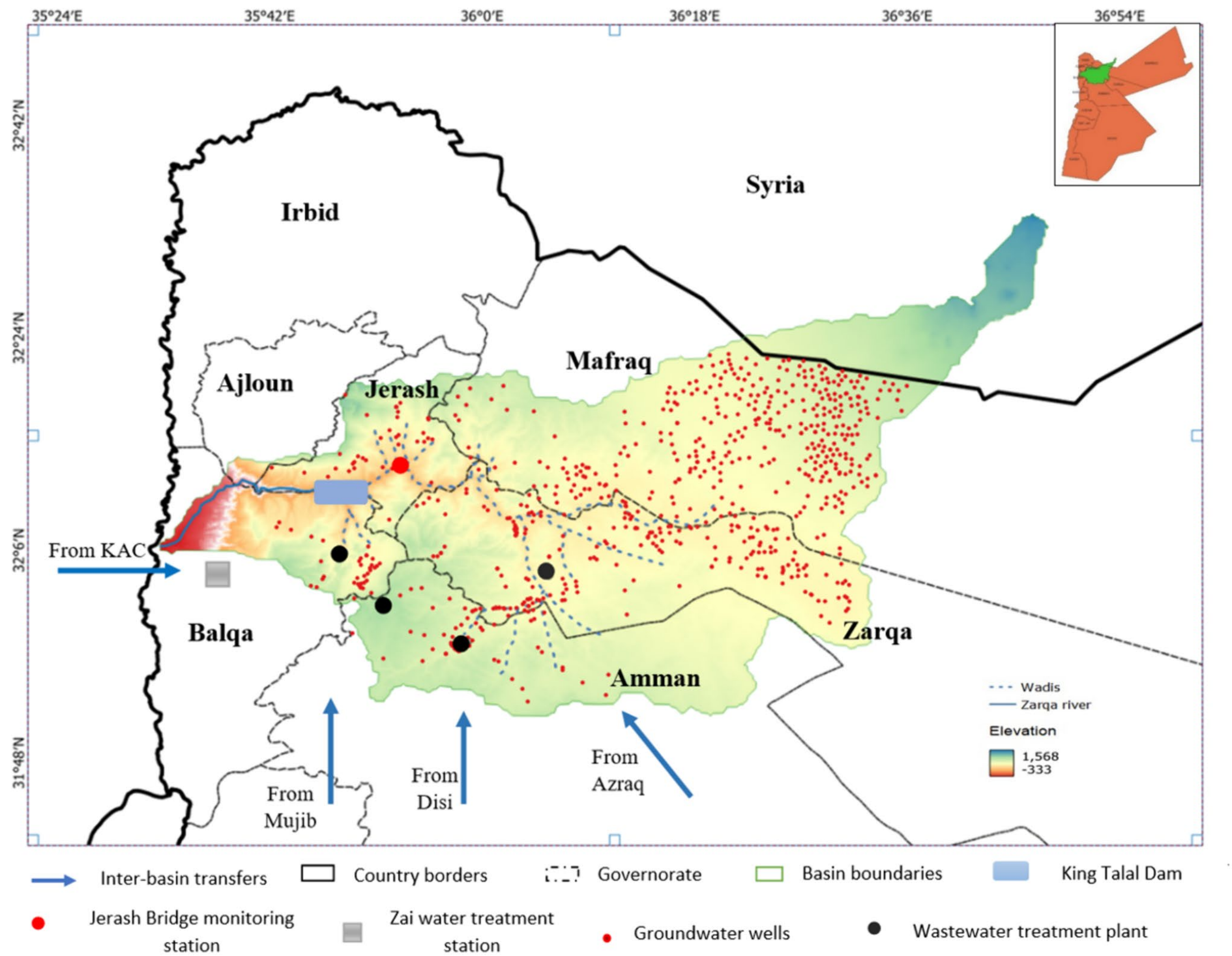

Fig. 1 Amman-Zarqa Basin location map

Water resources in the basin include groundwater aquifers and surface water from the Zarqa River.

The main groundwater layer is the A7/B2 limestone formation, which serves as the primary groundwater source in the basin due to its extensive areal coverage and high hydraulic conductivity (Al-Qaisi 2010; Al-Zyoud et al. 2015; MWI and BGR 2017). Consequently, it enables a large volume of groundwater storage (Almomani et al. 2018). Water supply in the basin is mainly provided from the groundwater aquifers to agriculture, industry, livestock, and tourism sectors through privately owned wells. The domestic water supply is sourced from government-owned wells, supplemented by inter-basin transfers from the Disi fossil aquifer, some wells in the Mujib and Azraq basins, and surface water from the King Abdullah Canal (KAC) after treatment at the Zai station.

The main surface water course is the Zarqa River. Since the 1990s, the river has also been used as a carrier of treated wastewater, mainly from the domestic sector. This wastewater undergoes treatment at four major plants (As-Samra, Jerash, Abo Nseir, and Baq'a) before re-entering the Zarqa River and mixing with freshwater at King Talal Dam (KTD). The Zarqa River receives approximately 100 Mm^3/year of treated wastewater annually (Al-Bakri et al. 2016). A small portion of treated wastewater is utilized for restricted agriculture along the river by agreements between MWI and local farmers. The remainder is combined with stored rainfall water in KTD and reserved for irrigation in the Jordan Valley.

Over time, the AZ basin has been experiencing a decline in surface and groundwater resources. Consistent over-extraction, often doubling the aquifers' annual safe yield of 88 Mm^3/year (MWI 2015), has led to a rapid decrease in groundwater levels (Al-Zyoud et al. 2015). Continuous excessive withdrawals, particularly extensive agricultural pumping in the basin's northern region, have caused the formation of a depression cone within the aquifers and a decline in static water depth to -400 m at the cone's centre

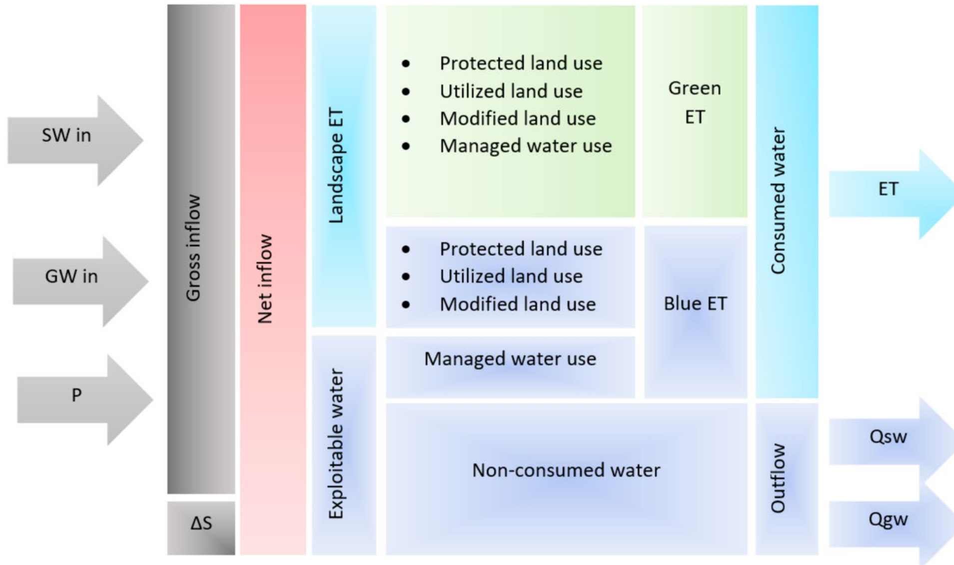

Fig. 2 WA + resource base sheet

(Brückner et al. 2021; MWI and BGR 2017). On the other hand, the annual flow of the Zarqa River has diminished from 37 Mm^3/year in 1989 to 27 Mm^3/year in 2017 (Shammout et al. 2021). This decrease is attributed to a drop in the river's baseflow from 25.4 Mm^3/year in 1989 to 10.2 Mm^3/year in 2017, caused by over-pumping of groundwater in the basin (Al-Shibli 2018; Shammout et al. 2021). Concurrently, flood flow rose from 11.7 Mm^3/year in 1989 to 17.2 Mm^3/year in 2017 due to rapid urbanization, which impacted runoff response in the basin (Shammout et al. 2021).

Overview of the WaPOR based WA + framework

The WaPOR-based WA + framework employs WaPOR V2 data on precipitation, reference, and actual evapotranspiration within the PixSWAB model to compute monthly hydrological pixel-based fluxes and storages, including surface runoff, baseflow, evapotranspiration from green water resources and blue water resources and storage change (see PixSWAB methods section and annex 2 for detailed model description).

These outputs are essential inputs for the WA + resource base sheet (Fig. 2), which summarizes the water balance based on the following equation (Kiptala et al. 2014):

$$\frac{dS}{dt} = P - ET_{blue} - ET_{green} - Q \quad (1)$$

where:

P is precipitation in Mm^3/year.

ET_{green} is ET_a from precipitation in Mm^3/year (per land class).

ET_{blue} is ET_a from blue water in Mm^3/year (per land class).

Q is water outflow in Mm^3/year.

$\frac{dS}{dt}$ is storage change over time in Mm^3/year.

The resource base sheet provides a comprehensive overview of a basin's annual water budget. Inflows include precipitation (P), surface (SW_{in}) and groundwater inflows (GW_{in}). Outflows encompass surface (Q_{sw}) and groundwater outflows (Q_{gw}) and consumed water (ETa). WA + classifies ETa by its source, either from precipitation or blue water, across various land classes such as protected, utilized, modified and managed classes. The outflows are also categorized into landscape ET and exploitable water. Exploitable water represents inflows managed primarily through irrigation or not consumed within the basin.

Basin managers can derive key performance indicators for water assessments based on the resource base sheet, including the basin closure index, ET fraction, and available and managed water fractions.

Overview of the modified WaPOR-based WA + framework

Figure 3 summarizes the approach followed to modify and implement the WaPOR-based WA + framework.

The modified WaPOR-based WA + framework involves five steps. The first two steps focus on modifying the framework. This includes modifying the water balance equation (Eq. 1) to include non-irrigation man-made consumption and its return flow (i.e., treated wastewater) (step 1), as well as updating the WA + resource base sheet to reflect the modifications made to Eq. 1 (step 2). Step 3 involves using spatial data from WaPOR to execute PixSWAB simulations. The resulting fluxes are combined with ground observations on non-irrigation consumption and

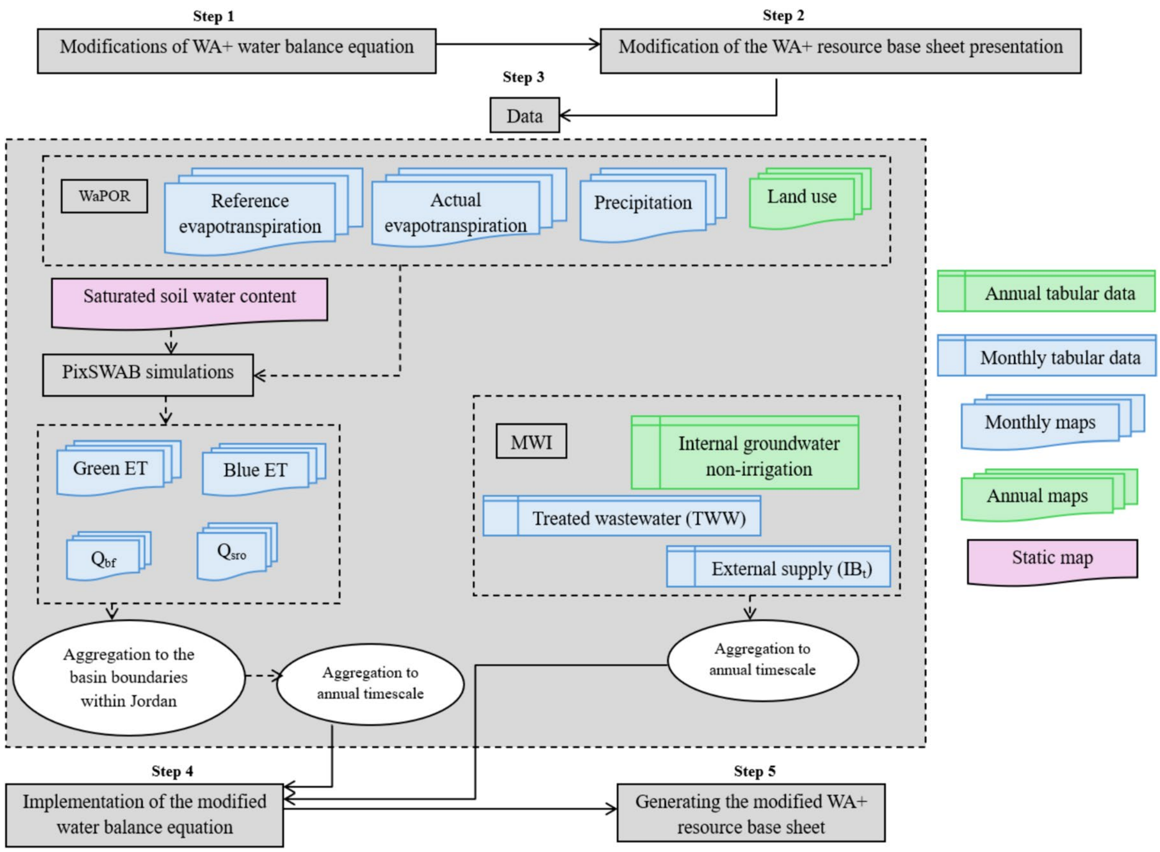

Fig. 3 The modified WaPOR-based WA + framework workflow

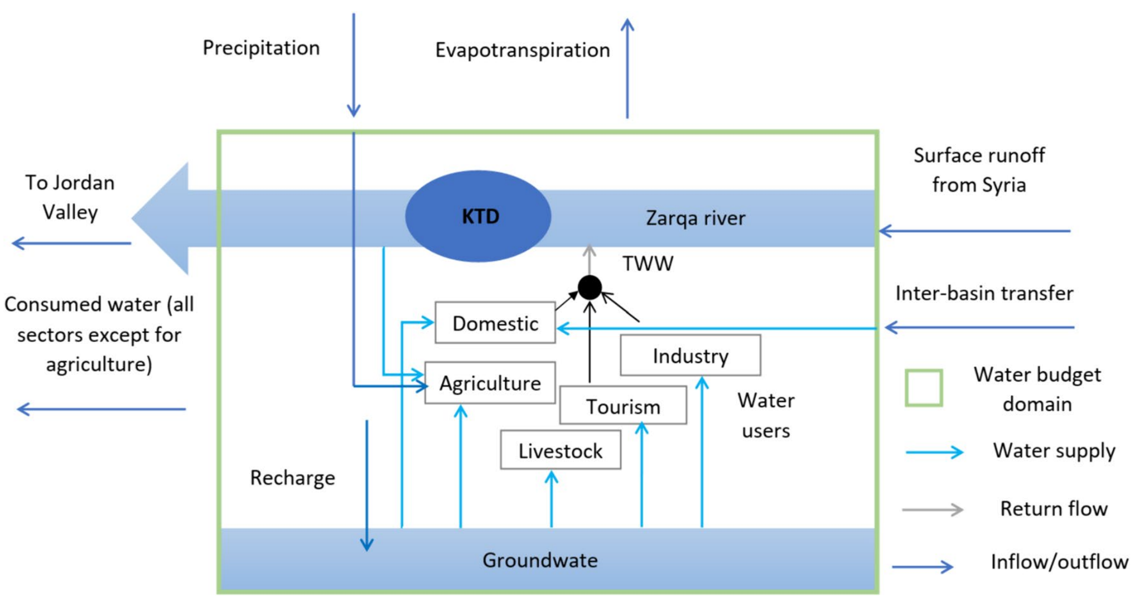

Fig. 4 Water budget domain and components in the AZ basin

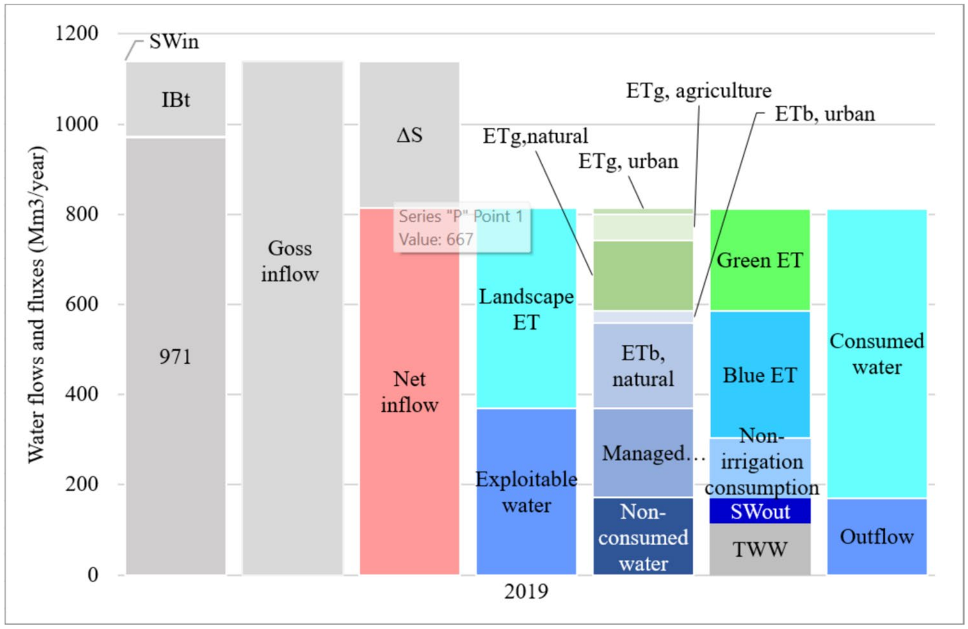

Fig. 5 The modified WA + resource base sheet

return flow to execute the modified water balance equation (step 4). Finally, the results are presented in a modified version of the WA + resource base sheet (step 5).

Modifying the water balance equation

Figure 4 represents the water budget domain and components in the AZ basin. The budget domain is defined by the basin's boundaries within Jordan. The basin's inflows consist of precipitation, surface runoff from the small portion of the basin in Syria, and inter-basin water transfers. Water is supplied from internal groundwater aquifers for agriculture, industry, livestock, and tourism. Domestic water supply is sourced from both internal groundwater aquifers and inter-basin transfers. Water consumption within the basin includes evapotranspiration across all land classes, including agricultural areas, as well as water used by industry, livestock, tourism, and domestic sectors. Treated wastewater from non-irrigation water use is returned to the Zarqa River, contributing to the surface water outflow that exits the basin and flows into the Jordan Valley.

Based on the above, the water balance equation for the AZ basin can be written as follows:

$$\frac{dS}{dt} = P + IB_t + SW_{in} - ET_{green} - ET_{blue} - W_{consumed} - Q_{sro} - Q_{bf} - TWW \quad (2)$$

where:

P is precipitation in Mm^3/year.

IB_t *is* inter-basin transfer (e.g., water imported from outside the basin to supplement water users).

SW_{in} is surface water inflow from the portion of AZ basin in Syria in Mm^3/year.

ET_{green} is ET_a from precipitation in Mm^3/year (per land class).

ET_{blue} is ET_a from blue water in Mm^3/year (per land class).

$W_{consumed}$ is the consumed in domestic, industry, livestock, and tourism sectors (non-irrigation consumption) in Mm^3/year.

TWW is the treated wastewater resulting from water supply to domestic, industry, and tourism sectors in Mm^3/year.

Q_{sro} surface runoff in (Mm^3/year).

Q_{bf} baseflow contribution to the river (Mm^3/year).

$\frac{dS}{dt}$ is storage change over time in Mm^3/year.

Modifying the resource base sheet

The resource base sheet was modified to reflect the changes in the water balance equation. Furthermore, the WA + land use classification was simplified by reclassifying the WA + land classes were from utilized, protected, managed (as shown in Fig. 2) to agricultural land use (rainfed, fallow, and irrigated areas), urban areas, and residual land classifications integrated into the natural land category (Fig. 5) (see Annex 3 for land use reclassification).

Equations used to quantify the components of the modified WA + resource base sheet are presented in Table 1. Key performance indicators derived from the WA + resource base

Table 1 Equations used to derive the modified WA + resource base sheet (Mm^3/year)

WA + category		Equation	Flux source
1	Gross inflows Q_{inflow}	$Q_{inflow} = P + SW_{in} + IB_t$	P: is obtained from WaPOR (CHIRPS) and aggregated over the portion of the basin located within Jordan SW_{in}: is obtained from PixSWAB followed by aggregating runoff for the portion of the basin located in Syria IB_t: records of IB_t were obtained from MWI ground observations and aggregated annually
2	Net inflow $Q_{inflow\text{-}net}$	$Q_{inflow-net} = Q_{inflow} \pm \Delta S$	For Q_{inflow} see category 1, and for ΔS see category 14
Flow paths			
3	Landscape ET	$ET_{landscape} = ET_{green-natural} + ET_{green-urban} + ET_{green-agricultural} + ET_{blue-urban} + ET_{blue-natural}$	Total ET: WaPOR ET_a ET split to green and blue across land classes was done in PixSWAB
4	Exploitable water	$W_{exploitable} = Q_{inflow-net} - ET_{landscape}$	For $Q_{inflow\text{-}net}$ see category 2, and for $ET_{landscape}$ see category 3
5	Green ET	$ET_{green} = ET_{green-natural} + ET_{green-urban} + ET_{green-agricultural}$	Green ET was derived across land classes through PixSWAB
6	Blue ET	$ET_{blue} = ET_{blue-natural} + ET_{blue-urban} + ET_{blue-agricultural}$	Blue ET was derived across land classes through PixSWAB
7	Treated wastewater TWW	$TWW = TWW_{As-Samra} + TWW_{Jerash} + TWW_{Baqaa} + TWW_{Abo-nseir}$	TWW records were obtained from MWI and aggregated annually
8	Non-irrigation consumption $W_{consumed}$ (domestic, industrial, livestock and tourism)	$W_{consumed} = IB_t + Q_S - TWW$	IB_t and TWW were obtained from MWI records and aggregated annually Q_s which refers to non-irrigation water abstractions from the basin's groundwater wells (domestic, industry, tourism and livestock) was obtained from MWI records
9	Surface water outflow SW_{out}	$SW_{out} = Q_{sro} + Q_{bf}$	Q_{sro} and Q_{bf} were obtained through PixSWAB
10	Managed water use $W_{managed}$	$W_{managed} = W_{consumed} + ET_{blue-agricultural}$	For $W_{consumed}$ see category 8 $ET_{blue\text{-}agriculture}$ was obtained through PixSWAB
11	Non-consumed water $W_{non\text{-}consumed}$	$W_{non-consumed} = SW_{out} + TWW$	For SW_{out} see category 9 and for TWW see category 7
Outflows			
12	Consumed water $W_{consumed\text{-}total}$	$W_{consumed-total} = ET_{green} + ET_{blue} + W_{consumed}$	For ET_{green} see category 5, for ET_{blue} see category 6 and for $W_{consumed}$ see category 8
13	Basin Outflow Q_{out}	$Q_{out} = SW_{out} + TWW$	For SW_{out} see category 9 and for TWW see category 7
14	Storage change ΔS	$\Delta S = Q_{inflow} - W_{consumed-total} - Q_{out}$	For Q_{inflow} see category 1, for $W_{consumed\text{-}total}$ see category 12 and for Q_{out} see category 13

Table 2 The key performance indicators of original and modified WA + resource base sheet

WA + resource base indicators

Indicator	Description	Equation
ET fraction	ET fraction indicates the proportion of total water inflow that is consumed. A value exceeding 100% signifies over-exploitation or reliance on external resources	$ET\,fraction = \frac{ETa}{Gross\,inflow}$
Stationarity index	The Stationarity Index reflects changes in water resources. Positive values signify an increase in groundwater and/or surface water storage, while negative values imply a depletion of these storages	$Stationarity\,index = \frac{\Delta S}{ETa}$
Basin closure index	Basin closure refers to the percentage of total available water resources (precipitation plus basin inflow) that is either consumed or stored within the basin. A value of 100% signifies that all available water is being used and/or stored in the basin	$Basin\,closure = \frac{outflow}{Gross\,inflow}$
Available water	Available water is the total amount of water that is available to be managed	$Available\,water = Gross\,inflow - Landscape\,ET - reserved\,flow$
Managed water	Managed water is the total amount of water that is abstracted and managed	Managed water = Blue ET of managed water use
Managed fraction	Managed fraction is the percentage of water that is managed from the total amount of water that is available	$Managed\,fraction = \frac{Managed\,water}{Available\,water}$

Modified WA + resource base sheet indicators

Indicator	Modification description	Modified equation
Consumed water fraction	The indicator was modified to include non-irrigation consumption. The indicator name was changed to consumed water fraction	$Consumed\,water\,fraction = \frac{ETa + W_{consumed}}{Gross\,inflow}$
Stationarity index	$W_{consumed}$ was added as it is part of the total consumption in the basin representing non-irrigation consumption	$Stationarity\,index = \frac{\Delta S}{ETa + W_{consumed}}$
Basin closure	No change was made to original WA + basin closure index	$Basin\,closure = \frac{Outflow}{Gross\,inflow}$
Available water	No change was made to original WA + available water indicator	$Available\,water = Gross\,inflow - ET_{landscape} - Q_{out}$
Managed water	Non-irrigation water consumption was added to the equation	Managed water $= ET_{blue\ agriculture} + W_{consumed}$
Managed fraction	No change was made to the original WA + managed fraction indicator	$Managed\,fraction = \frac{Managed\,water}{Available\,water}$

sheet were also modified to reflect the resource base sheet modifications (Table 2).

PixSWAB

PixSWAB description

PixSWAB is a soil water balance model developed by IHE Delft (IHE Delft 2020) based on principles from the Budyko framework (Zhang et al. 2008). The model is open access and available within the WaPOR-based WA + GitHub repository (GitHub-WAPORWA). PixSWAB is implemented for catchment scale blue and green water fluxes analysis based on the climatological characteristics of a study area (Budyko 1974). It combines data on precipitation, evapotranspiration and the aridity index (ET_o/P, where ET_o is reference evapotranspiration and P is precipitation) to simulate the hydrological processes within a basin, offering a detailed understanding of water fluxes and storage changes (Fig. 6).

A basin's water balance is simulated in PixSWAB following Eq. 3:

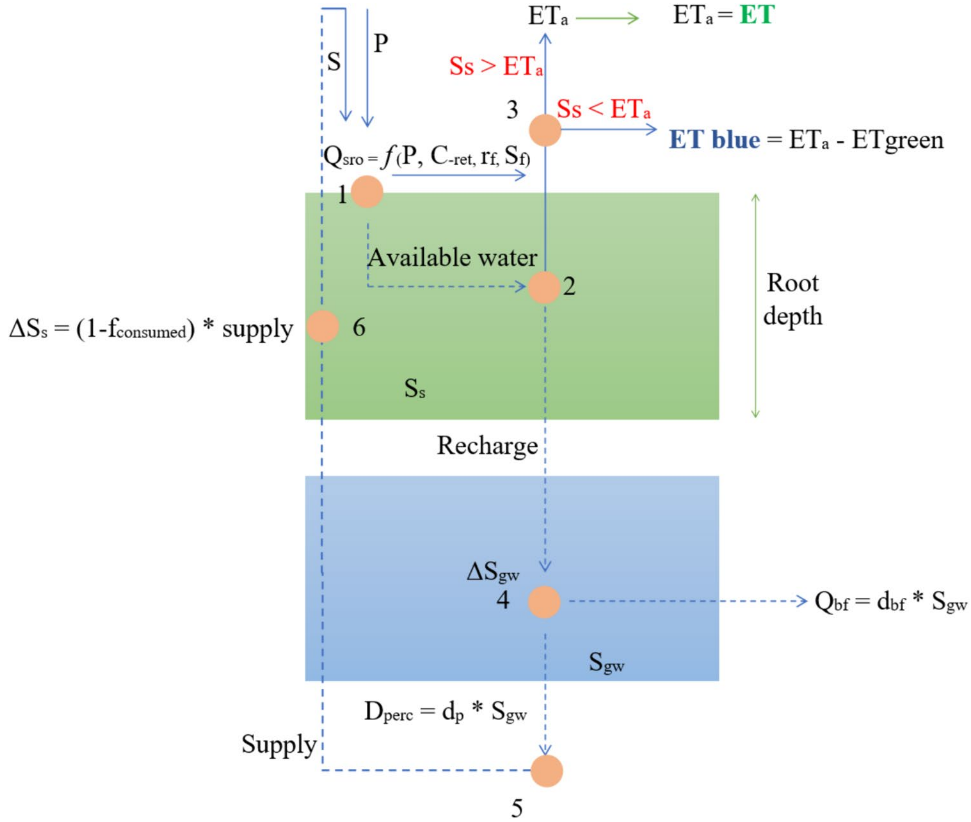

Fig. 6 Illustrative description of PixSWAB (after Michailovsky et al. 2020)

$$\frac{dS}{dt} = P + S - ET_{blue} - ET_{green} - Q_{sro} - Q_{bf} - d_{perc} \quad (3)$$

where:

$\frac{dS}{dt}$ is storage change (mm/month).

P is precipitation in (mm/month) obtained from CHIRPS.

ET_{blue} is evapotranspiration from blue water resources in (mm/month).

ET_{green} is evapotranspiration from rainfall that contributes to soil moisture in (mm/month).

S is blue water supply from deep aquifers to satisfy ET when there is no green water available (mm/month).

Q_{sro} is surface runoff (mm/month).

Q_{bf} is baseflow (mm/month).

d_{perc} is deep percolation (mm/month).

The PixSWAB model incorporates four key calibration parameters: the groundwater storage constant (d_{bf}), deep percolation constant (d_p), retention adjustment factor (r_f), and slope factor (S_f) (Michailovsky et al. 2020). These parameters allow for the model to be tailored to specific basin conditions, for more reliable performance in diverse hydrological settings. A detailed description of the model and its parameters is provided in Annex 4.

PixSWAB input data preprocessing

Table 3 describes input data to PixSWAB. Precipitation, actual evapotranspiration, reference evapotranspiration, the land use maps were obtained from WaPOR V2 level 2 data. A soil map from the High-Resolution Soil Maps of Global Hydraulic Properties (HiHydroSoil) was used to parameterize the soil moisture (de Boer 2016).

Input data preprocessing involved two steps: 1) resampling precipitation and reference evapotranspiration maps to a 100 m resolution using the nearest-neighbour method and WaPOR land use map as a template (GDAL 2023), and 2) validating the land use, precipitation and actual evapotranspiration maps.

Land use validation

The WaPOR database provides annual land cover maps from 2009 to date, relying on the Copernicus land cover product from 2015 as its base (FAO 2020). In the AZ basin, sixteen primary land classes were identified. Six tree cover classes were merged into a single category, while other classes from the WaPOR dataset were maintained as original. Bare lands, shrublands, and grasslands comprised 69% of the total basin area, followed by fallow croplands, urban zones, shrublands, rainfed, and irrigated land classes.

Table 3 PixSWAB input data

Variable	Source	Spatial resolution	Temporal resolution
Precipitation	WaPOR v3 Level 1/based on the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS)	5,000 m	Monthly
Actual Evapotranspiration	WaPOR	100 m	Monthly
Reference Evapotranspiration	WaPOR	20 km	Monthly
Saturated Soil Water Content	HiHydroSoil	0.008333 degree	Static
Land Cover Maps	WaPOR	100 m	Yearly

A thorough validation of the WaPOR land use maps was not possible due to the lack of ground truthing data or a recent land use map of the basin. Nevertheless, a comparative assessment was conducted for irrigated areas between the WaPOR maps and the most current literature (Shammout et al. 2021), which provided a validated map of irrigated areas in the basin in 2017. The total irrigated area obtained from WaPOR was about 40 km^2, mostly concentrated in the highlands within the basin. However, ground-truthing conducted by Shammout et al. (2021) revealed a value close to 170 km^2. Further analysis showed a 90% overlap between WaPOR's irrigated, rainfed, and fallow croplands and the validated irrigated areas map from 2017.

The discrepancies in irrigated area estimates could be attributed to the irrigation mapping method employed by WaPOR, which is based on the Water Deficit Index (WDI). Although the initial land cover data from Copernicus underwent validation using high-quality training points and supplementary datasets, achieving an accuracy of 80%, the mapping of WaPOR irrigated areas utilizing WDI was not cross-referenced with training points (FAO 2020).

Therefore, the WaPOR land use maps were updated to incorporate the validated irrigated areas in the AZ basin in 2017, assuming no change in irrigated areas between 2009 and 2021. The validated irrigated areas map, sourced from Shammout et al. (2021), was overlayed with the WaPOR land use maps to identify overlapping areas. Overlapping areas were clipped out from the WaPOR land use map and reclassified as irrigated areas. This has resulted in an updated land use map for the basin with irrigated areas of approximately 170 km^2 (Fig. 7).

Albeit the assumption that irrigated areas of 170 km^2 did not change between 2009 and 2021 might generate uncertainty in our study, earlier investigations reported that agriculture expanded by 10% between 1989 and 2017, with a total 0.17% growth between 2011 and 2017 (Shammout et al. 2021) and almost stabilized between 2017 and 2019 (Al-Bakri et al. 2023). As a result, our assumption is in line with previous studies.

Precipitation validation

Monthly precipitation maps from WaPOR were validated via in situ observations from 23 rain gauges within the basin, obtained from the MWI from 2009 to 2019. Daily records were aggregated to monthly values and compared with corresponding WaPOR data at station locations using various metrics. The Pearson correlation coefficient ranged from 0.8 to 0.91, and the root mean square error (RMSE) varied between 8 and 39 mm/month, with an average of 22 mm/month. These results reveal a strong correlation between ground observations and WaPOR data, with good agreement of the monthly precipitation at more than 70% of the stations from 2009 to 2019, as detailed in Annex (5).

The annual precipitation volume over the basin is an essential variable in the water budget. Therefore, it was compared with national water budget reports for 2018–2021. The precipitation volume calculated from WaPOR maps was higher than that in the budget reports in 2018 and 2021 by 214 Mm^3/year and 161 Mm^3/year, respectively. However, it was lower by -115 Mm^3/year in 2019. In 2021, WaPOR's precipitation volume closely matched the water budget report, differing by -27 Mm^3/year.

These discrepancies can likely be attributed to the quality of CHIRPS data, or the methodology used by the MWI for deriving precipitation volume. The MWI methodology relies on the weighted average rainfall depth from only 23 stations in the basin, indicating lower spatial coverage compared to WaPOR's finer resolution.

Evapotranspiration validation

In the absence of in situ ground observations of evapotranspiration, remote-sensing evapotranspiration is evaluated by comparison with other remote-sensing products (Tran et al. 2023; Pan et al. 2020). Therefore, we compared the WaPOR evapotranspiration data with those of six other remote sensing products (Table 4)and the reported evaporation values over the AZ basin in the national water budgets.

To estimate annual evapotranspiration, monthly average values across the basin were obtained from the seven

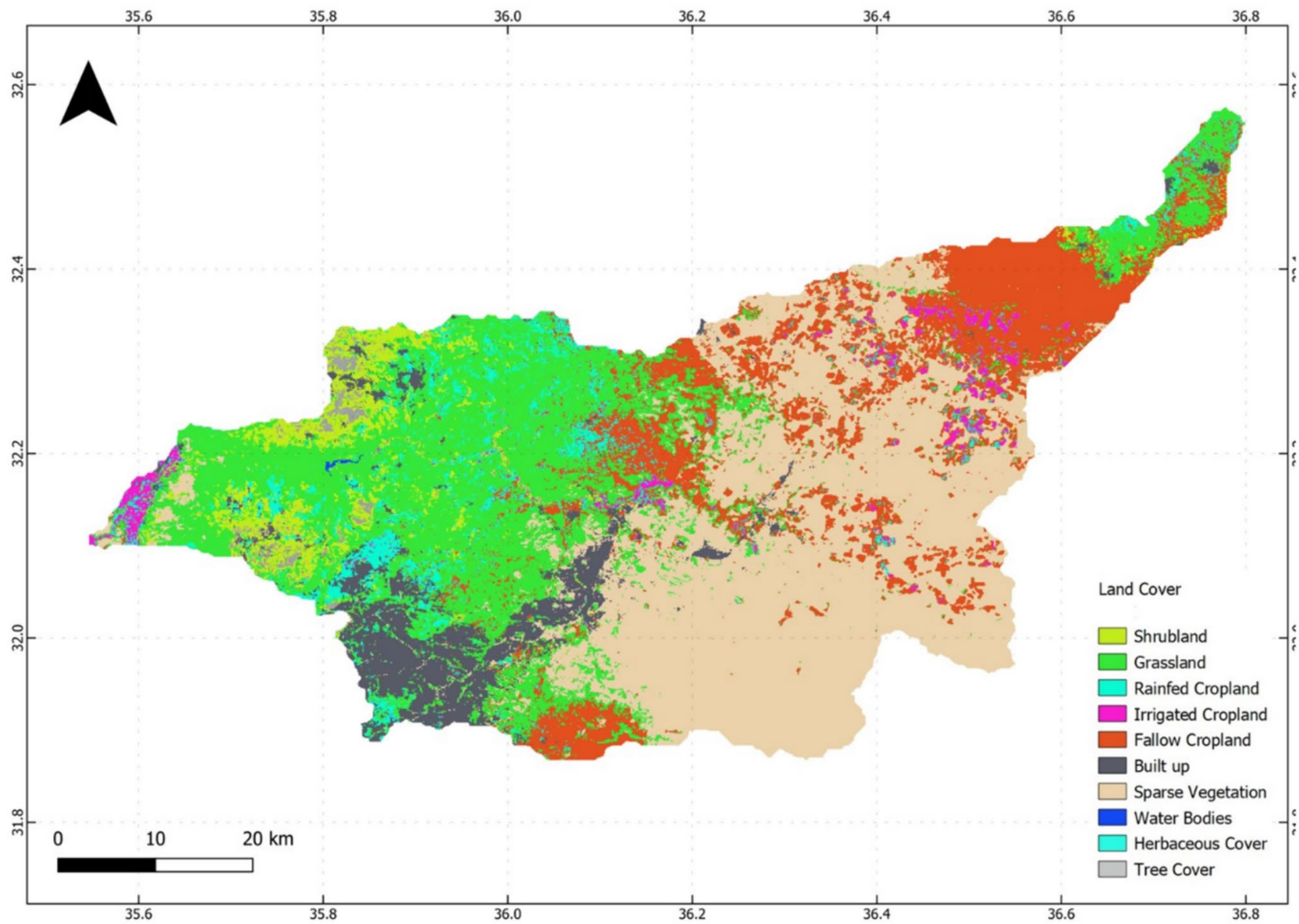

Fig. 7 Corrected WaPOR land cover land use map in AZ basin-2021

Table 4 Actual evapotranspiration datasets used for comparison with WaPOR Eta data

Dataset name	Source	Spatial resolution	Temporal resolution	Data series
MOD16A2 V105	NASA (Mu et al. 2014)	1 km	8-day	Sep. 2009–Aug. 2014
MOD16A2 Version 6	NASA (Running et al. 2021)	500 m	8-day	Sep. 2009–Aug. 2021
SMAP	NASA (O'Neill et al. 2021)	9 km	2–3 days	Sep. 2016–Aug. 2021
Penman−Monteith-Leuning V2[a]	(Zhang et al. 2019)	500 m	Daily	Sep. 2009–Aug. 2020
SSEBop	(Senay et al. 2013)	1 km	Monthly	Sep. 2009–Aug. 2021
GLDAS	(Rodell et al. 2004)	27,830 m	Daily	Sep. 2009–Aug. 2021

[a]SMAP ETa is an additional research product but not validated like the main SMAP product which is soil moisture

datasets and aggregated into annual values. A correlation analysis of these yearly values was then conducted to compare the datasets.

Table 5 summarizes the correlation analysis results. Remarkably, the MODIS datasets showed a consistent solid correlation with the remaining datasets and a good correlation with the WaPOR dataset, ranging between 0.67 and 0.69. The highest correlation for the WaPOR dataset was found with SMAP; however, this observation is limited to six years, as SMAP data is available from 2016 onwards.

Figure 8 compares the annual evapotranspiration volume derived from the seven datasets over the AZ basin. The average annual WaPOR evapotranspiration was approximately 528 Mm^3/year, which is less than the average of other datasets, ranging from 623 to 906 Mm^3/year. Further assessments of WaPOR ETa are provided in Annex 6.

On the other hand, total evapotranspiration from WaPOR was compared with evaporation estimates reported in water budgets from 2018 to 2021 (MWI 2019, 2020, 2021, 2022). The reported evaporation in the MWI budget surpassed

Table 5 Correlation analysis of annual ETa datasets in the AZ basins

Dataset	MODIS 1 km	MODIS 500 m	Penman–Monteith-Leuning	WaPOR	SSE-Bop	SMAP	GLDAS
MODIS 1 km	1.00						
MODIS 500 m	0.99	1.00					
Penman–Monteith-Leuning	0.72	0.71	1.00				
WaPOR	0.69	0.67	0.54	1.00			
SSEBOP	0.74	0.73	0.61	0.60	1.00		
SMAP	0.74	0.78	0.59	0.76	0.92	1.00	
GLDAS	0.31	0.27	0.60	0.43	0.05	0.06	1.00

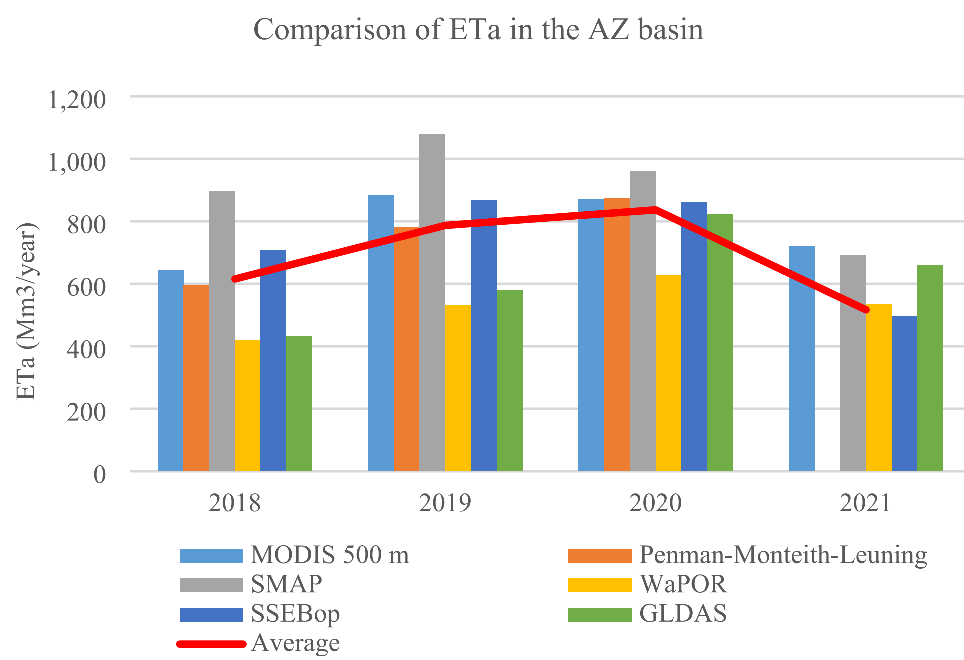

Fig. 8 Comparison of multiple evapotranspiration remote sensing products in the AZ basin (Mm^3/year)

WaPOR's data by 129–436 Mm^3/year from 2018 to 2020. However, in 2021, the reported evaporation fell short of the WaPOR's data by -72 Mm^3/year. It is important to note that the budget evaporation figures are derived from estimates and readings at scattered climatic stations within the basin. These figures do not consider land use and its impact on evaporation rates.

PixSWAB simulations and validation

The PixSWAB model was set up at 100 m for the entire AZ basin. Simulations were conducted for the hydrological years 2010 to 2021.

Calibration was performed using monthly river discharge observed at Jerash Bridge station. The validation was performed using monthly river discharge observed at the entrance to KTD (see the location of the two stations in Fig. 1). Monthly river discharge data and treated wastewater effluent discharge to the Zarqa River were obtained from MWI covering the period from 2010 to 2016. Since the observed river flow includes treated wastewater effluent, the latter was subtracted from the total observed flow to isolate the natural monthly discharge.

Two automated machine learning algorithms, HyperOpt (Bergstra et al. 2015) and Bayesian optimization (Bayes) (Ma et al. 2022), were employed for the calibration process. The calibration began with 100 iterations using the HyperOpt algorithm, designed to explore a broad parameter space efficiently. This was followed by an additional 70 iterations using the Bayes algorithm, which focused on refining the calibration by exploring promising regions identified in the initial phase. Ten parent nodes were used in the Bayes algorithm to guide its search process.

The performance of the model was evaluated based on minimizing errors through the calculation of three key metrics:

Nash–Sutcliffe Efficiency (NSE) (Nash and Sutcliffe 1970) – Eq. 4,

Kling–Gupta Efficiency (KGE) (Gupta et al. 2009) – Eq. 5,

F_{score} which is a metric that computes the harmonic mean of the previous two efficiencies, giving equal importance to both in error minimization to improve the calibration process efficiency (Hand et al. 2021): – Eq. 6.

$$NSE = 1 - \frac{\sum_{t=1}^{T} \left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T} \left(Q_o^t - \overline{Q}_o\right)^2} \tag{4}$$

where:

Q_o^t is the observed discharge at time t (m^3/month).

Q_m^t is the modelled discharge at time t (m^3/month).

$\overline{Q}_o$ is the mean observed discharge (m.^{3}/month)

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \tag{5}$$

where:

r represents the linear correlation between the observed and simulated discharges.

α is a measure of the flow variability error.

β is a bias term

$$F_{score} = \frac{2 * KGE * NSE}{KGE + NSE} \tag{6}$$

Ground observations on non-irrigation water supply and treated wastewater

Data on non-irrigation water supply and treated wastewater were sourced from MWI for the hydrological years 2018 to 2021 (Table 6). Water supply from internal groundwater aquifers was received as annual volume over the study duration and classified by use type into domestic, industry, tourism and livestock. Inter-basin transfers were received as the monthly water volume to each of the five governorates that intersect the AZ basin. However, because administrative boundaries do not coincide with the basin's geographical boundaries (see Fig. 1), water imports utilized within the basin were calculated using population density maps from 2017 to 2020 sourced from the Open Spatial Demographic Data and Research (WorldPop). These maps were used to estimate per capita water imports (in m3/capita/year) for each governorate. The per capita import figures were multiplied by the population residing within the AZ basin boundaries. This approach provided an estimate of the monthly water imports utilized within the basin. The monthly inter-basin transfers were then aggregated per the hydrological years from 2018 to 2021. Treated wastewater was received as monthly effluent volume discharged to the Zarqa River from the four treatment plants within the basin. These volumes were aggregated annually for the hydrological years from 2018 to 2021.

Table 6 Non-irrigation water supply (from internal groundwater aquifers and via imports), and treated wastewater in the AZ basin (Mm^3/year)

Flux	2018	2019	2020	2021
Non-irrigation abstractions (from internal GW)	76	82	90	101
TWW	113	114	126	124
Inter-basin transfers	164.9	165.7	162	178

WA + water balance simulations and reporting

The simulated fluxes from PixSWAB, including blue ET, green ET, Q_{sro}, and Q_{bf}, were aggregated annually for the hydrological years 2018 through 2020 using the WAPORWA Python notebooks. Q_{sro} and Q_{bf} were aggregated spatially using the basin boundaries within Jordan to quantify the basin's surface water outflow. Q_{sro}, and Q_{bf}, generated from the catchment headwaters in Syria were aggregated spatially over the basin's portion within Syria and treated as surface water inflow into the basin's boundaries within Jordan. Blue and green ET were aggregated for each modified land use class within the basin boundaries in Jordan. The aggregated PixSWAB outputs, annual non-irrigation water supply, and treated wastewater (Table 6) were used to execute Eq. 2 in Excel and calculate the storage change in the basin at the end of each hydrological year. These results were then presented in the modified WA + resource base sheet for hydrological years 2018 through 2021.

Results

PixSWAB simulation results and evaluation

The highest NSE and KGE values achieved through automated calibration were 0.69 and 0.84, respectively, with an F_{score} of 0.75. These values correspond to the following model parameters:

- d_{bf}: 0.098,
- d_p: 0.941,
- r_f: 0.826,
- and S_f: 2.

Figure 9 compares the calibrated PixSWAB discharge (using the parameters that achieved the highest NSE and KGE) with the observed discharge at the Jerash bridge

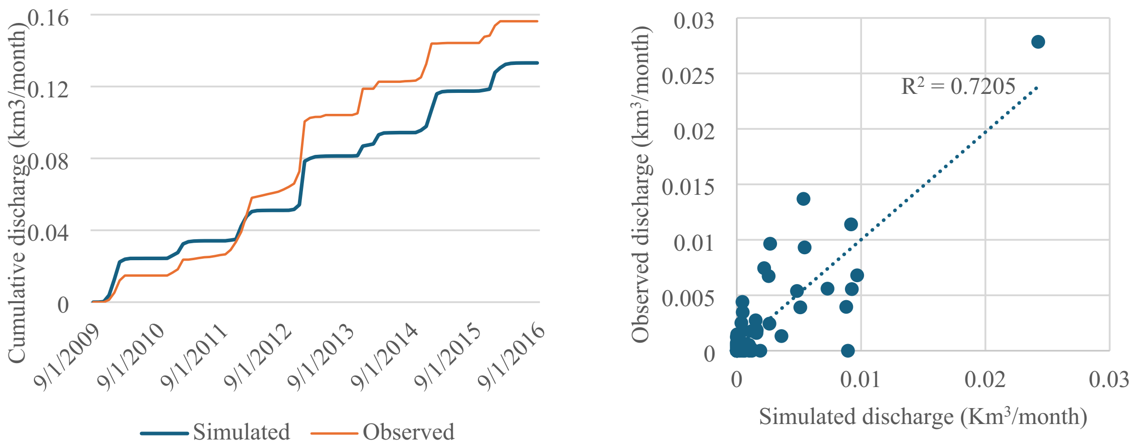

Fig. 9 A comparison between simulated and observed discharge at Jerash Bridge station

station. The results revealed a positive moderate correlation, with a Pearson coefficient of 0.84 between the simulated and observed flows and a Spearman rank correlation coefficient of 0.6. Further details on PixSWAB performance can be found in Annex (7).

Model validation at the KTD yielded an NSE of 0.72 and a KGE of 0.80. Descriptive statistics comparing the observed and simulated discharge data at KTD revealed that the monthly mean simulated and observed discharges were relatively close: 0.0016 km3/month and 0.0018 km3/month, respectively (see Table 7). The total simulated discharge was slightly lower than the observed discharge. Overall, the validation results exhibited behaviour similar to those of the calibrated discharge at the Jerash Bridge station.

To further assess the model's plausibility in the AZ basin, we compared two calibrated parameters that influence groundwater dynamics (i.e., d_{bf} and d_p) with findings from previous studies. The d_{bf} parameter, which affects the baseflow contribution to river discharge, has a low value of 0.098. This indicates a minimal baseflow contribution to the Zarqa River, thereby preserving its perennial nature during the dry season. This observation aligns with the understanding that most of the baseflow drains directly into the Jordan Rift, and that groundwater springs seep from soil surfaces or bedrock fractures downstream of the gauge stations (Al-Shibli 2018).

The d_p parameter influences the amount of water that percolates into deep aquifers. A value of nearly 0.9 suggests that water stored in the shallow groundwater bucket in PixSWAB likely drains to deeper aquifers during rainy seasons as rainfall surpasses evapotranspiration demand, signifying groundwater recharge. Additionally, groundwater aquifer formation indicates that shallow aquifers above the A7/B2 formations likely have limited water-holding capacity, whereas deeper limestone formations receive and store recharged water (MWI and BGR 2017).

Table 7 Descriptive statistics of observed and simulated discharge at validation point KTD (km^3/month)

Metric	Simulation	Observation
Mean	0.0016	0.0018
Standard error	0.0004	0.0004
Median	0.0001	0.0002
Mode	0	0
Standard deviation	0.0035	0.0040
Sample variance	0	0
Kurtosis	20.940	22.042
Skewness	3.997	4.112
Range	0.0246	0.0278
Minimum	0	0
Maximum	0.0246	0.0278
Sum	0.1379	0.1563
Count	85	85
Confidence level (95.0%)	0.0008	0.0009

Our results suggest that PixSWAB might underestimate monthly discharge, particularly during peak rainfall between December and March when runoff is generated. This could be attributed to several factors. First, errors in determining observed natural discharge may arise from inaccuracies in data collected on river discharge or effluents from treatment plants upstream of the gauge station (Al-Shibli 2018). These data are routinely manually collected and documented, which might involve human error. Another potential source of error is the use of river water for irrigation along the river (Al-Bakri et al. 2016). Additionally, the steep topography in certain areas of the AZ basin makes accurate runoff estimation challenging (Al-Shibli 2018). Potential errors may also stem from the remote sensing climatic data used in the model, as these data directly influence the model's outputs. Additionally, PixSWAB operates on a monthly time step, which might impact the accuracy of discharge estimates from short-duration, high-intensity storms. However, it is important to note that this study primarily focuses on the annual water balance, where river peak flows are less influential.

The modified WaPOR based WA + assessment

The modified WA + resource base sheets, summarizing the AZ basin's water budgets for the hydrological years 2018 to 2021 are presented in Fig. 10.

Water inflows into the AZ basin ranged from a high of 1,139 Mm3/year in 2019 to a low of 846 Mm^3/year in 2021. Precipitation accounted for 84% to 85% of total inflows between 2018 and 2020, but in 2021, precipitation decreased to 79% of total inflows. Inter-basin transfers, or water imports into the basin, ranged from 162 to 165 Mm^3/year. In 2021, these imports increased to 178 Mm^3/year, primarily due to water purchases from Israel to supplement domestic water supplies. The low rainfall in 2021 underscores the need for additional water within the basin through inter-basin transfers. The final inflow component is surface water from the basin's headwaters in Syria, which ranged from 1 to 2 Mm^3/year over the study period.

Landscape water consumption, or natural ET, increased from 347 Mm^3/year in 2018 to 510 Mm^3/year in 2020, before decreasing to 455 Mm^3/year in 2021. This indicates that ET demand was the highest in 2020. Exploitable water within the basin increased steadily from 359 Mm^3/year in 2019 to 402 Mm^3/year in 2020 but decreased slightly to 374 Mm^3/year in 2021. Exploitable water includes two components: 1) managed water consumption, which encompasses water consumed in agriculture, domestic, industry, tourism, and livestock sectors, and 2) non-consumed water within the basin.

Managed water consumption rose steadily from 191 Mm^3/year in 2018 to 226 Mm^3/year in 2021. This increase in managed water consumption likely contributes to the rise in exploitable water, reflecting growing water demands from various users in the basin.

The non-consumed water, equivalent to basin outflows through the Zarqa River, increased from 168 Mm^3/year in 2018 to 186 Mm^3/year in 2020, primarily due to increased domestic water use and larger volumes of treated wastewater discharged to the river. However, in 2021, basin outflows decreased to 148 Mm^3/year due to a drop in the Zarqa River natural discharge from 54 to 60 Mm^3/year between 2018 and 2020 to just 24 Mm^3/year in 2021, a reduction attributed to decreased precipitation.

The total water consumption within the basin, including that from natural ET and human activities, increased from 538 Mm^3/year in 2018 to 725 Mm^3/year in 2020, before decreasing slightly to 681 Mm^3/year in 2021, primarily due to a slight decrease in landscape ET demand in 2021.

Overall, the increased water consumption within the basin indicates the growing water demands from both natural ET and human activities. The increase in human activities demand, required the utilization of increasing amounts of water within the basin, as evidenced by the decreasing storage change over the study duration. According to our results, the storage changes at the end of the hydrological year (after utilization) decreased dramatically from 310 Mm^3/year to only 17 Mm^3/year, indicating increasing water availability challenges.

Table 8 summarizes the performance indicators of the AZ basin. The consumed fraction ranged from 53 to 80% between 2018 and 2021, indicating that not all inflows were fully utilized. Excess water contributed to surface and groundwater reserves. The stationarity index varied significantly, dropping from 58% in 2018 to just 2% in 2021, signalling an increasing depletion of the basin's water resources. The basin closure index averaged 80% over the study period. Water availability from surface and groundwater resources in the basin ranged from 502 Mm3/year to 243 Mm3/year, with managed fractions rising dramatically from 38% in 2018 to 93% in 2021.

Discussion

Jordan's water resources are under increasing strain due to natural scarcity and rising demand. Despite efforts to balance limited availability with growing needs through major projects and sector reforms, the country faces a significant water crisis (Al-Addous et al. 2023). Given that water resource planning often relies on scattered observations, estimates, and long-term averages, and considering the need for basin-level assessments, this paper applies a modified version of the WaPOR-based WA + approach to establish the water budget for the Amman-Zarqa basin as a case study. The study integrates non-irrigation manmade consumption, and its return flows into the WaPOR-based WA + approach and reports the AZ basin water budgets for the hydrological years 2018 through 2021.

The results of this study indicate that water availability in the AZ basin is highly sensitive to precipitation levels. From 2018 to 2020, periods of higher precipitation were associated with greater water availability. However, in 2021, a 28% reduction in precipitation compared to the previous years led to a significant 50% decrease in water availability. This demonstrates that interannual variability in precipitation directly

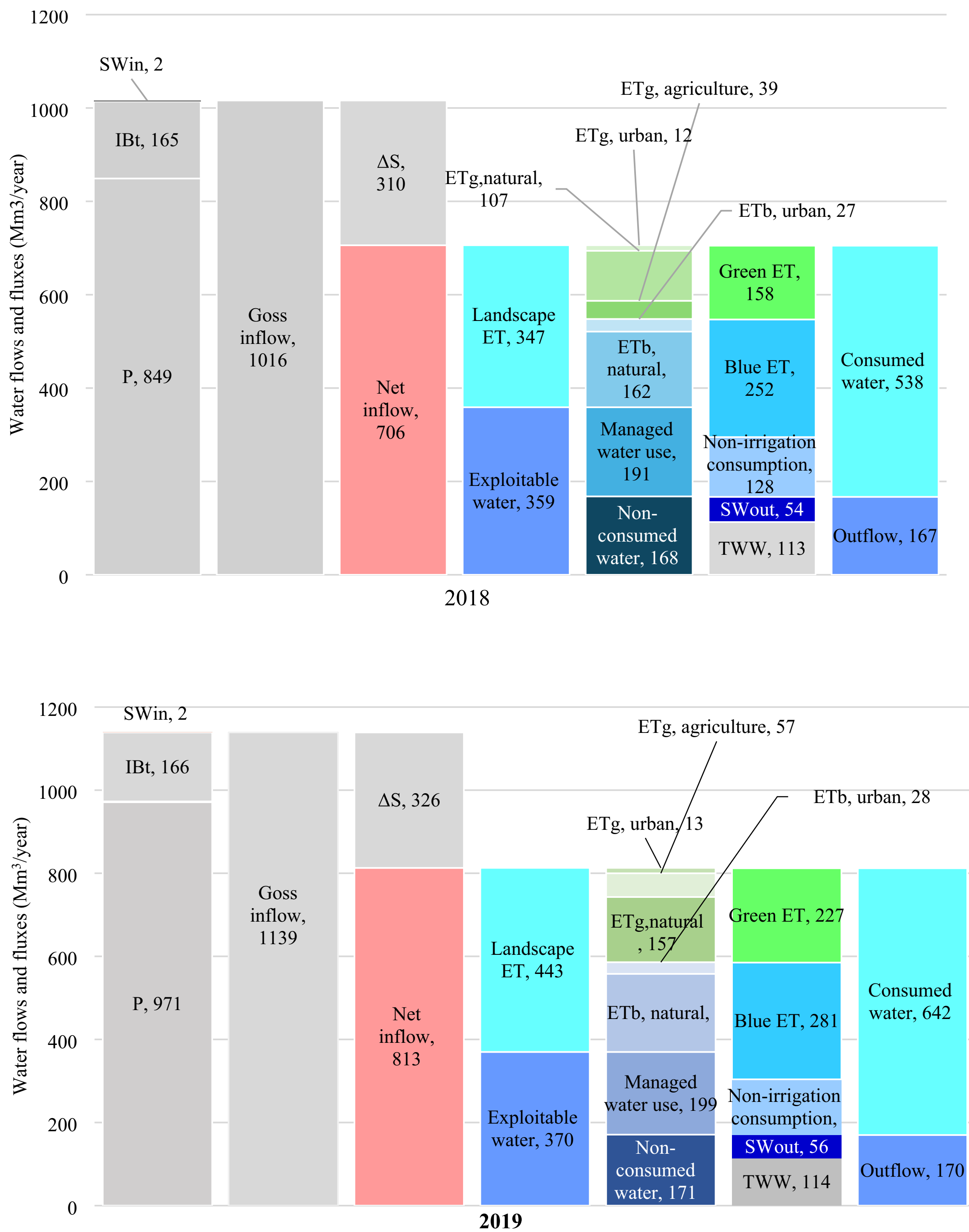

Fig. 10 The AZ basin's modified resource base sheets 2018–2021 in Mm^3/year

impacts water availability in the basin, primarily affecting groundwater aquifers.

Water availability averaged 425 Mm^3/year. However, previous research has shown that the aquifers underlying the AZ basin experience significant outflows toward the neighbouring Yarmouk and Azraq basins, often surpassing inflows. This is due to the aquifer's horizontal hydraulic conductivity being ten times higher than its vertical conductivity, indicating substantial lateral flows (MWI and BGR 2017; Abdulla et al. 2020). As a result, available water within the

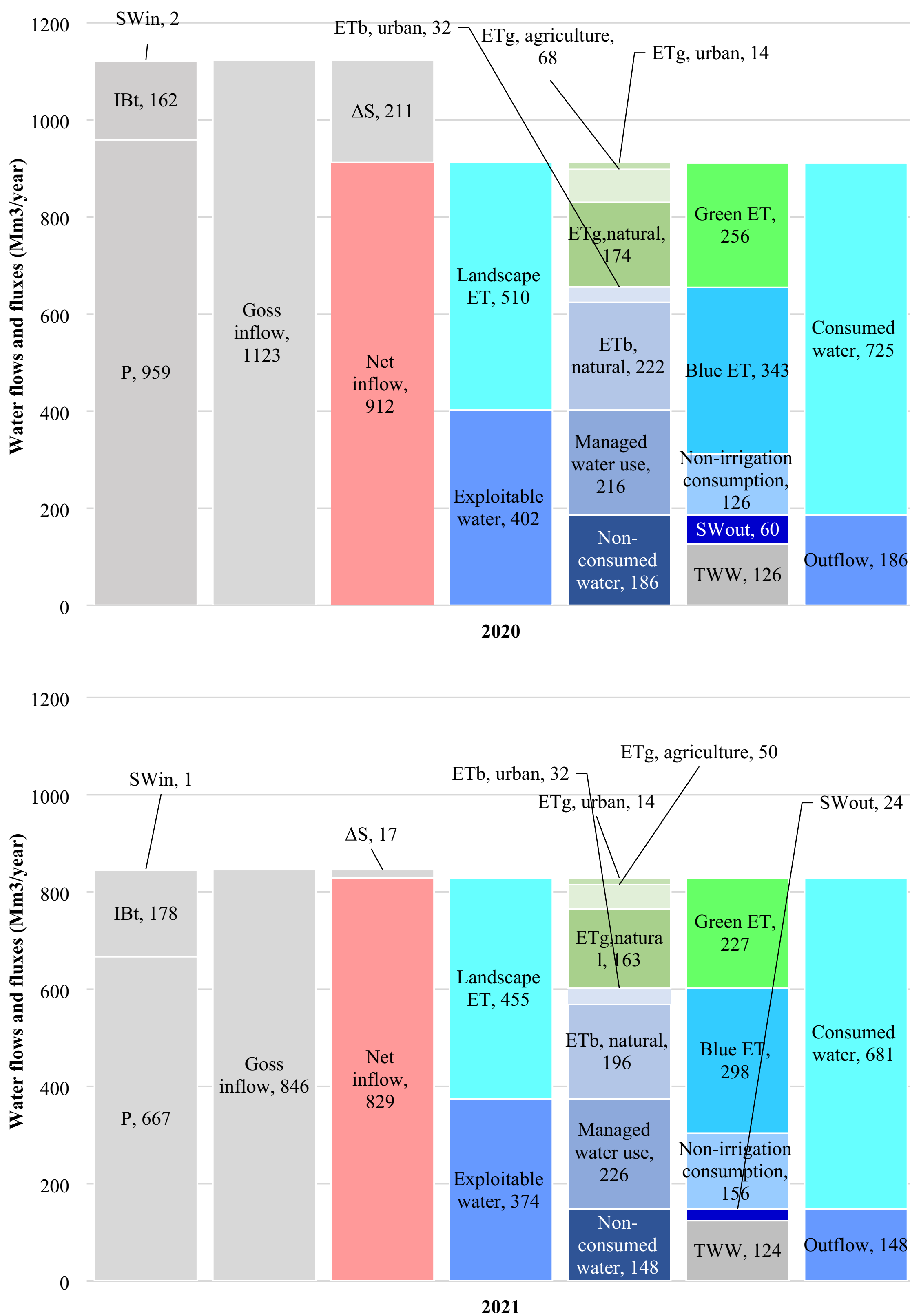

Fig. 10 (continued)

Table 8 The modified WA + indicators for the AZ basin

Indicator	2018	2019	2020	2021	Average (2018–2021)
Consumed fraction	53%	56%	65%	80%	64%
Stationarity index	58%	51%	29%	2%	35%
Basin closure index	69%	71%	81%	98%	80%
Available water (Mm3/year)	502	526	427	243	425
Managed water (Mm^3/year)	191	199	216	226	208
Managed fraction	38%	38%	51%	93%	55%

basin, quantified using the WA + approach may be overestimated. Water availability estimates could be improved by incorporating groundwater inflows and outflows into the water balance equation (Eq. 2). Due to the unavailability of these flow estimates in Jordan, we could not include them in our study. Nevertheless, our results suggest that the AZ basin receives considerable direct recharge from rainfall that may contribute to water availability in neighbouring basins through groundwater outflows.

According to the MWI, the safe yield of the groundwater aquifers beneath the AZ basin is estimated at 88 Mm^3/year. The basin receives an average of 164 Mm^3/year of freshwater through inter-basin transfers, bringing the total average water available for utilization to approximately 252 Mm^3/year. The managed water consumption within the basin and outflows through the Zarqa River (committed for irrigation in the Jordan Valley) account for an average of 375 Mm^3/year. Comparing these two figures suggests that the basin's consumptive demand for human activities is 150% larger than available water. Of all manmade consumption, agriculture accounted for between 33 and 45% from 2018 to 2021, indicating an increasing trend in water use for agriculture from the basin's groundwater aquifers. Given that water supply to other users is primarily sourced from water imports, our results suggest that groundwater abstractions for agricultural use are the largest among all sectors. These results indicate the need to explore options for increasing water supply and implementing water use efficiency measures in the basin.

Recent water resources assessments of the AZ basin available in the literature have focused on assessing the basin's water resource status by observing changes in groundwater levels (e.g., Al Wreikat and Al Kharabsheh 2020; Al-Zyoud et al. 2015) and changes in the Zarqa River discharge (Shammout et al. 2021) under single drivers such as precipitation, land use changes, and groundwater abstractions. In one study, models such as lumped soil moisture accounting models (e.g., Modele du Genie Rural a 4 Parametres Journalier (GR4J) (Edijatno and Michel, 1989)) and rainfall-runoff models (e.g., the Australian Water Balance Model (AWBM) (Boughton 2004)) were used to assess the hydrological behaviour of the Zarqa River under changing climate and land uses (Al-Shibli 2018). However, our study provides a more comprehensive framework for basin assessments as it captures water generation in surface and groundwater, and accounts for the influence of precipitation, natural evapotranspiration, human activities, and land use on water availability. However, in the case of the AZ basin, lateral groundwater flows play an essential role in the water balance. PixSWAB simulates the vertical water flow through deep percolation into groundwater but does not account for lateral groundwater movement. Therefore, improving groundwater dynamics representation in models used with WA + is important. A successful example is the SWAT-FARS model, which was employed to simulate the interactions and exchange between aquifers and different subbasins where the aquifer boundaries do not match the boundary of subbasins (Delavar et al. 2020). Therefore, future research could focus on integrating the PixSWAB with a groundwater model or improving the groundwater processes in the PixSWAB model to improve water assessments in groundwater-dependent basins.

Study limitations

The WA + framework

The WA + framework is based on remote sensing derived data. Therefore, it quantifies the consumed water within the basin but does not account for water withdrawals. Quantifying actual water withdrawals, particularly for irrigation, is crucial in Jordan due to the widespread illegal abstractions. Achieving this would require integrating water consumption and average irrigation efficiency in irrigated areas. This would require understanding crop types and farm-scale irrigation efficiency. Therefore, the framework can inform consumption-based assessments rather than withdrawal-based assessments.

Secondly, PixSWAB quantifies the direct groundwater recharge through deep percolation. However, it does not account for lateral groundwater flows. Therefore, the deep percolation within PixSWAB should not be mistaken for actual recharge, as actual recharge requires integrating lateral groundwater flows to quantify groundwater availability within the AZ basin accurately. Additionally, our modified framework reports storage changes at the end of the hydrological year, reflecting storage change after utilization. As a result, the reported storage changes in the modified WA + resource base sheets should not be mistaken for recharge.

Data

Open-access remote sensing products, like WaPOR, have made it easier to assess water availability and consumption in basins with limited ground data. This is especially beneficial for Jordan, where hydrological balance components heavily depend on expert judgment and long-term averages, making it challenging to evaluate interannual variations in water availability and affecting the quality of annual water budgets. However, as with all remote sensing products, the accuracy of these assessments is limited by the lack of sufficient ground data for validation. Therefore, the suggested framework could be evaluated using other remote sensing products, and stakeholders could be involved in integrating local expertise in choosing pertinent datasets or collaboratively developing ensemble datasets for Jordan. This process can improve the results of this framework.

The PixSWAB model was calibrated and validated using ground data from Jerash Bridge station and KTD, the two stations with complete time series data in the basin. The calibration parameters obtained were subsequently employed for model simulations. However, the basin's topography steepens downstream of both stations, and numerous springs fed by baseflow exist (Al-Shibli 2018). MWI data shows that almost 150 springs are present within the basin, predominantly located downstream. Documented spring discharge varied from 0 to 800 m3/hour between September 2017 and August 2021. However, the discharge data from these springs is sparse, with only 1 to 4 readings per spring recorded annually. If more spring data were available, it could help refine the baseflow calibration and enhance the accuracy of the PixSWAB model.

Finally, ground observations on non-irrigation water withdrawals are vital in this framework, accounting for 55% to 67% of managed water consumption. However, these supplies are reported to include large losses in municipal networks, but there are no accurate estimates of these losses (MWI and USAID 2022). Incorporating these losses, along with accounting for wastewater collected in septic tanks, might improve storage change estimates in the basin.

Conclusions and recommendations

This study modified the WaPOR-based WA + approach to report the AZ basin's water budgets for 2018 through 2021.

The modified framework contributes to improving water budget development in Jordan in two key aspects:

1. It improves data availability for developing the basin-level hydrological balance using remote sensing data on precipitation, evapotranspiration, and simulated fluxes on surface water outflow and storage change. The framework relies on near-real-time data, steering away from long-term averages and estimates employed for the water budget in Jordan. The framework reports the annual water balance in the modified WA + resource base sheets, delineating annual inflows, consumption, and outflows, along with the performance indicators. This information can improve understanding interannual variations in the basin's water availability, influenced by interannual variability in climatic conditions and human demand.
2. The modified WA + framework systematically integrates diverse data types at the basin level, including remote sensing, simulated data and ground observations. However, as the basin imports are recorded at an administrative scale in Jordan, conducting basin-level assessments of water availability, utilization, and consumption remains challenging. Our approach provides a method for estimating the imports utilized within the basin, thereby reconciling the mismatch in spatial scales between water use and the hydrological balance. This facilitates basin-level assessments which are important for water resources planning.

The modified WaPOR-based WA + framework can be utilized to report surface basin budgets in Jordan, which can be integrated to report the national water budget. The framework can enrich the national water budget with intricate tracking of water resources, from generation through utilization to consumption pathways, and improve estimates of overall water availability, consumption and remaining renewable resources after utilization. If long-term data on non-irrigation manmade fluxes (i.e., water supply and return flows) are available for all basins, a time series of water budgets can be constructed. This would provide a better understanding of basin-level hydrological processes and the impact of long-term water utilization across Jordan, revealing details about the unique settings and challenges faced in each basin and informing further targeted assessments in critical basins.

Future research could test this approach with other remote-sensing datasets to evaluate how input data affects the basin's water budget. Another area that could be studied is improving the representation of groundwater processes within PixSWAB or integrating PixSWAB with a groundwater model to improve groundwater availability assessments.

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Author contributions NA, MM, SS and GJ conceptualized the methods; NA collected the data and conducted the analysis; NA wrote the first draft; all authors reviewed and edited the paper; MM, JB and GJ supervised the research activities; NA, GJ and MM acquired funding.

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Data availability The authors declare that the data supporting the findings of this study are available within the paper, its supplementary information files, and the FAO's portal to monitor Water Productivity through open access of remotely sensed derived data (WaPOR): data.apps.fao.org/wapor/

Declarations

Conflict of interest The authors report there are no competing interests to declare.

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