From Data Gaps to Water Futures:

Adapting Global Tools for Sustainability in Jordan's Human-Water Systems

Nafn Amdar

FROM DATA GAPS TO WATER FUTURES: ADAPTING GLOBAL TOOLS FOR SUSTAINABILITY IN JORDAN’S HUMAN-WATER SYSTEMS

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DISSERTATION

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus Prof.dr.ir. H. Bijl,
chair of the Board for Doctorates
and
in fulfilment of the requirement of the Vice Rector of IHE Delft
Institute for Water Education, Prof.dr. G.P.W. Jewitt,
to be defended in public on
Monday, 13 April 2026 at 17:30 hours

by

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This dissertation has been approved by the (co)promotors.

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This research was conducted under the auspices of the Graduate School for Socio-Economic and Natural Sciences of the Environment (SENSE)

Published by IHE Delft Institute for Water Education
www.un-ihe.org
ISBN 978-90-73445-81-9

ACKNOWLEDGEMENTS

This PhD has been a long, winding road, filled with late nights, endless cups of coffee, quiet doubts, and small victories that sometimes only I could see. There were moments when the finish line felt impossibly far away, but what carried me through was never determination alone. It was the people around me, the ones who stood beside me, lifted me when I was tired, celebrated the milestones, and gently reminded me to breathe when everything felt overwhelming.

My deepest gratitude goes to my family, my constant anchor through it all. To my husband, Faris, my partner in every sense of the word, who has carried so many roles with love and patience: friend, cheerleader, father, husband, and the calm in every storm. I truly could not have done this without you. To our daughters, Sima and Mira, whose laughter, curiosity, and hugs brought light to even the hardest days and reminded me what truly matters. To my brothers, Abdul and Ahmad, whose quiet confidence in me never wavered, thank you for always believing. And to my extended family, aunts Hana and Kifaya, cousins Maha and Kazim, and my in-laws, you have been my backbone. Your reassurance and support came exactly when I needed them most, and I carry that love with me always.

I feel incredibly fortunate to have been guided by such generous mentors. To my supervisor, Dr. Marloes, my North Star throughout this journey, your wisdom, patience, and unwavering belief in me changed not only this research, but me as a person. You taught me to trust my thinking, to be brave in my ideas, and to grow into the scholar I hoped to become. I will always be grateful for your mentorship. To Prof. Gaham and Prof. Jawad, thank you for your guidance, your time, and your belief in me, it has truly been a privilege to learn from you. To Dr. Martine Rutten and Prof. Stefan Uhlenbrook, thank you for supporting me in the early years and for the confidence you placed in me at the very beginning of this path.

To the Schlumberger Faculty for the Future community, you have been far more than a scholarship. You have been a family. Thank you for the generous support that made this possible, for the opportunities you opened, and for creating such an inspiring network of women in STEM that I am proud to be part of.

I am grateful to the International Water Management Institute for providing not only a professional home, but a community that supported me throughout this work. Thanks to IWMI management and colleagues for supporting me throughout this journey. A special thank you to Dr. Youssef Brouziyne and Dr. Petra Schmitter for your trust, flexibility, and encouragement when I needed it most. I would also like to extend my sincere appreciation to Dr. Mikhail Smilovic from the International Institute for Applied Systems

Analysis, Dr. Amgad Elmahdi from the Green Climate Fund, and Dr. Arif Anwar for their insights, collaboration, and encouragement along the way. I am equally thankful to the FAO WaPOR project team for the data and knowledge that supported this research. I am also deeply thankful to the IHE Delft Institute for Water Education, a place I had dreamed of joining for many years, which gave me opportunities that have shaped my path and will continue to shape my future. I am proud to be among its graduates and grateful to all the staff and fellow PhD candidates who were part of this journey.

To my friends, especially Luma and Seersa, thank you for the laughter, the perspective, and the gentle reminders that life exists beyond deadlines. You made the difficult days lighter. Seersa, thank you for the wonderful cover page photo.

A PhD is often described as an individual achievement, but this one has never felt that way to me. It has been carried by love, mentorship, friendship, patience, and partnership. For all of that, and for everyone who held me up along the way, I am deeply, wholeheartedly thankful.

SUMMARY

More than four billion people globally live in areas of water stress, with Jordan representing one of the most severe cases worldwide. Situated in an arid region, Jordan is characterised by limited surface water resources, rapidly depleting groundwater aquifers, and escalating demand driven by population growth, economic development and persistent geopolitical pressures. Surface water is largely sourced from transboundary systems controlled by upstream countries, further constraining Jordan's long-term water security.

In this context, robust water information systems are both essential and largely insufficient. As is common across the Middle East and North Africa (MENA) region, Jordan's water data landscape is limited by sparse monitoring networks, and planning has historically relied on statistical estimates and long-term averages rather than spatially and temporally resolved assessments. This limits the country's capacity to implement integrated supply-demand interventions and to plan effectively under growing uncertainty.

This research addresses these limitations by enhancing the availability and quality of water information in Jordan with the main goal of advancing evidence-based water resources planning. The research follows an exploratory approach, beginning with a systematic diagnosis of water information gaps and their implications for planning. It then adapts two globally recognised coupled human-water systems assessment tools: Water Accounting Plus (WA+) and the Community Water Model (CWatM) to the specific context and needs of Jordan. The research then applies scenario-based analysis to generate an overview of water resources for the period 2025-2050 with the Amman-Zarqa basin serving as the primary case study.

A central finding of this research is that existing water resources assessments in Jordan generate predominantly supply-oriented information, typically lacking demand-side disaggregation necessary for integrated planning. The National Water Budget, the main output of Jordan's annual water resources assessment, was found to suffer from data inaccuracy, double counting of certain fluxes, and a scalar mismatch between the reporting of water availability and water use. These limitations collectively undermine its reliability as a planning instrument.

To address these challenges, this research modified the WA+ framework to fit Jordan's needs and institutional context. The modified framework enhances spatial and temporal data coverage through the integration of remote sensing, hydrological modelling and ground data. Furthermore, it reconciles the scales at which water availability and use are assessed, thereby improving water budget accuracy. As the WA+ framework, in its reliance on remote sensing, does not support forward-looking scenario analysis, CWatM was employed to simulate water availability and use under multiple climate trajectories

through to 2050. The model was further used to assess the potential contribution of irrigation efficiency interventions to Jordan's future water security, providing quantified insights into the limits and opportunities of demand-side management.

The results indicate that renewable water availability in Jordan is projected to decline by up to 23% by mid-century. Concurrently, the supply-demand gap is projected to nearly double the current gap, reaching 1,200 Mm^3/year, driven mainly by rapid growth in domestic water demand. While irrigation efficiency interventions remain essential, their contribution to closing the gap is found to be limited relative to the scale of projected demand increase. Accordingly, the research recommends an integrated planning strategy that combines supply augmentation through desalination for the domestic sector with expanded use of treated wastewater in irrigated agriculture.

Beyond the empirical findings, the research establishes the methodological complementarity of WA+ and CWatM, and advocates for capitalising on the distinct strengths of each approach within an integrated planning architecture. WA+ improves data coverage in space and time, fosters transparency and accountability, and is well suited for short-term operational decision-making. CWatM, on the other hand, provides the forward-looking, scenario-based perspective that is essential for long-term strategic planning under climate uncertainty. Together, the two approaches constitute a coherent and complementary information system.

Overall, this research contributes knowledge that extends beyond Jordan's specific water security challenges. The methodological adaptation, lessons learned and planning insights generated are directly transferable to other water-scarce countries, particularly in the MENA region, that face similar constraints in data availability and the urgency of integrated water resources planning.

SAMENVATTING

Stel je voor dat je in een land woont waar water zo kostbaar is als goud, elke druppel telt, maar je watervoorraad blijft slinken. Voor de meesten mensen lijkt dit misschien een extreme vergelijking, maar het is de realiteit in Jordanië, een land dat misschien wel het meest bekend staat als een van de landen met de grootste waterschaarste ter wereld.

Jordanië wordt van nature gekenmerkt door waterschaarste. Het land is sterk afhankelijk van grondwatervoorraden die snel uitgeput raken door de toegenomen vraag en beperkte neerslag. Oppervlaktewater in Jordanië is beperkt en komt voornamelijk uit grensoverschrijdende bronnen die worden beheerd door stroomopwaarts gelegen landen. Bovendien heeft het land te maken met geopolitieke veranderingen vanwege zijn ligging in het midden van een politiek instabiele regio, waardoor de vraag naar water voor verschillende gebruikers toeneemt.

In deze kwetsbare situatie is het zowel een uitdaging en een prioriteit om goed geïnformeerd waterbeheer en -planning te implementeren. Daarom is een goed waterinformatiesysteem van cruciaal belang. Net als in veel andere landen in het Midden-Oosten en Noord-Afrika (MENA) is de beschikbaarheid van watergegevens echter beperkt door schaarse monitoringnetwerken, en is de planning vaak gebaseerd op statistieken en langetermijngemiddelden.

Dit onderzoek heeft tot doel de beschikbaarheid en kwaliteit van waterinformatie in Jordanië te verbeteren en zo een beter geïnformeerde planning van watervoorraden te bevorderen. Het onderzoek volgt een verkennende gefaseerde aanpak die begint met het diagnosticeren van beperkingen in waterinformatie en hoe beperkte informatie kan leiden tot onvoldoende planning. Het onderzoek omvat het aanpassen van wereldwijd erkende waterbeoordelingsinstrumenten aan de context en behoeften van Jordanië, waarbij gebruik wordt gemaakt van twee benaderingen: waterboekhouding en geïntegreerde hydrologische en watersysteemmodellering. De studie past deze instrumenten verder toe om aan te tonen hoe ze kunnen bijdragen aan de planning van watervoorraden met behulp van scenarioanalyse voor de periode 2025-2050.

Uit dit onderzoek blijkt dat water systeem analysen in Jordanië vaak algemene informatie opleveren die leidt tot aanbodgerichte oplossingen en reactieve interventies, waarbij informatie over de vraagzijde doorgaans ontbreekt en geïntegreerde interventies op het gebied van vraag en aanbod niet mogelijk zijn. De nationale waterbalans in Jordanië, die de belangrijkste output is van de jaarlijkse evaluatie van de watervoorraden, kampt met problemen in verband met onnauwkeurige gegevens, dubbeltelling van sommige waterstromen en een discrepantie in de beoordelingsschaal tussen de beschikbaarheid en het gebruik van water, waardoor de betrouwbaarheid ervan voor de planning van watervoorraden beperkt is.

Rekening houdend met deze uitdagingen heeft dit onderzoek het Water Accounting Plus-raamwerk aangepast om een alomvattende aanpak voor waterbudgettering in Jordanië te ontwikkelen en te rapporteren, waarbij het Amman-Zarqa-bekken als casestudy werd genomen. Het aangepaste raamwerk pakt tal van uitdagingen aan, waaronder het verbeteren van de gegevensdekking in ruimte en tijd met behulp van remote sensing en modellering, en het afstemmen van de schaal waarop de beschikbaarheid en het gebruik van water worden gerapporteerd, waardoor de nauwkeurigheid van het waterbudget wordt verbeterd. Aangezien het raamwerk echter afhankelijk is van remote sensing, maakt het geen scenario-gebaseerde planning mogelijk. Daarom werd het Community Water Model (CWatM) gebruikt om de beschikbaarheid en het gebruik van water onder verschillende klimaatvoorspellingen voor het jaar 2050 te simuleren. Bovendien werden efficiëntiemaatregelen in de geïrrigeerde landbouw binnen CWatM geëvalueerd om hun potentiële bijdrage aan de toekomstige waterzekerheid van het land te kwantificeren.

De bevindingen van dit onderzoek gaan niet alleen in op de realiteit van het waterlandschap in Jordanië, maar bieden ook een kritische beoordeling van WA+ en CWatM, waarbij hun sterke punten, tekortkomingen en doelstelling worden onderzocht. Zo zal de beschikbaarheid van hernieuwbaar water in Jordanië tegen het midden van deze eeuw naar verwachting met maar liefst 23% afnemen. Tegelijkertijd kan het verschil tussen vraag en aanbod oplopen tot 1200 Mm^3/jaar, bijna een verdubbeling van het huidige tekort. Efficiëntiemaatregelen zijn weliswaar essentieel, maar leveren slechts een beperkte bijdrage aan de verbetering van de beschikbaarheid van water, gezien de enorme toename van de vraag naar water, voornamelijk in de huishoudelijke sector. Daarom beveelt dit onderzoek een geïntegreerde planningsaanpak aan, door het vergroten van de toevoer van ontzilt water naar de huishoudelijke sector en het vergroten vanhet gebruik van gezuiverd afvalwater in de geïrrigeerde landbouw.

Ten slotte pleit het onderzoek voor de complementariteit van WA+ en CWatM, waarbij wordt opgeroepen om de sterke punten van beide benaderingen te benutten: WA+ verbetert de gegevensdekking, bevordert de transparantie en is zeer geschikt voor operationele beslissingen op korte termijn. CWatM daarentegen biedt een toekomstgericht, op scenario's gebaseerd perspectief dat essentieel is voor planning.

Over het geheel genomen heeft het onderzoek kennis opgeleverd die verder gaat dan inzicht in de realiteit van de uitdagingen van Jordanië op het gebied van waterzekerheid. Het biedt lessen die zijn geleerd uit het gebruik van WA+ en CWatM om lokale waterproblemen op te lossen, en voorbeelden die kunnen worden gekopieerd in landen met een vergelijkbare context.

CONTENTS

1
INTRODUCTION

1.1 BACKGROUND

Freshwater availability is under growing pressure due to climate change and rapidly growing human demands (Rodell et al., 2019; Baggio et al., 2021; Mishra, 2023). This situation is most evident in the Middle East and North Africa (MENA), one of the most naturally water-scarce regions in the world. The region is home to nearly 6% of the world's population. However, it holds only 1-2% of the global freshwater resources (Ismail et al., 2018). This natural imbalance has created a gap between supply and demand that is anticipated to worsen under future climate change, putting the region under a growing challenge to achieving water security (Zekri and Al-Maamari, 2020; Bhattarai and Yousef, 2025).

Water resources assessments under the combined impact of climate variability and change, and human activities, represent a scientific and practical challenge (Qasem and Scholz, 2025). Therefore, there has been a growing demand for the hydrological community to address the interconnected nature of water systems more effectively.

Frameworks such as the Rio-Dublin and Integrated Water Resources Management (IWRM) had long emphasised this coupling. The Panta Rhei decade (2013 - 2022) of the International Association of Hydrological Sciences (IAHS) marked a renewed effort to embed coupled human-water systems at the core of hydrological research (Montanari et al., 2013; Kreibich et al., 2025). More recently, the IAHS HELPING initiative (2023-2032) has been seeking to expand these efforts by advocating a bottom-up research approach that relies on local data and knowledge to create transferable solutions over time and across different scales (Arheimer et al., 2024).

These conceptual advancements are particularly relevant for Jordan, where the availability of fresh water per person falls far below the global water scarcity threshold (MWI, 2023). Water availability in Jordan is influenced by a unique combination of factors such as natural aridity, reliance on upstream inflows for surface water, overabstraction of groundwater, and demand shocks, caused mainly by multiple waves of refugee influxes in the past twenty years (Schyns et al., 2015; BGR and MWI, 2017; MWI, 2023; Hussein et al., 2020). To tackle these issues, Jordan has adopted IWRM as the main approach to water management in its National Water Strategy (2023-2040). Current efforts focus on integrating demand management and increased utilization of non-conventional water resources such as treated wastewater for irrigation and desalination for domestic use along with the needed policy reforms (MWI, 2016, 2023). Nonetheless, these strategies often remain broad and lack effective implementation and monitoring plans due to technical and institutional constraints.

Jordan typically depends on sparse monitoring networks and long-term averages for water assessments. This data often yields general assessments that cannot capture the complexity of Jordan's water landscape (Droogers et al., 2012; Al-Shibli, 2018; Al-Kharabsheh, 2020; Yoon et al., 2021; Maftouh et al., 2022). Consequently, there remains a need to improve the spatial and temporal coverage of water data and utilize advanced assessment tools that can capture the interconnected nature of water systems.

This research investigates the potential of combining two assessment approaches, Water Accounting Plus (WA+) (Karimi et al., 2013) and the integrated hydrology and water systems model: the Community Water Model (CWatM) (Burek et al., 2020), to understand better their potential in addressing current assessment gaps in the MENA and Jordan. WA+ offers a spatially explicit, remote sensing-based assessment framework of water availability, use, and depletion. Therefore, it is useful in data-scarce regions (Karimi et al., 2013). CWatM, on the other hand, enables the simulation of complex coupled human-water systems interactions under climate trajectories. Therefore, it is useful for forward-looking planning (Burek et al., 2020). By examining the use of WA+ and CWatM for Jordan's context, the study seeks to advance the understanding of coupled human-water systems, and advocates for evidence-based planning in data-scarce regions.

The remainder of this chapter explores existing research on coupled human-water system assessment tools, with a particular focus on water accounting frameworks and integrated hydrological and water systems models. This is followed by the problem statement, research objectives and questions, and an overview of the research activities. The chapter concludes with a reading guide that outlines the thesis structure.

1.2 COUPLED HUMAN WATER SYSTEMS ASSESSMENTS

Coupled human-water systems' assessments are essential for sustainable water management and planning, more specifically where water use has exceeded the recovery limits of hydrological systems (Yin et al., 2021; Yang et al., 2021). These assessments have become central to the IWRM approach, which emphasizes the coordinated development and management of water, land, and related resources to maximize economic and social welfare without compromising ecosystem sustainability (GWP, 2000). IWRM explicitly recognizes that water systems are inherently coupled with human activities, making coupled human-water systems' assessments a fundamental requirement for effective IWRM implementation rather than an optional analytical tool. Various tools and frameworks have been developed in the past two decades to support this goal (Yang et al., 2021; Bilalova et al., 2023). This section highlights two approaches used in assessing coupled human-water systems: water accounting and integrated hydrological and water systems modelling.

1.2.1 Water accounting: origin, evolution, and relevance

The concept of water accounting has evolved over the past several decades, shaped by growing concerns over how water is managed, utilized, and consumed (Figure 1.1).

Water accounting roots can be traced back to the 1950s in the United States, where early efforts focused on assessing irrigation efficiency to understand the potential for water conservation in irrigated agriculture (Israelsen, 1950; Jensen, 2007). By the 1990s, it had become clearer that local efficiency metrics did not capture the broader impacts across an entire watershed. Throughout the 90s and early 2000s, more improvements were made to water accounting by introducing ideas such as consumptive water use and effective efficiency which acknowledged that water saved in one area might reduce availability elsewhere within a basin (Jensen, 1993; Keller and Keller, 1995; Perry, 2007).

This progress in water accounting concepts laid the foundation for more value-linked frameworks that classify water use as beneficial versus non-beneficial and recoverable versus non-recoverable (Willardson et al., 1994; Allen et al., 1996, 1997), thereby taking water accounting beyond a mere measurement approach.

Water accounting was formalized in the late 90s by the International Water Management Institute (IWMI) through the development of IWMI's Water Accounting Framework (IWMI-WA) (Molden, 1997). IWMI-WA focused on water consumption and productivity in irrigation. Its concepts were later refined by integrating satellite data, environmental flows, and socio-economic indicators, presented in a more advanced version called Water Accounting Plus (WA+) (Karimi et al., 2013).

By definition, water accounting is a systematic approach to assessing water resources through collecting, analysing, and presenting data on water stocks and fluxes in ways that reflect both hydrological processes and human impacts (Batchelor et al., 2016). The goal is to create quantitative accounts that support decision-making, highlight emerging challenges, and track changes over time. However, the most valuable aspect of water accounting is its integration of the physical and social dimensions of water systems through linking hydrological processes, such as rainfall, runoff, and evapotranspiration, with human activities, such as irrigation, urban water use, and return flows. This integration helps clarify how human water use reshapes natural hydrology, and how environmental limits, in turn, constrain human development.

Today, water accounting frameworks generally fall into two types, with both emphasizing the need to understand the link between hydrology and human water use, suggesting that water accounting should be a key pillar in IWRM. These two types are:

- Flow-based frameworks: which track water withdrawals, returns, and use.
- Depletion-based frameworks: which track water depletion (the consumptive use of water rather than withdrawals). Water is depleted by evapotranspiration, flows to sinks, incorporation into products or degradation of quality (Karimi et al., 2013).

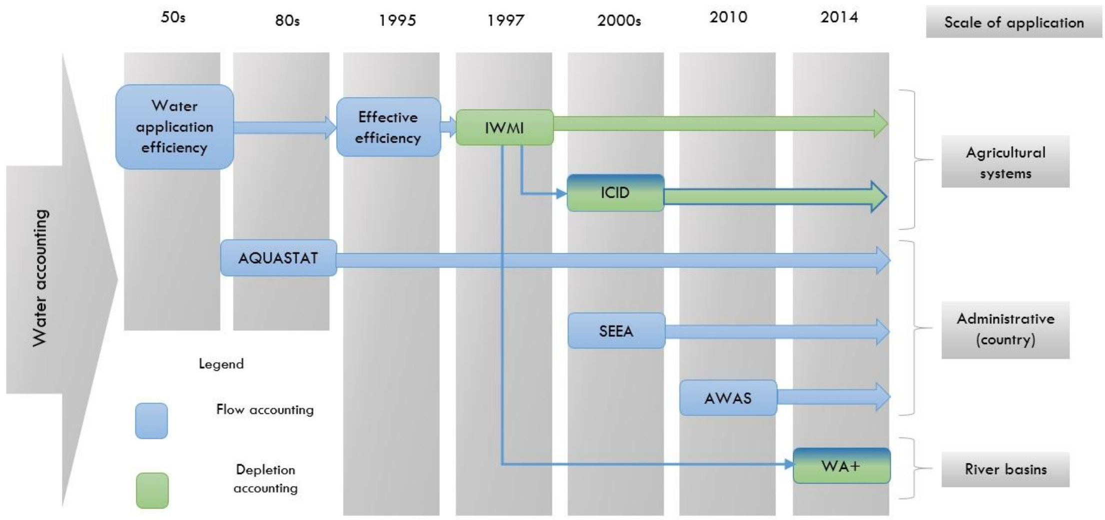


Figure 1.1 Chronological representation of water accounting frameworks from 1950 to 2014

Flow water accounting

Flow accounting focuses on reporting water withdrawals by tracking where water is sourced from and how it is utilized (Karimi et al., 2013). One example of flow water accounting is the FAO's AQUASTAT, established in the 1980s. AQUASTAT reports global water statistics with a focus on agricultural water use across more than 180 countries (FAO, 2025). However, as it relies on national statistics, and reports only long-term averages, it cannot be used beyond general assessments.

Another example of flow water accounting is the System of Environmental Economic Accounting (SEEA-Water), developed by the United Nations Statistics Division (United Nations, 2012). SEEA-Water aligns water accounting with economic reporting principles and creates standardized reports for flows, assets, and economic accounts. It distinguishes between inland water resources and water use, providing a detailed overview of both volumes and the economic implications of water use (United Nations, 2012). SEEA-Water is considered a data-heavy water accounting system, making it less applicable where such a level of detailed data is lacking.

Australia's Water Accounting Standard (AWAS), released in 2010, applies financial reporting standards to water accounting. It generates general-purpose reports focused on physical flows and storage changes, steering clear of economic framing of water accounts to avoid misunderstandings (Australian Bureau of Meteorology, 2012). However, similar to SEEA-Water, AWAS depends on detailed data from monitoring stations, which restricts its use in data-limited regions.

In conclusion, flow accounting systems primarily track water as it moves through human-built infrastructure, focusing on water withdrawals from sources (rivers, groundwater, reservoirs), diversions through distribution systems, and return flows back to water bodies. Therefore, it is a data-intensive approach that is suitable for administrative and infrastructure-focused decisions.

Depletion water accounting

Depletion accounting tracks the amount of consumed water; water that is no longer available for reuse within a basin. The first depletion water accounting framework was developed by IWMI (Molden, 1997). IWMI’s framework employs a simplified water balance that accounts for rainfall, surface and groundwater inflows, and outflows such as evapotranspiration, as well as changes in storage. It categorizes water use based on land use, purpose, and availability. Despite some uncertainties in estimating certain components, the framework provides useful indicators on system performance, including water productivity and basin closure.

Another depletion-based framework was developed by the International Commission on Irrigation and Drainage (ICID). ICID's framework differs from IWMI's WA in focusing on the beneficial use of water rather than depletion (Perry, 2007). However, both frameworks require intensive data which limits their practical application in data-scarce regions.

Advancements in remote sensing techniques have led to the development of Water Accounting Plus (WA+), a collaborative initiative by IWMI, IHE, and FAO (Karimi et al., 2013). WA+ has improved the applicability of earlier depletion accounting frameworks by integrating remote sensing to estimate water flows and productivity, making it useful in poorly gauged basins. WA+ reports water flows and fluxes in four key reporting sheets: the resource base, evapotranspiration, productivity, and withdrawals. This structure enables users to assess water use across different land use types, identify areas of overuse or inefficiency, and generate basin performance indicators such as exploitable water, beneficial evapotranspiration fraction, and basin closure (Karimi et al., 2013).

Among the depletion frameworks, WA+ can be considered the most advanced approach to coupled human-water assessment. WA+ introduces land use and remote sensing to improve the coverage of assessments in space and time, allowing for more accurate quantification of water consumption across different landscapes and human activities.

Furthermore, it classifies consumed water into blue and green categories[1], capturing the impact of human use on a basin' water balance and storage. WA+ reports this information through visual outputs and accessible summaries, which can better support evidence-based decision-making.

In conclusion, depletion-based accounting represents a fundamental shift from tracking water movements to understanding true water consumption patterns. By focusing on evapotranspiration and other permanent losses, depletion accounting provides a more accurate picture of water availability for sustainable basin management. WA+, as the most advanced depletion accounting framework, overcomes the data limitations of earlier approaches through remote sensing integration, making comprehensive water consumption assessment feasible even in data-scarce regions like the MENA.

The distinction between flow and depletion-based water accounting approaches extends beyond measurement tools to fundamental differences in how water use is conceptualized. Flow-based accounting tracks water as it moves through infrastructure, withdrawals, diversions, and return flows, but typically stops at the point of withdrawal, often ignoring what happens to the water after abstraction. In contrast, depletion water accounting focuses on consumptive use: water that is permanently removed from the system through evapotranspiration, incorporation into commodities, discharge to saline sinks, or degradation of quality. This distinction has profound implications for water management. For example, flow-based water accounting may classify a 50% efficient irrigation system as wasteful, when in reality the "lost" 50% might recharge local aquifers or contribute to downstream flows accessible to other users. This example represents the irrigation efficiency paradox (Grafton et al., 2018) discussed further in Chapter 4, where improvements in field-level efficiency do not necessarily translate to water savings at the basin scale if the "saved" water was previously being reused within the system.

1.2.2 Integrated hydrological and human water systems models

Integrated hydrological and human water systems modelling is a holistic approach that combines various scientific methods to comprehensively analyse water resources under the impact of climate variability, land use changes, and human activities (De Graaf et al., 2014; Yang et al., 2021). These models can also be used to simulate future conditions and management interventions, thereby supporting sustainable planning and informed decision-making.

[1] Blue water refers to water stored in surface and groundwater bodies. Green water refers to precipitation that infiltrates and is stored as soil moisture in the unsaturated soil layer and is transpired by vegetation.

In concept, integrated hydrological and human water systems models include two main components that interact with each other through feedback loops:

A hydrological component: A hydrological model simulates the natural water cycle and its components, such as evapotranspiration, runoff, and recharge (Chow et al., 1988). Hydrological models differ in how they represent spatial and temporal variability (Chow et al., 1988; Shaw, 1988; Jajarmizadeh et al., 2012), and can generally be categorized into three types:

- Empirical models: This is the simplest model type, which uses basic equations to describe hydrological relationships, typically between rainfall and runoff. Empirical models are often applied in ungauged basins and are considered lumped models as they do not explicitly represent physical processes (SCS, 1956).
- Conceptual models: These models use simplified representations of physical processes and can be categorized into lumped and distributed. They require calibration using ground observations, but they offer more realism than empirical models (Devi et al., 2015).
- Physically based models: This is the most complex type of models because it relies on conservation of mass and energy equations to represent hydrological processes in detail over time and space. However, they require extensive parameterization and calibration (Jaiswal et al., 2020; Sitterson et al., 2020).

In the context of coupled human-water systems, physically based models are widely used because they support operational forecasting and planning, even in data-scarce regions (O'Neill et al., 2021). Typically, these models are used at large spatial scales and have been criticized for the resulting coarse spatial resolution due to reliance on global datasets. That said, the rapid advancements of high-resolution global datasets and advancements in computational capacities, have enabled integrating downscaling routines within these models. Consequently, these models hold promise for more detailed assessments of coupled human-water systems at local scales (Burek et al., 2020).

A human water systems component: The human water systems component simulates human water use in various sectors based on their demand and allocates available water resources to these users based on pre-defined allocation rules. These models integrate socio-economic developments and their impacts on human-water systems by incorporating population growth, gross domestic product, and land use changes (Burek et al., 2020).

Integrated hydrological and human water systems models have been employed to evaluate global water stress and scarcity (Vörösmarty et al., 2000; Alcamo et al., 2003; Wada et al., 2011; 2013; 2014), analyze water availability and the effects of human interventions on river flows (Doll et al., 2009), measure variabilities in water storage (Alkama et al., 2010), assess climate impacts on water resources (Boko et al., 2020; Dibaba et al., 2020), and conduct water accounting studies (Delavar et al., 2020). These models account for human changes to the hydrological cycle by assessing water demand from irrigation and non-irrigation users (Doll et al., 2014; Nazemi and Wheater, 2015; Wada et al., 2014; Pokhrel et al., 2015; Wada et al., 2017). Non-irrigation demands are usually estimated from national statistics, while irrigation demands are derived based on crop modelling and irrigation efficiencies (Penman, 1948; Allen et al., 1998).

Building on the preceding review of depletion-based water accounting and integrated hydrological and human water systems models, it becomes clear that both aim to integrate human water use into water resources assessments. However, they do so through distinct conceptual and methodological lenses. For example, WA+ focuses on actual consumption, i.e., water that is no longer available for reuse, providing a retrospective, observation-based assessment of basin dynamics. In contrast, integrated models simulate the demand for and allocation of water, projecting how it might be used under different socio-economic and climatic change pathways. These differences highlight how human water use is treated within each approach, with WA+ treating human water use as a hydrological endpoint, unlike CWatM, which embeds it as a dynamic component of the broader hydrological system through feedback loops. As a result, each approach influences how water-related issues are diagnosed, understood, and addressed.

1.3 PROBLEM STATEMENT

Jordan's water challenges are not just a result of natural scarcity, but an outcome of a more profound disconnect between how hydrological systems function and how their components are observed, used and managed. In line with global efforts to improve the representation of human activities in water assessments and the need for bottom-up approaches, it is essential to recognise that human-water systems are tightly coupled. However, current governance and planning frameworks often treat these dimensions separately, resulting in fragmented and reactive responses to mounting water stress. Key gaps, therefore, remain and may hinder the achievement of the intended goals in the national water strategy (2023–2040) (MWI, 2023). Specifically, goal 2:

"Restore balance between available and sustainable water supplies and water demand to sufficiently meet Jordan's health and economic development needs to achieve lasting water security" With the target of: "*Water demand – supply balance is maintained from 2030"*.

Achieving this ambitious target requires moving beyond the current fragmented assessment approaches toward integrated methodologies that can accurately quantify both water availability and demand within coupled human-water systems. However, significant knowledge and methodological gaps currently limit Jordan's capacity to develop and implement the evidence-based strategies necessary for sustainable demand-supply balance. This research therefore aims to bridge the following gaps:

- **Limited information on coupled human-water systems**: The lack of sufficient data from ground observations and human water use patterns hinders the ability to conduct comprehensive assessments of coupled human-water systems. Currently, routine water resources assessments fail to capture the complexity of human-water interactions and their impact on water availability (Al-Shibli et al., 2017).
- **Insufficient integrated water resources assessments**: Although advancements in coupled human-water systems assessments have created new opportunities, their application in Jordan remains limited. There is an urgent need to transfer these advancements to Jordan, so that more accurate and spatially explicit information on water availability, use, consumption, and their changes over time becomes available to decision-makers (Al-Addous et al., 2023; Al-Bakri et al., 2023).
- **Limited understanding of the impact of demand-side management:** Improving water-use efficiency is set as a primary goal in national water strategies, mainly in irrigated agriculture (MWI, 2023). However, there is limited clarity on how efficiency measures could affect water availability. Irrigated agriculture consumes more than 50% of Jordan's freshwater resources (MWI, 2023). Policies regulating groundwater abstractions for irrigation are in place, but their implementation has been inconsistent (Al Naber and Molle, 2017). Therefore, the impact of efficiency measures in irrigated agriculture might stay limited (Beithou et al., 2022; Al-Bakri et al., 2023).

1.4 RESEARCH OBJECTIVES AND QUESTIONS

This research builds on, amongst others, the IAHS Panta Rhei and HELPING initiatives, aiming to enhance our understanding of coupled human-water systems at a local level. In this context, "local" refers not only to the hydrological scale (i.e., a basin or sub-basin) but also to the use of local data and context-specific knowledge to address local water challenges. This research, therefore, adapts globally recognised assessment tools to the unique context of Jordan. By integrating context-specific data and knowledge with context-adapted assessment tools, this research aims to support more informed and effective planning of water resources in Jordan. The specific research objectives are:

Objective 1: Assess information needs and limitations in current water management practices in the MENA region, with a focus on Jordan, with respect to coupled human–water systems.

Research question 1.1. What are the key challenges facing water resources management in the MENA region?

Research question 1.2. What water-related data are currently available in the region, and where do the most critical gaps lie?

Research question 1.3. To what extent does WA+ address the information needs of decision-makers in the region? What are the main limitations?

Research question 1.4. How can water accounting be enhanced to better address the challenges in the region?

Objective 2: Enhance water resources assessments by improving the representation of human activities and demand-side dynamics.

Research question 2.1. How can human activities be better integrated into WA+ to improve water availability estimates in Jordan?

Research question 2.2. What is the current and projected future water availability in Jordan based on CWatM modelling?

Objective 3: Explore scenario-based futures to evaluate the impact of locally relevant solutions on water availability and sustainability.

Research question 3.1. What is the impact of irrigation demand management on water availability under current and future climate conditions and socio-economic developments in Jordan?

Research question 3.2. How could combined supply and demand interventions contribute to Jordan's water security?

This research explores the distinct roles of WA+ and the CWatM in assessing coupled human-water systems in Jordan. Each approach is applied independently to investigate distinct yet interrelated aspects. Furthermore, the research extends to assessing irrigation efficiency measures in agriculture, based on a field empirical study, and links its outputs back to broader water resources planning using CWatM and WA+.

On the one hand, WA+ provides a spatially explicit evaluation of water depletion, use, and utilisation across various land-use types. The use of remote sensing in WA+ for a data-scarce context, such as Jordan, helps identify water use inefficiencies and quantify consumptive use, offering critical insights into basin closure, beneficial versus non-beneficial water use, and the overall sustainability of water resources under current practices. On the other hand, CWatM complements this analysis by simulating complex, dynamic interactions between natural hydrological processes and human water use and interventions. Tailored to Jordan's conditions, CWatM generates projections of water availability, use and consumption under climate change, population growth, and intervention scenarios, enabling an assessment of long-term risks and the impact of adaptive strategies. The impact assessment of efficiency measures on water availability builds on the field study outcomes to simulate the potential future impact of water conservation in irrigation under climate change and socio-economic development.

By comparing outputs from these two tools and the field study, the research identifies areas of convergence, divergence, and complementarity. This multi-lens approach is particularly valuable in evaluating irrigation demand and use management, one of Jordan's most critical water management challenges. The study thus contributes both practically by informing national planning, and methodologically by advancing the integration of diagnostic, empirical and scenario-based assessment tools in data limited, water-stressed regions.

1.5 RESEARCH APPROACH AND DESIGN

This research adopts an exploratory, multi-method approach to better understand the challenges facing water resources management in the MENA. With Jordan being the focus, this research is structured to deepen understanding across three dimensions:

- Diagnosing systemic limitations of water assessments.
- Enhancing water assessments to better reflect the coupled human-water systems.
- Exploring solutions for potential futures using scenario analysis.

Central to this research is the application and use of two methodologies to water resources assessments: WA+ and CWatM, each contributing uniquely to addressing the research questions.

The research is organized in three core phases, each building on the findings of the previous one as outlined in the following four chapters (Table 1.1). The phased design of this thesis aims to generate a cumulative and iterative inquiry that progresses from problem identification to tool adaptation, scenario application, and ultimately to synthesis and policy relevance.

Phase 1: Diagnosing the problem space

This phase focuses on understanding the problem by identifying data gaps in water resources assessments in the MENA region, with a focus on Jordan. Two methods were employed in this phase:

- A systematic literature review on regional water management challenges, and related gaps in data availability, consistency, and application.

- Semi-structured interviews with stakeholders in Jordan to contextualise the regional findings, grounding them in local experiences and institutional realities.

At this phase, we also introduce the WA+ methodology through a global review of its applications, assessing its applicability for Jordan and laying the foundation needed to adapt it to the context of Jordan.

Phase 2: Adapting assessment tools to context

Building on phase 1 this phase focuses on tailoring WA+ and CWatM to the context of Jordan. The first part of this phase involves modifying the WA+ framework to reflect the full spectrum of water uses in Jordan. Non-irrigation water use was integrated into the WA+ resource base sheet to move beyond the focus on irrigated agriculture and reflect the actual water use profile in the country. The modified framework was applied to the Amman-Zarqa (AZ) basin, one of the country's most water stressed and economically important basins. Importantly, the modification approach was developed to be replicable so that it can be extended to other basins in Jordan, laying the foundation for a consistent, national-level water accounting system.

Given the retrospective focus of WA+, the second part of this phase examines the utility of the Community Water Model (CWatM), a spatially distributed, process-based model developed by IIASA (Burek et al., 2020). CWatM is designed to simulate water availability under various scenarios, considering key drivers to water resources and use changes such as climate change, population growth, land use, and water management interventions. CWatM was set up for Jordan and validated using observed data and scenario inputs to simulate future water availability and up to 2050.

The application of WA+ and CWatM in this phase establishes two components of the assessment framework:

- A diagnostic component utilizing WA+ to capture current conditions with spatial detail.
- A predictive component utilizing CWatM to simulate future conditions under uncertainty.

Phase 3: Irrigation efficiency scenario, proof of concept and nationwide impact

This phase examines the potential of irrigation demand management as a strategic intervention to reduce the pressure on water resources. This phase integrates empirical fieldwork to provide proof of concept and help conceptualize the modelling of this intervention nationwide using CWatM scenario analysis.

To achieve this, a field study was conducted to evaluate the impact of on-farm efficiency measures using water conservation technologies (WCTs). The goal of this study is to estimate potential water savings achievable at the farm scale, taking a sample of farms located in the Amman-Zarqa basin in Jordan as an example. The findings were then extrapolated to the Amman-Zarqa basin farms to estimate potential water savings at the basin scale.

The study generated evidence on the efficiency gains achievable sustainably under current farming conditions in the most critical basin in Jordan, in terms of water use for irrigation. The field study outputs were then used to inform the design of an efficiency intervention scenario to be simulated using CWatM across Jordan.

This phase, therefore, focuses on comparing two approaches to quantifying the impact of efficiency measures, enabling a critical evaluation of how bottom-up (field-based) and top-down (model-based) approaches differ in their estimates and implications.

Following the field study, irrigation efficiency intervention was conceptualized and simulated within CWatM across Jordan to better understand the macro-scale impact of efficiency measures on water availability, considering climate change, population growth and resulting growing demand and hydrological feedback at the country and basin levels. The simulation captured the effects of improved irrigation efficiency not only on total water savings but also on water availability for other users, and resource sustainability in Jordan. The comparative assessment of the two methods is presented in the last chapter of this thesis, focusing on understanding points of convergence and divergence between the two approaches. This methodological pluralism is especially critical in contexts like Jordan, where water conservation in irrigated agriculture is essential to the country's planning, yet its potential impacts are not well researched or understood especially within the broader context of multiple changes due to climate change and population growth. Consequently, this phase generates a deeper understanding of how to anticipate outcomes of water efficiency interventions, as well as what the realistic conservation targets are and their role in bridging the growing gap between demand and supply across Jordan.

Table 1.1 Research design matrix showing the three-phased research approach

Research objectives	Research questions	Methodology	Outputs	Chapters
Assess information needs and limitations in current water management system in the MENA region, with a focus on Jordan, with respect to coupled human–water systems (phase 1).	What are the key challenges facing water resources management in the MENA region?	Systematic literature review on water resources assessments in the MENA region Semi-structured interviews on water resources assessments in Jordan	Gaps in water data and water resources assessments in the MENA with a focus on Jordan	Chapter 2
	What water-related data are currently available in the region, and where do the most critical gaps lie?			
	To what extent does water accounting address the information needs of decision-makers in the region? What are the main limitations?	Systematic literature review on water accounting case studies globally	Areas in water resources assessments that can be improved with water accounting	
	How can water accounting be enhanced to better address the challenges in the region?	Information synthesis and analysis	Way forward to adapting water accounting to address the region challenges	
Enhance water resources assessments by improving the representation of human activities and demand-side dynamics (Phase 2).	How can human activities be better integrated into water accounting to improve water availability estimates in Jordan?	Adapting WA+ framework by integrating non-irrigation water consumption and return flows (i.e., non landuse based water users)	Methodology to tailor WA+ to local contexts	Chapter 3

Research objectives	Research questions	Methodology	Outputs	Chapters
	What is the current and projected future water availability in Jordan based on coupled human-water systems assessment?	Assessing the impacts of climate change and socio-economic drivers on future water availability using CWatM	Methodology to use global models locally for coupled human-water systems assessments and knowledge on current and future conditions related to water availability and use	Chapter 5
Explore scenario-based futures to evaluate the impact of locally relevant solutions on water availability and sustainability (Phase 3).	What is the impact of irrigation demand management on water availability under current and future climate conditions and socio-economic developments in Jordan?	Field study in relation to irrigation efficiency	Knowledge of the impact of local practices on water use in irrigated agriculture	Chapter 4 Chapter 5 (sections 5.4.3, 5.4.4, and 5.4.5)
	How could combined supply and demand interventions contribute to Jordan's water security?	Implementing CWatM with irrigation efficiency scenario	Knowledge of the impact of irrigation efficiency interventions on future water availability and use	Chapter 5 (section 5.5)

1.6 READING GUIDE

This thesis is organized into six chapters as follows:

Chapter 1: Introduction
This chapter establishes the need for research, the research objectives, problem statements, research goals and questions, and research significance.

Chapter 2: Water Accounting Plus: Limitations and opportunities for supporting integrated water resources management in the Middle East and North Africa (Adapted from Amdar et al., 2024a)
This chapter establishes the diagnosis of problem space through a study that explores the limitations and opportunities of Water Accounting Plus (WA+) for addressing water management issues in the MENA, focusing on Jordan, addressing research questions 1.1 and 1.4.

Chapter 3: Developing a Water Budget for the Amman-Zarqa Basin Using Water Accounting Plus and the Pixel-Based Soil Water Balance Model (Adapted from Amdar et al., 2024b).
This chapter focuses on the first part of phase 2 which focuses on adapting assessment tools to Jordan's context, addressing research question 2.1. It introduces key modifications to the WaPOR-based WA+ framework to better capture human influences beyond irrigated agriculture, specifically, non-irrigation manmade consumption and associated return flows.

Chapter 4: Insights into the Potential of Water Conservation in Irrigated Agriculture – A Case Study from the Arid Mediterranean Highlands (Adapted from Amdar et al., 2025).
This chapter focuses on the first part of phase 3, specifically addressing research question 3.1 by providing a proof of concept on the impact of irrigation efficiency measures on water conservation at the farm scale focusing on the highlands of the Amman-Zarqa basin.

Chapter 5: Navigating Jordan's Water Resources Futures: Hydrological Modelling Under Socio-Economic Developments and Climate Change
This chapter focuses on the second part of phase 2 and phase 3, addressing research questions 2.2, 3.1, and 3.2. It investigates water availability, demand and use in Jordan for the timeframe 2025-2050. This chapter shows how CWatM and open-access data can be used to support water resources planning under climate change scenarios and socio-economic pathways in Jordan.

Chapter 6: Conclusion

The final chapter summarizes key findings, compares the methods applied in this research for coupled human-water systems assessments, and provides recommendations for future research.

2 WATER ACCOUNTING PLUS: LIMITATIONS AND OPPORTUNITIES FOR SUPPORTING INTEGRATED WATER RESOURCES MANAGEMENT IN THE MIDDLE EAST AND NORTH AFRICA

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 water strategy appraisals. The findings suggest that WA+ can enhance the spatio-temporal coverage of water resources assessments, refine estimates of irrigation water consumption, and facilitate demand management. Quantifying recharge and surface runoff generation requires integrating WA+ with hydrological models, while addressing the impact of climate change on future water resources requires integrating climate change projections with WA+.

The content of this chapter is adapted from Amdar, N., Mul, M., Al-Bakri, J., Uhlenbrook, S., Rutten, M., and Jewitt, G.: Water Accounting Plus: limitations and opportunities for supporting integrated water resources management in the Middle East and North Africa. *Water International*, *49*(7), 880-907, 2024a.

2.1 INTRODUCTION

Water scarcity is a deeply rooted issue affecting many Middle East and North Africa (MENA) countries. The region is characterized naturally by an 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 and Gorelick, 2017).

Water resources in 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 being 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 (Ahmed et al., 2024; Avisse et al., 2020; Kucukmehmetoglu and 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; Selvaraju, 2013; United Nations, 2012; Sowers et al., 2011; Hinrichsen et al., 1997). Climate change is expected to further decrease water availability due to altered precipitation patterns and increased temperatures (Ahmadi et al., 2022; 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 (Ministry of Water and Irrigation, 2015; Al-Kharabsheh, 2020). 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 either be manageable or unmanageable. WA+ land classes encompass (Karimi et al., 2013):

- 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;
- 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;
- the utilized land use class, designated for a variety of ecosystem services that have undergone minimal human intervention - for instance, grasslands;
- and 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 et al., 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).

2.2 MATERIALS AND METHODS

The WA+ approach can inform three stages of the IWRM planning process: issue assessment, strategy evaluation, and monitoring and evaluation. 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 (Appendix A.1) 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 2.1 summarizes the methodological approach, and the following section describes the methods.

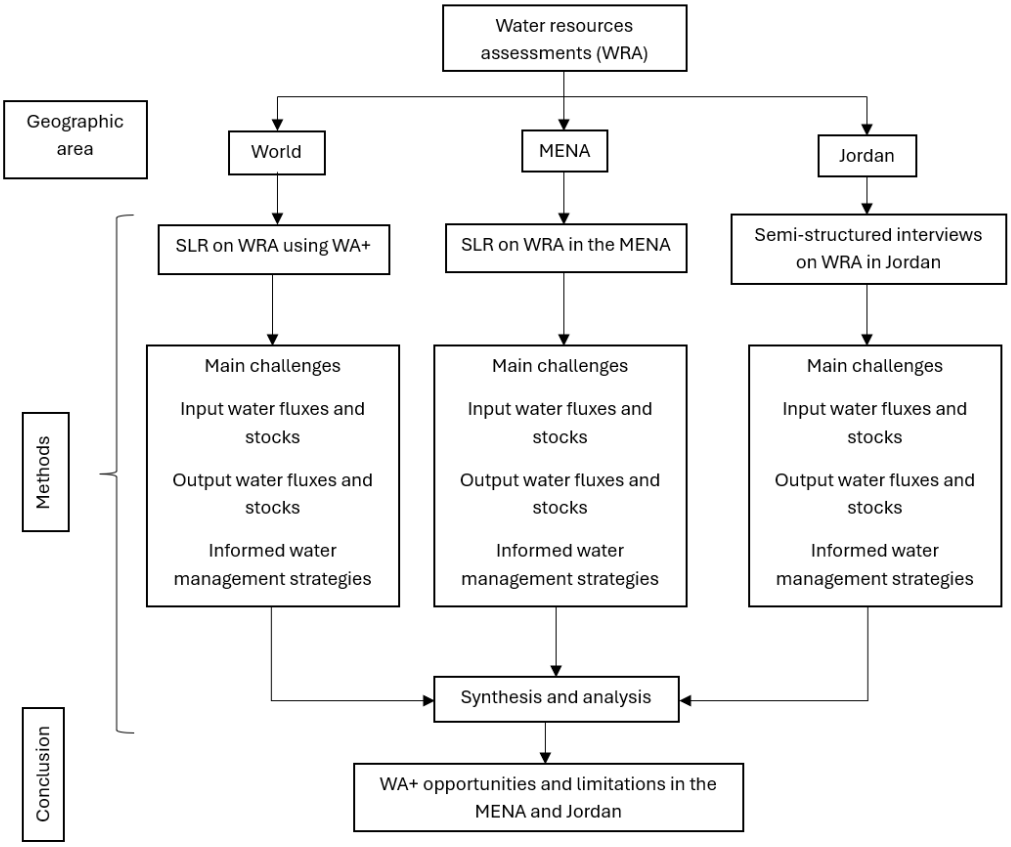


Figure 2.1 A flow chart of the study's methodological approach

2.2.1 Systematic literature review

The systematic literature reviews (SLRs) 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 (Appendix A.2) 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.

2.2.2 Semi-structured interviews

While 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. 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 2.2). Responses were analysed using descriptive statistics in Excel and validated against available literature (e.g., Al-Bakri et al., 2023; Al-Kharabsheh, 2020; Al-Shibli et al., 2017; Al-Bakri, 2016; Ministry of Water and Irrigation, 2015).

Figure 2.2 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).

2.3 RESULTS

2.3.1 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 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 (Appendix A.3).

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 2.1).

Table 2.1 Frequency of data types applied in water resources assessment in the MENA region and their sources.

Input Flux/stock	# Papers	# Fluxes and stocks considered in water resources assessments	Rank	# Fluxes and stocks per data source		
				Ground measurements	Reported in previous research	Satellite observations
Precipitation	35	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		37	36	13
Percentage of fluxes and stocks per data source		100%		43%	41%	15%

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 and Qasim, 2019; Tramblay et al., 2018), and it determines the amount of water generated within a basin and directly impacts soil moisture, groundwater recharge (Omer et al., 2023; Rajosoa et al., 2021; Rajsekhar and Gorelick, 2017; Chenoweth et al., 2011). 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 hydrologic system, such as reservoirs, groundwater pumping development and irrigation schemes (Al-Kharabsheh, 2022; Avisse et al., 2020; Keith et al., 2017). 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 since data on water usage is not openly shared among riparian countries (Shentsis et al., 2019; Rajsekhar and Gorelick, 2017).

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 and 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, 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 be directly measured. 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 datasets (e.g., FAO AQUASTAT, the Coupled

Model Intercomparison Project Phase 6 (CMIP6)) (Omer et al., 2023; Ahmadi 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 datasets, 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 et al., 2024; Omer et al., 2023; Ahmed, 2020; Avisse et al., 2020; Müller et al., 2016; Saber et al., 2015). Actual evapotranspiration observations were obtained from MOD16 (Comair et al., 2012), while 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 et al., 2024; Ahmed, 2020). 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 transboundary river context where data sharing among riparian countries is limited (Ahmed et al., 2024; Ahmed, 2020).

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 2.3). 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 majority had a lower resolution. The spatial 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 and Qasim, 2019; Roth et al., 2018; Rajsekhar and Gorelick, 2017). 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 2.4). Detailed figures on the spatial and temporal resolution of input data to water resources assessments in the MENA can be found in Appendix A.4 (Figures A.4.1, A.4.2).

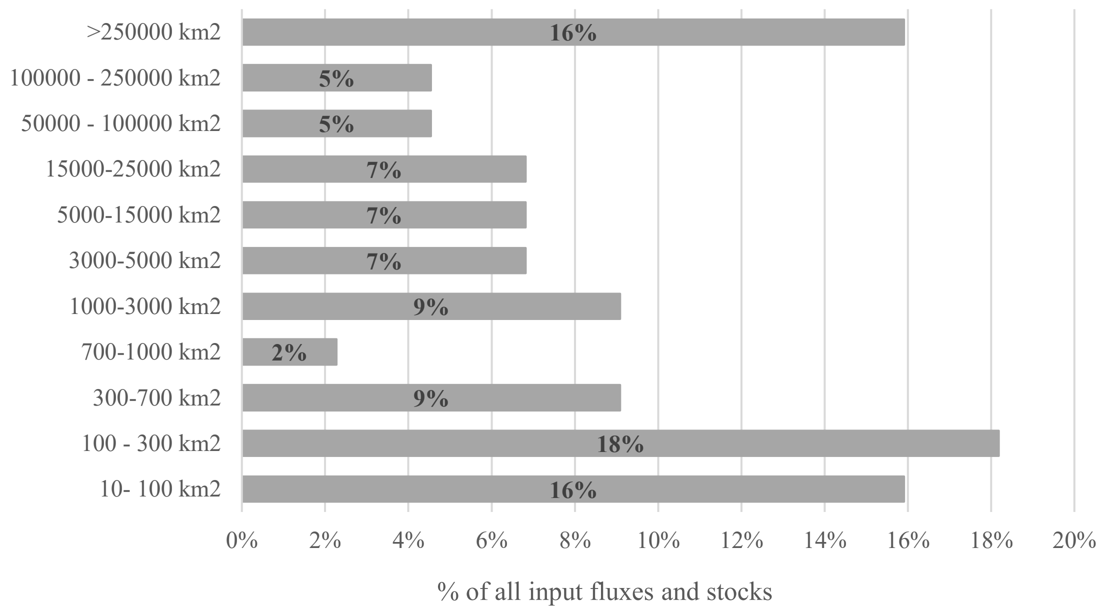


Figure 2.3 Spatial resolution of input data used in water resources assessments in the MENA regardless of data type (data point/area)

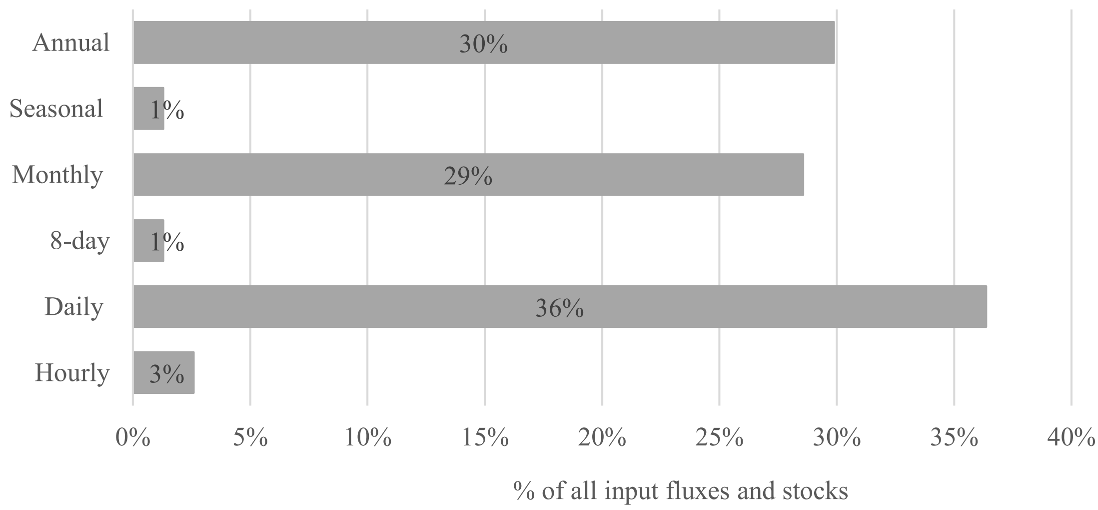


Figure 2.4 Temporal resolution of input data used in water resources assessments in the MENA regardless of data type

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., 2023; Mengistu et al., 2021; Youssef et al., 2020; Roth et al., 2018), 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) (Rajosoa et al., 2021; Kucukmehmetoglu and Geymen, 2014; Kucukmehmetoglu, 2002) 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 2.2).

Table 2.2 Fluxes and stocks generated as output from water resources assessments in the MENA.

Output fluxes/stocks	#Of 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	[2]GWS = TWS – SMS – SWS 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 (Allen et al., 1998)
Storage change in surface water	4	5	Rainfall runoff modelling

[2] GWS: groundwater storage, TWS: total water storage, SMS: soil moisture storage, SWS: soil water storage

			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	1	8	Rainfall-runoff modelling
Total number of fluxes and stocks (data points)	59		

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 (Omer et al., 2023; Rajosoa et al., 2021; Rajsekhar and Gorelick, 2017; Müller et al., 2016; Kucukmehmetoglu et al., 2010). Precipitation changes in wet and dry seasons were of particular interest (Ahmed et al., 2024; Mengistu et al., 2021; Tramblay et al., 2018; Imteaz et al., 2017). 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 sub-regional scales (Ahmed et al., 2024; Ahmadi et al., 2023; Omer et al., 2023; Al-Mukhtar and Qasim, 2019; Imteaz et al., 2017; 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; Roth et al., 2018; Conway, 2005). Groundwater storage change was found as output in studies exploring groundwater availability (Rajosoa et al., 2021; Abdelhalim et al., 2020; Ahmed, 2020; 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 time scale (Figure 2.5, Figure 2.6). Detailed figures on the spatial and temporal resolution of output information from water resources assessments in the MENA can be found in Appendix A.4 (Figures A.4.3, A.4.4)

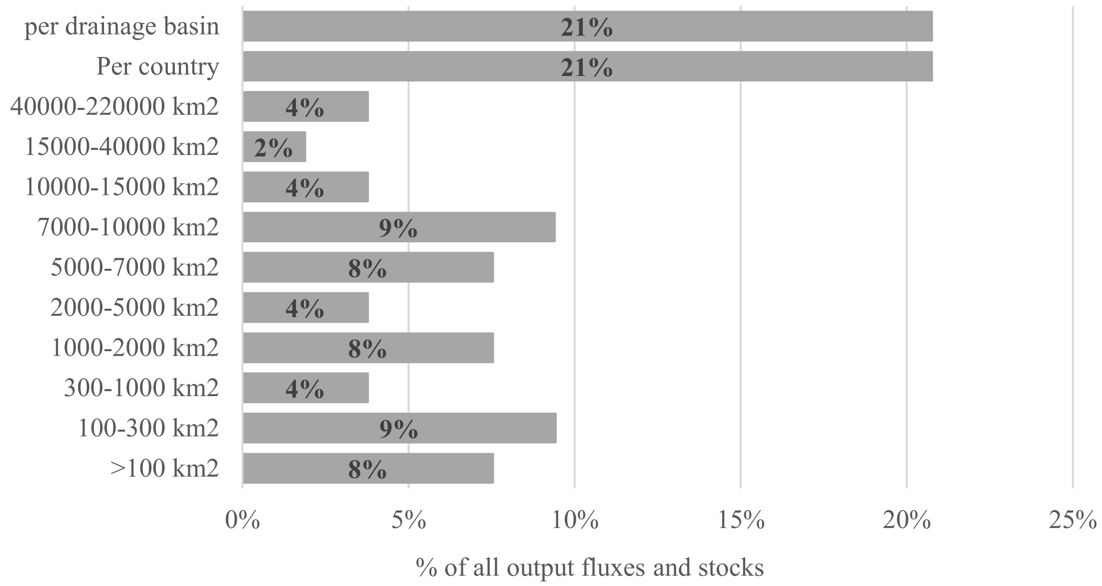


Figure 2.5 Spatial resolution of output water information from water resources assessments in the MENA regardless information type (data point/area)

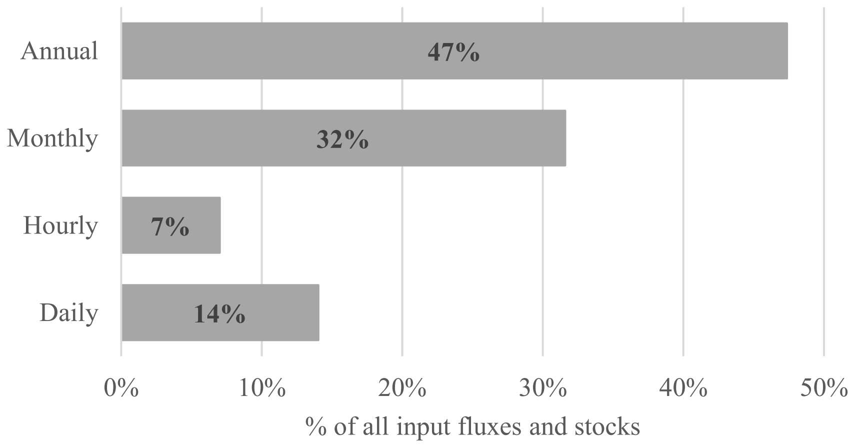


Figure 2.6 Temporal resolution of output water information from water resources assessments in the MENA region regardless of information type

Strategy Evaluation

Comprising different tools like policies, regulations, infrastructure, and technologies, fourteen of the forty 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, while 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 (Appendix A.5). 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 (Youssef et al., 2020; Kucukmehmetoglu et al., 2010). 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 (Rajosoa et al., 2021; Abdelhalim et al., 2020; Chenoweth et al., 2011). In transboundary rivers, climate change adaptation was explored through dynamic reservoir management to improve inter-annual water availability downstream (Ahmed et al., 2024; Keith et al., 2017; Kucukmehmetoglu and Geymen, 2014; Ohara et al., 2011). However, 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 (Appendix A.5).

2.3.2 Jordan

Overview of Jordan's Water Sector

Jordan's water management and planning are centralised 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 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 2.7). 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 socio-economic 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 organisations and non-governmental organisations have supported the Ministry of Water and Irrigation since its inception, assisting with water sector policies, reforms, and projects.

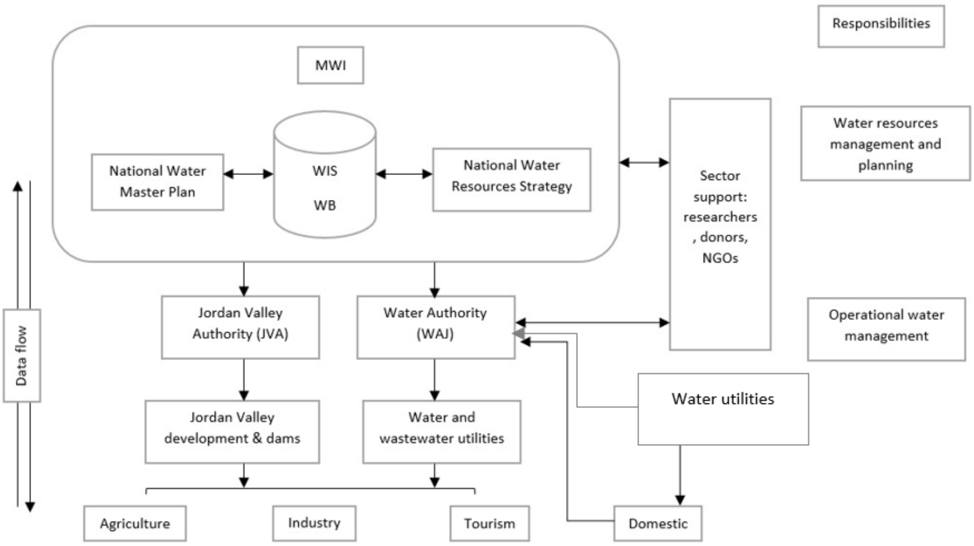


Figure 2.7 Jordan's water sector structure[34]

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 2.3)

[3] This figure was developed based on insights from the interviewees in Jordan

[4] WIS refers to Water Information System and WB refers to Water Budget

Table 2.3 Water resources monitoring stations in Jordan (Ministry of Water and Irrigation, 2015).

<table>
<tr><th rowspan="2">Monitoring station</th><th colspan="5">Type</th></tr>
<tr><th>Telemetric</th><th>Daily Manual Gauge</th><th>Semi-automatic</th><th>Totalizers</th><th>Total</th></tr>
<tr><td>Rainfall stations</td><td>59</td><td>131</td><td>18</td><td>22</td><td>230</td></tr>
<tr><td>Evaporation stations</td><td>19</td><td>22</td><td>0</td><td>0</td><td>41</td></tr>
<tr><td rowspan="3">Runoff stations (Wadi/river)</td><td rowspan="2">Baseflow</td><td colspan="3">Flash flood</td><td rowspan="3">35</td></tr>
<tr><td>Semi-automatic</td><td colspan="2">Telemetry</td></tr>
<tr><td>18</td><td>14</td><td colspan="2">3</td></tr>
<tr><td>Groundwater levels</td><td>86</td><td>110</td><td>0</td><td>0</td><td>196</td></tr>
<tr><td>Spring discharge</td><td>0</td><td>600</td><td>0</td><td>0</td><td>600</td></tr>
</table>

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 2.4).

Table 2.4 Ranking of water fluxes and stocks in terms of their importance to water resources assessments in Jordan (Based on the interviewees' opinions).

Fluxes/stocks[5]	Rank[6]	Existing data[7]	Source	Spatial coverage (station/km^2)[8]	Recording frequency
Precipitation (mm/hr)	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	Meters	-	-
Withdrawals per sector (Mm^3/year)	1	Yes	Meters	-	-
Surface runoff (m^3/second)	1	Yes	Runoff stations	2,481	Hourly and daily
River/wadi discharge (m^3/second)	2	Yes	Discharge gauges	2,481	Hourly and daily
Storage change in dams (mm/day)	2	Yes	-	-	Hourly
Evaporation (mm/day)	2	Yes	Class A-Pan	4,254	Daily
Evapotranspiration (mm/day)	2	No	-	-	-

[5] Units are derived from the Annual Water Budget

[6] Rank is the average of all responses received from the interviewees.

[7] This column is validated against (Table 2. 3)

[8] Estimated based on the total area of Jordan divided by the number of monitoring stations.

Soil moisture (mm)	3	No	-	-	-
Return flow (Mm^3/year)	3	No	-	-	-

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 natural 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 8,210 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 and 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 over irrigated areas 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 2.8).

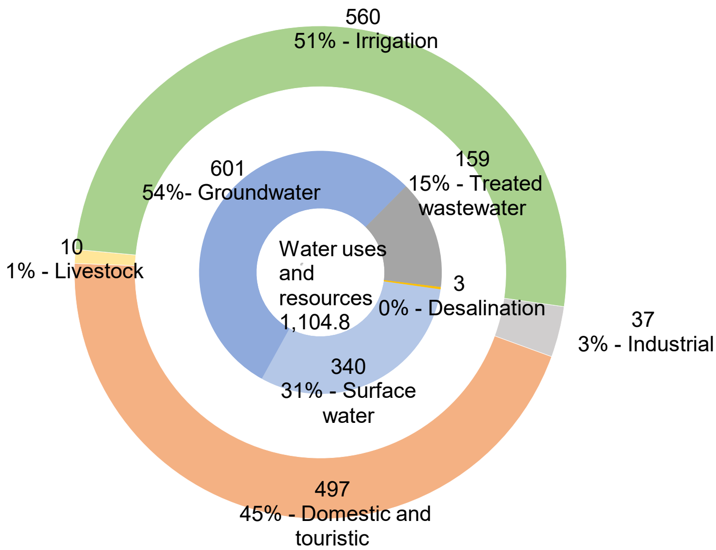


Figure 2.8 Jordan's water budget Mm^3/year (2019) (source: MWI, 2019)

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. The following equation 2.1 is used to estimate the surface water resources available annually based on the runoff volume generated from precipitation over the 15 surface water basins:

$$R = P - E - Re \qquad (2.1)$$

- 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: annual evaporation (Mm^3/year) (calculated as a rate of annual precipitation in each basin)

- Re: annual groundwater recharge (Mm^3/year) (calculated as a rate of annual precipitation in each basin)

Annual 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 and ground observations 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 till 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 (incl.

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 scarce water 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.

2.3.3 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 (Appendix A.6), 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.

Input data to WA+

Hydro-climatic data used in WA+ case studies are listed in Appendix A (Table A.10). Actual evapotranspiration and precipitation were the two significant inputs in all studies since 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; Delavar et al., 2022) or from satellite remote sensing products such as WaPOR (based on CHIRPS) (FAO and IHE Delft, 2019, 2020b, 2020d; Ghorbanpour et al., 2022; Kivi et al., 2022) and TRMM (P. K. Singh et al., 2022), SSEBop (Patle et al., 2023). Actual evapotranspiration was obtained from satellite remote sensing products or hydrological modelling (e.g., SWAT) (Delavar et al., 2020; Delavar et al., 2022). 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 2.9). This is due to the use of the most recent satellite products (e.g., WaPOR) (FAO and IHE Delft, 2020a, b, c, d; Ghorbanpour et al., 2022; Kivi et al., 2022), with their current routine monitoring capturing nearly all components of the water balance and 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 (incl. surface, ground, and soil water) obtained from GRACE. When soil water balance tools were used (e.g., WaterPix), soil moisture data was generated at a higher resolution (less than 1 km^2) (FAO and 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 (Kivi et al., 2022; Ghorbanpour et al., 2022).

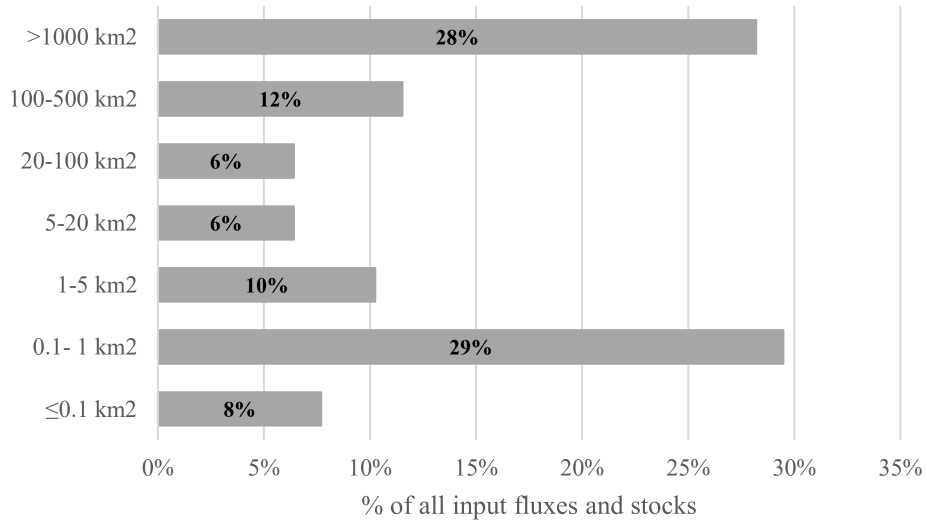


Figure 2.9 Spatial resolution of input data used in the WA+ studies regardless of the flux/stock type (data point/area)

On the other hand, the temporal resolution of input data was mainly monthly, followed by annual and daily timesteps (Figure 2.10). 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 was used when the analysis involved implementing hydrological models that run at a daily time step. Annual data was 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 Appendix A (Figures A.7 and A.8).

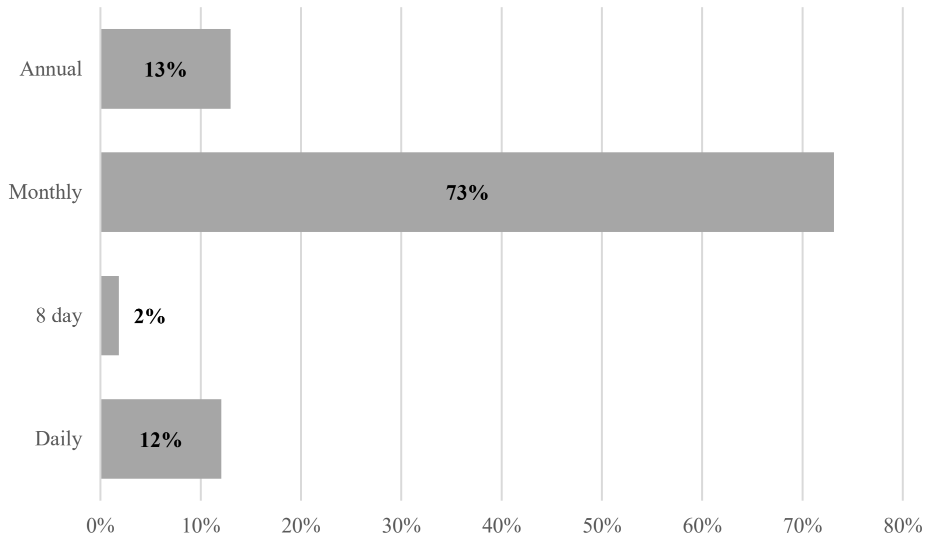


Figure 2.10 Temporal resolution of input data used in WA+ case studies regardless of the flux/stock type

Output water information

Following the WA+ methodology, water fluxes and stocks were reported in six sheets (Appendix A.11). 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., 2022; Delavar et al., 2020; Peiser and Bastiaanssen, 2015; Karimi et al., 2014).

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 et al., 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 bio-mass production (Karimi et al., 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 (Karimi et al., 2014; Dost et al., 2013).

Strategy evaluation

Assessing water strategies using WA+ requires implementing scenario analysis and hydrological modelling. 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 undertaken by Karimi et al. (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 and 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 (Appendix A.9). For example, Karimi et al. (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 (Patle et al., 2023; Ghorbanpour et al., 2022; P.K. Singh et al., 2022). Another WA+ study identified the need to develop new water resources by observing the basin closure index (FAO and 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 inter-basin 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., 2017; Salvadore et al., 2018). 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 (Salvadore and Mul, 2020;

Peiser and Bastiaanssen, 2015). 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 and 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 datasets, 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 and 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. While 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.

2.4 DISCUSSION

In much of the MENA region, water management relies on water data derived from ground monitoring networks and global reanalysis products (see Table 2.3). This data has 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), nor the interannual 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; Keith et al., 2017; Kucukmehmetoglu and Geymen, 2014; Ohara et al., 2011; Chenoweth 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 (Rajosoa et al., 2021; Abdelhalim et al., 2020; Chenoweth et al., 2011). WA+ could improve data availability on water generation, consumption and demand in space and time. This data captures 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) (Bozorg-Haddad et al., 2020; Al-Alaween et al., 2016). 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 the MENA countries (Hlavaty, 2018; Al-Karablieh and Salman, 2016). The reported national water budget suffers from inaccuracies related to limited data availability and simplifications of water fluxes, stocks and use estimates (Al-Bakri et al., 2023; Al-Kharabsheh, 2020; Al-Shibli et al., 2017; Al-Bakri, 2016). 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 subsequent year conditions to a certain degree. Furthermore, WA+ also provides 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). Second, 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).

2.5 CONCLUSIONS

This paper assesses the potential and limitations of WA+ to support IWRM in the MENA and Jordan. It concludes that the main water management challenges faced in the MENA region have been addressed using WA+ in other regions. The main aspect that WA+ can improve is the accuracy of water assessments in the MENA and Jordan as it utilizes high-resolution data in space and time, provided 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 its 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 MENA and Jordan could yield more precise evaluations regarding its effectiveness in addressing local water management challenges.

3
DEVELOPING A WATER BUDGET FOR THE AMMAN-ZARQA BASIN USING WATER ACCOUNTING PLUS AND THE PIXEL BASED SOIL WATER BALANCE MODEL

Water resources assessments are important 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+) is relevant in this case as it integrates remote sensing data and the Pixel-Based Soil Water Balance (PixSWAB) model to simulate a basin's water balance. However, this framework relies on remote sensing. Therefore, it does not account for non-irrigation water use and its return flows.

This paper modifies the WaPOR-based WA+ framework to include non-irrigation manmade consumption and its return flows. The modified framework provides a comprehensive water budget for the Amman-Zarqa (AZ) basin, presented in a modified WA+ resource base sheet for 2018 through 2021.

The results indicate that water availability in the AZ basin is highly responsive to precipitation changes. A 28% reduction in precipitation in 2021, compared to the period from 2018 to 2020, led to a 50% decrease in water availability, underscoring the impact of precipitation variability on groundwater resources. Average water availability estimated based on water yield over the study period was approximately 425 Mm^3/year. However, significant groundwater lateral outflows to neighbouring basins suggest potential overestimation of the basin's water availability. Water consumption by human activities increased by 18% from 2018 to 2021, and the total consumptive demand exceeds available water by 150%. This highlights the urgent need for enhanced water supply options and conservation measures. Future studies could focus on improving the representation of groundwater dynamics in the modified framework by improving these processes within PixSWAB or linking PixSWAB with a groundwater model. This can improve water availability estimates in groundwater-reliant basins. Additionally, the proposed framework could benefit from testing using other remote sensing datasets.

The content of this chapter is adapted from: Amdar, N., Seyoum, S., Al-Bakri, J., Rutten, M., Jewitt, G., and Mul, M.: Developing a water budget for the Amman-Zarqa basin using water accounting plus and the pixel-based soil water balance model, Model. Earth Syst. Environ., 1–21, 2024b.

3.1 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). 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 Appendix B.1 for the methodology behind Jordan's annual water budgets).

Previous research has identified several issues regarding the quality of the national water budgets. The 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). Furthermore, 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, which are typically undertaken at the basin scale, the most appropriate unit for water resources assessments.

To address these challenges, a more refined approach to water accounting is needed (Al-Shibli et al., 2017).

Among the available water accounting methods, Water Accounting Plus (WA+), developed by IHE Delft, IWMI, and FAO, employs open-access remote sensing data to describe water resources clearly and consistently 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+ is a consumption-based accounting framework that tracks blue and green evapotranspiration. Therefore, it is often integrated with various 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). 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; Delavar et al., 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 portal (WaPOR) through Open-Access to level 2 remotely sensed data on evapotranspiration and precipitation. The framework provides essential Python tools for collecting and processing WaPOR data alongside a pixel-based soil moisture balance model (PixSWAB) to split evapotranspiration into its blue and green components and quantify water flows that cannot be directly obtained from remote sensing, such as runoff and deep percolation. These tools along with 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, which constitutes 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 water consumption and return flows to report a comprehensive water budget of the Amman-Zarqa (AZ) basin in Jordan. This modification is achieved by integrating 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.

3.2 MATERIALS AND METHODS

3.2.1 Study Area

The 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[9] (Al-Omari et al., 2013). The basin covers an area of approximately 4,100 km^2, with 93% in Jordan and 7% in Syria (Figure 3.1). 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).

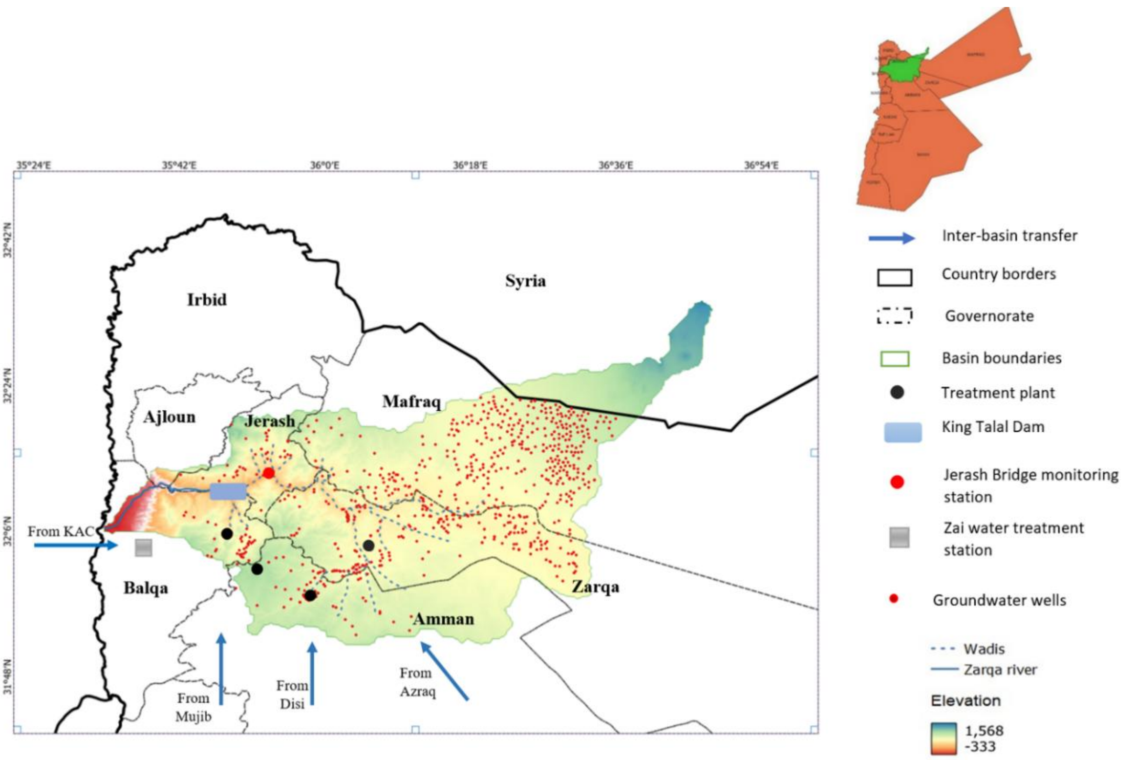


Figure 3.1 Amman-Zarqa Basin location map

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

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 the 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. 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 (Al-Bakri et al., 2016).

Over time, the AZ basin has been experiencing a decline in surface and groundwater resources. Consistent over-extraction, regularly exceeding 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 (Brückner et al., 2021; MWI and BGR, 2017). 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).

3.2.2 The WaPOR based WA+ framework

The WaPOR-based WA+ framework employs WaPOR V2 level 2 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 Appendix B.2 for detailed model description).

These outputs are essential inputs for the WA+ resource base sheet (Figure 3.2), which summarizes the water balance based on the following equation (Kiptala et al., 2014):

$$\frac{dS}{dt} = P - ET_{blue} - ET_{green} - Q \qquad (3.1)$$

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

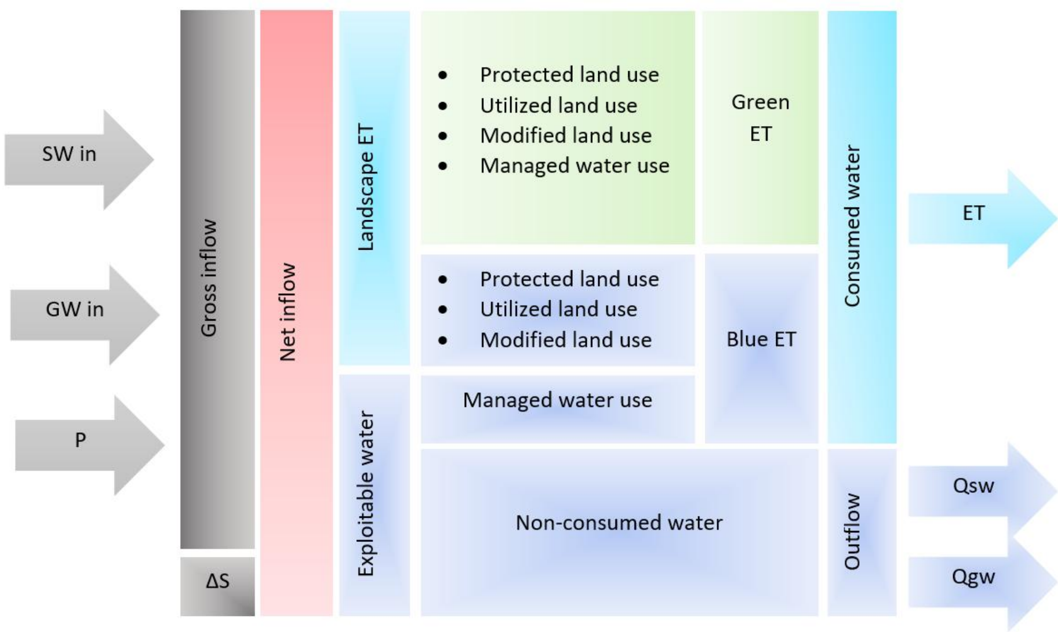


Figure 3.2 WA+ resource base sheet

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.

3.2.3 The modified WaPOR based WA+ framework

To reflect a more comprehensive water balance, the original equation (3.1) was modified to include non-irrigation manmade consumption and its return flow. This modification accounts for all water users within the basin (see Figure 3.3), resulting in the following equation (3.2):

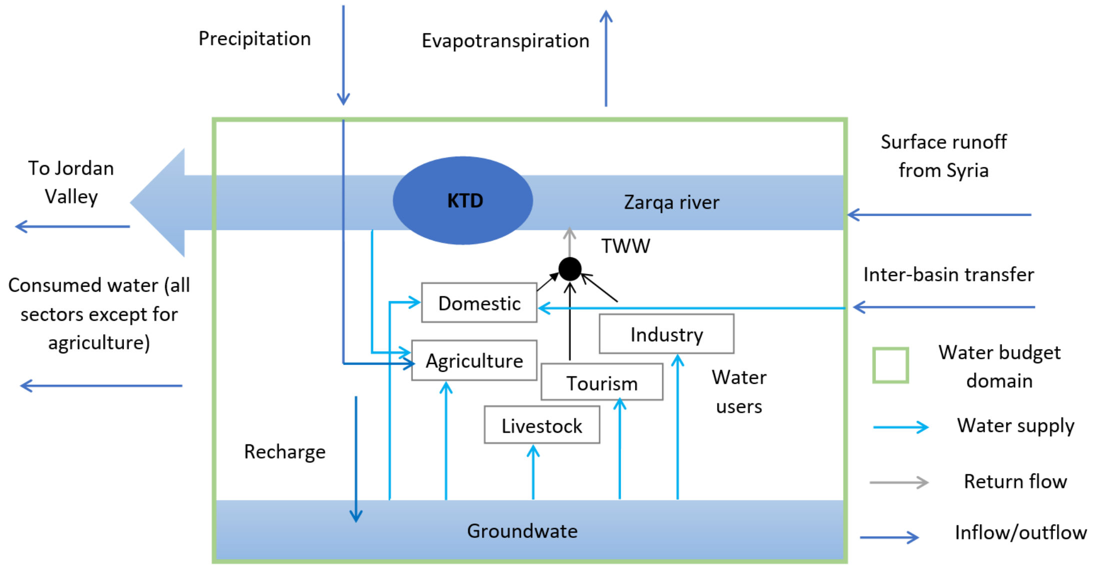


Figure 3.3 Water budget domain and components in the AZ basin

$$\frac{dS}{dt} = P + IB_t + SW_{in} - ET_{green} - ET_{blue} - (Qs - TWW) - (Q_{sro} + Q_{bf} + TWW) \quad (3.2)$$

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)
Q_s is the water supply to domestic, industry, livestock, and tourism sectors in Mm^3/year
TWW is the return flow from water supply to domestic, industry, and tourism sectors in Mm^3/year
$(Qs - TWW)$ makes up water consumed in domestic, industry, livestock, 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)
$(Q_{sro} + Q_{bf} + TWW)$ makes up Q_{out} (Mm^3/year) and ($Q_{sro} + Q_{bf}$) makes up natural surface water outflow (SWout) in (Mm^3/year)
$\frac{dS}{dt}$ is storage change over time in Mm^3/year

This modified framework includes inflows such as P, surface runoff from the headwater catchment in Syria (SW_{in}), and inter-basin transfers (IB_t) for domestic use. Outflows encompass evapotranspiration (ET_{green} and ET_{blue}), non-irrigation manmade consumption (expressed as the difference between water supply to non-irrigation users Q_s and its return flow as treated wastewater TWW), and river discharge, which includes runoff (Q_{sro}), baseflow (Q_{bf}), and TWW.

Hydrological flows, including P, SW_{in}, ET_{green} and ET_{blue}, Q_{sro}, Q_{bf}, and storage change ($\frac{dS}{dt}$) were simulated monthly using PixSWAB for the hydrological years (September to August) 2018 through 2021. Meanwhile, data on Qs, IB_t, and TWW were obtained annually from the MWI for the same period.

To simplify land use classification, WA+ land classes were re-classified from utilized, protected, managed, and modified to agricultural land use (rainfed, fallow, and irrigated areas), urban areas, and residual land classifications integrated into the natural land category (see Appendix B.3 for land use reclassification). Using this reclassification, Equation (2.3) was applied at an annual time scale, and the outputs were presented in a modified version of the resource base sheet (Figure 3.4). The equations used to develop the modified resource base sheet are presented in Table 3.1.

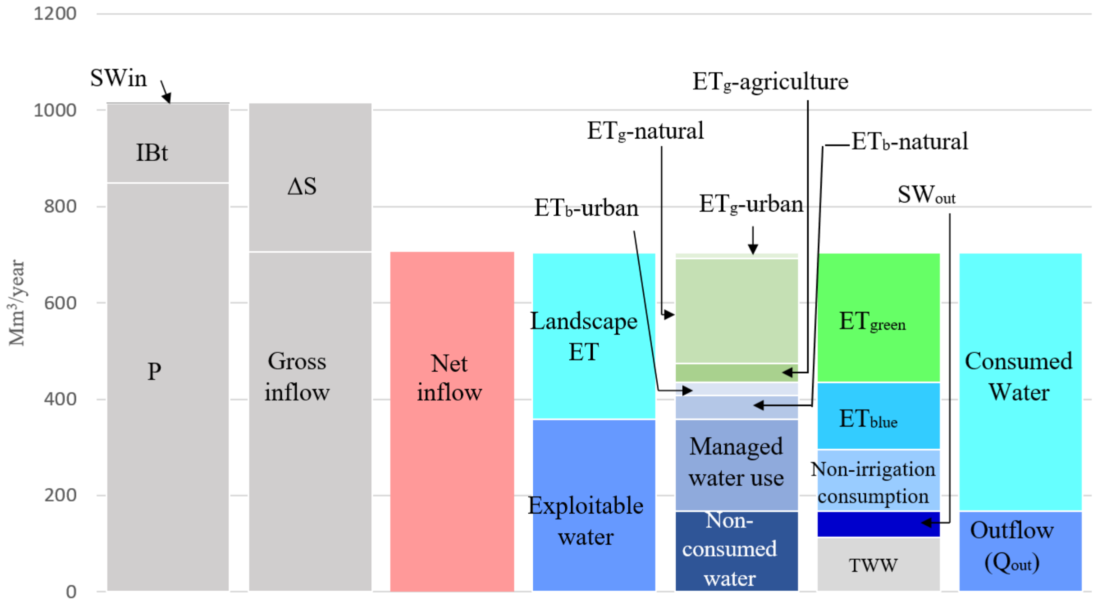


Figure 3.4 The modified WA+ resource base sheet

Table 3.1 Equations used to derive the modified WA+ resource base sheet (Mm^3/year)

WA+ category		Equation	Flux definition and source
1	Gross inflows	$Q_{inflow} = P + SW_{in} + IB_t$	P: WaPOR SW_{in}: PixSWAB IB_t: MWI ground observations
2	Net inflow	$Q_{inflow-net} = Q_{inflow} \pm \Delta S$	For ΔS see category 14
Flow paths			
3	Landscape ET	$ET_{landscape} = ET_{green-natural} + ET_{green-urban} + ET_{green-agricultural} + ET_{blue-urban} + ET_{blue-natural}$	PixSWAB
4	Exploitable water	$W_{exploitable} = Q_{inflow-net} - ET_{landscape}$	PixSWAB
5	Green ET	$ET_{green} = ET_{green-natural} + ET_{green-urban} + ET_{green-agricultural}$	PixSWAB
6	Blue ET	$ET_{blue} = ET_{blue-natural} + ET_{blue-urban} + ET_{blue-agricultural}$	PixSWAB
7	Non-irrigation consumption (domestic, industrial, livestock and tourism)	$W_{consumed} = Q_S - TWW$	MWI ground observations
8	TWW	$TWW = TWW_{As-Samra} + TWW_{Jerash} + TWW_{Baqaa} + TWW_{Abo-nseir}$	MWI ground observations
9	Surface water outflow	$SW_{out} = Q_{sro} + Q_{bf}$	PixSWAB

WA+ category		Equation	Flux definition and source
10	Managed water use	$W_{managed} = W_{consumed} + ET_{blue-agricultural}$	PixSWAB
11	Non-consumed water	$W_{non-consumed} = SW_{out} + TWW$	PixSWAB and MWI records
Outflows			
12	Consumed water	$Total\ W_{consumed} = ET_{green} + ET_{blue} + W_{consumed}$	See categories 5, 6 & 7
13	Outflow	$Q_{out} = SW_{out} + TWW$	See category 9
14	Storage change	$\Delta S = Q_{inflow} - Total\ W_{consumed} - Q_{out}$	See categories 1, 12 & 13

Key performance indicators derived from the WA+ resource base sheet were also modified to reflect the resource base sheet modifications (Table 3.2).

Table 3.2 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 and the portion that turns into renewable resources. 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.	$Basin\ closure = 1 - \frac{outflow}{Gross\ inflow}$
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	$Basin\ closure = 1 - \frac{Outflow}{Gross\ inflow}$
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.	$\text{Managed water} = ET_{\text{blue agriculture}} + W_{\text{consumed}}$
Managed fraction	No change was made to the original WA+ managed fraction indicator.	$Managed\ fraction\ = \frac{Managed\ water}{Available\ water}$

PixSWAB model and data

Model 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 (Figure 3.5).

A basin's water balance is simulated in PixSWAB following Equation (3.3):

$$\frac{dS}{dt} = P + S - ET_{blue} - ET_{green} - Q_{sro} - Q_{bf} - d_{perc} \qquad (3.3)$$

Where:

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

P is precipitation in (mm/month)

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)

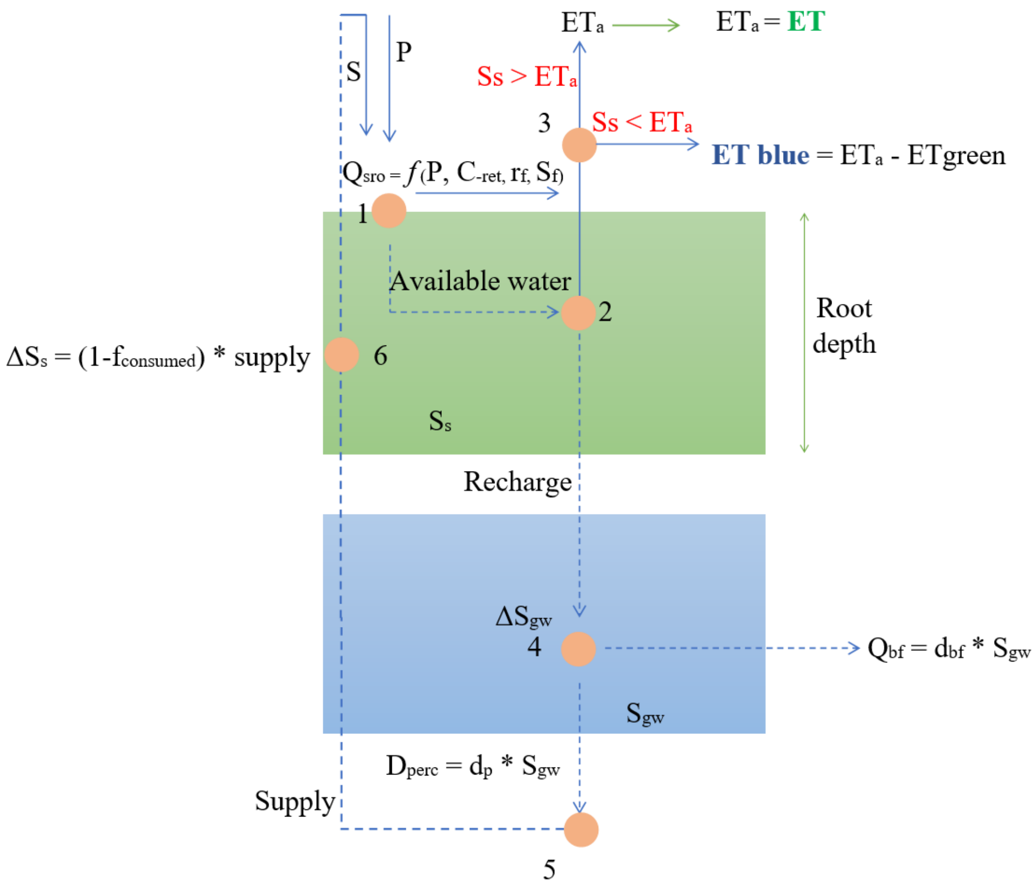


Figure 3.5 Schematic illustration of the PixSWAB model structure and simulated water balance components

The PixSWAB model incorporates four key calibration parameters: the groundwater storage constant (db_f), 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 Appendix B.4.

PixSWAB input data description and preprocessing

Table 3.3 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).

Table 3.3 PixSWAB input data

Variable	Source	Spatial resolution	Temporal resolution
Precipitation	WaPOR/ 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 Content	HiHydroSoil	0.008333 degree	Static
Land Cover Maps	WaPOR	100 m	Yearly

Input data preprocessing involved two steps: 1) resampling precipitation and reference evapotranspiration maps to a 100m resolution using the nearest-neighbour method and WaPOR land use map as a template (GDAL, 2021), and 2) validating the land use, precipitation and actual evapotranspiration maps.

PixSWAB input data validation

Land use

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, 2020a). 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 they were. Bare lands, shrublands, and grasslands comprised 69% of the total basin area, followed by fallow croplands, urban zones, shrublands, rainfed, and irrigated land classes.

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 overlaid 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 (Figure 3.6).

Albeit the assumption that irrigated areas of 170 km2 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.

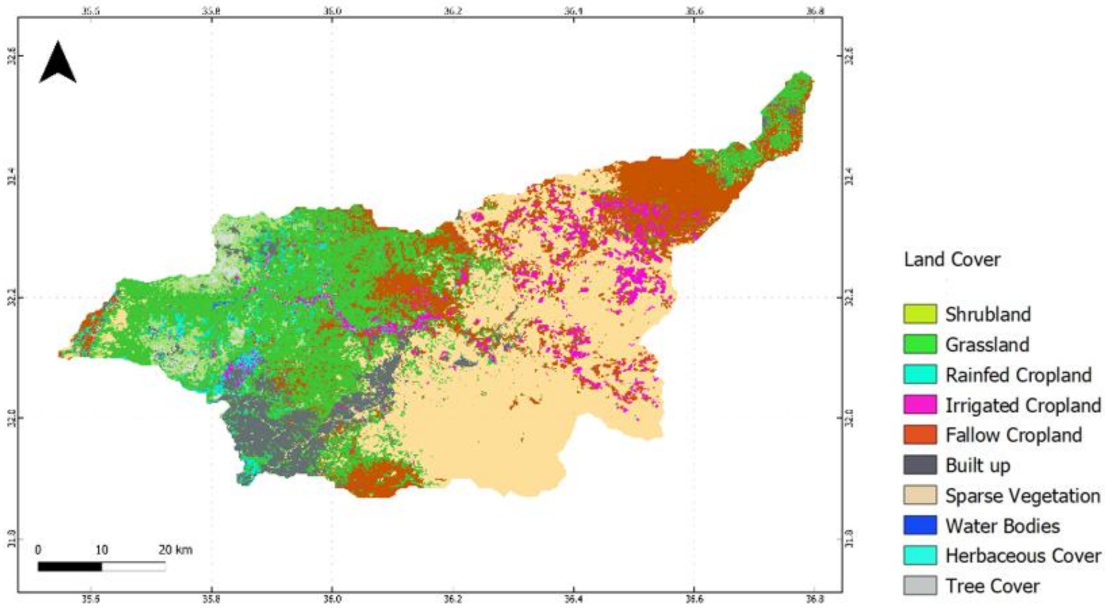


Figure 3.6 Corrected WaPOR land cover classes in AZ basin-2021

Precipitation

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 Appendix B.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

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 3.4) and the reported evaporation values over the AZ basin in the national water budgets.

Table 3.4 ETa 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	(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

To estimate annual evapotranspiration, monthly average values across the basin were obtained from the seven datasets and aggregated into annual values. A correlation analysis of these yearly values was then conducted to compare the datasets

Table 3.5 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.

Table 3.5 Correlation analysis of annual ETa datasets in the AZ basin

Dataset	*MODIS 1 km*	*MODIS 500 m*	*Penman–Monteith-Leuning*	*WaPOR*	*SSEBop*	*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

Figure 3.7 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 Appendix B.6.

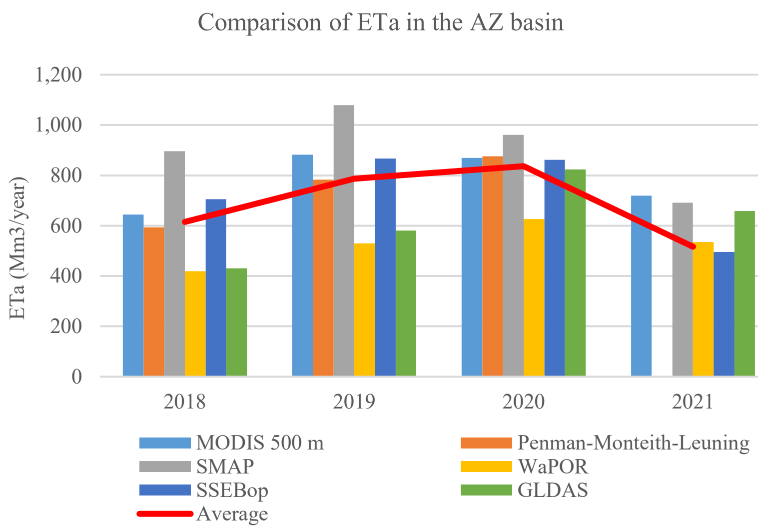


Figure 3.7 Comparison of multiple evapotranspiration remote sensing products in the AZ basin (Mm^3/year)

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 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 meters for the entire AZ basin. Simulations were conducted for the hydrological years 2010 to 2021.

Calibration was performed using the 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 Figure 3.1. 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., 2013) 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) – Equation 3.4,
- Kling–Gupta Efficiency (KGE) (Gupta et al., 2009) – Equation 3.5,
- 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): – Equation 3.6.

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q}_o)^2} \qquad (3.4)$$

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)

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \qquad (3.5)$$

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

$$F_{score} = \frac{2 * KGE * NSE}{KGE + NSE} \qquad (3.6)$$

Ground based observations of the non-irrigation water supply and return flows

Data on inter-basin transfers was acquired from MWI, detailing the annual volumes imported 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. 3.1), water imports utilized within the basin were calculated using population density maps from 2017–2020 sourced from the Open Spatial Demographic Data and Research (WorldPop). These maps were used to estimate per capita water imports (in m^3/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 total water imports utilized within the basin for the hydrological years 2018–2021. The final internal groundwater withdrawal inter-basin transfers are summarized in Table 3.6.

Table 3.6 Non-irrigation water supply (from groundwater 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

Generation of the modified WA+ resource base sheet

The modelling outputs from PixSWAB needed for the resource base sheet were aggregated annually based on the adjusted land classification for 2018 – 2021 using the WAPORWA Python notebooks. The annual PixSWAB outputs, annual non-irrigation water supply, and return flows (Table 3.6) were used to execute Equation 3.2 in Excel. These results were then presented in the modified WA+ resource base sheet.

3.3 RESULTS

3.3.1 PixSWAB simulation results

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 3.8 compares the calibrated PixSWAB discharge (using the parameters that achieved the highest NSE and KGE) with the observed discharge at the Jerash bridge 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 Appendix B.7.

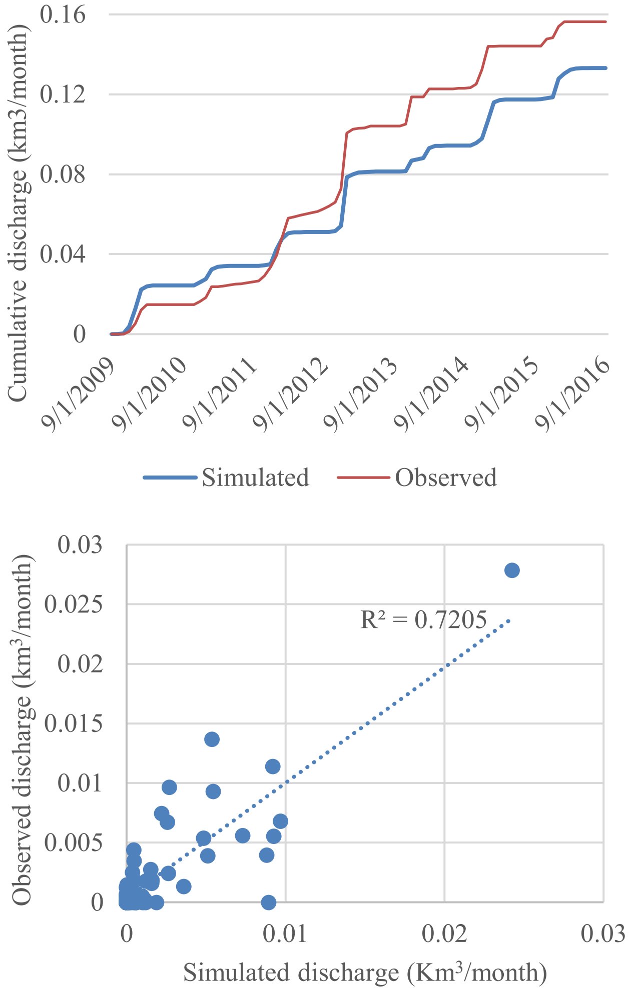


Figure 3.8 A comparison between simulated and observed discharge at Jerash Bridge station

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 3.7). 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.

Table 3.7 Descriptive statistics of observed and simulated discharge at validation point KTD (km³/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

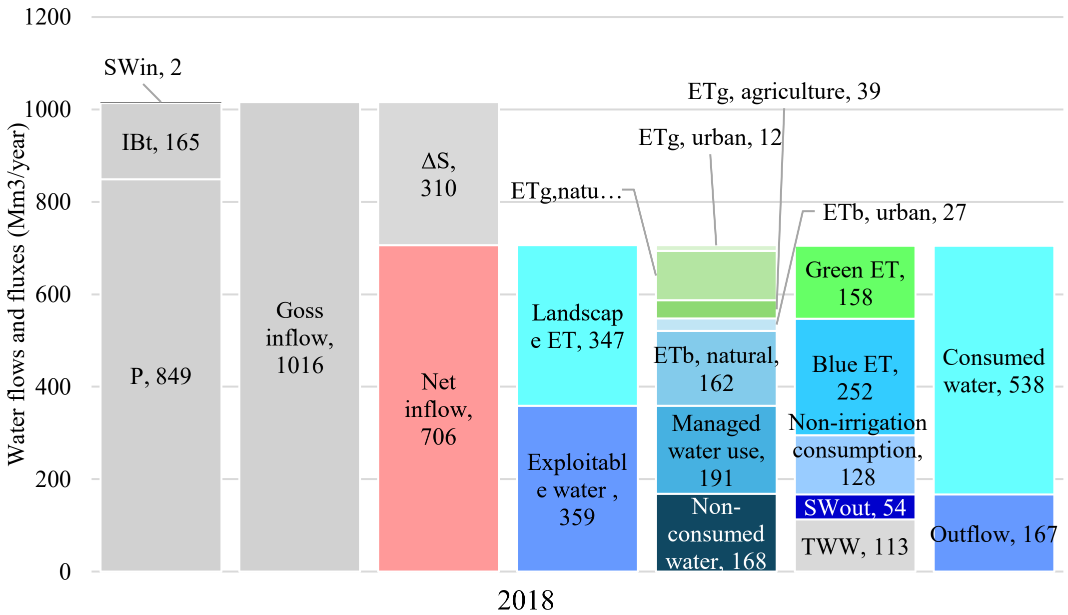
To further assess the model's plausibility in the AZ basin, we compared two calibrated parameters that influence groundwater dynamics (i.e., d_{bf} and d_p) with findings from previous studies. The d_{bf} parameter, which affects the baseflow contribution to river discharge, has a low value of 0.098. 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).

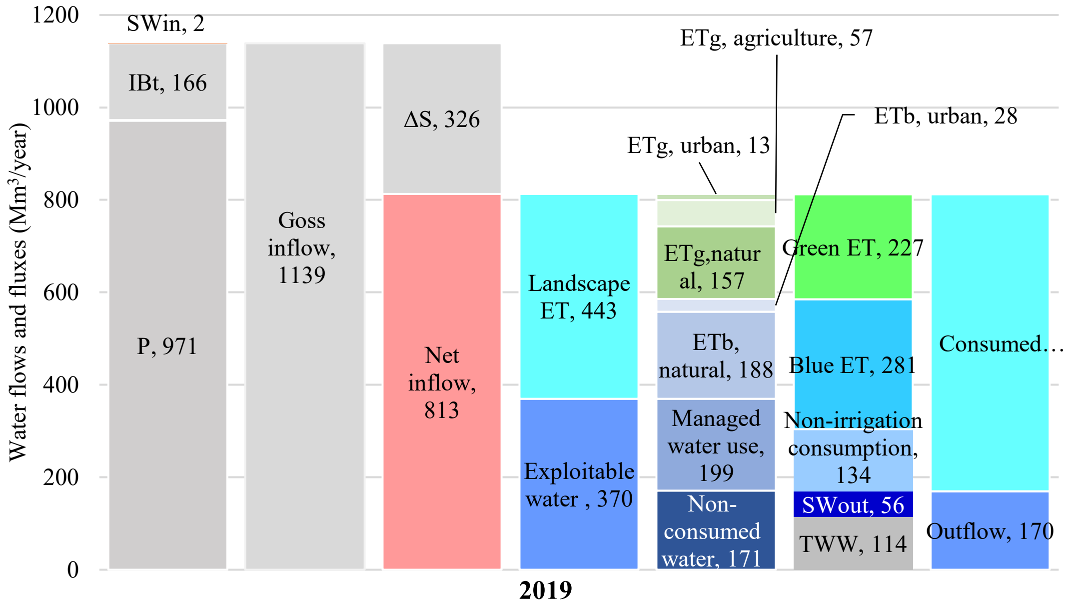
The d_p parameter influences the amount of water that percolates into deep aquifers. A value of nearly 0.9 suggests that water stored in the shallow groundwater bucket in PixSWAB likely drains to deeper aquifers during rainy seasons as rainfall surpasses evapotranspiration demand, signifying groundwater 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).

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.

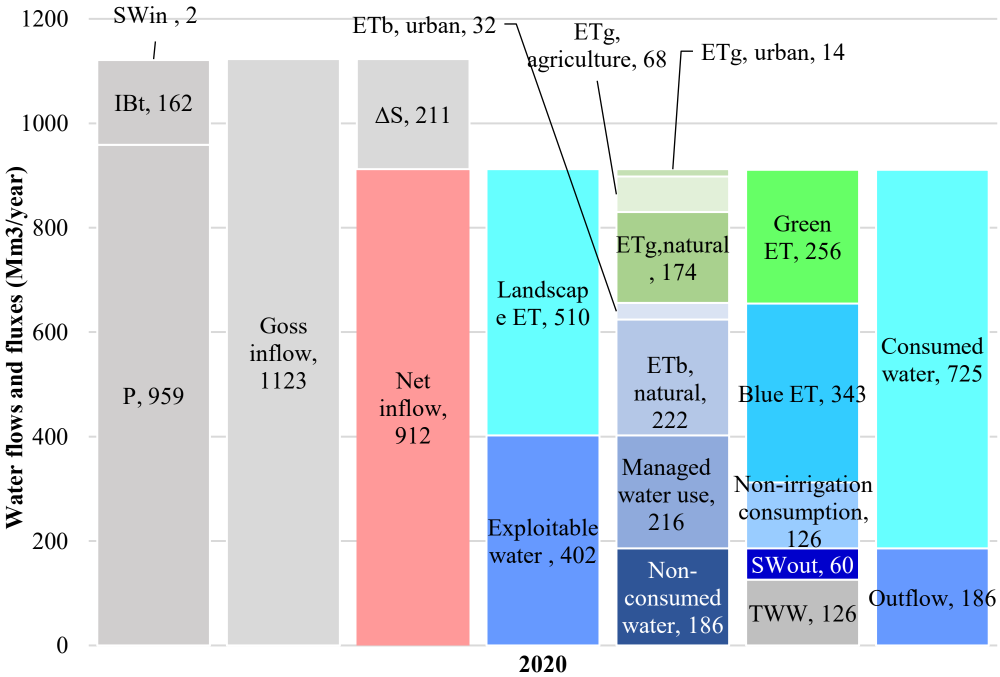
3.3.2 The adapted WaPOR based WA+ assessment

The adapted WA+ resource base sheets, summarizing the AZ basin's water budgets for the hydrological years 2018 to 2021 are presented in Figure 3.9.





Water flows and fluxes (Mm³/year)
SWin, 2
IBt, 166
P, 971
Goss inflow, 1139
ΔS, 326
Net inflow, 813
Landscape ET, 443
Exploitable water , 370
ETg, agriculture, 57
ETg, urban, 13
ETg,natural, 157
ETb, natural, 188
Managed water use, 199
Non-consumed water, 171
ETb, urban, 28
Green ET, 227
Blue ET, 281
Non-irrigation consumption, 134
SWout, 56
TWW, 114
Consumed…
Outflow, 170
2019



Water flows and fluxes (Mm3/year)
SWin , 2
IBt, 162
P, 959
Goss inflow, 1123
ΔS, 211
Net inflow, 912
ETb, urban, 32
Landscape ET, 510
Exploitable water , 402
ETg, agriculture, 68
ETg, urban, 14
ETg,natural , 174
ETb, natural, 222
Managed water use, 216
Non-consumed water, 186
Green ET, 256
Blue ET, 343
Non-irrigation consumption, 126
SWout, 60
TWW, 126
Consumed water, 725
Outflow, 186
2020

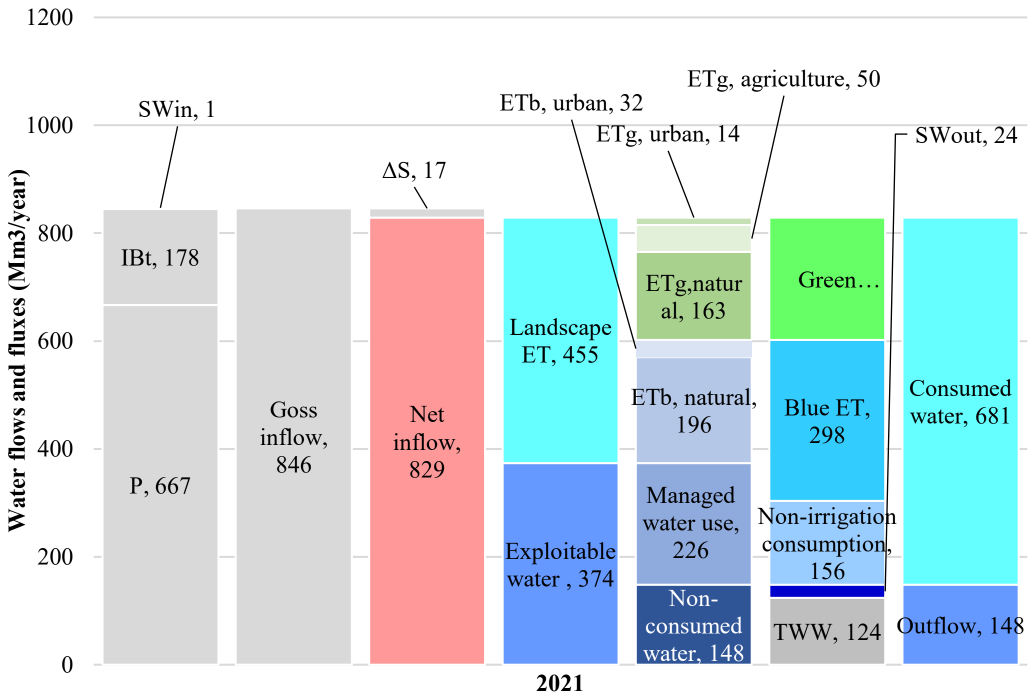


Figure 3.9 The AZ basin resource base sheet 2018 – 2021 in Mm^3/year

The WA+ assessment suggests that 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.

The assessment demonstrates that 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 main components: 1) managed water consumption, which encompasses water used for agriculture, domestic, industry, tourism, and livestock purposes, and 2) non-consumed water within the basin.

The analysis reveals that 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.

Assessment results indicate that 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 54-60 Mm^3/year between 2018 and 2020 to just 24 Mm^3/year in 2021, a reduction attributed to decreased precipitation.

The modified WA+ approach demonstrates that 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, increased water consumption within the basin indicates the growing water demands from both natural ET and human activities. This 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 3.8 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 84% over the study period. Water availability from surface and groundwater resources in the basin ranged from 502 Mm^3/year to 243 Mm^3/year, with managed fractions rising dramatically from 38% in 2018 to 93% in 2021.

Table 3.8 The adapted 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	84%	85%	83%	83%	84%
Available water	502	526	427	243	425
Managed water (Mm^3/year)	191	199	216	226	208
Managed fraction	38%	38%	51%	93%	55%

3.4 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 continues to face a significant water crisis (Al-Addous et al., 2023). Given that water resources planning often relies on scattered observations, estimates, and long-term averages, and considering the need for basin-level assessments, this paper applies 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 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. 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 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. 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 (allocated for irrigation in the Jordan Valley) account for an average of 375 Mm^3/year. Comparing these two figures suggests that the basins 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 to the basin combined with demand management through efficiency measures.

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, 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 horizontal groundwater flow. Therefore, the correct representation of groundwater dynamics 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 PixSWAB ground water representation by incorporating simplified lateral flow equations based on hydraulic gradients and aquifer properties to improve water assessments in basins that depend on groundwater.

3.5 STUDY LIMITATIONS

3.5.1 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 support 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 accurately quantify groundwater availability within the AZ basin. Additionally, our modified framework reports storage changes at the end of the hydrological year, meaning it reflects storage change after utilization. As a result, the reported storage changes in the modified WA+ resource base sheets should not be mistaken for recharge.

3.5.2 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 to integrate 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 almost 150 springs are present within the basin, predominantly located downstream. Documented spring discharge varied from 0 to 800 m^3/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.

3.6 Conclusions and Recommendations

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

The adapted 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, thus offering improved accuracy and reliability compared to Jordan's current water budget approach. First, the temporal resolution is improved, steering away from long-term averages and estimates employed in Jordan's water budgets. Second, the spatial resolution is improved through the use of spatially-distributed remote sensing data instead of point measurements of climate variables. The framework reports the annual water balance in the modified WA+ resource base sheets, delineating annual inflows, consumption, and outflows, thereby improving the understanding of interannual variations in the basin's water availability, mainly due to the interannual variability in climatic conditions. However, remote sensing data validation remains essential as discussed in the study limitations.

2- The modified WA+ framework in our study 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 remain 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 basins 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 can 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.

4

Insights into the Potential of Water Conservation in Irrigated Agriculture – A Case Study from the Arid Mediterranean Highlands

Jordan's Amman-Zarqa (AZ) basin faces increasing water scarcity due to increasing demands and persistent groundwater over-abstractions for irrigation. To address this issue, water conservation has been set as a national strategy, and several initiatives aiming to conserve water in irrigated agriculture have been implemented in the basin's highlands.

This study evaluates the impact of Water Conservation Technologies (WCTs) on irrigation water savings in the AZ basin highlands. Monthly data on irrigation applications were collected from 22 farms over three crop seasons (2019-2022) for four dominant orchards. Farm-scale potential water savings were calculated and projected to the basin scale under two scenarios: a sustainability scenario aligning groundwater abstraction with irrigation needs under WCTs and an economic scenario expanding irrigated areas using the saved water.

Results show that irrigation efficiency before the influence of WCTs was below 55%, with farmers applying an average of 1,277 mm/year. After implementing WCTs and farmers fine-tuning their irrigation practices, irrigation application decreased to an average of 795 mm/year, resulting in 38% water savings. Projecting these savings basin-wide, WCTs could conserve 44 Mm^3/year of water under the sustainability scenario.

The results provide a solid basis for informing water conservation targets in this region. However, successful water conservation using WCTs depends on farmer-led testing to ensure that reduced irrigation does not compromise crop yields. Pilot programs supported by trusted technical advice through farmer field schools and appropriate incentives can achieve sustainable water conservation in this region. Concurrently, monitoring is required to regulate irrigation expansion as it could undermine water savings.

The content of this chapter is adapted from: Amdar, N., Anwar, A., Elmahdi, A., Al-Bakri, J., Jewitt, G., & Mul, M.: Insights into the potential of water conservation in irrigated agriculture: a case study from the arid Mediterranean highlands. *Water Conservation Science and Engineering*, *10*(2), 81, 2025.

4.1 INTRODUCTION

Irrigation plays a crucial role in global food production, particularly in regions where rainfall is insufficient to meet crop water demands. Globally, irrigation accounts for 70% of freshwater withdrawals (Haddeland et al., 2014). With the growth of population and increasing water scarcity, particularly in water-stressed regions, the efficient use of water in irrigation has become critical to meeting the growing food demand while conserving the limited freshwater resources for long-term food and water security (Lankford et al., 2020; Fan et al., 2021).

Jordan, one of the most water-scarce countries in the world, faces severe challenges in water management due to its naturally limited water resources and increasing demands. Official records show that irrigation consumes more than 50% of the country's available freshwater resources (MWI, 2023). However, remote sensing studies, corroborated by ground surveys, suggest that actual irrigation abstractions might be twice as high as the official figures, indicating widespread unauthorised irrigation (Al-Bakri et al., 2016; 2023).

The highlands of the Amman-Zarqa (AZ) basin are one of the most important irrigated areas that supply high-quality fruits and vegetables to local and international markets (Al-Raggad and Belhaj, 2019). However, over the last two decades, excessive groundwater abstraction for irrigation has led to a severe decline in groundwater levels, approaching --2.95 m/year and causing wells to dry up (MWI and BGR, 2017; Radaideh, 2022). As a result, farmers have resorted to deepening existing wells or illegally drilling unauthorised new wells to meet their irrigation needs, further exacerbating the existing water scarcity crisis (Al Naber and Molle, 2017; Al-Zyoud et al., 2016).

In response to over-abstraction, the government introduced several regulatory measures, such as raising water tariffs and closing illegal wells (Al Naber and Molle, 2017; Liptrot and Hussein, 2020). However, political pressure compelled the Ministry of Water and Irrigation to allow farmers to deepen existing wells. Concerns over increasing unemployment from well closures have further hindered policy enforcement (Liptrot and Hussein, 2020).

Given the persistent over-abstraction and challenges in enforcing corrective policies, the focus has shifted toward demand management in irrigated agriculture. This approach has been highlighted in Jordan's National Water Strategies for 2016–2023 and 2023–2040 (MWI, 2016; 2023). Various initiatives have promoted water conservation technologies (WCTs), such as advanced drip irrigation systems to improve water use efficiency at the field-scale (e.g., Mercy Corps, 2022; USAID, 2022).

Irrigation efficiency (IE) is defined as the ratio of crop water use to the total water applied and expressed as a percentage (Israelsen, 1950). WCTs aim to increase IE by minimising water distribution losses and delivering water more effectively to plant roots (Frenken and Gillet, 2012; Taylor and Zilberman, 2017; Pronti et al., 2024).

However, previous research suggests that improving IE through WCTs does not always reduce overall water use and may sometimes increase water "consumption", particularly in arid regions. This phenomenon, known as the "IE paradox", occurs when water saved at the field level is actually used by farmers to expand irrigated areas or intensify crop production, ultimately increasing total water use (Pfeiffer and Lin, 2014; Loch and Adamson, 2015; Grafton et al., 2018; Pérez-Blanco et al., 2020). Additionally, while improving IE reduces water losses at the farm level, it can decrease return flows, water that would otherwise contribute to downstream availability (Grafton et al., 2018).

Previous studies often assess the impact of WCTs by predicting farmers' responses to improved farm water availability, driven by farmers' economic ambitions, prioritising economic efficiency and correlating higher productivity with greater water consumption (Pfeiffer and Lin, 2014; Loch and Adamson, 2015; Grafton et al., 2018; Pérez-Blanco et al., 2020). These studies focus on subsidised WCTs, which reduce perceived irrigation costs, making irrigation more economically attractive to farmers, without necessarily promoting broader shifts in water management practices. This approach overlooks the varying effects of improved IE on water flows across different contexts and spatial-temporal scales, potentially leading to oversimplified conclusions (Lankford et al., 2020).

Therefore, evaluating the impact of WCTs requires empirical research using observational data to assess their effectiveness in achieving their intended outcomes while avoiding unintended consequences (Huang et al., 2017; Cai et al., 2023). This exploration is especially relevant in the context of the United Nations' Sustainable Development Goal (SDG) 6.4, which promotes improving water use efficiency, including irrigation, to address water scarcity (Cai et al., 2023).

Given the critical importance of water conservation and the limited research on the impact of WCTs in Jordan's context, this study aims to empirically assess the impact of implementing WCTs in irrigated agriculture in the Mafraq highlands of Jordan, located within the Amman-Zarqa basin, and provide recommendations for water conservation initiatives by addressing the following questions:

- How much water can be saved at the field scale through the application of WCTs in the Mafraq highlands?
- What is the potential for water savings in the Amman-Zarqa basin if WCTs are adopted across key crops in the basin?
- What recommendations can be derived from this study to support water conservation initiatives that promote the adoption of WCTs in the Mafraq highlands?

4.2 Materials and Methods

This study employs a bottom-up approach to evaluate the impact of WCTs at the field scale and extrapolates these results to the basin scale. An irrigation monitoring system was established to directly measure changes in irrigation application across various crop types following the implementation of WCTs. The data collected were used to calculate water savings and improvements in irrigation efficiency at a field scale. This field data was then used to develop scenarios that examine the potential impact of WCTs on groundwater use at the basin scale.

4.2.1 Study Area

This study focuses on irrigated areas in the Mafraq governorate, located within the Amman-Zarqa (AZ) basin in Jordan (Figure 4.1). This highland region experiences an arid to semi-arid climate, with hot summers beginning in April (average highs of 29°C) and mild winters starting in November (average lows around 7°C). Annual precipitation is approximately 107 mm/year (World Bank, 2024). The irrigated area spans about 10,617 hectares (ha), with orchards comprising 83% and vegetables 17% of the land (Al-Raggad and Belhaj, 2019). Stone fruits (44%) and olives (37%) dominate the orchards, while pomegranates and grapes each cover 1% of the irrigated area. The main irrigation season extends from March to November and a brief off-season between December and February. Irrigation in this region relies on groundwater sourced from registered farmer-owned wells, which establish formal water rights for these farmers (Lankford and Mwaruvanda, 2007), as well as unauthorized wells drilled by farmers (Al-Bakri et al., 2023).

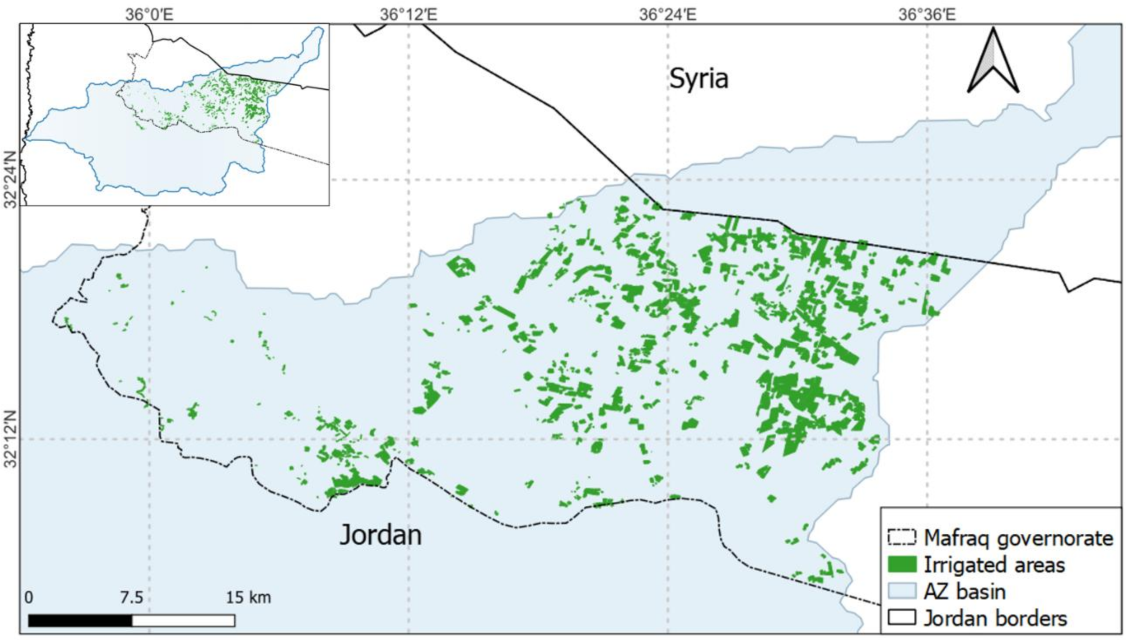


Figure 4.1 Mafraq governorate location map and its irrigated areas[10]

A sample of 22 large farms, each ranging between 20 and 60 ha, was selected for this study based on farmers' willingness to participate in field-scale irrigation monitoring. These farms, which primarily cultivate grapes, stone fruits, pomegranates, and olives, represent the main crops of the region (Al-Bakri et al., 2023; Al-Raggad and Belhaj, 2019). The irrigation systems typically used in this region are as follows:

- **Glass-Reinforced (GR) drip system**: This system uses laterals with cylindrical emitters attached to the inner wall, each with four inline holes releasing 4-8 litres per hour (l/h). Emitters are spaced 20-30 centimeters (cm) apart, and two irrigation laterals are placed along each tree line, delivering a flow of 16-20 l/h per 20-30 cm of pipe length. It is primarily used for irrigating grapes, pomegranates, and olives.
- **Mini sprinklers**: This system employs one or two online emitters per tree, with a flow rate of 100-200 l/h, and is predominantly used for stone fruits and olives.

WCTs were introduced on subsections of these farms, replacing the existing irrigation systems with two types of WCTs:

- **Improved GR system**: Featuring a single lateral with inline emitters spaced at 30-40 cm intervals. The improved GR system reduces water flow by using fewer

[10] Irrigated farms file was sourced from Al-Bakri et al., (2023).

emitters and one lateral per tree line, making it a more efficient alternative to the commonly used GR drip system in this region.

- **Pressure-compensating (PC) drip systems**: Designed to improve irrigation uniformity, this system features a standard flow of 24 l/h with 2-4 emitters per tree.

Table 4.1 provides an overview of the areas equipped with WCTs across the sampled farms, including crop types and the specific WCT applied. The total area where WCTs were installed is 307 ha, with 83.2% equipped with PC systems and 16.8% with improved GR systems. The crop composition across these sites was 26% grapes, 31% stone fruits, 18% pomegranates, and 25% olives.

Table 4.1 Overview of areas under WCTs within the sampled farms

Crop type	Area under WCTs (ha)		Total area (ha)
	PC	Improved GR	
Grape	63.2 (80%)	15.8 (20%)	79 (26%)
Stone fruits	79.5 (82%)	17.5 (18%)	97 (31%)
Pomegranate	51.7 (94%)	3.3 (6%)	55 (18%)
Olive	60.8 (80%)	15.2 (20%)	76 (25%)
Total area (ha)	255.2 (83.2%)	51.8 (16.8%)	307

It is important to note that the crop-type composition in our study area (approximately 10,617 ha) was derived from a remote sensing classification conducted by Al-Bakri et al. (2023). According to that study, grapes and pomegranates each account for about 1% of the total irrigated area (roughly 106 ha per crop). However, due to intercropping (e.g., olives mixed with grapes or stone fruits), these figures should be viewed as approximate rather than exact. While grapes and pomegranates represent a relatively small share of the overall landscape, they are high-value crops at the field scale. They are also important in other agricultural regions of Jordan. Field selection for our monitoring campaign was based on the farmers' willingness to participate rather than achieving a representative sample of crop types. As a result, a large share of the grape and pomegranate area was included in the trial though this occurred by coincidence rather than by design. We consider this extensive coverage beneficial, as the irrigation insights gained may support improved practices both among participating farmers and, more broadly, through extension services working with these crops.

4.2.2 Field monitoring and data collection

A simple monitoring system was established across 22 farms. This system involved installing two analogue meters on comparable plots (<1,500 m^2) within each farm to measure the volume of water applied at the field scale[11]. The choice to install the meters on small plots was to address farmers' concerns about water use tracking and data privacy. One plot served as the control with the existing irrigation technology (either GR or mini sprinklers), while the other was a treatment plot representing areas under WCTs. Both plots were identical in crop type, age, and variety but differed in their irrigation systems.

Figure 4.2 illustrates the monitoring system setup, showing meters installed on both the control and treatment plots. The plots were located close to each other to ensure they were within the same irrigation pressure zone but on different laterals. This arrangement allowed farmers to adjust irrigation scheduling for each plot according to the irrigation technology used.

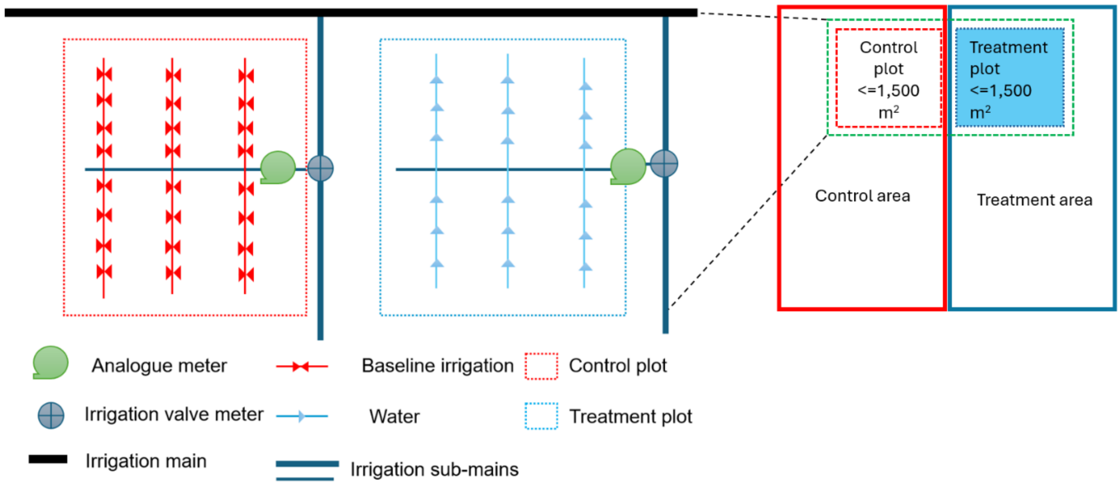


Figure 4.2 Schematization of the setup of the field irrigation monitoring system

A total of 66 plots were monitored across the 22 farms (Table 4.2). Each farm had a monitoring system installed for two paired plots, one control and one treatment, for each crop type. However, two farmers opted to test two different WCTs on their grape crops. As a result, these farms had two separate treatment plots for grapes with a shared control plot for comparison.

[11] Field scale is defined here by the size of treatment and control plots – not exceeding 1,500 m^2.

Table 4.2 Composition of monitored control and treatment plots

Crop type	Control plots			Treatment plots		
	Mini sprinklers	GR	Total	Improved GR	PC	Total
Grape	3	4	7	3	6	9
Stone fruits	4	8	12	3	9	12
Pomegranate	2	6	8	3	5	8
Olive	3	2	5	2	3	5
Total	12	20	32	11	23	34

The control and treatment plots were monitored for monthly water application over three cropping seasons (2019/2020, 2020/2021, and 2021/2022), each running from March to the following February, with data collected at the end of each month. A total of 1,152 monthly readings were recorded for the control plots and 1,224 for the treatment plots.

Monthly irrigation depths on all plots were calculated as follows:

$$I_{d\ (i,k,m,s)} = \frac{r_{(i,k,m,s)} - r_{(i,k,m-1,s)}}{a_{(i,k)}} * 1000 \qquad (4.1)$$

Where:

$I_{d\ (i,k,m,s)}$	is the monthly irrigation depth on plot *i* of type *k* (treatment *k=1* or control *k=2*) in month m of season s (mm/month).
$r_{(i,k,m,s)}$	is the meter reading at plot *i* of type *k* in month m of season s (m^3).
$r_{(i,k,m-1,s)}$	is the meter reading at plot *i* of type *k* in the previous month $m-1$ of season s (m^3).
$a_{(i,k)}$	is the area of monitored plot *i* of type *k* (m^2).
1000	conversion factor from irrigation volume (m^3/m^2/month) to irrigation depth (mm/month)

Irrigation depths were documented for the paired control and treatment plots along with their meta data including the following:

- Crop type (j= 1,2,3,4)
- Type of irrigation technology used on the control plot
- Type of WCT used on the treatment plot

4.2.3 Irrigation Depth Analysis

Estimation of average monthly and seasonal irrigation depths

Average monthly irrigation depths were calculated using two classifications:

- **Crop type - plot type:** Average monthly irrigation depths were calculated for each crop type (grapes, stone fruits, pomegranates, and olives) based on the plot type (control or treatment).
- **Plot type - irrigation technology:** Average monthly irrigation depths were calculated based on the irrigation technologies used on the control plots (GR, mini sprinklers) and the treatment plots (PC, improved GR), regardless of crop type.

The average monthly irrigation depths under these two classifications were calculated as follows:

$$I_{d\,(k,m,s)} = \frac{\sum_{i=1}^{n} I_{d(i,k,m,s)}}{n_k} \tag{4.2}$$

Where:

$I_{d\,(k,m,s)}$ is the average monthly irrigation depth for plots of type *k* in month *m* of season s (mm/month), calculated first per crop type, then per irrigation technology regardless of crop type

$\sum_{i=1}^{n} I_{d(i,k,m,s)}$ is the sum of monthly irrigation depths for plots (*i*=1 to n) of type *k* in month *m* of season s (mm/month). The aggregation was first done by crop type, then by irrigation technology regardless of crop type

n_k is the number of monitored plots of type *k.* The number of plots was calculated first per crop type and second per technology type regardless of crop type

Seasonal average irrigation depths were derived by aggregating the monthly values by crop and plot type and by plot type and irrigation technology. This provided the seasonal average irrigation depths for each of the four crop types on control and treatment plots and the seasonal averages for the different irrigation technologies on the control and treatment plots.

Estimation of irrigation efficiency

IE is a key metric used to assess the impact of WCTs (McCartney et al., 2007; Lankford et al., 2020). In this study we calculate IE by comparing irrigation depth with the net crop water requirement (CWR_{net}).

The CWR for the four orchard types were sourced from previous studies (Al-Bakri et al., 2016; Al-Raggad and Belhaj, 2019), which developed monthly CWR values for this region using the FAO Penman-Monteith method based on regional weather data (Allen et al., 1998).

To account for the influence of rainfall on crop growth, monthly effective rainfall was calculated using precipitation data derived from the **C**limate **H**azards Center **I**nfra**R**ed **P**recipitation with **S**tation data (CHIRPS), accessed through the FAO's portal to monitor **WA**ter **P**roductivity through **O**pen access of **R**emotely sensed derived data (WaPOR[12]). CHIRPS data were used due to the limited availability of ground observations within the study area. A previous study confirmed the accuracy of CHIRPS data in comparison with ground observations in the AZ basin (Abu Romman et al., 2021). Given the arid to semi-arid climate of the region, effective rainfall was calculated using the following equation (Stamm, 1967):

$$P_{e(m)} = P_m * f_r \tag{4.3}$$

Where:

$P_{e(m)}$	is the average monthly effective rainfall in the study area in month m (mm/month)
P_m	is the average monthly rainfall in the study area for month m (mm/month)
f_r	is a reduction factor derived from Stamm (1967) (U.S. Bureau Of Reclamation Method)[13]

[12] WaPOR data can be accessed here: FAO WaPOR

[13] The reduction factor values are provided on this webpage: Chapter II. Measurement of effective rainfall (fao.org) – Table 5

The monthly CWR_{net} was calculated as follows:

$$CWR_{net\,(m)} = \max\left\{CWR_{m} - P_{e\,(m)}, 0\right\} \qquad (4.4)$$

Where:

$CWR_{net\,(m)}$	is the net monthly *CWR* for each of the four crops in month m (mm/month)
CWR_{m}	is the total monthly *CWR* for each of the four crops in month m (mm/month)
$P_{e\,(m)}$	is the effective rainfall in month m (mm/month)

The net seasonal CWR for each crop type was derived by aggregating the monthly CWR_{net} for each cropping season.

IE was computed for both control and treatment plots of each crop type using the following equation:

$$IE_{(k,s)} = \frac{CWR_{net(s)}}{I_{d\,(k,s)}} \qquad (4.5)$$

Where:

$IE_{(k,s)}$	is the average IE in season *s* for plot of type *k* for each of the four crop types and expressed as percentage (%)
$CWR_{net(s)}$	is the net crop water requirement for each of the four crops in season s (mm/year)
$I_{d\,(k,s)}$	is the average seasonal irrigation depth in season s observed on plots of type *k* for each of the four crop types (mm/year)

IE was calculated for each of the four crop types across both control and treatment plots over the three cropping seasons.

Estimation of plot level water savings

Plot level water savings were calculated following Equation:

$$S_{(i1,m,s)} = I_{d\ (i2,m,s)} - I_{d\ (i1,m,s)} \tag{4.6}$$

Where:

$S_{(i,m,s)}$	is the average monthly water savings due to the adoption of WCTs on treatment plot *i1* in month *m* of season s (mm/month)
$I_{d\ (i2,m,s)}$	is the average monthly irrigation depth observed on control plot *i2* in month *m* of season s (mm/month)
$I_{d\ (i1,m,s)}$	is the average monthly irrigation depth observed on treatment plots *i1* in month m of season s (mm/month)

Average monthly water savings were calculated for all crop types. These monthly savings were aggregated to derive the *average seasonal water savings* using two classifications:

- **By crop type:** to determine the average annual water savings per crop type.
- **By irrigation technology:** to determine the average annual water savings for each combination of baseline technologies and WCTs used on control and treatment plots.

The *total seasonal water savings* achieved from applying WCTs across the 22 farms were calculated as follows:

$$S_s = \sum_{j=1}^{4} \left(S_{(j,s)} * A_j * 10 \right) \tag{4.7}$$

Where:

S_s	is the seasonal water savings achieved on sites treated with WCTs for the four crop types in the 22 farms in season s (m^3/year)
$S_{(j,s)}$	is the average annual water savings due to the adoption of WCTs on crop *j* in season s (mm/year)
A_j	is the total area under WCTs for crop type *j* (ha), derived from Table 4.1
10	is a conversion factor from mm/year to m^3/year

The annual water savings were then aggregated to derive the total water savings achieved over three seasons across a total area of 307 ha within the 22 farms.

4.2.4 Scenarios development

To evaluate the potential impact of on-farm WCTs on basin-scale water availability, we developed two scenarios to explore the potential outcomes of scaling water savings across all orchard farms in the Mafraq highlands, considering two distinct futures: 1) no expansion of irrigated areas, where water savings are retained (Sustainability Scenario), and 2) using the saved water to expand irrigation (Economic Scenario).

- **The sustainability scenario:** this scenario envisions a future where all farmers in the Mafraq highlands, cultivating grapes, stone fruits, pomegranates, and olives, adopt WCTs. This scenario assumes that farmers are driven by a heightened awareness of local water scarcity and the substantial costs of depleting groundwater resources and the rising energy expenses required to pump water from significant depths, ranging from over 200m to as much as 500m in certain locations (MWI and BGR, 2017).

  In this scenario, the primary objective is to sustain current areas of irrigated agriculture while reducing water abstraction through the effective use of WCTs. Under these assumptions, farmers are expected to reduce their water abstraction by the amount saved through implementing WCTs (Equation 4.8).

$$\Delta W_s = S_s \tag{4.8}$$

Where:

ΔW_s is the change in groundwater withdrawals due to the use of WCTs on the four crops in the Mafraq highlands in season s (m^3/year)

Areas cultivated with the four crops in the Mafraq highlands were sourced from Al-Raggad and Belhaj (2019) based on a field survey conducted in 2019 as shown in Table 4.3.

Table 4.3 Area of the four main orchards in Mafraq highlands (2019)

Crop type	Total area (ha)
Grape	132
Stone fruits	4,635
Pomegranate	54
Olive	3,968
Total	8,789

- **The economic scenario:** this scenario assumes that farmers in the Mafraq highlands cultivating grapes, stone fruits, pomegranates, and olives adopt WCTs to enhance profitability. Their strategy involves utilising the saved water using WCTs to expand the total irrigated area. This expansion includes investing in new agricultural lands and irrigation infrastructure while continuing the use of WCTs to optimise irrigation efficiency across the newly irrigated areas.

i. The potential increase in irrigated areas resulting from the adoption of WCTs is estimated using the following calculation:

$$A_{new} = \frac{S_s}{I_{d(avg)} * 10} \tag{4.9}$$

Where:

A_{new} is the expansion in irrigated area due to the adoption of WCTs on the four crops in the Mafraq highlands (ha)

S_s is the total water savings achieved from adopting WCTs across the four crop types in season s (m^3/year) (derived from the sustainability scenario)

$I_{d(avg)}$ is the average seasonal irrigation depth for the four crop types over the three monitoring seasons under WCTs (mm/year), derived from the treatment plots.

10 is a conversion factor of the area from m^3/mm to ha

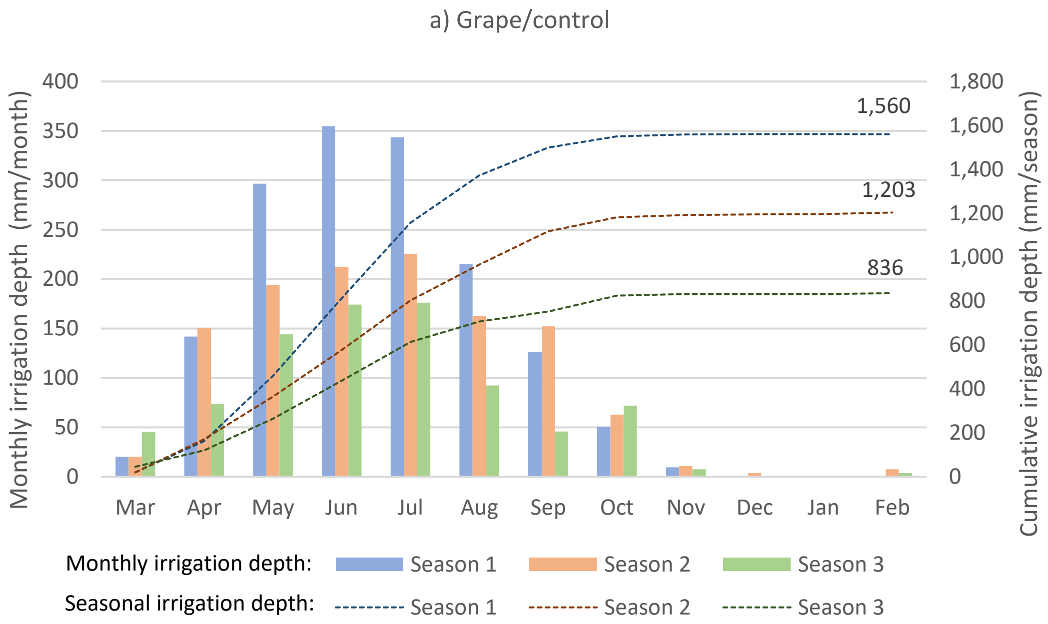
4.3 RESULTS

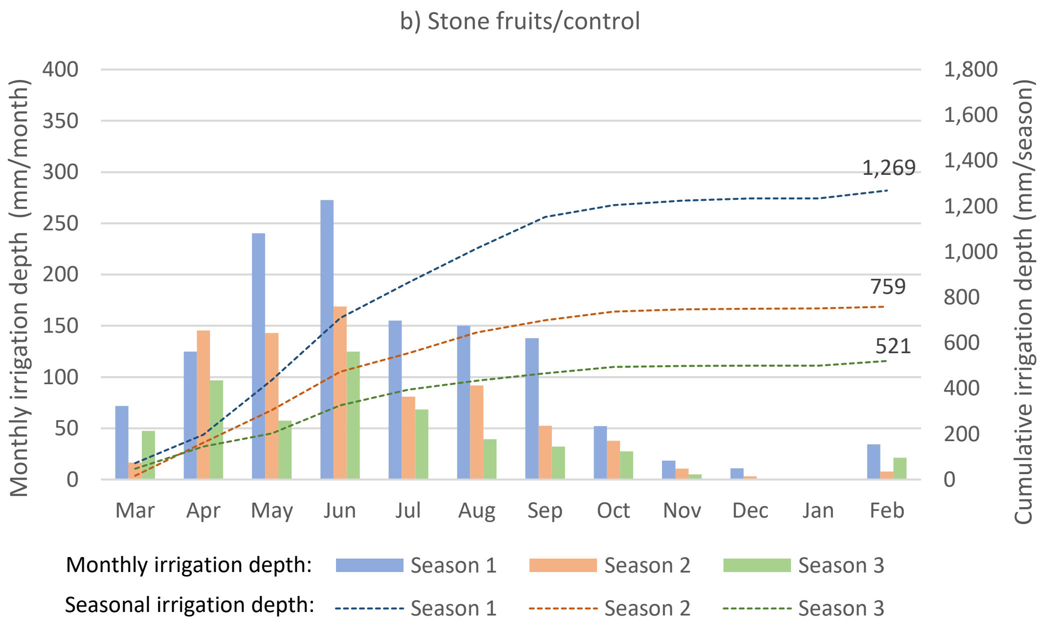
4.3.1 Irrigation depth on control and treatment plots

Figure 4.3 presents the average monthly and seasonal irrigation application on control plots for grapes, stone fruits, pomegranates, and olives over three seasons. During the first season, irrigation depths were notably higher across all crops compared to subsequent seasons. Grapes received the highest irrigation reaching 300–350 mm/month from May to July. Stone fruits followed closely, with maximum irrigation application of 250–300 mm/month in May and June. Pomegranates peaked at around 200 mm/month from June to August, while olives reached just above 200 mm/month in June. Irrigation application then gradually decreased in the second and third seasons. By the third season, the highest monthly irrigation depths were significantly lower, with grapes reaching approximately 170 mm/month in June and July, pomegranates at 199 mm/month in August, stone fruits at 125 mm/month in June, and olives at 82 mm/month in August.

Overall, irrigation depths on control plots declined substantially over the three seasons, with reductions ranging from about 40% to over 50% for most crops. Grapes and stone fruits showed the most pronounced reductions, indicating a marked shift toward more water-conservative practices over time.

Seasonal irrigation trends mirrored the monthly irrigation patterns. In the first season, grapes received the highest irrigation at 1,560 mm/year, followed by stone fruits (1,269 mm/year), pomegranates (1,212 mm/year), and olives (1,038 mm/year). However, by the third season, these values decreased to 836 mm/year for grapes, 521 mm/year for stone fruits, 965 mm/year for pomegranates, and 520 mm/year for olives.


a) Grape/control
Monthly irrigation depth (mm/month)
Cumulative irrigation depth (mm/season)
400
350
300
250
200
150
100
50
0
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
1,560
1,203
836
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Monthly irrigation depth: Season 1 Season 2 Season 3
Seasonal irrigation depth: Season 1 Season 2 Season 3


b) Stone fruits/control
Monthly irrigation depth (mm/month)
Cumulative irrigation depth (mm/season)
400
350
300
250
200
150
100
50
0
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
1,269
759
521
Mar
Apr
May
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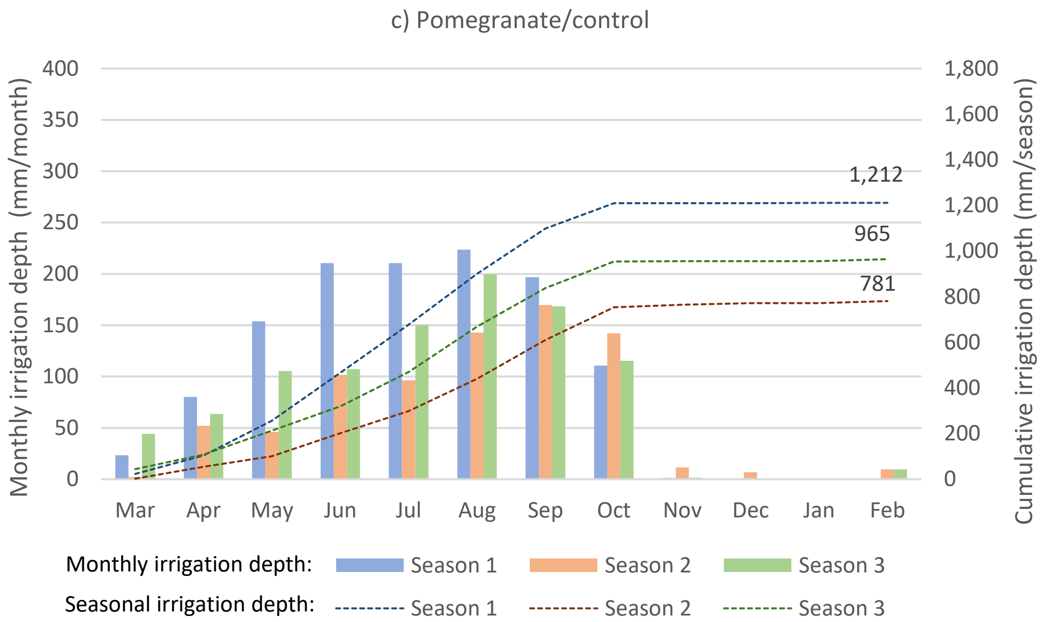
Monthly irrigation depth: Season 1 Season 2 Season 3
Seasonal irrigation depth: Season 1 Season 2 Season 3



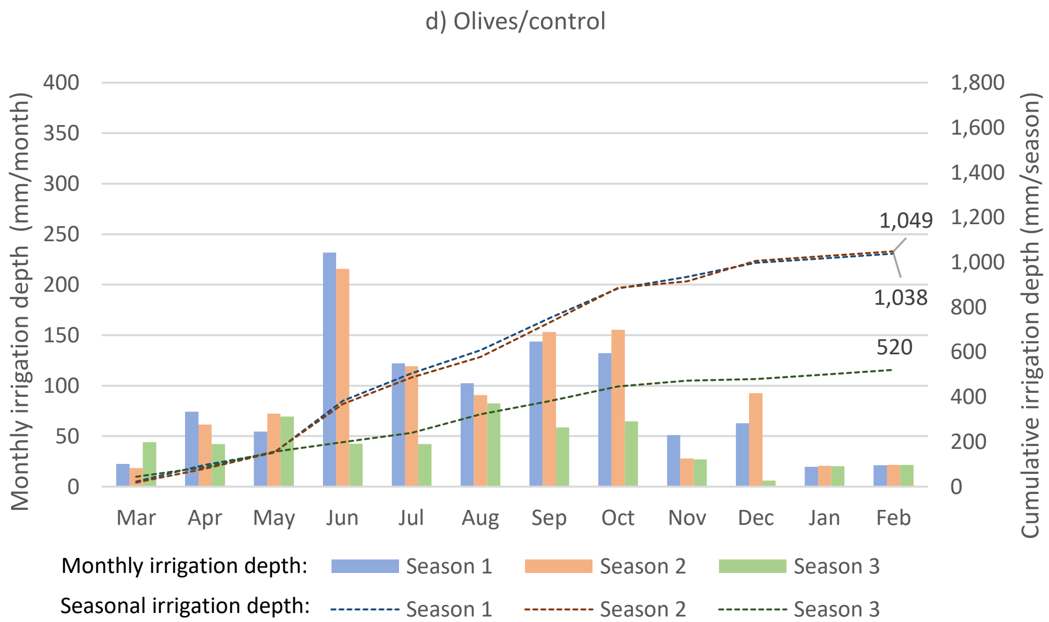
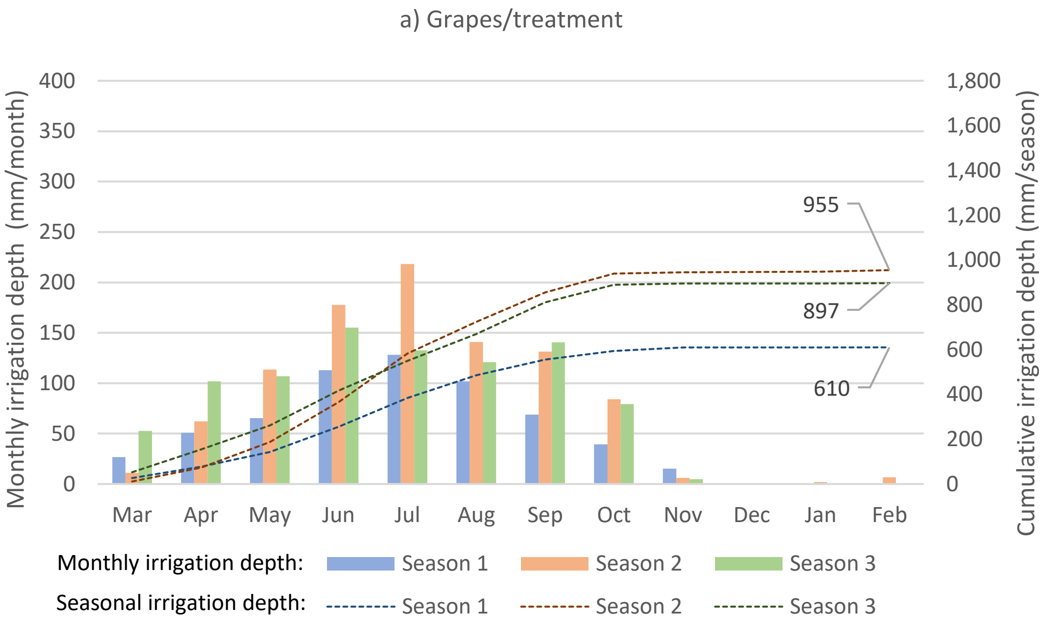


Figure 4.3 The average monthly and seasonal irrigation depths on the control plots of grape, stone fruits, pomegranate and olive in Mafraq highlands for three crop seasons.

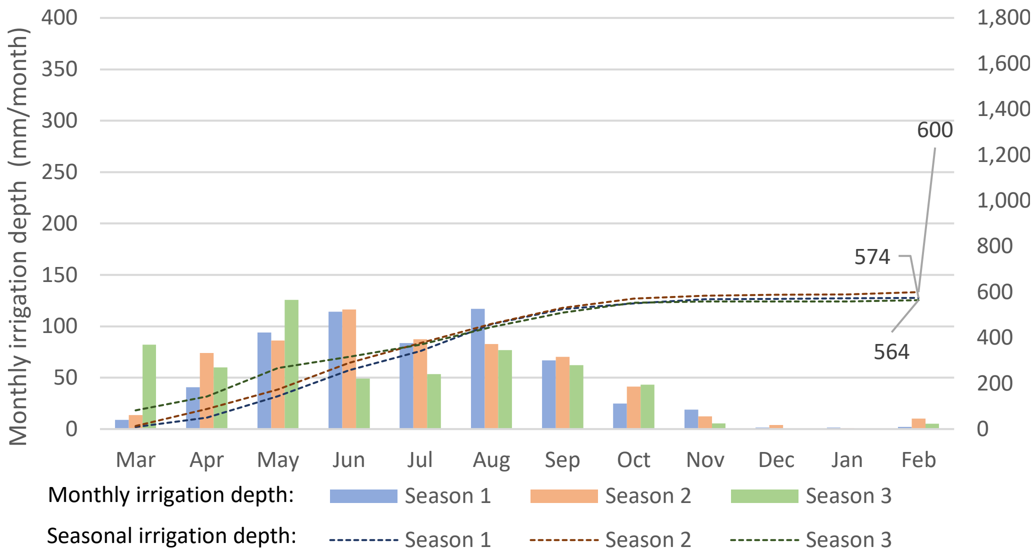
On the other hand, the average irrigation depths on the treatment plots, as shown in Figure 4.4, varied depending on the crops and seasons. Grapes received the highest monthly irrigation, peaking at 218 mm/month in July during the second season. Stone fruits received a maximum of 125 mm/month in May of the third season, while pomegranates received 247 mm/month in August of the first season. Olives received the highest monthly irrigation of 121 mm/month in July of the second season. Overall, the maximum monthly irrigation depths on treatment plots were lower than those observed on control plots in the first season, except for pomegranates.

The seasonal average irrigation for grapes ranged from 610 mm/year in the first season to 955 mm/year in the second season. Irrigation application on stone fruit plots consistently averaged around 579 mm/year across the three seasons. Irrigation on olive plots increased from 482 mm/year in the first season to 696 mm/year in the third season. Irrigation on pomegranate plots increased from 979 mm/year in the first season to 1,164 mm/year in the third.

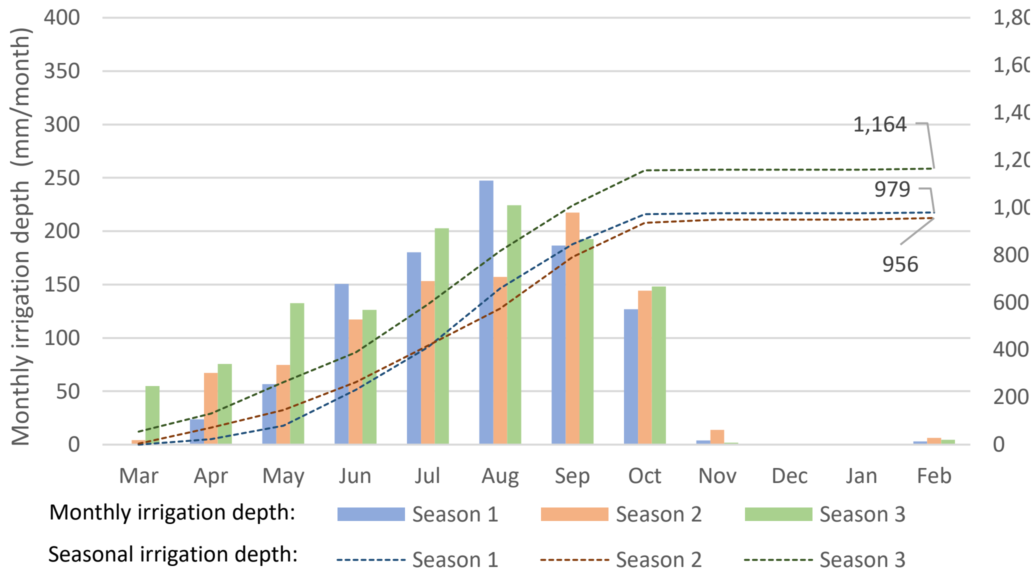
In summary, while grapes and stone fruits under treatment generally received less water than in the control plots, olives and pomegranates under treatment showed modest increases in irrigation over time. These differences likely reflect crop-specific water requirements and adaptive irrigation practices by farmers using WCTs.



b) Stone fruits/treatment



c) Pomegranate/treatment



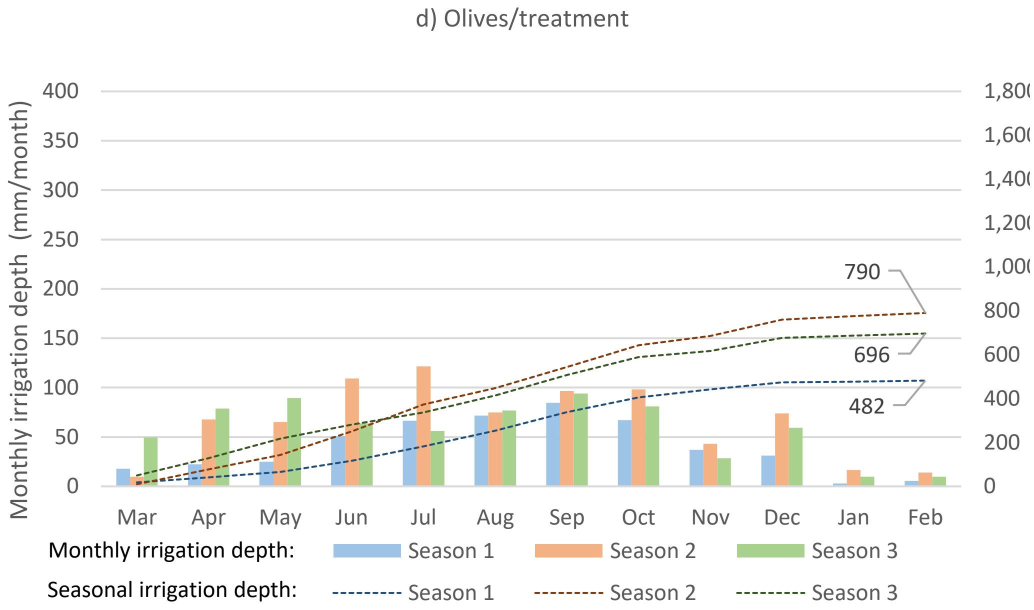


Figure 4.4 The average monthly and annual irrigation depths on the treatment plots of grape, stone fruits, pomegranate and olive in Mafraq highlands for three crop seasons.

The average seasonal irrigation application on control plots gradually decreased over time. By the third season, irrigation on grape plots decreased to 836 mm/year; and to 520 mm/year for stone fruits and olives. These seasonal irrigation amounts were comparable to those observed on the treatment plots, which were 896 mm/year for grapes, 564 mm/year for stone fruits, and 696 mm/year for olives by the third season.

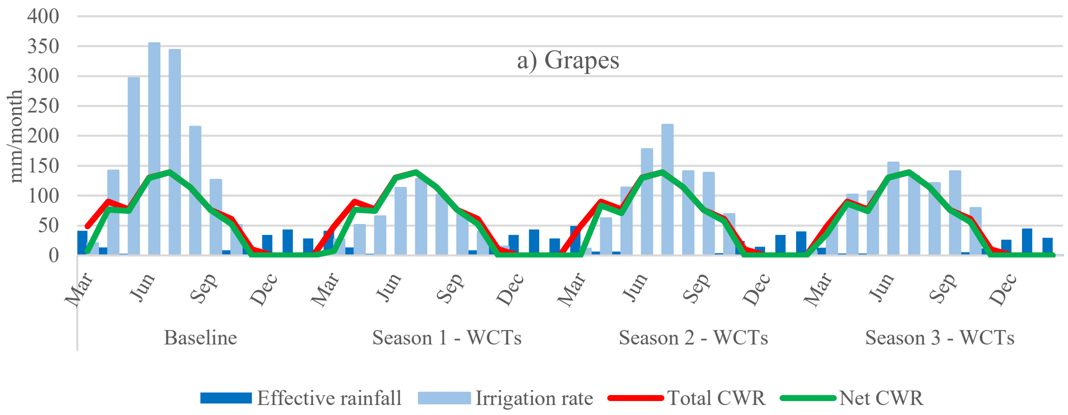
For pomegranates, the seasonal irrigation application was higher than that observed for other crops. Treatment plots received between 955 to 1,163 mm/year, while control plots received between 780 and 1,212 mm/year. During our field visits, farmers explained that they irrigate pomegranates more generously during the harvest season to prevent fruit cracking and maintain marketability. This practice contributed to the minimal change in irrigation application with WCTs for pomegranates.

The results suggest that farmers growing grapes, stone fruits, and olives may have gradually adjusted irrigation schedules on control plots to mirror the more efficient water use observed on treatment plots using WCTs. However, these changes typically occurred only after the first season, once farmers were confident that reduced water use with WCTs did not negatively impact crop production. To avoid introducing bias from these adjustments, only irrigation data from the first season, when control plot practices had not yet been influenced by the treatment, were used as the baseline for estimating water savings. This ensures that our comparisons reflect water use prior to any indirect effects from the adoption of WCTs.

4.3.2 Irrigation efficiencies

The average seasonal CWR for fruit orchards, including grapes, pomegranates, and stone fruits in the study area, was estimated at 746 mm/year (Al-Raggad and Belhaj, 2019). As shown in Figure 4.5, approximately 50% of the CWR for fruit trees were needed during June, July, and August, ranging from 114 to 139 mm/month. However, CWR for these orchards were negligible between December and January due to dormancy. On the other hand, the CWR of olive trees was slightly less averaging 689 mm/year, with peak CWR occurring from June to August, between 81 and 95 mm/month, accounting for nearly 40% of their seasonal CWR.

Rainfall occurred in the study area during October - May, averaging 208, 197 and 150 mm/year over the three cropping seasons, respectively. Effective rainfall, on the other hand, totalled 190, 179 and 137 mm/year in the first, second, and third seasons, respectively. The contribution of effective rainfall to meeting the crop needs was observed in October, November, and March, bringing the seasonal net CWR of fruit orchards to between 670 and 711 mm/year over the monitoring duration. However, the effective rainfall contribution to meeting the CWR of olives was more significant than the other orchards, as olives are irrigated all year round in this region. Hence, the net CWR for olives were between 536 and 596 mm/year over the monitoring period.



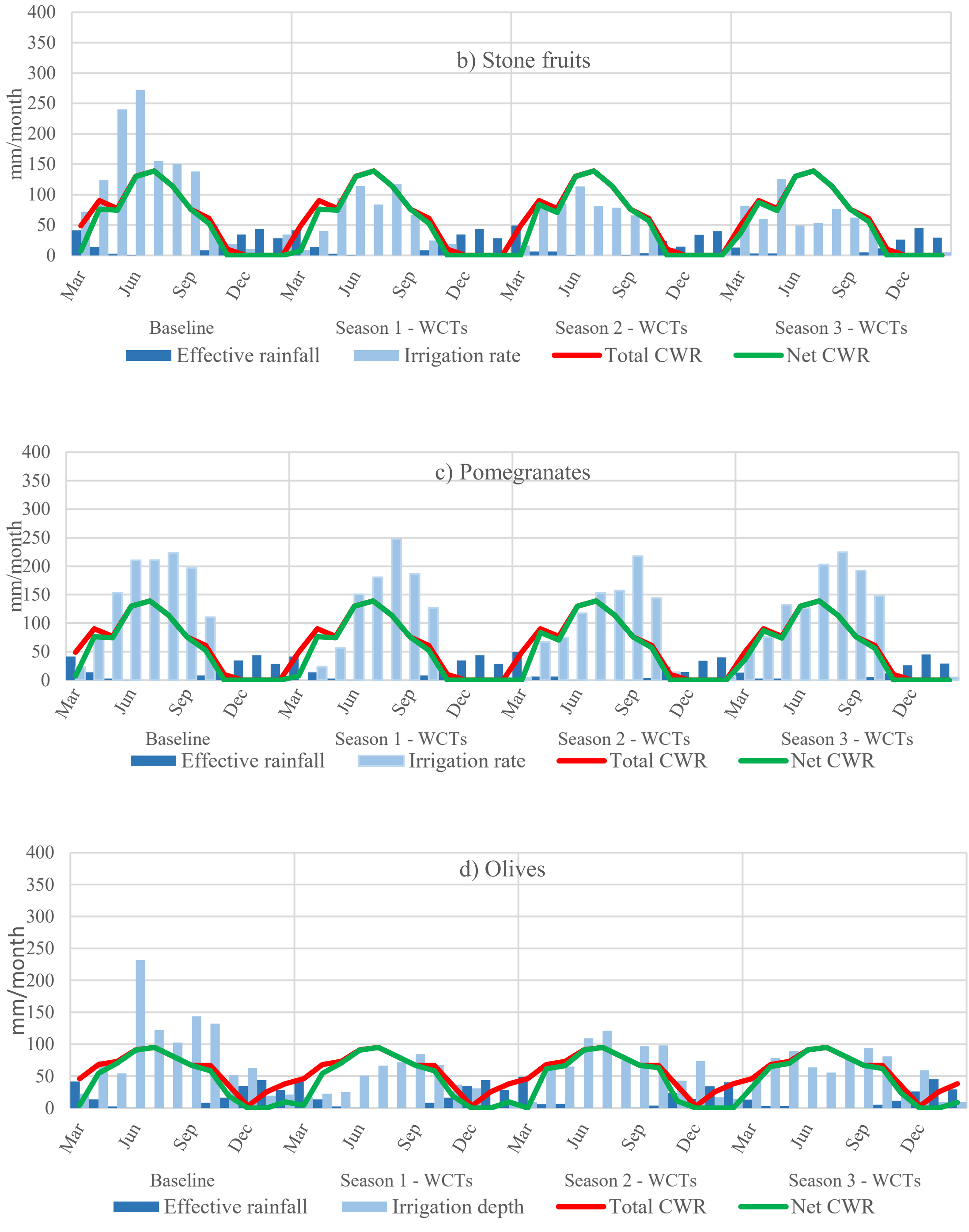


Figure 4.5 Comparison between the average monthly irrigation depths, total, and net CWR under baseline conditions and WCTs on the main orchards in Mafraq highlands (Grapes, Stone fruits, Pomegranates and Olives) over the three monitoring seasons.

Irrigation efficiencies calculated for the four crop types under baseline conditions and WCTs over the three monitoring seasons are illustrated in Figure 4.6. Under baseline conditions, irrigation efficiencies ranged from 43% for grapes to 55% for pomegranates, suggesting over-irrigation likely due to extended schedules or operational inefficiencies. This is expected among commercial farms in the region, where growers aim to increase fruit weight by over-irrigating, a practice colloquially referred to as “selling water within the fruits”.

In the following two seasons, adjustments in irrigation depths reflecting improved scheduling and adaptation to WCTs, brought irrigation efficiencies to acceptable levels for drip irrigation. In the second and third seasons, efficiencies were 71% to 79% for grapes, 68% to 61% for pomegranates, and 68% to 86% for olives, respectively.

In contrast, irrigation efficiencies for stone fruits consistently exceeded 100% across the three seasons. This could be due to the sample including young (3-5 years) and mature (over 10 years) orchards. Young orchards require less water and are therefore irrigated less than mature orchards. Additionally, peak irrigation was observed in May and June, earlier than the estimated CWR peak in July, suggesting that farmers grow early varieties of stone fruits (Figure 4.5). These growers typically start irrigation in February, earlier than the usual March or April, to align with May harvest. Rainfall in February and March may have also contributed to crop growth, reducing irrigation needs. Additionally, commercial farmers in this region typically harvest stone fruits before they fully ripen, as the fruits undergo a freezing stage before being distributed to local or international markets. This freezing process allows the fruits to ripen later, which may also explain the lower irrigation application compared to the estimated net CWR. Furthermore, the sustained lower irrigation application compared to the net CWR over three years implies a possible overestimation of actual CWR, as farmers would typically increase water use to protect crops. With stone fruits covering 44% of irrigated areas in the Mafraq highlands, accurately determining CWRs for different varieties considering agricultural practices is essential.

Overall, adopting WCTs significantly improved irrigation efficiencies for grapes, olives, and stone fruits by the third season. However, pomegranates saw only a modest increase in efficiency, rising by 6% to reach 61% in the third season.

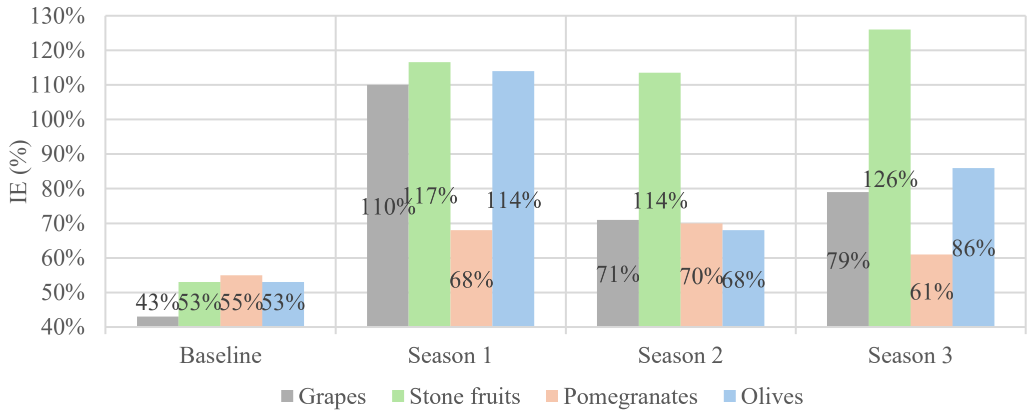


Figure 4.6 Irrigation efficiency across crop types and monitoring seasons

4.3.3 Plot level water savings

Figure 4.7 represents the average plot level water savings for the four crops. Water savings were the most consistent on stone fruit plots (n=12), averaging 694 mm/year, 669 mm/year, and 704 mm/year for the first, second, and third seasons, respectively. These results suggest that WCTs led to steady and reliable reductions in irrigation for stone fruits, equivalent to saving nearly 7,000 m^3/year on a typical 1-hectare plot.

On grape plots (n=9), water savings averaged 950 mm/year in the first season, 605 mm/year in the second, and 663 mm/year in the third. This reflects a strong initial reduction in water use, with fewer but substantial savings in the following two seasons, potentially due to farmers learning how to manage WCTs.

Water savings on pomegranate plots (n=8) ranged between 256 mm/year in the second season and 48 mm/year in the third, indicating that WCTs had a smaller impact on irrigation efficiency for this crop, likely due to the need to maintain crop marketability.

On olive plots (n=5), savings decreased from 557 mm/year in the first season to 248 mm/year in the second, and to 342 mm/year in the third. While initial reductions were significant, the variability in the following two seasons suggests that some adjustments in irrigation application on treatment plots or changes in rainfall timing may have influenced ongoing efficiency.

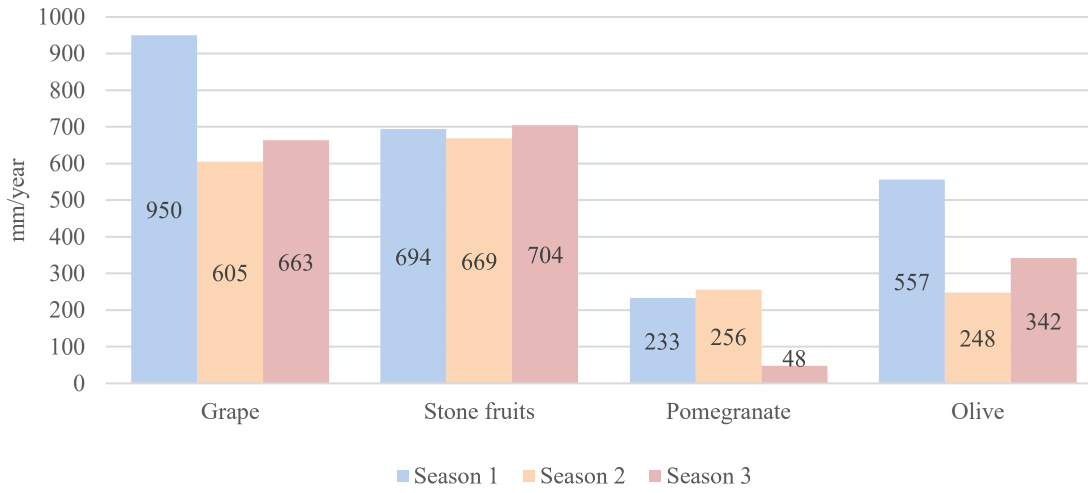


Figure 4.7 The average water savings achieved on treatment plots in Mafraq highlands over three seasons

Figure 4.8 shows the average seasonal water savings classified by technologies utilized under baseline conditions and WCTs used on treatment plots.

Converting from mini sprinklers to PC, observed on (n=11) plots, led to the highest water savings ranging from 839 to 999 mm/year. This translates to annual water reductions of roughly 8,000 to 10,000 m^3/ha. Savings were consistently high for all crop types across all seasons. Switching from mini sprinklers to improved GR, observed on (n=3) plots, resulted in an average seasonal savings of between 299 and 579 mm/year. Switching from GR to improved GR, observed on (n=7) plots, resulted in average seasonal water savings of between 183 and 427 mm/year. However, converting from GR to PC, observed on (n=13) plots, yielded the least savings of between 9 and 39 mm/year. In this group of plots where GR was replaced by PC, increased water application on some treatment plots was observed compared to the baseline conditions. This suggests that PC systems are not universally more efficient when replacing GR, possibly due to mismanagement, system incompatibility, or crop-specific needs.

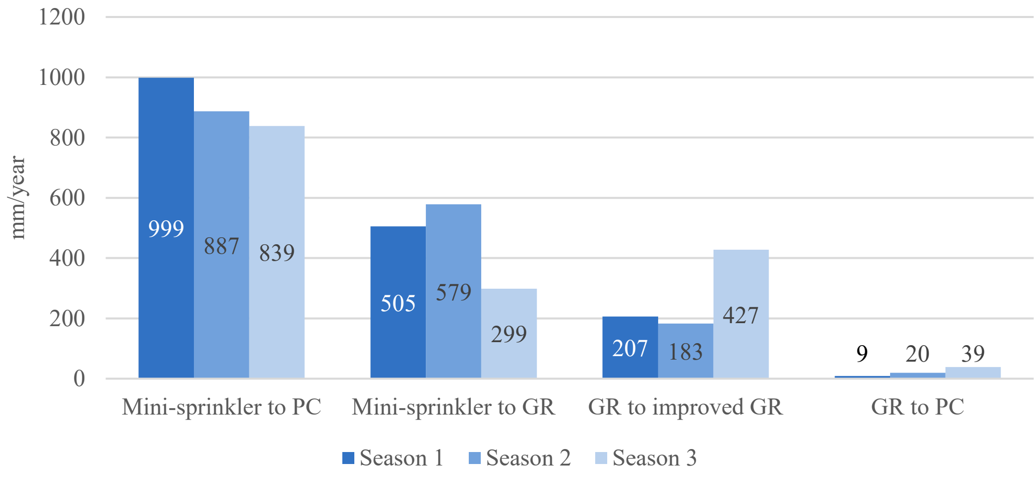


Figure 4.8 Average water savings classified per combination of technologies used on treatment and control plots regardless of the crop type over three seasons.

The use of WCTs across the 307 ha within the 22 farms resulted in a total water savings of 4.9 Mm^3 during the monitoring period. The highest savings occurred in the first season, amounting to 1.9 Mm^3/year in irrigation application relative to the baseline. In the subsequent second and third seasons, savings decreased to 1.4 Mm^3/year (Table 4.4). These findings suggest realistic sustainable annual water savings of 1.4 Mm^3/year for the sampled farms. Based on this pattern, the sustainable long-term savings of approximately 1.4 Mm^3/year for these farms, can supply the annual water needs of about 5,109 households (based on an average demand per person of 150 litre per day (MWI, 2023), and an average household size of 5 persons, equivalent to household demand of 274 m^3/year). Based on these results, and with reference to Figure 4.8, the average water savings that are considered realistic and sustainable[14] in the study area are 634 mm/year for grapes, 687 mm/year for stone fruits, 152 mm/year for pomegranates, and 295 mm/year for olives.

[14] The values of potentially sustainable water savings were calculated as the average water savings in the second and third seasons.

Table 4.4 Water savings due to the use of WCTs in the selected farms over the three monitoring seasons

Season water savings	Grapes	Stone fruits	Pomegranates	Olives	Total per season
	(m^3/season)				
Season 1	750,349	673,583	127,960	422,988	1,974,881
Season 2	478,081	649,030	140,740	188,703	1,456,555
Season 3	524,053	683,263	26,240	259,966	1,493,522
Total water savings per crop type over the study period (m^3)	1,752,483	2,005,876	294,940	871,658	4,924,958

4.3.4 Scenarios

The sustainability scenario

Adopting WCTs across all farms cultivating grapes, stone fruits, pomegranates, and olives in the Mafraq highlands within the AZ basin, which occupy an area of 8,789 ha, could lead to reducing irrigation water abstractions by 44 Mm^3/year (Table 4.5). This reduction equates to 50% of the AZ basin aquifers' annual safe yield of 88 Mm^3/year (MWI, 2016). This figure aligns with the previously reported over-irrigation in this region, determined using remote sensing techniques and estimated at 40 Mm^3/year (Al-Bakri et al., 2016). It is important to mention again that this scenario assumes that WCTs would lead to reducing abstractions by an amount equivalent to the water saved on farms. Further elaboration on this assumption is provided in the discussion.

Table 4.5 Potential water savings from adopting WCTs on main orchards in the Mafraq highlands

Crop type	Total area (ha)	Average water savings mm/year[15]	Potential reduction in irrigation abstractions Mm^3/year
Grapes	132	634	0.84
Stone fruits	4,635	687	31.83
Pomegranates	54	152	0.08
Olives	3,968	295	11.71
Total	8,789	506[16]	44.46

The economic scenario

Under the economic scenario, adopting WCTs on the selected sites with an area of 307 ha, within the 22 sample farms, could expand irrigated areas by 186 ha, increasing the total to 493 ha, a 61% growth (Table 4.6). If all growers of grapes, stone fruits, pomegranates, and olives in the Mafraq highlands adopt WCTs, the irrigated area could expand by 5,592 ha, reaching 14,381 ha, a 64% increase. This scenario assumes optimal WCTs application on initial and newly expanded lands, with an average irrigation depth of 795 mm/year. Consequently, water savings from WCTs adoption would be fully utilized for new cultivation, negating conservation efforts and reverting water use to pre-adoption levels.

Table 4.6 Calculations of potential expansion in irrigated areas due to the adoption of WCTs under the economic scenario

Variables	The sample 22 farms	The Mafraq highlands
Total average water savings (Mm^3/year)	1.48	44.46
Average irrigation depth using WCTs (mm/year)	795[17]	795
Initial irrigated area (ha)	307	8,789

[15] This average is calculated from the savings in the second and third seasons.

[16] Weighted average calculated by multiplying the average water savings of each crop by its respective cultivated area, summing these values across all crops and then dividing by the total orchard area.

[17] This figure is the two-year average of observed weighted average irrigation depth across sample crops

Irrigated area expansion (ha)	186	5,592
Irrigation expansion percentage (percentage of initial areas equipped with WCTs)	61%	64%

4.4 Discussion

4.4.1 Impact of WCTs on irrigation application and water savings in the sampled farms

The findings of this research provide valuable insights into water savings achievable at the farm scale through WCTs in the Mafraq highlands of Jordan. Prior to the introduction of WCTs, irrigation applications on the four orchards (grapes, stone fruits, pomegranates, and olives), were 1,560 mm/year, 1,269 mm/year, 1,212 mm/year, and 1,048 mm/year, respectively. These figures corresponded to irrigation efficiencies ranging from 43% to 55%, indicating significant over-irrigation.

Figure 4.9 A farmer picking grapes in one of the monitored control plots in Mafraq, Jordan, June 2019

The implementation of WCTs resulted in observed water savings of 1.9 Mm^3/year across the sampled farms in the first season. However, the savings decreased in the subsequent two seasons to 1.4 Mm^3/year, suggesting that the sustainable water savings achievable across the sampled sites are approximately 1.4 Mm^3/year. These savings corresponded to increases in irrigation efficiency of 36% for grapes, 6% for pomegranates, and 33% for olives, resulting in final efficiencies of 79% for grapes, 61% for pomegranate, and 86% for olives in the third season. The average irrigation depths sustained by farmers, as observed in the second and third seasons on treatment plots, were 922 mm/year for grapes, 1,160 mm/year for pomegranates, and 743 mm/year for olives.

As water savings were the highest in the first year of adopting WCTs, our analysis indicates that this observation is due to the slight reduction in irrigation application on treatment plots, with depths of 610 mm/year, 574 mm/year, 979 mm/year and 482 mm/year on grapes, stone fruits, pomegranates and olives respectively, compared to the following seasons. In the second and third seasons, farmers adjusted their irrigation practices, increasing irrigation depth with WCTs. This adjustment suggests that farmers have calibrated irrigation application based on experimenting with WCTs, gradually aligning water use with crop needs for this region. This hands-on experience contributes to the sustainable adoption of WCTs as farmers continue to improve their irrigation practices over time.

However, stone fruit plots exhibited a different behaviour compared to other crops. During the three monitoring seasons, irrigation efficiency on treatment plots exceeded 100%. This observation initially suggests under-irrigation due to the use of WCTs. However, this interpretation is likely inaccurate because the net CWR used to calculate irrigation efficiency in our case study is based on average values for stone fruits in the Mafraq highlands, derived from FAO 56 guidelines (Al-Raggad and Belhaj, 2019). These estimates do not consider specific stone fruit varieties, age, or the impact of agricultural practices such as early harvesting on crop needs. As far as we know, no more accurate CWR for stone fruits is available for this region. Therefore, the consistent average irrigation depth of 576 mm/year observed over the three seasons on stone fruits represents the realistic irrigation needs for the sampled plots. This finding indicates the need to improve CWR estimates for this region taking into account the different stone fruit varieties and local agricultural practices. Such information is important for improving irrigation advisory services in this region.

To further assess the sustainability of reduced irrigation application using WCTs, we compared the weighted average of observed irrigation application to a recent remote sensing study conducted in the study region during the same period (Al-Bakri et al., 2023). That study estimated irrigation water needs for the region's total irrigated area of 18,243 ha, of which 10,617 ha are cultivated with orchard trees, while the remaining area is planted with vegetables, cereals, and fodder. The estimates were based on an assumed irrigation efficiency of 70%. The study concluded that the gross irrigation needs for the region ranged between 101.5 and 118.2 Mm^3/year from 2017 to 2019, corresponding to areal irrigation depths of 556–648 mm/year over the same period (Al-Bakri et al., 2023). In comparison, our calculated irrigation depths, sustained by farmers following the introduction of WCTs was 795 mm/year (+18% to +30%), suggesting that the irrigation depths observed using WCTs align more closely with the region's estimated average irrigation needs to maintain crop production. This indicates that WCTs are effective tools for improving irrigation water management in the study area, and farmers' success in applying these technologies to optimize irrigation application in the sampled farms.

Reflecting on seasonal irrigation patterns observed in the control plots, our findings show a decreasing trend towards the third season. Although the control plots were established to monitor irrigation application under baseline conditions, our observation shows that farmers reduced irrigation even on these plots, attempting to replicate the more efficient water use observed on treatment plots using WCTs. This behaviour emphasizes our recommendation on the importance of farmer-led testing and evaluation of WCTs. Water conservation initiatives should prioritize pilot programs that enable farmers to experiment with WCTs on a small scale. This approach allows farmers to directly observe the impact on crop yields and helps alleviate concerns about potential risks. Once farmers are confident that reduced water use does not negatively affect production, larger-scale adoption can follow. Providing ongoing support and technical advice from trusted sources such as farmer field schools during the early stages of WCTs adoption can further encourage farmers to optimize their irrigation practices.

In terms of technologies and their impact on irrigation application, our findings indicate that the type of irrigation system affects farmers' irrigation applications. This is evident with the observed high irrigation application on plots irrigated with mini sprinklers (high flow emitters) across all monitored orchards. Changing mini sprinklers to improved GR or PC yielded the most significant reduction in irrigation application. Therefore, it is important to expand their use among farmers in Jordan. Notably, farmers successfully maintained these lower irrigation levels in the second and third growing seasons, suggesting that system inefficiencies were the primary drivers of over-irrigation in the sampled farms.

A previous study conducted in this region found that farmers who perceived a decline in physical water availability and faced agricultural losses tended to irrigate more frequently, often relying on self-judgment to determine their irrigation needs (Kafle and Balasubramanya, 2021). This reactive behaviour, driven by concerns about water scarcity and potential crop loss, can lead to inefficient water use. Our findings further highlight the role of irrigation technologies in influencing irrigation practices as observed with mini sprinklers. However, when provided with appropriate and tested technologies, farmers can improve the precision of their irrigation decisions.

4.4.2 The potential impact of WCTs on the Amman-Zarqa basin

Extrapolating findings from the sampled farms to all farms cultivating the grapes, stone fruits, pomegranates, and olives within the AZ basin shows that the potential for water savings under the sustainability scenario could reach 44 Mm^3/year, reducing the pressure on the groundwater aquifers by 50%. This scenario assumes that farmers would reduce their irrigation abstractions by an amount equivalent to the total on-farm water savings achieved through WCTs. However, translating this scenario into practice via restrictive groundwater abstraction policies presents a significant challenge due to the widespread presence of unauthorized wells and the difficulty of enforcing such policies.

Given these challenges, water conservation efforts should prioritize incentivizing farmers to voluntarily reduce groundwater use once WCTs are implemented. An example of potential incentives is the energy cost savings associated with matching irrigation abstractions with the total farm irrigation needs under WCTs. In the Mafraq highlands, high energy costs result from pumping groundwater from high depths, making irrigation increasingly costly for farmers. Presenting financial savings from reduced groundwater pumping as part of a business case could motivate farmers to conserve water. Farmers could be shown how much money in USD they could save for every cubic meter of water saved using WCTs instead of extraction from rapidly depleting aquifers. This approach aligns the use of WCTs with economic incentives, encouraging farmers to implement these technologies while promoting water conservation.

Conversely, under the economic scenario, our results indicate that if farmers use all saved water to increase profits through irrigation expansion, the irrigated area could increase by 64%. This would jeopardize water conservation efforts and exacerbate over-abstraction of the basin's aquifers. The rapid decline in groundwater levels in this region between 2000 and 2017 has already been linked to the expansion of irrigated areas (Shammout et al., 2021). Therefore, water conservation initiatives should monitor and regulate irrigation expansion alongside the implementation of WCTs. Remote sensing-based crop mapping studies have proven the effectiveness of remote sensing techniques in detecting and monitoring changes in irrigated areas (Al-Bakri et al., 2016; Al-Bakri et al., 2023). By leveraging these techniques, water authorities can ensure the saved water is not diverted to more irrigation development in this region.

4.5 Conclusions

This study investigates the water conservation potential in irrigated agriculture in the Mafraq highlands of Jordan using two WCTs: PC drip systems and improved GR systems. The study focused on a sample of 22 farms representative of the region's crops. Irrigation application was monitored on 32 control plots representing baseline irrigation technologies and practices and 34 treatment plots where WCTs were implemented.

The findings reveal a substantial water savings potential of approximately 44 Mm^3/year using WCTs. The most significant and consistent water savings were observed on plots transitioning from mini sprinklers to WCTs, particularly in grape and stone fruit orchards.

The successful implementation of WCTs in this region depends on farmers' ability to test and monitor the impact of WCTs to ensure they can sustain their crops. Given that, farmers can gradually optimise their irrigation application under WCTs and achieve water savings. However, incentivizing farmers to voluntarily reduce their water abstractions in line with the actual irrigation needs through WCTs is crucial for the success of water conservation efforts. In parallel, monitoring and regulating irrigated area expansion is essential to avoid unintended consequences of water conservation initiatives.

This research did not include crop production data to assess the impact of WCTs on water productivity, due to the lack of detailed plot-level yield records. Farmers typically maintain records of average yields which limits the ability to directly measure water productivity. Remote sensing offers a promising method for analysing biomass production. Combining remote sensing with irrigation application observations could enhance future assessments of WCTs' effectiveness in improving water productivity while sustaining crop yields.

5
Navigating Jordan's Water Resources Futures: Hydrological Modelling Under Socio-Economic Developments and Climate Change

This study investigates the impact of climate change and socio-economic trajectories on Jordan's water resources, demand, and use from 2025 to 2050 using the Community Water Model (CWatM). CWatM was calibrated and validated with publicly available data and existing literature on Jordan's water availability and use. A management intervention involving an improvement of 15% in irrigation efficiency was implemented through scenario analysis.

The results indicate that water availability in Jordan is projected to decline by nearly 20% by 2050. Withdrawal needs, on the other hand, are projected to increase by up to 113% by 2050. Although irrigation efficiency measures offer some gains in water availability, they are insufficient to close the future water deficit. Addressing this challenge requires implementing combined interventions of efficiency measures, seawater desalination, more utilization of treated wastewater for irrigation, as well as stronger policy enforcement to ensure that efficiency gains will translate into actual reductions in groundwater withdrawals. Moreover, strengthening transboundary water cooperation is essential to maintain sufficient inflows into Jordan considering changing climatic conditions and increasing water demands.

5.1 INTRODUCTION

Water resources planning and management are becoming increasingly challenging due to the rapid climatic and human-driven changes affecting global water systems (Ravinandrasana and Franzke, 2025). This is especially critical in groundwater-fed systems, where irrigation water use has accelerated groundwater depletion (Seneviratne et al., 2021; Ehtasham et al., 2024; Rüttenauer, 2024; Correia de Araujo et al., 2019; Cotera et al., 2023).

Jordan is among the most water-scarce countries worldwide (Zittis et al., 2022). Freshwater availability is estimated at 61 m^3/capita/year and is projected to decrease by 50% in 2100 due to climate change and population growth (Zittis et al., 2022; Yoon et al., 2021; Bashabsheh and Alzboon, 2024; Alsalal et al., 2024).

Groundwater, the country's main freshwater resource, is facing rapid depletion and salinization affecting its exploitability (MWI, 2023). Irrigation accounts for more than 50% of the country's freshwater use (Al-Bakri et al., 2023), with specific regions such as the highlands, being identified as irrigation hotspots, evidenced by remote sensing studies showing that actual groundwater abstractions are twice as high as the government's records due to low on-farm efficiency and unauthorized groundwater pumping (Al-Bakri et al., 2016; 2023).

To address the rapid depletion of groundwater, Jordan has implemented, among other measures, on-farm efficiency improvements through several projects (e.g., Mercy Corps, 2022; USAID, 2022) and continues to emphasize this approach in the national strategies to control groundwater over abstraction (MWI, 2023). However, to date, the impact of these interventions on future water availability in the context of climate change and increasing demand in other sectors remains unclear. Existing impact studies are often conducted post projects considering short-term impacts (e.g., Al-Bakri et al., 2016; 2023; Amdar et al., 2025). Consequently, there is a need to predict the impact of these interventions taking into account climate-induced changes and increasing demand.

Global open-source hydrological models are among the commonly used tools for evaluating the combined effects of climate change and water management on global water resources, particularly as these models increasingly integrate human activities into their hydrological processes. Examples of these models include WaterGAP (Alcamo et al., 2003; Flörke et al., 2013), H08 (Hanasaki et al., 2008, 2018), MATSIRO (Pokhrel et al., 2012), LISFLOOD (De Roo et al., 2000; Udias et al., 2016), and PCR-GLOBWB (Van Beek et al., 2011; Wada et al., 2014; Sutanudjaja et al., 2018). While most of these models are typically applied globally, the rapid development of advanced computational capacities and the availability of global datasets at higher resolution have made them increasingly relevant for national water resources assessments as they can save time in data collection, parameterization, and computation of complex and interacting water and hydrological systems processes (Sohi et al., 2024; Skoulikaris, 2024; Budhathoki et al., 2023).

The recently developed Community Water Model (CWatM) by the International Institute for Applied Systems Analysis (IIASA) advances these efforts by combining the foundations of existing large-scale models, best practices from hydrology and related disciplines, and a large number of supporting datasets to facilitate regional and basin-scale assessments efficiently (Burek et al., 2020). CWatM distinguishes itself through its open-access, user-friendly, modular structure, and the possibility to increase the spatial resolution from the standard 30 arcmin (~50 km by 50 km at the Equator) applied in global assessments to 5 arcmin, (~9 km by 9 km) (Burek et al., 2020). While the core model is written in C++, it is integrated with a Python environment, visualization tools, and is compatible with model intercomparison projects standards such as WaterMIP (Haddeland et al., 2011), ISIMIP (Warszawski et al., 2014), and CMIP6 (Eyring et al., 2016). These projects provide climate change-related data based on a framework for collating a set of consistent, multi-sector, multi-scale climate-impact simulations, grounded in scientifically and politically relevant historical and future scenarios (Warszawski et al., 2014). As a result, CWatM provides a robust and transparent alternative to developing local models from scratch, with regional adjustments achievable through pre- or post-processing (Dione et al., 2024). CWatM has been applied to assess groundwater availability under climate change, irrigation and extremes impact on water utilization, and for irrigation planning in transboundary basins (Cheng et al., 2024; Shah et al., 2021; Palazzo et al., 2024; Awais et al., 2024; Becher et al., 2024).

This study applies CWatM to evaluate the potential mid-term impacts (by 2050) of climate change and socio-economic development on Jordan's water availability and use. Through strategy simulations, the study also examines how improvements in irrigation efficiency could impact future water availability throughout the country. This analysis is complemented with reporting key performance indicators adapted from Water Accounting Plus (WA+) (Karimi et al., 2013; Amdar et al., 2024b). By combining the outputs of CWatM and WA+ indicators, the study goes beyond merely quantifying water savings to investigating whether these savings remain within the system, can be redirected for other uses, or could cause unintended consequences. This exploration is essential for evaluating the real-world implications of efficiency interventions, their potential trade-offs and synergies within the broader water system.

Previous climate change studies in Jordan have mainly examined the impact of climate change on hydrological parameters such as runoff and groundwater recharge (e.g., Abu-Allaban et al., 2015; Abdulla and Eshtawi, 2015; Hammouri et al., 2017). Only one study has addressed the combined effects of human activities and climate change (Yoon et al., 2021), recommending mainly supply augmentation from alternative water resources, rehabilitation of the municipal network to reduce water losses, and reallocating water from agriculture to urban use. However, this study focuses on another under-explored yet important dimension: the impact of improving irrigation efficiency on the country's future water resources and use. This investigation is timely given the government's focus on efficiency measures in national strategies (MWI, 2016; 2023). Therefore, this chapter aims to respond to this need by answering the following research questions:

- What are the potential changes in Jordan's water availability and use in the near future (2025-2050) under climate change, compared to the baseline period from 1980-2014?
- What could be the impact of improved irrigation efficiency throughout the country on its future water availability over the same timeframe?
- What combination of interventions could improve Jordan's future water security over the same timeframe?

5.2 STUDY AREA

Jordan covers an area of 89,342 km^2 and supports a population of about 11.5 million as of 2024. The country experiences an arid to semi-arid climate. Its hydrological landscape consists of fourteen surface water basins, many of which are transboundary, shared with its neighbours Syria, Iraq, Palestine, Israel, and Saudi Arabia (Figure 5.1). This study focuses on the hydrological basins delineating into Jordan with an area of roughly 149,347 km^2, and elevations ranging from 2,300 meters above sea level to -420 meters at the Dead Sea (Figure 5.1).

Jordan's water resources include both surface and groundwater. According to Jordan's water budget reports, as of 2022, the long-term average precipitation was estimated at 8,184 Mm^3/year, while evaporation stood at 7,783 Mm^3/year, resulting in a long-term average internal water yield of 401 Mm^3/year (MWI, 2022). At the same time, water supply for various sectors was estimated at 1,127 Mm^3/year. However, the available renewable freshwater, calculated based on the safe yield of groundwater aquifers and transboundary water imports, is estimated at 715 Mm^3/year, leading to a deficit of 412 Mm^3/year. This deficit is mainly met by overexploiting the country's groundwater resources (nearly 65%) and using treated wastewater (nearly 35%) generated from the domestic sector return flows for irrigation in the Jordan Valley (MWI, 2022).

Jordan's total irrigated area increased from 64,300 ha to 96,407 ha between 1990 and 2019 (FAO, 1999; Al-Bakri et al., 2023). Even though most irrigated areas are equipped with drip systems (MWI, 2023), actual withdrawals, estimated using remote sensing techniques, have exceeded the official records of the Ministry of Water and Irrigation (MWI) by nearly 140 Mm^3/year (Al-Bakri et al., 2016; 2023). This discrepancy suggests significant levels of unauthorized groundwater pumping for irrigation, and potentially inefficient irrigation water use at the farm level (Al-Bakri et al., 2023).

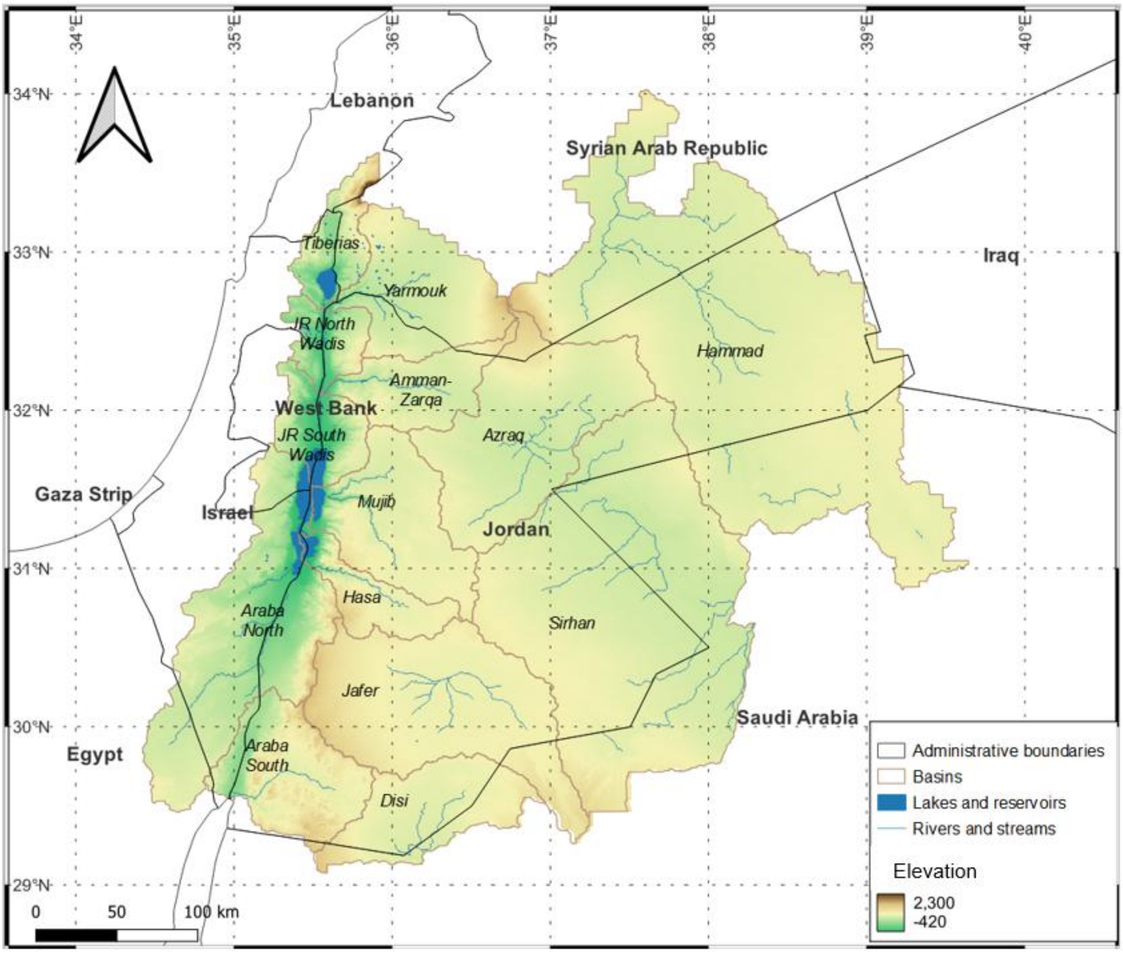


Figure 5.1 Jordan's hydrological and administrative boundaries, and surface water basins

5.3 DATA AND METHODS

5.3.1 Overview of the Community Water Model (CWatM)

CWatM is an open-access grid-based hydrological and water resources model that simulates the global and local water cycle on a daily time step (Burek et al., 2020). CWatM quantifies water availability considering human interventions such as human withdrawals from surface and groundwater, land cover changes and reservoir management. Additionally, it incorporates an accounting routine of how water availability will be affected by climate change, management practices, and future water demand (Burek et al., 2020). CWatM is available at spatial resolutions of 0.5° and 5'. However, the sub-grid resolution considers the heterogeneity of topography, soil, and landcover. Furthermore, a sub-daily time step for soil, lakes and reservoirs, and river routing is used in the simulations (Burek et al., 2020). A schematization of processes included in CWatM is presented in Figure 5.2.

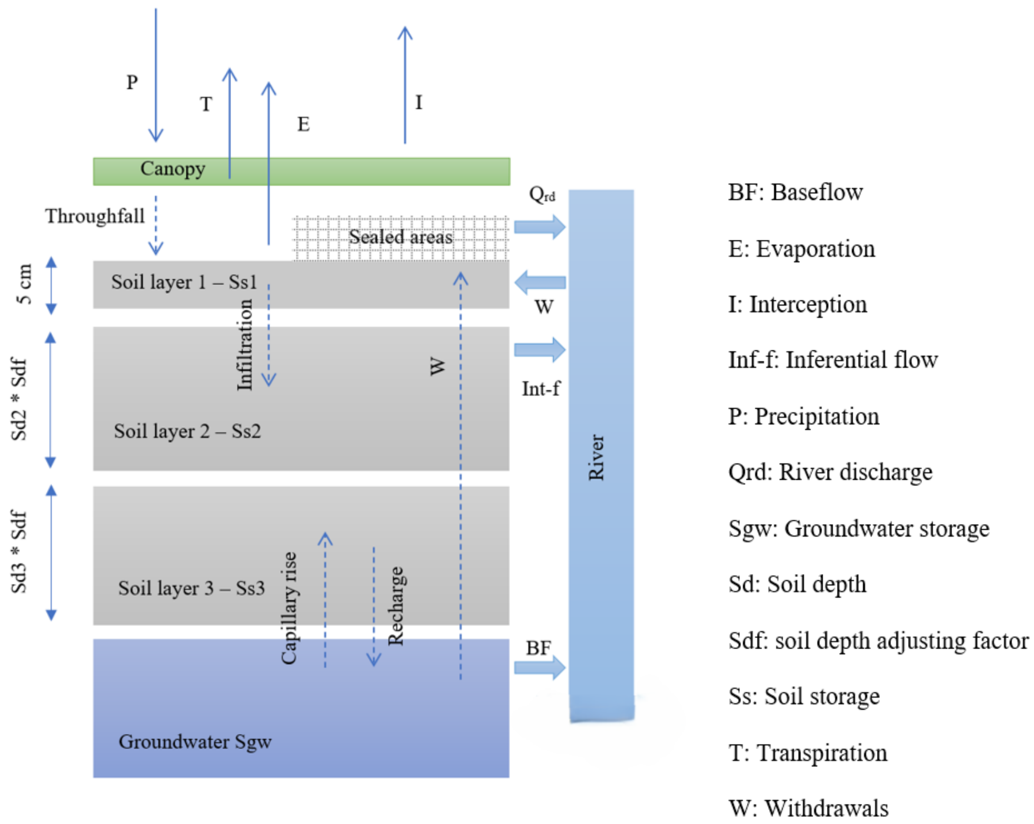


Figure 5.2 Schematic illustration of CWatM

CWatM represents hydrological processes through five storages: canopy, three soil layers and groundwater storage. CWatM considers 6 land cover classes: irrigated – paddy irrigated – sealed – forest – water and other landcover class. Each grid cell represents landcover heterogeneity through maps indicating the percentage of each class within the cell. Fluxes and storage changes for each land cover class are aggregated to the grid scale based on the fractional area of each class within the cell (Burek et al., 2020).

Hydrological fluxes considered in CWatM include evaporation from land surface, transpiration from plants, interception, soil storage, infiltration, capillary rise, groundwater storage, baseflow, and recharge. On the other hand, CWatM represents human activities through water demand for irrigation, domestic, industrial and livestock uses, and calculates their consumption, withdrawals and return flows. A description of the methods followed to simulate the above-mentioned hydrological and water use processes are provided in Appendix C.

The water balance is presented in CWatM as follows:

$$\frac{dS}{dt} = P - ET_n - ET_{irr} - C_{n-irr} - E_c - E_{wb} - Q \qquad (5.1)$$

Where:

$\frac{dS}{dt}$ the change in water storage over a specified period (Mm^3/year)

P total precipitation received within the basin (Mm^3/year)

ET_n evapotranspiration from the land surface, excluding that from irrigation (Mm^3/year)

ET_{irr} evapotranspiration over irrigated areas (Mm^3/year)

C_{n-irr} water consumption from non-irrigation uses, including domestic, industrial, and livestock sectors (Mm^3/year)

E_c evaporation losses from water channels (Mm^3/year)

E_{wb} evaporation losses from natural or artificial water bodies, such as lakes or reservoirs (Mm^3/year)

Q discharge at the basin outlet (Mm^3/year)

5.3.2 CWatM setup, calibration and validation

The model was configured for the study area using a spatial resolution of 5' (~10 km) and a daily time step. Typical input data for CWatM, as presented in Table 5.1, were utilized. As the paper focuses on irrigation efficiency intervention, the default irrigated areas used in CWatM based on global datasets (Döll and Siebert, 2002; Siebert et al., 2005; 2010), were compared with the reported irrigated area in Jordan between 1990 and 2019. Irrigated areas increased from 64,300 ha in 1990 to 96,407 ha in 2018 (FAO, 1999; Al-Bakri et al., 2023). However, CWatM irrigated area fraction map indicated approximately 60,000 ha, falling below the average of 1990-2019 of about 80,000 ha. Therefore, a recent global irrigated area map was adopted (Meier et al., 2018), where Jordan's irrigated area is estimated at approximately 89,000 ha. This map was converted into a fraction map and incorporated into CWatM for the simulations.

Table 5.1 CWatM input datasets

Dataset	Source	Original resolution
Static		
Mask map	User specific – outlines the area of interest	5'
Digital Elevation Model (DEM)	Jarvis et al. (2008), Hydro1k (USGS, 2002)	3', 1km
Local Drainage Direction map (LDD)	DRT (Wu et al., 2011)	5'
River channel maps	IIASA (Burek et al., 2020) (using Kinematic Wave equations, DEM and LDD)	5'
Soil	Harmonized World Soil Database 1.2 (HWSD), (FAO, 2012)	30"
Soil Pedotransfer	Rosetta3 (Zhang and Schaap, 2016)	-
Groundwater	Global Hydrogeology Maps of permeability and porosity (GLHYMPS) (Gleeson et al., 2014)	100 km^2
Lakes and Reservoirs	The HydroLakes database (Lehner et al., 2011; Messager et al., 2016)	Shapefile
Annual temporal data		
Land cover	Forest land cover (Hansen et al., 2013) Sealed (impervious) land cover (Elvidge et al., 2007) Irrigated areas (Meier et al., 2018) Hyde 3.2 database (Klein Goldewijk et al., 2017)	1" 30" 1 km 5'
Crop coefficient	MIRCA 2000 (Portmann et al., 2010)	5'
Albedo	GlobAlbedo dataset (Muller et al., 2012)	3'
Daily temporal data		
Meteorological data (measured) (Max, min, average temperature, humidity, surface	GSWP3-W5E5 (ISIMIP2a) (Dirmeyer et al., 2006; Hyungjun, 2017; Lange, 2019; Cucchi et al., 2020)	0.5°

pressure, radiation, wind speed, precipitation)		
Population and GDP	FAO (2012), Gleick et al. (2009), Wada et al. (2011), Burek et al. (2020)	5'
Livestock water demand	Burek et al. (2020)	5'
Industry water demand	Shiklomanov (1997), Kummu et al. (2018), Burek et al. (2020)	5'
Domestic water demand	Wada et al. (2011), Burek et al. (2020)	5'

CWatM produces a wide range of output variables relevant to hydrological and water use processes. For the purposes of this study, which centres on analysing the water balance and withdrawals (Equation 5.1), we focus on a subset of key outputs. These include precipitation, evaporation from water bodies and channels, total land/natural evapotranspiration, evapotranspiration from irrigated areas, irrigation return flow, irrigation non-productive losses in evaporation, domestic, industrial, and livestock withdrawals, non-irrigation consumption, non-irrigation return flow, and outlet discharge. These variables were selected to comprehensively capture both supply and demand components of the study area water balance under current and future scenarios.

CWatM setup and evaluation followed a stepwise approach to ensure systematic improvement of model performance (Figure 5.3). The approach included both model calibration and validation manually. The model calibration parameters are described in Table 5.2.

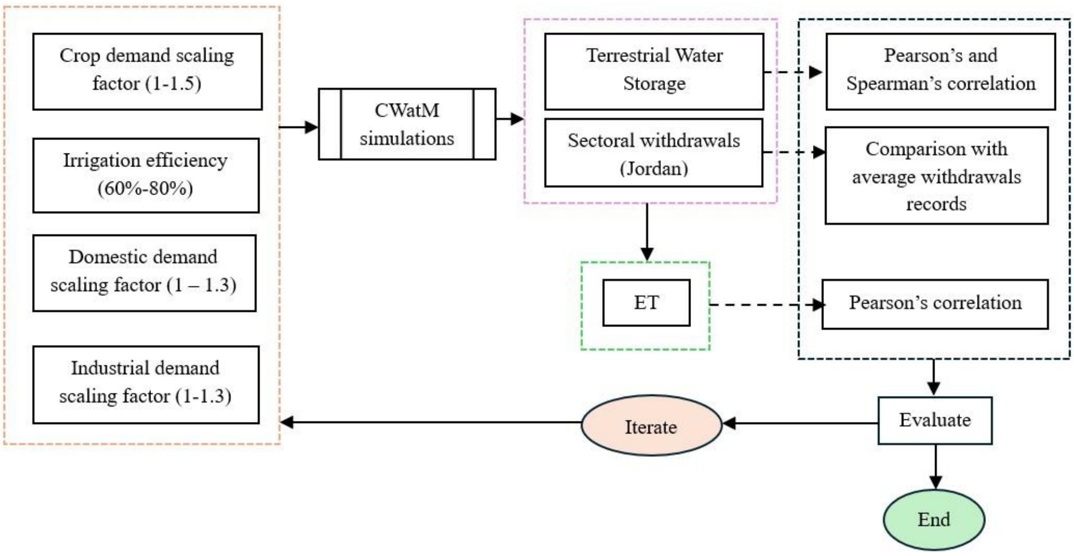


Figure 5.3 CWatM calibration and validation approach[18]

Table 5.2 CWatM calibration parameters

Calibration parameter	Definition	Calibration range
Crop demand scaling factor	Adjusts evapotranspiration from irrigation by increasing or decreasing it, affecting total irrigation withdrawals	0.8 – 1.4
Irrigation efficiency	Represents the average irrigation efficiency in the simulated area	0.6 – 0.8
Domestic demand scaling factor	Modifies domestic water demand, affecting total domestic withdrawals	1 – 1.3
Industrial demand scaling factor	Modifies industrial water demand, affecting total industrial withdrawals.	1 – 1.3

CWatM was set up for Jordan for the period 2001–2019, with the following starting values for calibration parameters: irrigation efficiency set at 70% due to the widespread use of drip irrigation, a crop demand scaling factor of 1, and scaling factors of 1 for both domestic and industrial water demand.

[18] ET is actual evapotranspiration. TWS is total water storage.

Model calibration was performed manually by comparing the simulated total water storage with GRACE (Gravity Recovery and Climate Experiment) terrestrial water storage (TWS) for the period 2002-2016. GRACE provides monthly TWS anomalies indicating changes in soil moisture, surface water, and groundwater relative to a 2004–2009 baseline (Swenson, 2012). Pearson's and Spearman's correlation coefficients were used in the calibration. Model validation on the other hand was undertaken by comparing the simulated average water withdrawals by sector with the reported withdrawals from Jordan's MWI for the period from 2002 to 2018. Additionally, the simulated monthly evapotranspiration (ET) was compared with remote sensing-based ET datasets (Table 5.3).

Table 5.3 Actual evapotranspiration datasets used for comparison with CWatM simulated ETa.

Dataset name	Source	Spatial resolution	Temporal resolution	Data series
MOD16A2 V105	NASA (Mu et al. ,2014)	1 km	8-day	Jan. 2002 – Aug. 2014
Penman–Monteith-Leuning V2	(Zhang et al., 2019)	500 m	Daily	Jan. 2002 - Dec. 2019
GLDAS	(Rodell et al., 2004)	27,830 m	Daily	Jan. 2002 – Dec. 2019
Terra Climate	(Abatzoglou et al., 2018)	~4-km	Monthly	Jan. 2002 - Dec. 2019
WaPOR (V2)	(FAO, 2020)	100 km	Monthly	Jan. 2009 – Dec. 2018

5.3.3 Climate change scenarios

The Intergovernmental Panel on Climate Change (IPCC), a United Nations organization tasked with advancing knowledge on climate change, uses a collection of climate and socio-economic projections for modelling and research. The climate/emission projections, called the Representative Concentration Pathways (RCPs), are projections of greenhouse gas (GHG) concentrations as a result of human activities. The four RCPs range from very high (RCP8.5) to very low (RCP2.6) future GHG concentrations. The numerical values of the RCPs (2.6, 4.5, 7.0 and 8.5) refer to the GHG concentrations in 2100. RCP2.6 shows greenhouse gas concentrations increased slightly until 2040, then reduced to around 2000 levels by 2100. RCP8.5 shows rising emissions throughout the period up to 2100. On the other hand, the socioeconomic projections, called the Shared Socioeconomic Pathways (SSPs), are five narratives of development cooperation, and priorities (SSP1, SSP2, SSP3, SSP4, and SSP5). Each of the SSPs is associated with quantitative projections of population, Gross Domestic Product (GDP is a measure of the value of the goods and services produced), and urbanization. For example, SSP1 is called the Sustainability Path and imagines a world acknowledging environmental boundaries, increasing equality and education, economic growth inspired by human well-being, and sustainable use of resources and energy. SSP3 is called Regional Rivalry and represents fossil fuel future development (Riahi et al., 2017).

In this paper we utilize 3 RCP-SSP combinations to explore potential futures for Jordan, namely:

- Green road: SSP 1 with RCP 2.6 (SSP126) which imagines a sustainable future fostered by global efforts to reduce emissions and sustain natural resources.
- Rocky road: SSP 3 with RCP 7.0 (SSP370) which imagines a future with higher conflicts, slower economic growth, high demands, and less efficient use of natural resources.
- Taking the highway: SSP5 with RCP 8.5 (SSP585) which imagines a fossil fuel intensive future, high demands, and less efficient use of natural resources.

For each of the RCP-SSP combinations, climate data (atmospheric forcing) was sourced from the Inter-Sectoral Impact Model Comparison Project (ISIMIP) repository version 3b. ISIMIP version 3b provides daily, bias-adjusted climate forcing data at a 0.5° spatial resolution from five climate models, namely: GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL (Lange et al., 2024). Precipitation data from these five models were evaluated for their alignment with the projected precipitation trends over the study area, reported in previous climate research and the National Communication reports of Jordan. According to Jordan's National Communication (NC) report, average annual precipitation over Jordan is very likely to decrease by 2050, with more severe decreases by 2100. Based on that, climate models that show a decrease in precipitation under climate change were selected for this study, specifically GFDL-ESM4 and IPSL-CM6A-LR. Table 5.4 summarizes the climate simulations input data used in this study.

Table 5.4 CWatM input data for RCP-SSP simulations

Continuous temporal data		
Dataset	Source	Spatial Resolution
Atmospheric forcing (simulated) (Max, min, average temperature, humidity, surface pressure, radiation, wind speed, precipitation)	ISIMIP3b (GFDL-ESM4, IPSL-CM6A-LR) (Lange and Büchner, 2021)	5'
Livestock water demand	(Burek et al., 2020)	5'
Industry water demand	(Burek et al., 2020)	
Domestic water demand	(Burek et al., 2020)	

The calibrated CWatM was used to run the simulations using data presented in Table 5.4 for the baseline period of 1980-2014 for the two climate models, and future scenarios (2015-2050) of the six combinations of SSPs and RCPs (Table 5.5). Results presentation focused on the period 2025-2050. These simulations are referred to in this paper as "business-as-usual" given they represent water resources under climate change and socio-economic pathways considering no intervention.

Table 5.5 Climate change simulations summary under the business-as-usual case

Model	Baseline simulations (Run period)	Future simulations (Run period)	Future Scenarios
GFDL-ESM4	1980 - 2014	2015 - 2050	SSP126 – SSP370 – SSP585
IPSL-CM6A-LR	1980 - 2014	2015 - 2050	SSP126 – SSP370 – SSP585

5.3.4 Management strategy

Irrigation efficiency interventions are important in the context of Jordan given the national focus on projects aimed at enhancing water conservation measures in irrigated agriculture (MWI, 2023). Therefore, this study explores the impact of improving irrigation efficiency across the country by 15% improvement in irrigation for the timeframe 2025 to 2050. According to Amdar et al. (2025), the range of efficiency gains achievable in the most critical irrigation hotspot (AZ basin) is between 6% for pomegranates and 54% for stone fruits, depending on crop type. A 15% improvement was chosen as a conservative but realistic and achievable target at the national scale, taking into account constraints such as farmers' ability to adopt Water Conservation Technologies (WCTs) across Jordan, the risk that water saved at the plot level is reinvested in irrigation expansion rather than reducing abstractions, and Jordan's limited capacity to restrict unauthorised groundwater use.

5.3.5 Results presentation

The study results focus on reporting water balance, availability and withdrawals over the study area and in each of the 14 surface water basins. The water balance was presented as water circles along with performance indicators (Smilovic et al., 2024).

The water balance is reported as the annual average of all models for each climate change scenario and socioeconomic pathway, covering both the historical period (1980–2014) and the future period (2025–2050), representing the business-as-usual scenario. This same approach is applied to present the results of the management strategy for the future period (2025–2050). These results are visualized using water circles; flexible water cycle diagrams that aggregate and display the water balance (Smilovic et al., 2024).

Additionally, the average annual water availability in the region and each of the 14 surface water basins was calculated using Equation 5.2 and presented in water circles, which compare available water with average annual withdrawals, consumed water from human activities and return flows, calculated using Equation 5.2 and Equation 5.3. This is done for the historical period and the future business-as-usual and management scenarios.

$$AW = Max\left(\frac{P - ET_n - E_c - E_w}{P}, 0\right) \tag{5.2}$$

Where:

AW available renewable water (Mm^3/year)

P precipitation (Mm^3/year)

ET_n evapotranspiration from the land surface, excluding irrigation-induced evapotranspiration (Mm^3/year)

E_c evaporation losses from water channels (Mm^3/year)

E_w evaporation from natural or artificial water bodies, such as lakes or reservoirs (Mm^3/year)

$$\Delta_{AW} = AW - W_{irr} + W_d + W_i + W_l = AW - ET_{irr} + C_{n-irr} + R_{irr} + R_{n-irr} \quad (5.3)$$

Where:

Δ_{AW} Change in available water after human withdrawals (Mm^3/year)

If AW>0, it indicates a surplus, if AW is =0 it indicates no available water to meet withdrawal needs

W_{irr} withdrawals for irrigation purposes (Mm^3/year)

W_d withdrawals for domestic water use (Mm^3/year)

W_i withdrawals for industrial water use (Mm^3/year)

W_l withdrawals to meet livestock water demands (Mm^3/year)

ET_{irr} evapotranspiration resulting from irrigation activities (Mm^3/year)

C_{n-irr} water consumption from non-irrigation uses, including domestic, industrial, and livestock sectors (Mm^3/year)

R_{irr} return flow from irrigation water use (Mm^3/year)

R_{n-irr} return flow from non-irrigation water uses (i.e., non-consumed water) (Mm^3/year)

Additionally, key performance indicators, adopted from the modified Water Accounting Plus framework of Jordan (Amdar et al., 2024), were reported to provide an overview of the country's water resources overall situation and each of the 14 surface water basins (Table 5.6). These indicators capture the effects of climate change and human activities under both the business-as-usual and management scenarios.

Table 5.6 Indicators for CWatM results presentation

Indicator	Definition	Formula
Available water fraction (AWF)	Is the percentage of available water to the precipitation	$AWF = \frac{P - ET_n - E_c - E_{w-}Q}{P}$
Naturally consumed fraction (NCF)	Represents the percentage of water consumed via evapotranspiration from all land classes except for irrigation to the precipitation	$NCF = \frac{ET_n + E_c + E_w}{P}$
Consumed water fraction (CWF)	Represents the percentage of water consumed naturally and due to human activities	$CWF = \frac{ET_n + E_c + E_w + ET_{irr} + C_{n-irr}}{P}$
Withdrawals fraction (WF)	Is the percentage of withdrawals to the available water	$WF = \frac{W_{irr} + W_d + W_i + W_l}{AW}$
Managed water (MW)	Managed water is the total amount of water that is abstracted and managed	$MW = ET_{irr} + C_{n-irr}$
Managed fraction (MF)	Is the percentage of water consumed by humans (irrigation, domestic, industry, livestock) to the available water	$MF = \frac{ET_{irr} + C_{n-irr}}{AW}$
Stationarity index (SI)	The Stationarity Index reflects changes in water storage. Positive values indicate an increase in groundwater and/or surface water storage. Negative values indicate the depletion of these resources.	$SI = \frac{\Delta S}{ET_n + E_c + E_w + ET_{irr} + C_{n-irr}}$
Basin closure index (BCI)	Basin closure refers to the percentage of total available water resources 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	$BCI = 1 - \frac{Q}{P}$

5.4 Results

5.4.1 CWatM Calibration and Validation

The optimal model calibration parameters for Jordan were as follows: irrigation efficiency of 80%, a crop demand scaling factor of 1.1, a domestic demand scaling factor of 1.175, and an industrial demand scaling factor of 1.33.

The comparison between the model's TWS and GRACE's observed TWS yield a high correlation with Pearson's and Spearman's rank correlation coefficients of 0.89 (Figure 5.4). The mean annual change in TWS (from GRACE) was estimated at -0.94 cm/year by CWatM, closely aligning with the GRACE-derived observation of -0.95 cm/year for the timeframe 2002-2016 relative to the 2004–2009 baseline. Over the entire study period (2002–2016), the total storage depletion simulated by CWatM was -14.03 cm, compared to GRACE's observed TWS of -14.31 cm.

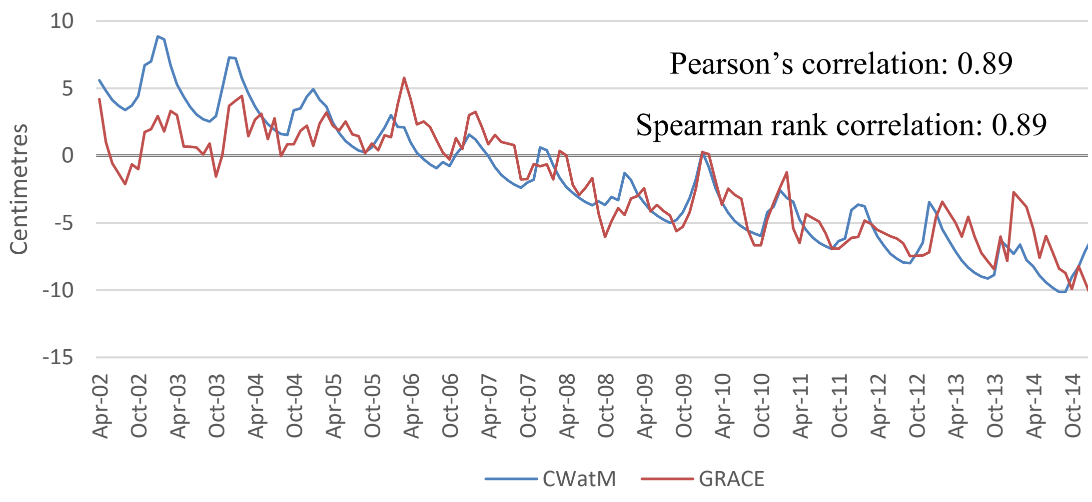


Figure 5.4 Change in terrestrial water storage relative to a 2004-2009 time-mean baseline, a) CWatM simulation (blue), GRACE observations (red)

CWatM-derived simulated withdrawals showed good agreement with records from the MWI for the period 2002–2018 (MWI, 2013, 2022). MWI data indicated annual domestic water use ranging from 249 to 480 Mm^3/year, irrigation withdrawals between 456 and 603 Mm^3/year, and industrial use from 32 to 51 Mm^3/year. CWatM simulations yielded average annual withdrawals of 426 Mm^3/year for domestic use, 450 Mm^3/year for irrigation, and 42 Mm^3/year for industrial use over the same period.

The cumulative water use over this period was 15,529 Mm^3 based on MWI records, closely aligning with the CWatM estimate of 15,606 Mm^3.

Looking into these results, CWatM effectively captures cumulative water use. However, it slightly underestimates irrigation withdrawals and overestimates domestic use. This discrepancy can be attributed to the sudden rise in domestic water demand in 2013, following the commissioning of the Disi Water Conveyance Project and the influx of Syrian refugees. The project aimed to increase the domestic water supply to Amman by an additional 120 Mm^3/year. However, given the sharp population growth in 2013, the new supply was utilized to compensate for the sudden increase in demand. Such abrupt demand shifts remain challenging in the context of long-term modelling presented in this study.

Additionally, MWI-reported irrigation water use includes treated wastewater (TWW) in the Jordan Valley, which increased from 70 Mm^3/year in the early 2000s to 149 Mm^3/year by 2018. When excluding these values, freshwater irrigation use is estimated at 392–454 Mm3/year, aligning well with CWatM-simulated irrigation withdrawals. While these variations may not affect the climate change baseline simulations, as they are reported up to 2013, the potential implications of such interventions for future climate change (2025–2050) are further discussed in the discussion section. It is important to note that Jordan's total water use accounts for an average of 52% of the total withdrawals within the simulated hydrological area which extends beyond Jordan's borders to include parts of Syria, Israel, Iraq, and Saudi Arabia.

On the other hand, ETa validation results show a good agreement between the average annual simulated using CWatM at 107 mm/year for the study period and the average derived from the remote sensing datasets, estimated at 109 mm/year (Figure 5.5). On the other hand, when comparing the long-term monthly average between CWatM simulated and observed ETa, the results indicate high correlation with GLDAS (0.93), and MODIS 500 (0.87), indicating good alignment with these datasets, However, correlation decreases to 0.64 with Terra Climate and to 0.58 with MODIS 1km. Overall, CWatM estimates align with the ensemble mean. However, they lie near the lower bound of the observed range, indicating a conservative but credible representation of ETa under current climate and land use conditions.

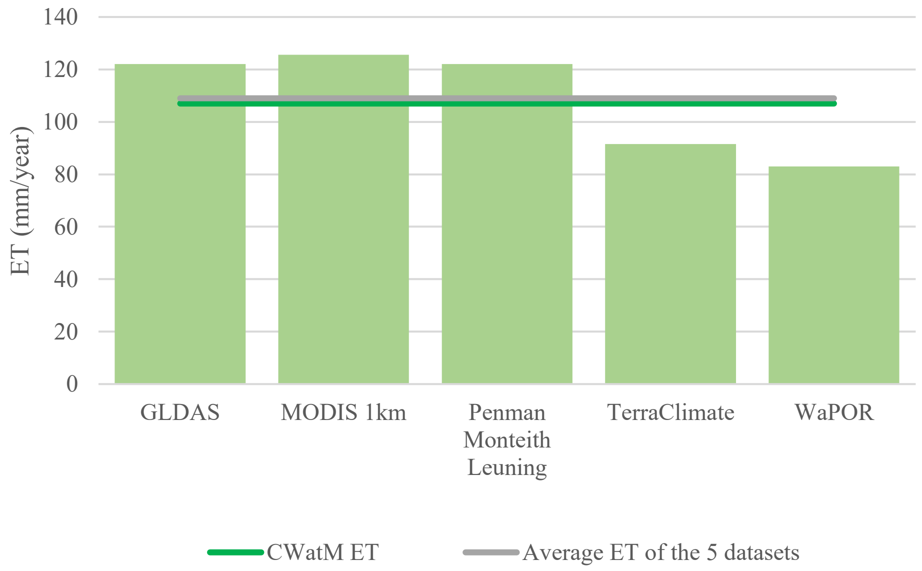


Figure 5.5 Comparison of average annual evapotranspiration between CWatM and observations from global datasets (2002-2019)

5.4.2 Business-as-usual scenario

The average water balance circles for the study area are presented in Figure 5.6 under the simulated historical climate change baseline (1980-2014), and SSP126, SSP370 and SSP585 (2025-2050). Under the baseline period, the average precipitation volume over the study area was estimated at 18,651 Mm^3/year. Natural evapotranspiration (ETn)[19] is estimated at 14,212 Mm^3/year, while evaporation from water bodies such as the Dead Sea and Lake Tiberias was estimated at 659 Mm^3/year. Human water consumption, classified into irrigation and other users (domestic, industry, livestock), was estimated at an average of 634 Mm^3/year and 320 Mm^3/year, respectively. Discharge at the outlet, which mainly feeds the Dead Sea, the lowest point of the area, and other low sinks such as Lake Tiberias and the Azraq mudflat, was estimated at 1,326 Mm^3/year. The increase in storage change was estimated at an average of 1,347 Mm^3/year.

[19] Natural evapotranspiration refers to evapotranspiration from natural landscape excluding irrigated areas, water bodies and channels.

Future projections indicate a decline in both precipitation and actual evapotranspiration by 6%-11% and 5%-9% respectively, between 2025 and 2050 and across all SSPs compared to the simulated baseline.

In contrast, evaporation from water bodies and channels is expected to increase significantly, ranging from a 244% rise under SSP585 to 264% under SSP126. Non-irrigation water consumption, driven by population growth, is projected to increase by 85% under SSP126, 125% under SSP370, and 173% under SSP585. Irrigation water consumption is also expected to rise, increasing by 7% under SSP126 and SSP370 and by 11% under SSP585, assuming no change in irrigated areas.

Future storage is projected to decline sharply, in contrast to the historical baseline. The average annual storage loss is estimated at -1,002 Mm^3/year under SSP126, -1,326 Mm^3/year under SSP370, and -1,432 Mm^3/year under SSP585 highlighting an increasingly critical water situation in the near future.

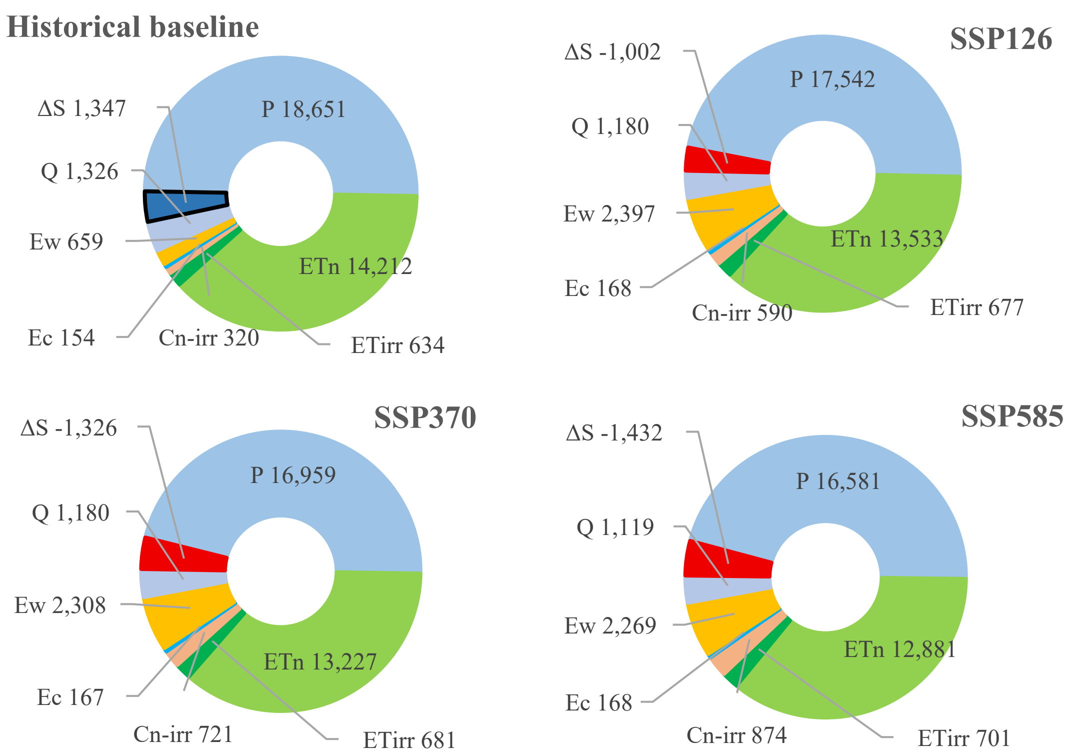
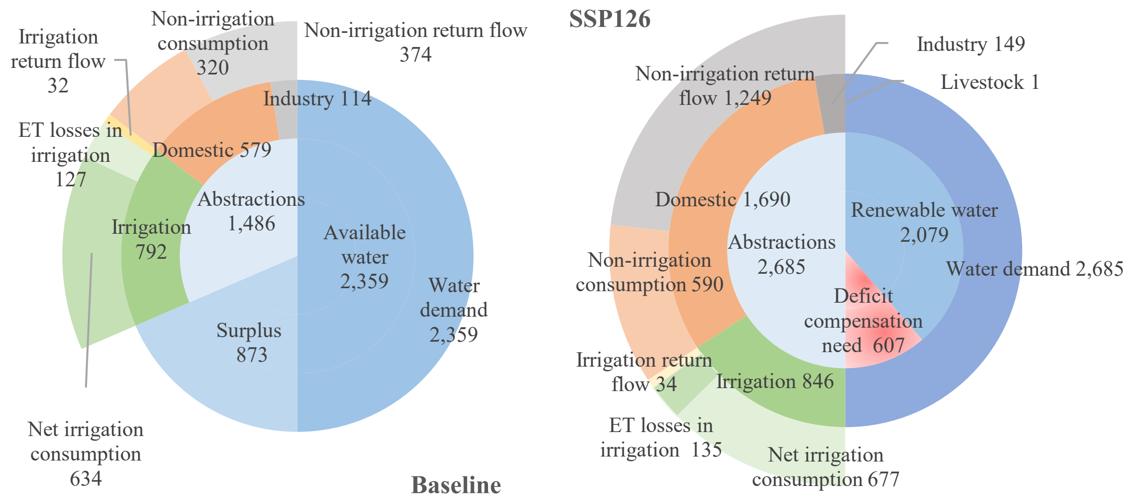


Figure 5.6 Simulated water balance under the business-as-usual scenario[20]

[20] Storage change is in red when it has a negative value

During the baseline period, the total available renewable water in the study area was estimated at an average of 2,359 Mm^3/year, equivalent to 14% of the average total precipitation. Water withdrawals on the other hand reached 1,486 Mm^3/year (Figure 5.7), equivalent to 62% of total available renewable water. Irrigation withdrawals ranked first with 53% of total withdrawals, followed by domestic withdrawals at 39%, industrial withdrawals at 8%, and livestock at less than 1%. Of total withdrawals, average consumed water was estimated at 954 Mm^3/year, equivalent to 64% of total withdrawals.

Under climate change, available renewable water is projected to decline by 12%, 23% and 18% under SSP126, SSP370 and SSP585, respectively. As water demand is projected to increase, withdrawal needs are projected to increase by 81%, 95%, and 114% annually under SSP126, SSP370 and SSP585, compared to the baseline. The most notable withdrawals increase is projected in the domestic sector due to population growth. It is important to note that we maintained irrigated areas in future scenarios similar to the baseline. Therefore, the increase in irrigation withdrawals and consumption simulated in CWatM can be attributed to the increased evapotranspiration demand under climate change. Consequently, freshwater availability is projected to decline, increasing water deficits across the study area by 607 to 1,251 Mm^3/year. This indicates that human-driven demand growth is the more dominant driver of future water stress, highlighting the need for serious actions to avoid a water crisis.



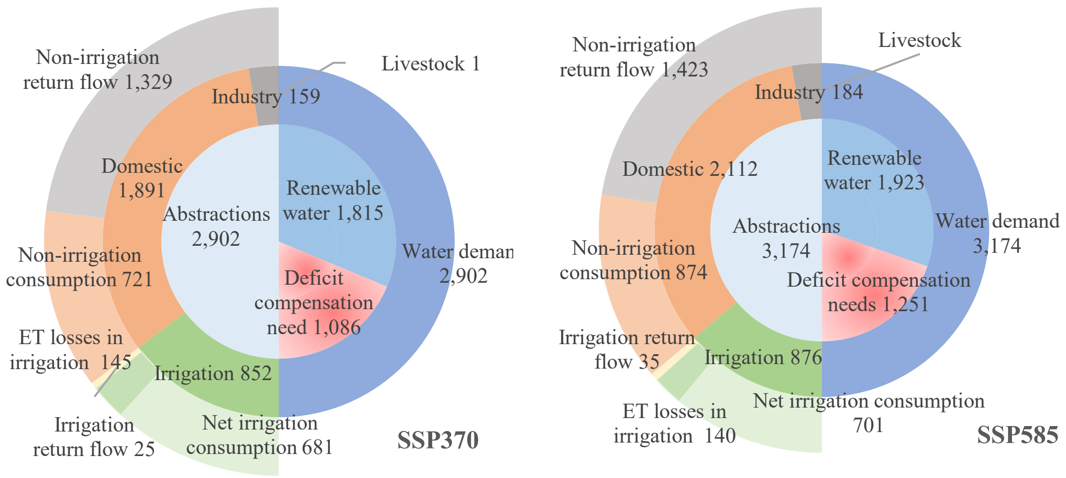


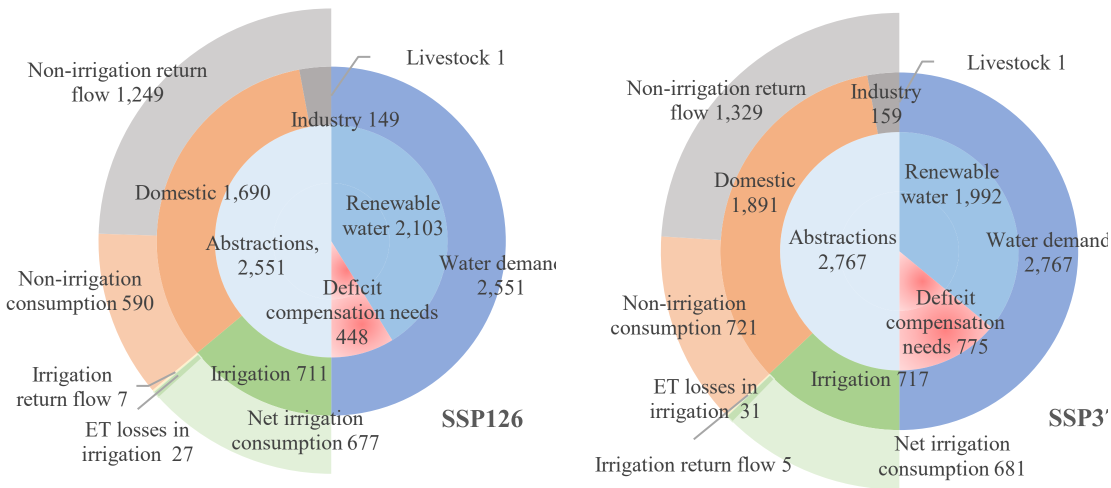
Figure 5.7 Simulated water availability and water withdrawals under the business-as-usual scenario

5.4.3 Management strategy

A 15% improvement in irrigation efficiency across the region would influence several key variables, namely irrigation withdrawals, non-beneficial evapotranspiration (losses through evaporation), and irrigation return flow. These changes would, in turn, affect total water withdrawals, and the deficit compensation needs. However, the irrigation efficiency change does not affect other CWatM outputs.

Figure 5.8 summarises the simulated system response for the management strategy. Under SSP126 15% efficiency improvements can reduce non-productive losses in irrigation by 80%, as well as return flows by 80%. Consequently, withdrawal needs for irrigation can be cut by 135 Mm^3/year, yielding an increase in renewable water availability of 24 Mm^3/year and reducing the deficit compensation need by 159 Mm^3/year. For SSP370 and SSP585, irrigation withdrawal needs can be reduced by 135 Mm^3/year and 139 Mm^3/year, respectively, yielding a reduction in deficit compensation needs by 311 Mm^3/year and 161 Mm^3/year.

Consequently, these technically plausible gains in field-level efficiency cascade non-linearly through the regional water system, delivering substantial reductions in both abstraction pressure and deficit compensation needs across the three scenarios. However, it remains important to note that CWatM assumes that water volumes saved at the plot translate one-for-one into reduced abstraction at the source. Therefore, such interventions require the right enabling environment, mainly policies and regulations that support reduced abstractions, so that on-farm water savings translate into improved water availability for reallocation.



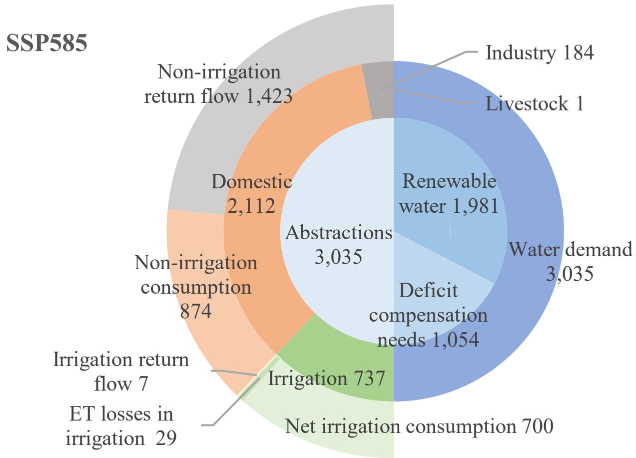


Figure 5.8 Simulated water availability and water withdrawals under the management strategy – 15% increase in irrigation efficiency

5.4.4 Performance indicators in the study area

Table 5.7 compares performance indicators for the whole study area under the baseline and projected near-future climate scenarios, both under the business-as-usual scenario and the management strategy. A clear trend across all scenarios is the decline in available water fraction, dropping as much as 23% under SSP370 with business-as-usual, though this reduction is slightly mitigated with improved IE, indicating that better water management can somewhat cushion the impact of climate change on water availability. The naturally consumed fraction increases across all scenarios from 81% at baseline to around 91–93% mainly driven by higher evaporation from water bodies, reflecting greater impact of climate change. Consumed water fraction also rises significantly, surpassing 100% in most future scenarios, suggesting increasing stress on water resources, particularly under SSP370 and SSP585. Water withdrawals increase sharply, by more than 100% in some cases compared to the baseline, though IE improvements slightly reduce this pressure. Managed water volumes and the managed fraction also increase markedly, pointing to a growing reliance on water infrastructure and management to meet increasing demands. However, these gains come with a trade-off with the stationarity index turning negative across all scenarios. This indicates less reliability and predictability of water availability in the future. However, the basin closure index remains relatively stable at around 93–94%. This can be explained by the fact that return flows from non-irrigation water use are projected to increase due to population growth. These flows typically flow back into rivers and terminal sinks, such as the Dead Sea. Overall, the results show considerable stress on Jordan's water systems under future climate and socio-economic changes. However, targeted efficiency measures can offer modest relief, especially in high-stress scenarios.

Table 5.7 Comparison of regional performance indicators between the baseline, and near-future climate change (business-as-usual and irrigation efficiency improvement)

Performance indicators	Baseline	Business-as-usual			Management strategy		
		SSP126	SSP370	SSP585	SSP126	SSP370	SSP585
Available water fraction (AWF)	2,359	2,079 (-12%)	1,815 (-23%)	1,923 (-18%)	2,103 (-11%)	1,992 (-16%)	1,981 (-16%)
Naturally consumed fraction (NCF)	81%	92%	93%	92%	91%	92%	92%
Consumed water fraction (CWF)	86%	99%	101%	102%	99%	100%	101%
Withdrawals fraction	63%	129%	160%	165%	121%	139%	153%
Managed water (MW)	954	1,267	1,403	1,575	1,266	1,403	1,574
Managed fraction	40%	61%	77%	82%	60%	70%	79%
Stationarity index (SI)	8%	-6%	-8%	-8%	-6%	-7%	-8%
Basin closure index (BCI)	93%	93%	93%	93%	93%	94%	93%

5.4.5 Basin level results

The average water balance of the 14 river basins and their changes under climate change are summarized in Appendix C. Water availability in Jordan (taking basins located entirely within Jordan's administrative borders) was estimated at 589 Mm^3/year under the simulated baseline, with the Mujib and Amman-Zarqa alone contributing approximately 92%.

Future projections indicate an intensified hydrological stress across all SSPs. Precipitation is projected to decline in all basins under all SSPs, most notably in the Jafer and Araba South basins (by up to 22% under SSP585 compared to the baseline). Given their natural hyper-arid conditions, these two basins might be particularly sensitive to incremental changes in precipitation. Other notable declines were projected in Araba North (17%), Lake Tiberias (13%), and Hammad (12%). In contrast, Disi, South Jordan River Wadis and Hasa exhibit relatively minor declines in precipitation.

Natural ET is also projected to decrease across most basins, mainly due to reduced precipitation and soil water availability. These changes are most significant under SSP370 and SSP585 exceeding 20% relative to the simulated baseline. The most affected basins include Jafer, Araba South, Hammad, and Sirhan, while moderate declines are projected for Azraq, Araba North, Yarmouk, Mujib, and Amman-Zarqa, and minor decline in the North and South Jordan River Wadis and Disi. However, evaporation from open water surfaces is projected to increase significantly, particularly in the Dead Sea (by up to 500%), and in the Yarmouk Basin by 16% to 22%. These variations in the magnitude of change in various hydrological components highlight a nonlinear response to climate forcing yet also confirm a severe impact across the 14 basins.

Renewable water availability and withdrawal needs across the 14 surface water basins are presented in Appendix C. The results show a region-wide decline in renewable water availability, with severe reductions in Araba North, Azraq, Jafer, Sirhan, Araba South, and Disi. Renewable water resources are projected to become functionally unavailable in these basins by 2050. However, it is important to note that these basins currently account for only 1% of the total renewable water available across the study area. On the other hand, basins with greater population density and economic activity, such as Mujib, the South and North Jordan River Wadis, Amman-Zarqa, and Lake Tiberias, are projected to experience renewable water reductions ranging from 4% to 24% annually by 2050. The Yarmouk Basin is expected to experience the most severe decline in renewable water availability reaching 29%-48%. In internal basins, Amman-Zarqa, Mujib, Azraq, Hasa, Jafer, and South Araba, water availability is projected to decline from 589 Mm^3/year, projected to 472-540 Mm^3/year under SSP126 and SSP585 respectively.

Withdrawal needs are projected to increase across all basins. The Amman-Zarqa, Yarmouk, and Sirhan basins will experience the highest withdrawal needs, accounting for

57% of total irrigation demand and 50% of domestic water demand across the region. The discrepancy between the required supply and demand is projected to approach 724 Mm^3/year under SSP126 to 1,235 Mm^3/year under SSP585, accounting for approximately 65% of the total water supply shortfall across the studied basins by mid-century.

While the general trend points to increasing water scarcity, the degree of hydrological vulnerability varies significantly across the basins. Some basins such as Mujib, Hasa, Lake Tiberias, and the Jordan River Wadis, are projected to maintain relatively stable renewable water contributions and may remain net-positive in terms of water balance under all scenarios. Consequently, they could play a strategic role in future water re-distribution frameworks.

Appendix C presents the average renewable water availability and withdrawals under the management strategy. The results show measurable benefits from efficiency measures particularly in Azraq and Hammad basins, where limited renewable water becomes available, contrasting with the complete depletion that would occur under the business-as-usual scenario. However, the Amman-Zarqa and the North Jordan River Wadis continue to experience declines in water availability and increases in demand, highlighting the limits of efficiency interventions in densely populated and heavily irrigated basins compared to the business-as-usual scenario. As a result, efficiency gains provide partial but insufficient mitigation of future changes impacts on water availability, emphasizing the need for additional supply from alternative resources such as desalination and treated wastewater.

Performance indicators for the 14 surface basins (presented comprehensively in Appendix C and under SSP 585 in Figure 5.9) were generated under baseline, business-as-usual scenario, and the management strategy. Under baseline conditions, naturally consumed water fractions exceeded 90% in Azraq, Disi, Sirhan, Jafer, Araba South, and Hasa, signalling high losses through natural evapotranspiration. Lower consumption fractions (59–68%) in Lake Tiberias and the Jordan River Wadis corresponded to higher available water fractions. The withdrawal fractions exceeded 100% in Amman-Zarqa, Yarmouk, Azraq, Disi, and Jafer indicating a growing reliance on non-renewable sources. In contrast, Mujib, Lake Tiberias, and the Jordan River Wadis showed lower withdrawal fractions (13–35%), indicating less stress on storage systems. Withdrawal fractions increase notably: by 17–54% in Mujib, Lake Tiberias, Hasa, and the Jordan River Wadis, and by 140–260% in Amman-Zarqa and Yarmouk, where consumed fractions exceed 100%, signalling critical water stress.

The management scenario, incorporating a 15% irrigation efficiency gain, improves available water fractions in irrigation-intensive basins such as Mujib, Amman-Zarqa, Yarmouk, and the Jordan River Wadis. It also leads to reduced withdrawal and managed water fractions. A slight decline in naturally consumed fractions is projected, though the overall effect remains limited due to the dominance of natural over irrigation evapotranspiration.

Notably, no withdrawal or consumption fractions could be computed for Araba North, Azraq, Hammad, Disi, Jafer, Sirhan, and Araba South under specific scenarios due to zero projected water availability. These basins are expected to depend entirely on inter-basin transfers or alternative sources to meet future demand.

A summary of the overall conditions and key observations from the basin level analysis is provided in Figure 5.9. Overall, Amman-Zarqa and Yarmouk basins emerge as the most critically stressed basins, with severe over-extraction and drastic reductions in water availability, even with improved irrigation efficiency. In contrast, basins such as Mujib, Hammad, and North and South Jordan River Wadis show moderate climate impacts and respond positively to the management strategy.

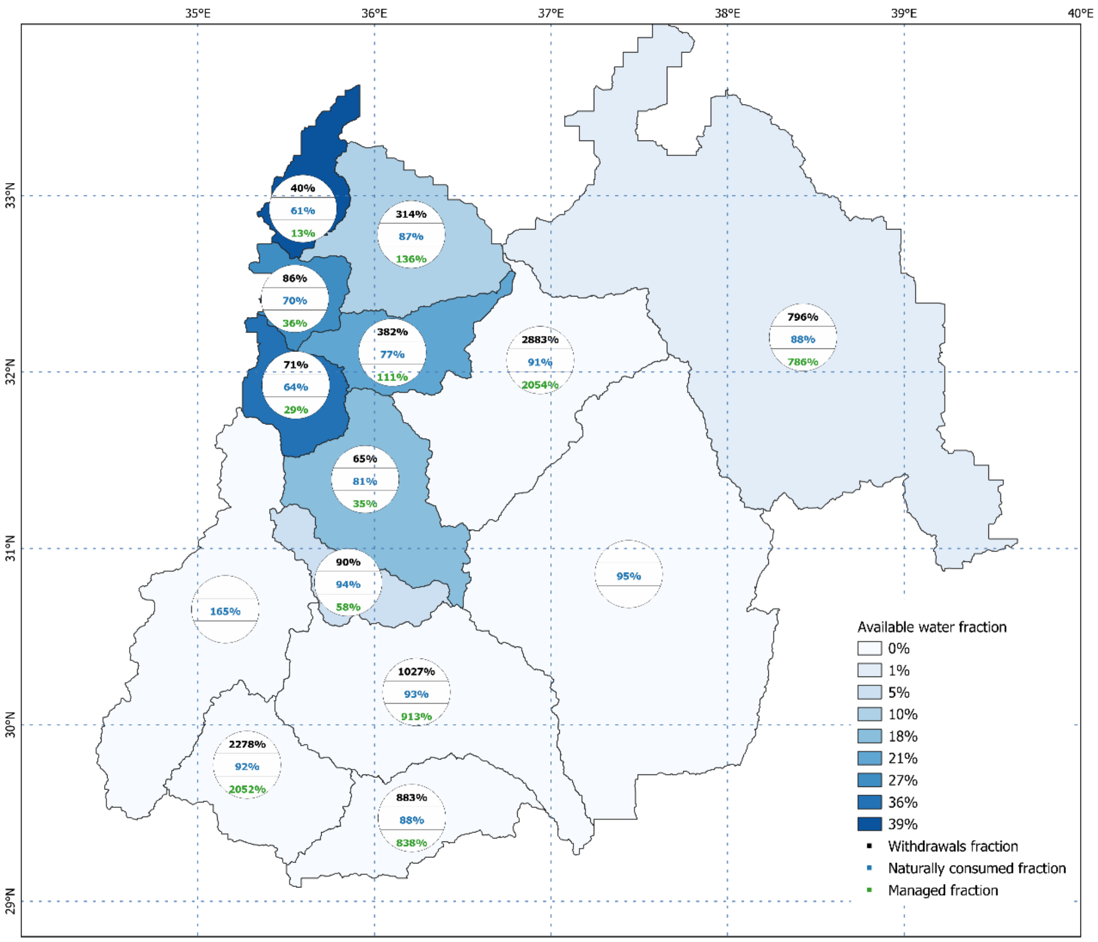


Figure 5.9 Performance indicators at the basin level under the most extreme climate scenario and socio-economic pathway SSP585

5.5 Discussion

The findings of this study emphasize the urgent need for a strategic approach to water management practices in Jordan, especially in light of projected climate change impacts and escalating human demand. Water availability across the study area is projected to decline by 12-23% by 2050. Withdrawal needs are expected to rise dramatically by 80 - 113% due to increasing human demand. This corresponds to an estimated water deficit range of 607-1,251 Mm^3/year, and aligns with previous research findings emphasizing the severity of supply-demand gap in Jordan (Akasha et al., 2023). Our projected decline in precipitation (6-11%) between 2025-2050, also aligns with earlier studies projecting a 7-14% decline in precipitation in Jordan between 2050 and 2065 (Abdulla, 2020; Yoon et al., 2021).

At the basin level, internal basins such as Amman-Zarqa, Mujib, Azraq, Hasa, Jafer, and South Araba contributed approximately 589 Mm^3/year during the baseline period (1980–2014). This figure is comparable to the MWI's reports of 605 Mm^3/year between 2005 and 2014 (MWI, 2015). Among all basins, Amman-Zarqa and Mujib contributed 544 Mm^3/year to water availability. This indicates their strategic importance in the national water supply.

However, the projected rise in national water demand, and ultimately withdrawal needs, ranging from 1,252 Mm^3/year under SSP126 to 1,506 Mm^3/year under SSP585, will create a critical supply-demand gap. Factoring in the current transboundary water inflows of 120 Mm^3/year and treated wastewater reuse of 140 Mm^3/year (MWI, 2024), the supply-demand gap can be reduced to 452-486 Mm^3/year. Consequently, there remains a need for interventions to improve water availability.

A 15% improvement in irrigation efficiency across the country could yield a reduction in irrigation withdrawal needs by 62-66 Mm^3/year, potentially decreasing the overall deficit to 390-420 Mm^3/year. However, these savings must be viewed with caution. Real world effectiveness may be compromised by factors such as irrigation expansion, whereby savings are used to increase cultivation; increased groundwater depletion and salinity; higher energy and emissions costs of pressurised systems; and inequitable access to technology, favouring wealthier farmers. These complexities reinforce the need for integrated solutions that align technical interventions with policy mechanisms ensuring demand management, environmental flow protection, equity safeguards, and energy efficiency.

In 2025, the Ministry of Water and Irrigation launched a desalination project to deliver 300 Mm3/year of desalinated seawater to Amman for domestic use (MWI, 2023). Taking into account this project contribution to meeting future demand, a shortfall of 90–120

Mm^3/year is projected to remain by 2050. Therefore, expanding the use of treated wastewater for irrigation, particularly in high-demand basins such as Amman-Zarqa, Mujib, Azraq, and the Jordan Valley, could help further close the gap (Tawfik et al., 2023; Al-Addous et al., 2023).

Lastly, the projected decline in water availability in the Yarmouk River (from 301 Mm^3/year under baseline conditions to 214–205 Mm^3/year under the business-as-usual scenario) poses a serious threat to Jordan's transboundary water security. Jordan relies on the Yarmouk River inflow from the upstream Syrian part of the basin for irrigation in the Northern Jordan Valley and domestic use in Amman. A 30% reduction in the basin's water availability risks reducing inflows to Jordan, emphasising the need for broader regional collaboration within the Yarmouk Basin.

Focusing on the modelling approach, the agreement between CWatM outputs and observational datasets demonstrates the model's capacity to capture key hydrological processes within Jordan's complex and rapidly evolving water landscape. Specifically, the strong TWS correlation (Pearson's r = 0.89) and the match in cumulative storage depletion (-14.03 cm simulated vs. -14.31 cm observed) indicate the model correctly reproduces the dominant trend of groundwater-driven storage depletion, lending directional credibility to the projected storage decline under future scenarios. The close alignment in cumulative withdrawals and the reasonable agreement between simulated ETa and the remote sensing ensemble mean further support the model's overall water balance consistency. However, CWatM's ETa estimates lie closer to the lower bound of the observed RS range, which may reflect the model's simplified treatment of soil evaporation under arid and semi-arid conditions, or limitations in the coarse 0.5° climate forcing. This conservative bias suggests that actual water availability may be slightly lower than simulated, implying that projected future water deficits could be more severe than reported here. Additionally, CWatM does not explicitly represent TWW reuse as an irrigation source, a structurally growing component of Jordan's water system that reached approximately 150 Mm^3/year by 2018, which is particularly relevant for future projections where TWW reuse is a central policy lever. Furthermore, while CWatM's single groundwater routine reproduces the aggregate GRACE TWS signal well, it cannot distinguish between depletion from renewable and non-renewable fossil aquifers (e.g., Disi), meaning the calibration may capture the right composite trend while masking differences in aquifer-specific stress. Moreover, the abrupt socio-political and infrastructural changes that occurred in 2013, primarily due to the mass influx of Syrian refugees, introduced structural breaks that static calibration methods may not fully capture. This indicates the need to develop dynamic calibration techniques or scenario-based demand projections to improve the relevance and accuracy of CWatM and other similar models. Together, these limitations suggest that CWatM's outputs are best interpreted as directional indicators of future water stress rather than precise forecasts, and that the basin-level results carry greater uncertainty than country-wide aggregates. Notwithstanding these constraints, the model’s performance across multiple independent validation datasets provides sufficient confidence for its use in comparative scenario analysis to support strategic water resources planning in Jordan.

As a result, Jordan's future water resources require a comprehensive and integrated planning approach including supply augmentation for domestic water use, demand management through efficiency measures and increased treated wastewater utilization in irrigated agriculture. This study also confirms that domestic demand will drive future imbalance unless sufficient supplies are made available through desalination.

5.6 CONCLUSIONS AND RECOMMENDATIONS

This study employed the CWatM model and open-access datasets to assess the combined impact of climate change and socio-economic developments on Jordan’s water resources by 2050. The results indicate that while climate change is expected to reduce renewable water availability by as much as 23% under the SSP370 business-as-usual scenario, the more pressing driver of future water stress is the steady rise in water demand, particularly from the domestic and agricultural sectors. Withdrawals are projected to increase to 165% of renewable availability under SSP585, compared to just 63% in the baseline. Consequently, water deficits are expected to grow substantially across all future scenarios, underscoring the need for coordinated and proactive water management.

A 15% increase in irrigation efficiency was found to yield meaningful, though limited, benefits. For example, under SSP370, improving irrigation efficiency reduces the withdrawal fraction from 160% to 139%, and slightly improves available water by 6% compared to the business-as-usual scenario. These gains must be part of a broader strategy that includes seawater desalination, expanded treated wastewater reuse, and demand-side interventions. Importantly, efficiency improvements must be accompanied by clear policies that prevent rebound effects through uncontrolled irrigation expansion and ensure actual reductions in water withdrawals.

The findings also highlight the vulnerability of Jordan’s water system to transboundary uncertainties, especially in basins such as the Yarmouk, where cooperation with upstream neighbours will be essential. However, given the large increase in population, it is anticipated that wastewater generation will increase (given supply augmentation from desalination). Therefore, there is significant potential to expand the use of treated wastewater in irrigated agriculture by partially substituting groundwater abstraction, where crop suitability and regulatory frameworks permit such a transition.

It should be noted, however, that these projections carry inherent uncertainties related to CWatM’s simplified groundwater representation, the absence of explicit TWW reuse as an irrigation source, and the challenge of capturing the abrupt demand shifts through static calibration - factors that suggest results are best interpreted as directional planning guidance rather than precise forecasts.

Future studies should build on these results by modelling additional management interventions in combination and aligning them with national water plans. Such integrated interventions can be simulated using the CWatM model, as it captures the combined impact of policy, technology, and climate on national water security, which presents an opportunity to explore more adaptive and resilient strategies in the face of increasing scarcity.

6
CONCLUSION

In this final chapter the research objectives and findings are revisited and synthesized into key research contributions, reflections on the methods and limitations, and recommendations for future research.

6.1 Information limitations and needs for improved understanding of coupled human-water systems in the MENA region

This section focuses on the first research objective, which aims to identify and analyse information needs and limitations in water resources assessments in the MENA region, with a particular focus on Jordan. The goal is to understand how coupled human-water systems are evaluated, identify critical information gaps, and assess the potential for WA+ to address existing gaps.

6.1.1 Information gaps and needs in the MENA

A systematic literature review on water resources assessments in MENA region, combined with semi-structured interviews with stakeholders in Jordan formed the methodological basis for addressing the first two research questions, specifically research question 1.1 which focuses on challenges currently facing water resources management in the MENA region, and research question 1.2 which examines the availability of water-related data across the region, identifying existing sources and highlighting gaps that might hinder effective planning.

The MENA region primarily relies on sparse in situ monitoring networks, low-resolution global reanalysis products and aggregated national statistics for water resources assessments. These data fail to capture the spatial heterogeneity and temporal variability of the region's hydrological systems (Dembélé, 2020; Lacombe et al., 2008). Particularly, the inability to represent ephemeral watercourses and the rapidly evolving demographic pressures undermine the efforts to develop a robust process-based understanding of water availability and use in the region. As a result, most assessments yield generalised conclusions that support reactive, supply-oriented interventions, often at the expense of integrated, demand-inclusive strategies (Abdelhalim et al., 2020; Chenoweth et al., 2011; Keith et al., 2017; Kucukmehmetoglu and Geymen, 2014; Ohara et al., 2011). These limitations are further reflected in the predominance of descriptive and statistical studies over the past five decades, and the limited advancement of predictive, process-based hydrological assessments for water resources planning in the region. However, some research efforts (e.g., Droogers et al., 2012) have referred to the potential of integrated modelling approaches that combine satellite remote sensing, in situ observations, and regional climate-hydrology simulations. These approaches are particularly relevant in water-scarce, data-limited countries like Jordan. Therefore, this research recommends targeted improvements in data infrastructure. This includes expanding ground monitoring networks, integrating satellite-based data (e.g., soil moisture, evapotranspiration, GRACE-derived groundwater anomalies), and utilising physically based hydrological models to fill data gaps on key processes such as runoff and recharge.

Additionally, fostering transboundary data-sharing initiatives would enhance the understanding of shared river basins and aquifer systems and regional water dynamics.

In Jordan, the national water budget remains the main water resources assessment output, but suffers from substantial limitations including inaccuracies in water data and overly simplified approaches to estimating water availability and use (Al-Bakri, 2016; Al-Bakri et al., 2023; Al-Kharabsheh, 2020; Al-Shibli et al., 2017). Additionally, instances of double-counting, such as treated wastewater, indicate the need for standardised water accounting guidelines. A mismatch in scales at which water availability (basin scale) and water uses (administrative scale) are assessed and reported further hinders the understanding of coupled human-water systems, necessitating improved assessments at the basin scale to better inform water resources planning.

6.1.2 Limitations and opportunities of WA+ in the MENA region

This section revisits research question 1.3 by assessing how well WA+ meets the information needs in the region and identifying its key limitations. It also addresses research question 1.4 which focuses on the required context-specific modifications of WA+.

A systematic review of global WA+ case studies was conducted to identify commonly used data sources and the challenges WA+ helped to address. This information was contrasted with those found in the MENA region water resources assessments case studies.

The WA+ case studies offered practical insights into real-world applications and facilitated a better understanding of how WA+ was applied and what outcomes it supports.

The results show that WA+ can be useful to identify water scarcity drivers and spot inefficient use. By structuring water information into accessible and actionable information, WA+ facilitated quantitative assessments of water availability and productivity and successfully guided informed decisions at both local and basin-wide levels.

When compared to conventional water resources assessments found in the MENA, WA+ shows potential in covering data gaps through remote sensing, and in improving the transparency and accuracy of these assessments, and better alignment of land and water resources planning.

In the case of Jordan, WA+ offers a more comprehensive and accurate approach to water budget development and reporting through its resource base sheet. This sheet represents a basin water balance and reports useful indicators to decision makers. However, it requires integrating the non-irrigation water consumption and associated return flows into the water balance to better serve water budgeting in Jordan. One limitation of the WA+ framework is its inability to simulate future and intervention scenarios given its reliance on remote sensing observations. Therefore, WA+ should not be viewed as an alternative to hydrological models, but rather as a systematic framework that supports the transparency and accessibility of water information.

6.2 Modifying water assessment tools to improve understanding of coupled human–water systems in Jordan

This section focuses on the second research objective, which aims to advance water resource assessments in Jordan by improving the representation of human activities to enable better understanding of coupled human-water systems and facilitate forward-looking planning in the country.

6.2.1 Water Accounting Plus

This section addresses research question 2.1, which aims to better integrate human activities into WA+ to improve the estimates of water availability in Jordan. The WaPOR-based WA+ framework (FAO and IHE Delft, 2020) was modified to align with the identified water information needs in Jordan and applied as a case study to the Amman-Zarqa basin. WaPOR based WA+ relies on remote sensing data and reports water consumption from irrigation in its resource base sheet. However, it does not account for non-irrigation water consumption, which constitutes a significant portion of total water use in Jordan (MWI, 2019, 2022). Therefore, the non-irrigation man-made water consumption and return flows, typically reported at the governorate scale, were resampled to the basin scale and integrated into WA+. This modification allowed for reporting a comprehensive water budget in the Amman-Zarqa (AZ) basin for the years 2018 to 2021.

The results indicate that the water naturally available in the AZ basin is strongly influenced by interannual precipitation variability. For example, a 28% drop in rainfall in 2021 resulted in a 50% decline in water availability compared to wetter years. On average, the basin had approximately 425 Mm^3/year of available water, including naturally occurring water from precipitation and interbasin transfers, compared to 252 Mm^3/year of available water reported by MWI based on the basin's safe yield and interbasin transfers. This discrepancy is likely due to horizontal groundwater outflows feeding neighbouring basins such as Yarmouk and Azraq (MWI and BGR, 2017; Abdulla et al., 2020). The average water demand, on the other hand, was estimated at 375 Mm^3/year. Agriculture is the primary consumer of this water, accounting for 33-45% of total manmade consumption sourced from groundwater. Given that domestic water use is mainly sourced from inter-basin transfers (i.e., imports), the findings indicate an increasing reliance on unsustainable groundwater extraction for irrigation. Consequently, there is an urgent need to strengthen both water supply augmentation and efficient water use strategies in the basin. Nonetheless, it is important to integrate climate change data and scenario development techniques to project the potential impact of these interventions in the future and enable more accurate forward-looking planning in the country.

6.2.2 The Community Water Model (CWatM)

This section addresses research question 2.2, which aims to quantify current and projected future water availability in Jordan using CWatM.

CWatM is an open-source global hydrological and water systems model. It relies on open-access datasets and has a modular structure, allowing for enough flexibility to modify and update to regional contexts. CWatM was modified by incorporating local data on irrigated areas and scaling non-irrigation water demand as per national statistics reported in Jordan. The model was set up for Jordan's hydrological area, calibrated and validated using remote sensing datasets on total water storage, evapotranspiration, and ground observations on withdrawals across the country. The calibrated version of the model was then used to simulate water availability and use under climate change and socio-economic pathways, focusing on the timeframe 2025-2050. Performance metrics developed within the WA+ framework were also derived from outputs of CWatM simulations.

The results make a critical contribution to the national water policy discourse. Based on the selected climate models, CWatM simulations indicate a reduction in renewable water availability of up to 23% by 2050. However, this figure reflects the range of the selected models only – other models within the ISIMIP ensemble, or from broader multi-model assessments, may project larger reductions in water availability, suggesting that the projected 23% reduction should be interpreted as a conservative estimate of the plausible range rather than an upper bound. On the other hand, growing human demand, particularly for domestic use, is the dominant driver of future water stress, with deficits between supply and demand approaching 1,250 Mm^3/year, indicating inadequacy of current water management strategies.

At the basin scale, the analysis revealed significant spatial heterogeneity. Basins like Amman-Zarqa and Yarmouk are already approaching or exceeding critical thresholds, whereas others, like Mujib and Lake Tiberias, show relative resilience. In the transboundary Yarmouk basin, climate change is projected to reduce river flow by 30% by mid-century, emphasising the importance of better regional cooperation in this river system. As a result, future planning in Jordan should be more geographically tailored to address these variable changes across the country.

Additionally, the research recommends exploring more dynamic demand projection models and calibration frameworks to better capture abrupt demand increases (such as in 2013 with the Syrian refugee influx to Jordan). Finally, engaging local stakeholders in developing assessment tools and results validation can improve the credibility and policy relevance of the model outputs.

6.3 EXPLORING SCENARIO-BASED SOLUTIONS FOR WATER SUSTAINABILITY IN JORDAN

This section addresses the third research objective which aims to understand the impact of efficiency measures in irrigated agriculture on future water availability in Jordan.

6.3.1 Impact of irrigation efficiency interventions

This section evaluates the potential hydrological impact of improving on-farm irrigation efficiency under climate change, addressing research question 3.1. The intervention was simulated in CWatM, building on the evidence generated from an empirical field study conducted in the Mafraq highlands, to identify the achievable efficiency improvements in this region.

Adopting a bottom-up approach, the empirical field study evaluated the efficiency improvement in a sample of representative farms in the Mafraq highlands using observed irrigation application data collected for key orchards over three years. The study concluded application efficiency averaged 55% across monitored crops with an average water application of 1,277 mm/year (equivalent to 38% reduction in irrigation application). Introducing WCTs and farmer-led adjustments of irrigation scheduling decreased water application to an average sustainable depth of 795 mm/year. Extrapolating this reduction basin-wide, water savings could approach 44 Mm^3/year. This constitutes nearly 50% of the AZ basin's aquifer safe yield. The study also highlighted that achieving these savings would require interventions that focus on farm-led experimentation of WCTs, access to trusted irrigation advisory services, and appropriate farmer incentives that ensure water saved on the farm translates into actual reduction in groundwater abstractions. Robust monitoring of irrigation expansion is essential to prevent unintended outcomes of efficiency interventions.

Based on the above, a conservative 15% improvement of application efficiency was assumed and simulated for all Jordan using CWatM. The results indicate that such an intervention can achieve significant hydrological gains, including reduced non-productive losses in irrigation and withdrawals. However, the findings also showed that due to increased domestic demand, the “saved water" in irrigation shall be reallocated to the domestic sector, as simulated within CWatM. Consequently, efficiency measures will not contribute to groundwater recovery unless an alternative water resource is allocated to support irrigation and domestic demands.

Additionally, the results showed non-linear responses to efficiency gains in the fourteen basins of Jordan. For example, in highly stressed basins (e.g., Amman-Zarqa) persistent deficits between demand and supply remain, emphasizing the need for supply augmentation.

Consequently, efficiency measures must be coupled with supply-side interventions. These include restricting reabstraction or use of saved water, increasing the use of desalinated and treated wastewater, reducing freshwater withdrawals through substitution strategies and limiting uncontrolled irrigation expansion. Otherwise, efficiency interventions might be offset by systemic demand pressures, resulting in a limited contribution to long-term groundwater recovery and basin sustainability.

6.3.2 Impact of combined supply-demand planning

This section addresses the final research question on the implications of coupled supply-demand interventions on Jordan's water resources by 2050. Climate based projections indicate that renewable water availability will decrease by 12–23%, while withdrawal needs will increase by 80–113% due to demographic and economic growth in Jordan. This will result in a water deficit of 607-1,251 Mm3/year across the three SSPs.

While the CWatM model did not simulate supply augmentation intervention directly, it enabled the quantification of residual deficits following the implementation of a 15% improvement in irrigation efficiency, which could reduce the national demand by 62–66 Mm^3/year, and therefore reduce the overall deficit to approximately 390–420 Mm^3/year. The year 2025 witnessed the commissioning of Jordan's desalination project, which will provide 300 Mm^3/year of desalinated seawater to the capital Amman by 2030. This amount will alleviate a substantial portion of the domestic water deficit; however, a shortfall of 90-120 Mm^3/year will remain, which requires either increasing seawater desalination or expanding treated wastewater reuse in irrigation agriculture so that internal freshwater is reallocated from irrigation to domestic use.

Ensuring the success of these combined interventions requires strong policy frameworks that involve capping groundwater abstractions for irrigation, setting and protecting environmental flows and aquifers' safe yields under future changes, improving efficiency in domestic water supply networks, and promoting equitable water access among user groups. Finally, strengthening transboundary water coordination is crucial for Jordan, particularly in the Yarmouk Basin, where water availability is projected to decline significantly due to climate change and rising demand, especially in the post-war recovery phase.

6.4 REFLECTION ON THE RESEARCH: COMPARATIVE AND INTEGRATIVE REFLECTION ON WA+ AND CWATM FOR COUPLED HUMAN-WATER SYSTEMS ASSESSMENTS

This section compares WA+ and CWatM for their strengths and limitations in coupled human-water systems assessments. Although the two tools rely on different methods, they both provide useful information for water managers: WA+ excels in retrospective diagnostics and water accounting, and CWatM enables a forward-looking scenario analysis and dynamic system assessment.

WA+ is clearly valuable for limited data basin contexts where transparency and standardised reporting of water information are important. By integrating satellite remote sensing datasets (e.g., WaPOR) with national statistics and in situ observations, WA+ produces basin-level water accounts and performance indicators to support annual water budgeting in Jordan. The core strength of the modified framework is its capturing of actual water use across sectors and identifying key stressors such as groundwater overexploitation and dependence on interbasin transfers. However, the main limitation of WA+ is its static nature, which does not allow scenario analysis.

In contrast, CWatM is a process-based, dynamic hydrological model tailored for scenario simulations. CWatM was used with climate projections to assess water availability under multiple futures. CWatM captures complex system interactions; however, it is also constrained by high data requirements and assumptions of institutional and policy continuity, assumptions that may not hold in politically volatile and institutionally fragmented settings.

Consequently, it is clear that each tool serves a distinct planning function: WA+ supports near-term, basin-scale diagnostics suited mostly for operational decision-making, whereas CWatM provides strategic foresight over multi-decadal timescales at the national level.

This thesis, however, argues that the real value of the two tools lies in their complementary application, which offers a more integrated understanding of water system dynamics across spatial and temporal scales. For example, both tools produce consistent basin-level water budgets and performance metrics. In the AZ basin, WA+ estimates the naturally consumed fractions at 53% - 80% between 2018 and 2021. CWatM reports an average of 76% for the timeframe 1980–2014. In comparison, both estimate the managed fraction at approximately 50–55%, which indicates the reliance on external water resources (interbasin transfers), and reinforces the conclusion that the basin is operating beyond its natural limits. However, relying solely on WA+ risks missing how water systems may change under future climatic and socio-economic changes. Conversely, using CWatM in isolation may detach the planners from the current institutional and empirical realities, given its reliance on climate change scenario data. Their combined use bridges this divide, anchoring long-term scenario planning in present-day conditions and linking urgent operational concerns with future-oriented strategies.

Finally, an important methodological difference lies in how the two tools consider water fluxes: WA+ distinguishes between green and blue ETa, while CWatM focuses on blue ETa. However, the split method used in WA+ assumes that irrigation occurs only when green water is insufficient to meet crop needs. This assumption could lead to inaccurate estimates of added irrigation as farmers' behaviour might deviate from this pattern (e.g., in Jordan, farmers might irrigate despite rainfall). On the other hand, CWatM estimates irrigation withdrawals based on crop modelling. Yet, the reliability of these estimates rely on the accuracy of crop data used within the model (i.e., crop types, factors etc). Therefore, understanding the assumptions and limitations of each tool is important for real-world interpretation of the results.

6.5 CONTRIBUTIONS OF THIS RESEARCH

This research has developed a tailored application of the WA+ for Jordan, enhancing its utility for water budget development and reporting. By integrating non-irrigation manmade consumption and return flows into WA+ resource base sheet, the framework goes beyond its main focus on irrigation to representing a comprehensive basin budget. Importantly, this adaptation positions WA+ as a flexible framework rather than a universal tool, that can be customised to better serve Jordan's needs.

Methodologically, the thesis also advances the use of global, open-source hydrological models for country-level scenario planning. It shows how CWatM can be used with local data and sectoral demand inputs to simulate the long-term implications of climate change and population growth on water availability. Additionally, the thesis discusses CWatM's limitations such as the reliance on static sociopolitical assumptions and global datasets that may not reflect context specific uncertainties and governance fragility. The research, therefore, calls for the research community to focus on developing dynamic calibration approaches that enable reflecting dynamic governance conditions, particularly in politically sensitive settings.

Additionally, the research contributes to a better understanding of irrigation efficiency implications as a planning lever. The empirical field study shows that irrigation losses can be reduced significantly with WCTs while maintaining crop yields. Through CWatM simulations, the research delves into the efficiency paradox (Grafton et al., 2018), highlighting the role of better governance mechanisms of efficiency measures to avoid exacerbating water scarcity. In this regard, the research shows that even with efficiency gains reallocated to the domestic sector, in a water-stressed context, efficiency measures should be accompanied by supply augmentation from alternative resources. Furthermore, in the settings of Jordan, there needs to be consideration of groundwater sustainability and recovery, meaning that reallocation could continue deteriorating groundwater, and there needs to be better planning for allocating alternative resources for both domestic and irrigation sectors to allow groundwater recovery. This brings another dimension to the efficiency paradox, which is groundwater recovery.

Consequently, effective planning requires technical interventions, policy reform, allocation rules, monitoring systems, and institutional capacity to manage trade-offs and ensure that interventions translate into real and equitable gains, including for groundwater sustainability. While these insights advance academic understanding of coupled human-water systems, they also offer clear recommendations that can benefit water resources modellers and planners in similar water scarce countries.

6.6 RESEARCH LIMITATIONS

Beyond the chapter-specific limitations outlined in this thesis, several challenges were identified throughout the research process. A major challenge lies between achieving scientific rigour and the operational constraints imposed by data scarcity and limited institutional capacity in Jordan. Advanced methodologies such as remote sensing, WA+ and CWatM are robust for assessing coupled human-water systems in Jordan. However, their implementation requires the right enabling environment within water institutions. Therefore, co-developing these tools with local stakeholders, and embedding them within established decision-making structures is essential for their uptake.

Additionally, while WA+ has the potential to improve water assessments in Jordan, it falls short in estimating unauthorised water abstractions in irrigation, due to its simplified approach to distinguishing between blue and green water. Similarly, CWatM cannot capture abrupt demand changes due to socio-political shocks (i.e., mass refugee influx to Jordan) and their implications for water demand and hence use.

Furthermore, the empirical study on WCTs and their impact on water availability helped inform the strategy simulation parameters in CWatM. However, the findings of the empirical study are limited by a small and potentially biased sample, as farmer participation in the study was based on voluntary involvement, which may have influenced the results in favour of better-resourced farmers. The results of efficiency gains, therefore, should be interpreted with caution, given the well documented "efficiency paradox" which emphasizes that without strong regulatory frameworks of land development and groundwater abstractions, water savings might be reused for more irrigation, diminishing their potential to alleviate water scarcity.

6.7 FUTURE STUDIES

The research has identified key challenges and opportunities for water resources management and planning in the MENA region and in Jordan. Reflecting on the study's limitations, the following recommendations for future research are proposed, emphasizing key areas that could not be fully addressed within the scope of this PhD but are essential for advancing knowledge in the field:

1. Model responsiveness to sudden demand shocks: The research shows that coupled human-water systems models, such as CWatM, cannot capture non-linear changes in human water demand. Demand simulations in these models often rely on the assumption of a gradual increase in population, which does not reflect reality especially in politically sensitive regions. Therefore, future research should focus on developing a more dynamic demand projection approach, a scaling mechanism, or improving the calibration techniques to capture unexpected surges in water use.
2. Overcoming persistent data limitations: Future studies should focus on improving data coverage in space and time in the MENA region. The region is characterized by high spatial and temporal variability in its water resources, which will likely

intensify under climate change. Therefore, improving the spatial and temporal coverage of monitoring networks is essential. Integrating remote sensing techniques and modelling tools is also important to develop more comprehensive data frameworks in the region. Combined, these improvements can support more evidence-based planning of water resources and demands in the region.

3. Given WA+'s demonstrated value in data-scarce regions, future research should focus on enhancing its applicability in groundwater-dominated systems. Currently, the models implemented within WA+ rely primarily on surface water and soil processes. In groundwater-dependent systems, such as those in Jordan, this approach may underrepresent subsurface water dynamics. Representing groundwater dynamics accurately within WA+ would, therefore, improve its reliability and applicability for water resources assessment in such contexts.
4. Refining the blue-green ETa partitioning methodology: WA+ relies on a simplified partitioning method of ETa into its blue and green components. When rainfall is sufficient and soil moisture is saturated, ETa is classified as green, and any crop water deficit is supplemented by irrigation resulting in blue ETa. However, this assumption does not always reflect real irrigation practices. For example, in the AZ basin, farmers often apply irrigation during the wet season, even when soil moisture is theoretically sufficient. As a result, blue water contribution to ETa occurs under conditions the model classify as green-water dominant. Therefore, future research should improve this partitioning approach by increasing the modelling timestep from monthly to daily and integrating irrigation practices as model parameters.
5. Engaging local communities, farmers, industry representatives, and policymakers is essential for developing tools that are contextually relevant and culturally appropriate. In this research, valuable insights were gained through interactions with stakeholders, including interviews with officials from the Ministry of Water and Irrigation and extensive fieldwork with farmers, which informed the analyses and findings presented in this thesis specifically chapter 2 and 4. Building on this foundation, future research, particularly efforts aimed at contextualizing assessment tools, should emphasize collaborative development with local stakeholders to enhance usability, acceptance, and sustainability, ensuring the tools can support implementable solutions.

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APPENDIX A

A.1. Systematic table on information required to evaluate the implementation of three stages in the IWRM process.

IWRM stage	Required information	Purpose
1. Issue assessment	Problem type	Identify major quantitative water problems facing the MENA region
	Water system (river basin, Wadi system, Groundwater system)	Identify any specific data requirements based on the system
1.1. Input data	Quantification method	To understand the type of tools used for water quantification
	Input data (water fluxes and stocks used as input)	Identify the mostly used data types
	Data source, spatial and temporal resolution of input data	Identify the typical spatial and temporal resolution of input data
	Quantification approach (land or flow based)	Identify trends in quantification approach and the relation to informed water interventions/strategies
1.2. Output information	Output information (fluxes and stocks generated based on input data and using the specified quantification tool)	Identify trends in water information used in decision making
	Spatial and temporal resolution of output fluxes and stocks	Identify the trends in spatial and temporal resolution of information used in decision making
2. Strategies evaluation	Strategies recommended to solve the problem	Identify trends in strategies implemented or needed
	Key paper recommendations	Building the paper recommendations considering previous research work
	Key paper limitations	Building the paper recommendations considering limitations faced in previous research work
3. Monitoring and evaluation	Key indicators to monitor the problem status	Identify the trends in water management indicators

A.2. Search strings used to extract relevant literature.

Topic	Search string
Water resource assessments in MENA	(("river basin" OR "catchment" OR "sub-basin" OR "watershed") AND ("water resources" OR "groundwater" OR "surface water") AND ("water scarcity" OR "water shortage" OR " water availability" OR "water management challenges" OR "anthropogenic" OR "biophysical" OR "supply and demand" OR "imbalances" OR "data scarcity" OR "climate change" OR "over exploitation" OR "drawdown" OR " man-made" OR "problems" OR "obstacles" OR "complexity" OR "uncertainty" OR "climate" OR "floods" OR "droughts" OR "extremes" OR " overuse") AND ("Middle East" OR "North Africa" OR "Jordan" OR "Algeria" OR "Bahrain" OR "Djibouti" OR "Egypt" OR "Iran" OR "Iraq" OR "Israel" OR "Kuwait" OR "Lebanon" OR "Libya" OR "Malta" AND "Morocco" OR "Oman" OR "Qatar" OR "Saudi Arabia" OR "Syria" OR "Tunisia" OR "United Arab Emirates" OR "Palestine" OR "Yemen" OR "Ethiopia" OR "Sudan") AND NOT ("water quality" OR " water pollution" OR "water contamination"))
Water Accounting Plus	"Water Accounting Plus"

A.3. Description of the MENA case studies.

System/Scale	Study area	Topic	References
River basins	Nile River basin	Increased water scarcity, climate change, climate variability, transboundary water allocation	Abdelhalim et al., 2020; Roth et al., 2018; Degefu et al., 2017; Wagena et al., 2016; Mengistu et al., 2021, Omer et al., 2023; Ahmed et al., 2024
	Euphrates and Tigris	Increased water scarcity, climate change, transboundary water allocation	Chenoweth et al., 2011; Imteaz et al., 2017; Kucukmehmetoglu and Geymen, 2014; Kucukmehmetoglu et al., 2010; Mianabadi et al., 2015; Ohara et al., 2014.
	Jordan River basin	Increased water scarcity, climate change, transboundary water allocation	Comair et al., 2012; Chenoweth et al., 2011; Kunstmann et al., 2006.
	Yarmouk River Basin	Increased water scarcity, climate change, transboundary water allocation	Avisse et al., 2020; Müller et al., 2016; Rajsekhar and Gorelick, 2017; Shentsis et al., 2019; Al-Kharabsheh, 2022
	Central Plateau basin, Persian Gulf and the Sea of Oman basin, Caspian Sea basin, the East Border basin,	Climate change	Ahmadi et al., 2023

	Lake Urmia basin, and Kara Kum basin (Iran)		
	Medjerda river basin (Tunisia, Algeria)	Climate change, transboundary water allocation	Rajosoa et al., 2021.
Sub-basin	North Africa	Climate change	Tramblay et al., 2018.
	Merguillel- Tunisia	Climate change	Lacombe et al., 2008.
	High Ziz (Morocco)	Climate variability	Diani et al., 2024
Wadi systems	Egypt (Nile wadi, Wadi El-Deeb)	Increased water scarcity	Saber et al., 2015; Youssef et al., 2020.
	Palestine (Wadi Natuf, Wadi Al-Qilt)	Increased water scarcity	Messerschmid et al., 2020; Thaher et al., 2017
	Jordan (Wadi Wala, Wadi Zabid)	Increased water scarcity	Jazim, 2006
	Gulf region (Ar-Rafiah, Limhah)	Increased water scarcity and climate change	Ghoneim, 2008; Nouh, 2006.
Groundwater Aquifer	North Africa Aquifer (Nubian aquifer, north-western Sahara aquifer)	Increased water scarcity and climate change	Ahmed, 2020.
	Jordan (Wadi Al-Arab)	Increased water scarcity and climate change	Rödiger et al., 2017.
	Palestine (Eastern groundwater basin – West Bank)	Increased water scarcity and climate change	Rabi et al., 2003.
Country scale	Iraq	Climate change	Al-Mukhtar and Qasim, 2019.

A.4. spatial and temporal resolution of input data used on water resources assessments and the resultant information in the MENA region

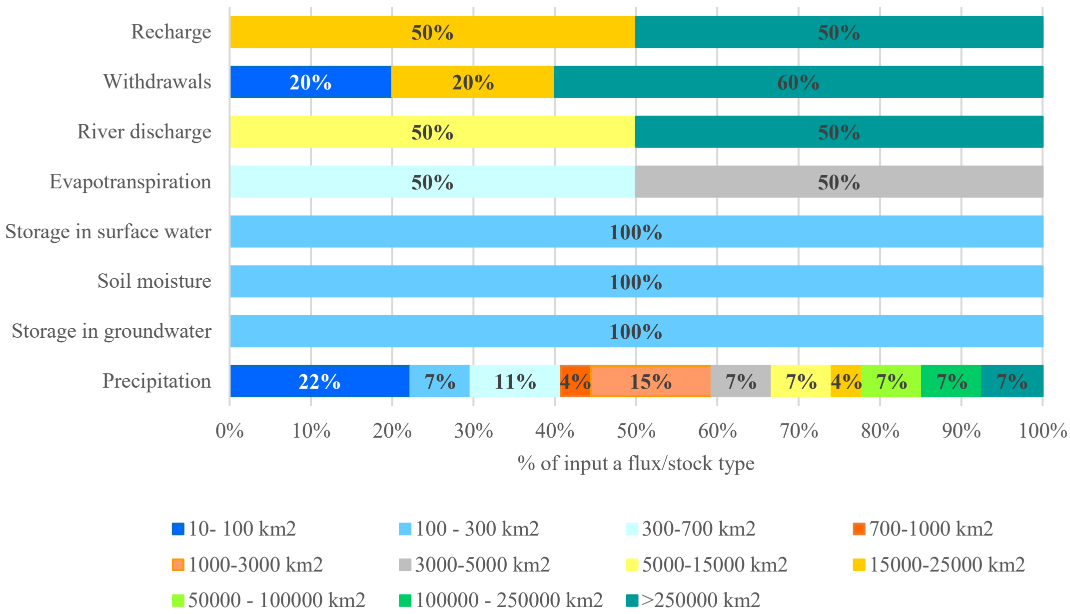


Figure A.4.1: Spatial resolution of input data used in water resources assessments in the MENA region classified by flux/stock type

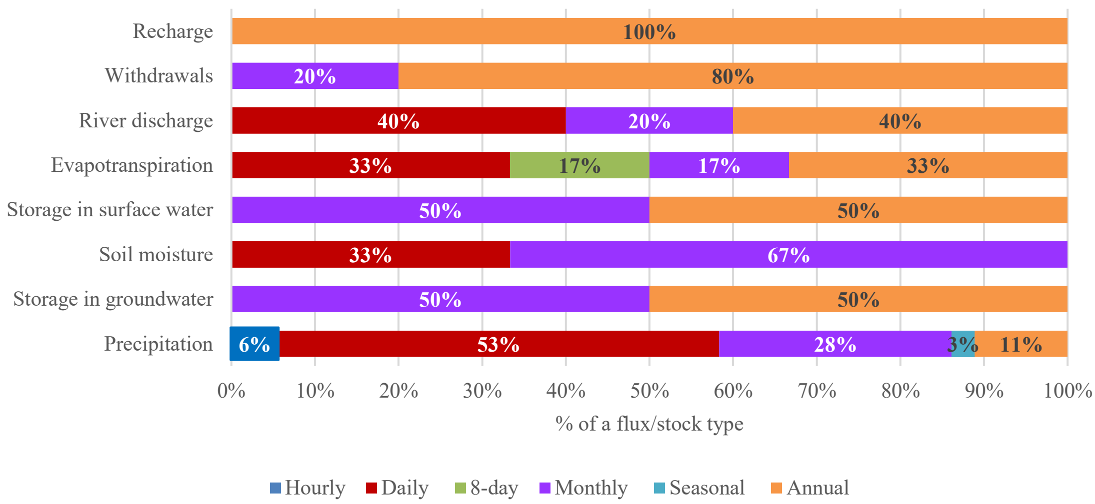


Figure A.4.2: Temporal resolution of input data to water resources assessments in the MENA classified by flux/stock type

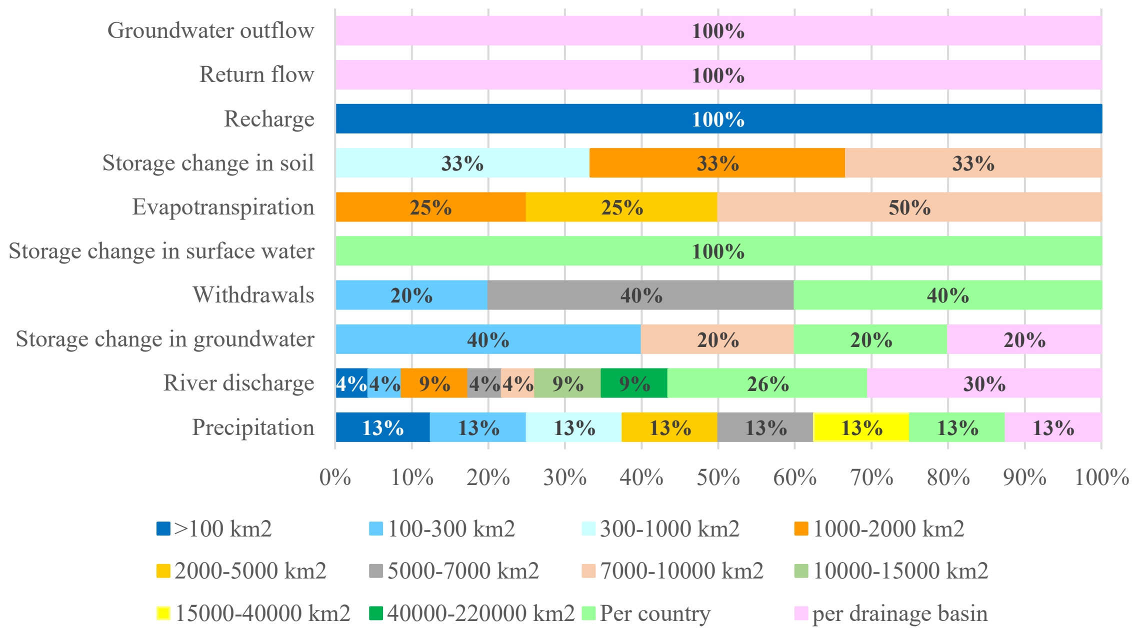


Figure A.4.3: Spatial resolution of output information from water resources assessments in the MENA region classified by flux/stock

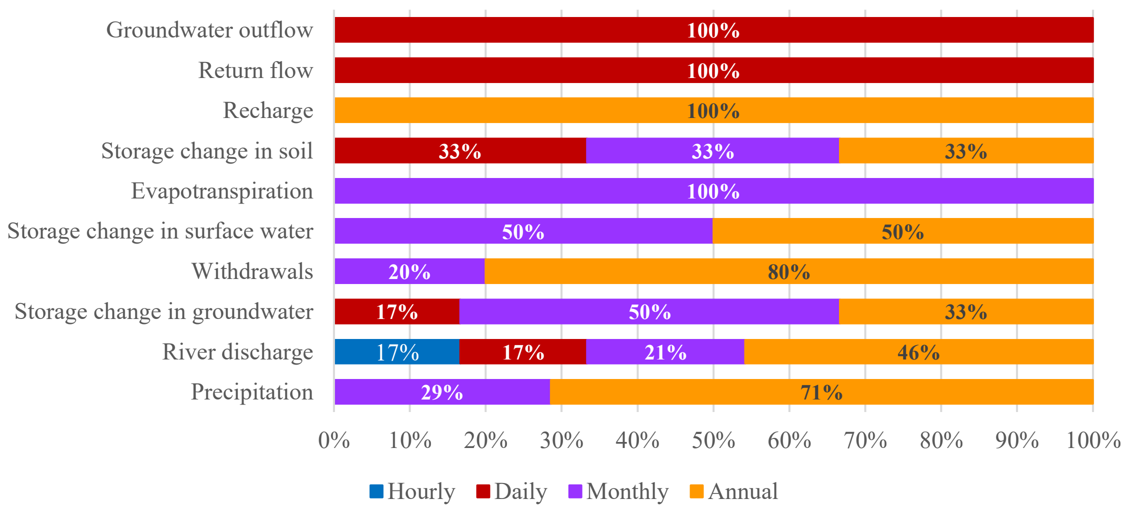


Figure A.4.4: Temporal resolution of output information from water resources assessments in the MENA classified by flux/stock

A.5. Strategies evaluated in the MENA and monitoring and evaluation indicators.

Issue identified	Proposed strategy	System	Reference	Intervention type	Monitoring and evaluation indicators
Rapid decrease in groundwater levels	Sustainable abstraction caps	Groundwater	Ahmed, 2020.	Flow based intervention that aims at controlling withdrawals (supply management)	Total withdrawals (Km^3/year)
Rapid decrease in groundwater levels	Artificial recharge and optimisation of abstraction locations	Wadi systems	Ghoneim, 2007; Youssef et al., 2020.	Flow based intervention that aims at improving groundwater availability (supply management)	No clear indicators provided to quantify the impact of artificial recharge and abstractions on groundwater
Unfair allocation of transboundary river water	Water allocation strategies based on the demand and availability of internal water resources in each riparian country (transboundary)	River basins	Degefu et al., 2017; Kucukmehmetoglu et al., 2010; Mianabadi et al., 2015.	Flow based intervention that aims at optimizing transboundary water allocation (supply management)	Annual river discharge received per country
Future decline in water availability due to climate change	Climate change adaptation (Modern irrigation)	River basins	Abdelhalim et al., 2020; Chenoweth et al., 2011.	Technological intervention that aims at improving irrigation efficiency and reducing water losses (demand management)	Aquifer storage change and river discharge
Future decline in water availability due to climate change	Climate change adaptation (Crop pattern changes along with assessments of resultant water productivity)	River basins	Rajosoa et al., 2021	Land based interventions that aims at changing cropping pattern to improve to achieve higher water	Agricultural water demand, Water productivity

				productivity (demand management)	
Future decline in water availability due to climate change	Climate change adaptation (Crop pattern changes to drought tolerant crops)	River basins	Chenoweth et al., 2011	Land based intervention that aims at changing cropping pattern to less water consuming crops (demand management)	Aquifer storage change and river discharge
Future decline in water availability due to climate change	Climate change adaptation (Water losses reduction)	River basins	Chenoweth et al., 2011	Mixed interventions including crop pattern changes, and technological to improve water distribution, and use efficiency (demand management)	Aquifer storage change and river discharge
Future decline in water availability due to climate change	Climate change adaptation (Dam management (fill rates and operation)	River basin	Keith et al., 2017; Kucukmehmetoglu and Geymen, 2014; Ohara et al., 2011; Ahmed et al., 2024.	Flow based intervention (supply management)	River discharge downstream in the dry season
Future decline in water availability due to climate change	Climate change adaptation (Desalination)	River basin	Chenoweth et al., 2011	Flow based interventions (supply management)	Supply VS water needs

A.6. Description of WA+ case studies.

Country	River basin	Topic	Duration of water accounts	References
Lebanon	Litany	Increased water scarcity	1 year	FAO and IHE Delft, 2019.
Jordan	Jordan	Increased water scarcity	1 year	FAO and IHE Delft, 2020b.
Egypt	Nile	Increased water scarcity	1 year	FAO and IHE Delft, 2020e

Ethiopia	Awash	Low water productivity (low production)	1 year	Dost et al., 2013; FAO and IHE Delft, 2020a; Karimi et al., 2014.
Benin, Guinea, Mali, Niger, Nigeria	Niger	Lack of water information to inform decision making	1 year	FAO and IHE delft, 2020c.
Ghana, Burkina Faso, Ivory Coast	Volta	Uncertain future water availability	50 years	Dembélé, 2020; Dembélé et al., 2023.
Afghanistan, Iran	Helmand	Increased water scarcity and low water productivity	1 year	Peiser and Bastiaanssen, 2015.
China, India, Pakistan	Indus	Increased water scarcity and low water productivity	1 year	Karimi et al., 2014.
India	Subarnarekha Krishna Tungabhadra Kali Sindh Wainganga Mahi	Low performing irrigation, increased water scarcity	2 years (wet, dry) 3 years (wet, dry, average) 1 year 12 years 17 years	V.G. Singh et al., 2022; Salvadore et al., 2020; Salvadore et al., 2018; P.K. Singh et al., 2022; Patle et al., 2023.
Myanmar	Irrawaddy	Lack of water information to inform decision making	6 years	Bremer, 2017.
Iran	Tashk bakhtegan Urmia Plasjan Karkheh	Increased water scarcity Lack of accurate information to inform decision making	30 years 1 year (Kivi et al., 2022) 6 years (Ghorbanpour et al., 2022)	Delavar et al., 2020; Karimi et al., 2019; Kivi et al., 2022; Delavar et al., 2022; Ghorbanpour et al., 2022.
Philippines	Agusan, Mindanao and Tagum-Libuganon	Inter-annual changes in water availability leading to less agricultural production	5 years	Seyoum and Mul, 2020.
Kazakhstan	Nura-Sarysu	Low performing irrigation	5 years	Michailovsky et al., 2020.
Mongolia	Selenge	Low water productivity	5 years	Michailovsky et al., 2020.
Cambodia	Tonle Sap Kamping Puoy Three S Upper Mekong	Low water productivity	16 years	Salvadore et al., 2017; Salvadore et al., 2020

	Lower Mekong Costal catchment			
Indonesia	Jratun Seluna Cimanuk Cisanggarung, Deli-Percut-Belawan Seputih Tulang	Increased water scarcity		Michailovsky and Bastiaanssen, 2018b
Sri Lanka	Mahaweli	Low water productivity	1 year	Michailovsky and Bastiaanssen, 2018a.
Vietnam	16 river basins	Lack of water information to inform decision making		Coerver, 2018.

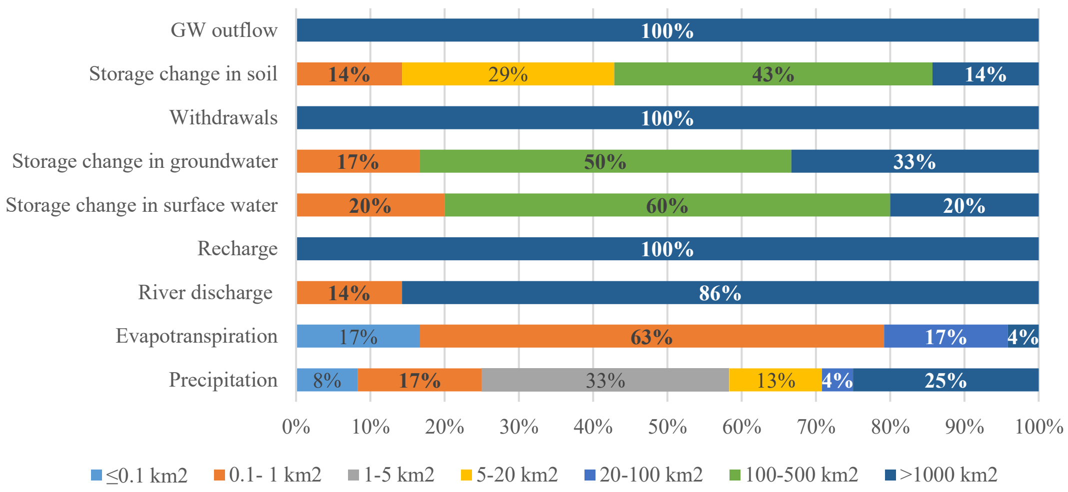


Figure A.7: Spatial resolution of input data used in WA+ case studies classified by flux/stock type

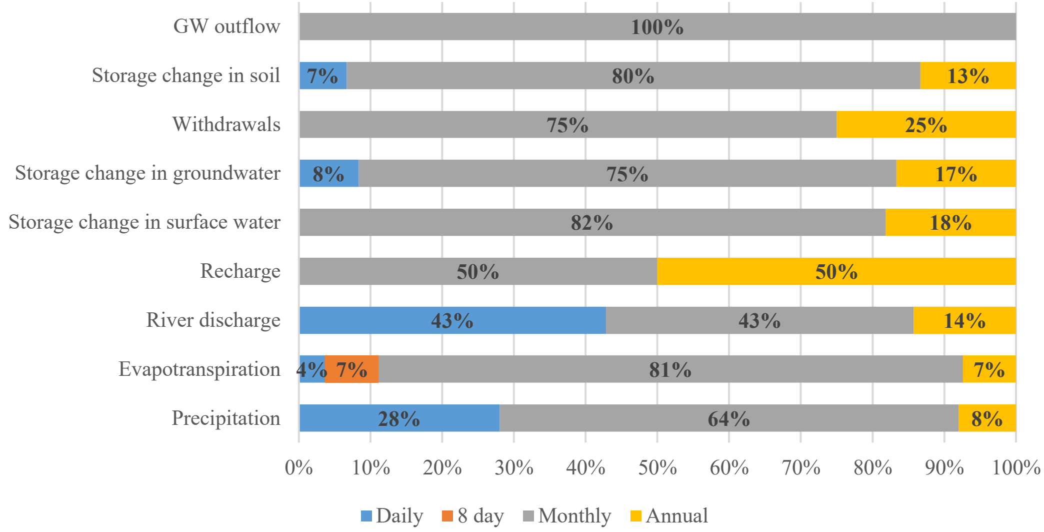


Figure A.8: Temporal resolution of input data used in WA+ case studies classified by flux/stock type

A.9 Strategies evaluated following WA+ and monitoring and evaluation indicators.

Challenge identified	Strategy proposed or evaluated	Reference #	Intervention type	Monitoring and evaluation indicators
Increasing water scarcity	Modern irrigation	Dembélé et al., 2023; Patle et al., 2023; Ghorbanpour et al., 2022; P.K. Singh et al., 2022; Delavar et al., 2020; Karimi et al., 2013	Technological intervention (Demand management)	Agricultural withdrawals ratio, return flow ratio, farm efficiency, basin efficiency, incremental ET, transpiration volume (Bm^3/year), water productivity, beneficial and non-beneficial ET
Increasing water scarcity	Changing cropping patterns to reduce water consumption and withdrawals	Delavar et al., 2020; Karimi et al., 2013	Land-based intervention (Demand management)	Consumption ratio, agricultural withdrawals ratio, incremental ET, transpiration volume (Bm^3/year)
Seasonal variations in water availability	Alternative water resources development (Treated wastewater, rainwater harvesting) to bridge the gap between supply and demands in the dry season	Dembélé et al., 2023; FAO and IHE Delft, 2020b.	Flow based intervention (supply management)	Basin closure index.

A.10 Input data applied in the WA+ studies.

Input flux/stock	# Of papers	Rank	Data source
Evapotranspiration	29	1	RS
Precipitation	28	2	RS and weather stations
Storage change in surface water	8	3	RS
Storage change in groundwater	8	3	RS and modelling
Storage change in soil	7	4	RS
River discharge	7	4	Gauge stations and modelling
Withdrawals (municipal and industrial)	6	5	Government records

A.11 Sheets reported in WA+ studies.

Sheet	#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

APPENDIX B

B.1 Description of Jordan's annual water budget components

The national water budget report, which aims to provide estimates for supply-demand gap, has three main components (MWI, 2019; 2020; 2021; 2022):

1- The water balance: it reports precipitation, surface runoff, recharge, and evaporation for the 15 surface water basins in Jordan using the following water balance equation (MWI, 2019):

$$Re = \mathrm{P} - E - Q_{sro} \qquad \text{Equation 1}$$

Where:

- P is precipitation in Mm^3/year
- E is evaporation in Mm^3/year
- Q_{sro} is surface runoff in Mm^3/year
- Re is recharge in Mm^3/year

Precipitation volume is calculated using ground observations from rain gauges distributed nationwide. The Thiessen Polygon method is used to determine the area-weighted average precipitation depth for each basin. This depth is then multiplied by the basin area to compute the volume.

To estimate evaporation, recharge, and runoff, the MWI employs a benchmarking method (minimum and maximum) to determine the percentages of these fluxes relative to precipitation, based on the hydrological year type (wet, dry, average) and historical data (Ta'ani, 2017). This method is primarily employed because measured data for evapotranspiration (ET) and runoff is not available for most of wadis and streams. Also, no hydrological models are used to generate information on groundwater recharge.

2- Annual water resources: annual water resources encompass groundwater, internal surface water resources, transboundary surface water resources, and non-conventional water. Groundwater availability is estimated by aggregating the safe yields of all aquifers, rather than considering the actual annual recharge. The safe yield estimates used in the budgets have remained unchanged since the 90s. Internal surface water resources comprise runoff, estimated using the hydrological balance (equation 1), as well as baseflow in wadis and springs which are mainly estimated based on monitoring a few wadis' discharge and few springs, and dams' storage. Transboundary surface water is mainly represented by the inflow from the Yarmouk River and Al Wehda Dam, and flow from Lake Tiberias to King Abdullah Canal (KAC). Non-conventional water includes treated wastewater effluents, desalinated brackish groundwater and desalinated seawater.

3- Water use: water use in Jordan is documented by MWI at administrative scale (e.g., governorate), and classified based on the use type into irrigation, industry, tourism, livestock and domestic. The budget reports annual water uses for the country per sector and per water source (e.g., groundwater, surface water, non-conventional).

B.2 PixSWAB description

To simulate the water balance at each time step, the model utilizes the principles used in the Budyko framework (Zhang et al., 2008; FAO and IHE Delft, 2020) to separate precipitation into direct runoff and water available for evapotranspiration and recharge.

Surface runoff (SRO) is computed as follows (1):

$$SRO = P - X \qquad \text{Equation 2}$$

Where X is water available for evapotranspiration and recharge, estimated at a monthly time step as follows:

$$X = P * F \qquad \text{Equation 3}$$

F is the Fu equation (Fu, 1981; Zhang et al., 2008) modelled based on Budyko concept, and it captures catchment characteristics determined by precipitation P, maximum available water (X0), basin's aridity $\left(\frac{X0}{P}\right)$, and its tendency to generate runoff (represented by catchment water retention, and ET efficiency) as follows:

$$F = 1 + \frac{X0}{P} - \left[1 + \left(\frac{X0}{P}\right)^{\frac{1}{1-\alpha}}\right]^{1-\alpha} \qquad \text{Equation 4}$$

After determining the surface runoff, available water at time step t is updated by subtracting the soil moisture content at the previous time step as follows:

$$W = X - SM_{t-1} \qquad \text{Equation 5}$$

Available water W is separated into recharge and ET based on computing ET opportunity (Y) as follows:

$$Y = W * F \qquad \text{Equation 6}$$

And recharge (Re) is computed as follows:

$$Re = (W - Y) + (SM_{t-1} - ETa) \qquad \text{Equation 7}$$

At time step t, soil water storage can be expressed as follows (2):

$$SM_t = W - Re - ETa \qquad \text{Equation 8}$$

When soil water storage is less than or equal to ETa, green ET is satisfied from soil moisture and becomes equal to ETa. In case soil moisture is less than ETa, ET green is satisfied from soil moisture, and blue ET is calculated as follows (3):

$$ET_{blue} = ETa - SM_{t-1} \qquad \text{Equation 9}$$

The source of blue ET in the model is assumed to be groundwater aquifers, hence the model simulates the supply needed to satisfy blue ET as follows:

$$S = \frac{ET_{blue}}{F_{consumed}}$$ Equation 10

Baseflow is an outflow from the groundwater storage as well, determined as follows (4):

$$bf = bf_p * GW_{t-1}$$ Equation 11

Where bf_p is a calibration parameter introduced to determine the catchment tendency to generate baseflow, contributing mainly to river discharge.

At time step t, groundwater storage is updated as follows:

$$GW_t = (1 - bf_p) * GW_{t-1} + Re$$ Equation 12

Deep percolation from the shallow groundwater layer to deeper aquifers is simulated as follows (5):

$$Dp = GW_t * dp_p$$ Equation 13

Where dp_p is a calibration parameter used to determine the catchment tendency to generate deep percolation.

At time step t, groundwater storage is then updated as follows:

$$GW_t = \left(1 - dp_p\right) * GW_t$$ Equation 14

Incremental percolation, representing return flow from irrigation is also simulated in the model based on the consumed fraction.

At time step t, soil water storage is updated to account for the supply made from groundwater to meet blue ET demand as follows:

$$SM_t = (1 - f_{consumed}) * S$$ Equation 15

B.3 Land use reclassification:

Table B.3.1: land use re-classification for the adapted WA+ in the AZ basin (only within the water budget zone)

Land use category - WaPOR	Area percentage	WA+ land classification	Adapted WA+ classification for the AZ basin	Percentage area
Rainfed cropland	4.90%	Modified	Agricultural	23.60%
Cropland, irrigated or under water management	1.40%	Managed		
Cropland, fallow	17.30%	Modified		
Built-up	7.00%	Modified/utilised	Urban	7.00%
Bare / sparse vegetation	37.37%	Utilised	Natural	69.40%
Water bodies	0.03%	Managed		
Tree cover	0.93%	Utilised		
Shrubland	4.54%	Utilised		
Grass land	26.55%	Utilised		

B.4 Calibration parameters for PixSWAB

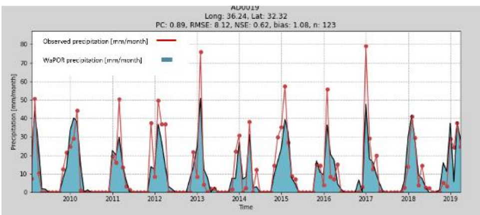
Table B.4.1: PixSWAB parameters description and recommended ranges

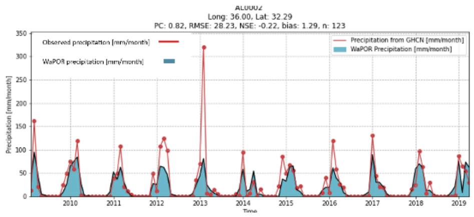
Parameter	Range	Parameter role in the model
d_{bf}	0-1	Controls the baseflow generation rate and groundwater storage dynamics. It influences the balance between water stored in the shallow groundwater bucket and water released as baseflow, which, in turn, affects streamflow.
d_p	0-1	Controls the rate of water movement from the shallow groundwater bucket to the deep groundwater aquifers. It determines how quickly water infiltrates into the deep layers and affects the dynamics of the groundwater system.
r_f	0-1	Is used to modify the catchment retention capacity (c-ret) based on land cover type, soil type and root depth, and optionally by the slope. This factor is used to fine-tune the model's performance to better represent the runoff behavior in the basin.
S_f	1-10	Is used to modify the catchment retention capacity based on the local terrain's slope characteristics. It adjusts the ability of the land to retain water, considering the impact of the slope on runoff potential.

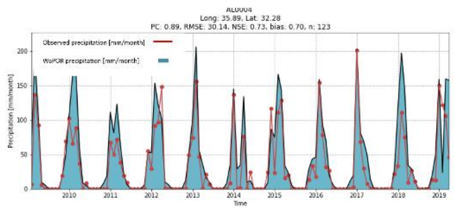
B.5 Precipitation validation

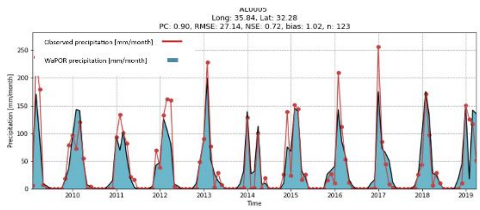
- Time series comparison

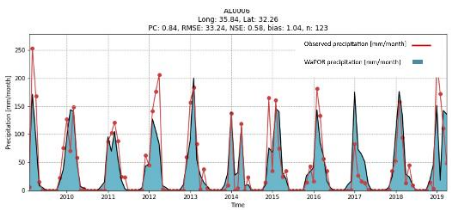
The study compared the WaPOR precipitation data with observed precipitation in 23 stations within the AZ basin from September 2009 to August 2019. The results varied for different stations. Out of the 23 stations, five showed high correlation coefficients (PC), high Nash-Sutcliffe efficiency (NSE), low Root Mean Square Error (RMSE), and low bias relative to other stations. These five stations were AD0019, AL0055, AL0066, AL0016, and AL005. On the other hand, five stations including AL0053 AL0057, AL0027, AL0017, and AL0022 showed relatively lower agreement with RS data with RSME ranging from 27 to 39 mm/month, despite having high PC correlation of between 0.8 and 0.89. For the remaining stations, the RS data performed relatively well. Out of the 23 stations, thirteen showed good correlation, high NSE, and lower bias. Out of these thirteen stations, errors represented by RSME were low in seven stations. Overall, there was a good agreement between WaPOR P and ground observations in 18 stations, indicating a good performance of WaPOR P in over 70% of the stations.

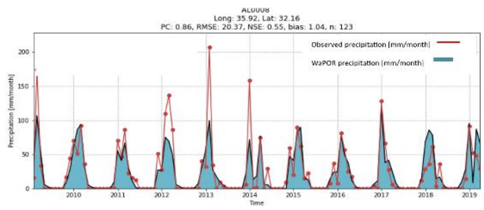


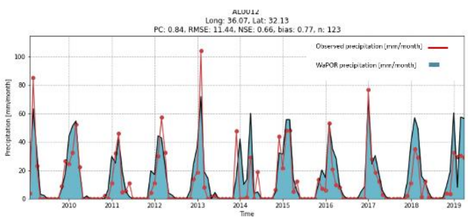


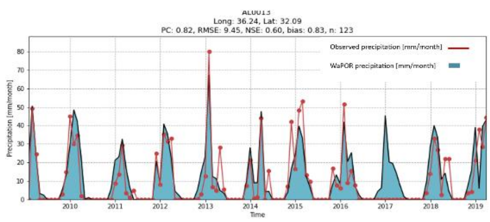


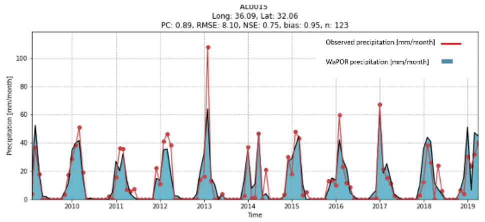


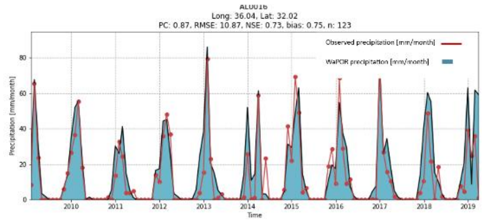


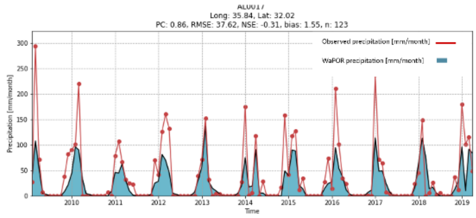


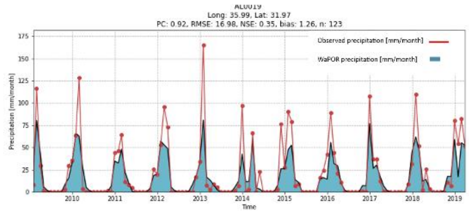


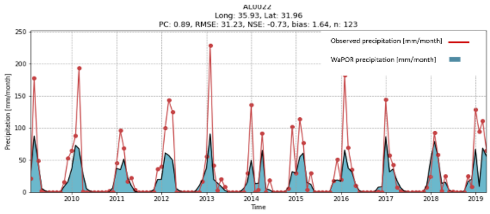


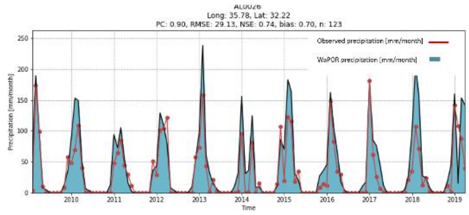

AL0015
Long: 36.09, Lat: 32.06
PC: 0.89, RMSE: 8.10, NSE: 0.75, bias: 0.95, n: 123
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time

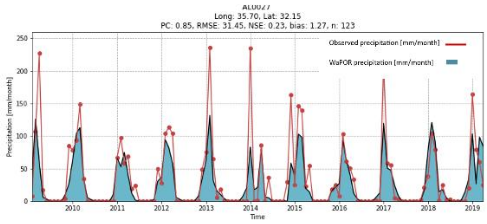

AL0016
Long: 36.04, Lat: 32.02
PC: 0.87, RMSE: 10.87, NSE: 0.73, bias: 0.75, n: 123
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time

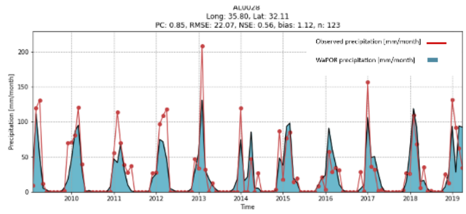

AL0017
Long: 35.84, Lat: 32.02
PC: 0.86, RMSE: 37.62, NSE: -0.31, bias: 1.55, n: 123
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time

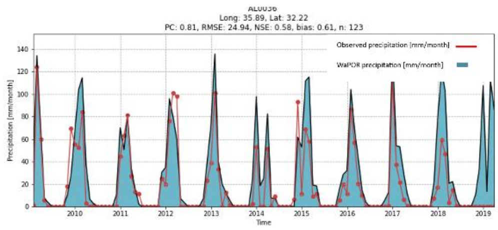

AL0019
Long: 35.99, Lat: 31.97
PC: 0.92, RMSE: 16.98, NSE: 0.35, bias: 1.26, n: 123
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time

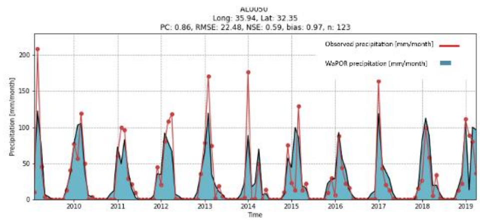

AL0022
Long: 35.93, Lat: 31.96
PC: 0.89, RMSE: 31.23, NSE: -0.73, bias: 1.64, n: 123
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time

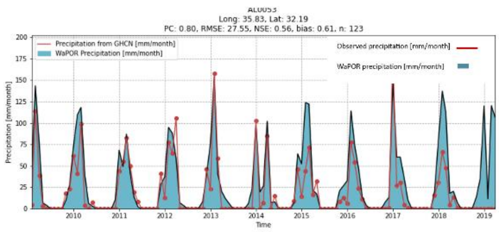

AL0026
Long: 35.78, Lat: 32.22
PC: 0.90, RMSE: 29.13, NSE: 0.74, bias: 0.70, n: 123
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time

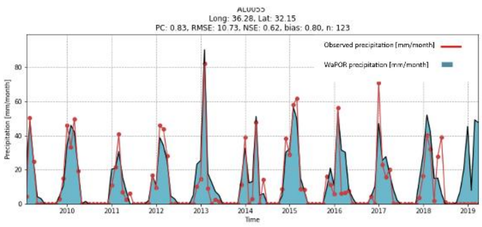

AL0027
Long: 35.70, Lat: 32.15
PC: 0.85, RMSE: 31.45, NSE: 0.23, bias: 1.27, n: 123
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time


AL0028
Long: 35.80, Lat: 32.11
PC: 0.85, RMSE: 22.07, NSE: 0.56, bias: 1.12, n: 123
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time


AL0036
Long: 35.89, Lat: 32.22
PC: 0.81, RMSE: 24.94, NSE: 0.58, bias: 0.61, n: 123
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time


AL0050
Long: 35.94, Lat: 32.35
PC: 0.86, RMSE: 22.48, NSE: 0.59, bias: 0.97, n: 123
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time


AL0053
Long: 35.83, Lat: 32.19
PC: 0.80, RMSE: 27.55, NSE: 0.56, bias: 0.61, n: 123
Precipitation from GHCN [mm/month]
WaPOR Precipitation [mm/month]
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time


AL0055
Long: 36.28, Lat: 32.15
PC: 0.83, RMSE: 10.73, NSE: 0.62, bias: 0.80, n: 123
Observed precipitation [mm/month]
WaPOR precipitation [mm/month]
Precipitation [mm/month]
Time

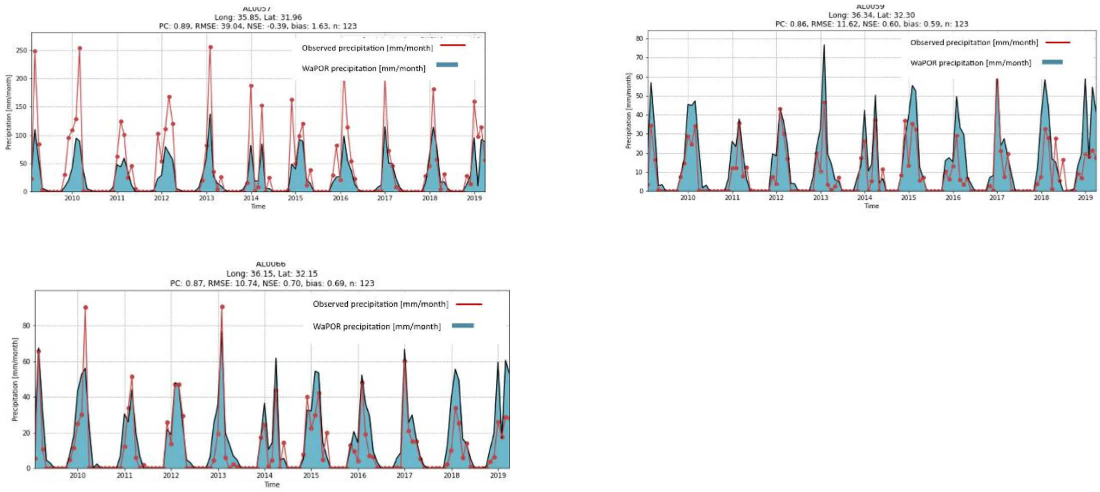
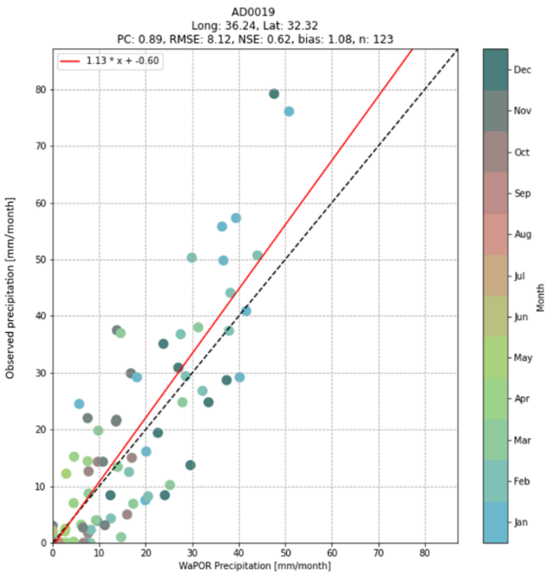
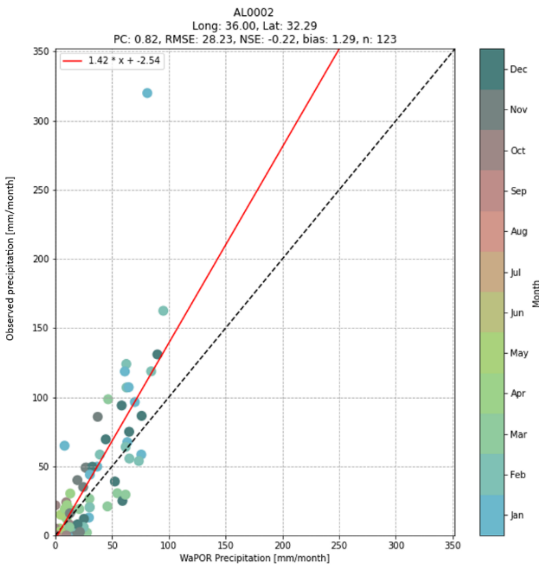
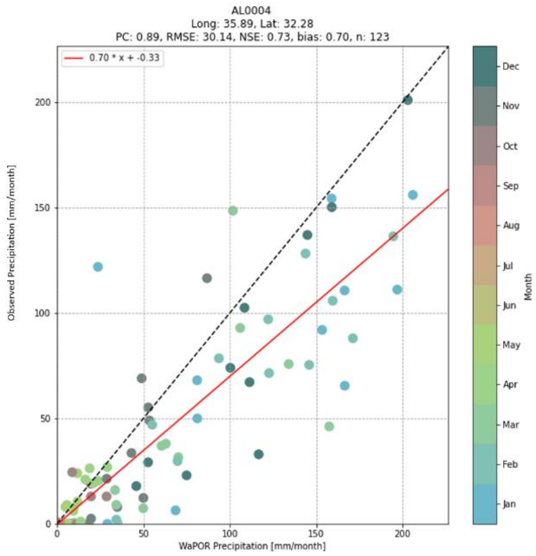


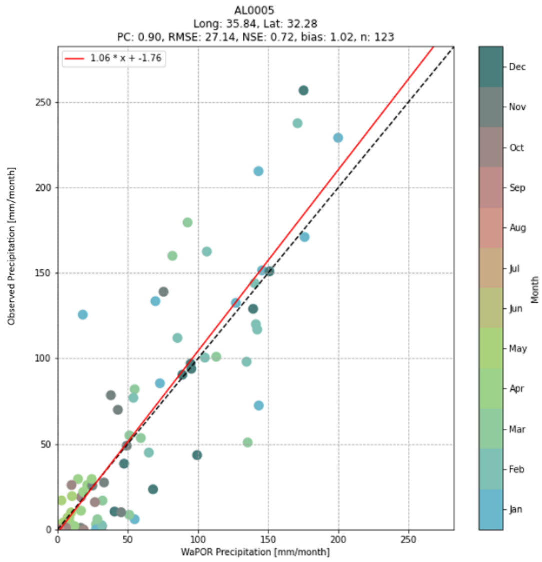
Figure B.5.1: comparison of monthly time series precipitation of WaPOR and ground observations in the AZ basin (September 2009-August 2019)

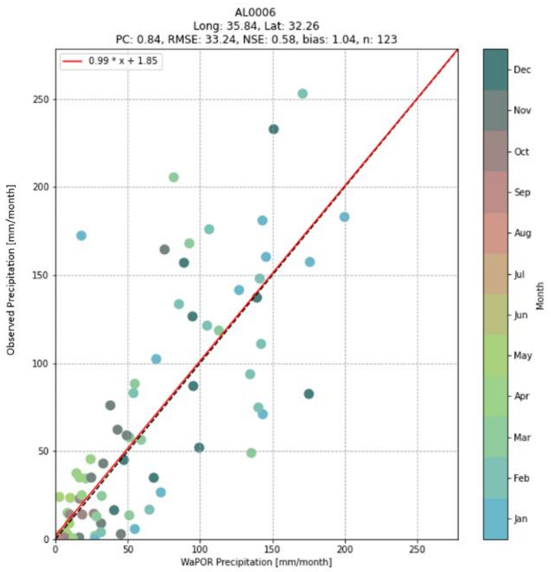
- Correlation analysis

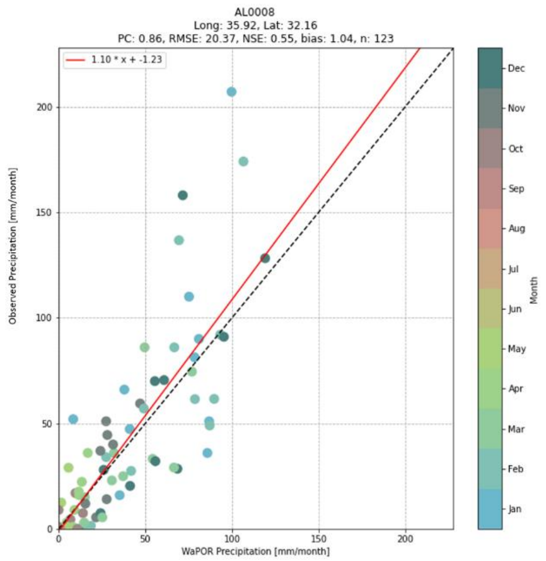


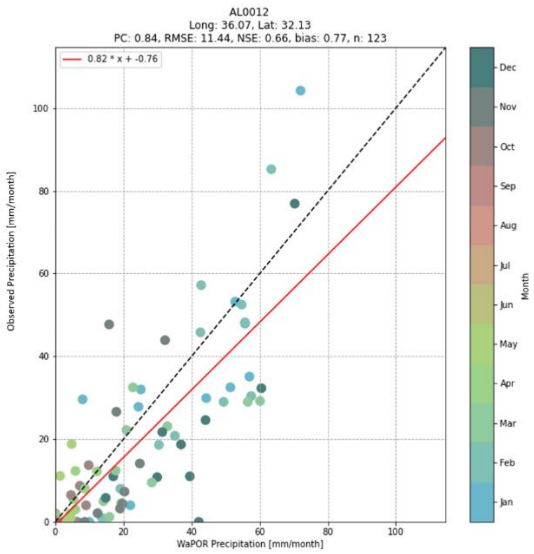


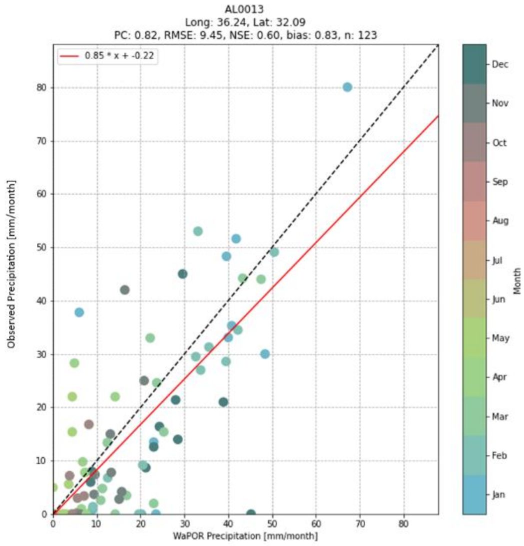

AL0004
Long: 35.89, Lat: 32.28
PC: 0.89, RMSE: 30.14, NSE: 0.73, bias: 0.70, n: 123
0.70 * x + -0.33
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan

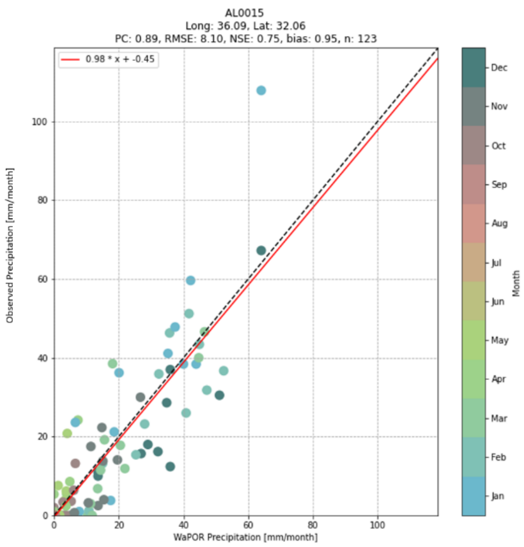

AL0005
Long: 35.84, Lat: 32.28
PC: 0.90, RMSE: 27.14, NSE: 0.72, bias: 1.02, n: 123
1.06 * x + -1.76
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan

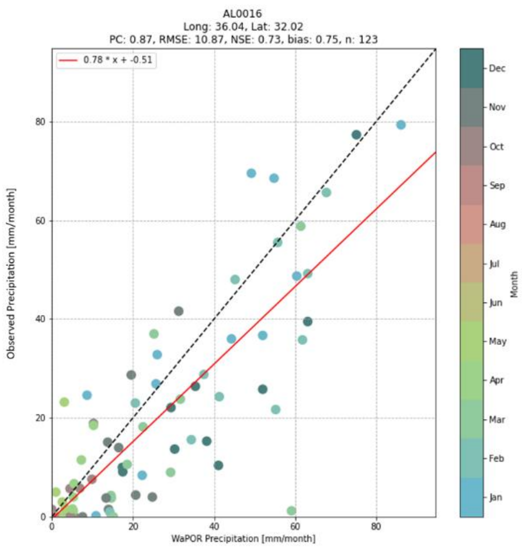

AL0006
Long: 35.84, Lat: 32.26
PC: 0.84, RMSE: 33.24, NSE: 0.58, bias: 1.04, n: 123
0.99 * x + 1.85
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan

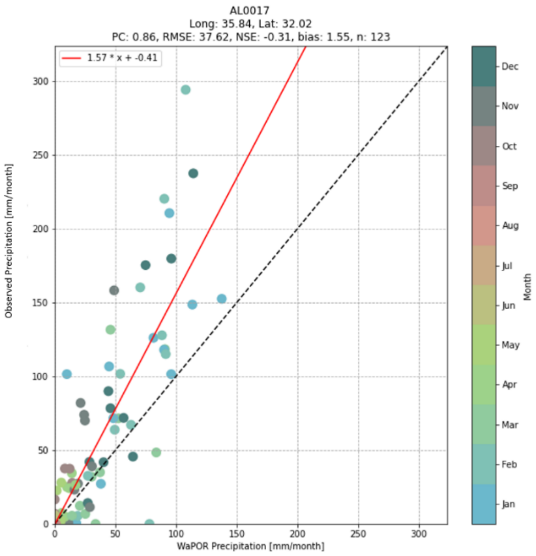

AL0008
Long: 35.92, Lat: 32.16
PC: 0.86, RMSE: 20.37, NSE: 0.55, bias: 1.04, n: 123
1.10 * x + -1.23
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan

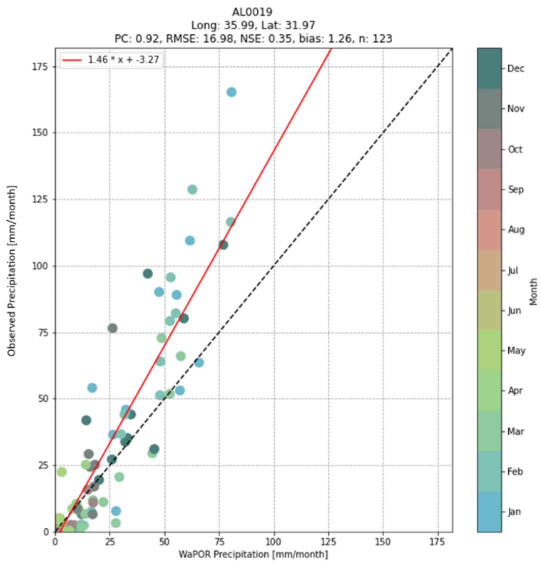

AL0012
Long: 36.07, Lat: 32.13
PC: 0.84, RMSE: 11.44, NSE: 0.66, bias: 0.77, n: 123
0.82 * x + -0.76
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month

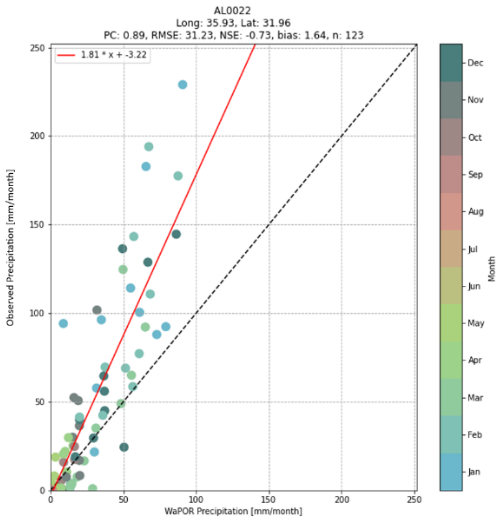

AL0013
Long: 36.24, Lat: 32.09
PC: 0.82, RMSE: 9.45, NSE: 0.60, bias: 0.83, n: 123
0.85 * x + -0.22
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month


AL0015
Long: 36.09, Lat: 32.06
PC: 0.89, RMSE: 8.10, NSE: 0.75, bias: 0.95, n: 123
0.98 * x + -0.45
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month


AL0016
Long: 36.04, Lat: 32.02
PC: 0.87, RMSE: 10.87, NSE: 0.73, bias: 0.75, n: 123
0.78 * x + -0.51
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month


AL0017
Long: 35.84, Lat: 32.02
PC: 0.86, RMSE: 37.62, NSE: -0.31, bias: 1.55, n: 123
1.57 * x + -0.41
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan


AL0019
Long: 35.99, Lat: 31.97
PC: 0.92, RMSE: 16.98, NSE: 0.35, bias: 1.26, n: 123
1.46 * x + -3.27
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan


AL0022
Long: 35.93, Lat: 31.96
PC: 0.89, RMSE: 31.23, NSE: -0.73, bias: 1.64, n: 123
1.81 * x + -3.22
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Dec
Nov
Oct
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Aug
Jul
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May
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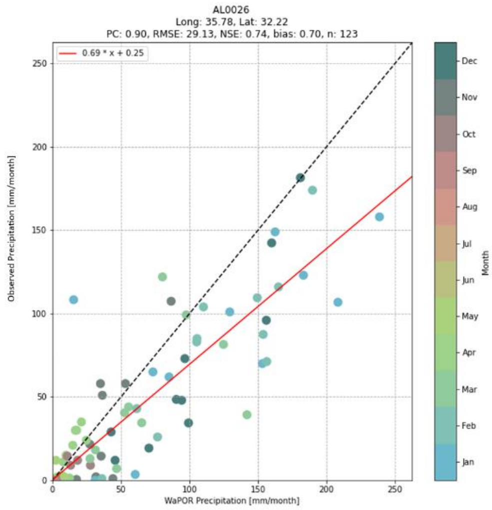
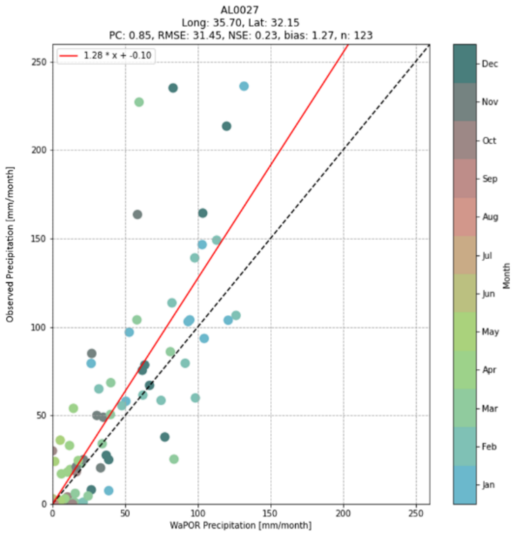
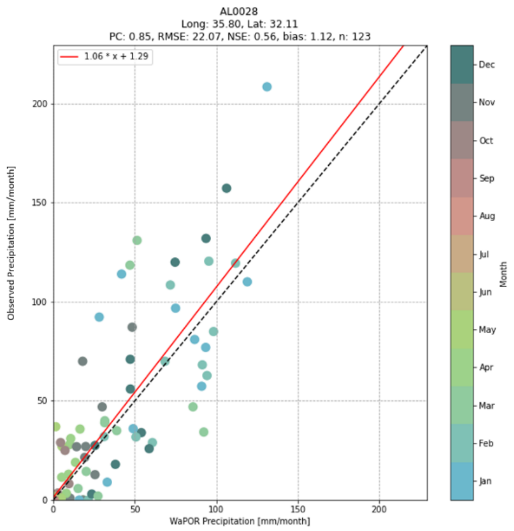
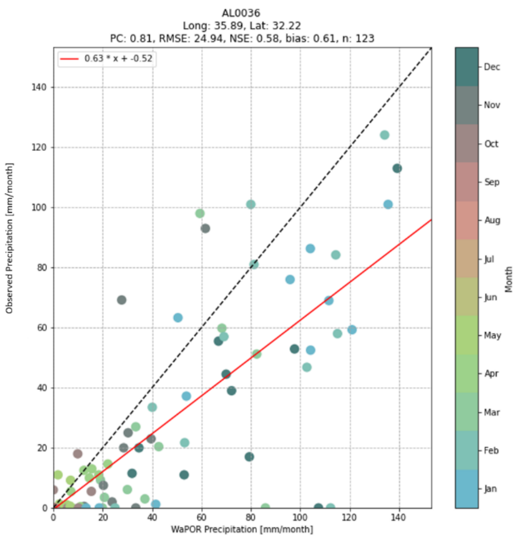
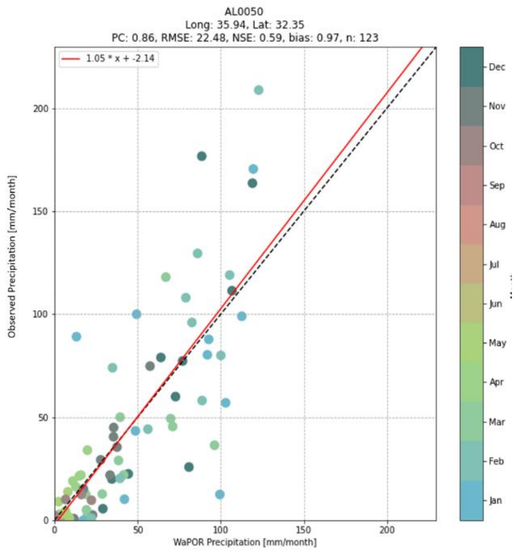
Feb
Jan

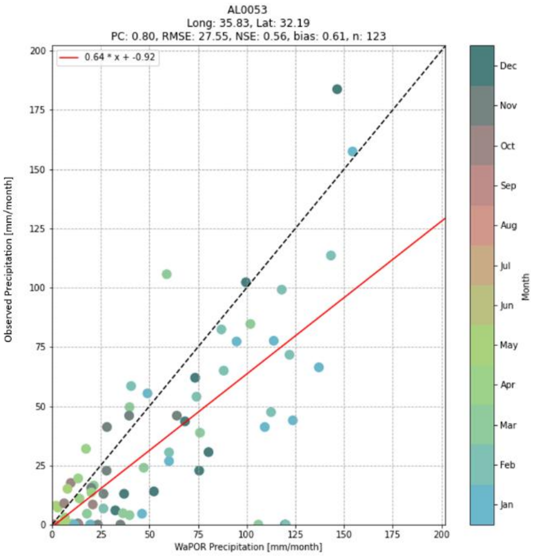

AL0026
Long: 35.78, Lat: 32.22
PC: 0.90, RMSE: 29.13, NSE: 0.74, bias: 0.70, n: 123
0.69 * x + 0.25
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan

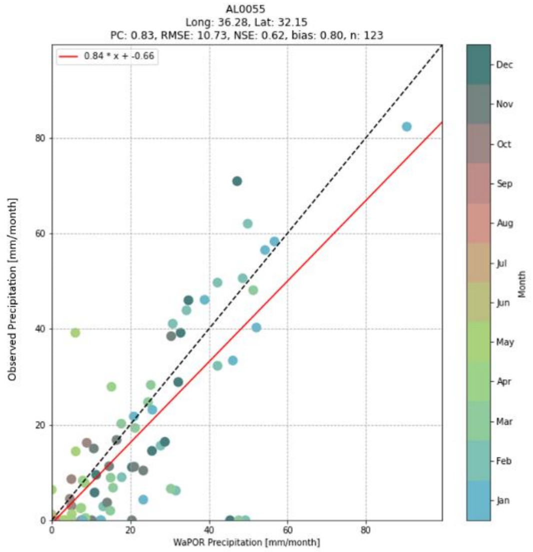

AL0027
Long: 35.70, Lat: 32.15
PC: 0.85, RMSE: 31.45, NSE: 0.23, bias: 1.27, n: 123
1.28 * x + -0.10
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan

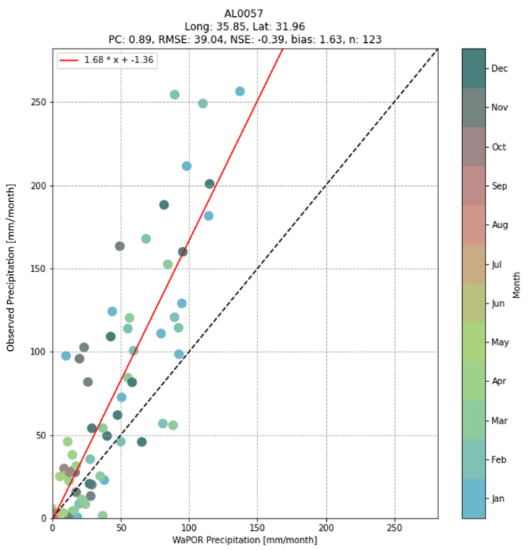

AL0028
Long: 35.80, Lat: 32.11
PC: 0.85, RMSE: 22.07, NSE: 0.56, bias: 1.12, n: 123
1.06 * x + 1.29
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan

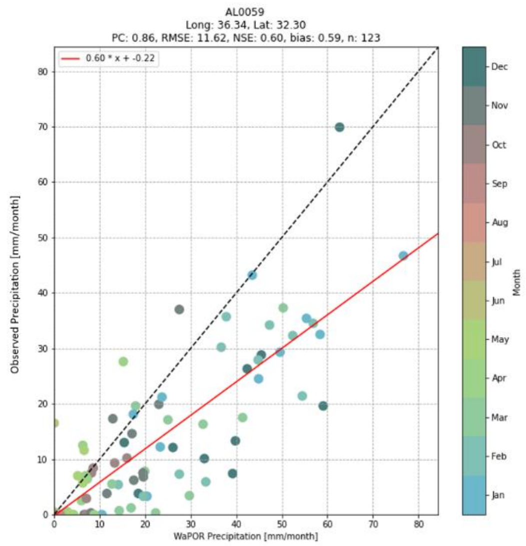

AL0036
Long: 35.89, Lat: 32.22
PC: 0.81, RMSE: 24.94, NSE: 0.58, bias: 0.61, n: 123
0.63 * x + -0.52
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan


AL0050
Long: 35.94, Lat: 32.35
PC: 0.86, RMSE: 22.48, NSE: 0.59, bias: 0.97, n: 123
1.05 * x + -2.14
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Dec
Nov
Oct
Sep
Aug
Jul
Jun
May
Apr
Mar
Feb
Jan


AL0053
Long: 35.83, Lat: 32.19
PC: 0.80, RMSE: 27.55, NSE: 0.56, bias: 0.61, n: 123
0.64 * x + -0.92
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


AL0055
Long: 36.28, Lat: 32.15
PC: 0.83, RMSE: 10.73, NSE: 0.62, bias: 0.80, n: 123
0.84 * x + -0.66
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


AL0057
Long: 35.85, Lat: 31.96
PC: 0.89, RMSE: 39.04, NSE: -0.39, bias: 1.63, n: 123
1.68 * x + -1.36
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


AL0059
Long: 36.34, Lat: 32.30
PC: 0.86, RMSE: 11.62, NSE: 0.60, bias: 0.59, n: 123
0.60 * x + -0.22
Observed Precipitation [mm/month]
WaPOR Precipitation [mm/month]
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

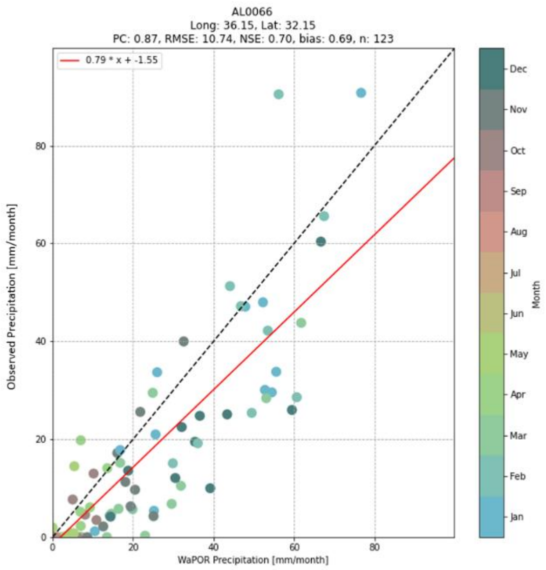


Figure B.5.2: Correlation of monthly precipitation from WaPOR and ground observations in the AZ basin (September 2009 – August 2019)

B.6 WaPOR ETa evaluation

- ETa seasonal variations

Seasonal variations in ETa within the AZ basin were determined by calculating the average monthly ETa from all datasets spanning 2009 to 2021 (Figure B.6.1). WaPOR and MODIS-500, along with SMAP show agreement on peak ET occurring in March. However, Penman-Monteith-Leuning, and MODIS 1km indicate peaks in January, while SSEBop exhibited two peaks in January and May. Despite these differences, a consistent temporal pattern emerged across most datasets: ETa increases from December to May/June, coinciding with the wet season in the AZ basin, and indicating that ETa is influenced by water availability conditions in the basin.

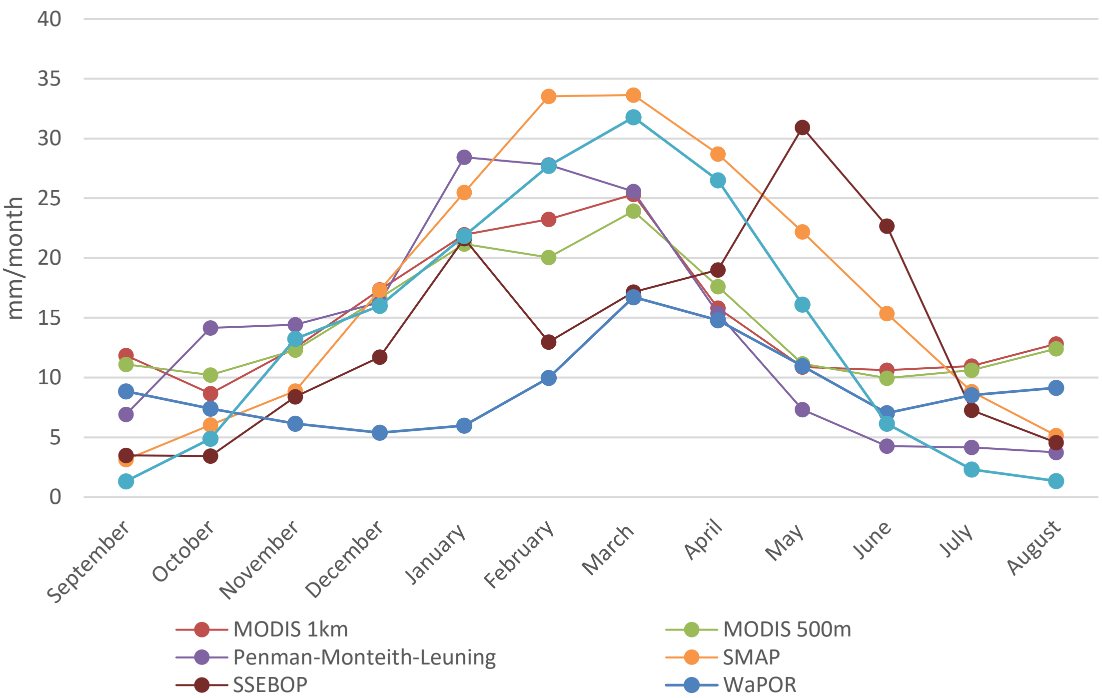


Figure B.6.1: Seasonal ETa variations of six datasets in the AZ basin

ET_a over irrigated areas is important in our case study as it represents manmade water consumption through irrigation. Therefore, a comparison of annual WaPOR ETa volume over irrigated areas (using the updated land use map) was undertaken with the other datasets for the years 2018 to 2021 (Figure B.6.2). This comparison showed that the average annual ETa over irrigated areas for that period was nearly 34 Mm^3/year, within the range of the average derived from the other datasets (29 to 39 Mm^3/year) over the same period. Previous work on irrigation consumption in the basin by Al-Bakri et al. (2023) assessed water usage in irrigated areas across Jordanian governorates between 2017 and 2019. This data from Al-Bakri et al. (2023) was clipped using the AZ basin boundaries, revealing that average ETa was approximately 78 Mm^3/year over irrigated areas. Average annual ETa over irrigated areas from WaPOR and other remote sensing datasets are lower than that of Al-Bakri et al. (2023). It should be noted, however, that Al-Bakri et al. (2023) used the normalized difference vegetation index (NDVI) and the crop coefficient (Kc) to map crop ET rather than satellite remote sensing ETa. As a result, differing methodologies may cause variations in outcomes. Nevertheless, WaPOR's ETa over irrigated areas remains within the range of other remote sensing products.

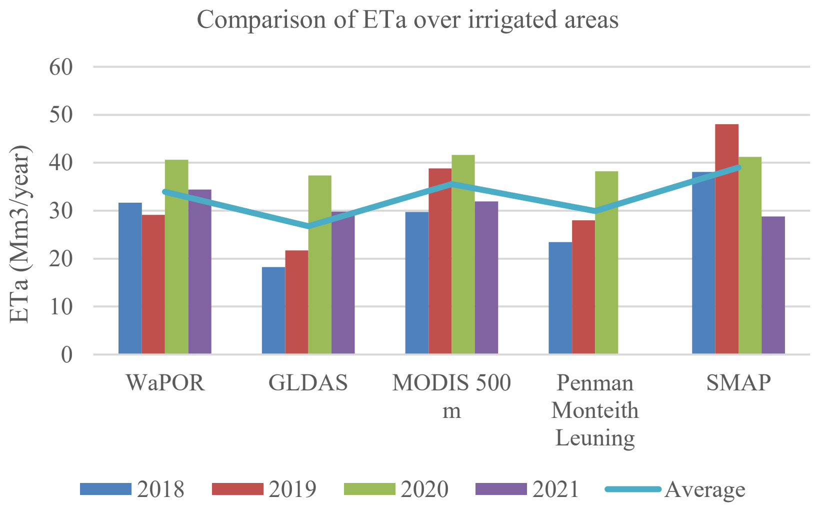


Figure B.6.2: Comparison of WaPOR ETa with other datasets over irrigated areas in the AZ basin

B.7 PixSWAB performance

Figure B.7.1 shows the parameter calibration results within the (-1,1) range for KGE and NSE. The PixSWAB parameter values show clustering patterns of slope factor around 2, a retention adjustment factor of between 0.8-0.9, a deep percolation constant between 0.7-1, and a groundwater storage constant between 0-0.1.

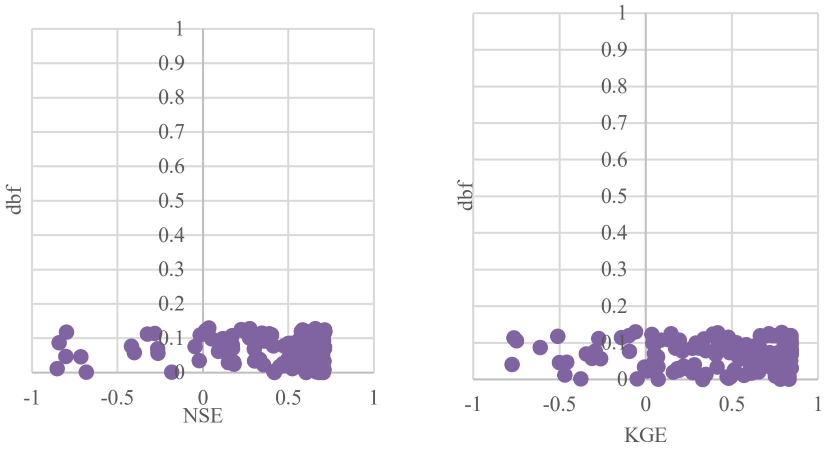


Figure B.7.1: Parameter driven calibration of PixSWAB in the AZ basin

Figure B.7.2 presents a comparison between the observed and simulated monthly discharge at Jerash Bridge station. It reveals that PixSWAB tends to underestimate the peak flows within the basin, particularly during the high rainfall periods of December and January. Such underestimation is attributable to PixSWAB's monthly time step using monthly precipitation data, which can overlook short-duration, high-intensity rain events that contribute to peak discharges in the basin.

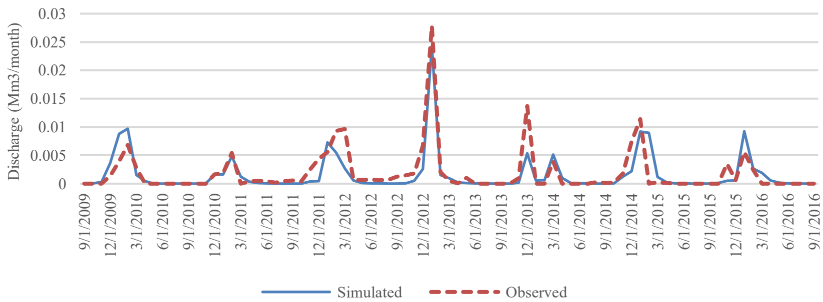


Figure B.7.2: a comparison between calibrated and observed discharge at Jerash Bridge station

B. 8 Comparison of blue ET, green ET and precipitation in the AZ basin

Rainfall in the Amman-Zarqa basin typically occurs from September through May, with the most falling between November and March. ET peaks from March to October when rainfall is absent, consequently, ET in dry season relies on blue water, known as blue ET. Conversely, in winter, nearly all ET is met from rainfall, referred to as green water (Figure B.8.1).

Figure B.8.2 shows the evapotranspiration of both blue and green water across all land classes in the basin for the period 2018 to 2021. The basin acts as a net water producer, given that precipitation consistently exceeds ET rates. The primary landscapes that contribute to water yield are grasslands, fallow lands, urban areas, and regions with sparse vegetation. Despite the modest rainfall these land covers receive due to their large extent, ET from blue water remains substantial because the seasons of high precipitation do not coincide with those of high ET rates. This mismatch leads to a scarcity of green water during dry periods.

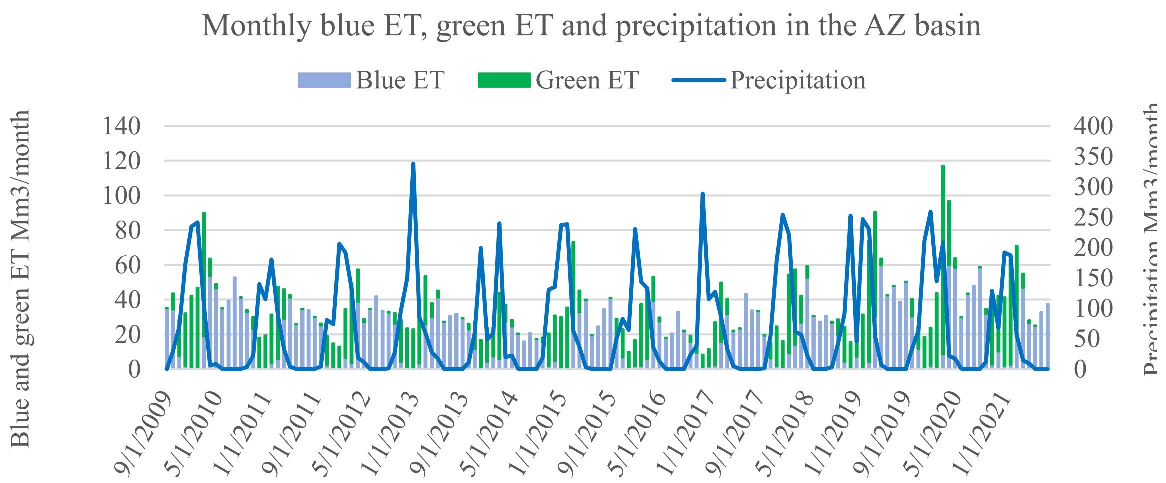
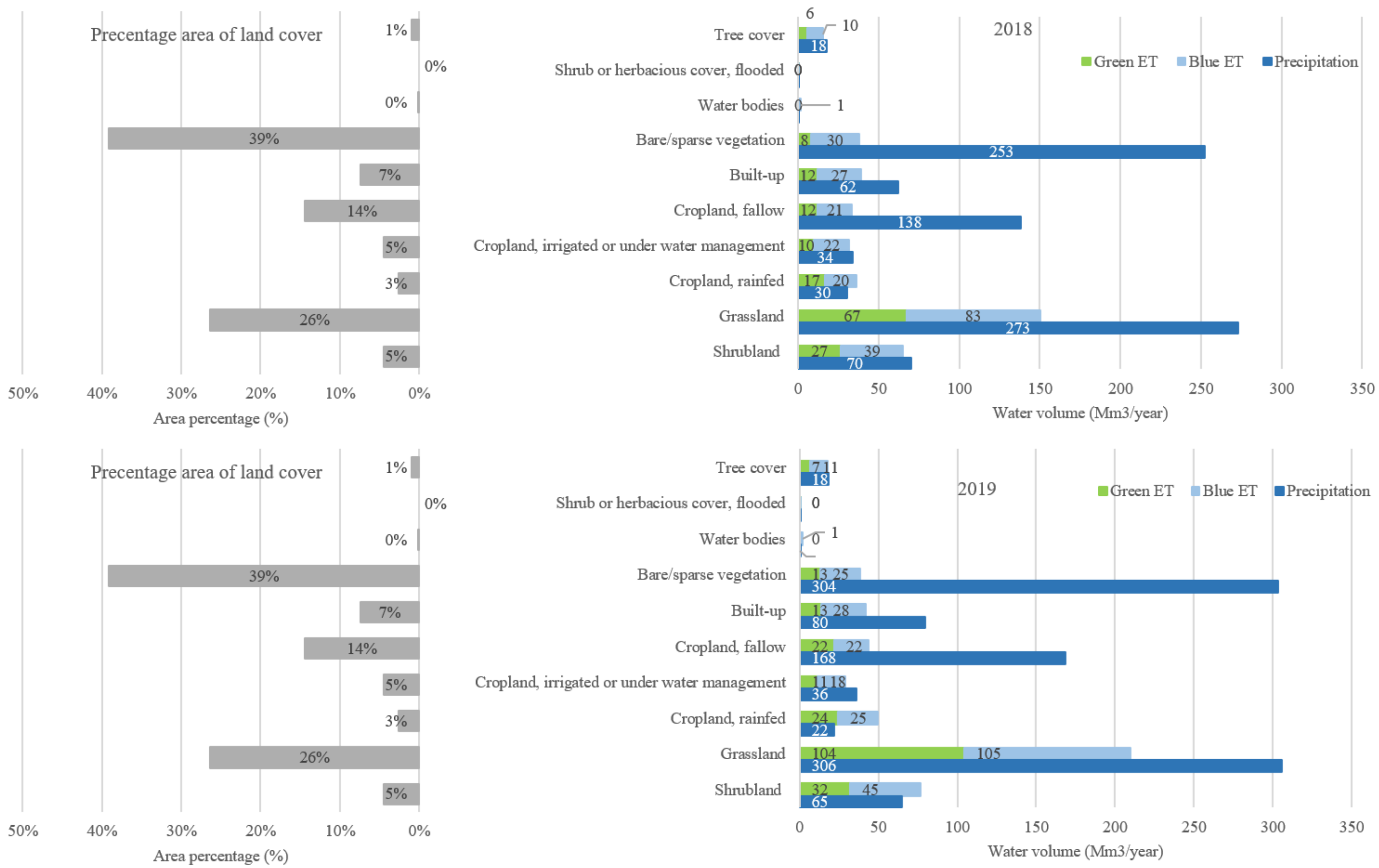


Figure B.8.1: comparison of monthly precipitation, blue and green ET in the AZ basin (September 2009 – August 2021)


Precentage area of land cover
1%
0%
0%
39%
7%
14%
5%
3%
26%
5%
50%
40%
30%
20%
10%
0%
Area percentage (%)
2018
Green ET
Blue ET
Precipitation
Tree cover
6
10
18
Shrub or herbacious cover, flooded
0
Water bodies
0
1
Bare/sparse vegetation
8
30
253
Built-up
12
27
62
Cropland, fallow
12
21
138
Cropland, irrigated or under water management
10
22
34
Cropland, rainfed
17
20
30
Grassland
67
83
273
Shrubland
27
39
70
0
50
100
150
200
250
300
350
Water volume (Mm3/year)
Precentage area of land cover
1%
0%
0%
39%
7%
14%
5%
3%
26%
5%
50%
40%
30%
20%
10%
0%
Area percentage (%)
2019
Green ET
Blue ET
Precipitation
Tree cover
7
11
18
Shrub or herbacious cover, flooded
0
Water bodies
0
1
Bare/sparse vegetation
13
25
304
Built-up
13
28
80
Cropland, fallow
22
22
168
Cropland, irrigated or under water management
11
18
36
Cropland, rainfed
24
25
22
Grassland
104
105
306
Shrubland
32
45
65
0
50
100
150
200
250
300
350
Water volume (Mm3/year)

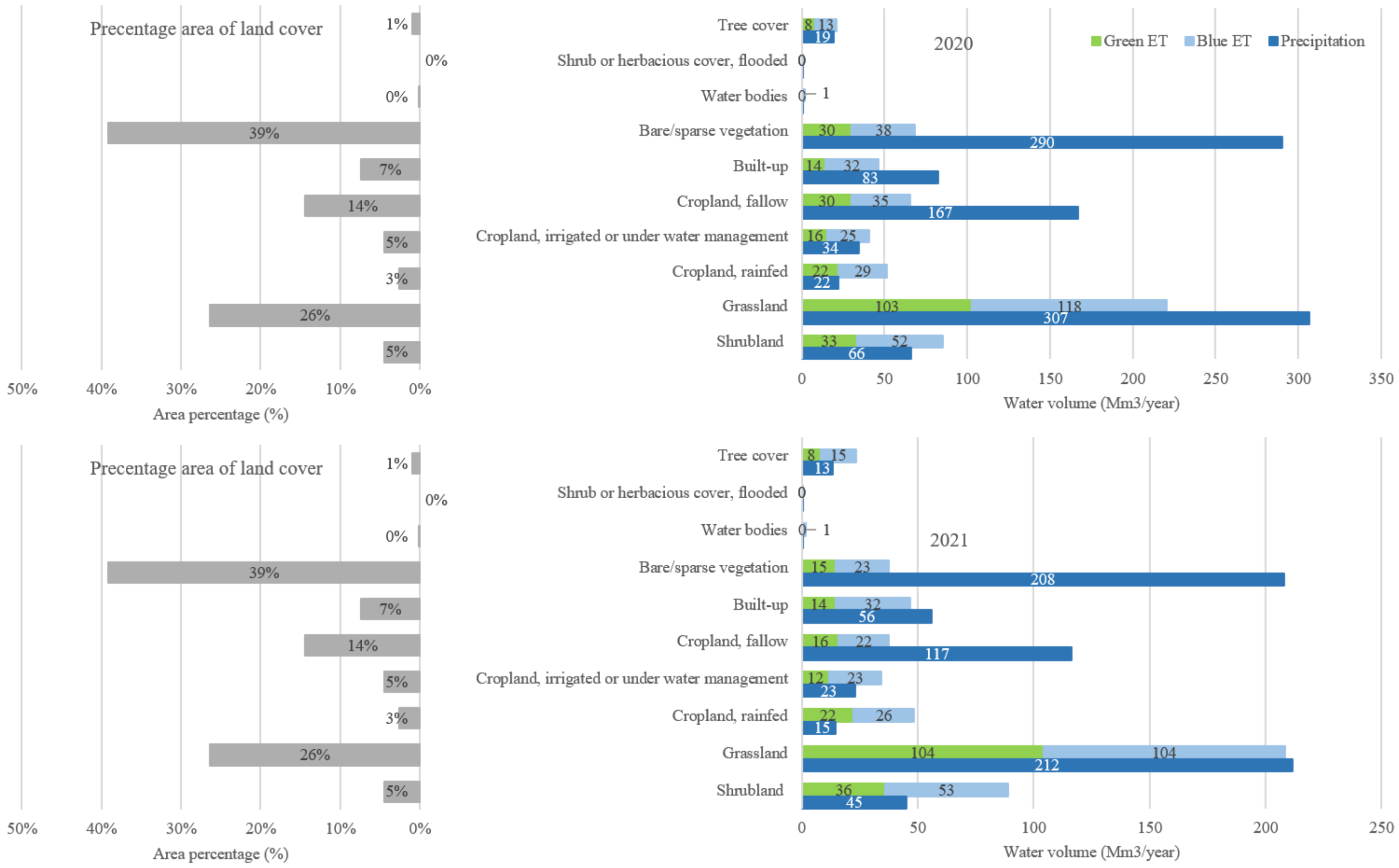


Figure B.8.2: The area percentage per land cover type (left), and annual precipitation, ETblue and ETgreen for the hydrological years 2018-2021

APPENDIX C

C.1 CWatM hydrological and water resources related processes

Hydrological processes considered in CWatM include the following:

1. *Potential evaporation from land surface:* the default option in CWatM is the FAO 56 approach described by Allen et al., (1998), which is used to calculate potential reference crop evaporation using the following general equation (Equation 1) for each landcover class in a grid:

   $$ET_{pot} = ET_{ref} * K_{crop} \quad \text{Equation 1}$$

   Where:

   ET_{pot} is potential crop evapotranspiration (m^3/day)

   ET_{ref} is potential reference evapotranspiration (m^3/day).

   K_{crop} is an empirical crop coefficient used to calibrate ET over vegetation land cover.

   The crop factor for bare soil and sealed areas has a default value of 0.2, while for open water it is 1. Over vegetation land cover ET_{pot} varies due to differences in vegetation characteristics, aerodynamic resistance, or surface reflectivity (albedo). Hence the K_{crop} is implemented to calibrate the crop coefficients used for ET_{pot}.

2. *Potential transpiration from plants*: it is determined using Equation 2.

   $$T_{ref} = ET_{ref} * Kc * K_s \quad \text{Equation 2}$$

   Where:

   T_{ref} is potential transpiration from vegetation cover (m^3/day).

   ET_{ref} is potential evapotranspiration (m^3/day).

   Kc is a crop-specific coefficient. This coefficient is available as a spatially distributed dataset for each land cover type every 10 days throughout the year derived from MIRCA2000, a global dataset of monthly irrigated and rainfed crop areas (Portmann et al., 2010).

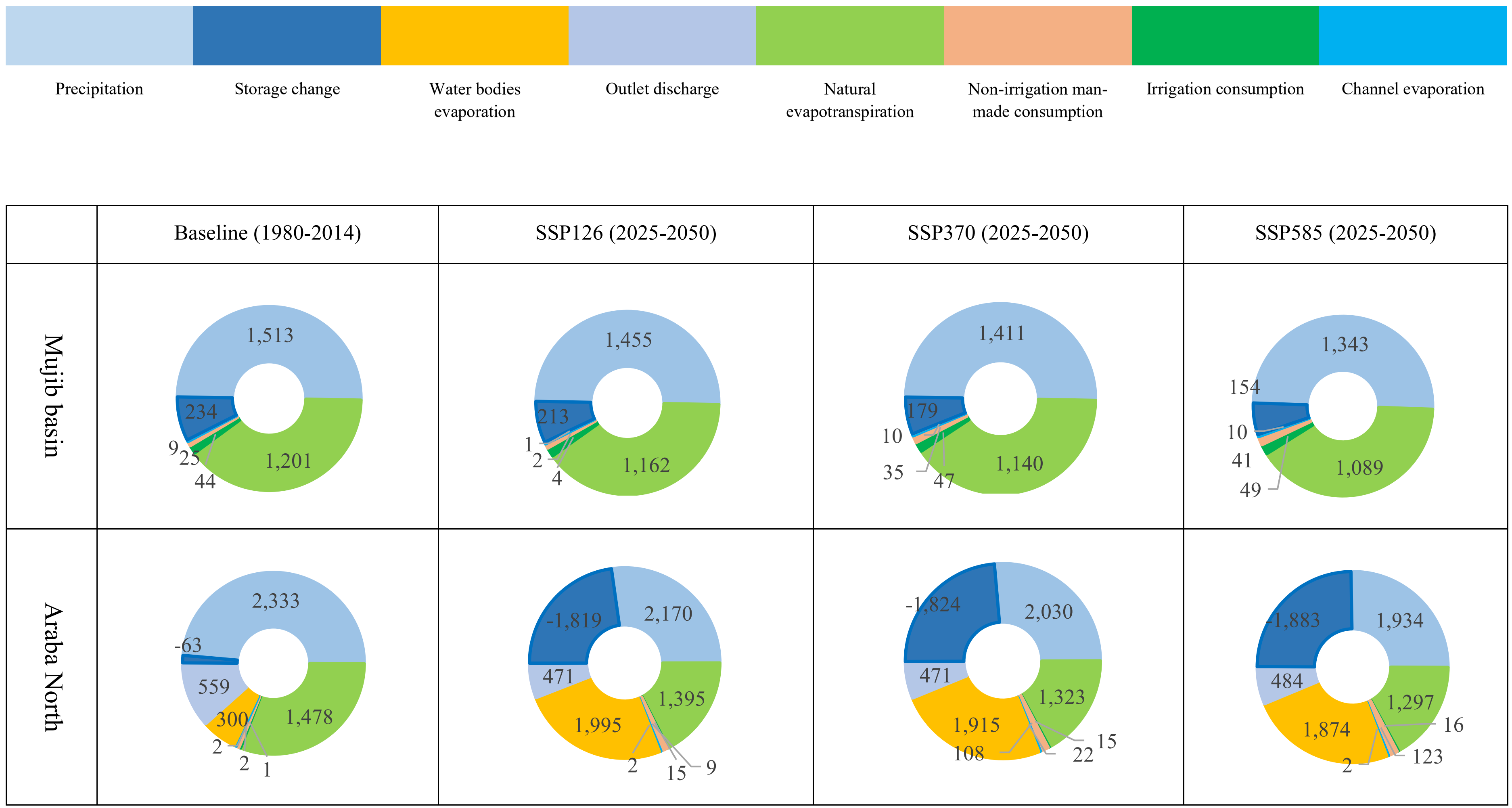
   K_s is a factor that limits transpiration based on water availability

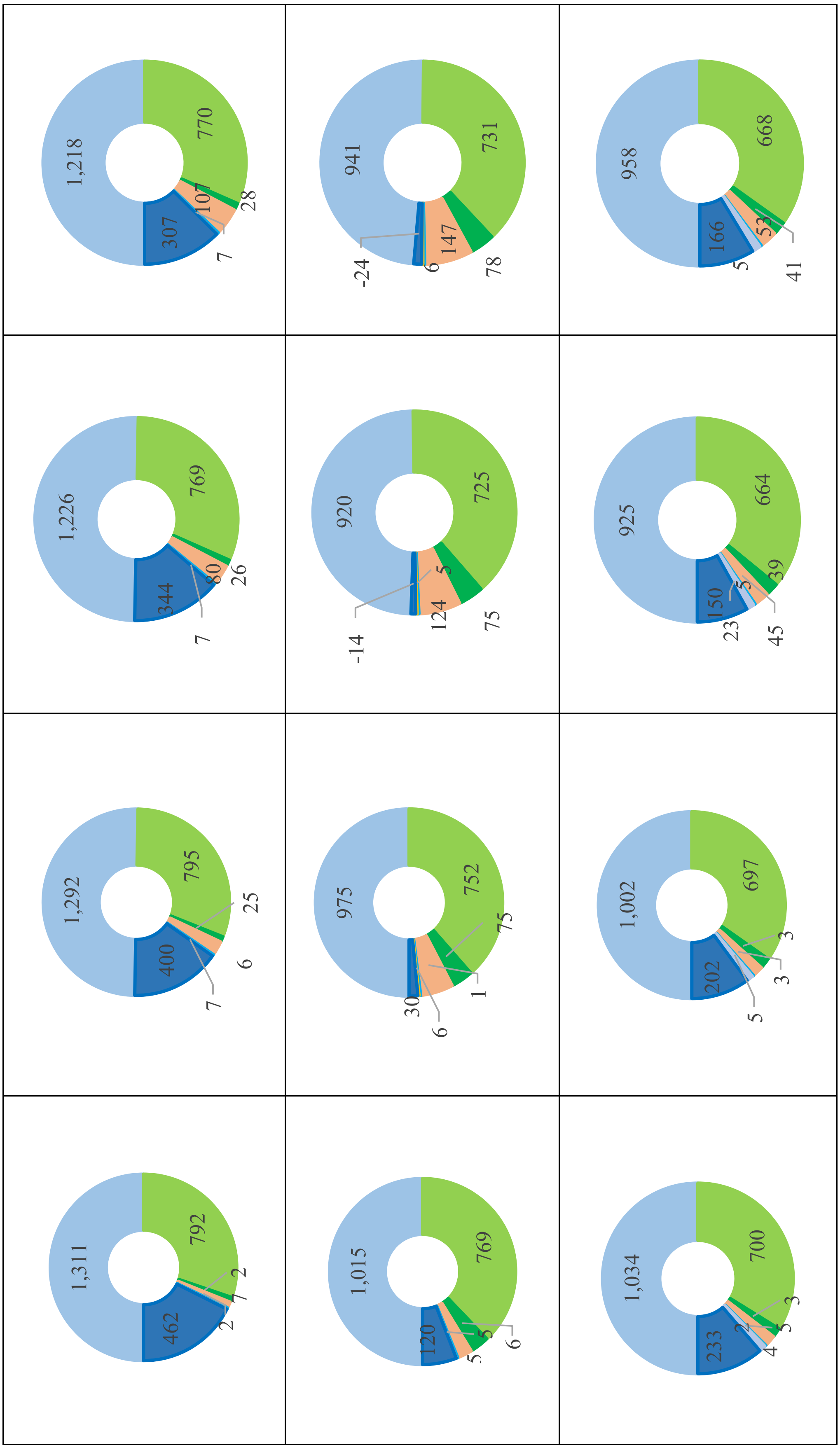
3. *Interception:* The interception calculations are based on Allen et al. (1998). Each land cover class has a defined maximum interception storage. This storage can be filled by rainfall and depleted by evaporation, using potential evaporation from open water. The remaining interception storage is then added to the water available for infiltration in the subsequent time step as throughfall.

4. *Soil processes:* CWatM considers three soil layers with a total fixed depth. The uppermost layer is 5 cm thick to allow comparison of soil moisture with remote sensing products for calibration and validation purposes. The second- and third-layers depths can also be adjusted using two calibration parameters. Soil thickness determines the storage capacity of a soil layer. Infiltration capacity of the soil is determined using concepts utilized in Arno Model (Zhao and Liu, 1995 and Todini, 1996). The saturated fraction of the upper two layers determines surface runoff. Part of the remaining soil moisture is redirected to the groundwater zone and determined based on a preferential flow factor. Actual infiltration is determined as the difference between water available for infiltration and preferential flow. Unsaturated flow is determined using Van Genuchten (1980) hydraulic functions based on the model of Mualem (1976) which implies that water flow in soil has consistent downward direction at a rate determined by the soil's conductivity, with free drainage serving as the lower boundary condition in the lowest soil layer. The approach generates the unsaturated soil conductivity for each soil zone which is used to simulate infiltration to the next zone. Capillary rise occurs only when groundwater is close to the ground surface (between 0-5 m). In this case, capillary rise is simulated based on unsaturated conductivity and field capacity (Wada et al., 2014).
5. Groundwater: Groundwater storage and baseflow are simulated using a linear reservoir model, similar to the methodology employed in LISFLOOD (De Roo et al., 2000; Udias et al., 2016). The groundwater zone receives water from percolation originating in the lower soil zone and preferential flow, while it is depleted through processes such as capillary rise and baseflow.
6. River routing: Flow through the river network is simulated using kinematic wave equations. River routing routine is performed on a sub-daily time step, based on the chosen spatial resolution.
7. Demand: Irrigation water demand is calculated by following the method developed in PCR-GLOBWB (Wada et al., 2011, 2014) using the MIRCA2000 crop calendar of Portmann et al. (2010) and irrigated areas from Siebert et al. (2005) to account for seasonal variability, different crops, and different climatic conditions. Livestock water demand is assumed to be the same as livestock water consumption and is calculated by the number of livestock in a grid cell with the daily drinking water requirement per individual livestock type (six livestock types in total) and per air temperature for seasonal change in drinking water requirement. The approach is taken from Wada et al. (2011). Calculation of industrial water demand also follows the method of Shen et al. (2008) and Wada et al. (2011) using the gridded industrial water demand data for 2000 from Shiklomanov (1997) and multiplying it by water use intensity. Water use intensity is a function of gross domestic product (GDP), electricity production, energy consumption, household consumption, and a technological development rate per country. Domestic water demand is calculated by multiplying the population in a grid cell by a country-specific per capita domestic water withdrawal rate taken from FAO (2007) and Gleick et al. (2009). Adjustments for air temperature and for country-based economic and technological development are carried out based on the approach of Wada et al. (2011).

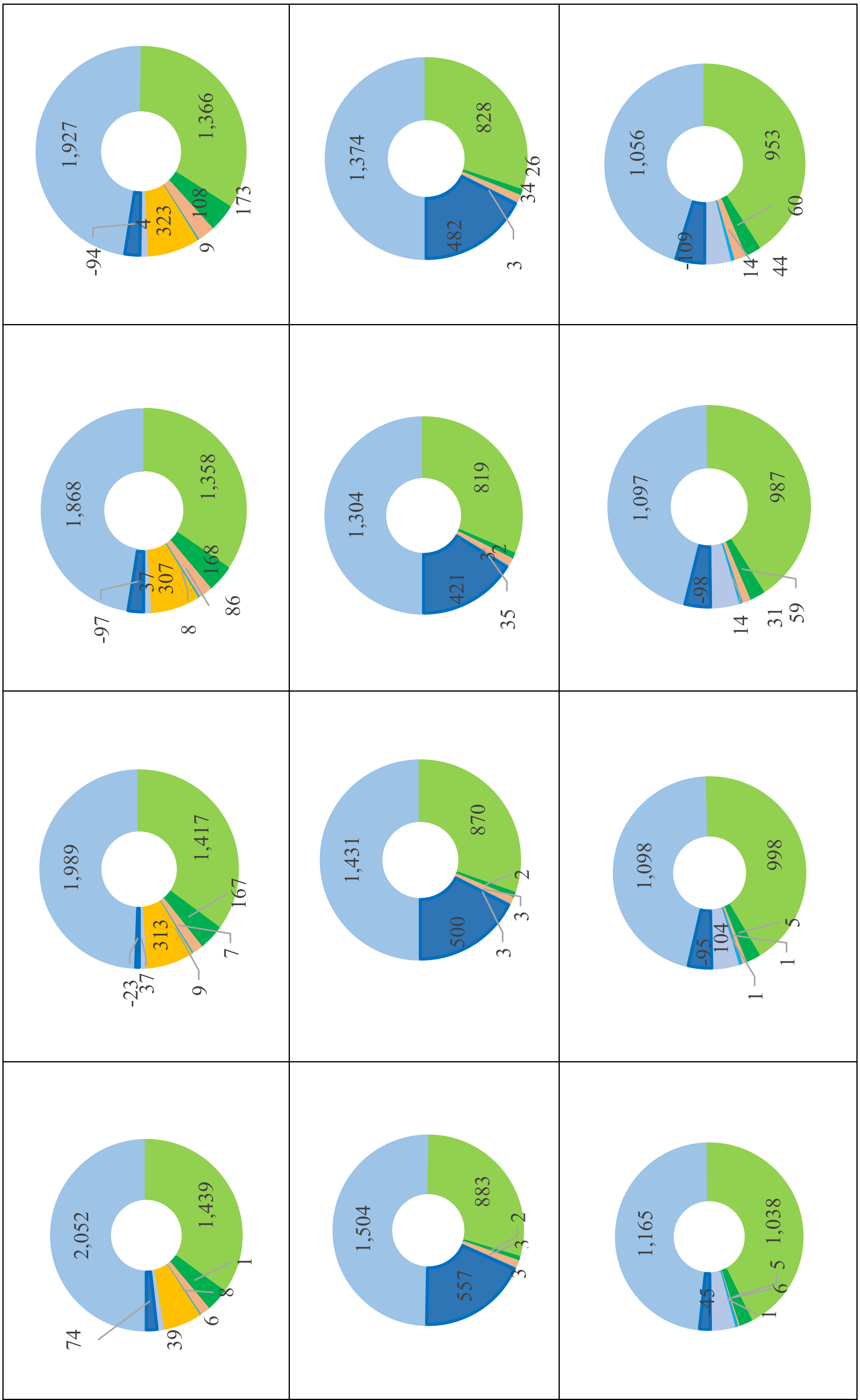
8. Withdrawals: The approach for calculating water withdrawal from different sources, water consumption, and return flows is based on the work of de Graaf et al. (2014), Wada et al. (2014), Sutanudjaja et al. (2018), and Hanasaki et al. (2018). Water demand can be fulfilled by surface water and groundwater. Based on the work of Siebert et al. (2010), groundwater for irrigation can be only used in areas that are equipped for irrigation. Groundwater is, at first, only abstracted from the renewable groundwater storage. Water demand that cannot be fulfilled purely from groundwater uses surface water from rivers, reservoirs, and lakes. If water demand still cannot be fulfilled, additional water is taken from non-renewable groundwater. At 5′ resolution, water demand cannot always be covered by surface or groundwater resources in the same grid cell; therefore, CWatM uses the approach of LISFLOOD (Burek et al., 2013) and takes water from up to five grid cells downstream moving along the local drainage direction. For irrigation, the return flow is calculated using the irrigation efficiency by Döll and Siebert (2002). For domestic and industrial use, the return rate is based on Shiklomanov (2000) (i.e., 90 % for the industrial sector and 85 % for the domestic sector). Fifty percent of return water from irrigation is lost to evaporation and 50 % is returned to the channel network. This assumption is taken from Hanasaki et al. (2018). 100% of domestic and industrial return flow is returned to the river channel network.

C.2 Water balance circles across the 14 surface water basins in the study area under the business-as-usual scenario (Mm³/year)

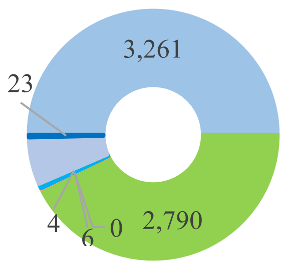
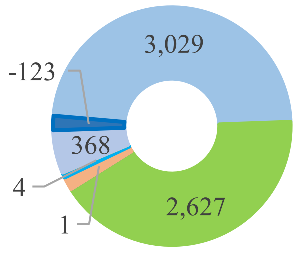
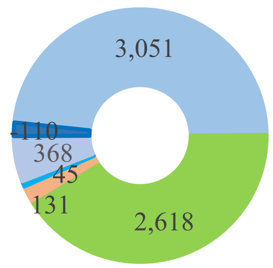
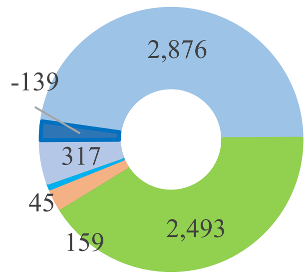
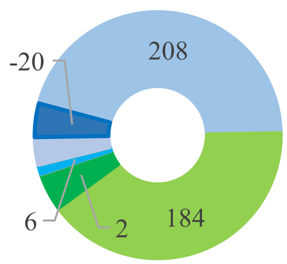
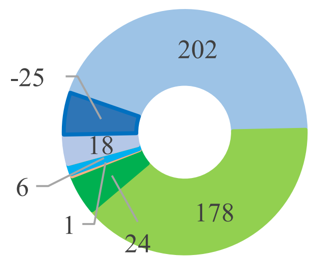
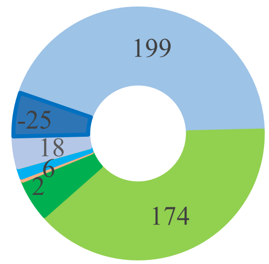
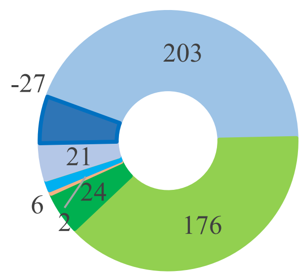
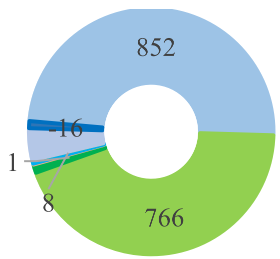
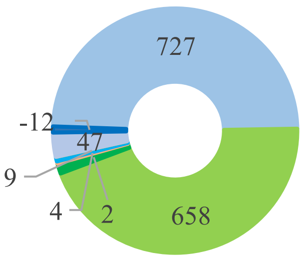
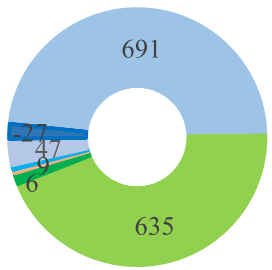
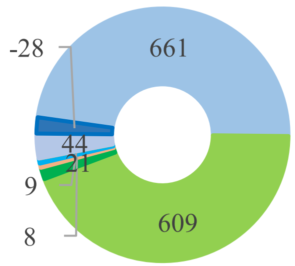




South JR Wadis	Amman Zarqa	North JR Wadis



Yarmouk	Lake Tiberias	Azraq

Hammad				
Disi				
Jafer				

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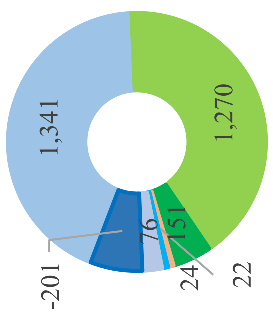
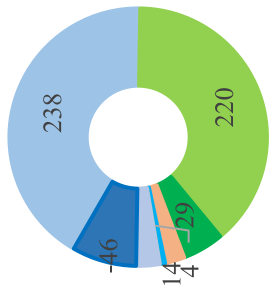
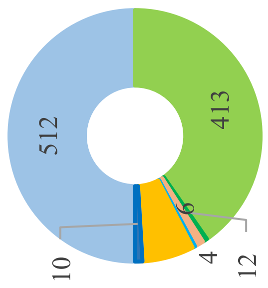
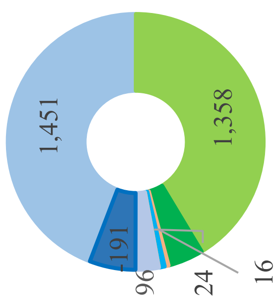
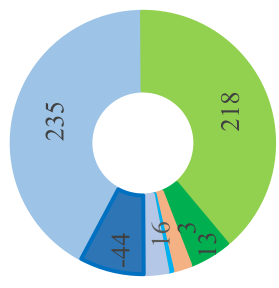
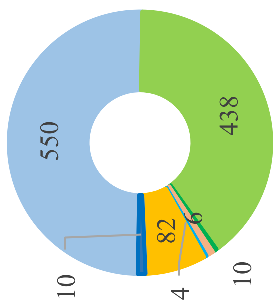
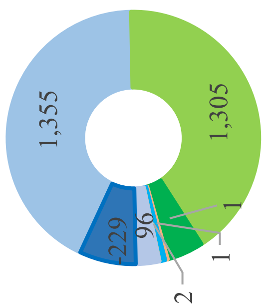
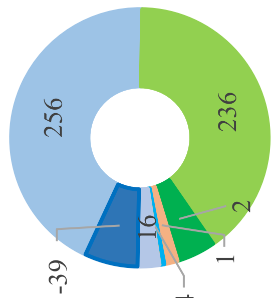
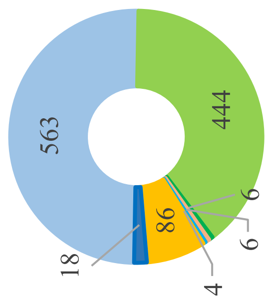
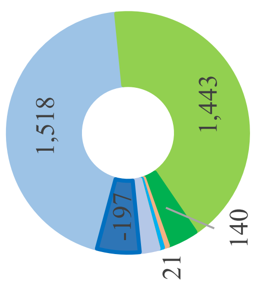
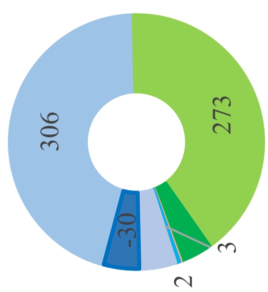
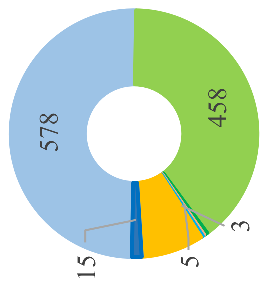
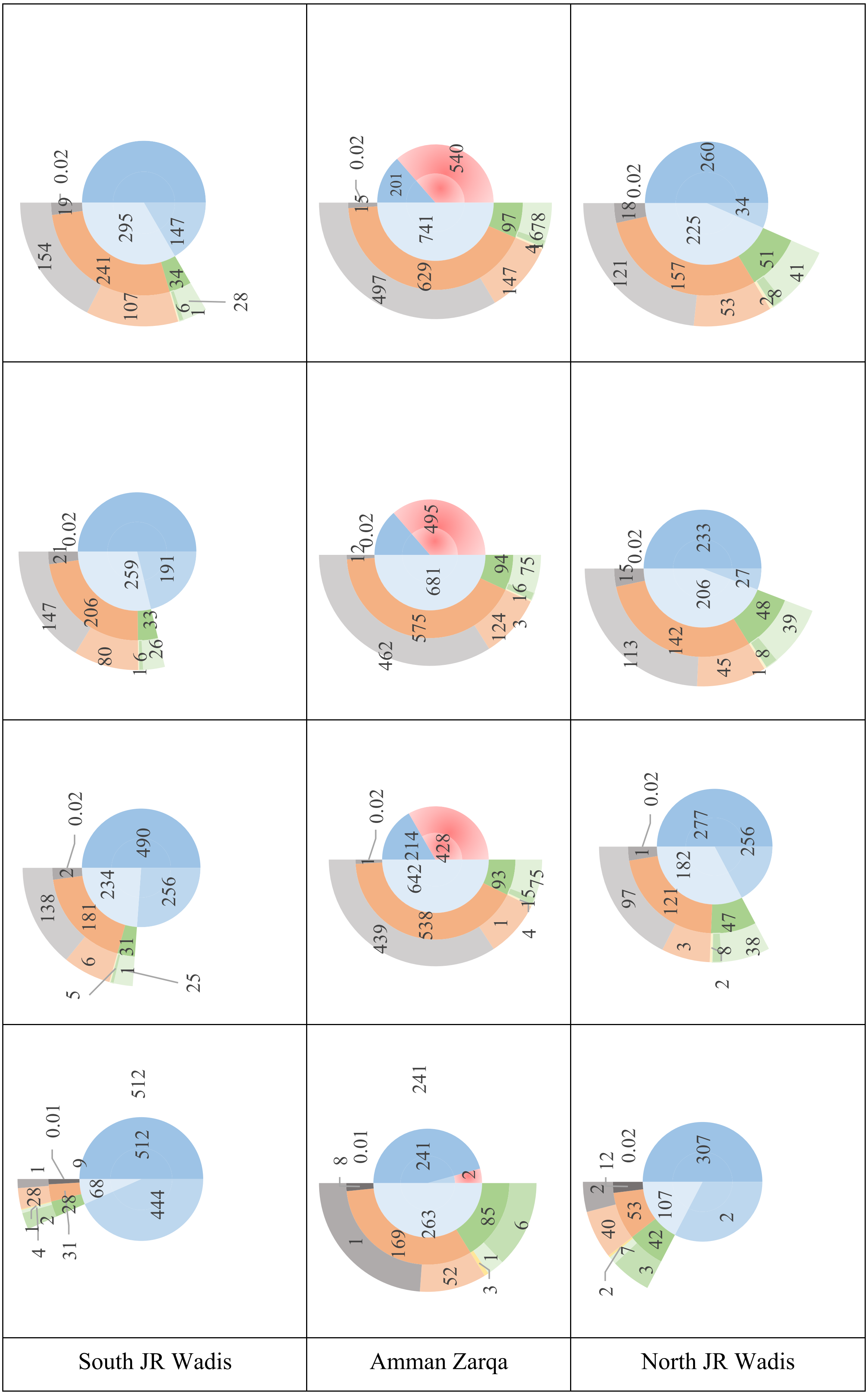
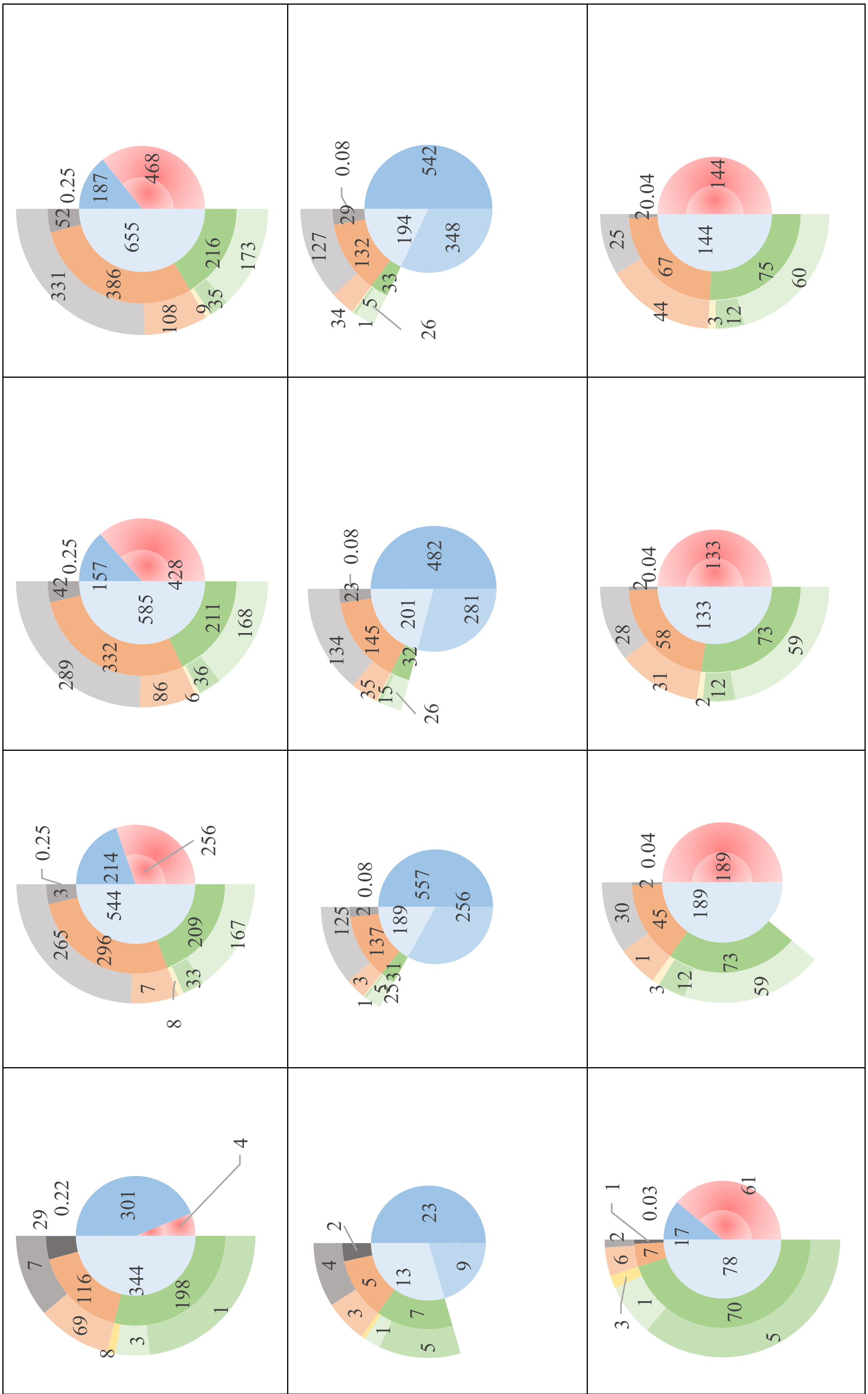
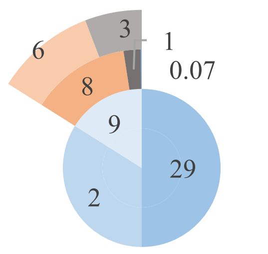
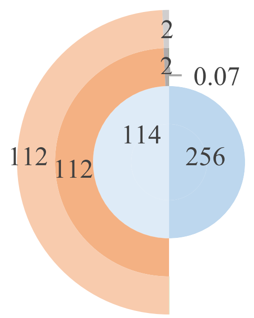
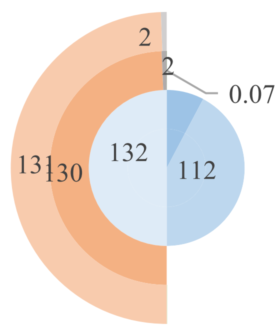
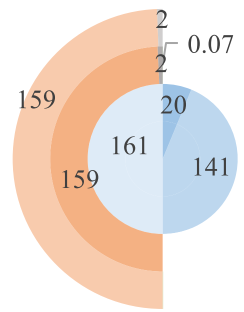
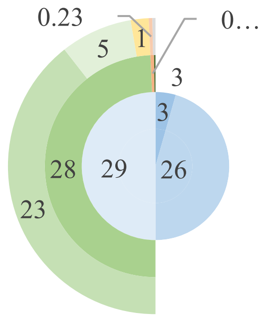
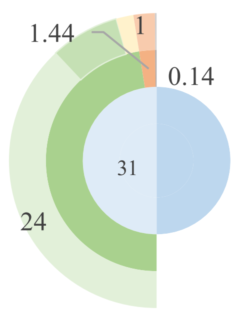
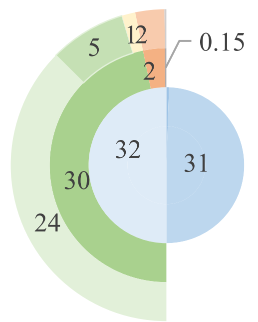
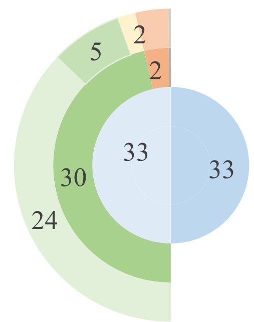
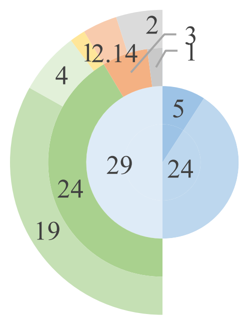
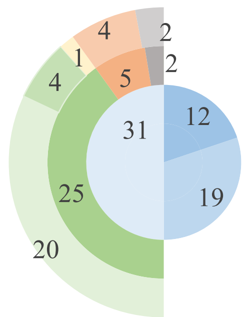
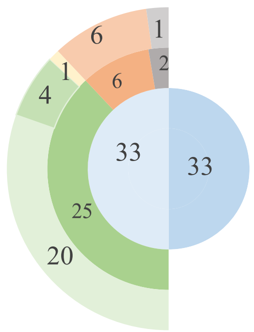
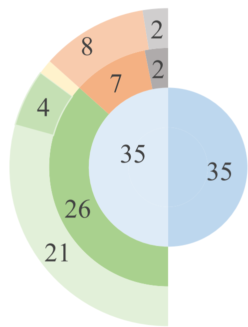
		
		
		
		
Sirhan	Araba South	Hasa

C.3 Available water and withdrawals circles across the 14 surface water basins in the study area under the business-as-usual scenario (Mm^3/year)


South JR Wadis
Amman Zarqa
North JR Wadis



Yarmouk	Lake Tiberias	Azraq

Hammad				
Disi				
Jafer				

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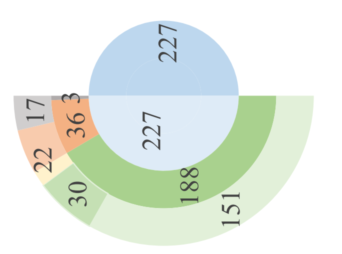
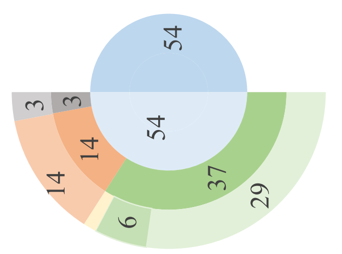
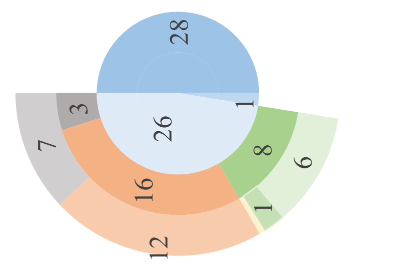
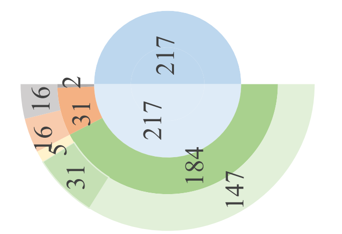
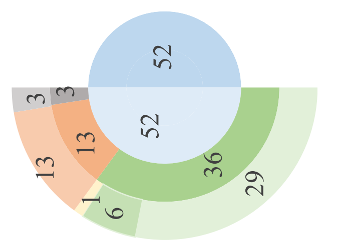
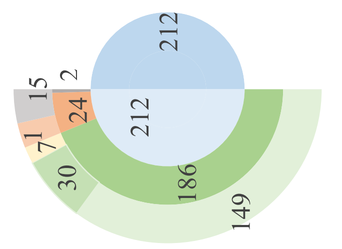
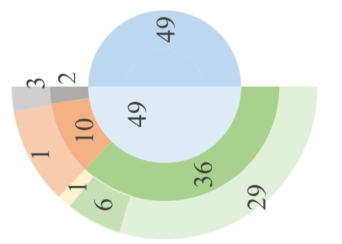
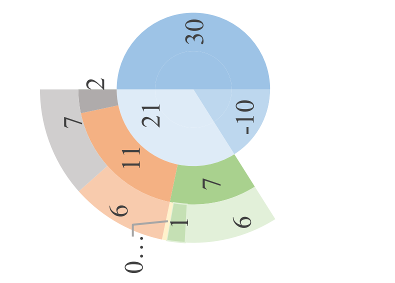
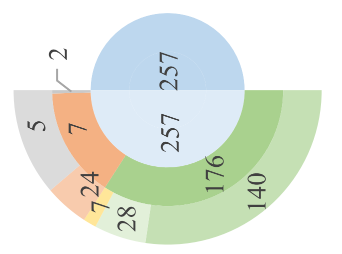
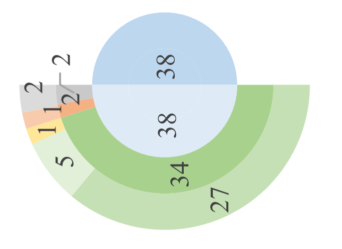
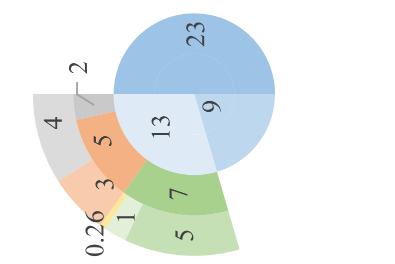
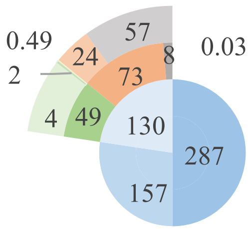
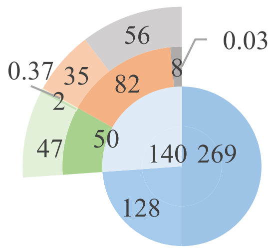
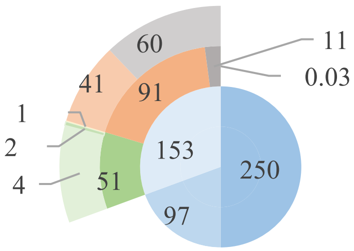
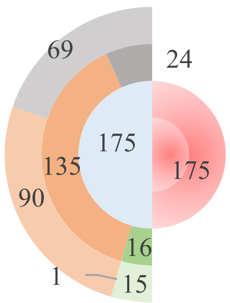
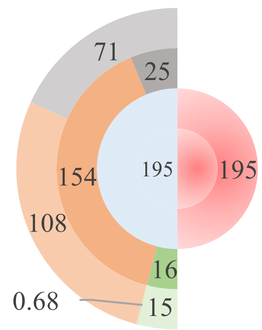
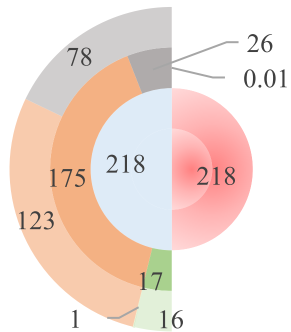
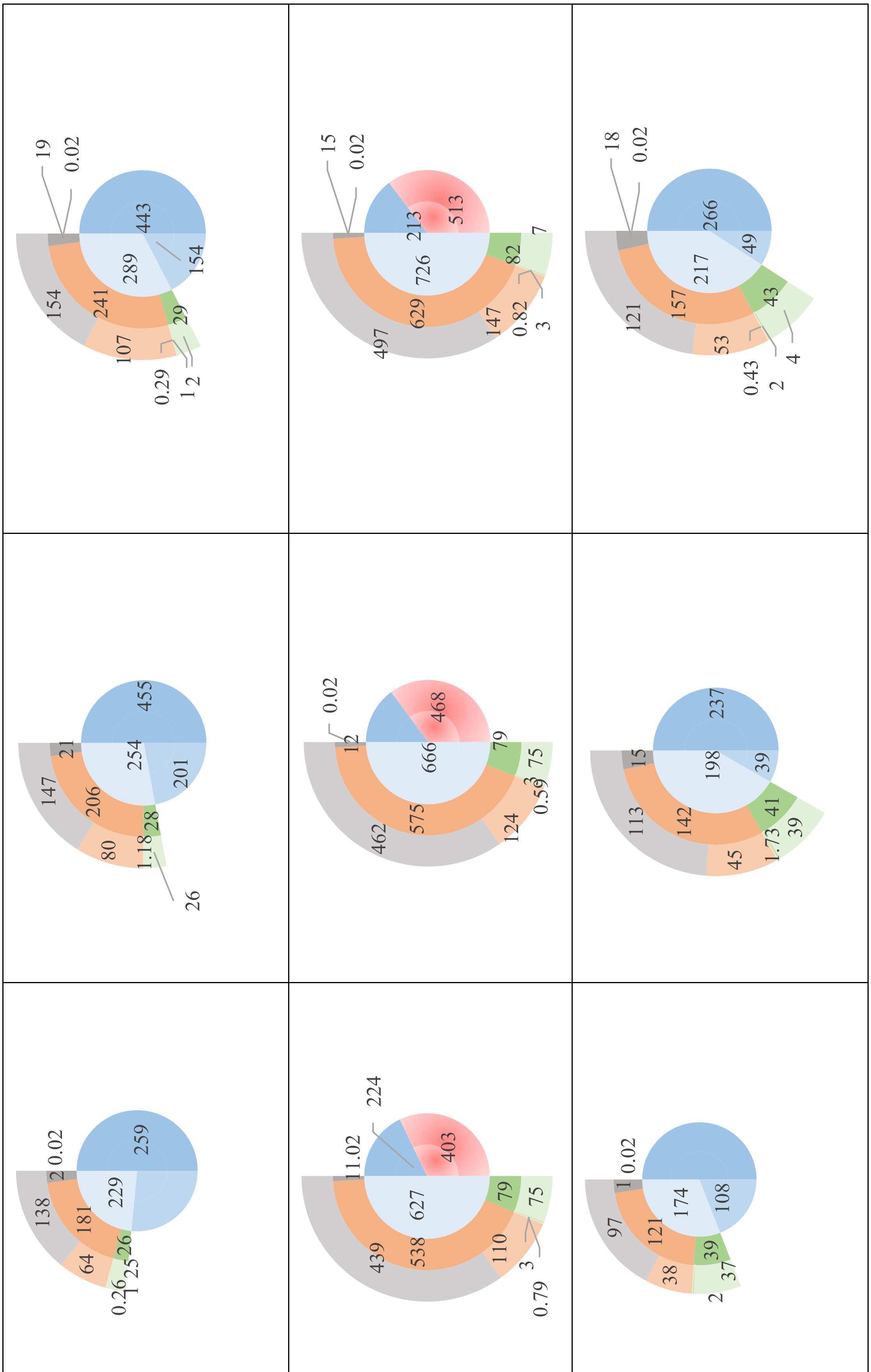
		
		
		
		

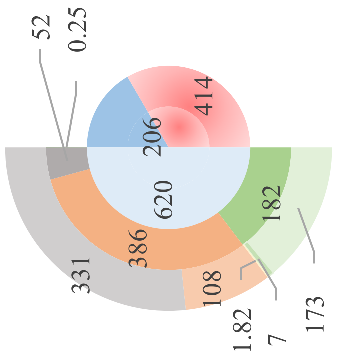
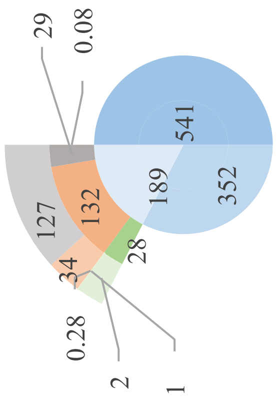
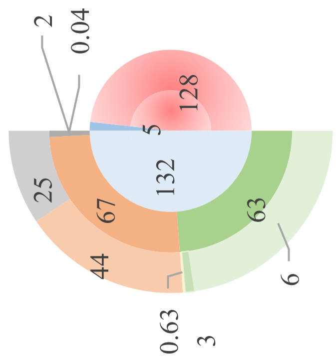
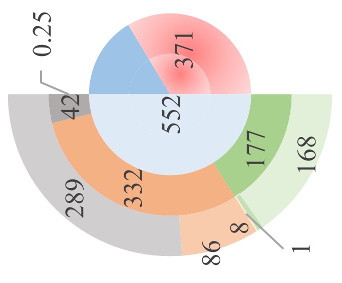
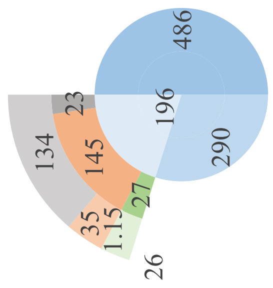
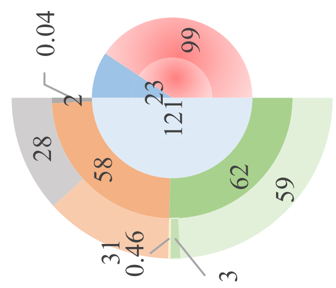
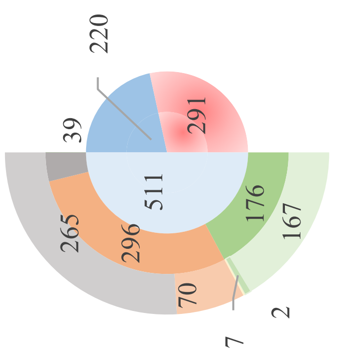
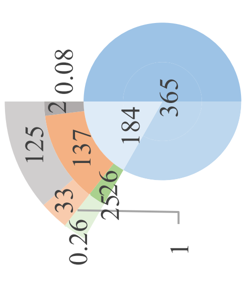
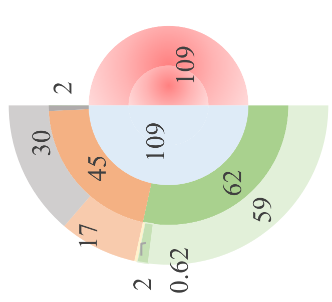
C.4 water resources and withdrawals circles across the 14 surface water basins in the study area under the management scenario

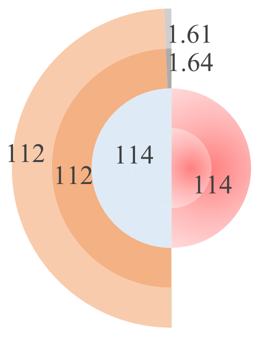
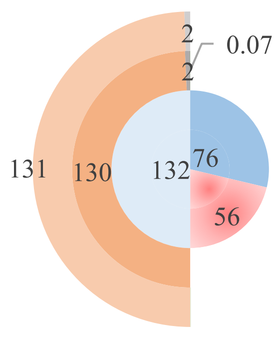
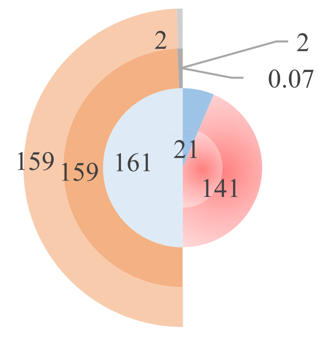
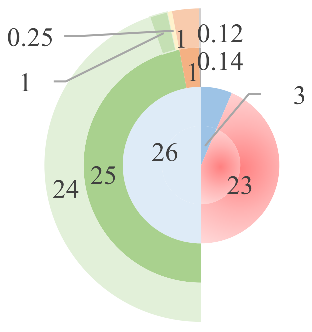
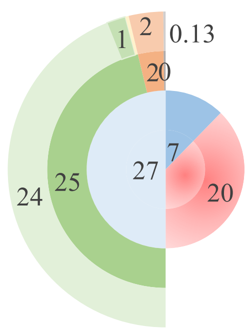
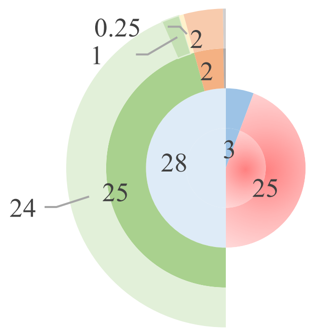
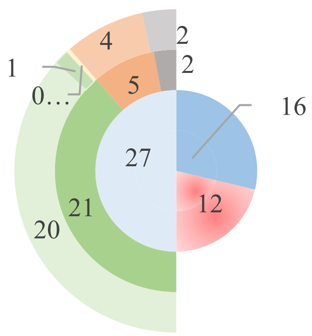
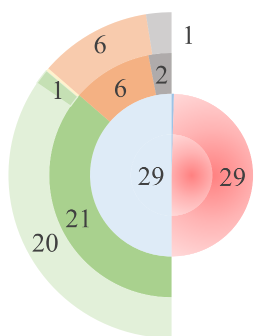
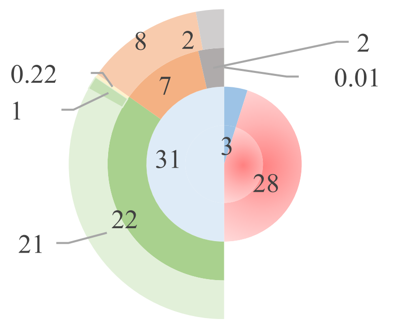
Renewable water | Surplus | Deficit compensation needs | Withdrawals | Irrigation withdrawals | Net irrigation consumption | Non-productive evaporation loss in irrigation | Irrigation return flow | Domestic withdrawals | Non-irrigation manmade consumption | Industrial withdrawals | Livestock withdrawals | Non-irrigation return flow

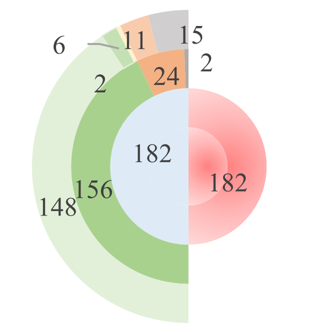
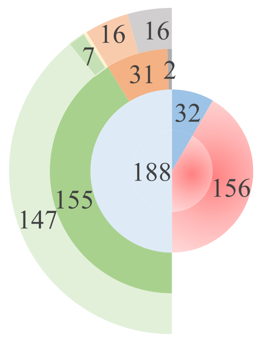
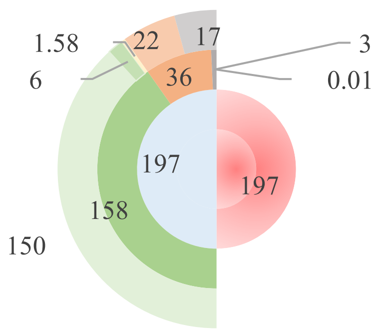
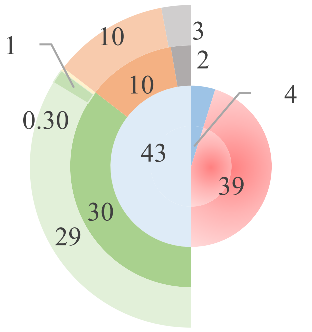
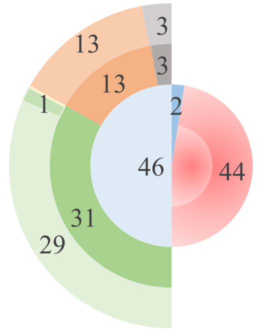
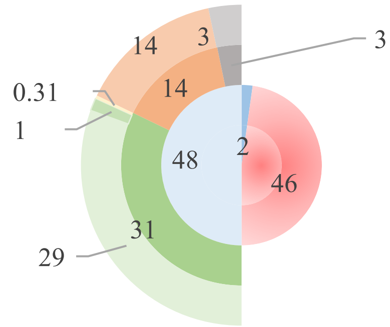
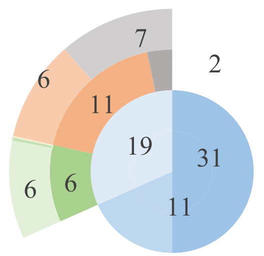
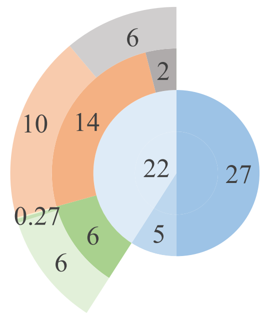
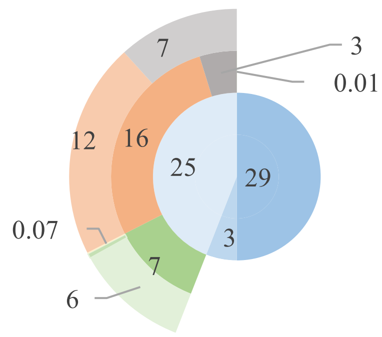
	SSP126	SSP370	SSP585
Mujib basin			
Araba North			



South JR Wadis	Amman Zarqa	North JR Wadis

Yarmouk	Lake Tiberias	Azraq
		
		
		

Hammad			
Disi			
Jafer			

Sirhan			
Araba South			
Hasa			

C.5 Key performance indicators in the 14 surface water basins in the study area under the baseline, business-as-usual, and management scenarios

Naturally consumed fraction							
Basin	Baseline	Business-as-usual			IE increase by 15%		
		SSP126	SSP370	SSP585	SSP126	SSP370	SSP585
Mujib	80%	81%	82%	82%	80%	81%	81%
Araba North	77%	157%	161%	165%	157%	161%	165%
South Jordan River Wadis	61%	62%	63%	64%	62%	63%	64%
Amman-Zarqa	76%	78%	80%	79%	77%	78%	77%
North River Wadis	68%	70%	72%	70%	70%	72%	70%
Yarmouk	83%	87%	90%	88%	87%	88%	87%
Lake Tiberias	59%	61%	63%	61%	62%	63%	61%
Azraq	90%	92%	91%	92%	91%	90%	91%
Hammad	87%	88%	87%	88%	88%	87%	88%
Disi	91%	91%	91%	90%	90%	89%	88%
Jafer	91%	92%	93%	93%	91%	93%	93%
Sirhan	96%	98%	95%	96%	96%	93%	95%
Araba South	90%	94%	94%	94%	92%	92%	92%
Hasa	96%	95%	95%	95%	95%	95%	94%
Available water fraction							
Basin	Baseline	Business-as-usual			IE increase by 15%		
		SSP126	SSP370	SSP585	SSP126	SSP126	SSP370
Mujib	20%	19%	18%	18%	20%	19%	19%
Araba North	0%	0%	0%	0%	0%	0%	0%
South Jordan River Wadis	39%	38%	37%	36%	38%	37%	36%
Amman-Zarqa	24%	22%	20%	21%	23%	22%	23%
North River Wadis	30%	28%	25%	27%	28%	26%	28%
Yarmouk	15%	11%	8%	10%	11%	10%	11%
Lake Tiberias	41%	39%	37%	39%	38%	37%	39%
Azraq	1%	0%	0%	0%	0%	2%	0%
Hammad	1%	0%	1%	1%	0%	2%	1%
Disi	1%	0%	0%	0%	2%	3%	2%
Jafer	1%	2%	0%	0%	2%	0%	0%
Sirhan	0%	0%	0%	0%	0%	2%	0%
Araba South	0%	0%	0%	0%	2%	1%	1%
Hasa	4%	5%	5%	5%	5%	5%	6%
Withdrawals fraction							
Basin	Baseline	Business-as-usual			IE increase by 15%		
		SSP126	SSP370	SSP585	SSP126	SSP126	SSP370
Mujib	33%	49%	57%	67%	45%	54%	65%
Araba North	NA	NA	NA	NA	NA	NA	NA
South Jordan River Wadis	13%	48%	58%	67%	47%	56%	71%
Amman-Zarqa	109%	300%	367%	369%	280%	359%	382%

North River Wadis	35%	66%	88%	87%	62%	85%	86%
Yarmouk	114%	254%	372%	350%	232%	351%	314%
Lake Tiberias	15%	34%	42%	36%	34%	41%	40%
Azraq	455%	NA	NA	NA	NA	NA	2883%
Hammad	32%	NA	645%	801%	NA	645%	796%
Disi	1128%	NA	9194%	NA	781%	7835%	883%
Jafer	547%	252%	NA	NA	174%	NA	1027%
Sirhan	NA	NA	NA	NA	NA	NA	NA
Araba South	NA	NA	NA	NA	NA	NA	2278%
Hasa	59%	68%	89%	95%	63%	85%	90%
Managed fraction							
Basin	Baseline	Business-as-usual			IE increase by 15%		
		SSP126	SSP370	SSP585	SSP126	SSP126	SSP370
Mujib	23%	25%	31%	37%	24%	31%	35%
Araba North	NA	NA	NA	NA	NA	NA	NA
South Jordan River Wadis	10%	18%	24%	30%	18%	24%	29%
Amman-Zarqa	50%	86%	108%	112%	82%	108%	111%
North River Wadis	24%	27%	36%	36%	27%	36%	36%
Yarmouk	75%	111%	162%	150%	108%	162%	136%
Lake Tiberias	10%	10%	13%	11%	10%	13%	13%
Azraq	364%	NA	NA	NA	NA	NA	2054%
Hammad	20%	NA	638%	792%	NA	638%	786%
Disi	898%	NA	7436%	NA	741%	7436%	838%
Jafer	402%	197%	NA	NA	156%	NA	913%
Sirhan	NA	NA	NA	NA	NA	NA	NA
Araba South	NA	NA	NA	NA	936%	NA	2052%
Hasa	35%	40%	61%	65%	39%	61%	58%

LIST OF ACRONYMS

AZ	Amman Zarqa
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CMIP6	Coupled Model Intercomparison Project Phase 6
CWatM	Community Water Model
CWR	Crop Water Requirement
ETa	Actual Evapotranspiration
GHG	Greenhouse Gas
GLDAS	Global Land Data Assimilation System
GRACE	Gravity Recovery and Climate Experiment
IE	Irrigation Efficiency
IPCC	Intergovernmental Panel on Climate Change
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project
IWRM	Integrated Water Resources Management
KAC	King Abdullah Canal
KGE	Kling-Gupta Efficiency
MENA	Middle East and North Africa
MWI	Ministry of Water and Irrigation
NSE	Nash-Sutcliffe Efficiency
PixSWAB	Pixel-Based Soil Water Balance
RCP	Representative Concentration Pathway
SMAP	Soil Moisture Active Passive
SSP	Shared Socioeconomic Pathway
TWS	Terrestrial Water Storage
TWW	Treated Wastewater
WA+	Water Accounting Plus
WaPOR	Water Productivity through Open access of Remotely sensed derived data
WCT	Water Conservation Technology

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ABOUT THE AUTHOR

Nafn Amdar was born and raised in Homs, Syria. She earned her Bachelor's degree in Civil Engineering, specializing in Irrigation and Drainage, from Homs University, Syria, in 2007. She then completed a Master's degree in Environmental Sciences and Management at the Hashemite University, Jordan, in 2013.

From 2008 to 2012, Nafn worked as an irrigation engineer at the Syrian General Authority for Agricultural Research – Irrigation Research Center. She then joined ARCADIS Jordan as a senior wet utilities engineer, serving from 2013 to 2017. In 2018, she moved to the International Water Management Institute (IWMI) as a senior research officer focusing on water resources management and accounting, a position she continues to hold.

Nafn began her PhD in 2021 at IHE Delft and TU Delft, where her research focused on water management in Jordan, with an emphasis on enhancing water information and assessment tools to support improved water resources planning. She completed her PhD in 2026 and will assume a regional researcher role at IWMI, concentrating on integrated water modelling.

Nafn received the Schlumberger Faculty for the Future Award, which supported her PhD research from 2022–2025. She is also a recipient of the 2021 World Food Forum Transformative Research Award for young researchers, in recognition of her research on water conservation in Jordan.

Journals publications

Amdar, N., Mul, M., Al-Bakri, J., Uhlenbrook, S., Rutten, M., and Jewitt, G.: Water Accounting Plus: limitations and opportunities for supporting integrated water resources management in the Middle East and North Africa. *Water International*, *49*(7), 880-907, 2024.

Amdar, N., Seyoum, S., Al-Bakri, J., Rutten, M., Jewitt, G., and Mul, M.: Developing a water budget for the Amman-Zarqa basin using water accounting plus and the pixel-based soil water balance model. *Modeling Earth Systems and Environment*, 1-21, 2024.

Amdar, N., Anwar, A., Elmahdi, A., Al-Bakri, J., Jewitt, G., and Mul, M.: Insights into the potential of water conservation in irrigated agriculture: a case study from the arid Mediterranean highlands. *Water Conservation Science and Engineering*, *10*(2), 1-16, 2025.

Conference proceedings

Amdar, N., Mul, M., Uhlenbrook, S., Rutten, M., Al-Bakri, J., and Jewitt, G.: *Relevance of Water Accounting Plus in the MENA region: A pragmatic analysis in light of the region's challenges to sustainable water management* (No. IAHS2022-588). Copernicus Meetings, 2022.

Amdar, N., Mul, M., Seyoum, S., Al-Bakri, J., Jewitt, G., Rutten, M., and Uhlenbrook, S.: Water accounting plus for improved water budget reporting in the Amman-Zarqa Basin–Jordan. In *XXVIII General Assembly of the International Union of Geodesy and Geophysics (IUGG)*. GFZ German Research Centre for Geosciences, 2023.

Amdar, N., Smilovic, M., and Mul. M.: Assessment of water stress in Jordan using a global hydrological model: The Community Water Model. In *XXVIII General Assembly of the International Union of Geodesy and Geophysics (IUGG)*. GFZ German Research Centre for Geosciences, 2023, July.

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Delft, 13 April 2026

SENSE coordinator PhD education

Dr Ir Peter Vermeulen

The SENSE Director

Dr Jampel Dell'Angelo

The SENSE Research School declares that **Nafn M. Amdar** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a workload of 41.2 EC, including the following activities:

SENSE PhD Courses

- A1: Environmental Research in Context (2021)
- A2 Research in context activity: 'Co-design Workshop Report on Irrigation Performance Assessment Tool in North Jordan Valley, Jordan' (2024)

Other PhD and Advanced MSc Courses

- Integrated Systems Modelling, IIASA (2020/2021)
- PhD Start-up ,TU Delft (2024)
- Scientific writing, IHE Delft (2022)
- Remote Sensing for Agricultural Water Management, IHE Delft Institute for Water Education (2020/2021)
- Remote Sensing for Water Resources Management, IHE Delft Institute for Water Education (2022)

Management and Organisational activities

- Organsing a session on Cairo Water Week 'From satellites to fields, innovations supporting farmers and water managers' (2024)
- Organising a session at the Baghdad International Water Conference 'From Idea to Impact: Co-Creating Water Innovations with People at the Centre' (2025)

Oral Presentations

- *Water Accounting Plus: Limitations and Opportunities to Support IWRM in the MENA*. IAHS/Montpellier, May 29th- June 3rd 2022, Montpellier, France
- *Navigating Jordan's Water Futures using CWatM*. IUGG/Berlin, 13-16 July 2023, Berlin, Germany
- *Institutionalization of WA+ - Jordan as a case study*. Stockholm Water Week, 24 August 2025, Online,

IHE DELFT

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Water scarcity in Jordan poses a significant challenge to its socio-economic development and resource sustainability. Addressing this issue requires robust planning based on reliable information. However, current assessments are hampered by fragmented data, and inconsistencies in scale and methodology.

This thesis advances water accounting and modelling methods to support evidence-based planning for Jordan's water sector. It critically reviews current water resource assessment practices, highlighting shortcomings in national water budgeting and gaps in representing human water use. The thesis evaluates the suitability of Water Accounting Plus for overcoming information limitations in Jordan and the broader MENA region. A tailored WA+ resource base sheet is developed for Jordan to improve water budget reporting, pinpoints both climatic and anthropogenic scarcity drivers and support decision-making.

The thesis further assesses water conservation in irrigated agriculture to improve water availability through a field-based study. These outcomes inform simulations with the Community Water Model, projecting water availability and demand through 2050 and evaluating the long-term impact of irrigation water conservation. The findings indicate that water security in Jordan will depend on a combination of efficiency gains, supply enhancement, wastewater reuse, and stronger governance. The thesis provides a reproducible framework for water planning in similar contexts.

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