Water Accounting Plus

limitations and opportunities for supporting integrated water resources management in the Middle East and North Africa

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Water Accounting Plus: limitations and opportunities for supporting integrated water resources management in the Middle East and North Africa

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ABSTRACT
This research explores the limitations and opportunities of Water Accounting Plus (WA+) for addressing water management issues in the MENA, focusing on Jordan. A comprehensive literature review and interview-based analysis were conducted to identify prevalent water management issues and evaluate information used in decision-making and strategy appraisals. The findings suggest that WA+ can enhance the spatio-temporal coverage of water resource assessments, refine estimates of irrigation water consumption, and facilitate demand management. Quantifying recharge and surface runoff requires integrating WA+ with hydrological models. Addressing climate change's impact on future water resources requires integrating climate change projections with WA+.

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Water security; remote sensing; water scarcity; WA,+; MENA; Jordan

Introduction

Water scarcity is a deeply rooted issue affecting many Middle East and North Africa (MENA) countries. The region is characterized naturally by arid and semi-arid climate, and water scarcity is exacerbated by human activities, including population growth, growing demands, and poor land and water management practices (Ahmed, 2020; Rajsekhar & Gorelick, 2017).

Water resources in the MENA include both surface and groundwater sources. All countries in the region share at least one aquifer with neighbouring countries, and over 70% of surface water resources are transboundary, such as the Euphrates and Jordan rivers (World Bank, 2018). Control by upstream states has led to water shortages downstream, particularly during dry seasons and droughts

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(Ahmed et al., 2024; Avisse et al., 2020; Kucukmehmetoglu & Geymen, 2014; Ohara et al., 2011). This pressure has caused rapid depletion of internal groundwater resources across the region, with per-capita renewable water supply in most MENA countries falling well below the water scarcity threshold of 1000 m^3/year (Ahmed, 2020; Avisse et al., 2020; Hinrichsen et al., 1997; Selvaraju, 2013; Sowers et al., 2011; United Nations, 2012). Climate change is expected to further decrease water availability due to altered precipitation patterns and increased temperatures (Ahmadi et al., 2023; Mengistu et al., 2021; Roth et al., 2018).

Among MENA countries, Jordan's water resource situation is the most critical, with only 76 m^3 of renewable water resources per capita annually (Selvaraju, 2013). Groundwater is the primary source of water supplies in Jordan, followed by surface water and treated wastewater (Ministry of Water and Irrigation, 2015). Groundwater extraction has significantly exceeded safe yields in most aquifers, and a growing gap between available water and demand persists (Al-Kharabsheh, 2020; Ministry of Water and Irrigation, 2015). Climate change is projected to reduce water availability by 15% by 2040, impacting all human activities in Jordan and making effective water resource management a vital aspect of climate change adaptation. (Ministry of Environment, 2021).

Successful water management depends on timely, accurate information about water resources, including their occurrence, distribution, and usage. This information helps decision-makers plan effective interventions to improve water security (Dembélé, 2020). The water accounting approach may be helpful in this sense as it reports the status of water resources in a standardized manner and acts as a water information system (United Nations, 2012).

Developed by the International Water Management Institute (IWMI), IHE Delft Institute for Water Education, and the Food and Agricultural Organization of the United Nations (FAO), Water Accounting Plus (WA+) provides insights on water generation, depletion, and withdrawals in complex river basins (Karimi et al., 2013). WA+ utilizes widely available satellite remote-sensing data to compensate for missing ground measurements of the water balance components (e.g., evapotranspiration; Karimi et al., 2013). Water accounts present an annual snapshot of total inflows in a basin, consumptive water use across land-use classes, and the quantity of water returned to the system, covering both surface water and groundwater (Molden, 1997). The unique aspect of WA+ is its integration of a unique land-use classification that enables a thorough analysis of a basin's water consumption, which can be either manageable or unmanageable. WA+ land classes encompass (Karimi et al., 2013):

(a) the managed water-use class, encompassing areas where the natural water cycle is altered through infrastructure, such as irrigation systems and urban domestic water use;
(b) the modified land-use class, which includes regions extensively altered by humans to produce food, feed, fibre, biofuels, and fish – examples include rainfed agricultural lands;
(c) the utilized land-use class, designated for a variety of ecosystem services that have undergone minimal human intervention – for instance, grasslands; and
(d) the conserved land-use class, areas earmarked for preservation with minimum human disturbance – such as protected nature reserves.

The WA+ information is reported in six central sheets – resource base, evapotranspiration, agricultural services, utilized flow, surface water, and groundwater – with indicators describing the basin's water resources' overall state, allowing for the assessment of the impact of biophysical and anthropogenic changes in a river basin by monitoring these indicators over time (Karimi & Bastiaanssen, 2014). However, several authors have questioned the WA+ approach from different perspectives. For example, V. G. Singh et al. (2022) argued that WA+ is limited in its suitability for water resources assessments because it cannot replace hydrological models in their functions to provide detailed information on the flow components of a basin (V. G. Singh et al., 2022). Delavar et al. (2022) and Dembélé (2020) noted that due to the reliance on remote-sensing data, the applicability of WA+ is limited to past and current situations, making it less useful for predicting water resources under climate change.

Thus, this paper aims to understand the limitations and opportunities for WA+ to contribute to addressing water resources issues in the MENA region and Jordan. It explores data types typically used in water resources assessments and the gaps in water management from a quantitative point of view to identify missing water information and assess the potential for WA+ to bridge information gaps for informed water resources management and planning. The paper targets river basin organizations in the MENA, and the Ministry of Water and Irrigation in Jordan with the goal of improving their understanding of the potential and limitations of WA+ to support integrated water resources management (IWRM).

Materials and methods

The WA+ approach is reported to inform three stages of the IWRM planning process: issue assessment, strategy evaluation, and monitoring and evaluation (Mul et al., 2023). To assess its potential to support IWRM, we conducted two systematic literature reviews to (i) capture how water resources assessments are conventionally implemented in the MENA region and (ii) how they are implemented following the WA+ approach. To further explore the case of Jordan, semi-structured interviews were conducted with key stakeholders from Jordan's water sector.

The collected information from the literature review and interviews was categorized using systematic tables (Annexe 1 in the online supplemental data) into three sections. The first section includes water issues and quantitative water information used in issue assessment, including water data used as input to the assessment and output information generated from it. The second section includes proposed or implemented strategies or interventions to address the identified problem, and the last section contains indicators used to monitor the impact of proposed strategies.

Information collected in the systematic tables was then synthesized into the challenges facing the MENA region and Jordan, specifically how water resources data and assessments have contributed to the water resources planning process and opportunities for WA+ to improve this process through contributions to the three stages identified above. Figure 1 summarizes the methodological approach, and the following section describes the methods.

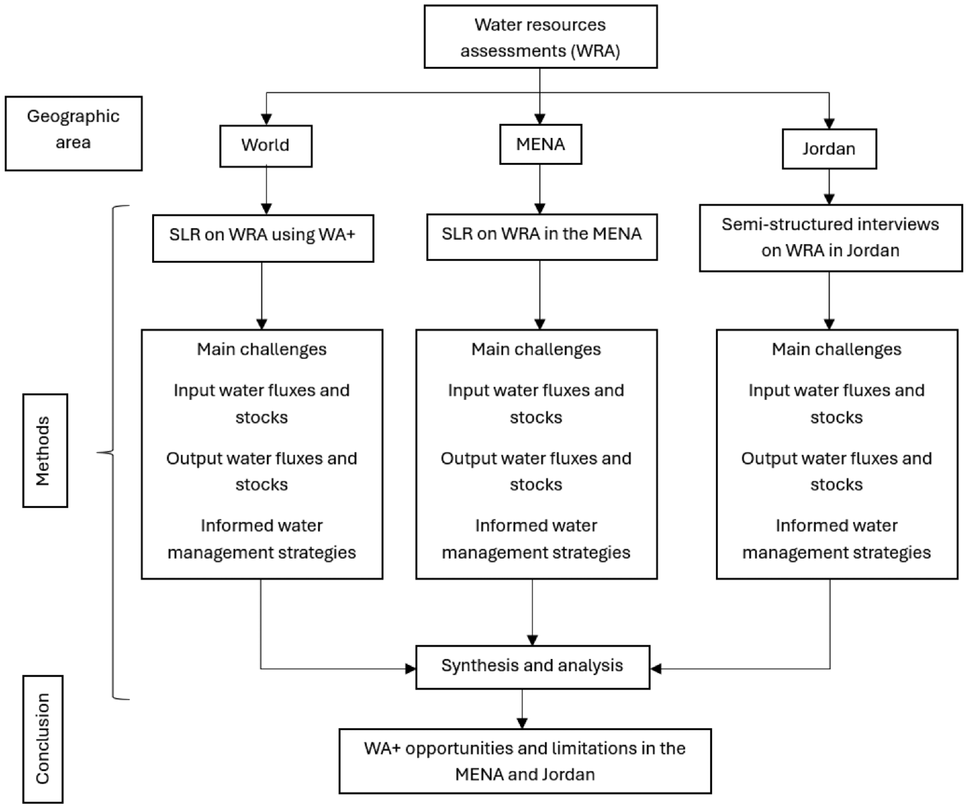

Figure 1. The study methodology flow chart.

Systematic literature review

The systematic literature reviews followed the Grant and Booth (2009) protocol. The protocol recognizes four steps in the review process: search, appraisal, synthesis, and analysis. We developed two Boolean search strings (Annexe 2 in the online supplemental data) to identify papers relevant to the MENA region and WA+ case studies on the Scopus search platform.

The search for MENA publications was restricted to peer-reviewed, English-language papers published between 2000 and 2024. Screening criteria included studies that employed quantitative water data (i.e., water fluxes and stocks), methods, and techniques. The search process was performed between 15 and 26 June 2021 and in March 2024. Sixty-nine relevant papers were initially identified and screened against the inclusion criteria, which resulted in 40 papers that were retained for detailed review.

The same approach was followed to find WA+ case studies literature. The Scopus search was conducted between 1 and 10 December 2021 and in March 2024, resulting in only nine papers. Further search on publications on the WA+ website (www.wateraccounting.un-ihe.org) uncovered 75 documents, mainly grey literature. The screening of WA+ case studies was intended to select quantitative WA+ studies that developed at least one sheet of the six WA+ sheets. Any literature review or WA+ conceptualization studies were excluded. The screening process resulted in 19 more WA+ documents, bringing the final number of WA+ publications considered for review to 29.

Information collected from the reviews was analysed using descriptive statistics in Excel. The results were summarized under five categories for each topic: an overview of studies, input data to water resources assessments, output water information, strategy evaluation, and monitoring and evaluation.

Semi-structured interviews

Although the literature review provided an overview of the MENA region, semi-structured interviews aimed to provide more insights into implementing the three stages of IWRM in Jordan. Interviews, in this case, could offer insights and opinions not usually addressed in the literature or provide more details on data availability, analysis tools, and decision-making process, facilitating a better assessment of the potential for implementing WA+ to support water management.

Interview questions were designed to obtain the details relevant to Jordan's water management process – specifically, water issues facing the country, data and information routinely used in water resources assessment, strategy development, evaluation, implementation processes, and monitoring and evaluation (see Annexe 9 in the online supplemental data for interview questions). Interviewees were selected based on their relevance to the three IWRM stages following a 'snowball' method (Johnson, 2014). We first approached the National Water Budget and Water Information System Department at Jordan's Ministry of Water and Irrigation, the central unit for dealing with water data and evidence generation for decision-making. Through the department, we were referred to the relevant people to inform our interviewees. The interviewees were six key persons from the Ministry of Water and Irrigation, Jordan Valley Authority, the Water Authority of Jordan, and a donor agency. The interviewees included two persons responsible for data collection, analysis, and water budget development, three decision-makers, and one project manager from a donor organization. The interviews were conducted in January 2022 (Figure 2). Responses were analysed using descriptive statistics in Excel

Figure 2. The first author conducting an interview with the Assistant Secretary General for Technical Affairs of the Ministry of Water and Irrigation, Mr Adel Alobeiaat (January 2022).

and validated against available literature (e.g., Al-Bakri, 2016; Al-Bakri et al., 2023; Al-Kharabsheh, 2020; Al-Shibli et al., 2017; Ministry of Water and Irrigation, 2015).

Results

The MENA region

Overview of the MENA case studies

Water management issues described in the Introduction were addressed across three water systems in the MENA region (river basins, groundwater, and wadi systems), and in one instance, the study was conducted at the country scale. Increased water scarcity and climate change were the two dominant issues in the MENA, mainly in transboundary river basins, followed by wadi systems and groundwater aquifers. A brief description of the topics addressed and study locations is provided in Annexe 3 in the online supplemental data.

Input data to water resources assessments

The count of water fluxes and stocks considered as input to water resources assessments in the reviewed studies totalled 86. These were ranked based on their usage frequency (Table 1).

Table 1. Frequency of data types applied water resources assessment in the MENA region and their sources.

				No. fluxes and stocks per data source		
Input flux/stock	No. papers	No. fluxes and stocks considered in water resources assessments	Rank	Ground measurements	Reported in previous research[1]	Satellite observations[2]
Precipitation	35[3]	38	1	18	15	5
River/wadi discharge	17	18	2	11	7	0
Evapotranspiration	6	6	3	2	3	1
Storage change in surface water	6	6	4	1	2	3
Withdrawals	5	5	4	2	3	0
Storage change in groundwater	4	4	4	1	1	2
Return flow	3	3	5	0	3	0
Storage change in soil	3	3	5	1	0	2
Recharge	2	2	6	0	2	0
Groundwater outflow (as spring discharge)	1	1	7	1	0	0
Total number of fluxes and stocks (data points)		86	41	37	36	13
Percentage of fluxes and stocks per data source		100%		43%	41%	15%

[1]This category includes reanalysis products (e.g., CRU University of West Anglia), global data sets (e.g., NOAA, FAO AQUASTAT), and data reported in previous research studies or government reports (including simulated data estimates).
[2]Data obtained directly from available satellite products (e.g., TRMM, GRACE).
[3]The number of papers does not equal the number of fluxes and stocks mainly in climate change studies where two precipitation data sets are used: baseline data (from stations), and precipitation projections from climate change models.

Precipitation was ranked first among all data types, as it was found to be a significant input in 35 papers. Precipitation is considered the most potent determinant of current and future water availability (Ahmadi et al., 2023; Al-Mukhtar & Qasim, 2019; Tramblay et al., 2018), and it determines the amount of water generated within a basin and directly impacts soil moisture and groundwater recharge (Chenoweth et al., 2011; Omer et al., 2023; Rajosoa et al., 2021; Rajsekhar & Gorelick, 2017). Additionally, it is used to anticipate the magnitude of climate change's impact on water availability (Keith et al., 2017).

River discharge was ranked second as an input variable in the reviewed studies. River discharge was used to calibrate the hydrological models implemented in the reviewed studies (Kunstmann et al., 2006) and quantify the impact of multiple natural and anthropogenic changes on the hydrological system, such as reservoirs, groundwater pumping development and irrigation schemes (Avisse et al., 2020; Keith et al., 2017; Al-Kharabsheh, 2022). In the transboundary river basins context (e.g., Jordan river, Yarmouk), river discharge was used as an indication of the level of water-resource development in upstream countries, especially because data on water usage are not openly shared among riparian countries (Rajsekhar & Gorelick, 2017; Shentsis et al., 2019).

Evapotranspiration was ranked third in the most-used data. However, as the direct measurements were not available in the MENA region, evapotranspiration was provided in the form of the best estimate under various climatic conditions and usually taken as a constant ratio of precipitation over a study area or as reported in previous research studies or government reports (Abdelhalim et al., 2020; Kucukmehmetoglu & Geymen, 2014; Kucukmehmetoglu et al., 2010). In a few instances, evapotranspiration was obtained from satellite remote-sensing observations in the form of actual evapotranspiration (Comair et al., 2012) or calculated based on pan evaporation records as potential evapotranspiration (Lacombe et al., 2008).

Other water data, such as withdrawals and storage change in surface and groundwater, were also used in the studies reported in the reviewed papers. Soil water, return flows, and spring discharge were the least used as they are either not available or difficult to measure directly. Hence, they are not readily available for use in water resources assessments.

Ground measurements constituted 43% of all data usage. When ground measurements were unavailable, global data sets (e.g., FAO AQUASTAT, the Coupled Model Intercomparison Project Phase 6 (CMIP6); Ahmadi et al., 2023; Omer et al., 2023), reanalysis products (e.g., NOAA; Keith et al., 2017), and data reported in government reports (Abdelhalim et al., 2020) were used. This group constituted 42% of all data usage. Despite the progressive development in remote-sensing data sets, only 15% of the data used in the reviewed papers were acquired from satellite remote-sensing products. For example, precipitation data were obtained from the Tropical Rainfall Measuring Mission (TRMM), the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), and the Global Satellite Mapping of Precipitation (Ahmed, 2020; Ahmed et al., 2024; Avisse et al., 2020; Müller et al., 2016; Omer et al., 2023; Saber et al., 2015). Actual evapotranspiration observations were obtained from MOD16 (Comair et al., 2012), whereas total water storage (TWS; including surface water, groundwater, and soil water storage) was obtained from the Gravity Recovery and Climate Experiment

(GRACE; in surface water, groundwater, and soil; Ahmed, 2020; Ahmed et al., 2024). The added value of using satellite remote-sensing products was the spatiotemporal coverage of its gridded data, which was essential for water resources assessments over large areas, where maintaining field monitoring networks would be economically expensive and labour-intensive, and in the transboundary river context where data sharing among riparian countries is limited (Ahmed, 2020; Ahmed et al., 2024).

We estimated the spatial resolution of input data by dividing the total study area by the number of stations/data points of climatological/hydrological variables (data point/km^2) whenever this information was available in the papers. In a few instances, spatial resolution was taken, as stated in the paper. Overall, the spatial resolution of input data was low (Figure 3(a)). Only 16% of the data utilized as input to water resources assessment in the MENA had a resolution as detailed as one measurement per 10–100 km^2; the

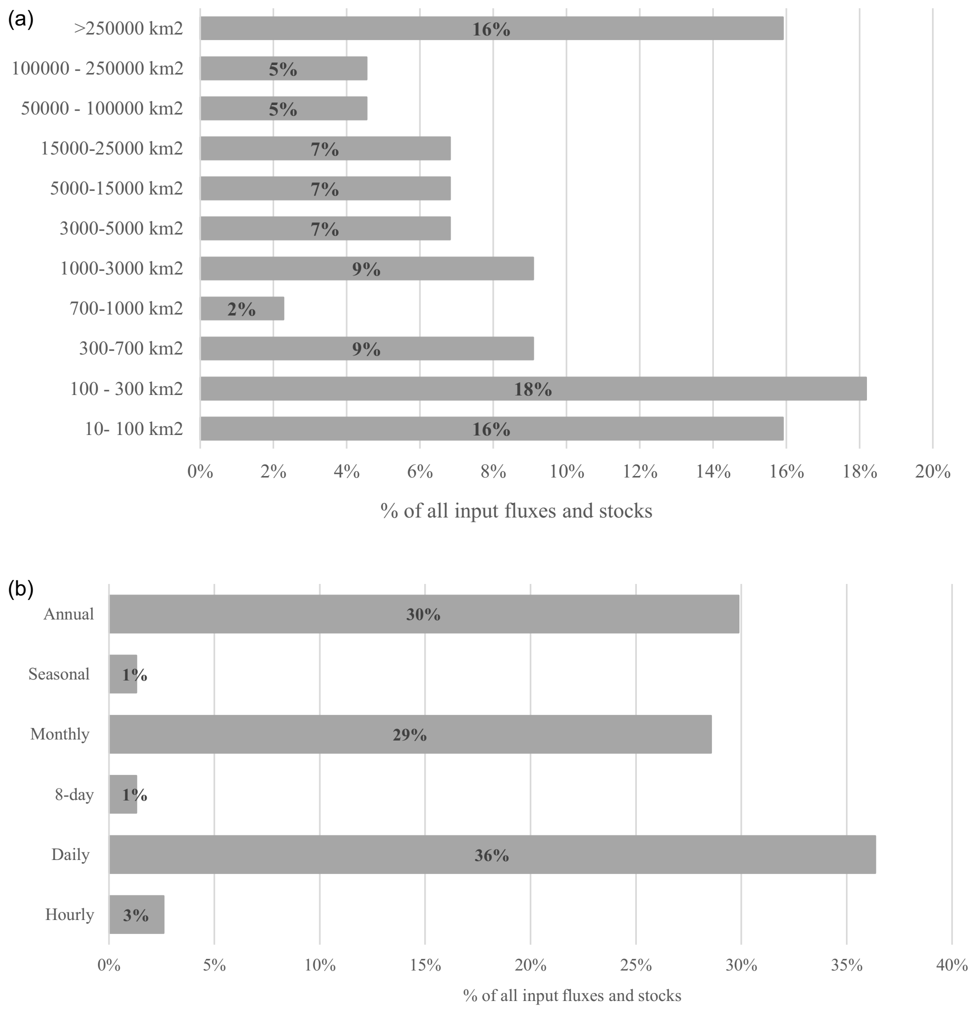

Figure 3. (a) Spatial resolution of input data used in water resources assessments in the MENA regardless of data type (data point/area). (b) Temporal resolution of input data used in water resources assessments in the MENA regardless of data type.

majority had a lower resolution. The resolution of input data might be considered low compared to the available high-resolution satellite remote-sensing products free of charge. This would also imply inadequate coverage of hydroclimatic data to capture the spatial changes in the hydrological cycle components induced mainly by topography (Al-Mukhtar & Qasim, 2019; Rajsekhar & Gorelick, 2017; Roth et al., 2018). The same results were found in the temporal resolution of input data, with the recording frequency being either annual or monthly in more than 49% of the identified fluxes and stocks. In comparison, 36% of input data were acquired at a daily time step, mainly when the analysis involved implementing hydrological models that run at a daily time step (Abdelhalim et al., 2020; Figure 3(b)). Detailed figures on the spatial and temporal resolution of input data to water resources assessments in the MENA can be found in Annexe 4 in the online supplemental data (Figures A1 and A2).

Output water information

The results showed that different analysis tools were utilized to generate water information. This included rainfall–runoff models (e.g., HEC-HMS, the Soil and Water Assessment tool (SWAT); Diani et al., 2024; Mengistu et al., 2021; Roth et al., 2018; Youssef et al., 2020), system dynamics models (e.g., Vensim Software Platform for modelling dynamic systems; Keith et al., 2017), water allocation models (e.g., the Water Evaluation and Planning (WEAP) system; the Euphrates and Tigris Basin Model (ITETRBM); Kucukmehmetoglu, 2002; Kucukmehmetoglu & Geymen, 2014; Rajosoa et al., 2021) and groundwater flow models (e.g., MODFLOW; Abdelhalim et al., 2020). A few papers used gaming and bankruptcy theories as optimization tools to address water allocation in transboundary rivers based on scenario analysis (Degefu et al., 2017; Mianabadi et al., 2015). Resultant fluxes and stocks were also analysed for usage frequency and spatial and temporal representation (Table 2).

Table 2. Fluxes and stocks generated as output from water resources assessments in the MENA.

Output fluxes/stocks	No. papers	Rank	Approach
River/wadi discharge	24	1	Rainfall–runoff modelling, water allocation modelling
Precipitation	7	2	Statistical downscaling – trend analysis – statistical analysis
Storage change in groundwater	6	3	GWS = TWS – SMS – SWS[1] Groundwater flow modelling Rainfall–runoff modelling
Withdrawals	6	3	Groundwater flow modelling Rainfall–runoff modelling Water allocation modelling
Evapotranspiration	5	4	Rainfall–runoff modelling, energy balance modelling, FAO-56 Penman Monteith approach
Storage change in surface water	4	5	Rainfall–runoff modelling Remote-sensing observations Water allocation modelling
Storage change in soil	3	6	Trend analysis of soil moisture data – rainfall–runoff modelling
Recharge	2	7	Groundwater flow modelling – soil water balance modelling
Groundwater outflow	1	8	Groundwater flow modelling
Return flow[2]	1	8	Rainfall–runoff modelling
Total number of fluxes and stocks (data points)	59		

[1]GWS = groundwater storage, TWS = total water storage, SMS = soil moisture storage, SWS = soil water storage.
[2]Water that returns to surface or groundwater after human use.

River discharge was the most significant output from water resources assessments in the reviewed studies, primarily those exploring the impact of climate change adaptation interventions on river discharge (Kucukmehmetoglu et al., 2010; Müller et al., 2016; Omer et al., 2023; Rajosoa et al., 2021; Rajsekhar & Gorelick, 2017). Precipitation changes in wet and dry seasons were of particular interest (Ahmed et al., 2024; Imteaz et al., 2017; Mengistu et al., 2021; Tramblay et al., 2018). The most-reported figures were the annual average, maximum and minimum discharge, presented as deviations from the long-term average figures.

Precipitation in the form of projections under climate change was found as an output in papers dealing with downscaling and debiasing climate change data to subregional scales (Ahmadi et al., 2023; Ahmed et al., 2024; Al-Mukhtar & Qasim, 2019; Imteaz et al., 2017; Omer et al., 2023; Wagena et al., 2016). Projected precipitation was reported as a per-cent change from the long-term average (Keith et al., 2017). Interannual precipitation variability under climate change was only explored in a few papers that deal with water availability for irrigation in a food security context and under expected future drought conditions (Ahmed et al., 2024; Conway, 2005; Roth et al., 2018). Groundwater storage change was found as output in studies exploring groundwater availability (Abdelhalim et al., 2020; Ahmed, 2020; Rajosoa et al., 2021; Thaher et al., 2017).

The spatial and temporal resolution at which the output fluxes and stocks were reported was low, with 42% being reported at the basin or country scale and 47% at an annual timescale (Figure 4(a,b)). Detailed figures on the spatial and temporal resolution of output information from water resources assessments in the MENA can be found in Annexe 4 in the online supplemental data (Figures A3 and A4).

Strategy evaluation

Comprising different tools like policies, regulations, infrastructure, and technologies, 14 of the 40 reviewed papers proposed or assessed strategies to address a specific water issue. We classified these strategies into three types: flow-based strategies, land-based strategies, and technological interventions. Flow-based strategies are those set to alter flows and fluxes directly, whereas land-based strategies aim to change the land characteristics that directly impact water flows and fluxes, aiming mainly to reduce water losses. Technological interventions refer to solutions in water management, such as advanced irrigation systems, aiming to improve water use efficiency (Annexe 5 in the online supplemental data). Strategies to inform sustainable groundwater management involved setting sustainable groundwater abstraction caps to limit groundwater withdrawals (Ahmed, 2020) and improving groundwater availability by utilizing seasonal wadi flows in artificial recharge (Kucukmehmetoglu et al., 2010; Youssef et al., 2020). The absence of in-situ observations of groundwater levels was evident in these cases; hence satellite remote-sensing products (e.g., water storage from GRACE) were vital to inform such strategies (Ahmed, 2020). Optimized water allocation schemes in transboundary rivers were also tested to enhance regional cooperative water management (Degefu et al., 2017; Wagena et al., 2016). Climate change adaptation strategies included crop pattern changes to climate-resilient crops, evaporation reduction techniques, efficient irrigation systems, and desalination (Abdelhalim et al., 2020; Chenoweth et al., 2011; Rajosoa et al., 2021). In transboundary rivers, climate change adaptation was explored through dynamic reservoir management to improve interannual water availability downstream (Ahmed et al., 2024; Keith et al., 2017; Kucukmehmetoglu & Geymen, 2014; Ohara et al., 2011). However,

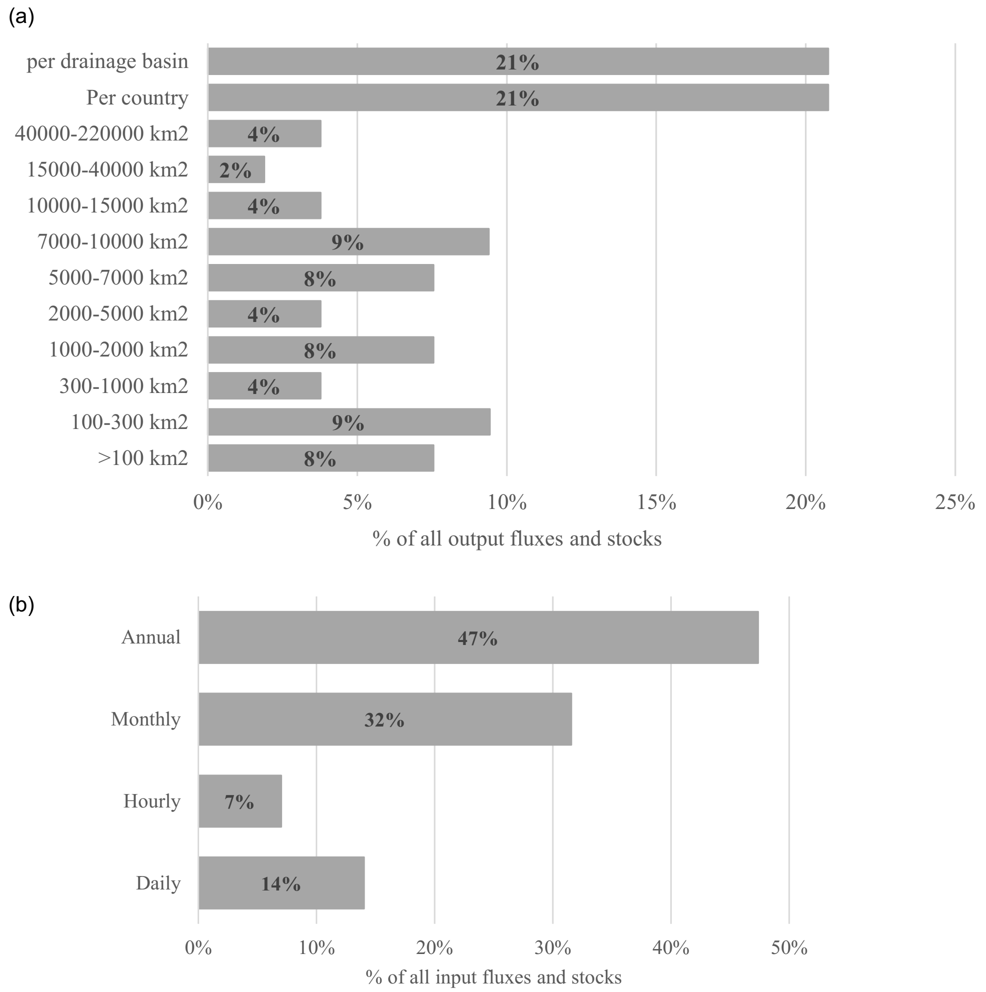

Figure 4. (a) Spatial resolution of output water information from water resources assessments in the MENA regardless of information type (data point/area). (b) Temporal resolution of output water information from water resources assessments in the MENA region regardless of information type.

none of the studies evaluated the long-term impact of interventions on future water availability.

The monitoring and evaluation aspect was the least discussed in the reviewed papers. A few papers proposed some indicators to monitor the impact of specific strategies on water resources, such as changes in river discharge, groundwater levels and withdrawals (Annexe 5 in the online supplemental data).

Jordan

Overview of Jordan's water sector

Jordan's water management and planning are centralized under the Ministry of Water and Irrigation. The Ministry of Water and Irrigation oversees strategic planning, research and development, and water resource monitoring. Operating under the

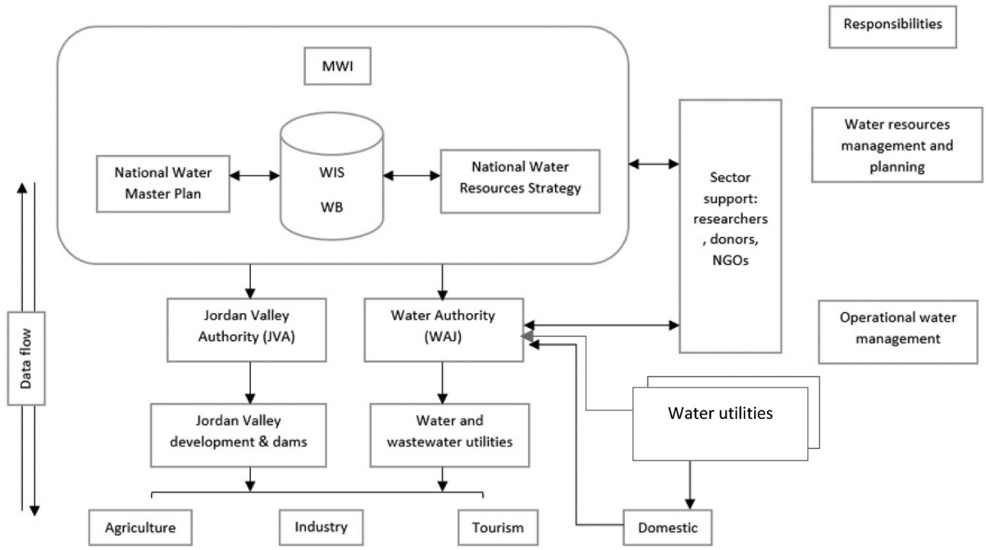

Figure 5. Jordan's water sector structure.[1,2]

Ministry of Water and Irrigation, the Jordan Valley Authority and the Water Authority of Jordan focus on daily water management activities and assist in long-term planning through data collection and service monitoring (Figure 5). The Water Authority of Jordan manages the planning, construction, operation, and maintenance of potable water and sanitation services directly or through subsidiaries like private water companies, Miahuna, Aqaba, and Yarmouk water companies. The Jordan Valley Authority facilitates socioeconomic development in the Jordan Valley, including irrigated agriculture and hydropower generation. It is also responsible for dam construction and operation, irrigation systems, and water provision. Numerous international donor organizations and non-governmental organizations have supported the Ministry of Water and Irrigation since its inception, assisting with water sector policies, reforms, and projects.

Input data to water resources assessments

The Ministry of Water and Irrigation and affiliated authorities produce a suite of monitoring services and products. According to the Jordan Water Sector Facts and Figures (Ministry of Water and Irrigation, 2015), water resources monitoring stations are summarized in Table 3.

Data collected from monitoring stations and water-use data collected via the Jordan Valley Authority and the Water Authority of Jordan are compiled in the Water Information System. The Water Information System is considered the primary data repository system hosted at the Ministry of Water and Irrigation, providing analytical tools and information for developing the National Master Plan and the National Water Strategy. However, the Water Information System is currently under restructuring and is anticipated to be fully updated through an ongoing project in the coming five years.

To understand the importance of water fluxes and stocks to water resources assessments in Jordan, we asked the interviewees to rank them based on their experience (Table 4).

Table 3. Water resources monitoring stations in Jordan (Ministry of Water and Irrigation, 2015).

Monitoring station	Type				
	Telemetric	Daily manual gauge	Semi-automatic	Totalizers	Total
Rainfall stations	59	131	18	22	230
Evaporation stations	19	22			41
		Flash flood			
Runoff stations (wadi/river)	Baseflow	Semi-automatic	Telemetry		
	18	14	3		35
Groundwater levels	86	110			196
Spring discharge	0	600			600

Table 4. Ranking of water fluxes and stocks in terms of their importance to water resources assessments in Jordan (based on the interviewees' opinions).

Fluxes/stocks[1]	Rank[2]	Existing data[3]	Source	Spatial coverage[4] (station/km^2)	Recording frequency
Precipitation (mm/h)	1	Yes	Rainfall stations	565	Hourly
Groundwater level change (mm/year)	1	Yes	Monitoring wells	455	Daily
Groundwater recharge (mm/year)	1	No	–	–	–
Withdrawals per source (mm^3/year)	1	Yes	Metres	–	–
Withdrawals per sector (mm^3/year)	1	Yes	Metres	–	–
Surface runoff (m^3/s)	1	Yes	Runoff stations	2481	Hourly and daily
River/wadi discharge (m^3/s)	2	Yes	Discharge gauges	2481	Hourly and daily
Storage change in dams (mm/day)	2	Yes	–	–	Hourly
Evaporation (mm/day)	2	Yes	Class A-Pan	4254	Daily
Evapotranspiration (mm/day)	2	No	–	–	–
Soil moisture (mm)	3	No	–	–	–
Return flow (mm^3/year)	3	No	–	–	–

[1]Units are derived from the Annual Water Budget.
[2]Rank is the average of all responses received from the interviewees.
[3]This column is validated against Table 3.
[4]Estimated based on the total area of Jordan divided by the number of monitoring stations.

The interviewees ranked primary data types (e.g., precipitation, groundwater level change, withdrawals, and river discharge) as the most important to water management in Jordan. All interviewees considered existing monitoring networks of acceptable spatial and temporal resolution. Other data types, such as evaporation (from the land surface and dams), groundwater recharge, and return flows, were ranked second, mainly due to concerns about the quality and integrity of the data and the complexities involved in their estimates (Al-Shibli et al., 2017). For example, according to the interviewees, groundwater recharge rates are standard (percentage of precipitation) for each basin and have not been updated in the last 50 years. This has caused uncertainties in groundwater safe yield estimates and, consequently, inaccuracies in the groundwater budget calculations. Margane et al. (2002) reported that groundwater recharge, estimated based on various water balance models, stands at 3.3% of the total annual precipitation in Jordan. Gropius et al. (2022) estimated groundwater recharge in Jordan using MODFLOW at 267 mm^3 in 2017, equivalent to 3.2% of the long-term average annual precipitation of 8210 mm^3 (Ministry of Water and Irrigation, 2019). According to water facts and figures (Ministry of Water and Irrigation, 2015), the recharge rate from 2005 to 2015 was estimated at an average of 4.3% of the total rainfall in Jordan, meaning that recharge volumes might be overestimated. Withdrawals, mainly for irrigation, are underestimated due to illegal abstractions in the highlands (Al Naber & Molle, 2017). Recent studies using remote-sensing data (Al-Bakri, 2016) revealed discrepancies between the metered and actual abstractions for private irrigation wells in one basin (Amman-Zarqa). The study concluded that abstraction rates are 2.2 times higher than official values. Losses in water supply networks (non-revenue water) are another issue that causes uncertainty in water availability estimates. According to Al-Sheriadeh and Amayreh (2020), non-revenue water is challenging to estimate due to inaccuracies in metering and billing systems, illegal tapping of the water network, and supply intermittency, which leads to the deterioration of water assets. Return flows and evapotranspiration were ranked third in importance, most likely due to the difficulties in estimating return flows and the dependence on measuring abstractions for irrigation rather than evapotranspiration-based consumption.

Output water information

Information on water resources is produced once a year and reported in the annual water budget by the National Water Budget and Water Information System department (Figure 6).

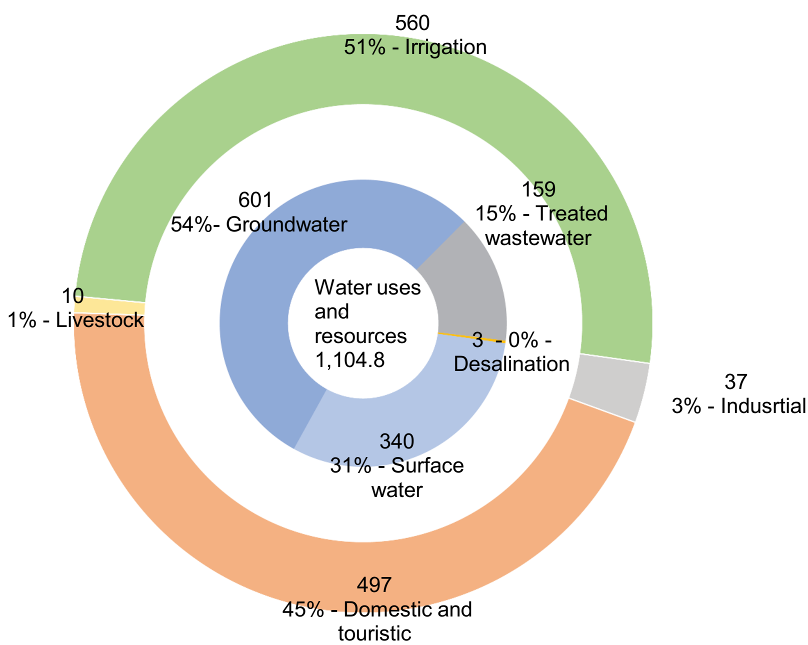

Figure 6. Jordan's water budget, mm^3/year (2019). Source: Ministry of Water and Irrigation (2019).

The water budget is considered the only document that includes comprehensive quantitative water information, including water generation from precipitation, its contribution to surface and groundwater resources per basin, supplies from conventional and non-conventional water resources, and annual abstractions from the surface and groundwater basins disaggregated per sector. The water budget summarizes surface water, groundwater, and non-conventional water resources per year and the water used by domestic, touristic, industrial, and agricultural sectors. Equation (1) is used to estimate the surface water resources available annually based on the runoff volume generated from precipitation over the 15 surface water basins:

$$R = P - E - Re \quad (1)$$

where

- R = runoff volume (mm^3/year),
- P = precipitation volume (mm^3/year) (calculated as basin area multiplied by a runoff factor and annual precipitation, mm/year),
- E = evaporation (mm^3/year) (calculated as a rate of precipitation in each basin), and
- Re = groundwater recharge (mm^3/year) (calculated as a rate of precipitation in each basin).

Evaporation and recharge rates are taken as the best estimates available as percentages of total rainfall annually.

This information is complemented with water-use information, obtained from abstractions records for agricultural, domestic, touristic, industrial, and livestock uses and reported at the national scale. Treated wastewater is included in the budget as a non-conventional water resource and is added directly to the total water available annually. According to the National Water Strategy (2015–2025), treated wastewater effluent is treated as an additional water resource for unrestricted irrigation (Ministry of Water and Irrigation, 2016). However, this water constitutes return flows from domestic water uses mainly supplied from groundwater, which might lead to double counting in the water budget. Furthermore, the accounting of evaporation and agricultural water abstractions might also lead to double counting (as agricultural water consumption is part of total evaporation).

Our findings on the water budget estimates align with previous work by Al-Shibli et al. (2017), who raised concerns about errors in measurements and calculations of the water budget aligned with the data-scarce region and the complexity of water system modelling. Therefore, implementing proper water accounting guidelines with the aid of satellite remote-sensing data is crucial to improve water budget estimates (Al-Bakri et al., 2023; Al-Shibli et al., 2017).

Strategy evaluation

The Ministry of Water and Irrigation released the National Water Strategy (2016–2025), focusing on water availability, demand, and supply targets. The interviewees referred to this document as the guidance for the water sector investments until 2025. However, they described strategic planning in Jordan as 'risky' for many reasons. For example, the strategy is implemented through projects funded by donor agencies rather than the

Ministry of Water and Irrigation, given the government's limited financial resources (Ministry of Water and Irrigation, 2016). Therefore, implementing these strategies remains constrained by funding availability. Another factor that affects strategy implementation is the government's will and priorities, including enforcing corrective water policies to conserve water resources.

The strategies tend to be based on one scenario rather than multiple scenarios considering potential future changes. For example, the groundwater conservation target requires reducing abstractions by a specific value annually to reach a safe yield by 2025. However, according to the interviews, this target can only be achieved if another water resource (e.g., desalination) is developed to compensate for reducing groundwater abstractions. This would add to the financial burdens of the ministry. A notable suggestion received during the interviews was to improve the water strategy by identifying a range of possible outcomes or even a discrete set of scenarios that consider all possibilities (including potential changes in climate, demand, and financial status) to allow amending the strategy in response to various potential changes.

Despite considering supply and demand management in the strategy (Ministry of Water and Irrigation, 2016), planning tends to focus on developing new water resources to augment the supplies. It is believed to be the most effective solution to Jordan's water scarcity, as noted by the interviewees and in the literature (Al-Bakri et al., 2023). However, such significant investments may not be the ultimate solution to Jordan's water scarcity. According to the interviews, improving domestic water delivery and efficiency could improve water availability by 40%, equivalent to the volume that could be provided through an alternative source, such as desalination, but at a lower cost. The interview with the donor agency also indicated that the planned financial support to the Ministry of Water and Irrigation would focus on improving existing shortfalls and enhancing the efficiency of existing water resource use and delivery rather than overlooking these aspects while seeking new costly resources. Furthermore, it is widely stated in the literature that focusing on supply-side approaches to water management in water-scarce settings would only intensify the pressure on water resources (Molle et al., 2010). Therefore, exploring the potential of demand management and water loss reduction in managing Jordan's water scarcity should be effectively explored.

Within Jordan's water sector, short-term planning responsibilities are handled by the Jordan Valley Authority and the Water Authority of Jordan, with support from the Ministry of Water and Irrigation. Short-term decisions involve operational infrastructure management, such as dams, water, and wastewater networks. Short-term decisions relevant to the scope of the Ministry of Water and Irrigation are those related to annual water allocation and resolving the gap between the demand and available supplies, which was described as a challenging task by the interviewees, mainly due to the uncertainties in predicting water availability. Based on the interviews, the water available for supply annually is estimated based on the amounts of precipitation received and contributed to dams' storage, the number of active wells and their caps, and the amount of treated wastewater available annually. The annual water allocation is based on the rule of thumb to allocate a 50% quota towards irrigation and to distribute the remaining available water among other municipal, industrial, and touristic users.

Regarding monitoring and evaluation activities, no specific entity is responsible for tracking and measuring the impact of different interventions, decisions, and strategies on water resources. Monitoring and evaluation at the operational level are conducted through monthly and semi-annual meetings and consultations with researchers and local experts. Ongoing projects funded by various donors are monitored during the project lifetime by the implementing agencies; however, once these projects end and are delivered to the Ministry of Water and Irrigation, impact monitoring stops, mainly due to financial and technical constraints within the Ministry of Water and Irrigation.

Water Accounting Plus

Overview of the WA+ case studies

The WA+ case studies were reviewed to extract the information as listed in the systematic table (Annexe 1 in the online supplemental data), mainly water data routinely used as input to WA+, resultant water fluxes information, strategies evaluated, and the indicators used to monitor the state of water resources. The reviewed case studies are located in Asia and Africa, where WA+ was followed to generate information relevant to addressing water scarcity, improving water availability and productivity, and supporting informed decision-making in water resources planning and management (Annexe 6 in the online supplemental data).

Input data to WA+

Hydroclimatic data used in WA+ case studies are listed in Table 5. Actual evapotranspiration and precipitation were the two significant inputs in all studies because they are essential for developing the evapotranspiration and resource base sheets. In these studies, precipitation data were obtained either from ground stations (Delavar et al., 2020, 2022) or from satellite remote-sensing products such as WaPOR (based on CHIRPS; FAO & IHE Delft, 2019, 2020b, 2020d; Ghorbanpour et al., 2022; Kivi et al., 2022) and TRMM (P. K. Singh et al., 2022) and SSEBop (Patle et al., 2023). Actual evapotranspiration was obtained from satellite remote-sensing products or hydrological modelling (e.g., SWAT; Delavar et al., 2022, 2020). More water information was derived from WA+ when other data types were available. For example, Bremer (2017) successfully generated distributed recharge rates following WA+ using surface and groundwater storage derived from GRACE data.

The spatial resolution of precipitation and evapotranspiration data is considered high, with 47% of this data being acquired at a spatial resolution of less than 5 km^2 (Figure 7 (a)). This is due to the use of the most recent satellite products (e.g., WaPOR; FAO & IHE Delft, 2020a, 2020b, 2020c, 2020d; Ghorbanpour et al., 2022; Kivi et al., 2022), with their current routine monitoring capturing nearly all components of the water balance and

Table 5. Input data applied in the WA+ studies.

Input flux/stock	No. papers	Rank	Data source
Evapotranspiration	29	1	Remote sensing
Precipitation	28	2	Remote sensing and weather stations
Storage change in surface water	8	3	Remote sensing
Storage change in groundwater	8	3	Remote sensing and modelling
Storage change in soil	7	4	Remote sensing
River discharge	7	4	Gauge stations and modelling
Withdrawals (municipal and industrial)	6	5	Government records

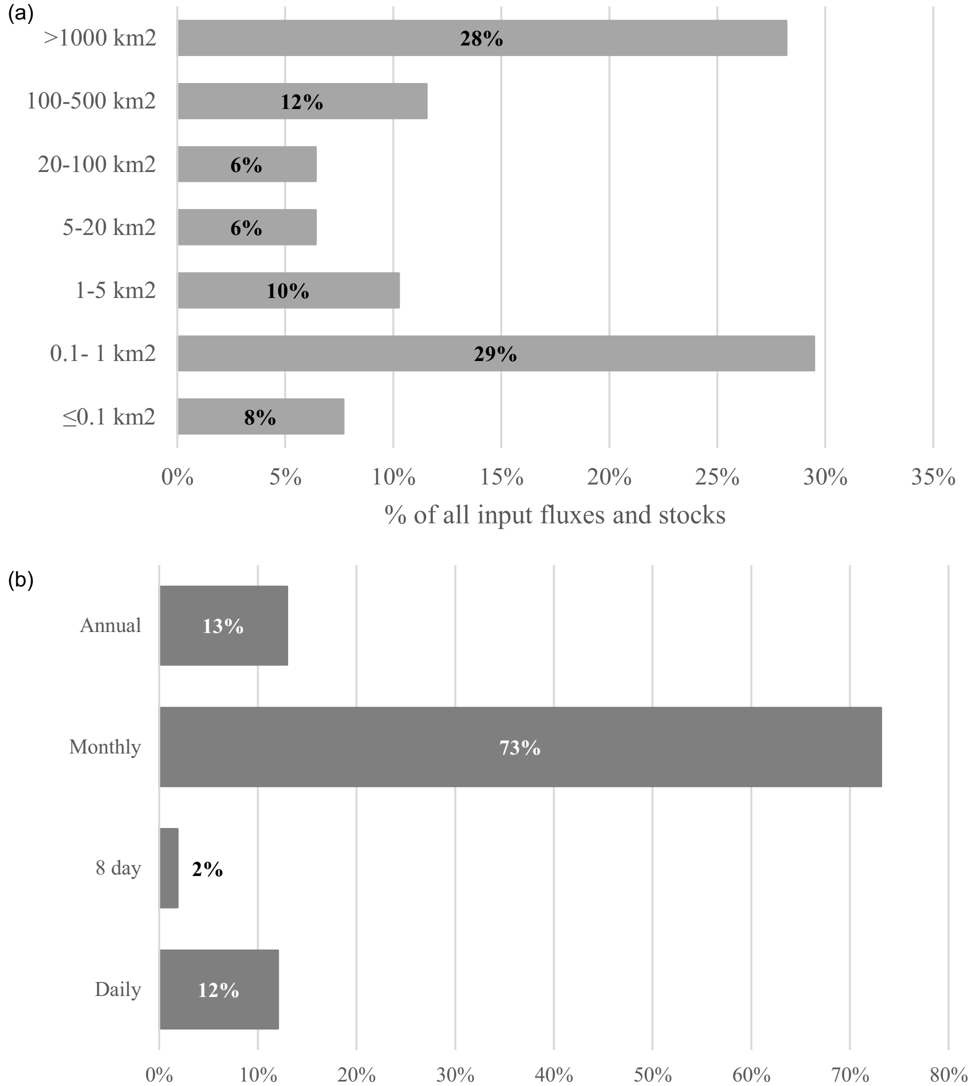

Figure 7. (a) Spatial resolution of input data used in the WA+ studies regardless of the flux/stock type (data point/area). (b) Temporal resolution of input data used in WA+ case studies regardless of the flux/stock type.

vegetation cover at high resolution (Sheffield et al., 2018). Nearly 12% of input data was obtained at 500 km^2 resolution. This data group represents total water storage (including surface, ground, and soil water) obtained from GRACE. When soil water balance tools were used (e.g., WaterPix), soil moisture data were generated at a higher resolution (less than 1 km^2; FAO & IHE Delft, 2020a, 2020b, 2020d). Nearly 28% of input data was acquired as one observation at the basin scale, mainly river discharge and withdrawals when utilized in WA+ studies (Ghorbanpour et al., 2022; Kivi et al., 2022).

On the other hand, the temporal resolution of input data was mainly monthly, followed by annual and daily time steps (Figure 7(b)). Some remote-sensing products were noted to be valuable due to their temporal continuity which is important in evapotranspiration quantification (e.g., WaPOR; Kivi et al., 2022). The monthly water information was acceptable for water resources assessments undertaken in the reviewed studies. Daily data were used when the analysis involved implementing hydrological models that run at a daily time step. Annual data were used in WA+, specifically in a few cases analysing intra-annual trends in water availability. Determining the suitable temporal resolution remains dependent on the issue of concern, available data, and the characteristics of water resources (World Meteorological Organization, 2012). Detailed figures on the spatial and temporal resolution of input data to WA+ case studies can be found in Annexe 7 in the online supplemental data (Figures A5 and A6).

Output water information

Following the WA+ methodology, water fluxes and stocks were reported in six sheets (Table 6). The evapotranspiration sheet was generated in all publications, followed by the resource base sheet generated in 96% of the reviewed publications. These two sheets summarize the state of water availability and consumption and the value of water use (beneficial or non-beneficial). The productivity sheet was generated in 41% of the reviewed publications, mainly those focusing on irrigation schemes (Ghorbanpour et al., 2022; Patle et al., 2023) A few papers extended the results to the withdrawals sheet to inform water allocation decisions (Delavar et al., 2020, 2022; Karimi & Bastiaanssen, 2014; Peiser & Bastiaanssen, 2015).

The resource base sheet avoids complex hydrological processes and provides a rapid assessment of the water resources state in a basin. In contrast, the withdrawals sheet explicitly provides surface and groundwater use estimates to support water managers in developing appropriate water management options for each resource (Karimi & Bastiaanssen, 2014). For example, Bastiaanssen et al. (2015) used the withdrawal sheet to inform seasonal water allocation and improve water availability in the dry season. The productivity sheet links water depletion with the benefits of biomass production (Karimi & Bastiaanssen, 2014). The productivity sheet was used to explore ways to improve the productivity in irrigated agriculture, such as improved irrigation systems and cultivation practices in low-productive crops (Dost et al., 2013; Karimi & Bastiaanssen, 2014).

Strategy evaluation

Assessing water strategies using WA+ requires implementing scenario analysis and hydrological modelling (Annexe 8 in the online supplemental data). Only three WA+ publications provided results on strategy evaluation. Delavar et al. (2020) implemented SWAT to generate projected water fluxes and stocks to assess the potential of modernizing irrigation to generate water savings and improve water availability. Similar work was

Table 6. Sheets reported in WA+ studies.

Sheet	No. papers	Rank
Evapotranspiration sheet	28	1
Resource base sheet	26	2
Productivity sheet	12	3
Withdrawals sheet	9	4
Groundwater sheet	5	5
Surface water sheet	1	6

undertaken by Karimi and Bastiaanssen (2014) to inform irrigation demand management interventions. Other tested strategies included land-based strategies (e.g., crop pattern changes to more productive and high-value crops; Delavar et al., 2020) and supply management strategies through new water resources development (e.g., treated wastewater and rainwater harvesting; FAO & IHE Delft, 2020b). Interestingly, under climate change scenarios, WA+ was utilized to evaluate the collective impact of integrated land and water management strategies. This included hybrid adaptation strategies that combine green, blue, and grey infrastructures, such as rainwater harvesting systems, managed aquifer recharge, bioswales, and green roofs for their contribution to water availability under future climate change (Dembélé et al., 2023).

Monitoring and evaluating water management strategies using WA+ were performed using many indicators generated from WA+ sheets (Annexe 8 in the online supplemental data). For example, Karimi and Bastiaanssen (2014) and Delavar et al. (2020) used consumption ratio, agricultural withdrawals ratio, incremental evapotranspiration, and transpiration volume to inform high-consumption locations where crop pattern changes could improve water availability. A few studies used the water productivity indicator along with beneficial and non-beneficial evapotranspiration fractions to identify locations that need irrigation efficiency improvements (Ghorbanpour et al., 2022; P. K. Singh et al., 2022; Patle et al., 2023). Another WA+ study identified the need to develop new water resources by observing the basin closure index (FAO & IHE Delft, 2020b).

Future scope of research in the WA+ framework

The reviewed studies revealed some limitations regarding the WA+ methodology and data availability. Although the WA+ methodology effectively measures water depletion and productivity within river basins, it does not account for water flows between different locations (Karimi et al., 2013). Consequently, it serves as a preliminary approach to water resource assessments in regions with limited data.

The WA+ resource base sheet provides an overview of water balance in river basins. However, to fully complete the resource base sheet, ground observations or hydrological models must supply interbasin transfers and basin outflows, including those from surface and groundwater. Some studies complemented WA+ resource base sheet with simulated inflows and outflows from hydrological models (e.g., PCR GLOBWB; Salvadore et al., 2018, 2017). However, some other studies omitted these flows due to data unavailability and treated them as part of the storage change component or approximated them with long-term flows from earlier studies (Peiser & Bastiaanssen, 2015; Salvadore & Mul, 2020). As a result, the WA+ approach could not reliably guide recharge estimates in river basins (due to missing lateral groundwater flows) or inform certain groundwater-related decisions, such as safe caps on utilized flows (FAO & IHE Delft, 2020a, 2020b).

Other limitations of WA+ stem from the quality of remote-sensing data, which requires validation through ground measurements or by comparison with other remote-sensing data sets, especially in the case of evapotranspiration. Confidence in remote-sensing data quality may impede the implementation of WA+, as it affects the results and overall trust in the method. Therefore, combining local and ground knowledge with remote-sensing data is advisable to enhance WA+'s quality and encourage stakeholder participation (Peiser & Bastiaanssen, 2015). Finally, the technical capacities of WA+ end-users, particularly their comprehension of its methodology, data requirements, and interpretation of results, constitute another factor that impacts the use of WA+ in the region. Although this aspect is out of the scope of this paper, it is crucial to incorporate it into evaluations for determining the feasibility of adopting WA+ in the region.

Discussion

In much of the MENA region, water management relies on water data derived from ground monitoring networks and global reanalysis products (see Table 3). These data have low spatial and temporal resolutions, which might not sufficiently reflect the heterogeneity in the region's topography and demography (Dembélé, 2020; Lacombe et al., 2008), or the inter-annual variability of its ephemeral water resources (e.g., wadis; Jazim, 2006). Consequently, water resources assessments allowed for rapid, albeit general, conclusions on water availability (Abdelhalim et al., 2020; Chenoweth et al., 2011; Keith et al., 2017; Kucukmehmetoglu & Geymen, 2014; Ohara et al., 2011). According to Droogers et al. (2012), most studies on the MENA region in the past 50 years were based on statistics rather than a full hydrological approach. This information mainly informed supply management interventions such as capping groundwater abstractions, developing new water resources, and improving dam operations in transboundary rivers to increase water availability downstream (Ahmed, 2020; Degefu et al., 2017; Wagena et al., 2016). However, the supply management approach has demonstrated its inability to bridge the 'water gap' between available resources and rising demands (Mualla, 2018). According to our review, information on water demands, their changes over time, and how they could be managed are limited. Among the reviewed papers, only three studies analysed the impact of demand management, mainly in irrigated agriculture, through improving irrigation efficiency and changing cropping patterns to climate-resilient crops (Abdelhalim et al., 2020; Chenoweth et al., 2011; Rajosoa et al., 2021). WA+ could improve data availability on water generation, consumption, and demand in space and time. These data capture changes in local climate, water consumption, land characteristics, and agriculture practices, which significantly affect water availability (Shtull-Trauring et al., 2016). This information can also serve water management in transboundary rivers in the region where transparent information sharing among riparian countries is lacking (e.g., water consumption and internal water resources; Al-Alaween et al., 2016; Bozorg-Haddad et al., 2020). In addition, the incorporation of the distinct WA+ land-use classification can assist in identifying appropriate measures that aim to decrease water demand (such as in irrigated agriculture), water resources protection (such as in wetlands and forests), and encourage cooperation among stakeholders to ensure that land-use decisions align with water management objectives.

In Jordan, the water situation is the most critical among MENA countries (Al-Karablieh & Salman, 2016; Hlavaty, 2018). The reported national water budget suffers from inaccuracies related to limited data availability and simplifications of water fluxes, stocks, and use estimates (Al-Bakri, 2016; Al-Bakri et al., 2023; Al-Kharabsheh, 2020; Al-Shibli et al., 2017). Some fluxes might have been double-reported in the budget, such as treated wastewater and irrigation water abstractions, necessitating the need for setting proper water accounting guidelines for water budget development. WA+ could provide the needed accounting foundation, and the use of satellite remote sensing can also improve water generation and consumption estimates (Al-Bakri et al., 2023). Implementing WA+ could also improve the annual water allocation by generating time series information on past water availability and consumption, allowing decision-makers to anticipate the consequent year conditions to a certain degree. Furthermore, WA+ also provided useful water management indicators such as basin closure ratio, agricultural withdrawals ratio, and consumption ratio.

However, for effective implementation in the region and Jordan, WA+ would require adaptation in different aspects. First, combining WA+ with hydrological models is essential to compensate for missing water data in the region and Jordan (e.g., runoff, recharge). WA+ should be improved to include scenario analysis to quantify water availability under individual or combined supply and demand interventions to help in strategy appraisal, especially under the impact of climate change (Dembélé, 2020). Third, modifications of the current land-use classification within the WA+ framework are required to ensure it aligns with Jordan's water budget requirements. Specifically, the budget report emphasizes total evapotranspiration across Jordan and water usage in various sectors such as irrigation, municipal, industry, and tourism. To enhance water management in Jordan, WA+ land-use categories should be streamlined to differentiate between areas where water is human-regulated and those under natural conditions. For instance, irrigated and urban areas, which indicate human-induced water consumption, can be grouped into a 'managed water use' category. The 'conserved land use' can still denote protected areas within the country. The remaining land categories could be consolidated into a single 'natural land' class that represents regions with minimal human impact on evapotranspiration. Fourth, WA+ indicators should be developed in alignment with the national pre-set goals in water resources plans (Delavar et al., 2020).

Conclusions

This paper assesses the potential and limitations of WA+ to support IWRM in the MENA with a focus on Jordan. It concludes that the main water management challenges faced in the MENA region have been addressed using WA+ in other areas. The main aspects that WA+ can improve is the accuracy of water assessments as it utilizes high-resolution data in space and time, providing that input remote-sensing data is evaluated for quality against ground data and local knowledge. In addition, it can improve demand management by integrating land-use classes, which can support informing water conservation mainly in irrigated agriculture. However, effective implementation of WA+ requires merging it with hydrological models to generate missing water information (e.g., recharge, surface and groundwater inflows and outflows) and incorporating climate change projections for informed water management under changing climate conditions.

It is essential to recognize that our assessment offers preliminary findings on the limitations and opportunities of WA+ in the region. To identify bottlenecks for implementing WA+ in the region, a thorough case study (e.g., basin) based assessment is needed. This assessment should clearly define the objective or problem to be addressed and determine if the WA+ methodology offers sufficient information to address the issue. Additionally, existing ground data must be evaluated for their potential to complement and validate remote-sensing data. If required, a hydrological model can be employed to supplement ground data. Selecting an appropriate model depends on the type of missing information needed to complete WA+. For example, simple rainfall–runoff models might be adequate for generating surface water inflow/outflow from a basin. However, groundwater models could be necessary for quantifying total recharge, especially lateral groundwater inflows and outflows, if the case study aims to inform groundwater-related decisions. It is also important to review the current land-use classification system used in WA+ with stakeholders to ensure it aligns with their water information reporting standards. Lastly, the alignment of WA+ indicators with the issue must be reviewed to ensure effective monitoring over time. Therefore, applying WA+ to case studies in the region could yield more precise evaluations regarding its effectiveness in addressing local water management challenges.

Notes

1. This figure was developed based on insights from the interviewees in Jordan.
2. WIS refers to Water Information System and WB refers to Water Budget.

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Author contributions

NA, MM, and GJ conceptualized the methods; NA conducted the literature review, interviews, and analysis; NA wrote the first draft; all authors reviewed and edited the paper; MM, JA, SU, MR and GJ supervised the research activities; NA, GJ, SU and MM acquired funding.

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Geolocation information

This study focuses on the Jordan (31.279862, 37.1297454).

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