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Advancing water resources management in arid regions through stakeholder engagement, digitalization, and policy integration: Jordan as a case study.

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opportunities might come your way, but they might slip through your fingers if you are unprepared.

… be prepared

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Abstract

Applying integrated water resources management (IWRM) is complex, especially in arid regions where groundwater is the primary water source, recharge occurs very slowly, and surface water is barely available. In such a scenario, the government does not have many options for water management besides overexploiting the groundwater aquifer to cover the water demand. The increasing gap between supply and demand further complicates the effective application of IWRM. This dissertation demonstrates the potential for improving the existing water management practices in arid regions by bringing together science, policy, and digitalization, focusing on Jordan as a case study. The implemented approach includes technical, institutional, and economic components and targets three levels: national, river basin, and wellfield.

At the national level, a comprehensive groundwater resources assessment for Jordan was carried out. The assessment results identified areas that are highly impacted by over-abstraction and specified the consequences of the abstraction on the groundwater system. The basalt plateau and Wadi Al Arab area are determined as the most affected areas in Jordan. At the basalt plateau, the over-abstraction reversed the groundwater flow regime towards the northwest of the Azraq basin instead of the original flow toward the basin's center. In contrast, the over-abstraction in the Wadi Al Arab wellfield shifted the confinement limit northward and changed the hydraulic conditions of the southern wells of Wadi Al Arab from confined to unconfined. As an outcome, heavy metal concentration increased in these wells. To meet the increased demand, the Jordanian government opted to drill deep wells for drinking water purposes in the northern part of the Azraq Basin. Given that the hydraulic condition is confined in that area, it is assumed, due to the over-abstraction, that a shift of the confinement limit eastward would change the confinement condition in the western part of the planned wellfield, potentially deteriorating the water quality, similar to the case of the Wadi Al Arab.

Governmental strategic decisions at the national level, such as the plan to drill deep drinking water wells in the Azraq Basin must be evidence-based. Therefore, at the river basin level, a methodology for assessing the relationship between the decision-makers and researchers was developed. The methodology defined the water-decision research gaps as the inability to decide on governmental water strategy goals through conducting a systematic peer and grey literature review at the basin level, and it was tested at the Azraq basin. The impact of the national water strategy (2008-2022) on the conducted research in the basin was also examined. The results show that the number of published water-related research documents increased from 37 between 1985 and 2007 to 62 between 2008 and 2018. However, this increase may not necessarily demonstrate a positive influence from the water strategy, as it aligns with the overall trend of increasing research production in Jordan. The methodology then introduces a matrix that links specific research focus areas with the government's water strategy topics, aiming to encourage the creation of innovative and demand-driven research in the future; it also enables researchers to identify and address research gaps,

strengthen the connection between the focus areas and the water strategy goals, and contribute to solving societal challenges.

At the wellfield level, a combination of bottom-up and top-down approaches was implemented to improve the monitoring, operation, and maintenance procedures in the Wadi Al Arab wellfield. The results showed that the implemented new monitoring system in 2017 has remarkably increased the data availability compared to the data collected before 2017. For instance, the total number of collected and stored dynamic groundwater level (DWL) measurements of the wellfield was 96 measurements for five years from 2012 to 2016; in contrast, the number of DWL measurements for years 2017 and 2018 was 266 and 230 measurements, respectively. Besides improving the monitoring system, a simple operational decision support toolbox that combines a wellfield information system (WFIS) in MS Access and an operational decision support tool (ODST) in MS Excel systems reduced the maintenance time of the wells from an average of 5.2 days/maintenance/well in 2012 to less than one day/maintenance/well in 2017. Such results verified the need to move toward digitalization in the water sector to improve wellfield management; therefore, the Decision Support Software and Database for Wellfield Management (DeMa) was developed. DeMa is the first software designed specifically for managing wellfields and individual wells. The software is divided into four modules (i) Database Management Tool (DbMT) to provide an organized platform to search, modify and retrieve wellfield data, (ii) Observation Based tool (OBT) to visualize the database in graphs, (iii) Research-Based tool (RBT), which is a user-friendly tool to help wellfield managers to apply novel research methodologies to the user's study area without needing technical skills in programming or mathematics, and (v) Documents Management Tool (DMT) to manage all documents related to the wells. The software is designed in modular sections, so it can be further developed by plugging in additional tools and options in subsequent versions. DeMa was tested using data and information from the Wadi Al Arab wellfield and contributed to providing an overview of wellfield management, operation, monitoring, and maintenance practices through its various tools.

The dissertation shows the vital role of multilevel stakeholder involvement in improving Jordan's groundwater monitoring system. At the same time, it emphasizes the importance of digital transformation for maintaining the communication channels between the stakeholders and helping the users visualize data and make informed decisions. Such an approach was tested on a wellfield level. It is recommended to apply this approach to other wellfields in Jordan. On the national level, it is crucial to regularly conduct water resources assessment studies for the whole country to be considered in the national water strategy and to guide other researchers to focus on the most important and critical areas. Simultaneously, researchers should support the government by considering the goals that the government aims to achieve in the strategy when conducting studies. Finally, it is recommended to establish a national water knowledge translation committee including members from research institutes and the MWI within the organizational hierarchy of the MWI that aims to use the research conducted within research institutes.

Zusammenfassung

Die Anwendung des integrierten Wasserressourcenmanagements (IWRM) ist komplex, insbesondere in Trockengebieten, in denen das Grundwasser die wichtigste Wasserquelle ist, dessen Neubildung sehr langsam erfolgt und Oberflächenwasser kaum verfügbar ist. In einem solchen Szenario hat die Regierung nicht viele Optionen für die Wasserbewirtschaftung außer der Übernutzung des Grundwasser-Aquifers zur Deckung des Wasserbedarfs. Die zunehmende Kluft zwischen Angebot und Nachfrage erschwert die wirksame Anwendung des IWRM zusätzlich. Diese Dissertation zeigt das Potenzial für die Verbesserung der bestehenden Wassermanagementpraktiken in Trockengebieten auf, indem sie die Wissenschaft, Politik und Digitalisierung am Beispiel Jordaniens zusammenführt. Der umgesetzte Ansatz umfasst technische, institutionelle und wirtschaftliche Komponenten und zielt auf drei Ebenen ab: die nationale, die Flussgebiets- und die Brunnenebene.

Auf nationaler Ebene wurde eine umfassende Bewertung der Grundwasserressourcen in Jordanien durchgeführt. Dabei wurden Gebiete ermittelt, die in hohem Maße von übermäßiger Entnahme betroffen sind, und die Folgen der Entnahme für das Grundwassersystem beschrieben. Das Basaltplateau und das Wadi Al Arab wurden als die am stärksten betroffenen Gebiete in Jordanien ermittelt. Auf dem Basaltplateau führte die Überentnahme zu einer Umkehrung des Grundwasserflusses in Richtung Nordwesten des Azraq-Beckens anstelle des ursprünglichen Flusses in Richtung des Beckenzentrums. Im Gegensatz dazu wurde durch die Überentnahme im Wadi Al Arab die Begrenzungsgrenze nach Norden verschoben, und die hydraulischen Bedingungen der südlichen Brunnen des Wadi Al Arab wurden von gespannt zu ungespannt geändert. Infolgedessen stieg die Schwermetallkonzentration in diesen Brunnen. Um den gestiegenen Bedarf zu decken, beschloss die jordanische Regierung, im nördlichen Teil des Azraq-Beckens Tiefbrunnen für Trinkwasserzwecke zu bohren. Da die hydraulischen Bedingungen in diesem Gebiet gespannt sind, wird davon ausgegangen, dass eine Verschiebung der Grenze des artesisch gespannten Grundwassers nach Osten die Spannungbedingungen des Grundwassers im westlichen Teil des geplanten Brunnenfeldes verändern wird, was zu einer Verschlechterung der Wasserqualität führen könnte, ähnlich wie in Wadi Al Arab.

Strategische Entscheidungen der Regierung auf nationaler Ebene, wie z. B. der Plan, tiefe Trinkwasserbrunnen im Azraq-Becken zu bohren, müssen auf Fakten beruhen. Daher wurde auf der Flusseinzugsgebietsebene eine Methode zur Bewertung der Beziehungen zwischen den Entscheidungsträgern und den Forschern entwickelt. Die Methode definierte die Forschungslücken im Bereich Wasserentscheidungen als die Unfähigkeit, über die Ziele der staatlichen Wasserstrategie zu entscheiden, indem eine systematische Überprüfung der Peer- und grauen Literatur auf der Ebene des Einzugsgebiets durchgeführt wurde, und wurde im Azraq-Becken getestet. Die Auswirkungen der

nationalen Wasserstrategie (2008-2022) auf die im Einzugsgebiet durchgeführte Forschung wurden ebenfalls untersucht. Die Ergebnisse zeigen, dass die Zahl der veröffentlichten wasserbezogenen Forschungsdokumente von 37 zwischen 1985 und 2007 auf 62 zwischen 2008 und 2018 gestiegen ist. Dieser Anstieg ist jedoch nicht unbedingt ein Beweis für einen positiven Einfluss der Wasserstrategie, da er mit dem allgemeinen Trend einer steigenden Forschungsproduktion in Jordanien übereinstimmt. Die Methodik führt dann eine Matrix ein, die spezifische Forschungsschwerpunkte mit den Themen der Wasserstrategie der Regierung verknüpft und darauf abzielt, die Schaffung innovativer und bedarfsorientierter Forschung in der Zukunft zu fördern; sie ermöglicht es den Forschern auch, Forschungslücken zu identifizieren und anzugehen, die Verbindung zwischen den Schwerpunktbereichen und den Zielen der Wasserstrategie zu stärken und zur Lösung gesellschaftlicher Herausforderungen beizutragen.

Auf der Ebene des Brunnenfeldmanagements wurde eine Kombination aus Bottom-up- und Top-down-Ansätzen umgesetzt, um die Überwachungs-, Betriebs- und Wartungsverfahren im Brunnenfeld Wadi Al Arab zu verbessern. Die Ergebnisse zeigten, dass das 2017 eingeführte neue Überwachungssystem die Datenverfügbarkeit im Vergleich zu den vor 2017 gesammelten Daten deutlich erhöht hat. So betrug beispielsweise die Gesamtzahl der gesammelten und gespeicherten dynamischen Grundwasserstandsmessungen (DWL) des Brunnenfelds 96 Messungen in den fünf Jahren von 2012 bis 2016; im Gegensatz dazu betrug die Anzahl der DWL-Messungen in den Jahren 2017 und 2018 266 bzw. 230 Messungen. Neben der Verbesserung des Überwachungssystems konnte durch eine einfache Toolbox zur Unterstützung operativer Entscheidungen, die ein Brunnenfeld-Informationssystem (WFIS) in MS Access und ein Tool zur Unterstützung operativer Entscheidungen (ODST) in MS Excel kombiniert, die Wartungszeit der Brunnen von durchschnittlich 5,2 Tagen pro Wartung pro Brunnen im Jahr 2012 auf weniger als einen Tag/Wartung/Brunnen im Jahr 2017 reduziert werden. Diese Ergebnisse bestätigten die Notwendigkeit, die Digitalisierung im Wassersektor voranzutreiben, um die Verwaltung der Brunnenfelder zu verbessern; daher wurde die Software zur Entscheidungsunterstützung und Datenbank für die Verwaltung von Brunnenfeldern (DeMa) entwickelt. DeMa ist die erste Software, die speziell für die Verwaltung von Brunnenfeldern und einzelnen Brunnen entwickelt wurde. Die Software ist in vier Module unterteilt: (i) Database Management Tool (DbMT) zur Bereitstellung einer organisierten Plattform für die Suche, Änderung und den Abruf von Brunnenfelddaten, (ii) Observation Based Tool (OBT) zur grafischen Darstellung der Datenbank, (iii) Research-Based Tool (RBT), ein benutzerfreundliches Tool, das Brunnenfeldmanagern hilft, neue Forschungsmethoden auf das Untersuchungsgebiet des Benutzers anzuwenden, ohne dass technische Kenntnisse in Programmierung oder Mathematik erforderlich sind, und (v) Documents Management Tool (DMT) zur Verwaltung aller Dokumente im Zusammenhang mit den Brunnen. Die Software ist in modularen Abschnitten aufgebaut, so dass sie in späteren Versionen durch zusätzliche Werkzeuge und Optionen weiterentwickelt werden kann. DeMa wurde anhand von Daten und Informationen aus dem Wadi Al Arab-Brunnenfeld getestet und trug mit seinen verschiedenen Werkzeugen dazu bei, einen Überblick über das Management, den Betrieb, die Überwachung und die Wartungspraktiken des Brunnenfelds zu geben.

Die Dissertation zeigt, wie wichtig die Beteiligung der verschiedenen Interessengruppen bei der Verbesserung des jordanischen Grundwasserüberwachungssystems ist. Gleichzeitig wird die Bedeutung der digitalen Transformation für die Aufrechterhaltung der Kommunikationskanäle zwischen den Interessengruppen und die Unterstützung der Nutzer bei der Visualisierung von Daten und der Entscheidungsfindung hervorgehoben. Ein solcher Ansatz wurde auf der Ebene eines Brunnenfeldes getestet. Es wird empfohlen, diesen Ansatz auf andere Brunnenfelder in Jordanien anzuwenden. Auf nationaler Ebene ist es von entscheidender Bedeutung, regelmäßig Studien zur Bewertung der Wasserressourcen im ganzen Land durchzuführen, die in die nationale Wasserstrategie einfließen und anderen Forschern die Möglichkeit geben, sich auf die wichtigsten und kritischsten Bereiche zu konzentrieren. Gleichzeitig sollten die Forscher die Regierung unterstützen, indem sie bei der Durchführung von Studien die Ziele berücksichtigen, die die Regierung mit der Strategie erreichen will. Schließlich wird empfohlen, innerhalb der Organisationshierarchie des MWI ein nationales Komitee für die Umsetzung von Wasserwissen einzurichten, das sich aus Mitgliedern von Forschungsinstituten und des MWI zusammensetzt und welches darauf abzielt, die in den Forschungsinstituten durchgeführte Forschung zu nutzen.

Affidavit

I hereby declare that the work presented in this Doctoral thesis is authentic and original unless clearly indicated otherwise, and in such instances full reference to the source is provided. I further declare that no unethical research practices were used. This dissertation was not submitted in the same or in a substantially similar version to another examination board.

Place and date:

Munich, May 11th, 2023

Name and signature

Mohammad Alqadi

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Scientific contributions

Research article

Title:	Causes and consequences of long-term groundwater overabstraction in Jordan
Authors:	Brückner,F., Bahls, R., **Alqadi, M.,** Lindenmaier, F., Hamdan,I., Alhiyari, M., Atieh, A.
Journal:	Hydrogeology Journal (published, 2021, https://doi.org/10.1007/s10040-021-02404-1)
Contributions:	Conceptualization, F.B. and R.B.; methodology, F.B., M.ALQ and R.B.; software, F.B., M.ALQ and R.B.; formal analysis, F.B., M.ALQ and R.B..; investigation, F.L., M.ALH, I.H. and A.A.; resources, F.L. and R.B.; data curation, F.B., M.ALH, I.H. and M.ALQ,.; writing—original draft preparation, F.B., and R.B. ; writing—review and editing, F.B., R.B.,F.L., M.ALH, I.H. and M.ALQ; visualization, R.B.,F.B., M.ALH, I.H. and M.ALQ.; supervision, F.L.. project administration, R.B. and F.L...

Title:	Implementation of Simple Strategies to Improve Wellfield Management in Arid Regions: The Case Study of Wadi Al Arab Wellfield, Jordan
Authors:	**Alqadi, M.,** Margane, A., Marwan Al Raggad, Subah, A., Disse, M., Hamdan, I. and Chiogna, G.
Journal:	Sustainability (published, 2019, https://doi.org/10.3390/su11215903)
Contributions:	Conceptualization, M.A. and A.M.; methodology, M.A.; software, M.A.; formal analysis, M.A.; investigation, M.A. and A.M.; resources, A.M. and H.A.S.; data curation, M.A. and I.H.; writing—original draft preparation, M.A. and G.C.; writing—review and editing, M.A., A.M., M.A.R., M.D., I.H., G.C.; visualization, M.A. and G.C.; supervision, G.C., A.M., H.A.S. and M.D.; project administration, A.M.

Title:	A Novel Method to Assess the Impact of a Government's Water Strategy on Research: A Case Study of Azraq Basin, Jordan.
Authors:	**Alqadi, M.,** Al Dwairi, A., Dehnavi, S., Margane, A., Al Raggad, M., Al Wreikat, M., & Chiogna, G.
Journal:	Water (published, 2021, https://doi.org/10.3390/w13152138)
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Title:	Development of a User-friendly Tool for Groundwater Wellfields Management
Authors:	**Alqadi, M.,** Aldwairi, A., Armin Margane, A., Brueckner,F., Schneider, M., Merchán-Rivera, P., Chiogna, G.
Journal:	IAHR congress (published, 2022, doi://10.3850/IAHR-39WC2521716X2022884)
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Title:	Presentation of DeMa (Decision Support Software and Database for Wellfield Management) and Its Application for the Wadi Al Arab Wellfield
Authors:	**Alqadi, M.,** Al Dwairi, A., Merchán-Rivera, P., Chiogna, G.
Journal:	Water (published, 2023, https://doi.org/10.3390/w15020331)
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Technical Reports

Title:	Wadi Al Arab Well Field Management- Description of Hydrogeological Conditions
Authors:	Dorsch, T., **Alqadi, M.,** Hamdan, I., Hiasat, T., Al-Subeh, A., Margane, A.
Year:	2020
Title:	Wadi Al Arab Well Field Management - Well Field Management Plan- Wadi Al Arab wellfield,
Authors:	**Alqadi, M.**, Margane, A., Hamdan, I., Al Kordi, R., Hiasat, T., Al Wriekat, M., Maharmeh, H., Bali, A., Taha, W., Mrayyan, K., Abu Alhaj, R., Karasneh, B., Melhem, S.
Year:	2018
Title:	Aqib Well Field Management - Well Field Management Plan- corridor wellfield.
Authors:	Hamdan, I., Margane A., Subah A, **Alqadi, M.,** Hiasat, T., Al Kordi O., Taha, W., Karasneh, B., G, Selawi.
Year:	2017
Title:	Aqeb Well Field Management - Well Field Management Plan- Aqeb wellfield,

Authors:	Hiasat T., Margane A., Subah A., Hamdan, I., **Alqadi, M.**, Al Kordi O., Taha W., Karasneh B., G Selawi.,
Year:	2017
Title:	Wadi Al Arab Well Field Management - WellField Assessment Report
Authors:	Dorsch, T., **Alqadi, M.,** Hamdan, I., Hiasat, T., Al-Subeh, A., Margane, A.
Year:	2017

Posters

Title:	Developing Decision Support Software and Database for Wellfield Management
Authors:	**Alqadi, M.,** Chiogna, G.
Event:	Doctoral Candidates' Day 2022
Place and date:	Munich (Germany), 14.07.2022

Title:	Innovative Engineering Injection Extraction systems for in-situ groundwater remediation (INE2)
Authors:	Chiogna, G., Rolle, M., Singh, T., **Alqadi, M.,** Ziliotto, F., Wienkenjohann H., Cogorno J.
Event:	IGSSE Forum 2022
Place and date:	Online (Germany), 24.05.2022

Title:	Impact of climate change on groundwater recharge in north of Jordan.
Authors:	**Alqadi, M.**
Event:	Annual Doctoral Seminar - Karlsruher Institut für Technologie, TU Dresden, Universität Stuttgart, TU München
Place and date:	Stuttgart (Germany), 18.05.2018

Conferences and talks

Title:	Development of a User-friendly Tool for Groundwater Wellfields Management
Authors:	**Alqadi, M.,** Aldwairi, A., Armin Margane, A., Brueckner,F., Schneider, M., Merchán-Rivera, P., Chiogna, G.
Event:	IAHR congress
Place and date:	Granada (Spain) 23.06.2022
Title:	Interdisciplinary approach for enhancing water security: Jordan as a case study
Authors:	**Alqadi, M.,**

Event:	Technical University of Denmark (DTU) research visit
Place and date:	Copenhagen (Denmark) 07.04.2022

Title:	Implementation of simple strategies and tools to improve water management in arid regions: the case study of Wadi Al Arab wellfield
Authors:	**Alqadi, M.**, Chiogna G., Margane, A., Disse, M., Alraggad, M., Wraikat M.
Event:	European Geosciences Union (EGU) General Assembly 2019
Place and date:	Vienna (Austra), 10.04.2019

Title:	Operational Aspects in Wellfield Management – case studies in Northern Jordan.
Authors:	**Alqadi, M.** , Al Wriekat, M.
Event:	The Eighth Environmental Symposium of German-Arab Scientific Forum For Environmental Studies
Place and date:	Amman (Jordan), 11.03.2019

Title:	Implications of projected climate change for groundwater recharge in North Jordan.
Authors:	Al Raggad M., Salameh, E., **Alqadi, M.**, Magri F., Disse M., Chiogna G.
Event:	European Geosciences Union (EGU) General Assembly 2018
Place and date:	Vienna (Austra), 09.04.2018

Title:	Groundwater recharge variation under climatic variability in Ajlun area and the recharge zone of Wadi Arab well field – Jordan.
Authors:	Al Raggad M., **Alqadi, M.**, Magri F., Disse M., Chiogna G
Event:	European Geosciences Union (**EGU**) General **Assembly** 2017
Place and date:	Vienna (Austra), 27.04.2017

Others

- *BBC interview* (can be found here)
- *Bridge to innovation grant (2023):* 50k Euro grant from TUMForte to bring DeMa (Decision Support Software and Database for Wellfield Management) from Technology Readiness Level TRL3/4 to TRL 5/6. The grant will be used towards the development and deployment of DeMa 1.0. The next version of DeMa will be launched in phases, over the next twelve months, with the final version available in early 2024.

Chapter 1

Introduction

Globally, fresh groundwater abstraction has exceeded the mean annual renewable recharge by around 10.5 % (UN-Water and UNESCO, 2022). This has been exacerbated by the increase in the population over the past years, which reached 7.9 billion in 2021 (UN-DESA, 2021), and it is expected to reach 8.7 billion and 10.2 billion inhabitants in 2030 and 2050, respectively (UN-Water and UNESCO, 2017). This increase will further escalate the pressure on the limited water resources (WEF, 2022), especially on groundwater, where around 50% of the global domestic water use is from groundwater resources (UN-Water and UNESCO, 2022). In 2015, the increased demand for natural water resources had already manifested in almost 30% of the global population living in countries under high water stress conditions (UN-Water and UNESCO, 2019). From among the 17 global Sustainable Development Goals (SDGs) established in 2015, SDG 6 aims to ensure water availability and sustainable management of water and sanitation for all. Although groundwater is mentioned in only one target (i.e., SDG 6.6), which aims toward the protection of groundwater aquifers (UN-General Assembly, 2015), this target is interconnected with more than 31% of the other SDG targets (Guppy et al., 2018).This suggests that the topic of water is interrelated with many sectors, and needs to be managed comprehensively (Shams & Muhammad, 2022; UN-Water and UNESCO, 2021).

The Global Water Partnership (GWP) defines Integrated Water Resources Management (IWRM) as "a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems" (GWP 2000,P.22). However, there is no specific standardized procedure to implement IWRM; rather, the implementation should be customized based on the conditions of the targeted country or region (De et al., 2020; UN-Water, 2008). Furthermore, the challenges in applying IWRM are also diverse, including poor water governance, climate change, urbanization, energy availability, population growth, and increased water demand (Agyenim & Gupta, 2012; Hafeez et al., 2021; Katusiime & Schütt, 2020; Mamassis et al., 2021; Mishra et al., 2021; Noureddine et al., 2021; Roestamy & Fulazzaky, 2021; Shams & Muhammad, 2022; Stringer et al., 2021;

Uhlendahl et al., 2011). To reduce the impact of these challenges on the successful implementation of IWRM, all respective actors should communicate and follow collaborative approaches (Compagnucci & Spigarelli, 2018; Grigg, 2016; Roque et al., 2022)

To apply an IWRM approach across different disciplines, the management process should start at the core of all management levels, the technical management level, where the operations of the water source and data collection occur, and it should end at the integral level, where the collaboration between the disciplines is achieved (Grigg, 2016). Shifting from a technical to an integral level, however, is challenging due to the various interconnected decision-making levels and disciplines within the water sector (Landström et al., 2019; Maynard, 2013). Within water management practices, a top-down approach originates when the top-level managers disregard the needs of the bottom level (Sherman & Ford, 2014). These challenges can be mitigated by counteracting the common top-down approach (Roque et al., 2022) with activities that engage stakeholders in all phases and levels of the water management process (Al-Qadi & Asce, 2020; Conallin et al., 2017; Megdal et al., 2017; Mott Lacroix & Megdal, 2016; Sherman & Ford, 2014). As part of this, it is vital to prioritize the needs of the lower management level (i.e., the bottom-up approach (Eicken et al., 2021)).

In general, the involvement of stakeholders from different levels and disciplines would either change the structure of an existing system or improve the response of people in a particular system to change (Bark et al., 2016; Norris et al., 2016; Pahl-Wostl, 2009). However, to be successful, different stakeholders should be involved throughout the change process (i.e., at different levels and steps) and encouraged to work closely together toward producing the desired outcomes (Macaulay, 2017). Still, achieving an efficient involvement of multilevel stakeholders is very challenging (Sherman & Ford, 2014), as it requires understanding different perspectives and managing tensions and controversies that may occur across different backgrounds and levels (Nicolini et al., 2012). Hence, multidimensional tensions usually are not solved by a single solution, and each stakeholder could require a unique solution (Lanier et al., 2018). Despite the challenges associated with multilevel stakeholder involvement in a change process, this approach remains crucial for creating a deep understanding of the variable elements in a system (Burns, 2012). Deep knowledge of the dynamics of changing systems is a crucial input to yield knowledge-based decisions (De Brucker et al., 2013; Eicken et al., 2021; Keskitalo, 2011).

Combining the elements of the top-down and the bottom-up approach would enhance the information flow and knowledge transfer between multilevel stakeholders (Pahl-Wostl, 2009; Smeds et al., 2003). However, data is needed to produce information flow and enrich knowledge (Zonta et al., 2020). There has been an evident shift toward data collection, transformation, and digitalization in all sectors (Mondejar et al., 2021; Schumacher et al., 2019; Zangiacomi et al., 2019), which was capped under the fourth industrial revolution (i.e., industry 4.0); a concept that was introduced in Germany to increase the levels of digital transformation within German industries in 2011 (Kagermann et al., 2011). This concept is now globalized across different sectors and countries (Guo et al., 2021; Jamwal et al., 2021; Y. Lu et al., 2022; Siqin et al., 2022; Turkyilmaz et al., 2021; T. Zheng et al., 2020) and has proven its capability to increase efficiency, reduce cost, and enhance the decision-making process in different sectors (Sezer et al., 2018).

Globally, the generated data, including social media interactions, emails, search queries, online transactions, data from IoT devices, surveillance footage, and corporate data, multiplied around 25 times between 2010 and 2020 (Montero & Finger, 2021). The increased volume of data is essential for making informed decisions, improving management (Merendino et al., 2018; Naqvi et al., 2021; Shamim et al., 2019), and crucial for successful digital transformation (Papadopoulos et al., 2021). Having more data leads to producing more information and improves processes in organizations by automating operational procedures and maintenance practices in different sectors (Q. Lu et al., 2020; Montero & Finger, 2021; Schmidt & Wang, 2016; C. Wu et al., 2020). In terms of maintenance practices, in recent years, many sectors have adopted predictive maintenance technology (Sezer et al., 2018; Zhang et al., 2019), which predicts failures based on statistical analysis models, continuous data acquisition, or knowledge transfer (K. Wang, 2016; Zhang et al., 2019; Zonta et al., 2020); with continuous data acquisition being the most used technique (Zhang et al., 2019). Depending on the sector, maintenance costs can be around 15-60% of the total cost of production (Zonta et al., 2020). As a result, predictive maintenance has become one of the main themes in the fourth industrial revolution (Cao et al., 2022; Drakaki et al., 2021, 2022; Müller-Czygan et al., 2021; Nordal & El-Thalji, 2020; Sajid et al., 2021; Teoh et al., 2021).

Currently, in the water sector, digitalization is required before applying predictive maintenance solutions (Espinosa Apráez, 2021). Still, effective digital transformations cannot be achieved without improving the collaboration between multilevel stakeholders from multiple sectors

(Montero & Finger, 2021). Therefore, involving multilevel actors before introducing new smart water solutions (Müller-Czygan et al., 2021), including multidisciplinary actors such as engineers, governmental agents, and industrial practitioners (Li et al., 2020); and ensuring the interactions between these actors will enhance the decision-making process in the future (Provost & Fawcett, 2013).

The European Commission report indicated that innovation in the water sector is still primitive (European Commission, 2016), which might be the reason why the water topic is still underemphasized in smart cities initiatives, initiatives aimed at improving the quality of life and sustainability of urban areas, compared to other sectors such as energy and transportation (Attaran et al., 2022; J. Lee et al., 2023; Moy De Vitry et al., 2019; Nikitas et al., 2020). There is still a technical and practical gap between the smart water solution provider and the market needs (Li et al., 2020). Moreover, the International Water Association (IWA) report stated that "Water and wastewater utilities must embrace digital solutions. There is really no alternative." (Will Sarni et al. 2019, P.38). This statement aligns with the trend observed in the past five years, as water sector has been increasingly shifting its focus toward digitalization (Müller-Czygan et al., 2021).

In general, to develop a successful innovation, interdisciplinary research is needed (Bromham et al., 2016). However, many researchers do not aim to produce interdisciplinary research because of the limited incentives (Haque & Freeman, 2021). Funds allocated for such research are limited compared to single discipline-based research (i.e., specified and narrow topics) (Bromham et al., 2016). Producing interdisciplinary practical research, on the other hand, involves a series of prerequisites, including that it should provide answers for a broad set of research questions, establish a substantial level of cooperation and partnership between researchers and policymakers (Theobald et al., 2018), and present a strategy to implement the results (Peters et al., 2013). As interdisciplinary research includes different topics and backgrounds, it often requires different expertise to understand it. Consequently, it is more difficult to communicate and simplify than a single discipline-based research (Bromham et al., 2016). That could be one of the reasons that there is still a gap between scientists and policymakers (Jones & Bice, 2021). Therefore, it is recommended when conducting interdisciplinary practical research to adopt knowledge translation processes, which convert the research results from specialist form to non-specialist form or vice versa (Shaxson, 2012; Ti et al., 2017; Worton & Furman, 2021), and consider approaches that define the applied uses of the research results for decision-makers (Parkhurst et al., 2021). However, even if the produced research is supported by experimental evidence, it will most likely not draw the attention of the decision-makers (Garciá, 2021) unless it contains a sociopolitical context in the analysis (Lowery et al., 2021).

The application of scientific research results in practice is described using numerous terms such as research utilization (e.g., (Benneworth & Olmos-Peñuela, 2018; Cernada, 2019; Magnolia et al., 2019), research use (Gaussel et al., 2021; Hopkins et al., 2019; Udo et al., 2019), implementation science (Curran, 2020; Lobb & Colditz, 2013; Ogden & Fixsen, 2015) and knowledge to actions (Fauquier et al., 2020; Khakee, 2019). Since the early 1980s, existing literature documented a lack in the incorporation of water-related research results into policymaking processes (Wisserhof, 1995), and there is no specific method to assess the extent to which government strategies in the water sector are informed by research output.

1.1 Challenges in Water Management in Jordan

Water scarcity is one of the leading sustainability challenges in Jordan (Al-Karablieh & Salman, 2016; Salameh et al., 2018), and it is prone to worsen due to the demographic growth of the country (Al-Mefleh et al., 2019; Krampe, 2020). Between 2004 and 2015, the total number of population increased from 5.6 to 9.5 million inhabitants (DoS, 2019). Additionally, one of the largest Syrian refugee camps, “Al Zaatari”, is located in Mafraq city in the north of Jordan. Hence, water scarcity is especially exacerbated in the northern parts of the country due to the recent settlement of Syrian refugees (Al-Karablieh & Salman, 2016; Farishta, 2014; Hussein et al., 2020; van der Helm et al., 2017). In the last decades, Jordan has been overexploiting their water resources at a critical rate (Abboud, 2018; Al Wreikat & Al Kharabsheh, 2020; Baylouny & J. Klingseis, 2018; Odeh et al., 2019; Shawaqfah et al., 2021), endangering its water security in the short to middle term and compromising the ability to meet the water needs of the population (MWI and BGR, 2019; Salameh et al., 2018).

Climate change further increased the pressure on water resources in Jordan. This has manifested through decreased precipitation and increased temperature (F. Abdulla & Al-Shurafat, 2020a; Abu-Allaban et al., 2014; Al-Zu’bi, 2009; Al Qatarneh et al., 2018; Raggad et al., 2018; Salamehet al., 2018; Smadi & Zghoul, 2006; Smiatek et al., 2011), consequently reducing the amount of groundwater recharge in different regions in Jordan (F. Abdulla & Al-Shurafat, 2020b; Kunstmann et al., 2007; Raggad et al., 2018). However, the Jordanian Ministry of Water and Irrigation (MWI) still considers in its reports, studies, strategies, and policies that the safe yield for groundwater abstraction is around 275 million cubic meters (MCM), an amount that was estimated and introduced by the Water Authority of Jordan (WAJ) in the mid-1980s (MWI, 1998, 2004, 2015, 2017). Several recent studies, however, have indicated that the natural groundwater recharge is decreasing in different regions in Jordan. Thus, the adopted safe yield should be revised to give consideration to the effects of climate change on natural ground recharge. In 1995, the total abstraction was already higher than the estimated safe yield amount (275 MCM) by 233 MCM (Margane et al., 2002); in 2004, the National Water Master Plan (NWMP) stated that: “As the present groundwater abstractions are not sustainable, the Government of Jordan envisages to reduce the groundwater abstractions continuously to reach the safe yield level by the year 2020.” (MWI, 2004) P.17. However, in 2020, the groundwater abstraction exceeded the safe yield by 600 MCM/year (GIZ, 2020).

Furthermore, the total water consumption exceeded the renewable water resources (i.e., surface and groundwater resources) in Jordan by 193 MCM in 2017 (MWI, 2017) and 219 MCM in 2020, and it is expected to reach 531 MCM in 2040 (GIZ, 2020). This increased gap between renewable water resources and the total water consumption is symbolized by the continuously declining rate of water availability per capita in Jordan (MWI, 2016c); it decreased from 3600 m^3/year in 1946 (MWI, 2008) to 200 m^3/year in 1993 (Hadadin et al., 2010), to less than 100 m^3/year in 2017 (MWI, 2017), and it is predicted to be 90 m^3/year in 2025 (Abu-Khader et al., 2022).

Due to the increasing stress on water resources, the Jordanian government is advancing the desalination of seawater as an alternative water source (Chenoweth & Al-Masri, 2021; Salameh & Abdallat, 2020). There are 22 desalination plants for brackish water, with a total capacity of 77 MCM (MWI, 2018). The aim is to build a seawater desalination plant on the red sea under the “National Conveyor” project to produce 100 MCM/year, 200 MCM/year, and 250 MCM/year by 2026, 2031, and 2036, respectively (GIZ, 2020). However, assuming that the “National Conveyor” project will operate at full capacity, the country will still suffer from a water deficit since the demand is projected to continuously increase.

Some of the challenges that have hindered the Jordanian government’s move toward seawater desalination are the related high capital investment and high energy costs that will be reflected commercially in the water price (Al-Saidi & Dehnavi, 2019; Walschot et al., 2020). Due to the lack of alternative sources in the case of Jordan, the Jordanian government has been forced to implement the desalination project despite the expected high-cost issues (Salameh & Al-Alami, 2021). Furthermore, water pumping consumes around 15% of the total energy consumption of the country (NEPCO, 2019). Nonetheless, this percentage is expected to increase due to the declining groundwater level and the increasing pumping lift (GIZ, 2020; Margane et al., 2015). This is likely one explanation for the recent increase in the number of researchers targeting the topic of energy-water nexus in Jordan (Chenoweth & Al-Masri, 2021; Farrar et al., 2022; Küblböck et al., 2021; Ramirez et al., 2022; Siam et al., 2022).

About 51% of the water resources in Jordan are used for agricultural purposes (MWI, 2020). However, studies showed that this percentage could be higher due to the illegal and unmetered abstractions for agricultural activities (Al-Bakri et al., 2016a; Margane et al., 2015). Therefore, different studies have aimed to identify methods for reducing the water demand by changing pricing strategies (Courcier et al., 2005; Doppler et al., 2002), farmer behaviors and irrigation techniques (Shammout et al., 2018), or transforming the existing agricultural land into solar farms (Al-Saidi & Lahham, 2019; GIZ, 2015). Despite the publication of a water demand management policy by the government (MWI, 2016b), which emphasized the importance of collaborating with research institutions to support the implementation of best practices in water demand management, maximizing the efficient use of water resources, and minimizing water losses in different sectors, these relevant studies were only conducted at pilot project scale. The government is yet to adopt the recommendations at a national level.

Another nationwide barrier that faces the Jordanian government is the water losses in the supply network. It is estimated that more than 50% of the supplied volume of water is lost (i.e., non-revenue water, including physical and administrative losses) in water distribution systems (MWI, 2018). This percentage reaches 70% in some governorates (Al-Ansari et al., 2014; Jeuland et al., 2021). However, the actual water losses are more than the current estimation, as the estimated 50% losses only consider the losses between the pumping station and the end-users, without including the water losses from wells to the reservoir (GIZ, 2020).

Water demand and supply issues are addressed within the goals outlined in MWI's water strategy (MWI, 2008; MWI, 2016a), indicating that the MWI is aware of the previously mentioned challenges. Traditionally, the MWI focused on increasing the water supply by exploiting the existing water resources to decrease the supply and demand gap (Bahls et al., 2019; Liptrot & Hussein, 2020; Odeh & Mohammad, 2020). Such practice has been confirmed by the increased number of active groundwater wells for drinking water supply from 553 to 805 wells between 2007 and 2017, respectively (MWI, 2017). Such poor water governance practices only worsen water scarcity in Jordan (Bonn, 2013; Salameh & Al-Alami, 2021) and can lead to further water crises (Rogers & Hall, 2003; Zeinali et al., 2021). There is still potential to improve the water governance practices and water policies in Jordan; however, such enhancements cannot be made without establishing close cooperation between the MWI and all stakeholders, including other ministries, at different levels of decision-making (Qtaishat, 2020; Al-Kharabsheh, 2020; MoE, 2020; Yorke, 2016).

The lack of reliable data is another challenge hindering the enhancement of water policies and the improvement of Jordan's decision-making processes (Bahls et al., 2019; Haddadin, 2006). While there has been a global increase in generated data over the past years thanks to the introduction of new technologies, such as smart metering, improved sounds and images processing technology, sensors embedded in electrical machines, higher quality cameras, improved data transmission, and internet of things (IoT) networks (Montero & Finger, 2021), the water-related data availability in Jordan has significantly decreased since the 1990s (GIZ, 2020). This decrease has taken place despite recent MWI strategies and policies addressing the topic of improving the monitoring systems and data availability (e.g., MWI 2016a; MWI 2008; MWI 2004; MWI 2016b), which indicating an issue in the implementation mechanisms of the water strategy goals (Daoud et al., 2022).

1.2 Problem Statement

Groundwater is the primary water resource in Jordan, representing around 75 % of the total water supply for drinking and 46% for agriculture, which consumes 52% of all water resources in the country (1053.6 MCM), while domestic uses need 45% of it. (MWI, 2017). To maintain this important resource in Jordan, enhanced groundwater management is needed at different levels (Al-Kharabsheh, 2020; MoE, 2020). The last comprehensive study that delineated the groundwater levels and estimated the decline rate in Jordan was done in 1995 (Margane et al., 1995); this study has been used as a reference for many studies by the government and researchers (Awawdeh & Jaradat, 2010; Hammouri & El-Naqa, 2008; Margane et al., 1999, 2009, 2010, 2015). However, structuring the decision-making processes around a 25-year-old study will not be beneficial for implementing effective groundwater management plans at different levels, such as national, basin, or wellfield. Therefore, a re-assessment of the groundwater resources and quantifying its depletion in Jordan will aid the government in producing improved strategies to cope with the limited groundwater resources in the country, assist the MWI in adopting evidence-based decisions making (EBDM), and support the researchers with new and updated groundwater information.

A recent re-assessment of the national groundwater situation in Jordan was conducted by the Federal Institute for Geosciences and Natural Resources (BGR) in cooperation with the Jordanian Ministry of Water and Irrigation (MWI). Such assessment can be labeled as demand-driven research, especially since it was required by the ministry and is expected to be directly used by the MWI to influence the decision-making process. However, it is unsubstantiated whether water-related research produced by other research institutes, has been utilized in the governmental decision-making process. For example, multiple research studies have confirmed that the natural groundwater recharge rates have been decreasing in different regions across Jordan. However, the government has continued to reference the values estimated in the 1980s national groundwater situation study (MWI, 1998, 2004, 2015, 2017). Furthermore, alongside the uncertainty of research application by the ministry, it is undetermined if the produced research meets the ministry's demand or if it fulfills the ministry's water strategy goals. Therefore, a study is needed to evaluate the relationship between the MWI's water strategy goals and the produced research. To the best of the author's knowledge, no method exists to evaluate such a relationship for the water sector. As a result, developing a method that defines the interactions between governmental strategies and water-related research and highlights the research gaps in the water sector is required.

Furthermore, in Jordan groundwater wells for drinking water supply operate 24 hours a day, every day of the week, especially during the summer season. Thus, unexpected failure in a drinking water well might have a direct impact on the end-user. For instance, water in most areas in Jordan is supplied for household use one day per week (MWI, 2017), and unexpected failure of a submersible pump might result in stopping the water pumping from the well for a few days until the problem is diagnosed and solved; subsequently, the amount of water pumped for a particular area would eventually be reduced and might impact water supply to households. To prevent unplanned maintenance and predict failures before they occur, continuous data collection is needed. However, the existing monitoring system is not sufficient to predict a well's failure and reduce its frequency; consequently, preventing unplanned maintenance is challenging. Therefore, developing a monitoring system within a wellfield is essential to prevent the unexpected failures of wells and decrease the needed time to re-operate halted wells.

Besides the issues of the existing monitoring system and the data collection process, there is also a problem with data management. For example, in Wadi Al Arab wellfield, most of the data prior to 2012 is lost due to a change in the management system that year. Furthermore, no database contains all the collected data related to the wells' operation and maintenance, which results in the data being fragmented in different departments within the water company; this makes retrieving data to make data-driven decisions complicated for the wellfield manager. It is essential to highlight that based on the field investigations and meetings with different people from the MWI, the BGR and the German Society for International Cooperation GIZ, lack of a good monitoring system and data management problems are not unique problems that exist only in the Wadi Al Arab wellfield; the data availability problem in Jordan's water sector exists throughout the country and at all levels of water management (GIZ, 2020). Wadi Al Arab wellfield was selected as a case study due to its importance for the drinking water supply; the wellfield provides more than 40% of the total drinking water supply of Irbid governorate, which is the second-largest governorate by the number of inhabitants after Amman, the capital of Jordan and is recorded to have the highest decline rate of a groundwater table in Jordan.

Finally, the lack of digitalization of various procedures managed by water utilities has led to the loss of data and documents, as well as unsystematic practices within and among water utility companies. For instance, the monitoring procedure, data management, and decision-making processes of the Wadi Al Arab wellfield are different from the Aqib wellfield, which is also located in the northeastern part of Jordan, providing around 17 MCM/year water supply and consisting of 45 wells (including the economic and Umaira wells) (Hamdan et al., 2017). Hence, processing the collected data and building connections between the observations is essential for adequately managing the groundwater wells.

1.3 Research Questions

In this dissertation, I aim to address one primary research question and five sub-questions, which will be investigated across five individual chapters. The central question in this dissertation is:

"How can data and evidence-based decision making be reached to improve groundwater management in arid regions?"

The sub-questions not only serve to ensure a thorough exploration of the topic but also structure the dissertation into sections, with each forming the basis of the chapters:

- What changes have occurred in the groundwater system in Jordan between 1995 and 2017, and which regions are at high risk in terms of groundwater availability?
- How should literature documents be classified to evaluate and improve the interaction between water-related research and the Jordanian governmental strategies? What role does grey literature play in evaluating this interaction?
- What are the most effective approaches to move toward informed-driven decisions at a wellfield level, and how can they be implemented in highly impacted regions?
- How can digital solutions contribute to assisting the wellfield manager in better understanding and improving a wellfield's data and information management?
- How can digital solutions improve the decision-making process in groundwater wellfields?

1.4 Dissertation structure

The previous literature review clarified the complexity of water challenges in arid regions, and in Jordan specifically. It was determined that water management cannot be improved by considering only one aspect, level, or discipline. Water management can be enhanced by evaluating the current situation of groundwater resources (Chapter 2), understanding and improving connections between research and application (Chapter 3), applying multilevel/interdisciplinary approaches (Chapter 4), and digitalizing water management procedures to improve data flow and make evidence-based decisions (Chapter 5 and Chapter 6).

Chapter 2 presents an updated groundwater contour map and defines the difference in groundwater levels between 1995 and 2017 in Jordan. It also underlines the reasons behind the high drawdown in three different areas: Basalt plateau, Wadi Al Arab, and Petra. Furthermore, this chapter emphasizes the consequences of the extreme drop in groundwater level and its impact on the studied areas' hydraulic conditions, water quality, and groundwater flow regime. According to the GIZ report on water resources availability and exploitability in Jordan (GIZ, 2020), the northern part will be the most impacted area from over-abstraction in 2040, where the amount of water will decrease by around 85% (i.e., only 15% of the current amount will be available). Therefore, this dissertation will focus on the basalt plateau of the Azraq basin and Wadi Al Arab area. Figure 1.1.

Chapter 3 advances a new method that investigates the connection between the conducted water-related research and governmental strategy goals. This connection is represented by a matrix that links different research focus areas with predefined strategy goals. Such a matrix can inspire researchers to develop and apply new topics and motivate future research to become more innovative and demand-driven. The new method presented in this chapter was applied at a river basin level, specifically in the Azraq Basin. The Azraq Basin was selected because it lies on the basalt plateau and is highly affected by the over-abstraction (i.e., over-abstraction reversed the groundwater flow direction of the Azraq Basin), as presented in Chapter 2. Moreover, the MWI plans to drill a wellfield north of the Azraq Basin, where the hydrogeological situation is similar to the one of Wadi Al Arab wellfield. Hence, such a situation offers an opportunity to apply Wadi Al Arab wellfield management approach (developed in Chapter 4), in the early stages of the new wellfield drilling process.

Chapter 4 depicts a comprehensive management approach for Wadi Al Arab wellfield, which provides groundwater for drinking purposes. The wellfield is the primary drinking water source for the northern governorates. It is also, as defined in Chapter 2, one of Jordan's most affected areas from over-abstraction, where the groundwater level drop in this area was around 100 m in the past 23 years. This chapter presents an overview of the wellfield, and the main problems facing the technicians in the field. It also provides a solution to prevent and reduce unexpected maintenance of wells by altering the existing approach in data collection, stakeholder involvement, and the decision-making process. Along with the approaches mentioned above, a simple MS excel dashboard is introduced for data visualization, which is connected with the collected data stored in MS access. The aim behind developing such a simple tool is to demonstrate the impact of digitalization approaches on the wellfield manager's decision-making process before developing a sophisticated software (Chapter 5).

Chapter 5 introduces a user-friendly Decision Support Software and Database for Wellfield Management (DeMa), which is an advanced and sophisticated version of the simple tool presented in Chapter 4. DeMa combines four main tools that aim to manage the groundwater data bank, produce graphs to support the users in decision-making processes and organize the files and documents of water companies. Moreover, the software allows the user to apply methods containing complex equations introduced in published articles without the need to have a mathematics or programming background by integrating the produced research through a user-friendly graphical user interface, improving the connection between research and decision-makers.

Chapter 6 includes the application of DeMa tools (Chapter 5) in Wadi al Arab wellfield as a case study. The chapter shows the data and information insertion process into DeMa, the achieved results, its implications, and highlights possible future developments of the software.

Chapter 7 summarizes the six main chapters and answers the primary and five sub-research questions. Furthermore, this chapter also highlights how the results of this research could have implications in different areas; it also includes a discussion on the need for further research.

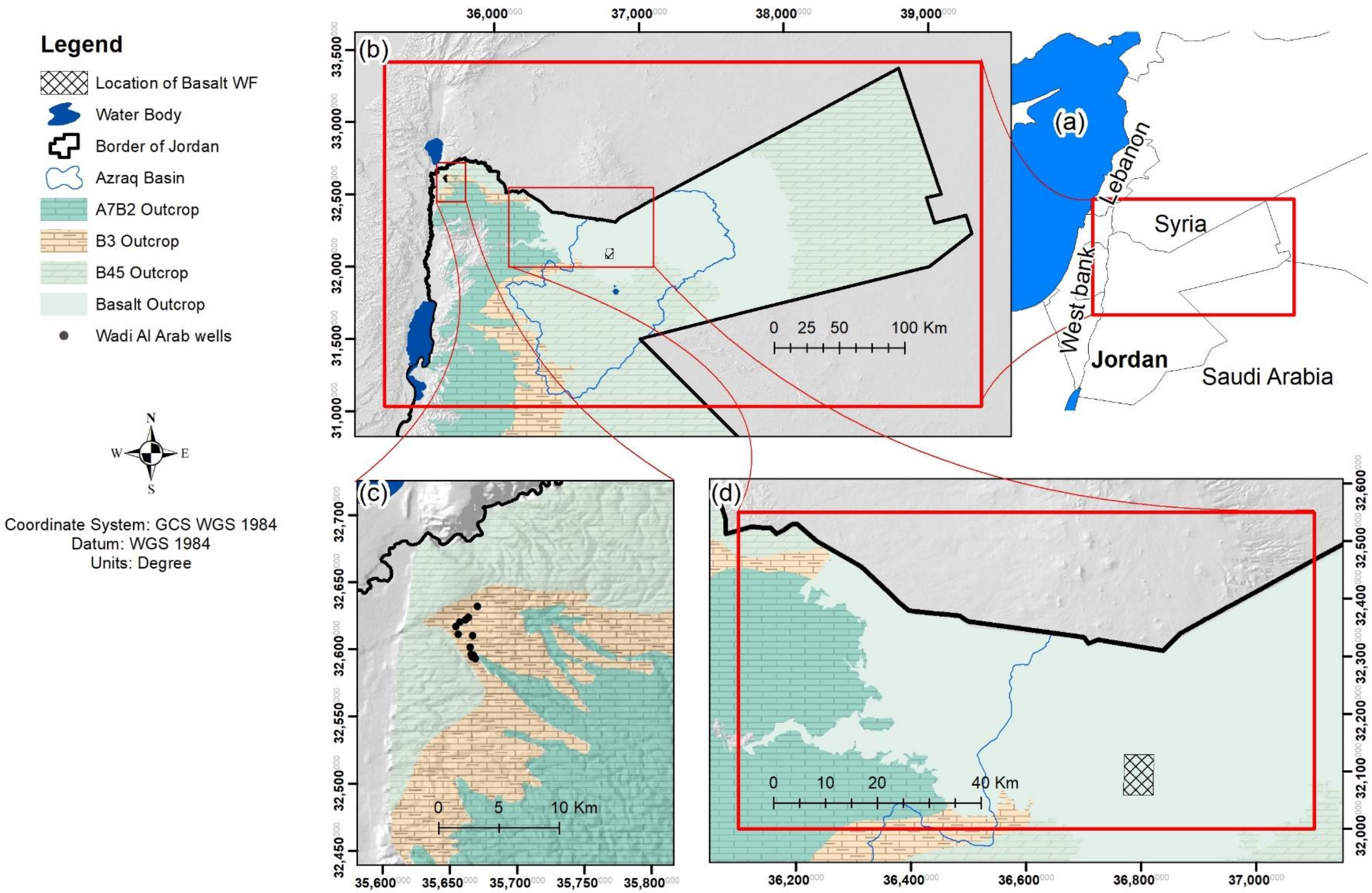


Figure 1.1: Overview map of the study area. (a) The location of Jordan and surrounding countries. (b) The lithological outcrops of Northern Jordan and the location of Azraq basin. (c) Wadi Al Arab area. (d) The basalt Plateau and the planned location the of basalt wellfield.

1.5 Methodologies

The methodological approach taken in this study is a mixed methodology based on the objectives that need to be achieved.

1.5.1 Chapter 2

An illustration of the followed steps is shown in Figure 1.2. The main method used in this chapter is an intensive field campaign to collect groundwater levels and measure the elevation of all the boreholes and springs using a Differential Global Positioning System (DGPS). A total of 98 manual water level measurement points were taken (i) to verify the collected measurements from the central database of MWI, the Water Information System (WIS), and from the online database (SEBA hydrometrie), and (ii) to correct them in case of evident mistakes such as sudden shifts or outliers. Furthermore, a total of 138 water level measurements from drilling and water companies were collected in areas where government data is insufficient. In addition to that, the elevations of 10 springs were considered, and 22 historical water wells from the WIS were extrapolated, applying the linear trend of the decline rate of the period 2012-2016.

The water level measurement points were plotted on a map using the open-source Geographic Information System (QGIS). The contour lines were drawn by hand, using the same approach used when the 1995 map was delineated and considering all factors that could impact the water levels, such as the surface elevation, geological structure, nearby production wells location, and the location of wastewater treatment plants (WWTP). Finally, to detect the areas where agriculture contributed to the over-abstraction, normalized difference vegetation index (NDVI) was calculated from Landsat images of August each year between 1995 and 2017 to confirm that these areas are irrigated by groundwater and are not rainfed.

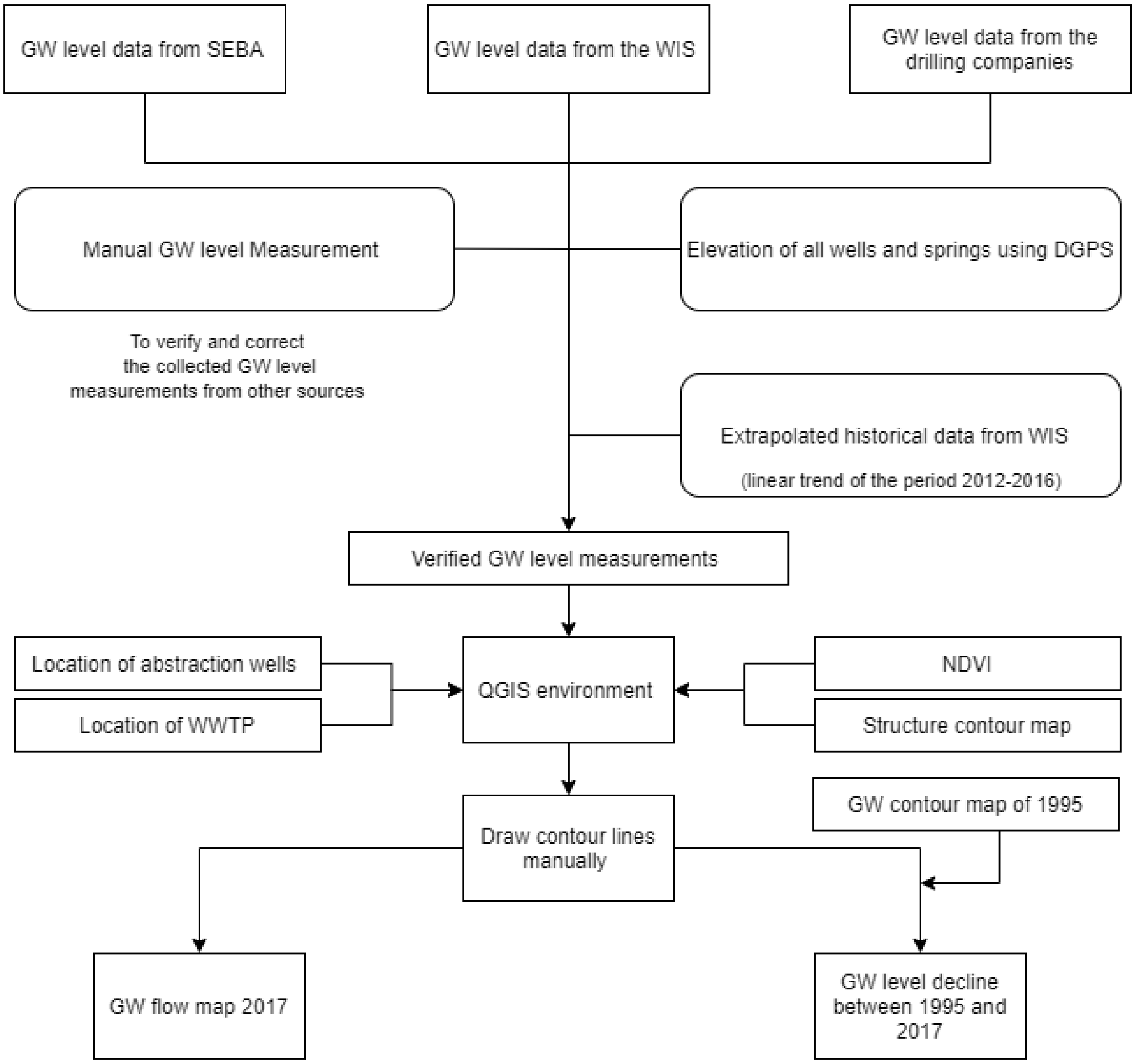


Figure 1.2 An illustration of the methodology of Chapter 2

1.5.2 Chapter 3

The methodology of this chapter is twofold. The first part included a one-month long field trip to Jordan between December 2019 and January 2020. During the trip, a total of 18 unstructured meetings were conducted. The meetings were held with current and retired MWI employees and local and international institutes working under the MWI umbrella. The main objective of the meetings was to understand the MWI's existing archiving system for reports and studies conducted within the ministry and to collect these reports. Furthermore, during the meetings, the idea of developing a new platform to improve the archiving system of the MWI was proposed.

Because of the lack of an archiving system, the field trip was fundamental for this research, and it helped to collect reports of studies and projects that are not published and otherwise inaccessible. Around 2200 digital documents in different formats (e.g., final reports, report sections, letters, incomplete reports, presentations, or report drafts), spanning from 1963 to 2019 were collected. Afterward, the collected reports were rearranged according to the basin and topic. Furthermore, grey literature was collected online through Google, Scopus, Web of Science (WoS) search engines, and the websites of the MWI and the international and local partners of MWI. Besides collecting the grey literature, an intensive peer-reviewed literature collection was conducted for the case study on the Azraq Basin.

The second part of the methodology focused on identifying the goals of the collected research and categorizing them based on their alignment with the MWI strategy goals. Any goal in the MWI strategy that registered no contribution from the collected research was considered a research gap. However, any research contributing to the MWI strategy goals was regarded as potentially demand-driven research. As shown in Figure 1.3, a comparison of the categorized research before and after the implementation of the MWI strategy was undertaken for each step in the methodology. Such a comparison assisted in observing if the research orientation changed towards the MWI strategy goals.

The interdisciplinarity of research is usually measured by detecting a word such as “interdisciplinarity“ or from the author’s affiliation or the reference list within the analyzed document (Bromham et al., 2016). In this chapter, the aim was not to measure the interdisciplinarity of the individual research document but to categorize the available contribution from researchers in different disciplines to the MWI goals, hence, indicating interdisciplinary contributions to the MWI goals. Therefore, the categorization was based on the topics considered within the collected research, which are referred to as Research Focus Areas (RFAs) and they were presented in a matrix showing the linkage between the RFAs and the MWI strategy goal. Furthermore, the peer-reviewed studies were categorized based on the authors’ affiliations, to determine the influence of different types of research institutions (e.g., academic, non-academic, national, and international) on the Azraq Basin’s research. This procedure was only used for peer-reviewed literature since the affiliation of the authors of grey literature are not always clearly defined.

It is essential to highlight that the conducted analyses did not include studies conducted after the year 2018 since the MWI published a new strategy for the period 2016–2025 in 2016, which amended the older water strategy (2008-2022). Due to the time-consuming nature of the scientific publication process, it was assumed that the old water strategy (2008-2022) used in the analysis may still impact water-related research up to two years after the publication of a new strategy.

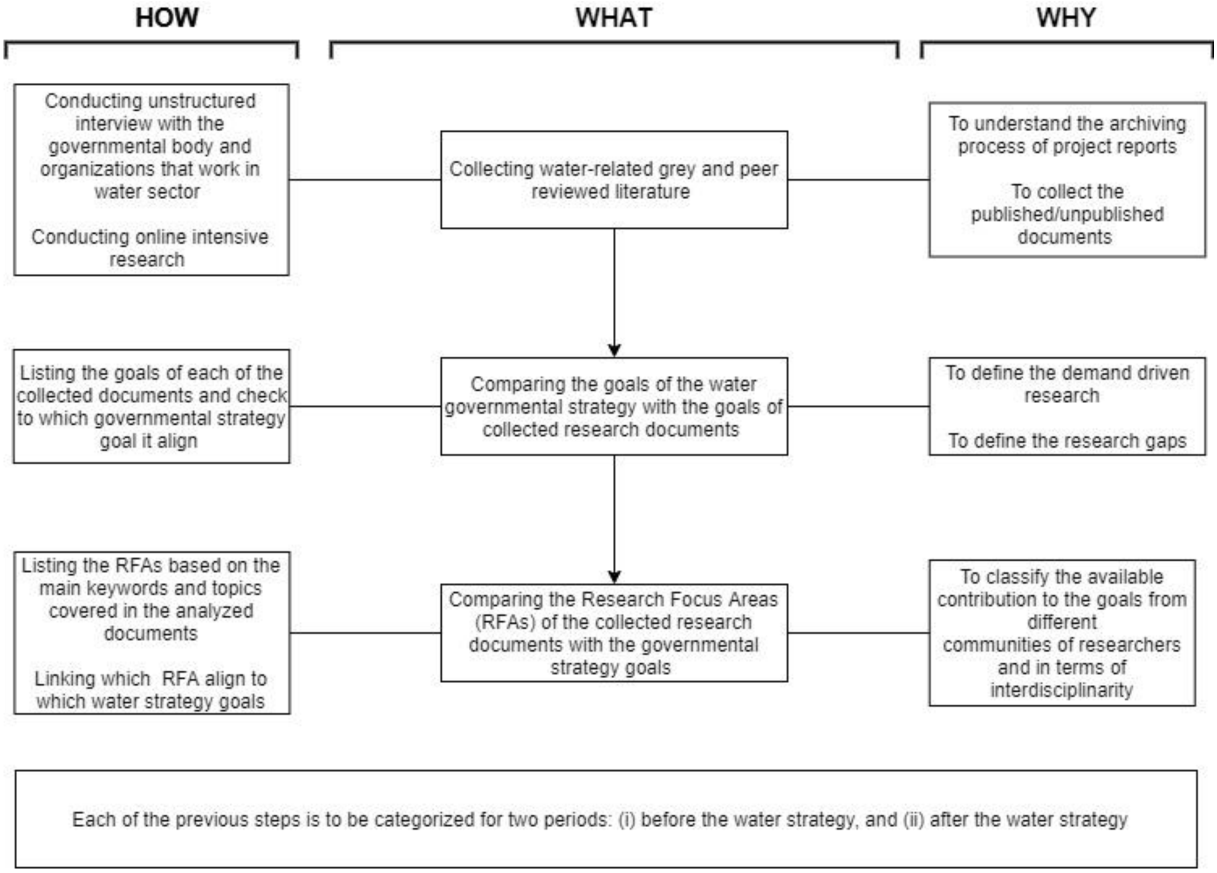


Figure 1.3: An illustration of the methodology of Chapter3. Research Focus Area (RFA) is a classification method that categorizes research documents based on their main topics and keywords to highlight interdisciplinary contributions to a water strategy goals.

1.5.3 Chapter 4

This research was done within a cooperation project, implemented by German Federal Institute for BGR and the MWI. An essential step in the chapter's methodology was to build trust between the project team and the management body of Wadi Al Arab wellfield. To achieve effective multilevel stakeholder engagement, actors from different levels within the water company and the MWI were involved in the decision process, and the flow of information was enhanced by conducting regular meetings between the actors and increasing the daily involvement of project members within the operation process. Consequently, changing the top-down approach to a combination of the top-down and bottom-up approaches was necessary. Part of the participatory systemic inquiry (PSI), presented by Burns (2012), was used in the stakeholder engagement approach, which aims to engage multilevel stakeholders to understand the challenges and obstacles from different points of view. Based on this, the existing monitoring system was enhanced.

Furthermore, a toolbox was developed to make use of the collected data. The toolbox includes (i) Wellfield information system (WFIS), which is based on Microsoft Access that represents the database's front-end (i.e., the user can insert, delete, update and retrieve the data) and back-end (i.e., the user can store the data into the water company's server), where all the available data in the form of hard copy, MS excel sheets, or scans at different departments of the water company were entered into the WFIS after processing them, (ii) Operational Decision Support (ODST), which was built by Microsoft Excel, ODST gives a visualization of the actual condition of the well from the data that is stored in MS Access, which act as an early warning system for well operations, and (iii) Wellfield Management Plan Report, which is a living document, where individual pages are replaced, omitted or added according to changes in situations, the document contains GIS maps of the wellfield and all the related information of each well in the wellfield including the ODST graphs. The last section of the document represents the action plan for the wells and wellfield. Figure 1.4 shows the followed steps, the rational for selecting those steps, and the approach employed to execute them.

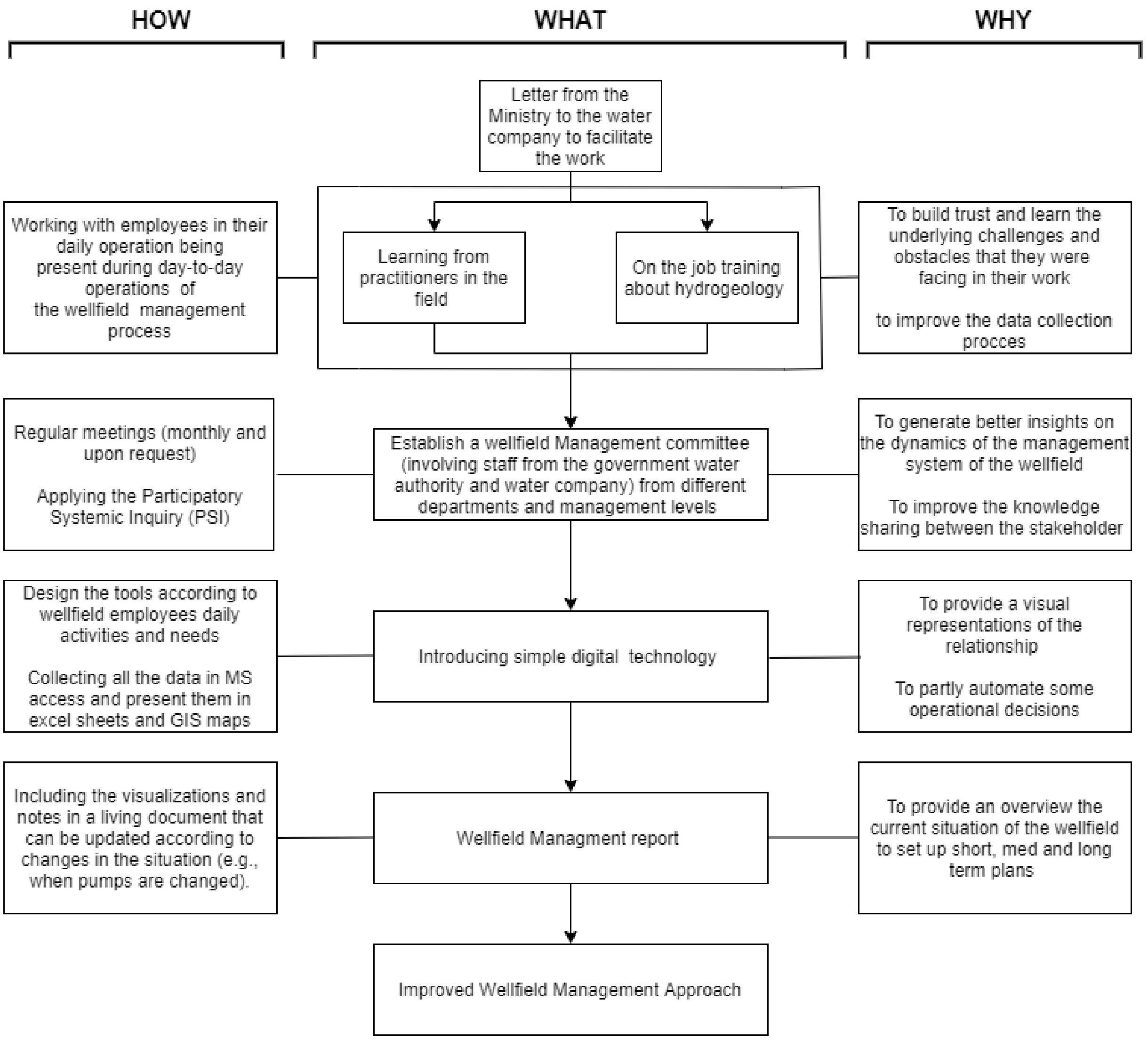


Figure 1.4: An illustration of the methodology of Chapter 4.

1.5.4 Chapter 5

The toolbox presented in Chapter 4 was limited in terms of (i) its ability to connect WFIS (MS Access) and ODST (MS Excel), (ii) its visualization options in MS Excel, (iii) its capacity to apply complex mathematical equations in MS Excel and Access, and (iii) the challenge of MS access toolbox scalability. Hence, to overcome these limitations, sophisticated software was developed to manage groundwater wells and wellfields. The graphical visualization of DeMa software development process is illustrated in Figure 1.5. The first step in the methodology was conducting intensive background research to define all the provided solutions by existing tools. A final list including all the desired solutions that were not provided in any of the existing tools/software was created to be integrated into later stages into DeMa software. Afterward, a conceptual design of the database that serves the software's purpose was built. Using Structured Query Language (SQL) with the SQLite3 Python library, the database was created and tested.

By using PyQt5 library, the modules and front-end of the software were developed, including (i) Database Management Tool (DbMT), to allow the user to update, delete, insert, and run database backup, (ii) Observation Based Tool (OBT), where the user can graphically visualize the data and the relations between different observations, (iii) Research-Based Tool (RBT) where the user can apply and include research methodologies in the well/wellfield management process, and (v) Documents Management Tool (DMT), where the user can manage documents related to specific wells and wellfields.

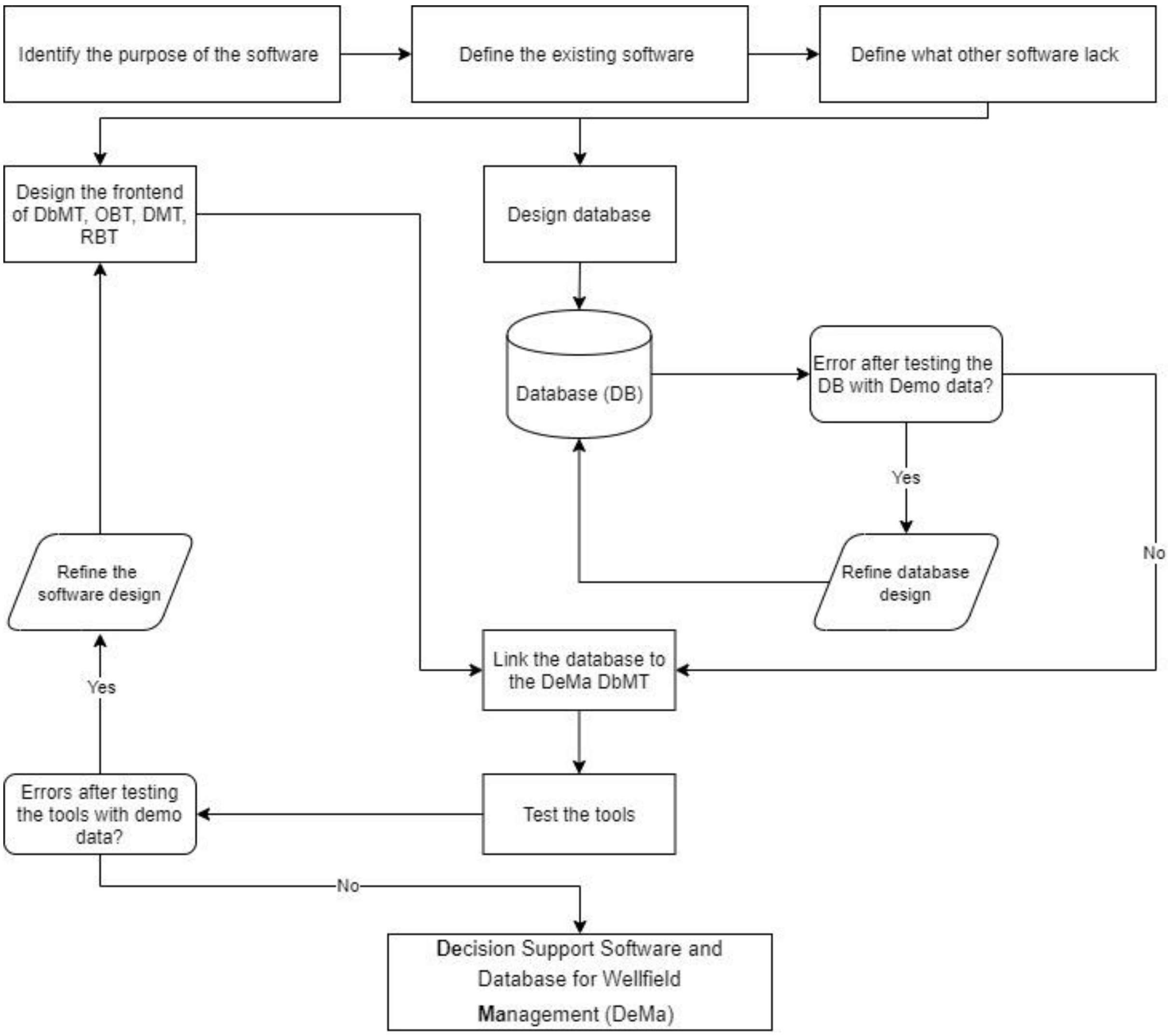


Figure 1.5. An illustration of the methodology of Chapter5.

1.5.5 Chapter 6

After developing DeMa as presented in Chapter 5, it was tested with real data from Wadi Al Arab wellfield. An intensive data and document collection process was conducted, as illustrated in Figure 1.6. The process included (i) online research to collect published articles, reports, and documents and (ii) unstructured interviews to collect unpublished project reports, drilling reports, and invoices. The management and operation data of Wadi Al Arab wellfield was compiled from various departments at the Yarmouk Water Company (YWC) and from fieldworkers, as explained in Chapter2 and Chapter4. The data was reorganized to fit the DeMa database structure and uploaded via the DbMT. Furthermore, the collected documents were integrated into the document management tool (DMT) and linked with the relevant wells or wellfield. After feeding DeMa with Wadi Al Arab data and information, OBT was tested by visualizing the collected data and interpreting the relationship between them.

Furthermore, DeMa used the documents as a data source for the database; during the software testing process, data from the documents (e.g., drilling report) stored in the DMT was extracted to fill the database. Lastly, the RBT was tested by retrieving data directly from the database (e.g., well radius) via DbMT and extracting information (e.g., transmissivity) from the documents stored in DMT.

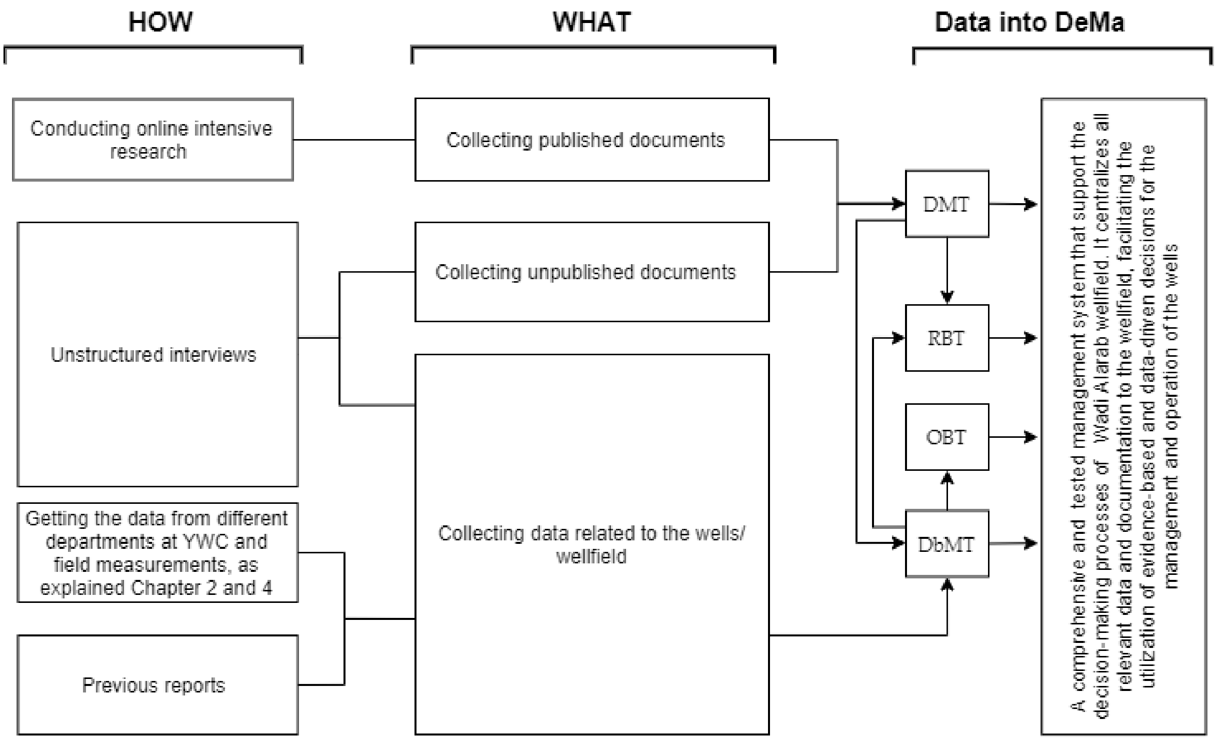


Figure 1.6. An illustration of the methodology of Chapter6

1.6 Summary

Improving the existing groundwater management system requires including multilevel and interdisciplinary approaches. This dissertation focused on the factors (e.g., communication, sense of ownership, economy, data, research, governance, and digital solutions) that might impact the management process of groundwater in Jordan. Figure 1. shows the graphical summary of the dissertation, and it illustrates the main research stages and activities at national, river basin, and wellfield levels. The activities in the dissertation included research at the national level to understand the status quo of the groundwater system. The research delivered a hydrological study delineating the groundwater table, identifying the highly impacted areas in terms of groundwater flow regime, water level decline rate, water quantity and quality, and possible causes. This has generated new research questions about those areas and produced more data and documents, which, in turn, it has led to an improvement in the production of water-related research. For the Azraq Basin, the interaction between water-related research and the MWI water strategy was assessed using a novel methodology that classified the collected peer and grey literature documents; and recommendations to improve the interaction were then provided.

At a wellfield level, a new methodology was provided to enhance Wadi Al Arab wellfield management considering stakeholder involvement, hydrogeological parameters, energy consumption, maintenance costs, installation specifications, field measurements, and well design. The methodology included providing a simple toolbox that supports the wellfield manager in handling and visualizing data via WFIS and ODST, as presented in Chapter 4. Due to the challenges in data collection and management presented in chapters 2, 3, and 4, and the arising opportunity from the implementation of a simple toolbox solutions to managing data and decreasing the failures of wells, there was an apparent necessity to move toward digitalization in the water sector. Hence, DeMa was developed to manage groundwater wells data in a comprehensive database management system, aid the decision-making process surrounding the management and operation of the wells, help wellfield managers to apply novel research methodologies to the study area, and organize the files and documents related to the wells/wellfields, as presented in Chapter 5. DeMa was tested on data collected from Wadi Al Arab wellfield, and the results showed that digital solutions could bring research into practice and support maintaining and managing the produced data and documents. It is crucial to point out that developing digital solutions for the problems encountered at a wellfield level will be effective if practitioners' knowledge is utilized. In return, the digital solution provides easy access to data and information about the jurisdiction area and increases the wellfield's manager knowledge. Finally, the application of DeMa can be downscaled to manage data of an individual well or upscaled to the national level, where all the wellfields and wells that the MWI manages can be included in DeMa.

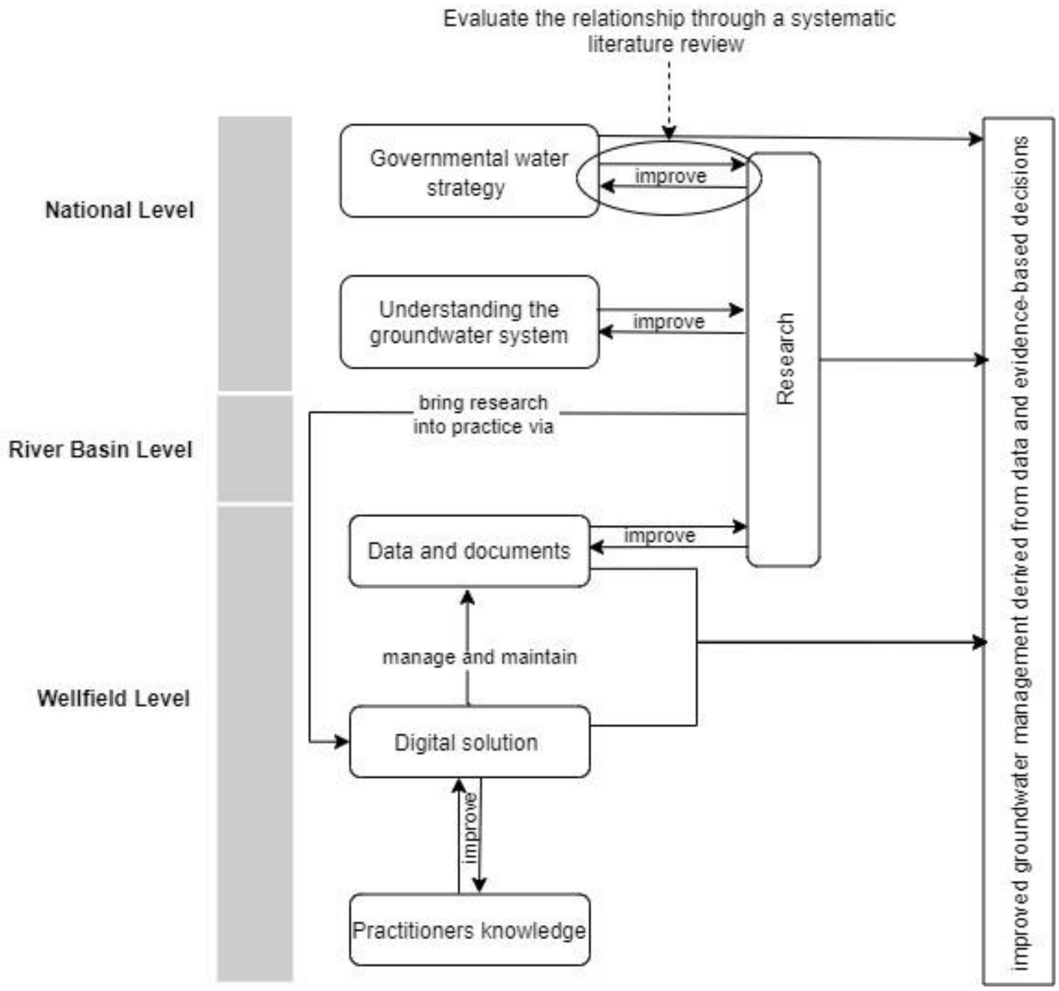


Figure 1. A graphical summary of the dissertation illustrating the key research stages and activities.

Chapter 2

Causes and consequences of long-term groundwater over-abstraction in Jordan

Brückner et al (2021)[1]

2.1 Abstract

In 2017, a comprehensive review of groundwater resources in Jordan was carried out for the first time since 1995. The change in groundwater levels between 1995 and 2017 is dramatic: large declines have been recorded all over the country, reaching more than 100 m in some areas. The most affected areas are those with large-scale groundwater-irrigated agriculture, but areas that are only used for public water supply are also affected. The decrease of groundwater levels and saturated thickness poses a growing threat for drinking water supply and the demand has to be met from increasingly deeper and more remote sources, causing higher costs for drilling and extraction.

Groundwater contour lines show that groundwater flow direction has completely reversed in some parts of the main aquifer. Consequently, previously established conceptual models, such as the concept of twelve "groundwater basins" often used in Jordan should be revised or replaced. Additionally, hydraulic conditions are changing from confined to unconfined - most likely a major driver for geogenic pollution with heavy metals through leakage from the overlying bituminous aquitard.

Three exemplary case studies are presented to illustrate and discuss the main causes for the decline of the water tables (agriculture and population growth) and to show how the results of this assessment can be used on a regional scale.

[1] Brückner, F., Bahls, R., **Alqadi, M.** et al. Causes and consequences of long-term groundwater overabstraction in Jordan. Hydrogeol J 29, 2789 – 2802 (2021). https://doi.org/10.1007/s10040-021-02404-1

2.2 Introduction

Overexploitation of groundwater resources in Jordan has been ongoing for at least 30 years and has become a growing threat to safe water supply in the country (Salameh, 2008). The main reasons for the water deficit are high population growth and the intensification of irrigated agriculture, but other factors such as climate change also play a role. 55% of all groundwater is used for agriculture and the remainder mainly for domestic water supply (MWI & GTZ, 2005); industrial groundwater consumption is less than 5% (Margane & Almomani, 1995). Many measures have been implemented to alleviate the deficit: wastewater reuse (A. Abdulla et al., 2016), leakage reduction (Al-Ansari et al., 2014), closure of illegal wells (MWI, 2017) and desalination of brackish surface and groundwater (World Bank, 2004). Tariff hikes have also been used to make illegal wells unprofitable (Al Naber et al., 2017). However, those efforts were not enough to keep pace with growing demand from agriculture and rising population (Yorke, 2016). Monitoring wells all over the country record dramatic declines over the last ~25 years, on average around 50 m but up to 100 m in extreme cases (Bahls et al., 2018) (Figure 2.1). Total five year average spring discharge in all aquifers decreased from 249 MCM/a from 1971-1975 to 136 MCM/a from 2011-2015 (MWI and BGR, 2019).

Different negative consequences arise from this ovexploitation. Because of the large drawdown, water for public water supply and agriculture has to be pumped from ever increasing depths. Boreholes of more than 500 m depth with a pumping lift of more than 300 m are common in Jordan (MWI, 2019). Numerous wells have been drilled to depths of 1000 m to investigate the potential of deep groundwater, some of which are now used for drinking water production, for example in the Lajjun wellfield in central Jordan (Margane et al., 2010). The electricity needed to pump groundwater already accounts for 15% of the national energy bill (NEPCO, 2018). Decreasing water quality due to overabstraction has been reported in some cases (Goode et al., 2013), for example by mobilization heavy metals due to changing redox conditions (Al Kuisi et al., 2015) or by extraction of deeper, more mineralized groundwater (Kaudse, 2014; Salameh, 1996). Furthermore, ecosystems are threatened by reduced baseflow and the cessation of spring flow. The most notable example for this are the springs that used to feed Azraq Wetland, an important stop for migratory birds and for ancient trade routes in the eastern desert of Jordan. The wetland is now at only 10% of its original size and is supplied with pumped groundwater (RSCN, 2015). Large scale hydraulic changes caused by overexploitation occur in many aquifers worldwide. Some well-known examples caused mainly by agricultural abstraction include the High Planes and Central Valley aquifers in the United States (McGuire, 2017; Scanlon et al., 2012), the North China Plain (Currell et al., 2012; Foster et al., 2004), northern India (Sanjeev et al., 2021) and Yemen (Alwathaf & Mansouri, 2012). Hydraulic changes due to rapid population growth are widespread around big urban centers such as Mexico City (Carrera-Hernández & Gaskin, 2007) and in many in rapidly growing megacities in Asia such as Bankok (Lorphensri et al., 2011), Dhaka (Islam et al., 2021; Khan et al., 2016), Jakarta (Kagabu et al., 2011) and Kolkata (Sahu et al., 2013). In addition to the negative effects already mentioned, groundwater overexploitation and subsequent decline often lead to land subsidence in alluvial aquifers (Galloway & Burbey, 2011) and seawater intrusion in coastal aquifers (Alfarrah & Walraevens, 2018).

In spite of the consequences, attempts to quantify the scale of the problem in Jordan are surprisingly rare: the last comprehensive evaluation of groundwater resources on a (sub-)national scale dates back to the early 1990's for southern Jordan (Hobler et al., 1991) and the mid 1990's for northern Jordan (Hobler et al., 2001). Water budget calculations based on climatic data and official abstraction data widely underestimate the deficit because of limited data. Water management decisions based on these data might therefore not be sufficient. To fill this gap, a comprehensive groundwater assessment study was conducted in 2017 (MWI and BGR, 2019). The study was published in 2019 with many supplemental maps, all available online (MWI and BGR, 2019).

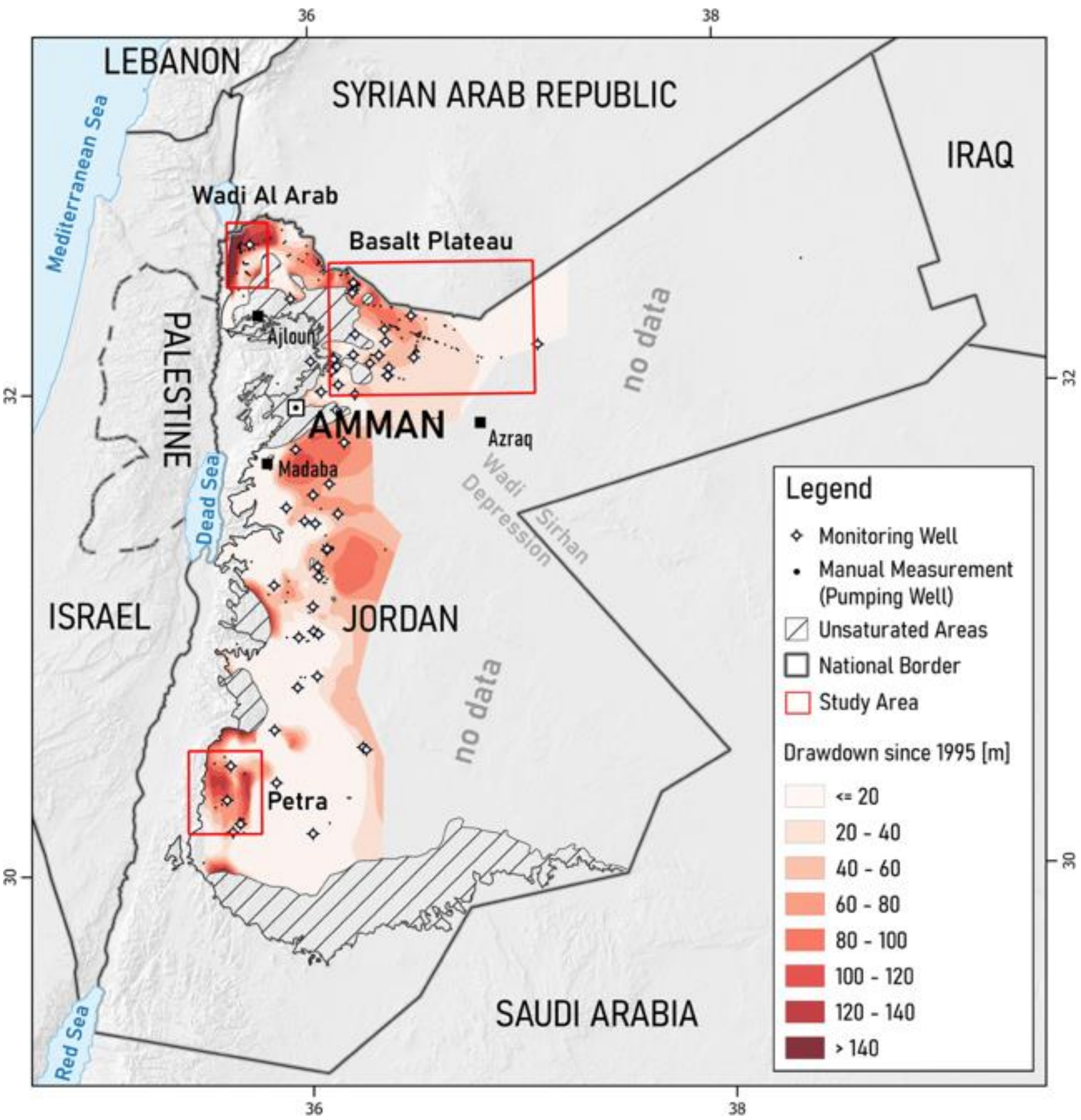


Figure 2.1 Location of case studies discussed in the text and drawdown in the main limestone aquifer (A7/B2) between 1995 and 2017 (modified from MWI and BGR, 2019)

The main output of this is an updated groundwater contour map (Figure 2.2). From this map, secondary maps showing groundwater levels since 1995, depth to groundwater and remaining saturated thickness, were derived. Together they form an important basis for the management of groundwater resources in Jordan, showing where wells might fall dry soon and where favourable locations for replacement wells still exist. Groundwater contour lines are also the main input to delineate groundwater catchment zones. The concept of twelve “groundwater basins”, introduced in the first National Water Master Plan (Vierhuff & Trippler, 1977) is still widely used in literature, without taking into account the changing groundwater flow patterns due to overabstraction.

This paper draws on three case studies to show what factors have contributed to the changes since the previous studies and highlight how the results of the new study can be used at the regional level. They represent some of the areas with the highest drawdown.

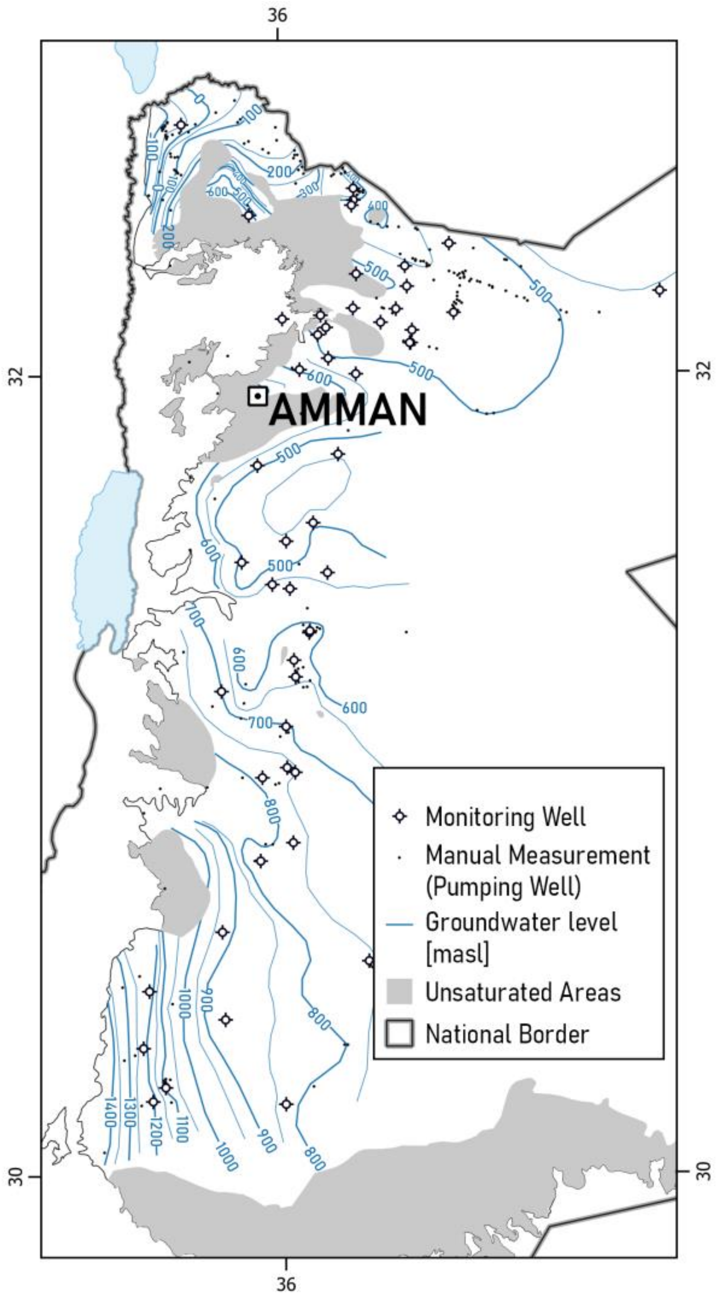


Figure 2.2 Groundwater levels in the A7/B2 aquifer in 2017. Modified from MWI and BGR (2019)

2.3 Study Area

Jordan is located in the northeast of the Arabic Peninsula. The climate is Mediterranean with hot, dry summers and cool winters. Rainfall occurs only during the winter months and its distribution is mainly controlled by topography and distance to the Mediterranean Sea (Margane & Zuhdi, 1995). The Jordan valley, with elevations of up to 400 m below Sea Level, receives average annual rainfall of around 300mm and has a subtropical climate. Rainfall increases with increasing elevation and reaches up to 600mm/a in the northern Jordanian Highlands. Towards the east and the south, climate is inceasingly arid. Ninety percent of the land area receives rainfall of less than 200mm/a. Temperatures reach up to 40 degrees in summer and can reach less than zero degrees in winter (Margane & Zuhdi, 1995).

Three main aquifer systems can be differentiated in Jordan. The oldest is a Cambrian to Lower Cretaceous sandstone complex that crops out along the Dead Sea Rift and in southern Jordan. Around 20% of all groundwater in Jodan is abstracted from this aquifer system (Hobler et al., 2001), almoste entirely from a single wellfield close to the border of Saudi Arabia, the Disi Wellfield (UN-ESCWA and BGR, 2013). Above this aquifer complex lies an Upper Cretaceous Limestone aquifer, locally known as the A7/B2 aquifer. This is the most important aquifer in Jordan, accounting for around 50% of all abstracted groundwater (MWI, 2019). The remaining come from different shallow aquifers, mostly basalt and Eocene chalks, which are becoming less and less important because many of the springs that emerge from them have fallen dry.

The focus on this study is on the main limestone aquifer (A7/B2), which occurs in most of the country with the exception of the southern desert and the escarpment of the Dead Sea Rift. It crops out along the Jordanian Highlands and dips slightly towards the Wadi Sirhan depression in the east (Figure 2.1), where it reaches its maximum thickness of up to 2200 m. The A7/B2 is principally a fractured rock aquifer but there is a moderate degree of karstification where it crops out in zones of higher precipitation, especially in the Northern Highlands. Horizontal hydraulic conductivity is generally between 10^{-6} m/s an 10^{-4} m/s and approximately 10 times higher than vertical hydraulic conductivity (MWI and BGR, 2019).

2.4 Material and Methods

Groundwater level data in Jordan are measured by the Ministry of Water and Irrigation (MWI), either manually at a monthly interval or by telemetric monitoring stations at a daily interval. Manual measurements are entered into the central database at the Ministry (Water Information System – WIS), whereas telemetric data are transmitted to an online-database (SEBA Hydrocenter). In 2017, the MWI and the German Federal Institute for Geosciences and Natural Resources (BGR) carried out an extensive field campaign to measure groundwater levels, both in monitoring wells for validation (n=34) and in pumping wells stopped for maintainance or rehabilitation (n=64) for a better spatial data distribution. measurements were used to verify the values the of both the WIS and SEBA databases and data were corrected if there were obvious mistakes such as sudden shifts or outliers. The absolute elevation [m NN] of all measured monitoring and abstraction wells as well as location of springs locations were re-measured by means of differential global positioning system (DGPS). In areas where government groundwater data are scarce, data from consultants, water suppliers and drilling companies were also used (n=138). This is particularly the case in eastern Jordan, where population density is low. Where other data were not available, the elevation of springs (n=10) and extrapolated historical data from WIS were used (n=22).For the latter, the linear trend of the last five years (2012 - 2016) was applied.

Groundwater contours were drawn by hand, using the same approach as in the previous studies from the 1990's in order to improve comparability. Furthermore, many factors that influence groundwater levels can be considered, such as topography, structural geology, location of production wells and wastewater treatment plants as well as known flow patterns from local studies (Brückner et al., 2015; Dorsch et al., 2020; Gassen et al., 2013; Margane et al., 2009, 2010, 2015). To calculate the difference between the new and the old maps, groundwater contours were then converted into a continuous surface (raster) using a geographic information system (GIS) environment. For the calculation of depth to groundwater, the raster of the groundwater levels was subtracted from a surface elevation raster (SRTM-1, (USGS, 2015)). Saturated thickness and areas where the aquifer is confined were calculated by combining groundwater levels with rasters of aquifer geometry (Brückner, 2018). Groundwater deficit was determined by multiplying the loss in saturated thickness with the corresponding area and the porosity, which is assumed to be between one and three percent (Bahls et al., 2018).

Agricultural areas in section 3.1 were mapped using the normalized difference vegetation index (NDVI) calculated from Landsat images of August each year (end of dry season) to make sure that these areas are irrigated by groundwater and are not rain-fed.

2.5 Results and Discussion

2.5.1 General Overview

Groundwater levels in the A7/B2 aquifer have fallen dramatically and in most areas where data were available since 1995 (Figure 2.1). The highest declines occur in the north along the border to Syria, south of the capital Amman and east of the archaeological site of Petra in southern Jordan (Figure 2.1). The decline is not constant over time: in many wells, the trend accelerates, reaching up to 10 m/a in 2017. An acceleration of drawdown can be observed in around 30% of all monitoring well time series. In production wells, this percentage is probably higher because some areas of high drawdown are underrepresented by monitoring wells. However, groundwater levels in production wells are not measured routinely, only for specific studies.

Unsaturated areas in the A7/B2 aquifer have increased by around 20% between 1995 and 2017. The loss in saturated thickness corresponds to a yearly average groundwater deficit of between 220 to 665 MCM/a in the A7/B2 aquifer, assuming a porosity between one and three percent, respectively. In contrast, the deficit calculated with reported abstraction data is only between 170 and 210 MCM/a for all aquifers. Only roughly half of this reported abstraction corresponds to the A7/B2 aquifer, so the deficit in this aquifer alone would be significantly lower (MWI, 2013, 2015, 2017).

Similar results showing that actual abstraction is higher than official abstraction are reported from other studies. Liesch et al. (2016) estimated groundwater storage losses from GRACE satellite data to be 205 MCM/a on average between 2003 and 2013 in northern Jordan, compared to 145 MCM/a calculated with reported abstraction. In two out of five areas they investigated, the deficit was twice as much as officially reported and in one area even four times as much. Al-Bakri et al. (2016b) calculated that documented abstraction for agriculture in 2015 was only 57 – 83% of crop water demand predicted from remotely sensed cropping patterns, whereas Margane et al. (2015) estimated that actual abstraction might be two to three times as much as officially reported based on loss of saturated thickness.

These discrepancies can mostly be explained with non-revenue water. Some of the most important issues are illegal abstractions and water theft, missing or false metering and leakage. Illegal wells and water connections have been depicted from satellite imagery by identifying irrigated crops that are far from licensed wells. (Al-Bakri et al., 2016b) . Between 2007 and 2017, 1443 illegal wells have been backfilled by the government (MWI, 2017). Fitch (2001) found that although 90% of surveyed farm wells (n=156) in the Amman-Zarqa Basin had a water meter, only 61% worked properly. A survey of bulk water meters (n=475) revealed even worse conditions in the public water supply. A total of 46% of the meters were not working at all and out of the remaining meters, 43% did not measure accurately (USAID, 2015). Leakage is common, but difficult to detect due to the intermittent water supply. Grimmeisen et al. (2016) identified water network leakage through high resolution monitoring of spring flow and composition. According to an analysis in Madaba governorate in central Jordan (Figure 2.1), leakage makes up two thirds of non-revenue water in the public water supply, or around 20% of total supplied water (Aboelnga et al., 2018)

The consequences of the groundwater decline vary across regions. Operational costs are increasing due to increased electricity consumption by larger, more powerful pumps and higher pumping lifts. When wells fall dry, replacement wells are often drilled deeper and far away from consumers (W. Taha, personal communication, 2019). The capital Amman receives water from the Amman Water Sewerage Authority (AWSA) wellfield near Azraq, roughly 80 km to the east and from the fossil sandstone aquifer on the southern border, almost 300 km away (and around 800 m lower in elevation).

In the following chapters, three case studies are used to highlight different causes and consequences of groundwater over-exploitation. In the basalt plateau of northern Jordan, development of irrigated agriculture lead to the decline of groundwater levels and large-scale reversal of groundwater flow directions. In Wadi Al Arab in northwest Jordan, extraction for drinking water supply lead to the decline of groundwater levels and change in confining conditions, causing geogenic contamination of the groundwater. Near Petra in southern Jordan, recent recharge is negligible and nearly all extraction is from fossil groundwater. A paleo-groundwater gradient towards the Dead Sea increases the decline of groundwater levels caused by abstraction for agriculture, domestic use and tourism.

2.5.2 Basalt Plateau case study

The basalt plateau is a characteristic desert landscape in northeast Jordan. Topography is mostly flat but rises gently towards the Jebel Al Druze Mountain in southern Syria, the main area for groundwater recharge. Smaller hills are formed by volcanic feeder channels, often lined along faults (Figure 2.3A). The dark basalt boulders that cover the surface are a product of the erosion of Miocene-Quarternary volcanics (Allison et al., 2000).

Due to a yearly average rainfall of less than 200 mm and absence of perennial streams or lakes, the area was traditionally populated by nomadic Beduins. The introduction of diesel pumps in the 1980's allowed groundwater-irrigated agriculture (UN-ESCWA and BGR, 2013), a practice that was actively encouraged by the government in order to develop the area economically and settle the Bedouins (J. Fitch, 2001). By the 1990's, over-abstraction had already become a problem and laws were established to regulate drilling, limit abstraction through licensing and to close illegal wells (Al Naber & Molle, 2017). However, expansion of agriculture in the area is still ongoing (Figures 3C and 3D), with a shift towards larger fields and high-value crops, managed by investors for the export market and run by foreign labour, often from Egypt or Yemen (Al Naber et al., 2017). Wells for the public water supply of the northern governorates are lined along the Baghdad road that connects Jordan and Iraq (Figure 2.3A). Most wells extract water from the main limestone aquifer (A7/B2), which is hydraulically connected to the overlying shallow basalt aquifer in the western part of the study area, forming a combined aquifer. In the eastern part, the two aquifers are separated by the marls of the B3 aquitard (BGR/ESCWA, 1996). Groundwater-irrigated agricultural areas in the study area have increased more than sevenfold from 3.2 km^2 in 1995 to 24.5 km^2 in 2017 (Figures 2.3C and 2.3D). The population in Jordan has approximately doubled from 4.8 million to ten million in 2017 (Figure 2.3C). Additionally, Jordan hosts more than 600.000 Syrian refugees, around 20% of which live in the study area, putting additional stress on the water resources. However, the accelerated decline of groundwater resources predates the onset of the Syrian Civil War in 2011 by several years. As an example, the monitoring graph of observation well AL3387 is shown in Figure 2.3C, where the acceleration of the decline started in 2007.

The updated groundwater contour lines suggest that a regional drawdown cone has formed around the agricultural zone north of the city of Mafraq that leads to a total reversal of groundwater flow direction in the eastern part of the area (Figure 2.3A) compared to that in 1995. . This means that groundwater catchment zones change with declining groundwater levels. The static concept of “groundwater basins” (Vierhuff & Trippler, 1977) does not take this into account because it was developed before widespread overabstraction occurred. In addition, the concept does not consider the different aquifer systems. It has been shown that significant leakage occurs between the aquifer systems – all groundwater eventually reaches the deep sandstone aquifer and flows towards the Dead Sea – the deepest drainage level on earth. Instead of “groundwater basins“ it is recommended to use individual aquifers or aquifer systems as a point of reference.

Depth to groundwater level increases from around 100 m in the south to the study area to 500 m on the slopes of Jebel al Druze near the Syrian border. In the public water supply wells along Baghdad Road, depth to groundwater level is mostly between 250 m and 300 m.The saturated thickness map (Figure 2.3B) shows the remaining saturated thickness and areas where the A7/B2 aquifer has already fallen dry (unsaturated areas). Many wells located in areas with less than 100 m saturated thickness are suffering from low productivity or might fall dry in the near future, among them three wells drilled for the water supply of Zaatari refugee camp, the biggest refugee camp in Jordan (van der Helm et al., 2017).

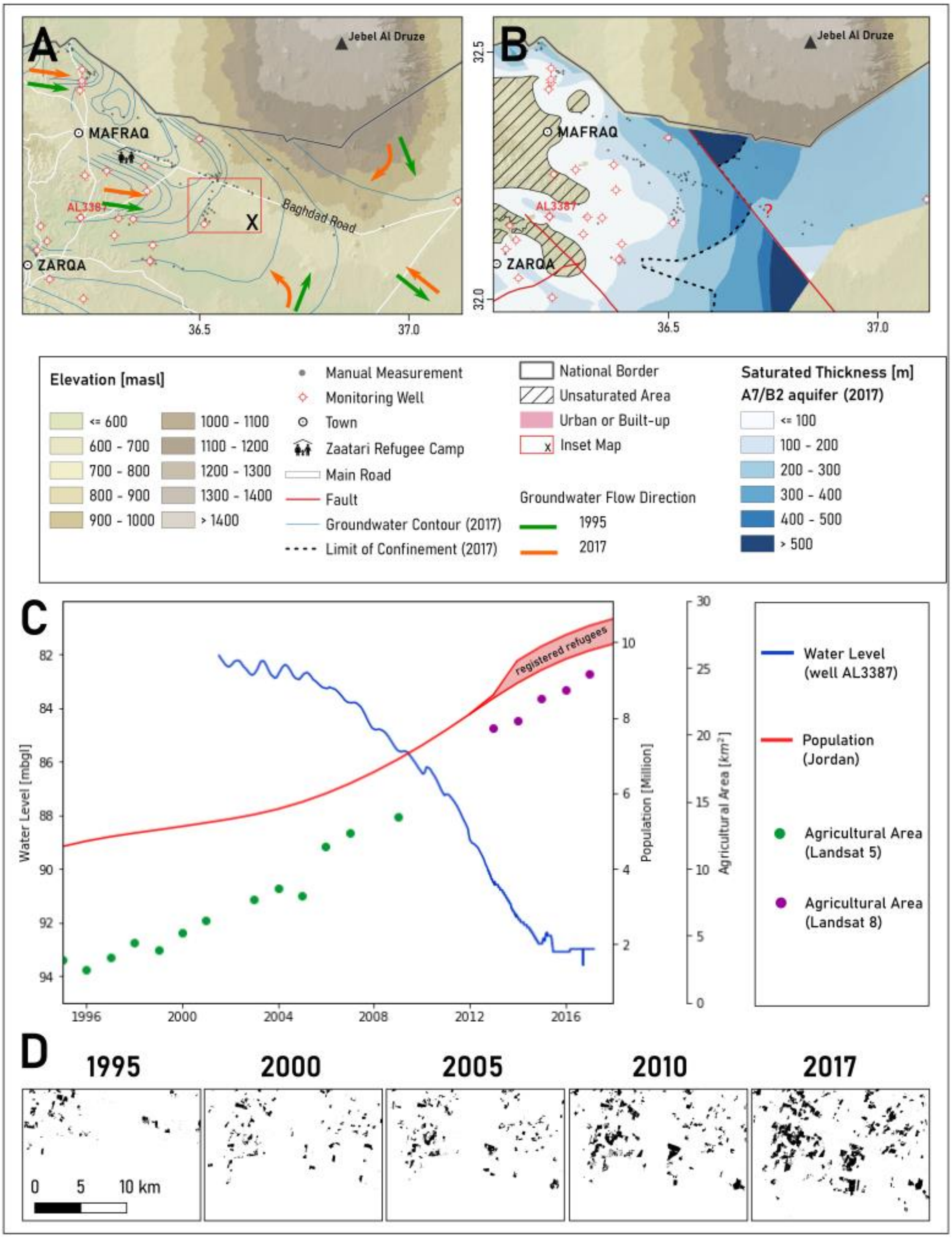


Figure 2.3 A: Change of groundwater flow direction between 1995 and 2017 B: Unsaturated areas and remaining saturated thickness C: Expansion of agricultural areas between 1995 and 2017 in inset map (dots), population growth and registered Syrian refugees (red line) and groundwater level decline as measured in monitoring well AL 3387 D: Agricultural areas between 1995 and 2017 in inset map

2.5.3 Wadi Al Arab Wellfield case study

Wadi Al Arab is a valley close to the confluence of the Jordan River and the Yarmouk River in the north western part of Jordan. The wellfield is located just upstream of the homonymous dam (Figure 2.4A), which lies at an elevation of 100 m below sea level. Recharge comes mainly from the Ajloun Highlands south of the study area that receive an annual mean precipitation of up to 550 mm, the highest recorded in Jordan. Rödiger (2014) determined that average recharge in the area is 12% of precipitation with a hydrological model calibrated with different independent data sets.

Wadi Al Arab wellfield provides around 40% of the drinking water supply of Irbid (Alqadi et al., 2019), one of the biggest cities in Jordan with almost one million inhabitants (DoS, 2019). When the wellfield was established in 1982, six out of nine wells of Wadi Al Arab wellfield were artesian. However, only a few years after production started, groundwater levels started to fall and spring flow in the area ceased almost completely (Subah et al., 2006a). Nowadays, groundwater decline rates in the wellfield are among the highest in Jordan. The closest monitoring well AE1003, located five kilometres upstream of the wellfield (Figure 2.4A and 2.4C), shows a decline of 3 m/a with a seasonal variation of around 1 m (Figure 2.4B). Measurements in production wells switched off for maintenance revealed that decline rates in the wellfield are actually up to 10 m/a (Dorsch et al., 2020).

Consequently, the aquifer is becoming increasingly unconfined. Further downstream towards the Jordan Valley, artesian conditions still prevail (Figure 2.4A and 2.4D). Stable isotope patterns of water samples show that water bypasses the aquitard and mixes with groundwater in the Jordan valley (Salameh, 2004), possibly via the Dead Sea Transform Fault.

The changing hydraulic conditions from confined to unconfined have implications on water quality: downward leakage from organic-rich sections in the overlying aquitard is assumed to be the main cause of rising concentrations of Molybdenum (Al Kuisi et al., 2015) and heavy metals (Dorsch et al., 2020). For now, the water supplier achieves drinking water quality through dilution with water from nearby Tabaqat Fahel wellfield (Subah et al., 2006a), but if more wells are affected, costly treatment is inevitable. Sealing the aquitard during well construction is likely to reduce concentrations but is not common practice yet. In the future, this process could affect large parts of northern Jordan that have a similar hydrogeological setup (Figure 2.4C). Apart from the quality problems, hydrogeological conditions in the wellfield are favourable, with a depth to water table of around 100 m and remaining saturated thickness of around 350 m in most of the wells.

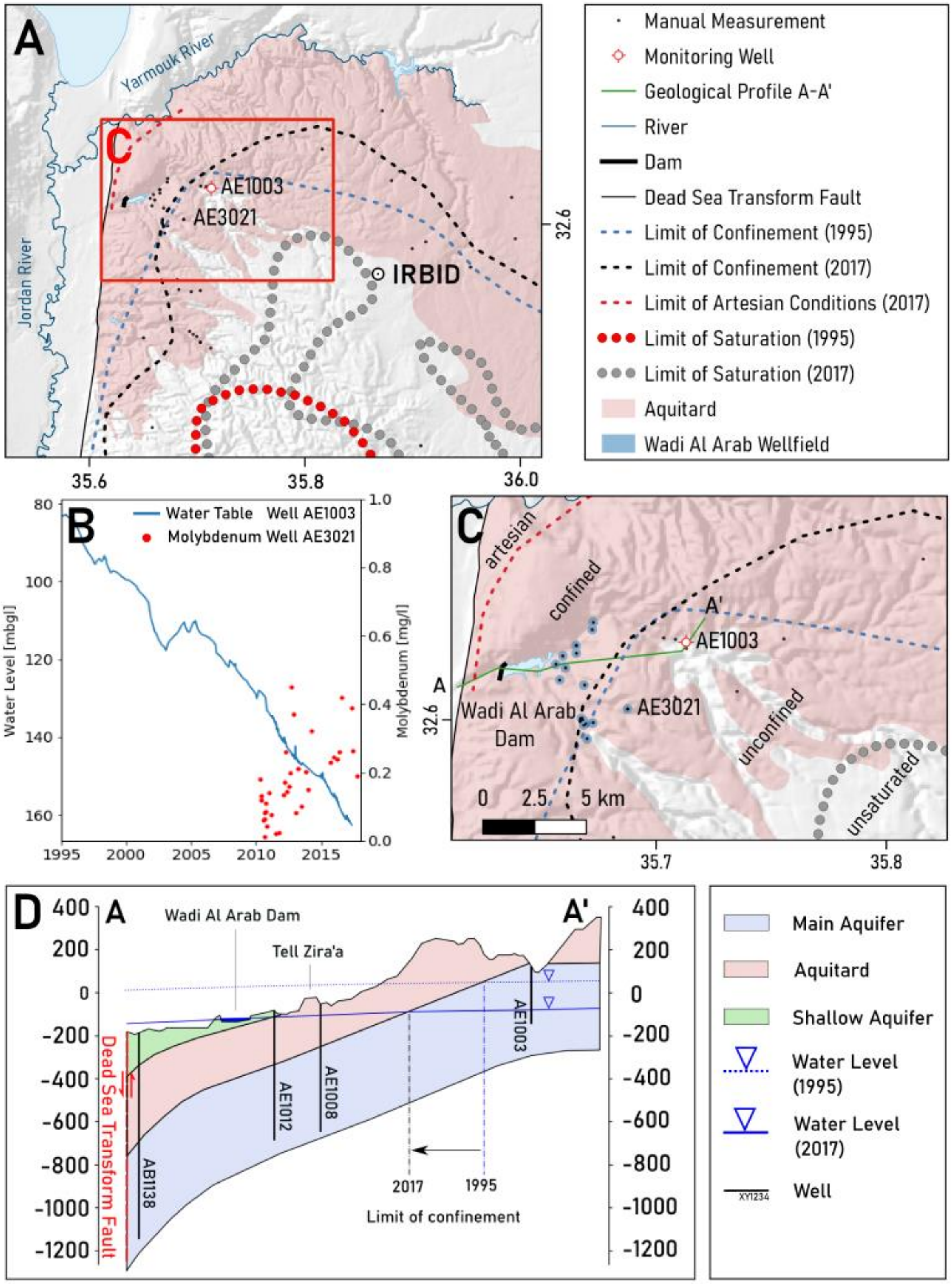


Figure 2.4 Wadi Al Arab Wellfield B: Groundwater levels in monitoring well AE1003 and molybdenum concentrations in well AE3021 (Dorsch et al. 2020) C: Regional hydraulic conditions D: Hydrogeological Profile A-A' (Location in 3A)

2.5.4 Petra case *study*

The ancient city of Petra is located midway between the Dead Sea and the Red Sea on top of the eastern graben shoulder of the Dead Sea Rift Valley. Petra was carved into sandstones that are overlain by the limestones of the A7/B2 aquifer east of the city in the Jordanian Highlands. West of Petra, topography falls off steeply towards the Rift Valley. Average yearly rainfall reaches up to 200 mm/a in the higher elevations of the study area but decreases to less than 50 mm/a towards the east (Figure 2.5B). Hobler (1991) determined recharge to be 10 % of rainfall in areas where annual rainfall exceeds 300 mm/a based on groundwater modelling. According to the authors, the proportion of recharge then decreases slightly with decreasing rainfall and in areas where rainfall is less than 75 mm/a, there is essentially no recharge. Due to the steep topography around Shobak in the northern part of the study area, the proportion of recharge might be even less due to high surface runoff. This means that nearly all groundwater in the study area is fossil groundwater. As early as 300 BCE, the ancient Nabateans channeled water from nearby springs to the rock-carved city of Petra as part of their elaborate water supply system for the city (Ortloff, 2005). Nowadays, nearly one million people visit the ruins every year, generating significant income, but also putting additional stress on the water resources. (Figure 2.5A).

Groundwater levels have dropped more than 90 m in the center of the study area since 1995 (Figure 2.5B). In addition to the seasonal variation of 1 m/a, the monitoring graph of well G1346 shows a sustained decline of 3 m/a that increases to 5 m/a from around 2007 (Figure 2.5C). Groundwater flows eastwards due to aquifer geometry, reaches the lower sandstone aquifer through leakage where it flows west towards the Dead Sea (Salameh & Udluft, 1985) (Figure 2.5A This flow pattern is closely connected to paleoclimate and tectonics: around 15.000 years ago, regional climate was humid and the Lisan paleolake occupied a large portion of the rift valley (Levy et al., 2019) (Figure 2.5A). Sedimentary records show evidence for a large wetland around 50 km east of Petra, now completely dry, that used to cover roughly half the size of the Lisan Lake, indicating a water table significantly higher than today (Mischke et al., 2015) (Figure 2.5A). Since then, climate has been roughly similar to today, with the exception of two shorter and less intense humid periods at ca. 10000 BP and 5000 BP, respectively. As a result of the changing climate, the water level of Lake Lisan - drainage level for both surface and groundwater - dropped by 200 m and the lake separated to form the Dead Sea and Lake Tiberias. The steeper gradient results in an increased outflow of groundwater towards the Dead Sea.

Groundwater modelling indicates that a new equilibrium is not reached yet and water tables are still declining because of this (Hobler et al., 1991). Over the last decades, the water level of the Dead Sea has been declining at a rate of almost 1 m/a (Figure 2.5C). The saltwater-freshwater interface is also retreating due to the decline, causing additional inflow of groundwater. Salameh (Salameh & El-Naser, 2009) calculate that an additional inflow of 461 MCM groundwater is needed every year to make up for the loss of saltwater and reach hydrostatic equilibrium. In addition, sinkholes form where the freshwater dissolves salt layers that were previously saturated with saline groundwater (Yechieli et al. 2016).

Climate change is another factor that decreases water availability: the two rainfall stations in the study area show an average decline of around 1.5 mm/a (G0009) and 4.5 mm/a (DA0003) over the last 25 years (Figure 2.5C). A similar trend can be observed in the rest of Jordan: Rahman *et al*. (2015) report an average decline of 0.41 mm/a from 58 stations in Jordan over 44 years. Projections of future climate predict the trend to continue along with rising temperatures, thus further decreasing recharge (MoE & UNDP, 2014). As of 2017, the average depth to water table in this study area is around 100 m, with about 200 m of remaining saturated thickness.

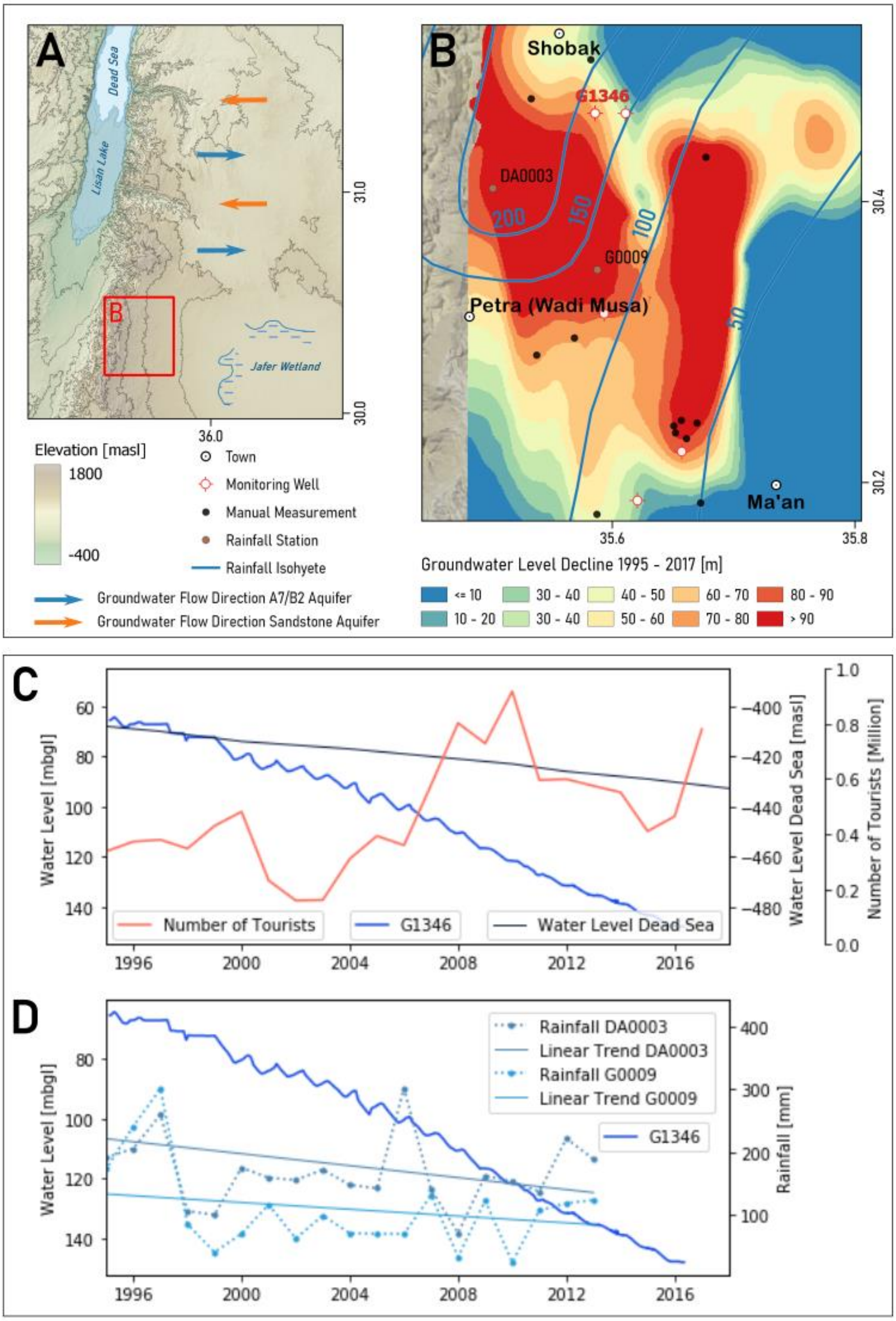


Figure 2.5. A: Location map, paleohydrological features (modified from Levy et al. 2019, Mischke et al. 2015) and regional groundwater flow directionB: Groundwater level decline between 1995 and 2017 and average annual rainfall (WIS database) C: Time series of decreasing groundwater and Dead Sea water level, compared to the increase in number of tourists D: Time series of groundwater levels (G1346 monitoring well) and rainfall

2.5.5 Methodological Challenges and Limitations

In addition to the results, important observations about groundwater monitoring were revealed during analysis. The quality of monitoring data in Jordan varies from excellent, long-term data series to short series with jumps, gaps, and shifts that can often be related to the introduction of telemetric monitoring (and the end of manual measurements) starting in 2010. The main deficit is the absence of quality control before data are entered into the database, so extensive and time consuming selection, validation, and cleaning of data is necessary to ensure their usefulness. The most common errors identified were data entry errors in the case of manual measurements and wrong calibration, low battery power, vandalism and sensors above the groundwater level in the case of telemetric measurements. Coordinates and elevation of wells are frequently inaccurate: instead of measuring coordinates in the field, they are often read from a map. Furthermore, the proposed location of a well is often entered into the WIS database, rather than the location where the well was actually drilled. In telemetric wells, outlier values and sensor drift are common. Due to financial constraints, monitoring wells are usually not purposely built. Instead, decommissioned, low yield pumping wells with questionable connection to the aquifer and/or unknown well design are converted into monitoring wells. In some cases, they are not far away from active pumping wells and do therefore record dynamic groundwater levels instead of the natural groundwater level. Extrapolation of historical data has to be used carefully, because trends and seasonal variations are not systematic and can vary significantly between areas. Although the approach of drawing contour lines manually results in a more accurate representation of the hydrogeological setting, it is based on expert judgement and thus difficult to reproduce. Some of the differences between the maps from the 1990's and the 2017 update might be caused by the different interpretation of data.

2.6 Conclusions

The first comprehensive groundwater assessment in Jordan since the 1990's (MWI and BGR, 2019) reveals dramatic groundwater level declines in large parts of the country. Validated data from monitoring wells and other sources give a continuous picture of the groundwater situation in large parts of Jordan's main aquifer, including flow directions, saturated thickness and drawdown since 1995.

Three case studies illustrate the major causes and consequences of long-term overabstraction: In the basalt plateau, groundwater-irrigated agricultural areas increased more than sixfold since

1995, while the population of Jordan has doubled during the same time. Due to the increased groundwater abstraction, groundwater flow direction has changed significantly and decreased saturated thickness affects well yields. In Wadi Al Arab wellfield, hydraulic conditions are increasingly becoming unconfined due to the high drawdown. This is suspected to be one of the main drivers for the downward leakage of geogenic contaminants from the overlying aquitard. Around Petra, recharge is much lower than abstraction due to the arid climate. The abstracted groundwater is mostly fossil groundwater from the last humid period, leading to large drawdowns. The drivers of groundwater decline are often overlapping and difficult to separate from each other. Nevertheless, the analysis of groundwater monitoring data can help to identify important gaps in data. For example, the abstraction from agriculture is likely underestimated by a factor of at least two. The set of maps presented in this study - groundwater contours, saturated thickness and average groundwater decline rate – provide key information to decision-makers, researchers, and the general public. The update of groundwater data shows that large changes have occurred which make it necessary to also update conceptual models such as the concept of Jordans 12 “groundwater basins”.

In addition to the results from the assessment, a thorough analysis of the monitoring network and data revealed several shortcomings. Although the monitoring network in Jordan is extensive, there are still some gaps, especially in the East of Jordan and in the highlands where not many wells exist. In some areas, monitoring wells are located too close to pumping wells or other monitoring wells. Consequently, it was necessary to use several additional data sources to produce the maps. Locations of monitoring wells and time series were corrected in the database. Due to shifts and sensor problems, telemetric wells should be checked against manual measurements at least twice a year to check their accuracy. In order to produce groundwater assessments more frequently in the future, data quality control and quality assurance are critical to decrease the time needed for data cleaning and validation.

Chapter 3

A Novel Method to Assess the Impact of a Government's Water Strategy on Research.

Alqadi et al. (2021)[1]

Abstract

Water scarcity drives governments in arid and semi-arid regions to promote strategies for improving water use efficiency. Water-related research generally also plays an important role in the same countries and for the same reason. However, it remains unclear how to link the implementation of new government strategies and water-related research. This article's principal objective is to present a novel approach that defines water-related research gaps from the point of view of a government strategy. The proposed methodology is based on an extensive literature review, followed by a systematic evaluation of the topics covered both in grey and peer-reviewed literature. Finally, we assess if and how the different literature sources contribute to the goals of the water strategy. The methodology was tested by investigating the impact of the water strategy of Jordan's government (2008–2022) on the research conducted in the Azraq Basin, considering 99 grey and peer-reviewed documents. The results showed an increase in the number of water-related research documents from 37 published between 1985 and 2007 to 62 published between 2008 and 2018. This increase should not, however, be seen as a positive impact of increased research activity from the development of Jordan's water strategy. In fact, the increase in water-related research activity matches the increasing trend in research production in Jordan generally.

[1] **Alqadi, M.,** Al Dwairi, A., Dehnavi, S., Margane, A., Al Raggad, M., Al Wreikat, M., & Chiogna, G. (2021). A novel method to assess the impact of a government's water strategy on research: A case study of Azraq Basin, Jordan. Water, 13(15), 2138.

Moreover, the results showed that only about 80% of the documents align with the goals identified in the water strategy. In addition, the distribution of the documents among the different goals of the strategy is heterogeneous; hence, research gaps can be identified, i.e., goals of the water-strategy that are not addressed by any of the documents sourced. To foster innovative and demand-based research in the future, a matrix was developed that linked basin-specific research focus areas (RFAs) with the MWI strategy topics. In doing so, the goals that are not covered by a particular RFA are highlighted. This analysis can inspire researchers to develop and apply new topics in the Azraq Basin to address the research gaps and strengthen the connection between the RFAs and the strategy topics and goals. Moreover, the application of the proposed methodology can motivate future research to become demand-driven, innovative, and contribute to solving societal challenges.

3.1 Introduction

Water scarcity is a severe problem for Jordan (Al-Kharabsheh, 2020; Hadadin et al., 2010; Salameh et al., 2018) and undermines the country's societal and economic development (Yorke, 2016) . Research in the water sector is important and necessary. Essential investments in water-related research have been made using internal funding and international aid (Pitman, 2004). Although collaboration between academia and decision-makers at different levels, from governmental institutions through to water works and private stakeholders owing water rights, offer multiple benefits for both (Young & Freytag, 2021), the impacts of new water-related policies on research outcomes and vice versa remains unclear.

Academia could provide policymakers and practitioners with evidence-based knowledge from the research findings that directly feed the decision-making process (Nutley et al., 2002). Even if some research findings do not directly contribute to the decision-making process, those findings can indirectly affect policy development and practitioners' actions (Bryman, 2012). Therefore, decision-makers are advised to use evidence in making policy decisions (Black, 2001; Solesbury, 2002) and should consider research findings in the policy development process (Wowk et al., 2017).

Although there is a growing emphasis on research-based policy decisions, such as "research utilization", "knowledge transfer", "knowledge brokering", and "evidence-based policy" (Newman et al., 2016), factors such as financial constraints, shifting timescales, and decision makers' experiential knowledge may reduce the direct influence of research evidence on decision making (Elliott & Popay, 2000). In this work, the aim is to present a methodology based on an extensive literature review and analysis to evaluate the impact of the Jordan's water strategy (2008–2022), developed by the Ministry of Water and Irrigation, on research production. The water strategy contains a set of goals to achieve a better management of the kingdom's water resources to achieve the vision of the ministry in 2022. In particular, the focus is on the identification of research gaps that have not been accounted for during the period of implementation of the strategy.

One of the aims of conducting and publishing this research is to identify research gaps and propose ways to advance and harness knowledge in order to fill these gaps(Gaziano, 2016). The definition of a research gap is context-dependent and can differ from topic to topic (Nyanchoka et al., 2019). In general, Robinson et al. (2011) refer to a research gap as "When the ability of the systematic reviewer to draw conclusions is limited." (Robinson, Saldanha, & McKoy, 2011) (p. 1). Accordingly, a research gap is deemed to be a missing body of information, information that is needed to address a specific and pressing research question (Müller-Bloch & Kranz, 2015). Understanding the nature of research gaps and their origin is regarded as the most critical step in producing good-quality research (D. Anthony Miles, 2017).

Moreover, while substantial methodological guidance already exists to identify the scope, conceptualization, analysis, and further synthesis of a "systematic literature review", a methodology to identify research gaps from these systematic reviews is still a matter of debate (D. Anthony Miles, 2017; Robinson, Saldanha, & Mckoy, 2011). Based on the works of Müller-Bloch and Kranz (2015) and Robinson et al. (2011), Miles (2017) identified seven types of literature gaps, namely: (1) evidence gaps arise when new-found research contradicts the conclusions of the previous study; hence, a need to collect more evidence to arrive at a concise conclusion; (2) knowledge gaps indicate the lack of knowledge (e.g., theories, methodologies) in a particular field or the delivery of some unexpected results from studies; (3) practical-knowledge gaps convey the need for new research when there is a difference between actual professional practices and research findings on a specific topic; (4) methodological gaps explore the conflict that may arise between research methods, the effects of research methods on research results, and the lack of research methods for a specific study area; (5) empirical gaps arise when a particular study area or topic has not been previously explored empirically in past research; (6) theoretical gaps explore the conflict that may arise when a certain topic is explored with a single theory or when one theory becomes superior to other theories; and (7) population gaps arise when a certain group of the population categorized based on race, ethnicity, economical status, etc. is underrepresented in the research.

Our work aims to present a comprehensive methodology for defining and identifying water-related research gaps, which can support demand-driven research, inspire new research topics to transform future research to become imaginative and innovative, and help the government to achieve the goals set within its strategy. Furthermore, the methodology developed helps to show the heterogeneous impact of the governmental strategy on various research focus areas (RFAs) and highlights the scientific fields contributing the most to the governmental strategy. The methodology was developed to evaluate the impact of Jordan's water strategy (MWI, 2008) on research involving the Azraq Basin (specifically) but can be applied to evaluate any context of impacts between government and academia.

3.2 Study Area

A total of twelve river basins exist in Jordan (MWI, 2017). The Azraq Basin is located in the northeastern region of Jordan and covers approximately 12,700 km^2; about 94 % of the basin lies in Jordan, while about 5 % and 1 % are in Syria and Saudi Arabia, respectively. The basin is the second-largest basin in size and the second most exploited after the Amman-Zarqa basin (Molle et al., 2017; MWI, 2017). Topographically, the basin is located within the highland region in Jordan, where the elevation ranges from 490 m above sea level in the Azraq Mudflat area, in the center of the basin, to more than 1300 m above sea level on Jabal Druze area in Syria (Figure 3.1). Jabal Druze is considered the main recharge area of basalt aquifer (Abu-Jaber et al., 1998; Bajjali & Al-Hadidi, 2006; Salameh, Toll, et al., 2018; Verhagen et al., 1991). The Azraq Basin climate is arid to semi-arid, with a dry and hot season extending from May to September, with a wet and cold season extends from October to April (Abu-El-Shar & Rihani, 2007; Gassen et al., 2017; MoE & UNDP, 2014). The primary water resource of the basin is categorized as renewable groundwater sources (MWI, 2017), and its importance is threefold: Firstly, besides supplying the Azraq area, the basin provides drinking water for major urban areas in Jordan, mainly Amman and Zarqa cities, (F. Abdulla et al., 2000; Al-Kharabsheh, 2000; Al Qatarneh et al., 2018; Amro et al., 2001). Secondly, it provides water for agricultural activities surrounding the basin area (Al-Bakri, 2014, 2015a; Demilecamps & Sartawi, 2010; MWI, 2017). Finally, the basin's ecological importance is manifested through the Azraq wetland, a prosperous provider of ecosystem services in the area, which has deteriorated over time due to over-pumping of groundwater resources (Al Eisawi, 2005; Riebe, 2018).

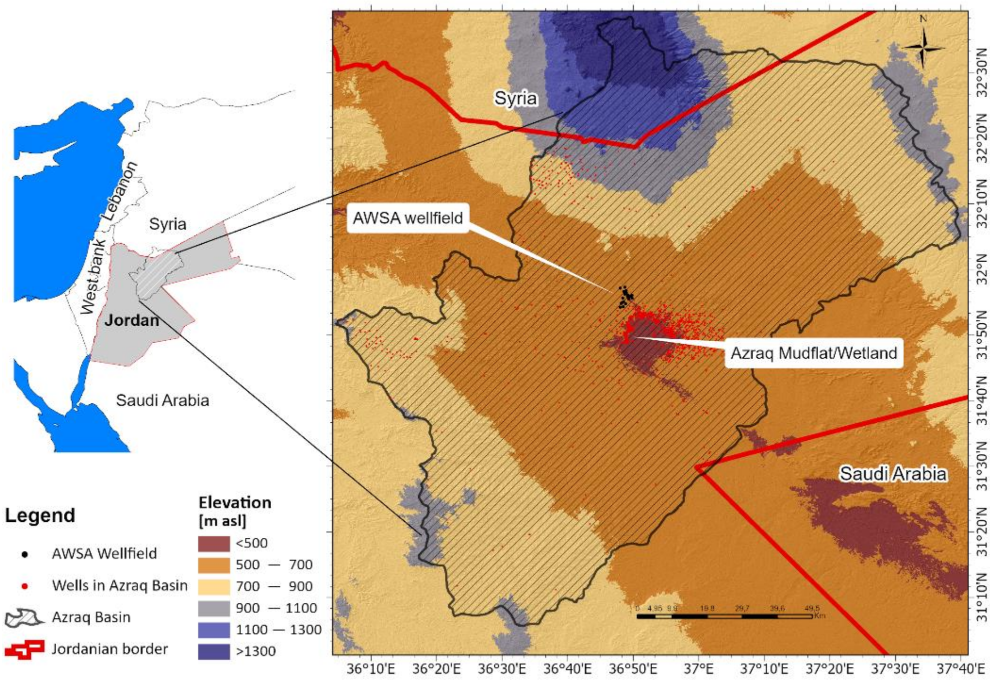


Figure 3.1. The elevation and extension of the Azraq Basin (the elevation unit is meters above sea level (m asl)).

3.3 Methodology

3.3.1 Collection Process

Between December 2019 and January 2020, the research team led a one-month field research trip/excursion to Jordan. The trip/excursion consisted of 18 unstructured interviews with current and retired employees of the Jordanian Ministry of Water and Irrigation (MWI) and employees of cooperation projects between the MWI and international partners. The visit aimed to (a) understand the current archiving process of project reports in the MWI, (b) collect the final reports that were conducted under the umbrella of the MWI, and (c) propose the development of an archiving system for final reports, taking into consideration the recommendations of the MWI and international partners. We have been able to collect 2200 digital documents (e.g., final reports, report sections, letters, incomplete reports, presentations, or report drafts) present in the Ministry's record, spanning from 1963 to 2019.

In addition to the collected research from MWI, grey literature was searched online through Google searching, Scopus, Web of Science (WoS) engines, and the websites of the MWI and the MWI partners' websites (e.g., Helmholtz-Zentrum Umweltforschung GmbH (UFZ), Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), United States Agency for International Development (USAID), Deutsche Gesellschaft für Internationale

Zusammenarbeit (GIZ)). In this work, we consider only conference proceedings and final reports from the government and their partners as grey literature. Dissertations, Master's and Bachelor's theses, and posters are excluded in the review and analysis (Table 3.1).

Table 3.1**.** Type of literature included/excluded in this study**.**

Included Literature	**Excluded Literature**
• Technical reports by MWI (available digital copy)	Technical reports by MWI (only available in hard copy)
• Technical reports by international projects (available digital copy)	Technical reports by international projects (only available in hard copy)
• Final reports/studies	Studies that are not related to Azraq Basin
• Peer-reviewed literature • Proceeding conference paper	Studies that are included within the daily activities of the MWI employees (e.g., small study to give a license to build a specific factory)
	Master's, Bachelor's and Ph.D. theses.
	References that are cited in other documents but were not accessible.

The search for peer-reviewed publications was collected using Google Scholar (GS), Scopus, and Web of Science (WoS) search engines. The literature collection process started with GS, given that it is the most comprehensive web search engine for literature, where it contains 95% and 92% of literature that exists in WoS and Scopus, respectively (Martín-Martín et al., 2018, 2020). To ensure the search remained as vast as possible, queries were used with general keywords (e.g., "Azraq Basin" OR "East* Jordan" AND "Water"). The obtained results were reviewed, and only research results related to water in the Azraq Basin were added to the literature inventory up to the year 2018; research published in and after the year 2018 was excluded. The same procedure was repeated using Scopus and WoS search engines, utilizing Publish and Perich 7 software to search and analyze academic citations (Harzing, 2007).

3.3.2 Analysis Process

The MWI published the "Jordan's Water Strategy 2008–2022" report (MWI, 2008), aiming to ensure the availability of water for people, businesses, and nature by accomplishing a set of goals within the topics of water demand, water supply, institutional reform, water for irrigation, wastewater, and alternative water resources in the year 2022. To achieve the objective of this paper, the goals of the collected research were compared to the water strategy goals, highlighting whether or not these research goals contributed to one or more of the MWI water strategy goals (Table 3.2). Some of the MWI strategy goals are excluded from the analysis as they focused on a specific study area different to the Azraq Basin. For example, the MWI water strategy goal 6.b., which states, "Desalination projects at the Red Sea are operational", cannot be compared with the collected research goals because this goal targets the Red Sea; consequently, we excluded goal 6.b. from the analysis of this paper.

Table 3.2. The topics and goals of MWI strategy (2008–2022).

	1. Water demand
1.a.	Water use for agriculture shall be capped.
1.b.	Jordanians are well aware of water scarcity and the importance of conserving and protecting our limited water resources.
1.c.	The management of water resources shall duly consider the potential risks derived from Climate Change induced impacts on the water balance.
1.d.	Viable options to reduce water demand within each sector are readily available.
1.e.	Water tariffs within and outside the water sector should support water demand management
1.f.	Non-revenue water to be 25% by 2022.
	2. Water supply
2.a.	Uninterrupted safe and secure drinking water supply achieved including continuous flow in Amman. Zarqa. Irbid. and Aqaba.
2.b.	Water supply from desalination is a major source.
2.c.	Drinking water resources are protected from pollution.
2.d.	Surface water is efficiently stored and utilized.
2.e.	Treated wastewater effluent is efficiently and cost-effectively used.
2.f.	Data on the availability of water resources will be acquired via a telemetric observation network safeguarding continuous information flow. Modern information technology will provide a sound basis for the monitoring and the management of Jordan's water resources.
2.g.	Special management plans to ensure safe yield principle being applied in groundwater extraction
2.h.	The concept of utilizing greywater and rainwater is fully embedded in the codes and requirements of buildings.
2.i.	Our shared water rights are protected.
	3. Institutional reform
3.a.	National Water Law is enacted and enforced.
3.b.	Strong policy development and water resource planning strategies and capabilities forged.
3.c.	Governance functions and operational functions are separated.
3.d.	"Wholesale" operations (national infrastructure) and "retail" operations (service delivery) are separated.
3.e.	A Water Council is operational allowing for broad stakeholder input into water management
3.f.	A Water Regulatory Commission of Jordan is established.
3.g.	Commercial principles drive water management while the needs of the poor are supported
3.h.	Staff is trained. Its number is optimized. Conflicts of interests are eliminated, and a dynamic working environment is created that is responsive to the needs of the sector.
3.i.	The National Water Master Plan is institutionalized representing the binding strategic management instrument of the Water Sector as stipulated by the National Water Law.
	4. Water for irrigation
4.a.	The annual water allocation for irrigation in the Jordan Valley will be increased to 377 MCM in 2022 (293 MCM in 2007) and in the Highlands reduced to 184 MCM in 2022 (297 MCM in 2007).
4.b.	Efficient bulk water distribution as well as efficient on-farm irrigation systems are established.
4.c.	All treated wastewater generated will be used for activities that demonstrate the highest financial and social return including irrigation and other non-potable uses.
4.d.	Jordan will have one service provider for irrigation water for the whole country, whereas the retail function for irrigation water will be privatized and/or handled by empowered farmers' associations.
4.e.	Appropriate water tariffs and incentives will be introduced in order to promote water efficiency in irrigation and higher economic returns for irrigated agricultural products.
4.f.	Alternative technologies such as rainwater harvesting for enhancing irrigation water supply will be promoted.

	5. Wastewater
5.a.	All the major cities and small towns in Jordan are provided with adequate wastewater collection and treatment facilities.
5.b.	All major industries and mines have wastewater treatment plants.
5.c.	New high-rise buildings use greywater for internal non-drinking purposes.
5.d.	Public health and the environment, in particular groundwater aquifers, are protected from contaminated wastewater in the areas surrounding wastewater treatment plants.
5.e.	Treated wastewater is used for activities that provide the highest return to the economy. For irrigation use in the Jordan Valley and in the Highlands, a comprehensive risk management system is in place.
5.f.	The quality of treated wastewater from all municipal and industrial wastewater treatment plants meets national standards and is monitored regularly.
5.g.	Tariffs for wastewater collection are rationalized.
5.h.	All treatment plants are operated according to international standards and manpower is trained accordingly.
	6. Alternative water resources
6.a.	Treated wastewater will be used for the activity that provides the highest social and economic return and standards for use in agriculture will be introduced and reinforced.
6.b.	Desalination projects at the Red Sea are operational.
6.c.	Rainwater harvesting is encouraged and promoted.
6.d.	Infrastructure for desalination of sea and brackish water is sufficient.
6.e.	An alternative energy source to keep the cost of desalination as low as possible is available.

In the analysis process, we followed the framework that Müller-Bloch (Müller-Bloch & Kranz, 2015) introduced to identify research gaps. Research gap results were first identified by synthesizing a systematic literature review of the subject by using straightforward localization methods such as the chart method. This method organizes the reviewed literature into a chart according to the MWI strategy goals. A goal in the chart can be associated with one or more literature documents, indicating that at least one document addresses this goal, or it can be left empty, indicating a research gap. After locating a research gap, verification processes continued by double-checking if no research could be sourced to fill the gaps; finally, the goals were presented according to the number of documents that were associated with each goal. According to the classification of Miles (D. Anthony Miles, 2017), the comparison between the conducted research and the MWI goals allow the identification of a “practical-knowledge gap”.

Any MWI goal that registers no contribution by the collected research is considered a research gap, and any research that contributed to the MWI strategy goals is regarded as potentially demand-driven research. To better assess the topic of demand-driven research, a comparison was conducted between the collected studies before and after the implementation of the MWI strategy, to highlight if a change in the research direction towards the MWI goals could be identified.

To study the variable impact on research involving the basin from different types of research institutions (i.e., academic, non-academic, national, and international), the peer-reviewed studies were first categorized based on the affiliations of the author. Such a procedure was only applied for peer-reviewed literature because the affiliation of each of the authors of specific grey literature is not always defined. Furthermore, the specific research focus of each study was then identified and listed according to nine main RFAs: agriculture, energy, hydrogeological field measurements, geophysics, modeling, remote sensing, socio-economy, laboratory soil sample analyses, and laboratory water sample analyses (Table 3.3). It is noted that the subdivision depends on the available literature, and it can vary in different catchments. The selection of the RFA is to some extent arbitrary and it is based on the main keywords and topics covered in the analyzed documents. The applied methodology, however, is not significantly affected by this choice. In fact, the key point of defining RFAs is not to identify which discipline is contributing more or less to the strategy goals, but to classify the available contribution to the goals from different communities of researchers and in terms of interdisciplinarity. Each document will have only one primary RFA and can have several secondary RFAs. The number of conducted studies were compared within each RFA before and after implementing the MWI strategy. Additionally, each RFA was categorized according to which MWI topic it targeted. A schematic diagram of the methodology we followed is shown in Figure 3.2.

Table 3.3. Description of the categorization of the research focus areas (RFAs) in the collected studies.

Research Focus Area (RFA)	Included:
Agriculture	Any study related to agriculture including irrigation efficiency, crop type, farming area, abstraction amount for agriculture.
Energy	Any study related to energy including current energy costs and renewable energy production.
Hydrogeological Field Measurements	Any study related to field surveys and to field measurement campaigns (water level, water and soil parameters, land cover/use classification).
Geophysics	Any study related to the application of geophysical methods (vertical electrical sounding, transient electromagnetics, seismic refraction).
Modeling	Any study related to the application of a mathematical model (groundwater flow model, solute transport, climate, surface water model, erosion, geochemical model, decision support system, vulnerability mapping, statistical analysis).
Remote Sensing	Any study related to satellite images use and processing.
Socio-Economy	Any study related to social or/and economic aspects (income, education, employment, community development, cost of water, the degree of public satisfaction with governmental decisions, degree of awareness of water scarcity in the basin, population growth).
Laboratory Soil Sample Analyses	Any study related to collection of soil samples to conduct biological and/or chemical analysis (nutrient or contaminant), and/or to investigate the physical properties of the soil.

Laboratory Water Sample Analyses	Any study related to surface or groundwater samples to conduct chemical, biological or physical analyses.

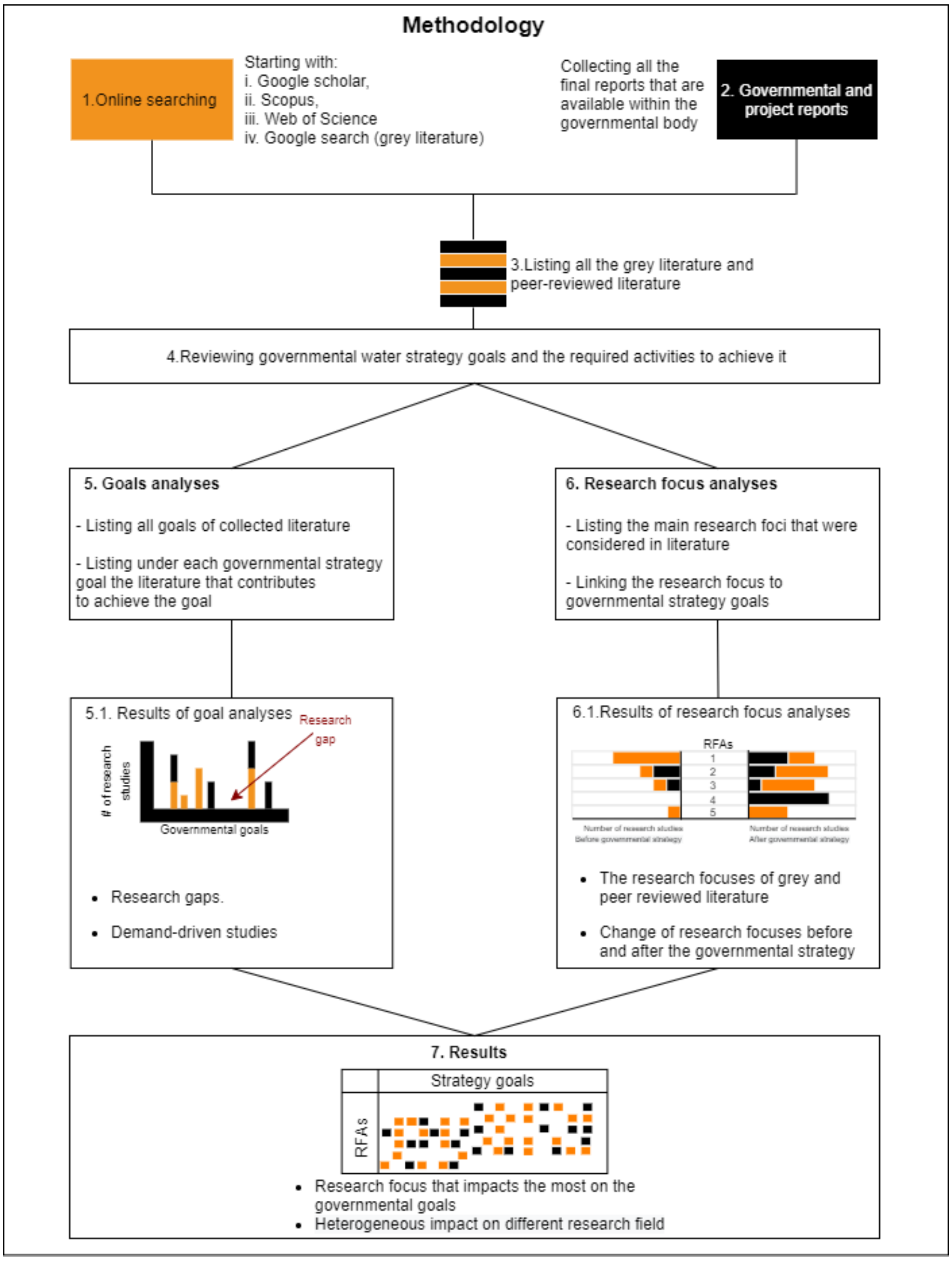


Figure 3.2. Schematic figure for the methodology we followed in this paper.

As stated previously, the collected research did not include studies conducted after the year 2018, because the MWI published a new strategy in 2016 for the period 2016–2025, which modified the older strategy. Considering the typical time needed for writing and publishing scientific works, it was assumed that the impact of the old strategy may still have an effect on water-related research up to two years after the publication of the new strategy.

3.4 Results

3.4.1 Collection Process

It was noticeable that there was no systematic way for archiving project reports at the MWI. When a project is concluded within the MWI or with international partners, the final report is usually submitted to the principal employee from the MWI (focal person of the project). At times, the final reports would be submitted to more than one person. Subsequently, these submitted reports remained scattered in different departments of the institution and were not allocated to a specific storage location, system, or person. For example, to have access to a specific report, the project's focal person must be identified and contacted to retrieve a copy of the report. In some instances, the employee may have already retired, which made the retrieval process difficult.

A total of 2200 documents were collected from the MWI. From these files, 26 final reports related to water resources in the Azraq Basin were extracted. This number is not to be taken as a representation of the total number of final reports on the Azraq Basin in the MWI, given that some reports were difficult to access because they were not available as digital copies. In addition, three reports were recovered through online research, as well as nine conference proceeding articles, totalling 37 grey literature sources. During the collection process, 62 peer-reviewed articles were recovered online, encompassing the period 1980 to 2018.

Figure 3.3a shows that the production of research documents increased between 1985 and 2020. The oldest grey literature report included was published in 1985 by Rimawi and Udluft (Rimawi & Udluft, 1985), and the oldest peer-reviewed article included in this analysis was from 1992 by (El-Waheidi et al., 1992). Overall, it is observed that peer-reviewed research production in the Azraq Basin has continuously increased since 1998. However, the only exception was for the year 2011, with no research relating to the basin published. The years 2014 and 2016 evidenced the largest number of conducted research studies (both grey literature reports and peer-reviewed articles combined) with nine studies. The year 2018 had the highest number of peer-reviewed articles, with eight published articles compared to all other years since 1985. Conversely, the years 1996, 2014, and 2015 showed the highest grey literature number with four studies per year.

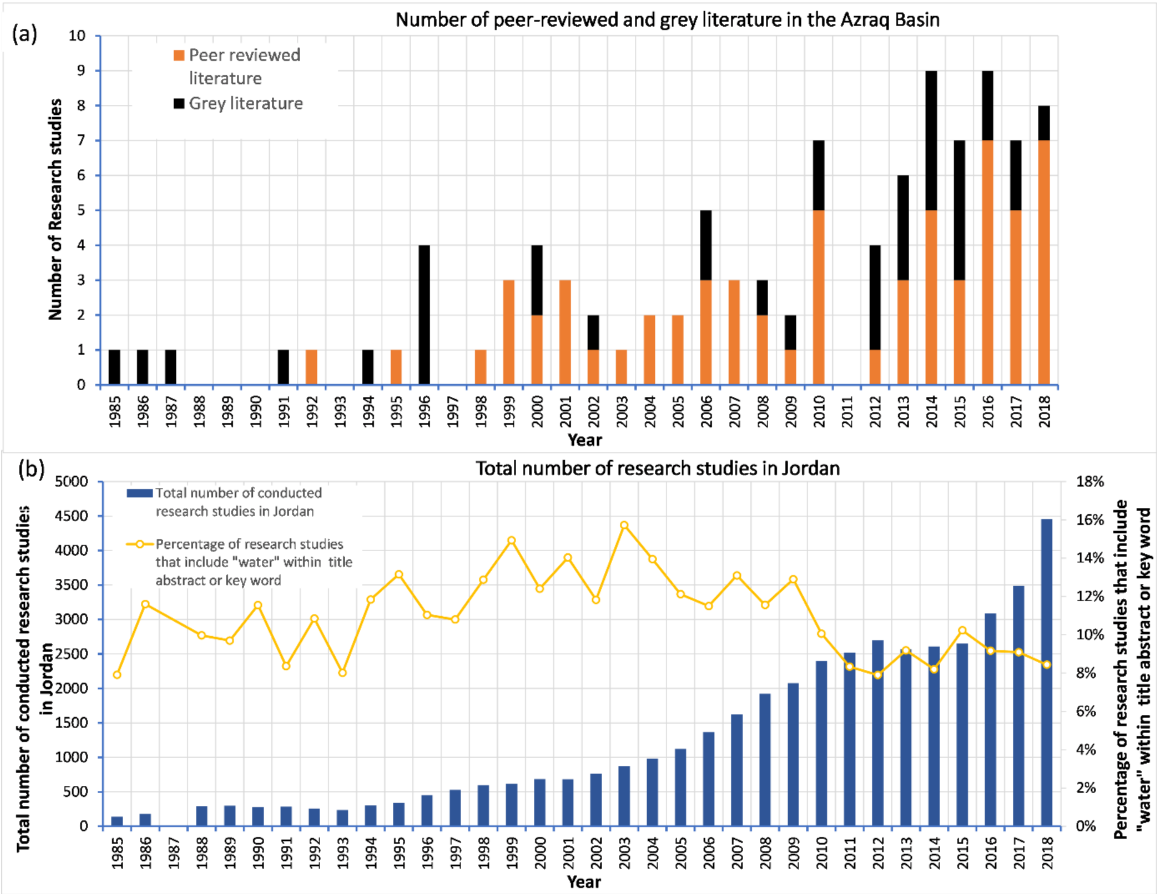
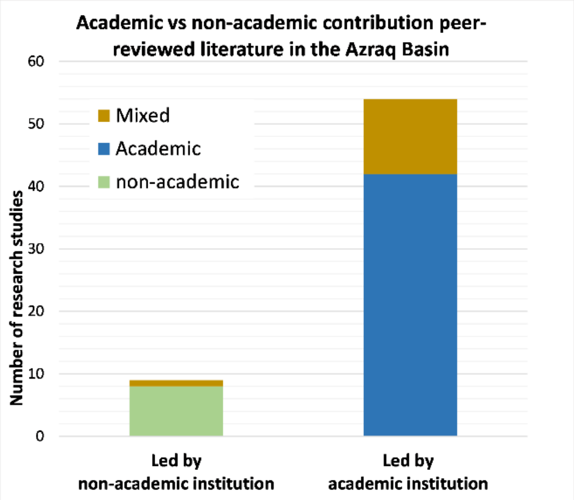


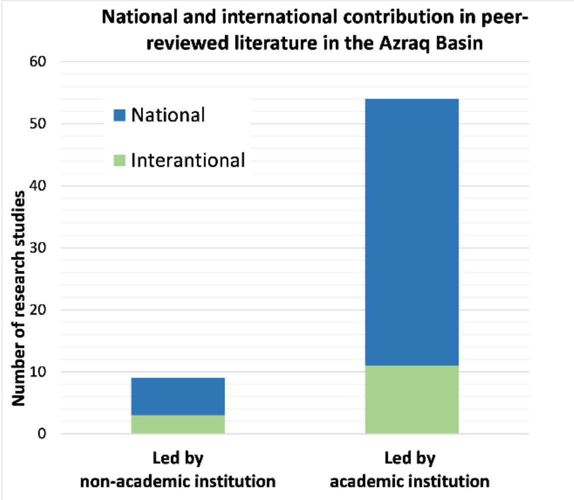
Figure 3.3. (a) Number of grey and peer-reviewed literature spanning the period (1985–2020). (b) Total number of documents that exist in the Scopus database produced by Jordanian institutions (blue column), percentage of number of documents stating the word "water" in the body of the document (orange line), percentage of number of documents stating the word "water" in a title, abstract or keyword of the document (grey line).

This result is consistent with overall research production in Jordan (Figure 3.3b). According to the database of Scopus, the total number of produced studies in Jordan increased from 139 to 4456 between 1985 and 2018. These studies consider all topics, including water-related topics. The percentage of studies that include the word "water" in the title, abstract, and keywords ranges between 8% and 16% over the whole period. At the same time, the number of studies that include the word "water" in the title, abstract, and keywords increased from 21 to 376. Therefore, the increasing trend in research production in the Azraq Basin follows the same upward trend of the number of studies produced in Jordan from all disciplines.

Most of the peer-reviewed publications were led by academic institutions. In 42 publications, only academic institutions contributed to the publication, while 12 publications were conducted by a combination of both academic and non-academic institutions. Conversely, nine publications were led by members from non-academic institutions, with only one of them in cooperation with an academic institution (Figure 3.4a). Academic international and national institutions published 11 and 43 studies, respectively. In contrast, non-academic international and national institutions published only three and six studies (Figure 3.4b).



(a)



(b)

Figure 3.4. Number of peer reviewed research studies conducted by (a) only academic, only non-academic and combination of academic and non-academic institutions, and (b) national and international institutions based on the affiliation of the first author of the literature.

3.4.2 Analysis Process

The analysis process categorized the documents based on their contribution to the MWI strategy goals and their research focus. The results showed that a total of 79 documents addressed at least one of the MWI strategy goals, 29 before and 50 after the water strategy; 20 documents are not aligned to the MWI strategy (8 before and 12 after the implementation of the water strategy). Additionally, the number of RFAs that were considered within each research varies between one and five focuses. Figure 3.5 shows a summary of the results of the conducted analysis process of peer-reviewed and grey literature.

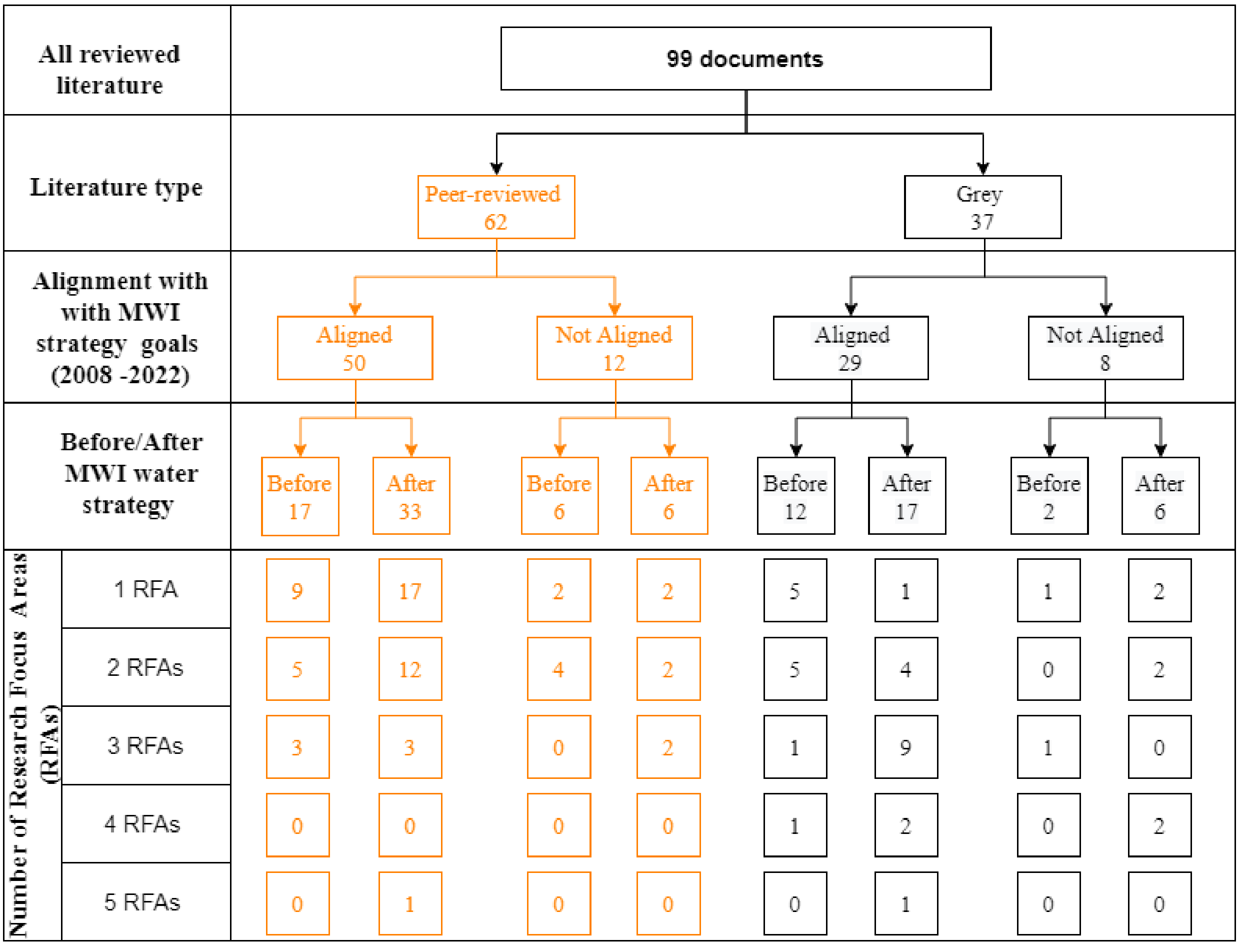


Figure 3.5. Summary of the results of the analysis process.

3.4.3 MWI Goals Analysis

The MWI strategy consists of 43 goals covering six topics (Figure 3.6). To define the research gaps in the Azraq Basin, the collected research goals were categorized with the MWI strategy goals (Figure 3.6). As stated previously, 79 studies are aligned to one or more of the MWI strategy goals. A total of 15 and 60 studies align with goals related to the two topics of water demand and supply, respectively. Water irrigation and alternative water resource goals are addressed in 13 studies and only two studies focus on goals related to wastewater.

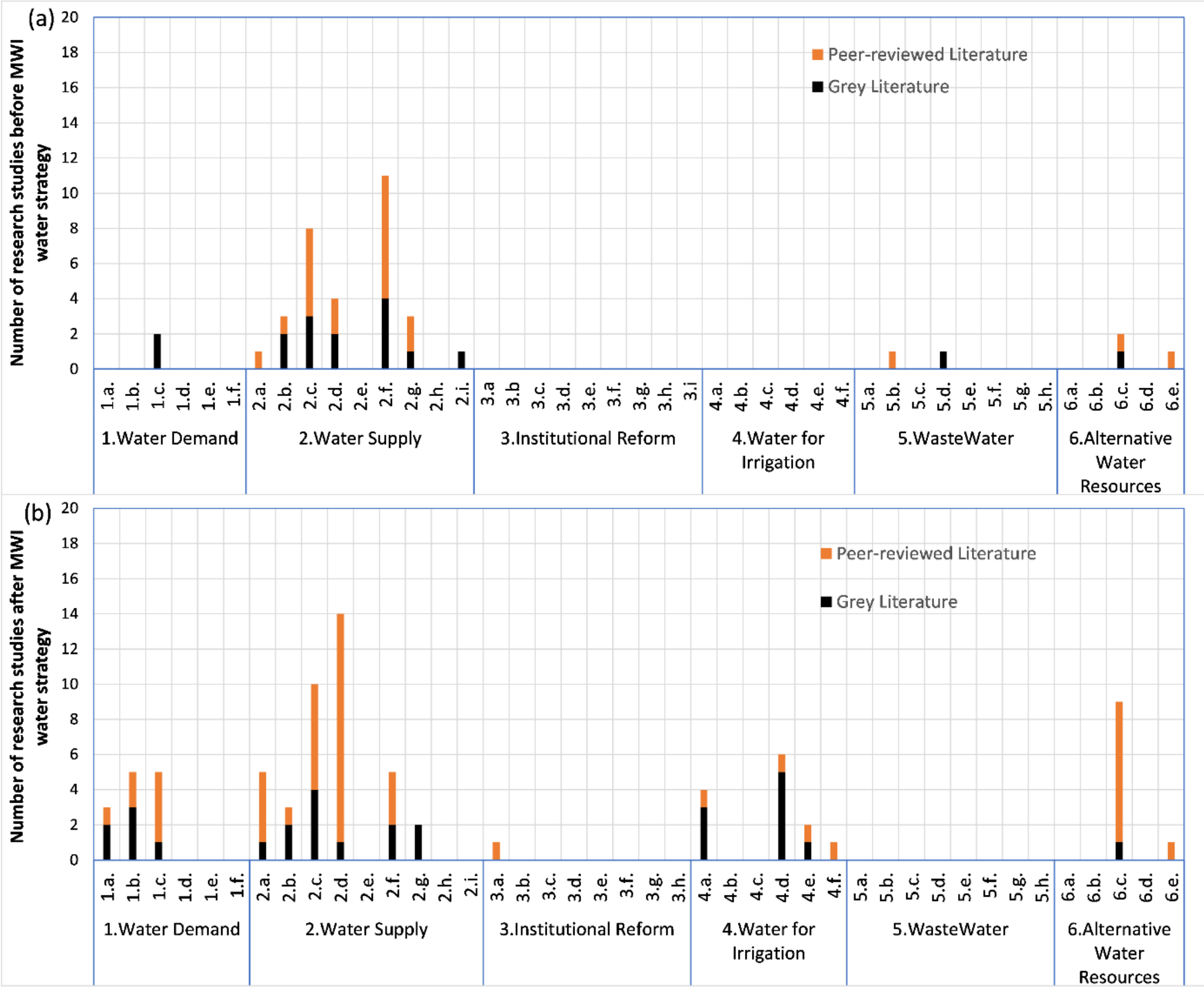


Figure 3.6. Number of grey and peer-reviewed studies that align with MWI water strategy goal 2008–2022 (a) before and (b) after the water strategy.

3.4.3.1 Goals Related to Water Demand

The number of studies contributing to the improvement of the water demand topic recorded the second-highest number of instances after the topic of water supply. Unlike the water supply goal, each of the studies listed under the improving water demand goal contributes to only one of the goals related to water demand. However, the 15 studies focusing on water demand contributed to three of the six goals. Three studies contributed to goal 1.a., aiming to reduce the water use for agriculture in the basin. These studies investigate the options of purchasing water rights from farmers (Al-Tabini et al., 2014), introducing energy farming (GIZ, 2015) and incentives for farmers (Demilecamps & Sartawi, 2010), acting as a guide to the ministry in issuing legislation for these alternatives. Goal 1.b. aims to increase the awareness of people about water scarcity and the importance of conserving water resources, where five studies focus on this topic; for example, Hamberger et al. (2009) mapped stakeholder networks to identify the links between the main stakeholders by interviewing farmers of the basin and Al Naber et al (2017) investigated the response of the farmers towards the challenges that they face and evaluated the factors that impacted the cost of the crops. Such studies may help the MWI to target the appropriate stakeholder groups who are unaware of/deny water scarcity. Al-Bakri (2015a), and Al-Bakri et al. (2016b) defined areas and the volume of illegal abstractions, and one study included the farmers in an association and conducted regular meetings that included technical and non-technical messages aiming to increase the awareness of water scarcity among farmers (Mesnil & Habjoka, 2012). Goal 1.c. focuses on improving water resource management, considering the impact of climate change on the water balance. From seven studies that address this goal, three studies investigated the impact of climate change on temperature, rainfall, and runoff (Al Qatarneh et al., 2018; Ayed, 1986; Consulting Engineers Salzgitter (CES) and Arabtech Consulting Engineers, 1994); three studies considered the impact of climate change as an input to a groundwater model (Y. A. Al-Zubi, 2009; Gaj et al., 2015; Taany et al., 2014) ; and one study examined droughts (Shatnawi, R. & AlAyyash, S., 2014). No study addressed the options to reduce water demand within each sector (goal 1.d.), evaluating the water tariff (goal 1.e.) or aiming to reduce the non-revenue water in the basin (goal 1.f.).

3.4.3.2 Goals Related to Water Supply

Approximately 60% of the references collected contribute to seven out of nine goals related to water supply; goal 2.a., which focuses on developing a secure and safe water supply in the area, is included in six studies; four focus on allocating new water sources (Aburub & Hadi, 2018; Al-Shabeeb et al., 2018; Margane et al., 2017; Yogeshwar et al., 2013), and two studies focus on sustainable management (Y. Al-Zubi et al., 2002; Taany et al., 2014). While six studies were found to be aligned with goal 2.b., which focuses on using desalinated water as a major source for water supply, four focused on saline water intrusion (Abu Rajab & El-Naqa, 2013; El-naqa et al., 2012; El-Waheidi et al., 1992; El-Naqa, 2010), one on hydrochemistry (Rimawi & Udluft, 1985), and one on salinization scenarios (Al-Momani et al., 2006). Additionally, a total of 18 studies contributed to the MWI strategy goal 2.c., which focuses on protecting drinking water resources from pollution. Jasem and Alraggad (2010), Al-Adamat et al. (2003) and Ibrahim, M. and Koch, B. (2015) presented a groundwater vulnerability map for the area, Gassen et al. (2013) delineated the protection zones of AWSA wellfield, and the remainder contributed to this goal by investigating the quality of groundwater in AWSA wellfield area (Al-Momani et al., 2006; Baïsset et al., 2016; El-naqa et al., 2012; El-Naqa et al., 2007; El-Naqa, 2010; K.

Ibrahim & El-Naqa, 2018; Kaudse et al., 2016; Worzyk & Hueser, 1987), in the northern region of the basin (Al-adamat et al., 2006; Baban et al., 2006), in the southern region of the basin (Obeidat & Rimawi, 2017), in Qaser tuba landfill (Batayneh & Barjous, 2005) and the Azraq Basin as a whole (Salameh, Toll, et al., 2018). Furthermore, 18 studies contributed to goal 2.d., which focuses on improving the efficiency of storing and utilizing surface water, with 17 addressing various opportunities to utilize the surface water quantity and defining the suitable locations for managed aquifer recharge (MAR) (Abu-Taleb, 1999; Al-Adamat, 2008, 2012; Al-Amoush, 2010; Al-Amoush et al., 2015, 2016; Al-Shabeeb, 2016; J. Al-Zubi et al., 2010; Alraggad & Jasem, 2010; Ayed, 1986; Saint-Jean & Singhroy, 2000; Shawaqfah et al., 2015; Steinel, 2012; Steinel et al., 2016; Taany, 2013; Taqieddin et al., 1995; Yusra Al-Husban, 2017). Only Salameh et al. (2014) addressed the topic of investigating the surface water quality.

Moreover, a total of 16 studies align with goal 2.f., which focuses on improving data availability and the monitoring system. Baïsset, M. et al. (2016) described how to improve the data availability and monitoring system, and the remaining studies focus on assessing the availability and sustainable exploitability of water resources in the basin (Abu-El-Shar & Hatamleh, 2007; Abu-El-Shar & Rihani, 2007; Abu-Jaber et al., 1998; Al-Kharabsheh, 1996, 2000; Al-Momani et al., 2006; Bajjali & Al-Hadidi, 2006; Dottridge & Abu Jaber, 1999; Gaj et al., 2015; Moqbel & Abu-El-Sha'r, 2018; Salameh, Toll, et al., 2018; Taany et al., 2014; UN-ESCWA and BGR, 2013; Verhagen et al., 1991). Only BGR/ESCWA (1996) indirectly targeted goal 2.i., which focuses on the protection of shar

participatory methods. These recommendations mainly align with the suggested legislation to manage the issues of "traditional water rights in Jordan", aiming to balance the traditional water rights with the state's water rights moving towards achieving a national water law that is enacted and enforced (goal 3.a). The remainder of the goals were not addressed directly by the collected studies.

3.4.3.3 Goals Related to Water Supply

Concerning goals related to institutional reform, only Leyroans et al. (2016) contended the one focusing on achieving sustainable and collective governance of groundwater re-sources: the Azraq Basin first needs to be recognized as a resource in "the commons" category, differentiated from being a private or public resource; second, the state needs to hold a subsidiary function that ensures the effective implementation of water management decisions made by the local population at the local level through adopting participatory methods. These recommendations mainly align with the suggested legislation to manage the issues of "traditional water rights in Jordan", aiming to balance the traditional water rights with the state's water rights moving towards achieving a national water law that is enacted and enforced (goal 3.a). The remainder of the goals were not addressed directly by the collected studies.

3.4.3.4 Goals Related to Water for Irrigation

According to the MWI water strategy 2008, irrigation practices in the highland region, including irrigation in the Azraq Basin, are not adequately controlled, and are categorized as exhibiting poor irrigation efficiency practices. Therefore, the MWI addressed the water irrigation topic in the strategy. The first goal 4.a. aims to reduce the annual water allocation for irrigation in the area, and a total of four studies were aligned with this goal; while GIZ (2015) and Al-Tabini, R. et al. (2014) analyzed the economic return of reallocation water use to sectors other than agriculture, Octavio, R. et al. (2008) focused on conducting a survey to evaluate factors affecting agriculture water use, and Demilecamps, C. and Sartawi, W. (2010) proposed project ideas to reduce water use in agriculture. Goal 4.d. recorded the largest number of studies contributing to the topic of water irrigation; four of the six studies focused on monitoring the abstractions in the basin, and two focused on establishing and empowering farmers' forums.

Furthermore, Al Naber et al. (2017), and Molle and Al-Naber (2016) investigated the economic returns of different crops in the basin, which aligned with goal 4.e., aiming to introduce a new tariff and incentive system to promote water efficiency in irrigation and higher economic returns for irrigated agricultural products. The promotion of methods and technology to enhance the irrigation water supply (goal 4.f.) is addressed only by Al-Zubi et al. (2010), who focused on water harvesting feasibility for irrigation use in the Wadi Muhweir catchment in the basin. The collected studies are neither aligned with the goal 4.b., which states, "Efficient bulk water distribution as well as efficient on-farm irrigation systems are established." nor with goal 4.c., which states that "All treated wastewater generated will be used for activities that demonstrate the highest financial and social return including irrigation and other non-potable uses.".

3.4.3.5 Goals Related to Wastewater

The ministry aims to expand the wastewater network in the kingdom and consequently increase the amount of treated wastewater for non-drinking purposes. Hence, eight goals were listed under the wastewater topic. However, only Baban et al. (2006) addresses goal 5.b., by estimating the impacts of cesspools on groundwater in the basin under various scenarios; the estimation and analysis of these impacts will inform the MWI of future locations for implementing treatment plants, in order to minimize the threats of wastewater disposal on adjacent drinking water resources. Additionally, Al-Adamat et al. (2006) targeted goal 5.d., which aims to protect the public health and environment; this study set specifications and standards procedures of septic tank usage in the Azraq Basin. The remainder of the goals related to wastewater were not addressed in any of the previous studies.

3.4.3.6 Goals Related to Alternative Water Resources

Given that Jordan's renewable water resources are limited (MWI, 2017), one of the MWI aims is to explore new water resources such as treated wastewater, greywater, and desalinated water. Therefore, the alternative water resources topic was addressed in the MWI strategy of 2008. Only two goals were addressed in the collected literature: firstly, goal 6.c., which aims to promote and encourage rainwater harvesting, where 11 studies addressed the potential of implementing rainwater harvesting in rural areas of the basin (Al-Adamat, 2008, 2012; Al-Amoush, 2010; Al-Shabeeb, 2016; J. Al-Zubi et al., 2010; Alraggad & Jasem, 2010; Saint-Jean & Singhroy, 2000; Steinel, 2012; Steinel et al., 2016; Taany, 2013; Taqieddin et al., 1995). These studies differ from each other mainly in that there is primary focus on different locations of the basin. Secondly, goal 6.e., which aims to find an alternative energy resource for desalination, was found to have only two contributing studies: Sawariah (2008) defined the areas with high potential for thermal water sources, and Mohsen (2001) studied the feasibility of using solar energy for water desalination in the basin. The remainder of the goals in this topic were not addressed by a reference.

3.4.4 Research before and after the MWI Strategy

Figure 3.6 shows that the number of grey literature studies in alignment with the MWI strategy goals increased after the MWI water strategy implementation by 30%. A greater increase is observed in the peer-reviewed literature, where the total publications doubled during the same period. While this result may be expected considering the overall increasing trend in research production shown in Figure 3.3, it is noteworthy to observe that prior to the implementation of the strategy, only two studies aligned with the goals related to water demand, while this number increased to 13 studies after the implementation of the strategy. More specifically, the number of studies that align with water supply only increased from 27 studies (four of which contributed to two goals) to 33 studies (six of which contributed to two goals) before and after the MWI strategy, respectively. No study aligned with the water irrigation goals before the MWI water strategy, while 13 studies align with water irrigation goals after implementing the water strategy. Furthermore, the number of studies that align with goals related to wastewater goals reduced from two to zero before and after implementing the MWI strategy.

3.4.5 Research Focus Areas Analysis

The analysis showed that 60 studies of the collected studies have more than one RFA, indicating that a large part of the collected studies are interdisciplinary. In such cases, the RFAs were categorized as either primary or secondary in nature, where the secondary area supports the primary RFA; for example, in the work of Abu Rajab and El-Naqa (2013) , geophysics is the study's primary RFA. However, the researchers collected and analyzed water samples to support the geophysics analysis; in this case, the laboratory water sample analyses are categorized as a secondary RFA. The following section represents a review of the collected studies categorized according to the primary RFA. Moreover, a complete overview is given in Appendix A.

About 35% of the collected documents focused on modeling in terms of: (a) estimating the recharge rate (Consulting Engineers Salzgitter (CES) and Arabtech Consulting Engineers, 1994; Rimawi & Al-Ansari, 1997), (b) enhancing the recharge amount (Al-Adamat, 2008, 2012; Al-Shabeeb, 2016; J. Al-Zubi et al., 2010; Alraggad & Jasem, 2010; Shawaqfah et al., 2015; Steinel, 2012; Steinel et al., 2016; Taany, 2013; Taqieddin et al., 1995), (c) studying the impact of climate change on water resources (Y. A. Al-Zubi, 2009), (d) assessing surface water and drought (Ayed, 1986; Shatnawi, R. & AlAyyash, S., 2014; Shatnawi et al., 2014), (e) locating potential areas for groundwater abstraction (Aburub & Hadi, 2018; Al-Shabeeb et al., 2018), (f) analyzing time series (Al Qatarneh et al., 2018; Goode et al., 2013), (g) building water quality models (K. Ibrahim & El-Naqa, 2018), (h) building groundwater models(F. Abdulla et al., 2000; Abu-El-Shar & Hatamleh, 2007; Abu-El-Shar & Rihani, 2007; Al-Kharabsheh, 2000; Dottridge & Abu Jaber, 1999; Gaj et al., 2015; Moqbel & Abu-El-Sha'r, 2018), (i) delineating isohyetal maps for rainfall (Yusra Al-Husban, 2017), (j) creating vulnerability maps (Al-Adamat et al., 2003; M. Ibrahim & Koch, 2015; Jasem & Alraggad, 2010), and (k) proposing sustainable water management plans (Y. Al-Zubi et al., 2002; Taany et al., 2014).

Although the modeling RFA had the most significant percentage among the collected literature, the basin was still an exciting area for researchers to conduct geophysical investigations to (a) study the saline water body in the basin (Abu Rajab & El-Naqa, 2013; El-naqa et al., 2012; El-Waheidi et al., 1992; El-Naqa, 2010; Worzyk & Hueser, 1987; Yogeshwar et al., 2013; Yogeshwar & Tezkan, 2017), (b) investigate the suitability of water harvesting of Laval tunnels in the north of the basin (Al-Amoush, 2010; Al-Amoush & Rajab, 2018), in Dier al Kahif region (Al-Amoush et al., 2015) and Asra dam (Al-Amoush et al., 2016); (c) investigate the impact of Qaser Tuba landfill on groundwater (Batayneh & Barjous, 2005); and (d) identify the geological formations of the Bishrya dam (Batayneh et al., 2001).

Socio-economy was the main focus of the studies that investigated: (a) the water governance in the basin (Leyronas et al., 2016; Molle et al., 2017), (b) the farming system and practices (Demilecamps & Sartawi, 2010), (c) the socio-economic factors that impact the farmer's practices (Al-Tabini et al., 2014; Hamberger et al., 2009; Octavio et al., 2008; United States Agency for International Development (USAID)/ISSP project, 2014b, 2014a), (d) the impact of governmental regulations and socio-economic impacts on farmers and agriculture practices (Al-Naber, 2016; Al Naber et al., 2017; Al Naber & Molle, 2017) (e) the challenges of managing groundwater in the basin (Mesnil & Habjoka, 2012), action plan to manage the groundwater (Mesnil et al., 2014), and (f) the socio-economic impact of applying solar farming in the basin (GIZ, 2015). Furthermore, two studies focused mainly on energy topics: one study to investigate the feasibility of applying solar energy for water desalination in the basin (Mohsen & Jaber, 2001), and another study to investigate the potential for using thermal water as an alternative energy source (Sawarieh, 2008).

Beyond the studies that conducted sampling campaigns as secondary RFAs (Abu Rajab & El-Naqa, 2013; Al-Adamat et al., 2003; Batayneh & Barjous, 2005; El-Naqa, 2010; M. Ibrahim & Koch, 2015; Steinel, 2012; Steinel et al., 2016), sampling campaigns were the main RFA in 20 studies. Water samples were collected, and isotopes were analyzed to (a) study the recharge rate in the Azraq Basin (Verhagen et al., 1991), (b) define the recharge origin in the basin (Abu-Jaber et al., 1998; Almomani, 1996; Bajjali & Al-Hadidi, 2006), (c) group water types (Obeidat & Rimawi, 2017; Rimawi & Udluft, 1985; Salameh, Toll, et al., 2018), (d) study the salination process (Al-Momani et al., 2006; Baïsset et al., 2016; El-Naqa et al., 2007; Kaudse et al., 2016), (e) evaluate nitrate leaching to groundwater (Al-adamat et al., 2006; Baban et al., 2006), and (f) inspect the eutrophication process of surface water (Salameh et al., 2014). Soil samples were collected in the basin to (a) explore soil suitability for agriculture (Khresat & Qudah, 2006; Rawajfih et al., 2002, 2005), (b) define the source of sulfur and gypsum (Ahmad & Davies, 2018), (c) estimate the recharge rate (Amro et al., 2001), and (d) map the soil moisture of the Al-Bagureyya area (Tansey et al., 1999).

Hydrogeological field measurement was the main RFA to (a) review the groundwater resources (Abu-Taleb, 1999; Al-Kharabsheh, 1996; BGR/ESCWA, 1996; UN-ESCWA and BGR, 2013); (b) create geological maps (K. Ibrahim, 1996); (c) delineate protection zones (Gassen et al., 2013); and (d) to set an action plan (Margane et al., 2017). Furthermore, Remote sensing techniques were used in the basin to (a) estimate the abstraction (Al-Bakri, 2014, 2015a, 2016; Shawash & Al-Bakri, 2015); (b) create hydrological maps (Saint-Jean & Singhroy, 2000; Shahbaz & Sunna, 2000), and (c) study land change over time in the basin (Al-Adamat et al., 2004; Essa & Detection, 2004; Kloub et al., 2010; Zanchetta et al., 2016). The agriculture RFA was not the main focus of any of the collected research; however, it was considered in 13 studies (Al-Bakri, 2015b; Al-Naber, 2016; Y. Al-Zubi et al., 2002; Al Naber et al., 2017; Al Naber & Molle, 2017; Baban et al., 2006; Demilecamps & Sartawi, 2010; GIZ, 2015; Mesnil & Habjoka, 2012; Shawash & Al-Bakri, 2015; Taany et al., 2014; United States Agency for International Development (USAID)/ISSP project, 2014a, 2014b), and more reports with regard to agriculture are expected to be found in the ministry of agriculture. Table A 1.

Figure 3.7 shows that the number of studies increased in all the RFAs after the implementation of the strategy, except in the laboratory sample analysis; the number of studies that focus on soil and water analysis decreased from 8 and 10 before the strategy to four and eight studies after the strategy, respectively. However, in the laboratory water sample analysis RFA, the number of peer-reviewed studies increased from five studies before the strategy to six studies after the strategy.

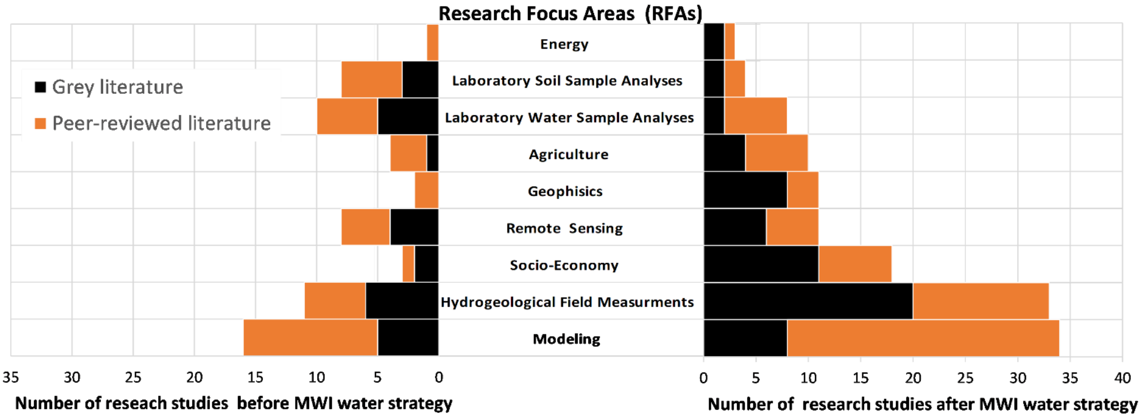


Figure 3.7. Research focus of the collected literature before and after the implementation of MWI water strategy.

Energy and agriculture were not the focus of any grey literature study before the MWI strategy implementation. However, after 2008, the work of GIZ (GIZ, 2015) and Mesnil A. et. al. (2014) considered energy in their research and eight grey literature documents considered agriculture by calculating crop water requirement (Al-Bakri, 2015a; Shawash & Al-Bakri, 2015), investigating farming systems (Al-Naber, 2016; Demilecamps & Sartawi, 2010; Mesnil & Habjoka, 2012; United States Agency for International Development (USAID)/ISSP project, 2014b, 2014a), and evaluating the economic return of current agriculture activities (GIZ, 2015). Additionally, the socio-economic component was only considered by Al-Adamat et al. (2006) and Ibrahim (1996) among the grey literature studies and by Al-Zu'bi et al. (2002) among the peer-reviewed studies before the implementation of the water strategy, while it increased to 11 grey literature studies (Al-Naber, 2016; Demilecamps & Sartawi, 2010; GIZ, 2015; Hamberger et al., 2009; Margane et al., 2017; Molle et al., 2017; Octavio et al., 2008; Steinel, 2012; United States Agency for International Development (USAID)/ISSP project, 2014b, 2014a) and seven peer-reviewed studies (Al-Adamat, 2008; Al-Tabini et al., 2014; Al Naber et al., 2017; Al Naber & Molle, 2017; Leyronas et al., 2016; Steinel et al., 2016; Taany et al., 2014) beyond 2008.

The total number of RFAs within each literature varied between one and five RFAs in both grey and peer-reviewed literature. The percentage of literature that focused only on one or two RFAs was approximately 86% of the peer-reviewed literature and 57% of grey literature. Furthermore, the documents that considered three RFAs represent approximately 13% of peer-reviewed literature and approximately 28% of grey literature. Approximately 13% of the collected grey literature studies considered four RFAs, while no peer-reviewed study considered four RFAs. However, only a single report (Steinel, 2012) and an article (Steinel et al., 2016) considered five RFAs, both of which were publications of a project conducted by the BGR in the basin. No peer-reviewed study, conducted by academic institutions, considered more than three RFAs (Figure 3.8).

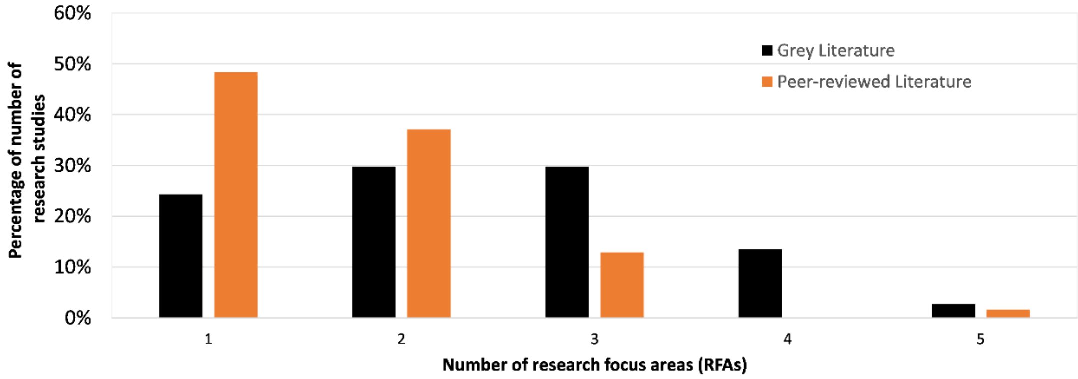


Figure 3.8. Number of research focus areas in grey and peer-reviewed studies.

In Figure 3.9, it was shown that before the implementation of the water strategy, only the studies with a research focus on remote sensing and modeling targeted three topics of the strategy (F. Abdulla et al., 2000; Abu-El-Shar & Hatamleh, 2007; Abu-El-Shar & Rihani, 2007; Al-Kharabsheh, 2000; Y. Al-Zubi et al., 2002; Al-Momani et al., 2006; Ayed, 1986; Baban et al., 2006; BGR/ESCWA, 1996; Consulting Engineers Salzgitter (CES) and Arabtech Consulting Engineers, 1994; Dottridge & Abu Jaber, 1999; Mohsen & Jaber, 2001; Rimawi & Udluft, 1985; Saint-Jean & Singhroy, 2000; Shahbaz & Sunna, 2000; Taqieddin et al., 1995). In contrast, after the MWI strategy publication, the studies with a research focus on remote sensing, modeling, socio-economy, and hydrological field measurement targeted four of the five water strategy topics, wherein each of the conducted studies was targeting one or two topics of the MWI strategy. Only the modeling work of Al-Zubi (2010) targeted three topics, namely: water supply, water for irrigation, and alternative water supply. The water supply topic was targeted by all research focuses, except energy, which targeted water demand, irrigation water, and alternative water resources only after the MWI water strategy came into effect. Conversely, only CES (1994) and Ayed (1986) include modeling as an RFA and targeted the water demand topic's goals before the strategy. Laboratory soil and water sample analyses and geophysics have neither contributed to the water demand topic before nor after the water strategy.

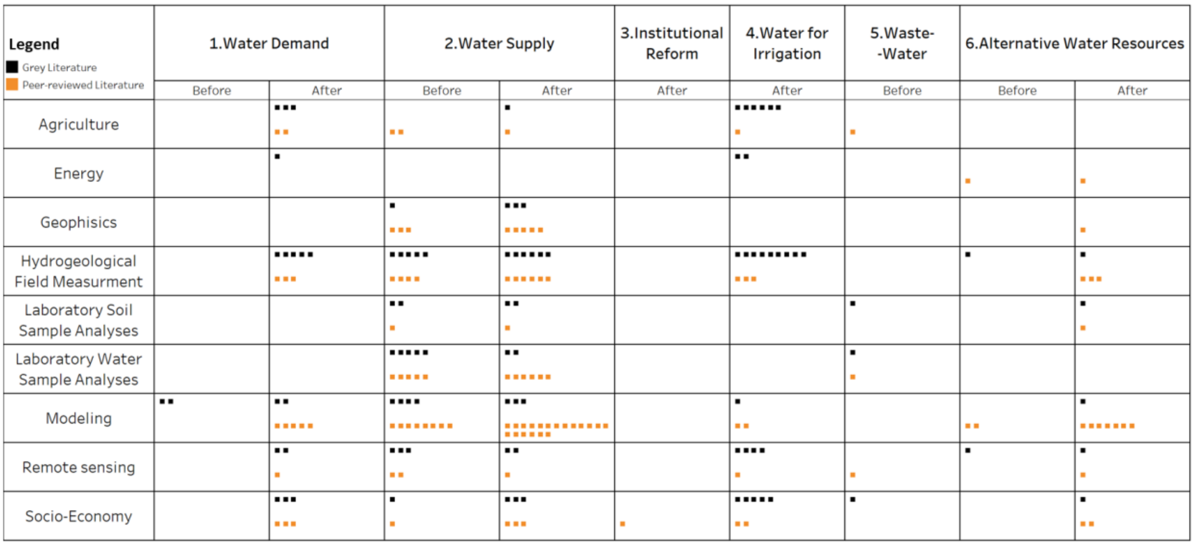


Figure 3.9. Relationship between the research focus areas (RFAs) and the MWI strategy topics.

3.4.6 Analysis of Research Topics Addressed by Documents Not Aligned to the Water Strategy Goals

As stated previously, 20 documents did not align with the MWI water strategy goals (Figure 3.10). These documents covered topics such as geology (Al-Amoush & Rajab, 2018; Al-Bakri, 2016; Tansey et al., 1999; UN-ESCWA and BGR, 2013), soil (Amro et al., 2001; Essa & Detection, 2004; Khresat & Qudah, 2006; Rawajfih et al., 2002, 2005; Tansey et al., 1999), land use change (Al-Adamat et al., 2004; Kloub et al., 2010; Zanchetta et al., 2016), and time series analysis (Goode et al., 2013; Shatnawi et al., 2014). Although the research of Ibrahim (1996), Al-Amoush and Rajab (2018), Ahmad and Davies (2018), Al Adamat et al al (2004) and UN-ESCWA and BGR (2013) aimed to deepen the knowledge of the hydrogeological conditions of the Azraq Basin, these publications do not align with the MWI water strategy goals on the basis that they do not explicitly answer questions related to water management and availability, which are the core of the strategy. Nonetheless, the references (Ahmad & Davies, 2018; Al-Amoush & Rajab, 2018; K. Ibrahim, 1996; UN-ESCWA and BGR, 2013; Yogeshwar et al., 2013) provide valuable information for the activities under the responsibility of the Ministry of Energy and Mineral Resources. Similarly, the MWI strategy did not explicitly address the topics of soil and land use change, which is a competence of the Ministry of Agriculture. Therefore, three studies (Al-Adamat et al., 2004; Kloub et al., 2010; Zanchetta et al., 2016) focusing on land use change, and six studies (Amro et al., 2001; Essa & Detection, 2004; Khresat & Qudah, 2006; Rawajfih et al., 2002, 2005; Tansey et al., 1999) focusing on soil science cannot directly contribute to the goals of the strategy. Amro et al. (2001) contains important isotopic analysis that could be used to estimate the groundwater recharge in the catchment. However, since such an analysis is missing, the research was not considered to be aligned with the MWI strategy. Molle et al. (2017) and Al Naber and Molle (2017) represent a comprehensive overview of Jordan's water governance and policy, and their impact on Azraq Basin water resources as well as the responses of people to these policies. Such an assessment is needed for all individual basins of Jordan; this would provide the government with a compass to achieve improved water governance; however, such an assessment is not foreseen in the water strategy. The works of Shatnawi et al. (2014) and Goode et al. (2013) focus on time series analysis of hydrological variables. However, neither aligned with the MWI water strategy because their analyses did not explicitly address any of the goals. In particular, Goode et al. (2013) presented trend analyses for groundwater levels and groundwater quality in the Azraq Basin, as a result of a cooperation project between USGS and the MWI, and still it did not align with the goals outlined in the MWI strategy. A similar event occurred in two reports (United States Agency for International Development (USAID)/ISSP project, 2014b, 2014a), which were a result of the cooperation project between USAID and MWI. Both reports present a comprehensive socio-economic survey of groundwater wells of the basin, and it is stated in the reports that "This study was requested by the Ministry of Water and Irrigation". In these cases, there is, however, no output that explicitly fits the water strategy goals. Therefore, the fact that these 20 documents did not match the MWI strategy goals does not necessarily mean that these documents were not demand-driven research. Moreover, our analysis shows that the water strategy may in the future consider a more holistic approach in the definition of its goals.

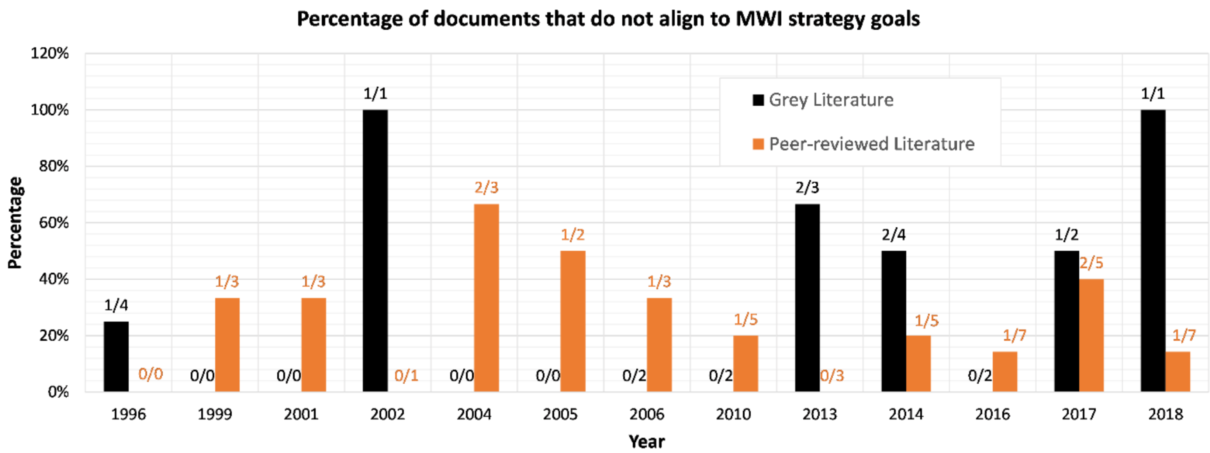


Figure 3.10. Percentage of studies that do not align with the MWI water strategy. The numbers above the bars represent the number of documents that do not align with MWI strategy and the total number of documents per year (the figure only represents the years, where the documents do not align with the MWI strategy goals).

3.5 Discussion

3.5.1 Research Gaps

Beyond the "practical-knowledge gap" identified in the comparison between conducted research and the MWI goals, the literature review allowed the recognition of a "knowledge gap", as defined by Miles (2017). In fact, a standard methodology to define a "practical-knowledge gap" in water-related research was not found; this study contributes to filling this gap. Decision-makers in the water sector need comprehensive studies and research to decide on a particular goal in a governmental water strategy. When missing research hinders taking a decision about a goal, it was deemed to be a "water-decision-research-gap", which is the inability to take a final decision about a governmental water strategy goal through conducting a systematic peer and grey-literature review at the basin level. It is essential to highlight when studies and research contribute to a specific goal; this contribution, however, does not guarantee that the necessary research is enough to make a decision related to the goal, and it could be that further research is needed. For instance, many studies contributed to the goal 2.d. (Abu-Taleb, 1999; Al-Adamat, 2008, 2012; Al-Amoush, 2010; Al-Amoush et al., 2015, 2016; Al-Shabeeb, 2016; J. Al-Zubi et al., 2010; Alraggad & Jasem, 2010; Ayed, 1986; Saint-Jean & Singhroy, 2000; Shawaqfah et al., 2015; Steinel, 2012; Steinel et al., 2016; Taany, 2013; Taqieddin et al., 1995; Yusra Al-Husban, 2017), which aims to store and utilize surface water efficiently; however, only Salameh et. al. (Salameh et al., 2014) focused on the surface water quality of the Rajil dam in the basin, while the remainder (17 studies) focused on the amount and the suitable location for surface water harvesting. Therefore, the lack of surface water quality research hinders the decision-maker's ability to derive a conclusion from the literature review to make well-informed decisions related to the goal 2.d. Thus, the lack of surface water quality studies in various locations in the basin, in this case, is a water-decision research gap.

Furthermore, although several researchers have studied water harvesting at the local level, it is still necessary to conduct further studies at the same level (local level), similar, for example, to the study by (J. Al-Zubi et al., 2010), which compared the feasibility of implementing water harvesting techniques at a micro and macro level in Wadi Muhweir for irrigation purposes. Goal 2.d. could be achieved if similar studies in all the locations (e.g., all main wadis and dams) were to be conducted. Furthermore, some goals (such as wastewater as an alternative water supply) in the strategy are found to be codependent, and they were not achieved because they required other goals (the goals related to wastewater) to be achieved prior, such as goal 6.a., which promotes treated wastewater as an alternative resource for agriculture; however, to study the treated wastewater viability as an alternative water resource, the goals in the wastewater topic (topic 5) must be further studied. This leads to the conclusion that a timeline for the strategy's topics and goals would help researchers to conduct demand-driven research.

It is crucial to clarify that when it is stated that a goal is not covered by literature, that this is in reference to the collected literature for the Azraq Basin within this research. The goal may be partially addressed by research work conducted on the national level, such as (Al al-Bayt University and InWEnt, 2005; Rothenberger, 2011), that targeted the goals of wastewater topic in Jordan, or addressed by research performed in other regions or subbasins that share similar hydrological and socio-economic conditions, or addressed by reports that are not accessible according to the presented methodology, such as studies that were conducted by private engineering companies and were shared with the ministry.

3.5.2 Heterogeneity Impact of Research on Goals

A clear presentation of goals in governmental water strategies, such as the MWI water strategy 2008–2022, can be perceived as a prerequisite for increasing the researcher's ability to conduct demand-driven research and to contribute to achieving these goals. As stated previously, the impact of the research on the strategy goals varies, where some of the RFAs have contributed to most of the topics that were addressed by the governmental strategy (e.g., modeling RFA), while other areas contributed the least (e.g., energy RFA). Such an assessment helps the government and researchers to address the goals from a different perspective. For instance, the energy RFA contributed to the goals related to water demand, the water for irrigation, and alternative water resources with only three studies. Consequently, beyond the aforementioned topics, there is a strong argument for the need to conduct more studies about energy and water supply or energy and wastewater in the basin.

3.5.3 Implications for the Identification of Research Needs

The application of the proposed methodology to the Azraq river basin demonstrated that some goals were not addressed by any of the research study collected (Figure 3.6), which directly translates to a research gap existing. However, there can be multiple reasons that justify the occurrence of such a gap and that can explain the lack of research documents. For instance, the lack of infrastructure for a centralized wastewater treatment in the basin partially hinders research for goals 5.a., 5.e., 5.f., 5.g., 5.h., and 6.a. In fact, the Arzaq Basin is not yet connected with wastewater treatment plants but only cesspools at the present time. Therefore, studies evaluating the current impact of all wastewater disposal sites on groundwater are needed, especially for newly proposed locations that might threaten the groundwater quality, contributing to goals 5.b. and 5.d. Beyond the environmental impact assessment of the proposed sites, socio-economic assessments, technical and economic feasibility assessments are equally crucial for installing new wastewater treatment systems in the area. Therefore, it is essential to highlight that during the field visit to the MWI in January 2020, MWI staff indicated that reports on the new wastewater plant proposal in Azraq exist but could not be accessed.

The fact that a goal is addressed by several research studies does not necessarily imply that further research is not required. For example, setting a cap on water use for agricultural purposes was addressed partly by three studies (Al-Tabini et al., 2014; Demilecamps & Sartawi, 2010; GIZ, 2015). However, innovative approaches to upgrade tools and technologies focusing on optimizing energy consumption and irrigation efficiency are urgently needed such that Jordanian farmers can contribute to the achievement of the goal. Goal 1.b. aims to increase awareness within the Jordanian society on the issues of water scarcity and some of the collected studies already provided measures for the farmer's awareness (Al Naber et al., 2017; Hamberger et al., 2009). Still, there is a need to conduct similar studies that analyze the level of awareness for other social groups, such as students and industrial stakeholders, including tourism, to set up effective educational programs concerning water scarcity for different grades. Likewise, the following areas of assessment and evaluation still require further investigation to achieve the MWI's strategic goals:

i. **Investigate and improve the existing water distribution systems** in terms of technical aspects (i.e., hydraulic), management, energy efficiency, operation and maintenance, water losses, and billing and collection systems; contributing to **goal 2.a.**
ii. **Examine the deep aquifer area** in terms of water quality and quantity; contributing to **goal 2.a.**
iii. **Explore the potential of using desalinated water** in terms of technical, economic, and environmental aspects for both saline groundwater abstraction and building treatment plants; contributing to **goal 2.b.**; and also in terms of using an alternative energy source for desalination; contributing to **goal 6.e.**
iv. **Assess the existing monitoring systems** and provide proposals to improve them in terms of water quality; contributing to **goal 2.c.;** and water quantity; contributing to **goal 2.f.**
v. **Evaluate the current situation of the dams** in terms of sedimentation and water quality, focusing on conducting economic feasibility studies for sediment removal and water treatment; contributing to **goal 2.d.**
vi. **Investigate the current use of water in the recharge area** of the transboundary basin enhancing research cooperation with Syrian partners, contributing to **goal 2.i.**
vii. **Study the current irrigation systems** in terms of estimating the cost of changing it into a more efficient system; contributing to **goal 1.a.**; and drafting a farmer's incentives system for the MWI as a result of the economic and environmental benefits of these efficient systems, contributing to **goal 4.a.**, and

viii. **Examining the feasibility of installing rainwater harvesting techniques at the farm level**, similar to (J. Al-Zubi et al., 2010), as an alternative water resource for irrigation is still needed, thus contributing to **goals 4.f. and 6.c.**

3.5.4 Application to Other Areas

The developed methodology could be applied to other basins and other water strategies. However, the RFAs can be modified according to the collected research topics and the strategy's goals. If a new topic is presented, it can be added to one of the existing research areas or a new RFA may be added. Furthermore, when the methodology is applied at a national level, the corresponding national goals should be added to the methodology, and the goals addressed at a basin level should be removed. Conversely, mapping the RFAs and governmental goals can be implemented in topics other than water. This concept creates demand-driven research and helps researchers to address the goals by using the RFAs not addressing specific governmental goals.

Furthermore, to have a comprehensive water management strategy, the responsibility should not only be on the water provider (Dingemans et al., 2020) and the method could be developed to include other governmental strategies besides the water strategy. For instance, in the case of Jordan, this method could further be extended to cover the goals of the strategy of the ministry of agriculture and the ministry of environment. The method could be developed as a platform that connects different ministries and research institutions, where researchers can update the platform with new research and address the gaps that are identified with the methodology presented in this work. Finally, the governmental body may update the strategy goals accordingly.

3.6 Conclusions

A comprehensive methodology to define research gaps in water-related studies was developed and tested by investigating the impact of Jordan's water strategy (2008–2022) on research production in the Azraq Basin. The number of documents focusing on the basin increased after issuing the MWI strategy but there is no significant proof that this increase is due to issuing the MWI strategy, as the total number of published studies in Jordan addressing all topics also shows a positive rate of increase. Therefore, categorization of the research produced according to the MWI strategy goals is suggested, to better identify if and how they are addressed by peer-reviewed and grey literature. The results showed that the number of documents that align with the MWI strategy varies depending on the goal of the strategy and the RFAs considered within the document.

Involving governmental actors in the research design and literature collection process represents one of the most innovative and relevant points in the proposed methodology. In fact, grey literature is generally not easily accessible without involving actors from the ministries and its relevance in filling research gaps has been demonstrated in our work. The methodology allows the identification of a methodological research gap. This lack of research may hinder taking decisions related to governmental water strategy goals at the basin level. Thus, the inability to take decisions related to governmental water strategy goals through conducting a systematic peer and grey-literature review at the basin level was defined in this paper as the "water-decision research gap". Although the methodology indicates that the conducted research in the basin aligns with the ministry's water strategy, it does not guarantee that the research affects the strategy, mainly because proper communication between the government and researchers does not exist.

The methodology not only defines the research gaps but also evaluates the relationship between academia and government. In the Azraq Basin, 54 of the 62 peer-reviewed literature documents are led by academic institutions, and approximately 75% of them are conducted without cooperating with any governmental body or non-academic institution. Furthermore, approximately 75% of the peer-reviewed documents published by academic institutions are produced by national universities. This shows the vital role of the national academic institutions in water-related research and the importance of strengthening the relationship between academia and the government.

It is expected that the water strategy would have had a larger impact on the produced research if the goals of the strategy were formed based on the research outputs of each basin individually. This would help researchers to fill the gaps accordingly, and the conducted research would then be more demand-driven. Conversely, if researchers were to explicitly state the goals of the MWI strategy that were targeted in their work, this would help the ministry to update the strategy and develop a living document of the water strategy. The concept of linking the RFAs with the governmental strategy goals would inspire researchers to target the strategy's goals with interdisciplinary and transdisciplinary approaches that address all of the strategy topics. We expect that this link will enhance research production in the basin by reflecting the RFAs across each strategy topic for every goal. This may lead to the creation of innovative and imaginative research and eventually improve the connection between decision-makers and researchers. The government could further profit by conducting a systematic literature review to optimize the allocation of the budget available for future studies.

Chapter 4

Improved Wellfield Management system in Wadi Al Arab wellfield

Alqadi et al. (2019)[1]

Abstract

Groundwater is the main source of drinking water supply in Jordan. Over the past 30 years, many wellfields have been drilled and expanded to cover increasing drinking water demand caused by natural population growth, development of life standards and as a result of the influx of refugees to Jordan. In particular, northern Jordan groundwater resources have been severely depleted. Therefore, water suppliers and utilities have been increasingly challenged to meet water demand and deliver water of adequate quality and quantity to households in a timely manner. Meeting these objectives requires good data management, proper maintenance of groundwater wells, and effective wellfield management plans. We developed a novel monitoring strategy that allows the collection of relevant data for wellfield managers (e.g., yield, static and dynamic water level, as well as energy consumption). The new monitoring system, implemented in 2017, has greatly enhanced data availability in comparison to the situation between 2012 and 2016. The data are used in an operational decision support tool based on simple interpretation of the field observations.

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[1] **Alqadi, M.,** Margane, A., Al Raggad, M., Subah, H. A., Disse, M., Hamdan, I., & Chiogna, G. (2019). Implementation of simple strategies to improve wellfield management in arid regions: the case study of wadi Al arab wellfield, Jordan. Sustainability, 11(21), 5903.

The implementation of the project was done using both bottom-up and top-down approaches for the Wadi Al Arab wellfield. Our results evidence that (i) simple strategies can lead to a significant improvement of wellfield management, reducing the maintenance time of the wells though appropriate monitoring (from an average of more than five days/maintenance/well in 2012 to less than one day/maintenance/well in 2017); (ii) the joint combination of bottom-up and top-down approaches leads to an effective implementation of the monitoring system; (iii) the simplicity of the proposed monitoring strategy makes it suitable for further implementation in other wellfields in Jordan and countries in a similar situation of both data and water scarcity.

4.1 Introduction

In many countries, especially those located in arid to semi-arid regions, precautions are taken against water scarcity (Cudennec et al., 2007; Prinz & Singh, 2000). Optimization of well field management practices and water quality protection received much attention in different regions in the world (Bauser et al., 2010; Braune & Xu, 2008; Cousquer et al., 2019; Gejl et al., 2019; Kawo et al., 2018; Marti et al., 2012; Redoloza & Li, 2019; Shekhar & Rao, 2010; Wagner, 1995). One of the effects of water scarcity is the lack of enough drinking water supply to the population and this issue can be worsened by improper wellfield management. In Jordan, for example, the gap between drinking water supply and demand has been increasing since the early 1980s (Al-Weshah, 1992; Jaber & Mohsen, 2001). In efforts to close this gap, four wellfields have been drilled in Northern Jordan since then. However, by reviewing the current dataset of the wellfields, the overall available information on these wells required for proper wellfield management has been very limited. Essential monitoring data, such as dynamic and static water levels (DWL and SWL, respectively), power consumption and yields are of limited availability, making it difficult to propose the right actions to reach an efficient wellfield management. On a national level, some studies were done in different wellfields, considering groundwater quality (Al-Harahsheh et al., 2015; Al Kuisi et al., 2014, 2015; Al Kuisi & Abdel-Fattah, 2010; Borgstedt et al., 2007; El-Naqa et al., 2007; El Naqa, 2004; Hamdan et al., 2016; Hammouri & El-Naqa, 2008) and groundwater quantity (Al-Kharabsheh & Al-Mahamid, 2002; Al Kuisi & El-Naqa, 2013; Alkhatib et al., 2019; Jassim & Alraggad, 2009; Salameh, 2004).

Among the reasons for water scarcity in Jordan are climate change (Hamdi et al., 2009; Margane et al., 2008; Ragab & Prudhomme, 2002; Rödiger et al., 2017; Sada et al., 2015; Salameh, 2016;

Suppan et al., 2008; Verner et al., 2013), population growth (DoS, 2017), geopolitical location as a downstream country, and refugee influxes due to political instability in the region (Margane et al., 2015). In Jordan, water scarcity poses serious challenges for the wellbeing, security and economic development of the country(Shammout et al., 2018). Although proper wellfield management cannot solve all complex social, environmental and economic issues related to water scarcity, it can help in reducing groundwater pumping costs, saving energy (Bauer-Gottwein et al., 2016) and granting a more constant and reliable supply of water to the population (Vaux, 2011). According to (MWI, 2015), around 73% of drinking water supply in Jordan comes from groundwater and 15% of energy consumption at the national level is used for water pumping and supply; hence, the relevance of implementing efficient wellfield management plans is crucial. Around 80% of groundwater wells are located in the northern part of the country. Northern Jordan is subjected to the highest water stress within Jordan since it is the most populous region of the country, with a high water demand and low water availability. According to (Kinzelbach et al., 2002) , the depletion in groundwater levels as a result of over-abstraction indicates that an aquifer is unsustainably managed. Groundwater in Northern Jordan is hence exposed to depletion as indicated by the rapid drop in groundwater levels (Margane et al., 2015), which puts the wellfields under pressure and leads to pump failure, riser line damage, corrosion and finally, to an unreliable water supply for the population. The highest groundwater level drop in the country was recorded in the Wadi Al Arab wellfield, with an average decrease of seven m/year between the year 1995 and 2017 (MWI and BGR, 2019). Standardized procedures to improve the management of existing wellfields, that are easy to be implemented and accepted by stakeholders, are hence, urgently needed.

Although many studies have been undertaken to improve groundwater resources management in Jordan, very few were implemented with consideration of multi-level stakeholder involvement (Wolf & Hötzl, 2011), most of them focused on either top level (ARD, 2006) or bottom level (*Water Innovation Technology 2018 - 2022*, n.d.) participation. Involving the top level (higher governmental level such as Ministry of Water and Irrigation (MWI)) in the implementation of management plans is important for building long-term strategies (J. Butler et al., 2015). Usually, a top-down approach would not consider or plan for the priorities identified at the bottom level in their strategy (Sherman & Ford, 2014). Brown (2008) mentioned that the knowledge culture varies at different stakeholder levels (J. Butler et al., 2015). In order to understand a system, we need to consider the perception of the different stakeholders. Although this may not help to understand all issues, it is a vital step to demonstrate the main relationships in the system (Burns, 2012) and understand the current constraints. It is difficult to achieve effective multi-level stakeholder engagement, but it can be improved by involving other levels in the decision process, by strengthening the information flow between the levels, and by combining elements from the top-down and bottom-up approaches (Pahl-Wostl, 2009; Smeds et al., 2003).

Jordan started following a top-down approach through the development and implementation of a national water strategy for the period of 2016–2025 to better manage its insufficient freshwater resources and to cope with water supply deficits. Integrated water resources management has been indicated as a key approach in the national water strategy of Jordan (MWI, 2016a). Moreover, the strategy states that "deeper knowledge of the availability, quality, and protection of water is the foundation for effective decision-making" (MWI, 2016a) (p. 3). Yet, no specific advice to also follow a bottom-up approach during the implementation phase was provided.

The objectives of this research were to reduce the frequency of pump failures per year and the maintenance period required to return a well to operation, and hence, to improve wellfield management for the Wadi Al Arab wellfield. The hypothesis that we investigate in this work is that through the implementation of more accurate operational wellfield monitoring systems, along with a multi-level stakeholder engagement, we can enhance wellfield management (by enhancing the operation and maintenance process) and improve the water supply security in Jordan. We tested our research hypothesis in the Wadi Al Arab (WA) wellfield in Northern Jordan, which covers approximately 40% of the drinking water supply for the second largest governorate in Jordan, Irbid. We also discuss the importance of having both the support of MWI and also of educating the technical staff of the local water utility on the benefits behind a proper wellfield management system. This paper is structured as follows: **Section 3.2** gives a general description of the study area. **Section 3.3** describes the methodology that was implemented, including the operational decision support tool (ODST), measurement procedure and stakeholder engagement. **Section 3.4** shows the quantitative results collected during the project. **Section 3.5** depicts the discussion of the results. Finally, **Section 3.6** presents our conclusions.

4.2 Study Area

The Wadi Al Arab (WA) wellfield is located in the north-western part of Jordan about 20 km from the city of Irbid (Figure 4.1). The wellfield taps into the A7/B2 upper cretaceous limestone aquifer. As data availability is limited in the catchment, the study area was extended to the east to include a higher number of groundwater monitoring and rainfall stations.

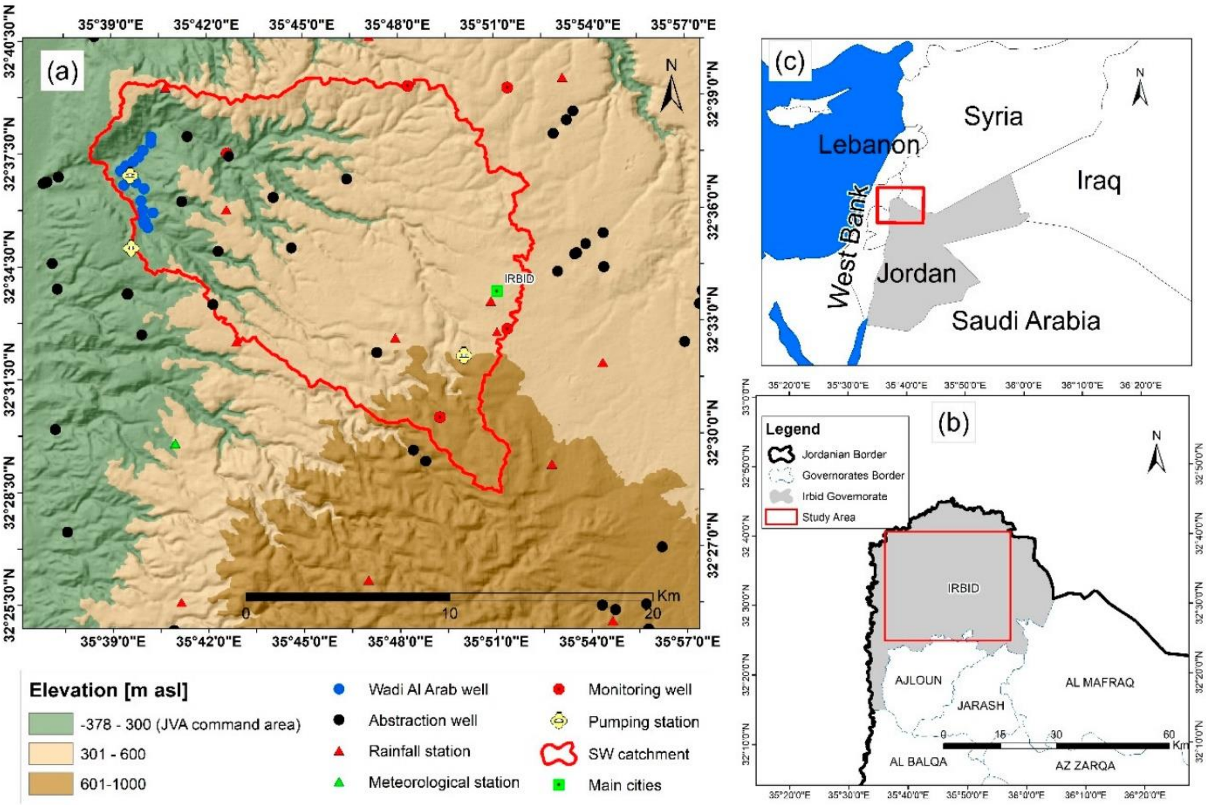

*Figure 4.1. Overview map of the study area. (**a**) Shows the location the wells, rainfall stations, meteorological station, pumping stations and surface catchment area, it also shows the area topography. (**b**) Shows the area of Irbid governorate and the study area. (**c**) Shows the location of Jordan and surrounding countries.*

Topographically, the area is considered as a high relief area. The elevation ranges from less than 300 m below sea level in the Jordan Valley in the north-west of the study area to 1000 m above sea level in the south of the study area, which is considered as the main recharge area of the A7/B2 aquifer (Al Kuisi et al., 2015; El-Naser, 1991; Rödiger et al., 2017; Salameh, 2004; Subah et al., 2006a). The area is characterized by a Mediterranean climate with hot, dry summers and wet, cool winters. During summer, the average monthly temperatures exceed 30 °C in the highland and more than 40 °C in the Jordan Valley. In contrast, temperatures may drop below 0 °C in winter. Rainfall in the area ranges from 300 mm/year in the Jordan Valley to around 600 mm/year in the Ajlun area (Subah et al., 2006a).

The Wadi Al Arab wellfield was established in 1982, with four of the wells now over 35 years old. According to the collected well completion reports, wells were initially artesian. However, due to the high abstraction, water levels have declined significantly and today, none are artesian. Table 4.1shows the location, elevation and completion date of all Wadi Al Arab wells.

Table 4.1. List of Wadi Al Arab wells with the coordinates, elevation and completion date.

ID	Name	Latitude "N"	Longitude "E"	Elevation [m asl]	Completion Date
AE1007	WA 1	32°36'41.05819"	35°39'25.91936"	9.42	Sep 82
AE1008	WA 2	32° 37'12.81401'	35°39'30.96736"	-35.36	Sep 82
AE1009	WA 3	32° 37'26.67630"	35°39'52.15763"	-26.08	Nov 82
AE3020	WA 3A	32°37'26.37884"	35°39'52.12241"	-25.87	Jun 09
AE1010	WA 4	32°37'57.04019"	35°40'18.63580"	19.56	Sep 82
AE1011	WA 5	32°35'48.60537"	35°40'01.84178"	47.00	Jan 83
AE3001	WA 6	32°35'43.46482"	35°40'07.20160"	63.57	Oct 1999
AE3005	WA 8	32°37'01.94312"	35°39'20.06533"	-14.89	Oct 2002
AE3006	WA 9	32°35'41.63346"	35°40'03.82200"	79.287	Feb 03
AE3016	WA 10	32°35'33.11840"	35°40'11.48428"	85.63	Mar 2008
AE3017	WA 11	32°36'01.24016"	35°40'01.28220"	74.65	Dec 2007
AE3034	WA 11 A	32°36'01.35869"	35°40'00.81987"	73.93	Mar 2016
AE3018	WA 12	32°37'17.37891"	35°39'44.09322"	-40.89	Dec 2007
AE3019	WA 13	32°36'34.43015"	35°40'04.71635"	104.87	Apr 08
AE3042	WA 13A	32°36'34.52057"	35°40'04.92756"	104.87	Feb 17
AE3021	WA 14	32°36'14.04827"	35°39'58.57560"	70.98	Jun 09
AE3024	WA 15	32°36'57.18547"	35°39'35.25914"	32.58	Jul 14
AE3027	WA 16	32°36'44.95781"	35°39'48.68497"	71.77	Sep 14
AE3030	WA 17	32°37'38.36044"	35°40'06.67220"	-34.31	Mar 2015
AE3035	WA 18	32°37'47.36505"	35°40'17.02858"	12.49	Mar 2016
AE3043	WA 19	32°35'55.26102"	35°40'18.24177"	109.59	May 2017

In general, a cost-effective groundwater well design should last at least between 20 and 25 years (Danert & Gesti Canuto, 2016). Harter (2003) states that good well design and proper well development will increase both the well and pump lifetime. On the other hand, with poor groundwater well design, more pump failures would occur. As water levels have dropped more than 100 m since the early 1980s, the wellfield is facing significant operational problems. One of them is the extreme corrosion of the equipment. In most wells, riser pipes and/or pumps do not last for more than two years (e.g., WA 14). Until the beginning of 2017, water levels were only sporadically measured (e.g., once/twice a year), which was not enough to efficiently operate the pumps and thus, save energy. This resulted in overly high production costs and low energy efficiency. As observed during the field investigations, some wells were unknowingly not pumping water due to corroded pumps or riser lines.

4.2.1 Rainfall and Temperature

Daily rainfall data was collected from 13 stations located in the area (Figure 4.1), while temperature is only available from one station outside the study area (20 km west from Irbid). In Jordan, the hydrological year lasts from October to September. The total monthly rainfall of the thirteen stations were averaged and plotted in Figure 4.2 for the period 2013–2018. The data shows that the highest amount of rainfall in the area was recorded in January 2013, with a monthly cumulated value of 250 mm. However, we can notice that in this study's period of interest, the precipitation patterns do not display a large annual variability and the different years are comparable from a hydrological point of view. This pattern can also be seen when analyzing the temperature data for the study area (Figure 4.3).

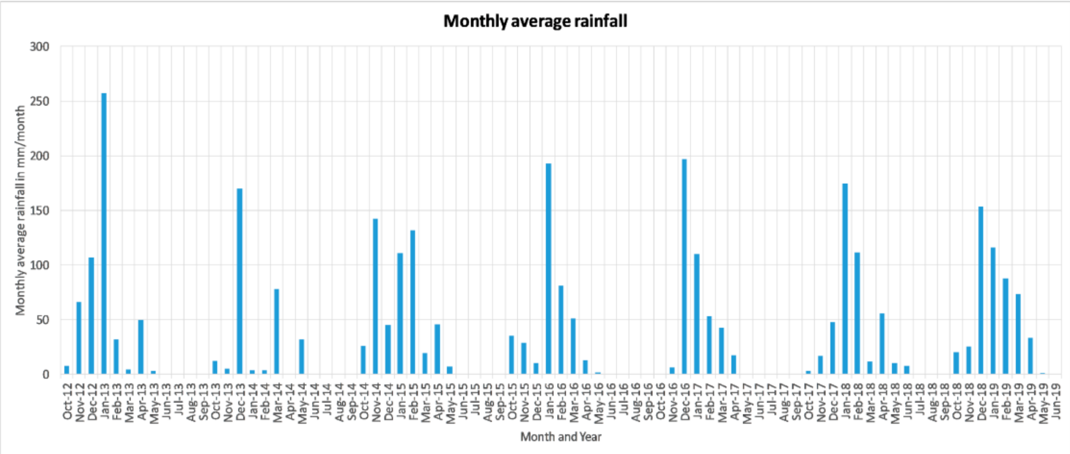

Figure 4.2. Average of monthly rainfall for the rainfall stations in the study area.

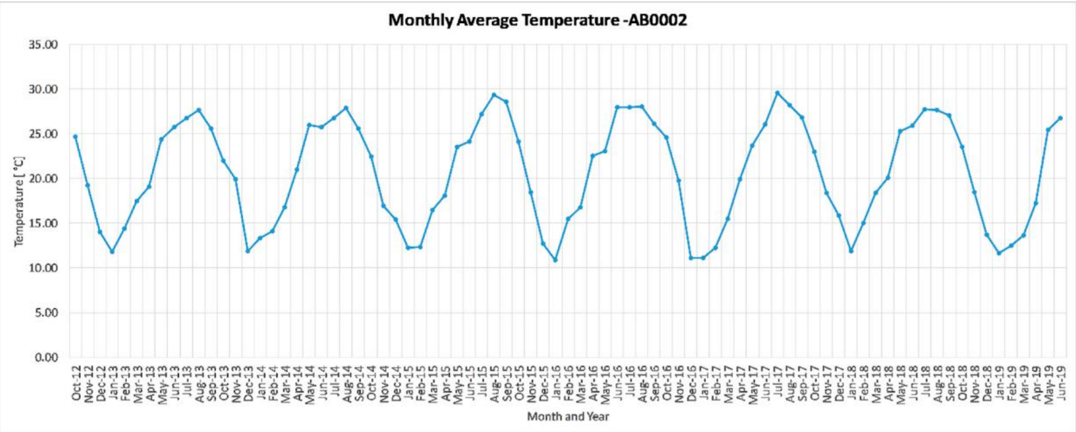

Figure 4.3. Average of monthly rainfall for the rainfall stations in the study area.

4.2.2 Hydrogeology

The Wadi Al Arab wellfield taps into the A7/B2 limestone unit (Upper Cretaceous), which is the main aquifer in the northern part of Jordan. This formation crops out in the southern part of the study area, where the majority of recharge occurs. In the northern part of the study area (including the wellfield), this aquifer is confined and overlain by the Muwaqqar Chalk Marl formation (B3 aquitard), which has a thickness of around 300 m in the Wadi Al Arab area (Table 4.2) (Moh'd, 2000).

Table 4.2. Description of the hydrogeological units in the study area (adopted from (Subah et al., 2006a).

Formation	Symbol	Lithology	Thickness [m]	Aquifer Unit
Wadi Shallala	B5	Chalky and marly limestone with glauconite	0-550	B4/B5
Um Rijam	B4	Limestone, chalk, chert	0-310	
Muwaqgar	B3	Chalky marl, marl, limestone chert	80-320	B3
Amman-Al Hisa	B2	Limestone, chert, chalk, phosphorite	20-140	A7/B2
Wadi Um Ghudran	B1	Dolomitic marly limestone, marl, chert, chalk	20-90	
Wadi As Sir	A7	Dolomitic limestone, limestone, chert, marl	60-340	

Static water level (SWL) measurements were collected from the Groundwater Resources Management (GWRM) project, MWI database and from field visits. The groundwater contour lines were drawn according to the SWL measurements and they show a groundwater flow towards the northwest of the study area (Figure 4.4). The 2017 groundwater contour map was compared with the 1995 groundwater contour map. The result shows that a large area of the southern part of the study area has become dry in recent years.

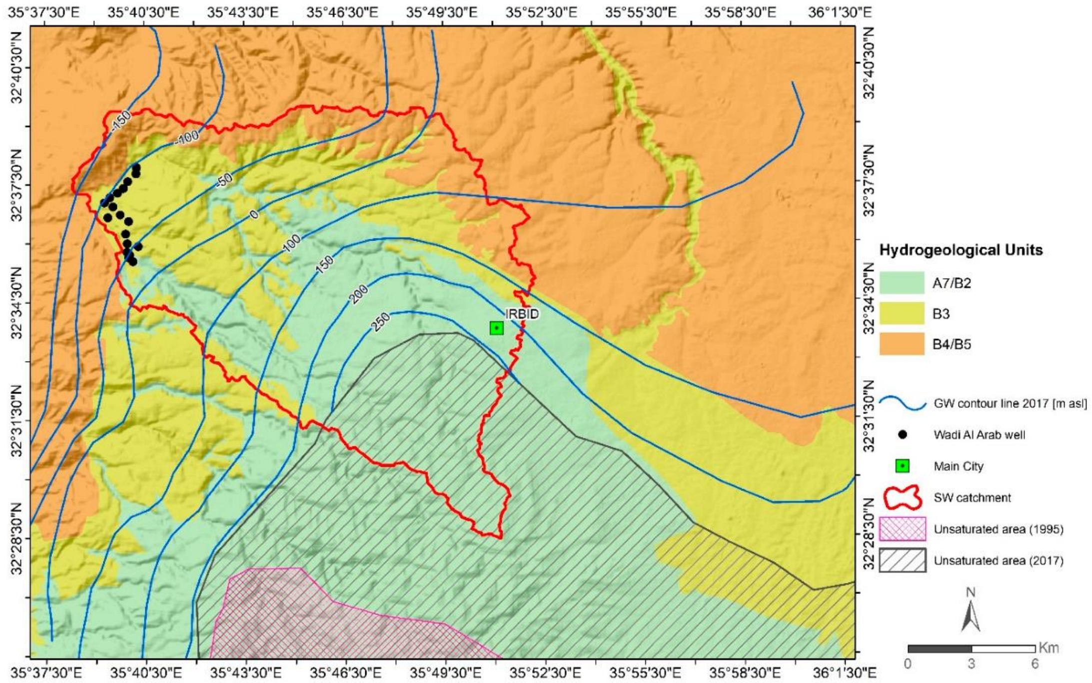

Figure 4.4. Groundwater contour map of the area of Wadi Al Arab

The water level in the Wadi Al Arab wellfield has decreased between 100 m and 150 m over the past 23 years (Figure 4.5). However, according to recent water level measurements, the current decline rate of the Wadi Al Arab wells reaches 10 m/year. All Wadi Al Arab wells were under confined conditions in 1995. Currently the confinement limit, where the groundwater level intersects with the base of the B3 unit, has shifted toward the northwest due to the drop in water level. This has resulted in the southern part of the wellfield being now unconfined.

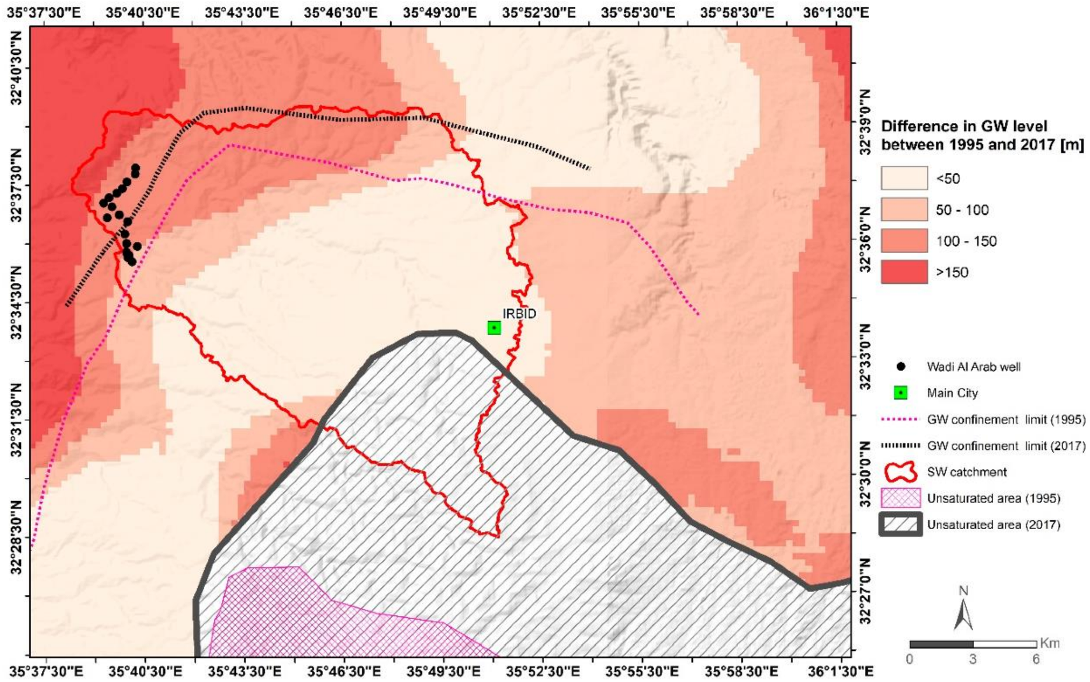

Figure 4.5. The decrease in the saturated thickness between the year 1995 and 2017.

4.2.3 Wellfield Data

Yarmouk Water Company (YWC) started managing the Wadi Al Arab wellfield in 2012. Because of this, a lot of operational and maintenance data is missing prior to 2012. Therefore, this study considered only the years 2012–2018.

Data were stored at different agencies and departments; for instance, the electricity consumption was archived in the financial department, the network data was with the geographic information system (GIS) department, and the wells maintenance logs were housed in the wells department. Additionally, the data format was not standardized, and, in some cases units or abbreviations were not clear without contacting the YWC staff. Descriptive metadata were also missing in the files, which made it difficult to clearly understand the existing data. While veteran employees were able to navigate these spreadsheets, the layered and unclear nature of information stored there slowed down the problem identification process and made the forecasting of upcoming failures nearly impossible. YWC technicians would therefore rarely make recommendations to their superiors on important well management interventions.

When a well was replaced, the replacement well was located close to the new well and mostly used the same name of the old well, followed by a letter (a, b, c, etc.). Usually, only one well works after the replacement. There are exceptions, however. For instance, wells WA3 and WA3a are still being operated at the same time, sharing the same electricity meter but having two different flow meters. Additionally, the collection of abstraction data and electricity consumption data were not possible for WA6 and WA2, as WA6 does not pump water to the WA pumping station (PS) and no flow meter reading was collected. Well WA2 has neither a flow nor an electricity meter. The electricity consumption of individual WA wells was not stored in the financial department of the YWC. Only the electrical consumption of one subscription that includes all Wadi Al Arab wells and three pumping station (PS1, PS2 and PS3) was found in the files of YWC since 2012.

4.3 Methodology

4.3.1 Tools Development

Tools play a significant role in data management and in decision making process (Rossetto et al., 2018). The developed wellfield management toolbox consisted of three parts: the Wellfield Information System (WFIS), the operational decision support tool and the Wellfield Management Plan (WFMP) report, which are detailed in the following sections.

4.3.1.1 Wellfield Information System (WFIS)

The project started in September 2015 by collecting data from all departments in YWC. These data were available in form of hard copy (e.g., monthly reports), soft copy (e.g., closed-circuit television (CCTV) records) or as scans (e.g., old well completion documents). All the collected data were (1) processed by highlighting the suspected errors, which were either corrected or removed; (2) standardized (data standardization in this context includes converting the data into a common format, such as having the same date format, or selecting one single label to identify the measurement type used, such as either SWL); and (3) entered into the WFIS. For the measurements which were not well documented and were not useful after processing, a new monitoring system was designed (Figure 4.6). WFIS is a customized Microsoft Access file to store, organize and manage wellfield/wells data. This comprises all available data acquired from: (a) the time when the well was drilled (e.g., pumping tests, well design), (b) field measurements (e.g., dynamic water levels), (c) maintenance activities (e.g., exchanging or repairing the pump), (d) operation activities (e.g., duration of downtime of wells), and (e) the operation and maintenance (O&M) costs (e.g., electricity consumption and costs for maintenance actions).

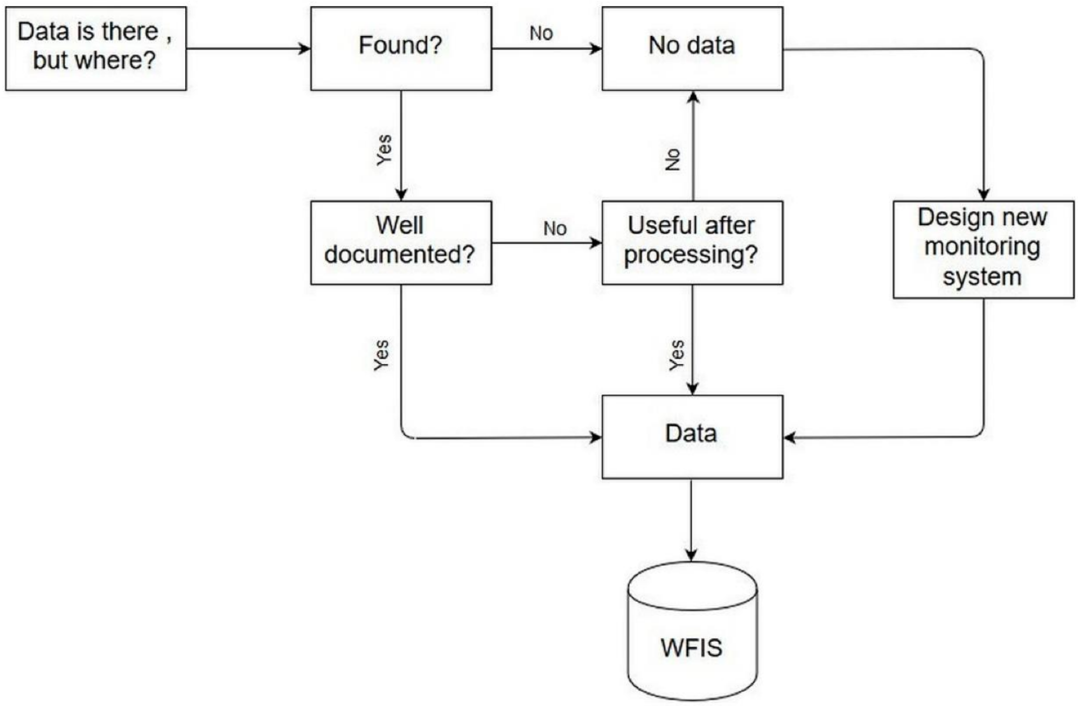

Figure 4.6. Schematic diagram for the followed processes to build the wellfield information system (WFIS).

Given that the YWC staff used an Environmental Systems Research Institute (ESRI) ArcMap, a template for GIS maps was created. It provided an overview of the general situation of Wadi Al Arab wells by mapping the spatial distribution of the measured values and recorded faults of each well. These maps can be updated by adding the latest measurement/observation into the GIS system.

4.3.1.2 Operational Decision Support (ODST)

An operational decision support tool (ODST) was developed and tested in the Wadi Al Arab wellfield as part of the Wellfield Management Plan (WMP). ODST gave a visual representation of the actual condition of a well. This ODST was a combination of schematic drawings and graphs of individual wells that was generated in a Microsoft (MS) Excel file containing the collected data from the MS Access database (well ID, well name, well depth, SWL, DWL, calculated drawdown, pump specifications, pump setting, yield, pumping lift). It also showed the electricity consumption and compared it with the needed consumption to determine the pump efficiency. All graphs and figures are shown in an interactive MS Excel dashboard (Figure 4.7). The ODST can also act as an early warning system, defining whether an urgent action has to be taken before failure of a well would occur. Figure 4.7 gives an example of how the schematic drawing looks for a well. It can be seen that an action must be taken; in this case, the water level was only a few meters above the pump and the warning is shown in a red stripe.

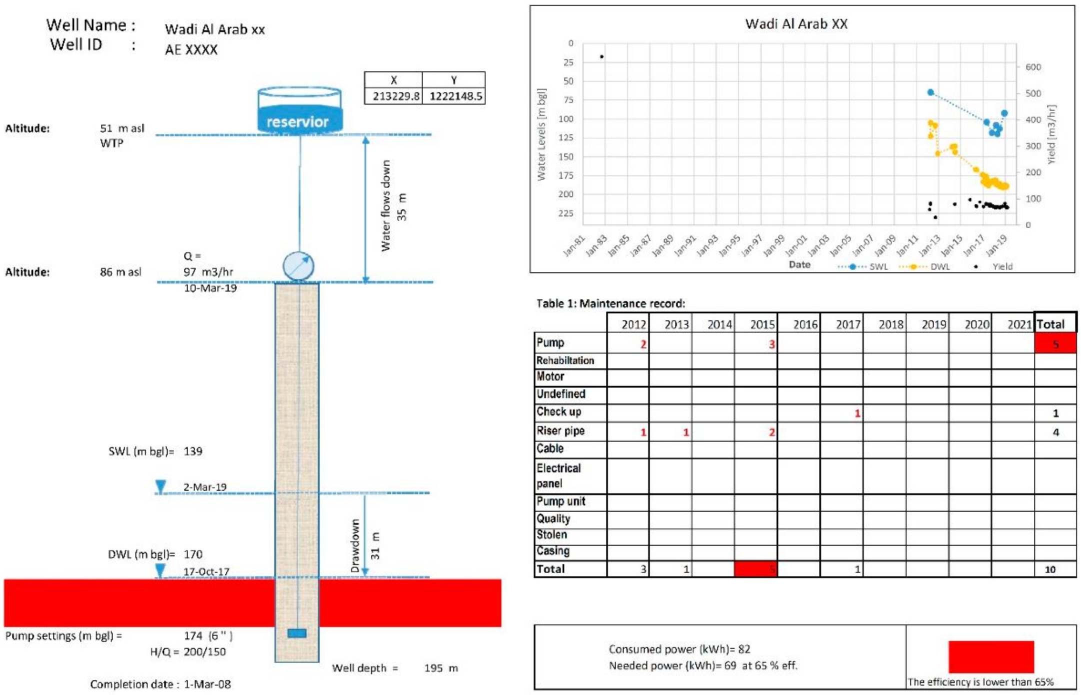

Table 1: Maintenance record:

	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total
Pump	2			3							5
Rehabiltation											
Motor											
Undefined											
Check up						1					1
Riser pipe	1	1		2							4
Cable											
Electrical panel											
Pump unit											
Quality											
Stolen											
Casing											
Total	3	1		5		1					10

Figure 4.7. Operational decision support tool for wellfield management.

4.3.1.3 Wellfield Management Plan Report

All the GIS maps, graphs and the schematic drawings were gathered and entered into one single document. This document comprised all the related information of each well in the wellfield (Figure 4.8). The last part of this document contained the proposed actions and their prioritization based on cost and their ability to improve water supply security. The proposed actions considered whether nation-wide projects mentioned in the National Water Strategy (MWI, 2016) were implemented or not, such as the Wadi Arab Water System (WAWS) II project. For instance, once the WAWS II project is operational, which is expected to bring 30 Million Cubic Meter (MCM) per year to Irbid, this will reduce the pressure on Wadi Al Arab wells and, consequently, it will be possible to stop some wells or convert a pumping well to a monitoring well. This Wellfield Management Plan (WMP) is a living document, based on the currently available information and is updated when new data and information becomes available. In the WMP, individual pages are replaced, omitted or added during the required regular updating, according to changes in the situation (e.g., when pumps are changed). The main purpose of this document is to overcome O&M problems in the wellfield. It is therefore used by the staff of the water utility (YWC), regulator (Water Authority of Jordan, WAJ) and resources management entity (MWI) in digital format and it is officially recognized by MWI.

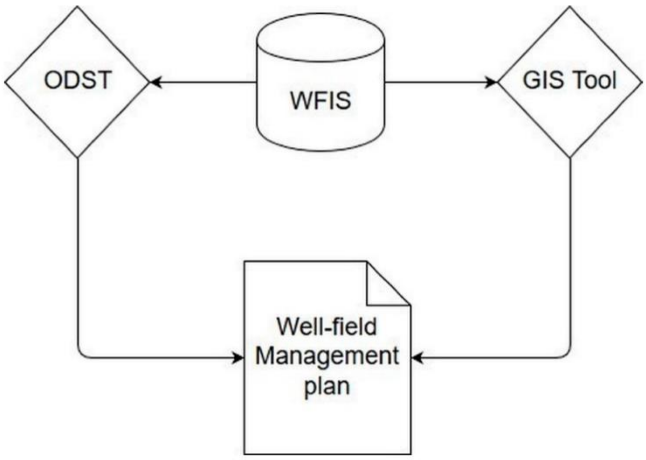

Figure 4.8. Wellfield management tools development flowchart.

4.3.2 Measurement Procedure

In general, field measurements were not taken systematically until the end of 2015. The DWL measurement was not measured regularly, even though this measurement was recommended to be recorded on a monthly basis for all wells (Alqadi et al., 2018). Due to the lack of SWL data in the area and no monitoring well to represent the wellfield SWL, the SWL in a well should be measured any time the pump was switched off for a time longer than the recovery time. However, since the priority of the wellfield manager was water provisioning, such a long stop of the pump was not always possible. The water level measurements taken during these intervals were therefore only providing a proxy for the SWL in the area, considering the influence of the other wells operating nearby. According to YWC staff, water level measurements were done in the past but many records of SWL could not be found as they were not systematically stored. Before the implementation of the Wellfield Management Plan, electricity consumption was sent to the YWC financial department for the subscription number, which contains the consumption of the three pumping stations and all Wadi Al Arab wells. The WMP recommends recording electricity consumption monthly and for each well individually. In the past, the monthly abstracted amount was calculated by multiplying the number of working hours of the pump by the volume of water per hour. However, this is inaccurate, as some pumps may not even be pumping water. Therefore, a metered electricity reading should be collected together with metered monthly yield. Through the Improved Groundwater Resources Management (I-GWRM) project, pressure gauges were installed for the wells with missing pressure gauges. Table 4.3 shows the main field measurements procedure that needs to be developed. We aimed to measure all the different field measurements on a monthly basis, except for SWL due to the aforementioned limitations (Table 4.3)

Table 4.3. Development of the field measurement procedure in Wadi Al Arab wellfield for static water level (SWL), dynamic water level (DWL), yield, volume of abstracted water, and electricity consumption of each well.

Measurement Type	**Before Development**	**Aim to Be Achieved**
Static water level	Measured but not recorded or recorded just in the drilling time	To be measured and recorded when the pump is turned off
Dynamic water level	Not systematic measurement	To be measured monthly
Yield (m3/hr)	Not systematic measurement	To be measured monthly
Abstracted volume of each well	Not measured	The flow meter reading should be collected monthly
Electricity consumption of each well	Not recorded	To be measured monthly
Pressure	Not for all wells, not collected systematically	To be collected monthly

4.3.3 Stakeholder Engagement

Stakeholder participation was central to this research for the I-GWRM project team. Two of the methodological characteristics, presented by (Burns, 2012), as part of the participatory systemic inquiry (PSI), were used in the stakeholder engagement approach. The project held meetings at three different group levels, namely: (a) High-level group, which included people who had significant impact on the water sector (upon our request); (b) head of department/directorate group, which included people from YWC and MWI who were responsible for the mid-level decisions, such as pumping stations and wells operation and maintenance (according to the needs of the project team); and (c) technician group, which included people who did the practical work in the field (upon their request). The following methodological characteristics described in (Burns, 2012) were used: Different starting questions for each of the inquiry strands and the idea of direct seeding from one group to another. PSI was introduced and defined as "learning and deliberation which involves multiple stakeholders in generating deep insights into the dynamics of the systems that they are trying to change" (Burns, 2012) (p. 88).

Changing the existing management and operation system started by building trust between the project team and technicians in the field. This was initiated through support by the Ministry of Water and Irrigation, who requested the water utility staff cooperate with the project team in December, 2015. This was an important step to start working with YWC staff in the field and understanding how monitoring, operation and management was done in the wellfield. However, it was not enough to induce change to the existing system. Therefore, being present during day-to-day operations of the wellfield management process was important to build trust and learn the underlying challenges and obstacles that they were facing in their work.

In parallel, it was necessary to train the technicians of the Wadi Al Arab wellfield and inform them about the importance of field measurements for improved management decisions. It was essential to clarify the benefits behind a proper wellfield management system. The aim of this approach was to permit the managers and operational staff involved in the tasks of planning, operation and maintenance of a wellfield to do so while having all the information related to decision-making on hand. A wellfield management committee for Wadi Al Arab was established involving, staff from MWI (4 members), YWC (4 members) and a member from the Water Authority of Jordan (WAJ). Besides the daily visits, regular meetings (monthly), organized by the I-GWRM project team, with the committee were set up to design the Wellfield Management Plan document in such a way that it fulfilled all mutually-agreed-upon objectives and requirements. Later on, the meetings were held based upon the needs and requests of YWC, MWI or the project team.

4.4 Results

Water pumping consumes around 15% of total electricity consumption in Jordan (NEPCO, 2017). In Wadi Al Arab, electricity consumption increased by 11% between 2012 and 2018 in the subscription which contains the three pumping stations (PS1, PS2 and PS3) and Wadi Al Arab wells, while the pumped volume of water (including the volume coming from other sources to PS1) remained almost the same throughout this period (Figure 4.9). This means that the electricity consumption of pumping a cubic meter of water increased due to an increase in the pumping lift or an increase of the number of wells (Figure 4.10). It can be also noticed that the electricity consumption decreased by 5% between 2017 and 2018 (Figure 4.9), the period in which the ODST tool was used by the wellfield managers. Overall, however, the increase in electricity consumption resulted in a twofold rise in the pumping costs between 2012 and 2018 (Figure 4.10). This cost increase has to also consider the increase of the electricity tariff, shown in Figure 4.11. The reasons behind the increase in the electricity costs were not always related to national drivers, and hence this will not be further investigated in this work.

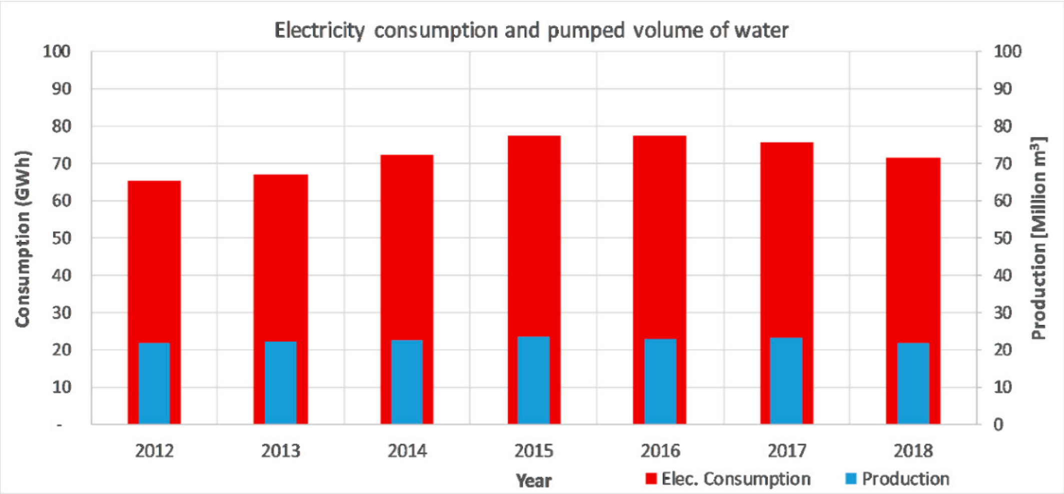

Figure 4.9. Total production (in the system) and Energy consumption of Wadi Al Arab wells and the three pumping stations 2012–2017.

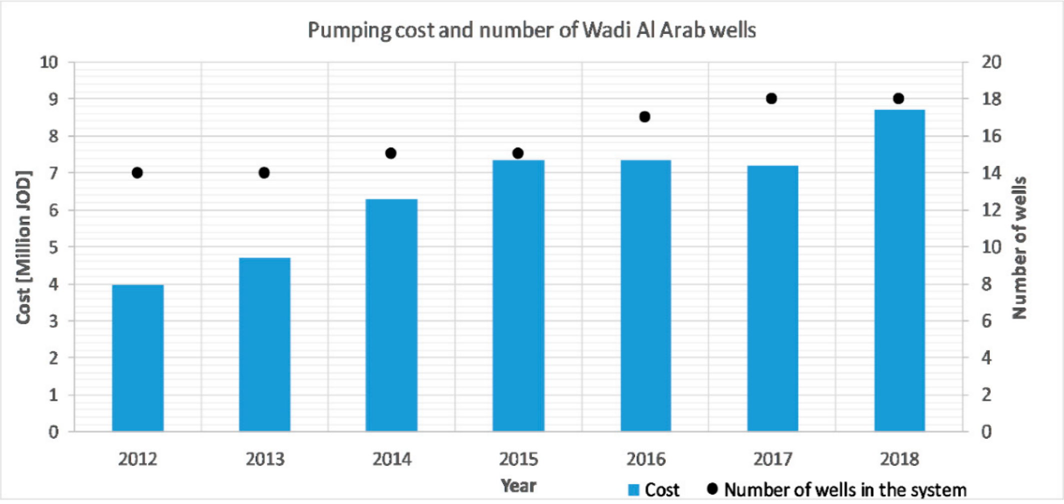

Figure 4.10. The cost of pumping the water from Wadi Al Arab wells and through the three pumping stations. The exchange rate during the mentioned period (1 JOD = 1.41 US dollar).

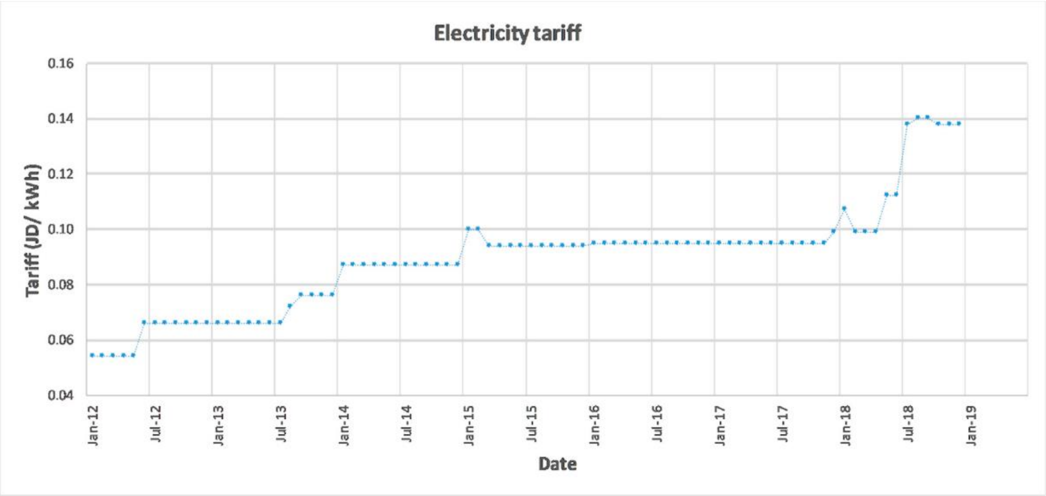

Figure 4.11. Average of the monthly electricity tariff for the water utility—Wadi Al Arab area (2012–2018).

Since January 2017, the electricity consumption and the production were collected for each well on a monthly basis, except for WA2 and WA6. Although the total electricity consumption of WA wells remained the same in 2018 (in comparison to 2017), the cost of pumping 15 MCM of water from 16 wells to the first pumping station was 1.03 million JOD in 2017, while its cost increased to 1.46 million JOD to pump the same amount from the same wells in 2018. This is due to the increase of the electricity tariff in 2018. The tariff increased from 0.061 JD/Kwh in 2012 to 0.122 JD/Kwh in 2018.

The electricity consumption of each well to pump a cubic meter of water to the pumping station varies within the Wadi Al Arab wellfield. For instance, in the years 2017 and 2018, the average electricity consumption to pump a cubic meter of water from WA-1 to the pumping station was 1.11 kWh while at WA-18, pumping consumed only 0.52 kWh (Figure 4.12). The overall energy consumption for abstracting a cubic meter from the wellfield remained the same in 2017 and 2018 with a value of 0.785 kWh/m^3. It can be seen that sometimes older wells had higher production than new wells (e.g., WA 4 and WA 17). In addition, the pumping cost from some old wells was lower than the costs for newer wells (e.g., WA 5 and WA 11a). These observations show that the age of the well was not the only factor influencing pumping costs and well production.

In general, the monitoring procedure has improved since the beginning of 2017. In fact, the number of measurements taken by YWC staff in 2017 and 2018 was much larger than in the years preceding the implementation of the ODST. Figure 4.13 shows the number of annual field measurements in the wellfield, without counting the electricity consumption measurements. An increase in the number of measurements started in 2016, while the following years, 2017 and 2018, had the highest number of field measurements. The number of measurements increased from 260 records in 2012 to 699 and 703 records in 2017 and 2018, respectively. No field measurement records were found for the year 2013, while the years 2014 and 2015 had 34 and 20 recorded field measurements, respectively. The total number of working wells increased from 14 wells in 2012 to 18 wells in 2018. However, seven wells were drilled between 2012 and 2018, two of them were replacement wells (WA11a and WA13a) and one well (WA19) was drilled and not operated due to water quality problems.

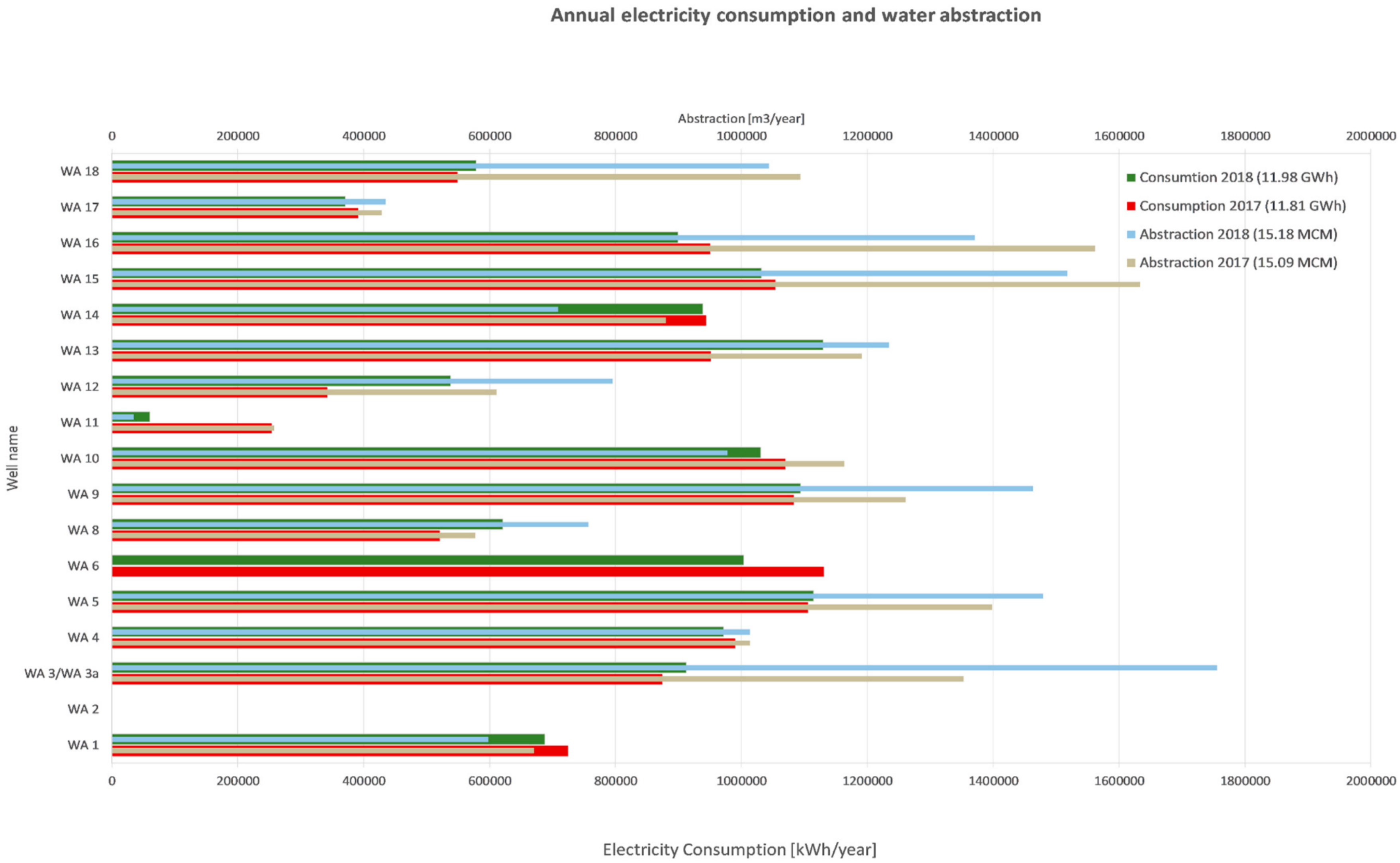

Figure 4.12. Electricity consumption and production in the wells of Wadi Al Arab (WA) wellfield in 2017 (no abstraction and electricity consumption as WA2. WA3 and WA3a had one electricity meter, no abstraction data was found for WA 6 as it doesn't pump water to the WA pumping station).

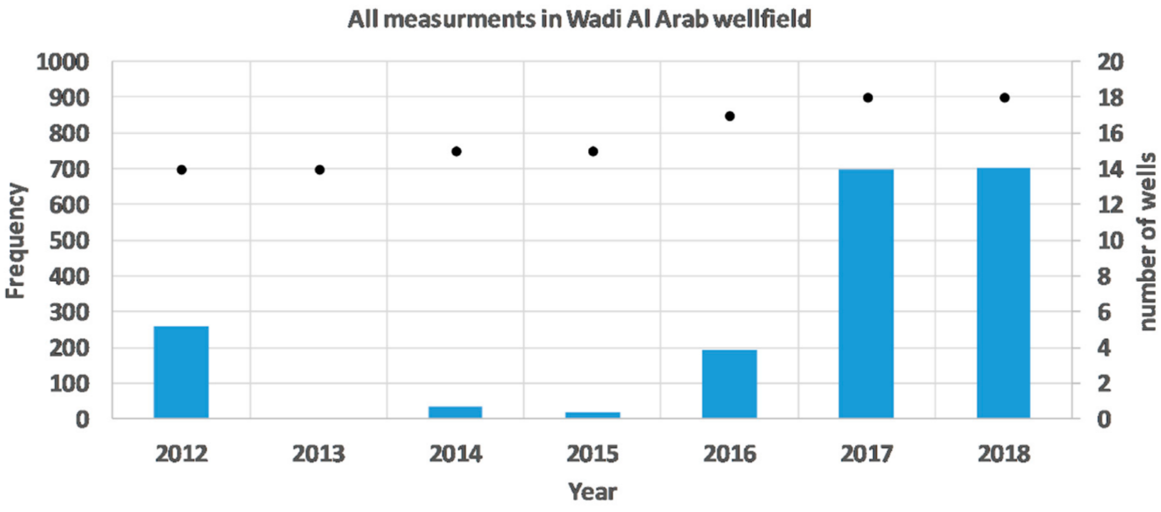

Figure 4.13. Number of annual field measurement between (2012–2018) (represented as columns) and number of wells (represented as scatter points).

The number of collected field measurements per month are shown in Figure 4.14. The highlighted area represents the period since the project started (September 2015) until the end of 2018. The transition period between the top-down approach (when the letter from MWI was sent to YWC and it is showed by the red color in the figure below) and the combination of the top-down and bottom-up approach (when people in the field were involved in the decision making process and showed by the green color in the figure below) can be seen by the improvement of data availability. Sometimes the number of monthly measurements was low (e.g., 21 measurements in June 2017), because the measurements of wells were taken at the beginning or end of the following or the preceding month, respectively.

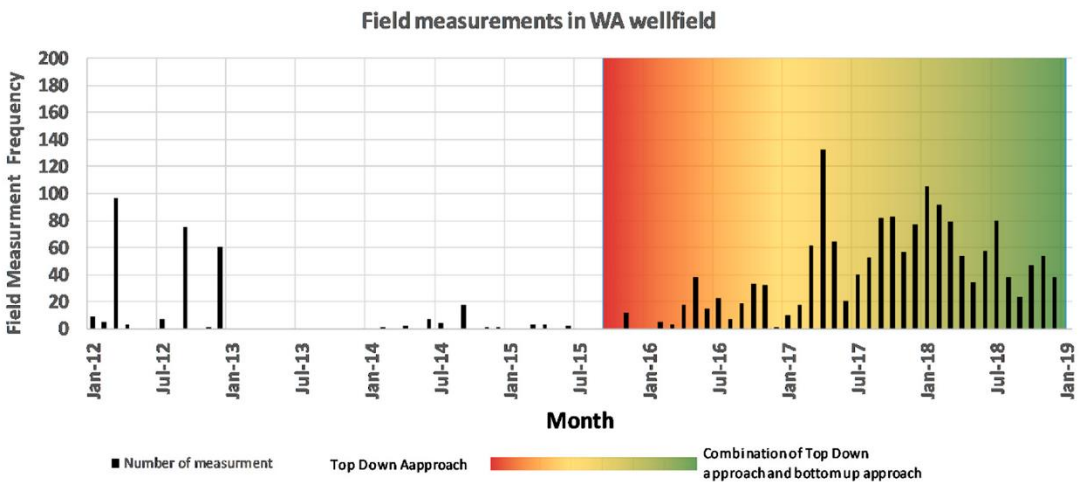

Figure 4.14. Number of monthly field measurements and the transaction period between top-down (red color) and the combination of top-down and bottom-up approaches (green color).

Figure 4.15 depicts a comparison of the annual measurement frequency of SWL, DWL and yield between 2012 and 2018. The number of DWL measurements increased from 43 measurements in 2012 to 266 and 230 in 2017 and 2018, respectively. Each of the monthly basis measurements, such as DWL and yield, were taken at least 12 times a year in 2017 and in 2018 for each well where measurement was possible. For instance, when a well is equipped with flow meter, the yield can be measured, but when the inch pipe is blocked, the water level cannot be measured. The SWL was measured each time the pump was stopped. Figure 4.16 shows the measurements of SWL, DWL and yield in WA-1 as an example of the improvement in field measurement after the beginning of 2017. Measuring DWL and yield for each well helped in identifying the needed maintenance. For instance, if the DWL increased in a well while the ampere reduced, it indicated that one of the riser pipes might be corroded and needed to be changed or welded. This is because part of the pumped water didn't reach the well head but it returned to the well, and the total volume of water that reached the well head decreased. SWL is important to identify the decline in water level on the wellfield scale and can, for example, be used later for choosing the location of a new well in the area.

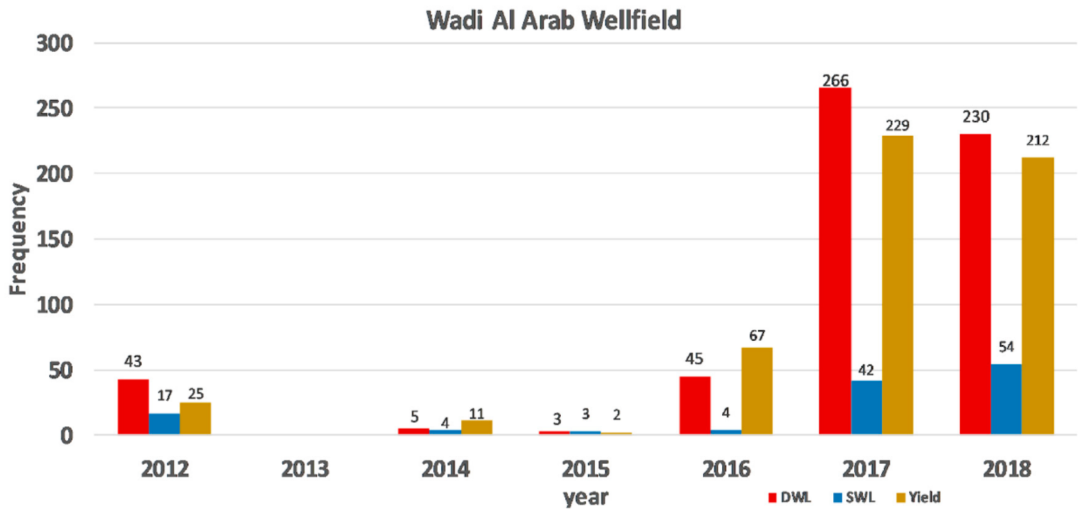

Figure 4.15. Number of field measurement frequency in Wadi Al Arab wellfield between the year 2012–2017 (2013 is missing).

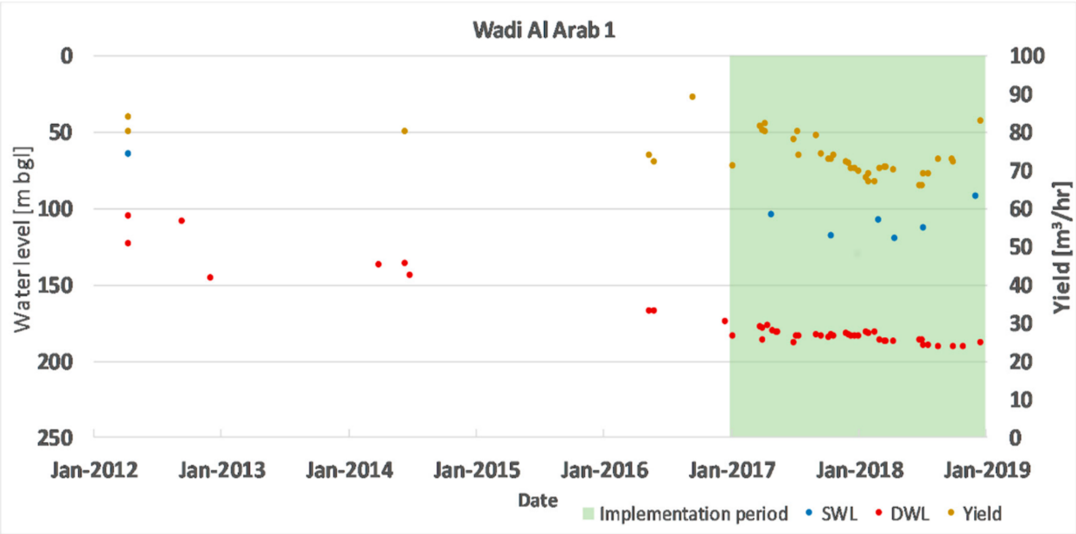

Figure 4.16. Improvement of field measurements (SWL, DWL and yield) before and during the implementation period of the tools, using WA-1 well as an example.

The maintenance intervals/periods mentioned in Table 4.4 represent only the maintenance when a well was stopped and the lifting devices were pulled out. The maintenance conducted for any equipment above the ground, electrical panel or flowmeter, was not considered in the mentioned table, and no data was found on it. The table also shows the number of days needed to maintain and restart operating the wells in the period of 2012–2015 (unplanned maintenance) and in 2017–2018 (planned maintenance). The year 2016 occurred during the transition period of unplanned to planned maintenance.

The wells were stopped 27 times in 2012, with a total period of 141 maintenance days. In only four instances was the maintenance finished during the same day. In comparison, the work was completed on the same day in 15 out of 19 times in 2017, and nine out of 10 times in 2018. WA-14 showed the longest maintenance period in 2012. It took 29 days to implement six maintenance intervals. The table also shows that maintenance times for well WA-3a increased in 2017 compared to 2012. However, the needed period to conduct maintenance for this well was 18 days in 2012 for one maintenance instance, while in 2017, maintenance was completed for one maintenance instance during the same day and the other one on the second day. All maintenance types conducted during the unplanned maintenance period were also conducted during the planned maintenance period, but with less maintenance intervals/period.

In general, the number of maintenance instances decreased when comparing the year 2012 with the years 2017 and 2018. Sometimes, the number of intervals increased in 2017 and 2018. For example, in 2015, WA-1 stopped one time for maintenance in 2015 for a period of five days and two times in 2018, however both maintenance work were done in the same day. The average length of maintenance intervals varies over the period 2012–2018. However, the years 2017 and 2018 recorded the lowest average intervals, where about 79% and 91% of the maintenance were done in the same day, respectively.

*Table 4.4. Maintenance period in 2012–2018. (Numbers indicate maintenance intervals: 1 indicates that the well was stopped, the well's lifting devices were pulled out, maintained/repaired/replaced, installed and re-operated in the same day, and the number 2 means that the well was re-operated in the second day and so on. X indicates that the well was not operated/drilled in that year, – indicates no records/no failures, ** indicates no failures.).*

Well name	2012	2013	2014	2015	2016	2017	2018
WA 1	2,6,14	3,2	19	5	3	**	1,1
WA 2	2,3	1	1	-	2,2	1	**
WA 3	-	-	1	-	**	**	**
WA 4	4,1	-	-	4,1,1	**	1	**
WA 5	2,1,1	3,1	-	-	**	1,1	1
WA 6	7,3,3	6	2	-	2	2,1	**
WA 8	2	-	2,2	2,32,1,1,1	1	1,1,1	1
WA 9	2,6	-	5,3	-	**	1	**
WA 10	8,2,2	2	-	1,1,2,2	**	1	**
WA 11	2,16	-	1,3	-	**	X	X
WA 12	-	5	-	-	**	1	**
WA 13	4	-	-	1	3	X	X
WA 3a	18	-	3	-	**	2,1	1
WA 14	4,6,1,4,13,2	1,2	1	2,2,1	**	1	1,2
WA 16	X	X	2,2	-	**	3	**
WA 15	X	X	X	3	**	4	1
WA 17	X	X	X	**	**	**	1
WA 11a	X	X	X	X	3	**	**
WA 18	X	X	X	X	**	1,1	1
WA 13a	X	X	X	X	X	**	**
Total well stop for maintenance [days]	**141**	**26**	**47**	**62**	**16**	**26**	**11**
Total maintenance intervals/Times	**27**	**10**	**13**	**18**	**7**	**19**	**10**
Average Days stopped for each maintenance	**5.2**	**2.6**	**3.6**	**3.4**	**2.3**	**1.3**	**1.1**

4.5 Discussion

4.5.1 Improvement to Previous Situation

Changing the existing management and operation system was challenging, and arguably, it could not have been achieved without building trust between the project team and technicians of YWC in the field. This can be observed in the period 2015–2017, in which the project started using only a top-down approach giving good results, but less effective than in the later period in which a bottom up approach was also adopted. Working with employees in their daily operation was an important step towards understanding the system and its limitations. Involving staff in discussions about possible solutions to the problems and establishing a joint committee that included multi-level stakeholders from WAJ, MWI and from the water utility were also influential steps in building a sense of ownership of the wellfield and ensuring a sustainable (i.e., long term) implementation of the plan. Notably, YWC field staff have continued collecting field measurements for the past year (2018) without the mandate of the project team.

It can be seen from the results that the number of recorded data increased in 2017 and 2018; around 260 readings were collected in 2012 and increased to 700 readings/year in 2017 and 2018. At the same time, the total number of well maintenance intervals decreased. This indicates that the implemented monitoring system helped in preventing unforeseen failures in the wellfield which would require several days to be solved. Besides the increased number of measurements in 2017 and 2018, the use of ODST assisted the committee in predicting failures and implementing systematic maintenance planning. The total needed period to conduct maintenance for the lifting devices (motor, pump or riser pipe) in the wellfield decreased from 141 days in 2012 (14 wells) to 27 and eight days for the years 2017 (18 wells) and 2018 (18 wells), respectively. Wells operate 24/7 at their highest capacity to cover the needed demand. Thus, the longer a well is stopped, the more problems occur, especially in summer when the water demand is high. It is important to minimize the period during which a well is stopped for maintenance, and maintenance should preferably be done in winter when the demand is relatively low.

The updated monitoring procedure helped define which well consumes more energy than others. Consequently, the wells with the highest energy consumption would be considered in future operational decision processes (e.g., to be stopped, replaced or abandoned). The main factor that affects the variation of the pumping cost between wells within the wellfield was not identified in this study. However, the age of the well, pumping lift, well design, well location and selected pump specifications play a role in the observed variation in pumping costs between wells.

4.5.2 Strengths and Weaknesses

The suggested monitoring approach depends greatly on the available human resources and the way the staff uses the tools. The technology was purposefully adapted to the local conditions and human capacity (i.e., choice of the software used to develop the ODST was limited by the knowledge of the well field managers about other operating systems) and it can be modified easily by the end-users. However, an in-depth understanding of the entire wellfield management system is needed to effectively apply the tool, so that it would not be easy to replace old trained employees with new untrained employees. In order to successfully apply such management tools in a sustainable way, regular trainings and knowledge transfer are therefore a must. The training should cover the following aspects: (i) hydrogeology of the area, (ii) the impact of good and regular measurements on wellfield management, (iii) how to use the ODST and WFIS and (iv) pump selection course. Otherwise, challenges would arise for new staff and result in higher maintenance and operational costs and longer maintenance intervals, which would ultimately lower the water supply security. This traditional weakness can be overcome by providing specific training courses for related employees, which address critical issues like the monitoring procedure. Involving all staff related to operation and maintenance of a wellfield in the Wellfield Management Committee ensured that the wellfield management approach became an integrated part of water supply management at YWC.

The low implementation costs and simplicity are the main strengths of this approach. The new monitoring system needs the following simple equipment: (a) dip meter for water levels, (b) electromagnetic flow meter to measure the yield and validate the reading of the fixed flowmeter, (c) clamp meter to measure voltage and current and (d) digital insulation tester to measure the insulation resistance of pump motor. This equipment is rather standard and generally available also in low-income countries, where personnel costs are not very high. Besides the low implementation costs, simple tools were generated to serve as early warning systems for wells needing maintenance. The use of this tool does not require any previous experience and only minimal training—in our case only two training sessions.

4.5.3 Application to Other Sites

The combination of the two approaches (top-down and bottom-up) can be implemented in most of the projects where data scarcity is a challenge. Additionally, the tool can be used by water utilities or by any project aiming to improve wellfield management, especially in arid areas and areas with over-abstraction, where the well conditions are constantly changing (e.g., rapid water level decline). The tool is now being tested in two other large wellfields in Jordan east of Mafraq city: Aqib and Corridor wellfields. It should be noted that multi-level stakeholder involvement is a slow process, and successful outcomes require adequate time and field presence. Therefore, for the application of the proposed methodology in other sites, enough time should be allocated for the stakeholder engagement and the training of the involved staff. In fact, in our view, the application of the suggested technical improvements, such as a finer resolution monitoring, is not effective without the necessary stakeholder engagement that can guarantee a sustainable development of the wellfield management plan. The implementation of the wellfield management tool does not solve the issue of water scarcity and over-abstraction, but still can contribute in saving energy and funds, which can be allocated for the development of alternative water supply sources, such as desalination and wastewater reuse.

4.6 Conclusions

In Jordan, groundwater resources are heavily over abstracted and cannot be managed in a sustainable manner with state-of-the-art technology and the actual water demand. It is exceptionally difficult to provide enough drinking water to the population and, at the same time, irrigate fields considering the future challenges of climate change and demographic trends. Nonetheless, improved wellfield management may enhance the lifetime of the aquifer and production wells and reduce the cost of water abstraction.

Before the implementation of the proposed methodology, the available data for WA wells were not sufficient to manage the wellfield in a way that would result in an efficient budget allocation; therefore, additional data collection was an important step to establish the improved Wellfield Management Plan. Missing descriptive metadata was a challenge in processing poor documented data and resulted in the loss of some old data. Currently, descriptive metadata have been added for the recorded data, which will help researchers in the future to acquire well documented data about the wellfields. In this regard, the number of recorded field measurements increased from 260 in 2012 to 699 and 703 measurements during 2017 and 2018, respectively.

In this work we show that it is not necessary to have highly advanced technology to change the operation and maintenance of a water supply system. The implementation of simple tools such as ODST and staff training courses, and the provision of needed equipment to facilitate Wellfield Management can make a substantial difference with relatively low costs. The new monitoring procedure, together with the use of the ODST, reduced the number of failures and the maintenance duration. Only 15% of the maintenance times were conducted in the same day in 2012, while the records showed that this percentage increased to 79% in 2017 and 91% in 2018. Additionally, this new system helped to identify variations in energy consumption between wells within the same wellfields, some of them showed a low energy consumption (e.g., WA-8 with a consumption of 0.52 kWh/m^3), while others showed a high energy consumption (e.g., WA-1 with a consumption of 1.11 kWh/m^3). This means that energy consumption of individual wells would be now considered in the decision making process for wellfield management. This is especially important as the overall electricity consumption has grown from 2012 to 2018. Because of the increase in energy costs, the water utility should optimize the use of alternative on-site energy production, like solar energy, to further lower the extraction costs.

Finally, the amount of collected data and the reduction of the maintenance period could not have been achieved without the combination of the strengths of top-down and bottom-up approaches. If a decision support system like the one created for Wadi Arab is to be used in another wellfield, it is necessary to start with investments in human capacity building and multi-level stakeholder participation.

Chapter 5

Groundwater Wellfield Management and Digitalization

Alqadi et al. (2022)[1]

Abstract

Most studies in the field of groundwater management focus on regional management of groundwater resources, and only a few focus on monitoring individual wells in terms of improving the management system and applying effective wellfield management plans. The lack of reliable monitoring systems hinders the proper management, planning, maintenance, and operation of wells, which consequently increases the management and operational costs and could add additional pressure on the water resource. Several tools have been developed to manage groundwater resources; however, there is not a specific software that comprehensively tackles all groundwater management aspects on well and wellfield levels. This research aims to develop a user-friendly **De**cision Support Software and Database for Wellfield **Ma**nagement (DeMa) that aids the decision making process surrounding the management and operation of the wells, which will be a continuation of the work conducted in Alqadi et al., (2019). The software is divided into four modules (i) Database Management Tool (DbMT) (ii) Observation Based tool (OBT) to visualize the database in graphs, (iii) Research Based tool (RBT), which is a user-friendly tool to help [2]wellfield managers to apply novel research methodologies to the user study area, and (v) Documents Management Tool (DMT) to manage all documents related to the wells.

[1] **Alqadi, M**.; Aldwairi, A.; Margane, A.; Brueckner, F.; Schneider, M. Development of a user-friendly tool for groundwater wellfields management. In Proceedings of the 39th IAHR World Congress, Granada, Spain, 19 – 24 June 2022; International Association for Hydro-Environment Engineering and Research: Granada, Spain, 2022; p. 10.

The software is conceived in a modular way, such that it can be enriched by plugging-in additional tools and options in subsequent versions. Future developments include water quality analysis and well rehabilitation support with the aim of creating an all-encompassing tool that meets the wellfield manager needs.

5.1 Introduction

Globally, groundwater contributes to around 50% of the drinking water demand (Smith, M., Cross, K., Paden, M. and Laban, 2016), and to more than 40% of the consumed water for agriculture purposes (OECD, 2015; Siebert et al., 2010), furthermore, groundwater is a vital resource to maintain balance of groundwater ecosystem services (Bradley et al., 2014; Groundwater Ecosystem Services: A Review, 2015). The increased water demand, due to the raised population (Chen et al. 2018; Godfray et al. 2010), and climate change impacts (Dehghani et al., 2022; Taylor et al., 2012) leads to groundwater stress (Herbert & Döll, 2019), which was estimated to impact around 37% of the global population (Herbert & Döll, 2019). Therefore, while limited groundwater resources should be properly managed, the scarcity of groundwater data minimizes the ability to adequately implement effective groundwater management policies and strategies (Montecino et al., 2016). On the other hand, enhanced data monitoring systems for groundwater wells decreases the number of failures, and consequently the maintenance cost of wells (Alqadi et al., 2019). Hence, it is recommended to improve the monitoring systems and increase the data availability, which would result in well informed and data-driven management decisions (Filali-Meknassi et al., 2018; Kumpel et al., 2020).

Many existing tools and software aim to improve and assist groundwater management (Nesetril & Sembera, 2014). Some software are used to store and visualize hydrogeological information and data (*Borehole Data Management*, n.d.; *Borehole Management - EDAMS*, n.d.; ESDAT, n.d.; Ribeka, 2018; RockWare, 2020). Some others focus on the computation of the radius of influence of the wells (Day-Lewis et al., 2011; Duffield, 2007) and support water managers in analyzing aquifer-test results (Barlow et al., 2015; Barlow & Moench, 2011; Halford, K.J. and Kunianksy, 2002) . More complex software also include the possibility of using a database (Rossetto et al., 2015) and the coupling of groundwater flow and transport models (McDonald & Harbaugh, 1988) to the database .

To the best of the authors' knowledge, none of the previously mentioned tools were envisioned to combine hydrological field measurements to well maintenance, operation, design, installation, and costs data. Thus, accurate management decisions based on the relationship between all these observations might be lacking. In Jordan, for instance, the absence of a comprehensive well-field management software yields in the data being scattered in different databases even within the same water institution; therefore, it restrains implementing an integrated wellfield management approach (Alqadi et al., 2019). Collecting and incorporating data and information from different sources is a fundamental step for Integrated Water Resources Management (IWRM), which is an essential principle for sustainable water resource management (Filali-Meknassi et al., 2018; Van Hofwegen & Jaspers, 2020). Moreover, the connection between research and practice in the water sector still needs to be enhanced (Alqadi et al., 2021). On top of this, lack of programming and modeling skills of water managers and practitioners impede the application of novel water management methodologies. Therefore, there is a need to provide water managers with user-friendly products to facilitate the application of cutting-edge science and technology at all levels. (Bittner et al., 2020; De Filippis et al., 2017)

The research aims to create a user-friendly software that connects a relational database structure with visualization tools to support data-driven decisions in the wellfield. The software will be based on set of data that can impact the operational decisions and maintenance planning in a wellfield. Furthermore, the research aim is to offer a software that include novel methodologies and numerical modules provided in recent research to be straightforwardly applied in any study area. The software will also include management tool documentation to organize all the files related to the wellfield.

5.2 Methodology

We conducted thorough research to identify existing software and tools that aim to manage groundwater wells and wellfields; then, we analyzed the features provided by these tools and compared it with the features that we aim to offer in the pre-released version of **De**cision Support Software and Database for Wellfield **Ma**nagement (DeMa-v0.10). We selected some essential features for operating and managing groundwater wells (e.g., field measurement graphs, hydrological unit graphs, database) in existing tools and included them in the general structure of the software. Hence, we identified the unique features that are not available in other software and tools and integrated them into the DeMa software (e.g., well failures record and installation specifications). After having a comprehensive overview of the components of the DeMa software, a conceptual design of a database that serves the software's purpose was built. The conceptual design included the necessary data, relationships, and constraints of data elements. Following building the database design, the first step was creating the database using Structured Query Language (SQL) with the SQLite3 Python library (Hipp, 2020). The database structure was tested to ensure its consistency and that the stored data is organized in tables properly.

After the database validation process, by using PyQt5 library, we developed the modules and front-end of the software, including: (i) Database Management Tool (DbMT), to allow the user to update, delete, insert and run database backup, (ii) Observation Based Tool (OBT), where the user can visualize graphically the data and the relation between different observations, (iii) Research Based Tool (RBT) where the user can apply and include novel research methodologies, and (v) Documents Management Tool (DMT), where the user can manage the related well and wellfield documents.

The DbMT and OBT are fully connected to the database; all the provided functions depend on the stored data in the database. The RBT and DMT, on the contrary, only partially depend on the database. For instance, if a method included in RBT requires data that are not included in the database, which can occur due to lack of measurements of major uncertainties, the user will be able to enter them manually only for that specific application. Similarly, through DMT, the user can associate the documents with the existing data in the database (e.g., invoices number and well names). Furthermore, it is also possible to organize the files without linking them to a database directly (e.g., standard protection zone assessment sheet). Figure 5.1 represents the main python libraries used to build the backend of the four tools in the DeMa software.

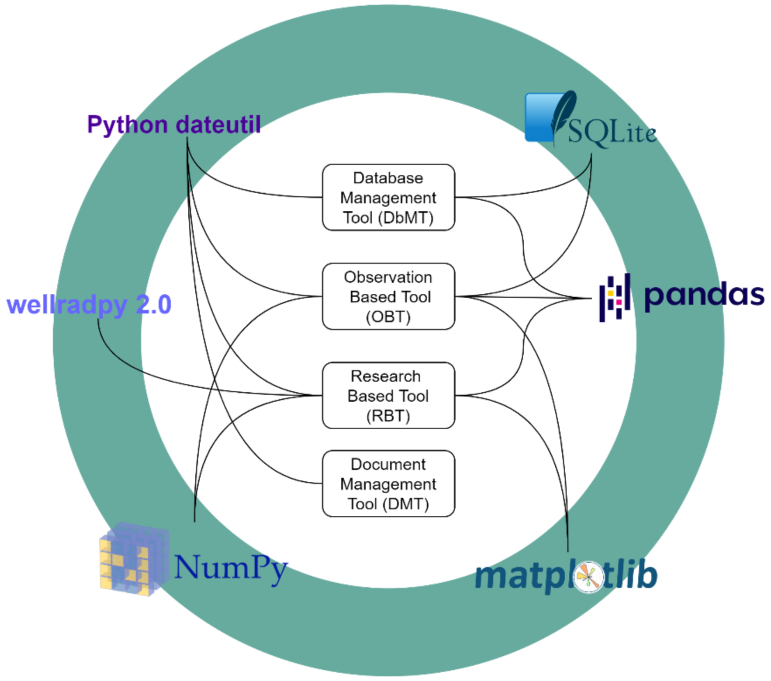

Figure 5.1: The main Python libraries (in green circle) used in development of the wellfield management software

5.3 Results

The DeMa software enables the user to store all the related data of the wellfield into a database. When the DeMa software is installed in a local computer (Figure 5.2), a database containing 34 interconnected tables about the lithology, energy consumption, maintenance costs, installation specifications, field measurements, and well design is created, and it is connected to the previously mentioned tools through a set of 53 Python files. The scripts are structured as follows:

- 42 files for Database Management Tool (DbMT)
- Four files for Observation Based Tool (OBT)
- Three files for Documents Management Tool (DMT)
- Two files for Research Based Tool (RBT)
- Two base constructor files

Furthermore, the user can generate demo data sets in the database to review and test the DeMa software functionality and features. A tutorial document is also provided with the software, where the user can practice the four tools. Table 5.1 presents a list of examples of applications of the DeMa tools that can support wellfield managers in their operational works.

5.3.1 Database Management Tool (DbMT)

As mentioned in the methodology section, the database is based on a relational data model that connects all 34 tables. The DbMT is a user-friendly tool to manage the database, where the user can upload the data as individual entries or import data from CSV or MS Excel files. The DbMT is designed in a way to keep the consistency of data. For instance, the standard values of specific parameters (e.g., cable diameter, casing specifications, riser pipe diameter, and material) are integrated into the software and, hence, the user can select them from the option list. In addition, this would help to standardize the entries and avoid syntaxis or spelling mistakes. Furthermore, if a user wants to add an item to the list, this option is also provided.

DbMT also provides the option to filter the data, search keywords, and modify the tables (Figure 5.3). An automatic weekly backup of the database is included as default. Also, a manual backup option is available. The database can be transferred from one computer to another. Furthermore, DbMT allows the user to view the changes that were done in the database by exporting a database auditing log. The latter provides a register of the modifications, including username and dates.

Table 5.1. Practical implications of the tools in DeMa software

Tool	**Objective**	**provided options (examples)**	**Practical implications for users**
DbMT	To store and manage all the groundwater wells related data in one environment	Insert and Import data	Guarantee the consistency of the inserted data.
		View, Update and Delete data	Efficient access to the data to easily find, view, change, or remove data for further analysis
		Export data	Provide a copy of the data in CSV or MS excel format to implement further analyses that DeMa might not determine.
		Database backup	Ensure long-term storage of the data and allow transferability of the data to different systems.
OBT	To visualize all the stored data	Abstraction vs. Electricity consumption graph	Define the value of pumped water in terms of energy

		Maintenance record vs. cost of maintenance graph	Define which factor contribute indirectly the most/least to the water price
		Consumed energy vs. needed energy graph	Represent the efficiency of the well over time
		Maintenance records vs. SWL, DWL, and yield records graph	Give an overview of whether the implemented maintenance impacted the DWL and yield or not.
		Current status of a well	Present an overview of the status of the well, in terms of well design, latest installation, and recorded measurements. This option helps the manager to decide about the well, such as riser pipe extending, abstraction reduction, well deepening.
		Failure vs Field measurement graphs	Define the relationship between frequent failure and field measurement. Consequently, define the possible reason behind the failure. (e.g., raise in water level, indicate there might be a hole in the riser pipe)
		Report	Produce a monthly and annual report for the wellfield and the individual wells.
		Visualization of time series	Monitor how the situation changes over time for a specific variable and decide if action is needed (e.g., increase the frequency of collected data of certain variable)
RBT*	To facilitate the recent research to be applied in the study area. By introducing recent research in user-friendly GUI	The radius of influence (RoI)	Identify protection area of a well, interference between pumping wells, siting well, improve the design of the wellfield.
DMT	To store and Organize all related documents	Upload document	Upload document to the tool and link it with the wells and/or wellfield (e.g., guideline, project report, thesis, invoices, contract, internal memo, completion report, scientific article) to enhance information management in the wellfield

		Find document	Easy access to metadata related to a well
		Template	Simple and fast access to all the standard templates the water company use (e.g., inspection sheets, Bill of Quantity of specific work, agreement forms, pumping test for)

* In this version, RBT includes only (Bresciani et al., 2020). More research is to be integrated into RBT

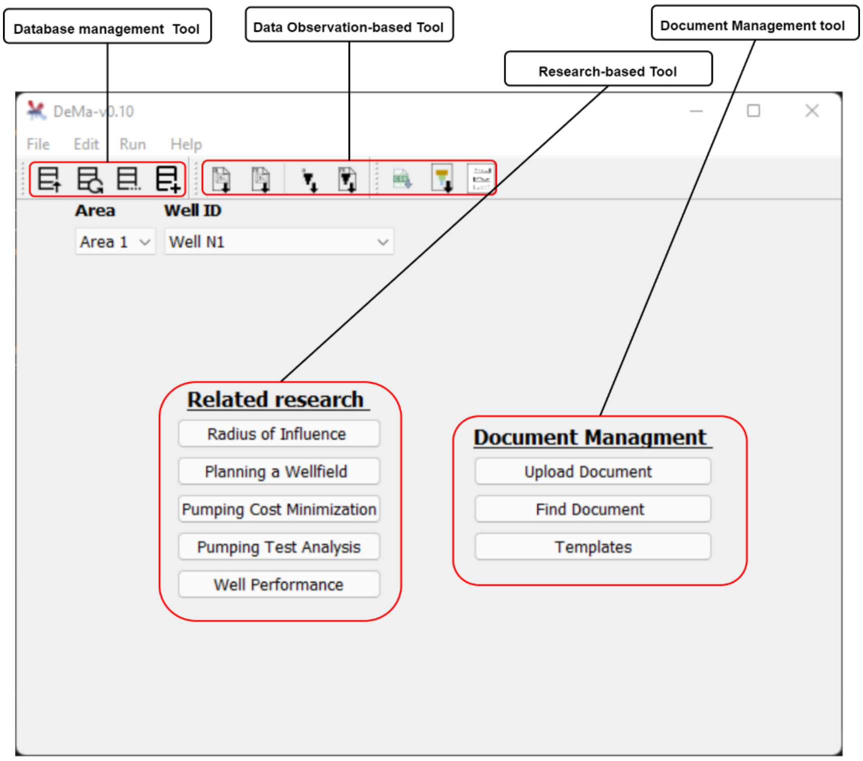

Figure 5.2: Overview of the Wellfield Management software

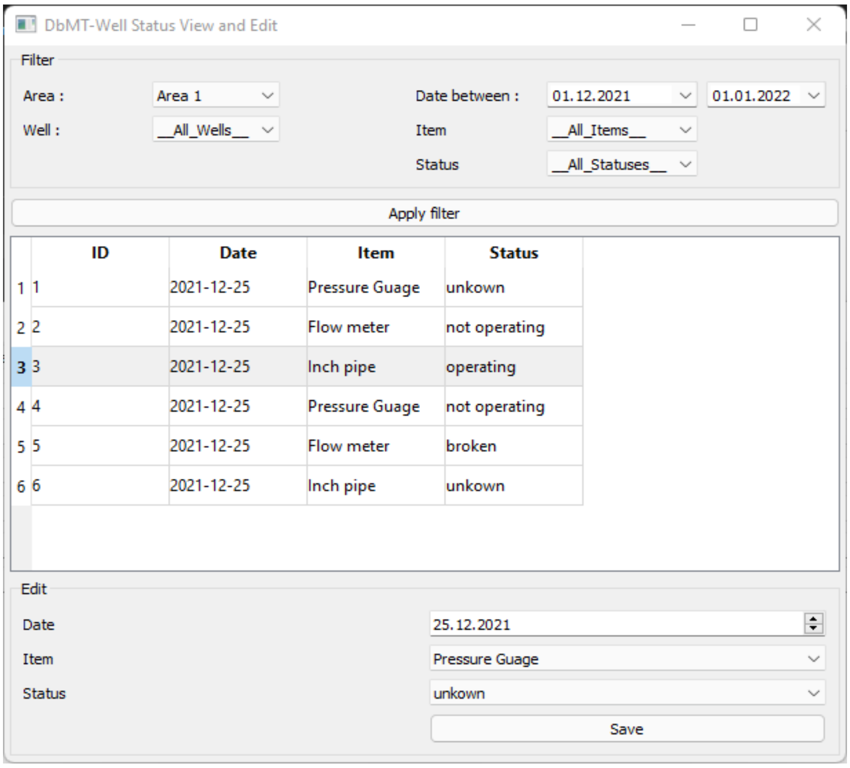

Figure 5.3: Example of the view and edit option in the DbMT, device status of the wells

5.3.2 Observation Based Tool (OBT)

OBT provides a visualization of all the observations stored in the database. This tool does not only visualize the raw data of the database but also provides interrelation visualization of different temporal observations that would help water managers decide or plan certain operations for wells (e.g., changing pump, extending riser pipe, welding riser pipe).

Besides the temporal data that shows the relationship between different measurements, the user also is able to compare different wells; for example, wells that have different consumption rates of energy per cubic meter of extracted water. This output can help the user in defining the factors that might influence the energy consumption of the selected wells, and consequently take action accordingly. Figure 5.4a depicts how the OBT presents the comparison of these different factors. Most of the listed factors in the table are imported directly from the database (e.g. DWL, pump specs, pump brand, motor power, the monthly abstraction, pressure, monthly operating hours, well depth, elevation difference, casing diameter, voltage, amperage). In contrast, pump efficiency and the cost of energy per cubic meter are calculated via the equations [5.1] and [5.2], respectively. So that,

$$p = \frac{Q * H}{367 * N} \text{ ,} \tag{5.1}$$

where is the pump efficiency, is the abstraction rate [m^3/h], is the total head [m], and is the pump shaft power. This equation can also be used to evaluate the current consumption of abstraction and predict a well's operating cost at a specified pump efficiency.

$$C = \frac{E(t)}{Qt} \text{ ,} \tag{5.2}$$

where *C* is the cost [Kwh/m^3], is the monthly energy consumption [kwh], and is the monthly abstraction of a well [m^3].

If a frequent failure occurs in a well, the wellfield manager needs a comprehensive overview of the status of the well in terms of the borehole's design, installations, lithological formations, and latest measurements. Such overview is accessible throughout the OBT (Figure 5.4b). Furthermore, the OBT tool enables wellfield managers to produce monthly or yearly reports associated with wellfields and individual wells. The OBT tool interface includes an export option for the produced report where the SWL, DWL, yield measurements, failures of the wells, total abstraction, and electricity consumptions are included representing an overview of what has been recorded and done in the wells/wellfield over a given timeframe.

5.3.3 Research-Based Tool (RBT)

Several research studies are available and produced every year about managing groundwater wells and wellfield (e.g., Chang et al., 2021; Katsifarakis et al., 2018; Nagkoulis & Katsifarakis, 2020). However, applying these methodologies often requires previous knowledge of mathematics, numerical modeling, and/or specific programming skills that are not always present in a wellfield manager. In order to make the best use out of the published articles, the tool offers a user-friendly interface that enables the users to apply the results of recent research focusing on improved wellfield management without a need for previous knowledge in programming. The RBT is structured in a modular way, such that more and more related research can be added over time. As an example, we incorporated the work of (Bresciani et al., 2020) in this tool. This article provides nine different equations to calculate the radius of influence (RoI) for a confined aquifer and a Python Library to solve the equations. The library was integrated as a tool module, and we created the corresponding user interface. Also, a bridge for the proper selection of the method is included. In practice, the user is required to enter the purpose for RoI calculation (e.g., impact assessment study (flow rate criterion or absolute drawdown criterion), design of a multiple well system, or design of a well interference test). Secondly, the tool identifies the suitable equation from the nine options and calculates the RoI.

Moreover, we provided an option to visualize the RoI of a well over time with different values of hydraulic parameters, such as discharge rates and transmissivity. The user must define the RoI parameters values and enter the reason for calculating RoI. As an option to obtain the RoI visualization graph, the user can define the maximum value for RoI and then select the appropriate pumping rate accordingly from the graph (Figure 5.5)

(a)

Factors	Well 1	Well 2	Well 3
DWL [m bgl]	100	120	150
Pump Specs (Q/H)	100/200	160/200	150/200
Pump brand	BRAND1	BRAND2	BRAND3
Motor power [kw]	75	70	72
Monthly operating hours [hr]	720	720	720
Monthly abstraction [m^3]	52560	77040	88560
Pressure [bar]	10	2	2
Total head [m]	200	140	150
Well depth [m bgl]	500	350	430
Pump depth [m bgl]	140	150	190
PS – Well head [m]	100	20	0
Well head Elevation [m asl]	715	720	726
Riser-pipe diameter [inch]	6	6	6
Casing diameter [inch]	10.25	10.25	10.25
Amperage [amp]	115	100	120
Electricity consumption monthly [kwh]	45892	39906	47888
Voltage [V]	400	400	400
Calculated eff.	62%	74%	76%
Cost [Kwh/m^3]	0.87	0.52	0.54

(b)

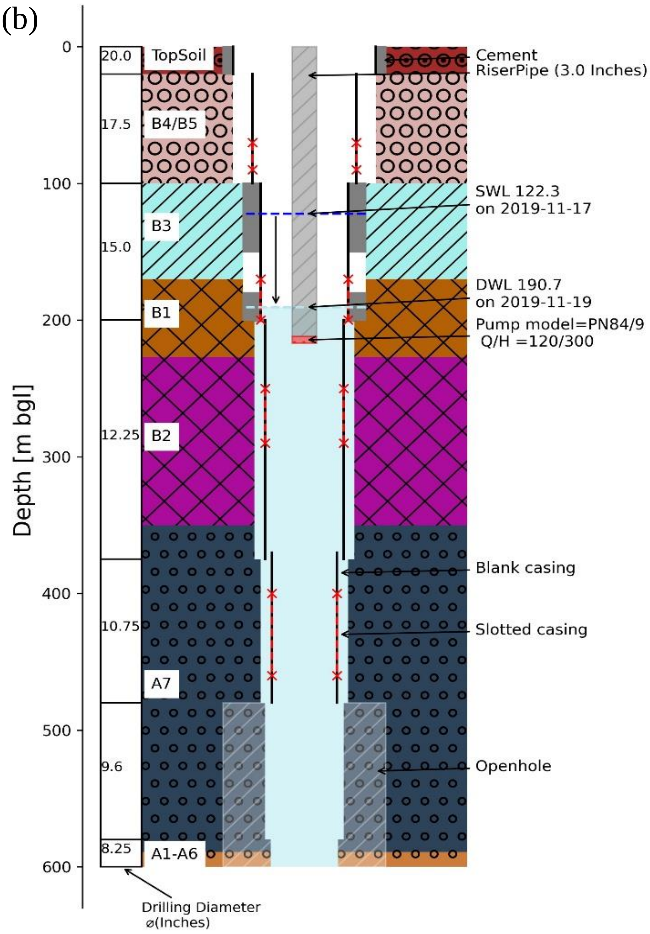

Figure 5.4: Example application of the OBT (a) comparison of 3 different wells with 3 values of electricity consumption per cubic meter, (b) overview of the status of a well.

5.3.4 Documents Management Tool (DMT)

The DMT is the fourth tool included in the DeMa software. Its purpose is to organize all the documents related to a specific well or a wellfield. The user can store and categorize the documents based on the well/wellfield and the document type (e.g., project report, thesis, completion report, article, guideline, minutes of meeting, internal memo, invoice, contract). However, the document type list can be updated by the user. The DMT tool will enable the user to search and find the required document when it is needed via the "Find Document" window. The user can also search keywords used when the documents are uploaded. To have a consistency of the regularly used documents and sheets, DMT also provides a templates window where all the templates used by the water company are listed. (Figure 5.6)

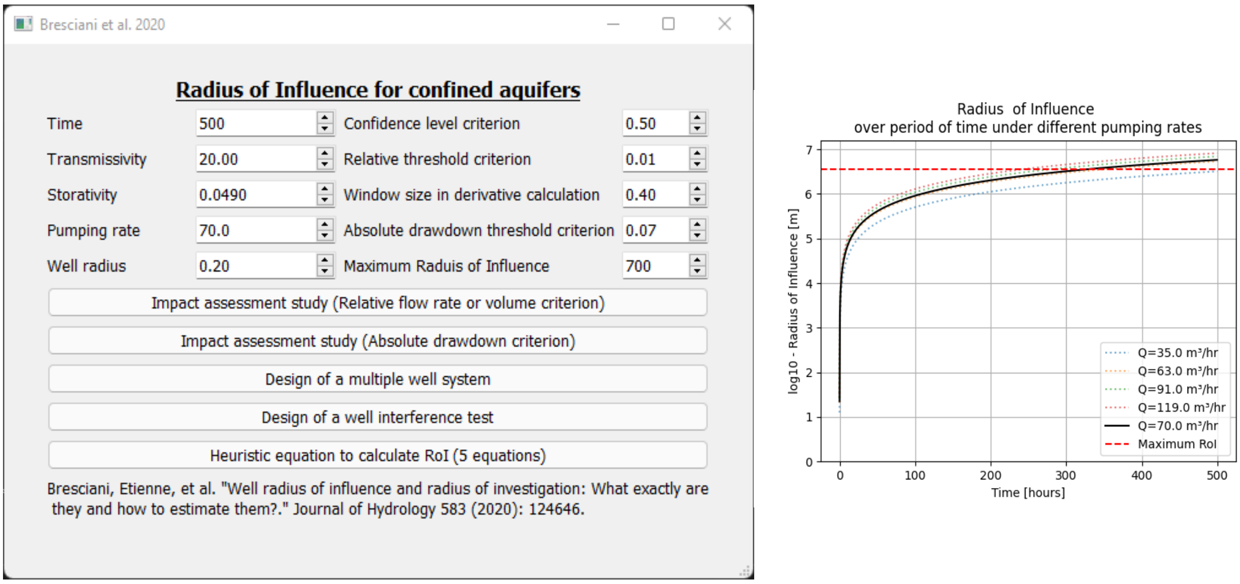

Figure 5.5: (a) GUI for the computation of the RoI (based on Bresciani et al., 2020) as part of the Research Based Tool (RBT), and (b) diagram of the RoI for different discharge rates over time with the maximum desirable RoI to illustrate the presentation of the results in the tool.

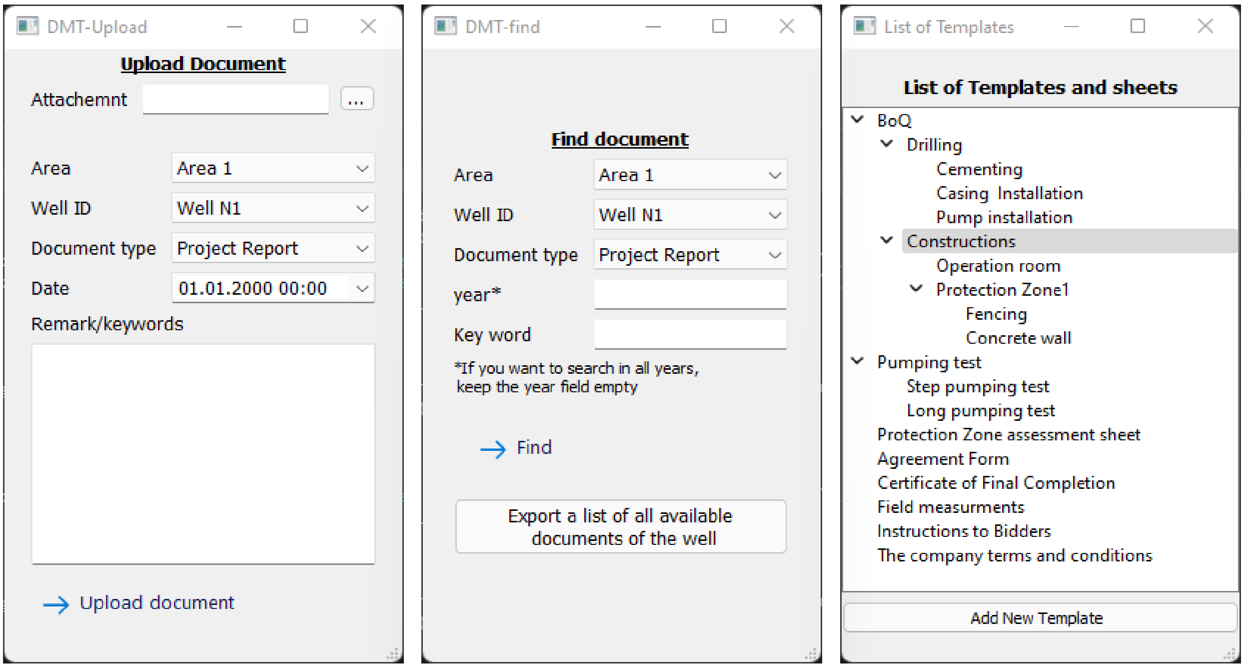

Figure 5.6: An overview of what is included in the Documents Management Tool (DMT)

5.4 Conclusions

DeMa is a pre-release of a decision support software and database for wellfield management. The software assists water companies in managing groundwater wellfields by supporting wells' planning, operation, and maintenance. DeMa is a set of four modules linked to one database managed by the Database Management Tool DbTM. Through the Observation Based Tool (OBT), managers can visualize and compare different measurements within the same well or compare different observations of different wells (e.g., water level, electricity costs, and pump efficiency) to assist them in implementing data-driven decisions. Furthermore, DeMa software introduces the Research Based tool (RBT); this tool connects research with practice by introducing a graphical user interface for recent research that provides new methods for managing groundwater wells. On top of this, the tool offers different methods to calculate parameters, such as the RoI of a well, to offer alternatives based on the reason behind and the available data. The idea behind the RBT is to be continuously fed with new research findings, consequently supporting making evidence-based decisions in a wellfield. The last tool in this software provides a document management tool (DMT) to support water companies in organizing all the documents related to individual wells or a wellfield, such as invoices, reports, articles, guidelines, and contracts. It also organizes the standard sheets and forms of a water company, facilitating easy access for the documents when needed by any user.

This version will be tested in real-world data to detect functional errors and performance and usability defect bugs. Moreover, the water quality data has not been included in the database yet; however, a tool dealing with water quality issues will be integrated into the upcoming versions of the software will include components for water quality evaluations and well rehabilitation support.

Chapter 6

Application of DeMa on the Wadi Al Arab wellfield

Alqadi et al. (2023)[1]

Abstract

This article aims to present the structure and the workflow of a new software DeMa (Decision Support Software and Database for Wellfield Management), to support wellfield managers in their decision-making processes. There is a recognized need to improve the management of groundwater resources, especially with the increased demand for fresh water in arid and semi-arid regions. DeMa differentiates from other available software, by combining data collected for the well's maintenance, operation, design, installations, and cost data with the collected hydrological field measurements. Additionally, DeMa links the different information and provides an effective graphical representation of the data. We applied the software to the Wadi Al Arab wellfield case study to support wellfield managers in the decision-making process of three typical problems: identification of missing data and information concerning the wells, identification of maintenance needs for a well, and identification of a suitable location for a new well. In the application to the Wadi Al Arab wellfield (Jordan), we collected data and documents from the Yarmouk Water Company (YWC), the Jordan Ministry of Water and Irrigation (MWI), and private drilling companies. The software application highlights the beneficial effects of the digitalization of water resources management by improving data availability and management and achieving data and research-based decisions on the wellfield.

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[1] Alqadi, M., Al Dwairi, A., Merchán-Rivera, P., & Chiogna, G. (2023). Presentation of DeMa (Decision Support Software and Database for Wellfield Management) and Its Application for the Wadi Al Arab Wellfield. Water, 15(2), 331.

6.1 Introduction

As the global population continues to rise, so does the demand for water (D. Butler & Memon, 2005; Schutte & Pretorius, 1997; Zubaidi et al., 2020). According to a recent report published by the UNESCO (UN-Water and UNESCO, 2022), the amount of abstracted fresh groundwater globally exceeds the mean annual renewable recharge by 10.5%. This abstraction rate is forecasted to increase further due to the increased water demand. The global population's continuous growth will strain the already limited water resources (Jahan et al., 2019; Polemio & Voudouris, 2022), especially the groundwater resources, which represent 50% of global drinking water (UN-Water and UNESCO, 2022). Hence, the global water crises slow down the movement of many countries towards sustainable water management practices (Koop et al., 2022), especially in semi-arid regions, such as Jordan, where water scarcity is a leading sustainability challenge (Al-Karablieh & Salman, 2016; Priyan, 2021; Salameh et al., 2018).

Therefore, it is essential to protect the water resource by applying improved groundwater management (Falkenmark & Widstrand, 1992; Mirdashtvan et al., 2021), preserving the quality of groundwater resources (Ahmed, 2021; Nzama et al., 2021), and by developing more sustainable practices than those currently adopted (Tang & Adesina, 2022; C. Zheng & Guo, 2022). Achieving improved groundwater management can be achieved through a better understanding of the groundwater system (Liu et al., 2021; Pollicino et al., 2021; Sarkar et al., 2021), improved groundwater information and data management (P. Fitch et al., 2016; Pierce et al., 2016; Rossetto et al., 2010), as well as upgraded modeling techniques and software (Aderemi et al., 2021; Avesani et al., 2021; Pierce et al., 2016). In this work, we focus on improving groundwater information and data management by presenting the software DeMa (Decision Support Software and Database for Wellfield Management).

Digitalization and modeling techniques reduce costs by automating operational procedures and maintenance practices in different sectors (Q. Lu et al., 2020; Montero & Finger, 2021; Schmidt & Wang, 2016; C. Wu et al., 2020). Maintenance costs could reach 60% of the total cost of production (Zonta et al., 2020), which, in the case of water production, can be reflected in the price of water (Mora et al., 2013; Singh et al., 2020). When no preventive maintenance policy is implemented, the failure of a pumping system might result in stopping the water being pumped from the well, or pumping might continue, but with a reduction in energy efficiency, the so-called "economic failure" (Beebe, 2004). Moreover, implementing preventive maintenance would reduce the frequency of failures and time of maintenance of groundwater wells (Alqadi et al., 2019). Predictive maintenance has become one of the main topics in Industry 4.0 for the above-mentioned reasons (Cao et al., 2022; Drakaki et al., 2021, 2022; Müller-Czygan et al., 2021; Nordal & El-Thalji, 2020; Sajid et al., 2021; Teoh et al., 2021). One of the goals of DeMa is to support water managers in this context.

Globally, the anticipation of a fourth industrial revolution can be witnessed through the improved digital technologies and increased volume of collected data across various domains (e.g., climate and natural sciences, finance, healthcare) (Sarker, 2021; Xu et al., 2018). Furthermore, utilizing the collected data (i.e., big data) can forge new paths for monitoring the environment (Chen et al., 2022; Sun & Scanlon, 2019) and ensuring sustainable development in the years to come (Gijzen, 2013; Seele & Lock, 2017). In recent years, water research and industry have been utilizing big data to support groundwater management (Gaffoor et al., 2020), map groundwater potential (S. Lee et al., 2019; Martínez-Santos & Renard, 2020), enhance water system models (Shafiee et al., 2018), increase water treatment systems efficiency (Ghernaout et al., 2018), and the accuracy of estimating water quality (Chen et al., 2022). However, the collected data needs to be processed appropriately to generate knowledge, creating a need for sophisticated data management tools and software that can efficiently manage and extract information from the data (Naeem et al., 2022). One of the problems faced when dealing with big data is data complexity and uncertainty (W. Wu, 2022). Nevertheless, data management tools can effectively utilize big data to make informed decisions (Abd Rahman et al., 2021; Rossi & Hirama, 2015; Shamim et al., 2019). DeMa addresses this problem by providing interactive graphics that allow users to explore the dataset and link different sources of information to enhance the knowledge of wellfield managers about their system.

Existing software and tools focusing on wellfield management allow the user to separately store, visualize, and analyze field measurement data (esdat.net, n.d.), subsurface information (RockWare, 2020), hydrological and water quality data (*Borehole Management - EDAMS*, n.d.; Ribeka, 2018), and aquifer testing data (Barlow & Moench, 2011; Halford, K.J. and Kunianksy, 2002). Other tools focus on supporting decision making in many water-related applications, such as water quality management (Machiwal et al., 2018; Selvaraj et al., 2020; Xin et al., 2021), water resources management (Hecht et al., 2021; Phan et al., 2019; Roozbahani et al., 2018; Rossetto et al., 2018), water supply and demand management (H. Wang et al., 2020; Yao et al., 2021), and reservoir operation management (Chelangat & Abebe, 2021; Huang et al., 2022). However, there is still a practical gap between the provided solutions and its applicability in the field (Li et al., 2020). Hence, DeMa aims to contribute to filling the previously mentioned practical gap.

The novelty of DeMa software stems from its ability to combine in one single environment multiple options that are offered from the previously mentioned software; for example, within DeMa, the user will be able to combine hydrological field measurements with well maintenance, operation, design, installation, and cost data to make data-driven decisions. Additionally, the research-based tool (RBT) offers the user the option to benefit from scientific research studies that focus on managing groundwater wells and wellfields. This article aims to present and test DeMa or the Wadi Al Arab wellfield case study. We show the benefit of using DeMa to centralize the water company's scattered data and visualize the relationship between different parameters to support the wellfield manager in making decisions related to wellfield operation and maintenance.

6.2 Study Area

The Wadi Al Arab wellfield is located in the northwest of Jordan, and it is considered one of the most critical wellfields in the country (Alqadi et al., 2019; Subah et al., 2006a), as it contributes around 35% (17.32 Mm^3/y) of the total drinking water supply to Irbid Governorate (Figure 6.1) the second largest governorate in Jordan in terms of number of inhabitants (DoS, 2019). Between September 1982 and February 1983, the Jordanian government drilled the first five wells in the Wadi Al Arab wellfield (WA-01, WA-02, WA-03, WA-04, WA-05), all of them artesian wells, with a total production of more than 25 Mm^3/y, in 1983 (Subah et al., 2006b). Due to the increased demand for drinking water, the number of wells increased to 18 operating wells by 2018, with a total production of around 18 Mm^3/y (MWI, 2019). Due to the overexploitation of the aquifer, the water level declined by around 130 m, between 1995 and 2017 (Brückner et al., 2021). It is also expected to continue declining until it reaches additional 100 m drop, by 2050 (Gropius et al., 2022). The large rate of decline in the groundwater table deteriorates the water quality (Al Kuisi et al., 2015; Brückner et al., 2021; Hiasat et al., 2020) and increases the challenges of operating the wells and implementing maintenance activities (Alqadi et al., 2018). Moreover, it increases the pumping costs from the dropping groundwater table to the first reservoir level (Margane et al., 2015), which exceeded an average of 0.13

USD/m^3 in the Wadi Al Arab wells (Alqadi et al., 2019). For the reasons mentioned above, accessing the Wadi Al Arab groundwater resources will be strenuous by 2040 (GIZ, 2020). Therefore, there is an urgent need to enhance the wellfield's management in order to ensure a regular water supply for the next two decades. In particular, due to the lack of alternative water sources and the impossibility of further reducing water allocation per capita, a reduction in water abstraction cannot be envisaged in the short term.

All the wells tap the Upper Cretaceous limestone aquifer (the A7/B2 aquifer). According to Basem (Moh'd, 2000), the geological structure in the area dips toward the northwest. The A7/B2 aquifer comprises three formations: (i) Wadi As Sir Limestone Formation (A7), with a thickness of 190–300 m; (ii) Wadi Umm Ghudran Formation (B1), where the thickness is 35 m; (iii) Amman-Hisa (B2), with a thickness ranges between 140–200 m. The A7/B2 aquifer outcrops in the southern part of the wellfield area, where the recharge occurs and the groundwater flows toward the northeast (Subah et al., 2006b). The A7/B2 overlain with the Paleogene oil-shale aquitard (B3 aquitard) toward the northwest of the area with a thickness of up 300 m. Topographically, the Wadi Al Arab wellfield is located in a hilly area, where the elevations of the wells range from 40 m below sea level in WA-12 to 110 m above sea level in WA-19. The hydraulic conductivity for the wells ranges between 8.8×10^{-7} to 2.2×10^{-4} m/s; the abstraction rate ranges in the wells from 70 m^3/h to 180 m^3/h (Dorsch et al., 2017).

The Wadi Al Arab wellfield has been managed by the publicly owned Yarmouk Water Company (YWC) since 2013. Currently, YWC serves around three million inhabitants living in the northern part of Jordan, and it manages and operates a total of around 350 wells; 240 wells operate with a total production of around 91 Mm^3/y, and the rest are under maintenance, abandoned, or not yet activated (WMI, 2020). Before 2013, YWC signed an agreement with the Veolia Aqua Company to improve the provided services for seven years, starting in September 2011. However, the contract was terminated, in March 2013, for political reasons (KFW, 2021; WMI, 2020). The Japan International Cooperation Agency JICA (2015) highlighted that one of the major activities within YWC is the well's maintenance activities. The report also stated that in October 2012, a computerized predictive system started to operate and recorded 342 maintenance orders within six months; however, the report did not show what kind of preventive maintenance was applied. Because of the termination of the agreement with the Veolia Aqua Company, the system stopped operating in April 2013.

The wellfield manager currently shares a monthly report with the wells department employees, including all the field measurements taken during the month. The shared data is gathered into an MS Excel file that contains a sheet for each well. Overall, each sheet has general data about the well (e.g., name, location, depth, casing specs), collected measurements (e.g., discharge, static water level (SWL), dynamic water level (DWL)), maintenance records (e.g., fault description and actions), installation records, and occasionally a summary of a pumping test. Moreover, this file is shared back with the wellfield manager upon request. The MS Excel file lacks data consistency (e.g., date format, unit of measurements). Additionally, when essential data for managing and operating the wells, such as invoices, bills, and electricity consumption are needed, they are requested from the financial department and, consequently, the information is not readily available for the user. As a result, this approach does not allow for a prompt detection of inefficient wells or upcoming maintenance needs. Hence, it is not effective as a decision support tool and only serves to store data without any sort of data engineering, analysis, or post-processing, thereby losing any further value for management purposes.

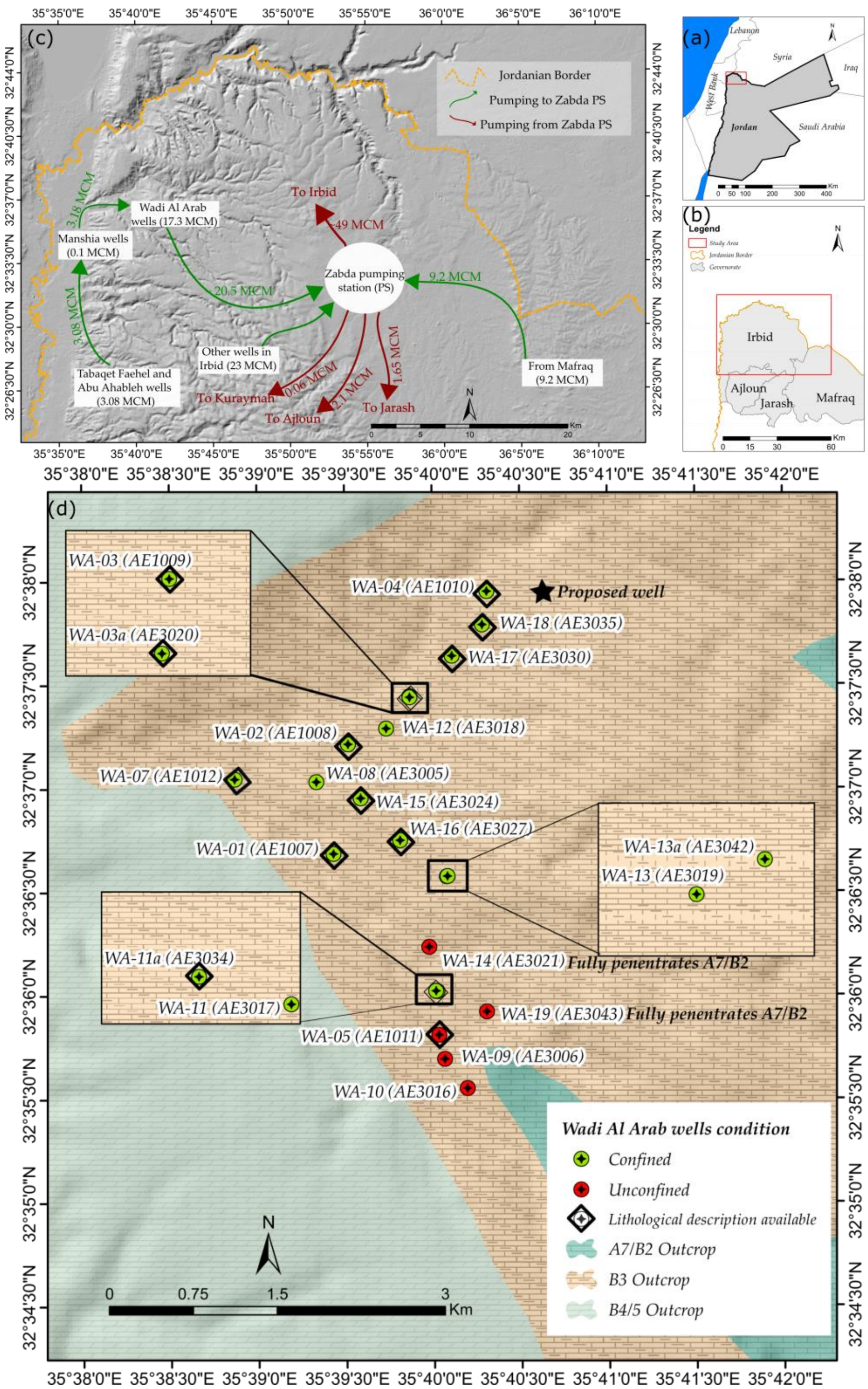

*Figure 6.1 Overview map of the study area. **(a)** The location of Jordan and surrounding countries **(b)** The area of Irbid governorate and the study area. **(c)** Schematic diagram showing the regional water supply system in 2017 (modified after* (Alqadi et al., 2018)*) and **(d)** The Wadi Al Arab well confinement condition and lithological availability map.*

6.3 Materials and Methods

This section provides a short description of the concept of the DeMa software and the technical description of the tools; further technical information is available in (Alqadi et al., 2022).

6.3.1 Concept of DeMa

The driving concept behind building DeMa is to bring forward practitioner knowledge, translate scientific research into action, and digitize data/reporting processes in one software aiming to move towards evidence-based practices in groundwater management. Through the database management tool (DbMT), DeMa provides a solution for storing and managing data that practitioners use to operate and implement maintenance activities of wells and wellfields, aiming to (i) guarantee data consistency, (ii) provide easy and fast access to data, and (iii) prevent loss of historical data by providing regular backup options (manually/automatically).

To operate and implement maintenance activities of wells and wellfields, DeMa has to be applied through the following procedure: (i) a database has to be created using the database management tool (DbMT); (ii) the data and the relation between different observations can be visualized in the observation-based tool (OBT), such that the well-field manager can plan the management according to current observations; (iii) well- and wellfield-related documents can be accessed through the documents management tool (DMT); (iv) the collected data can be used through the research-based tool (RBT) to generate new information, such as the computation of the radius of influence of a well.

The tables in the database are divided into three types: (i) standardized data tables, which contain all the data, its primary keys used as foreign keys in other tables; the tables include the standard values of specific parameters (e.g., cable, casing and drilling diameter and pump/motor brands and models), and categorization data (e.g., failure category, equipment status (new, used, repaired); (ii) basic data tables containing the data that are formed when the well is drilled and ready to operate; for instance, when a well is drilled, then data such as the location and depth of the well, lithology data, drilling diameter, casing installation, and cementation must exist; and (iii) extra tables containing all the data that frequently change over time, such as failure records, equipment installation, and measurement data. DbMT is designed to meet the current and the future need of the user, which is why it is flexible in terms of updating the parameter list and the categorization data; the adaptability feature provides the user with the responsibility of updating the list of parameters depending on the line of work and interest. For instance, the static water level (SWL) parameter is included in the database as standard. However, the user has the ability to expand the database, for example, adding additional SWL categories to the database, such as , SWL collected by manual and automatic measurements to differentiate among them and assess the consistency of the data.

Furthermore, the relationship between the stored data is visualized via the observation-based tool (OBT). The OBT helps users to compare the different observations made in one well (e.g., visualizing the current status of a well would support the user in deciding if it is possible to extend the riser pipe or reduce the pumping rate) or multiple wells (e.g., visualization of the comparison of the value of pumped water in terms of energy supplied between different wells could help the user to select which well to switch on/off according to their energetic efficiency). One of the examples of the graphical representation of the data is the well's status graph, which provides a comprehensive overview of the status of the well in terms of the borehole's design, installations (e.g., pumps specs, riser pipe (RP) specs), lithological formations, and the latest measurements. Such a comprehensive overview would help the wellfield manager to approve or disregard actions related to a well's operation.

Additionally, the document management tool (DMT) is built to organize all relevant documents to a specific well or wellfield, where the user can save and sort files by well/wellfield and/or file types (e.g., project reports, theses, final reports, articles, guides, pump curves and report, meeting minutes, internal bills, invoices, contracts, closed-circuit television (CCTVs)). The DMT does not only offer options to store and manage documents related to wells or a wellfield, but it also provides an interface for template edition, where all the previous templates used by the water company can be listed.

Moreover, aiming to bring science into practice, the research-based tool (RBT) enables users to benefit from the conducted research studies that focus on managing groundwater wells and wellfields. Although many scientific research studies (e.g., (Chang et al., 2021; Katsifarakis et al., 2018; Nagkoulis & Katsifarakis, 2020)) provide novel methods that are essential for improving wellfield management, it is not always easy for the practitioners to apply such methods as they lack a mathematic and/or programming background and skills. The RBT provides practitioners with a user-friendly graphical user interface (GUI) to select and apply certain methodologies directly to the managed wells, without requiring previous knowledge of mathematics and/or programming. For instance, there are different methods to calculate the radius of influence of a well (ROI). The method selection is based on the conditions in the field and the availability of data and information. Before the user selects a method to calculate the ROI, a list of different parameters and the conditions of the well pops up, and accordingly, the RBT selects the appropriate methods that fit the available data and conditions (Figure 6.2).

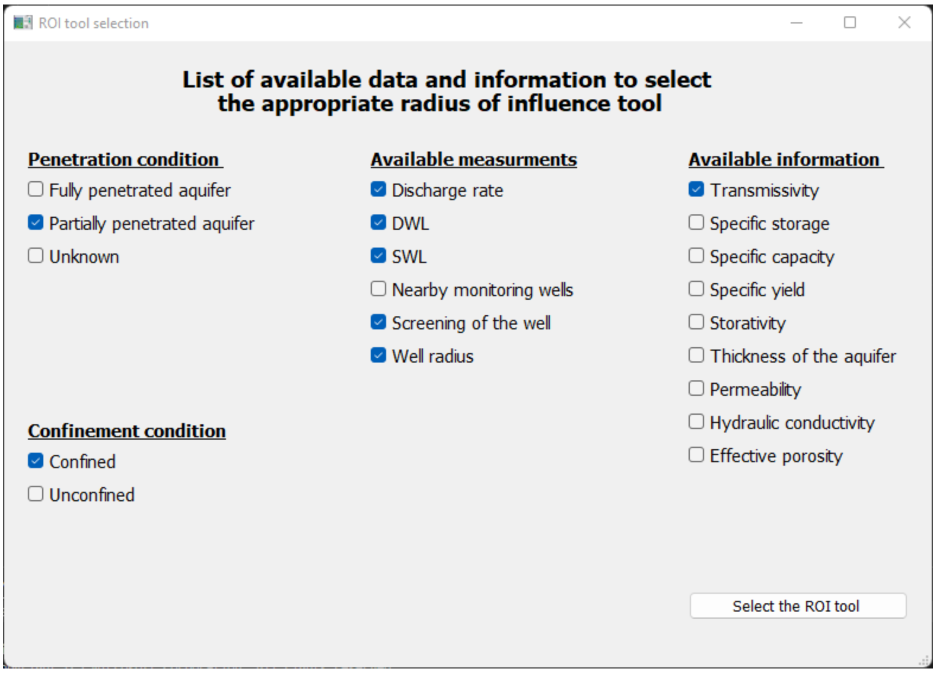

Figure 6.2 Selecting the appropriate ROI window based on the available data and information.

6.3.2 Technical Description

After listing the features of the existing tools and software that manage groundwater wells and the wellfield, it was compared with the features that DeMa aims to offer. The unique features that are not available in other software and tools were defined and integrated into DeMa (e.g., well failures record and installation specifications) (Alqadi et al., 2022).

The authors built, tested, and validated DeMa database using Structured Query Language (SQL) with the SQLite3 Python library (Hipp, 2020). The database, represented by 34 interconnected tables, includes all observations identified to serve the features that DeMa provides (e.g., lithology, energy consumption, maintenance costs, installation specifications, field measurements, and well design). The modules and front-end of the software were developed using the PyQt5 library, which includes a total of 53 Python files, structured as follows:

- Forty-two files to allow the user to update, delete, insert data, and run the database backup in the database management tool (DbMT);

- Four files to graphically visualize the data and the relation between different observations in the observation-based tool (OBT);
- Three files to manage the well- and wellfield-related documents in the documents management tool (DMT);
- Two files to use the best from the published scientific articles in the research-based tool (RBT);
- Two base constructor files.

6.3.3 Integrating the Study Area Data and Information into DeMa

The required data to be uploaded into the DeMa database was collected from different departments at the YWC (e.g., wells department, pumping station department, and accounting departments), and later reorganized to fit the database design and inserted into the database via the DbMT database management tool. Furthermore, an intensive literature review was conducted to integrate all the research documents related to the Wadi Al Arab wellfield into the DMT. The research documents were collected via online search tools such as Google Scholar and Web of Science (WoS) for peer-reviewed articles and gray literature. Furthermore, unstructured interviews were conducted with employees from different departments of MWI, international organizations, and YWC to collect the unpublished documents (such as project reports, drilling completion reports, templates, invoices, internal bills, and electricity consumption). All the collected documents were uploaded to the DMT to enhance the wellfield's information management. Compared to the existing MS Excel sheets that are used to store and manage the data, the DbMT provides fast and easy access to consistent and updated wellfield data that employees can access from different departments in the YWC. Furthermore, the consistency of the data would help the user either to extract the data and build customized graphics or to access automatic graphical visualizations via the OBT. Figure 3 summarizes the flow process that led to the development of DeMa and its application.

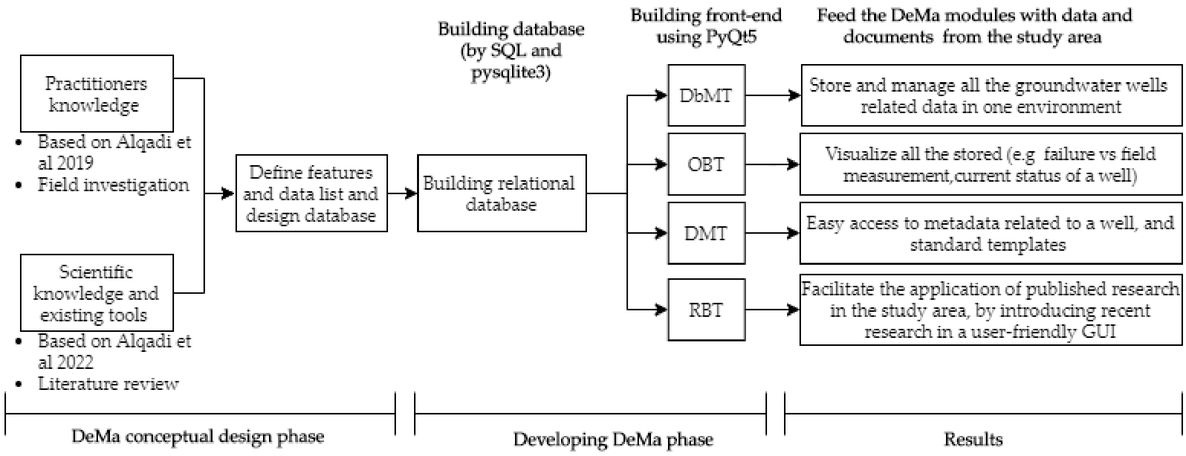

Figure 6.3 Schematic diagram for the method followed to apply DeMa on the Wadi Al Arab wellfield. Ac-ronym list: database management tool (DbMT), observation-based tool (OBT), documents-based tool (DMT), research-based tool (RBT).

6.3.4 Integrating the Analysis of the Radius of Influence of a Well in the Research-Based Tool

The calculation of the radius of influence (ROI) of a well is a key information for well field managers. To facilitate gathering this information, we implemented in the RBT the recent work of (Bresciani et al., 2020), which includes nine different equations to calculate the ROI. These equations are mainly based on the Theis solution and assume that “horizontal flow in a homogeneous, confined aquifer of infinite extent, constant-rate pumping, fully-penetrating well, and negligible wellbore storage and skin effects” (Bresciani et al., 2020) (p. 2). In this way, we aim to bring closer the results of academic research to the final user. The ROI can be calculated by choosing the “design a multiple well system” option in the RBT, which is based on the equations (Equations (6.1)–(6.3)) and considers the following parameters: pumping time t [days], transmissivity T [m^2/day], storativity S [-], well radius rw [m], and relative threshold criterion (α) [-] (i.e., the acceptable drawdown at a given distance).

$$ROI = 2\sqrt{\frac{TtE_1^{-1}(-\alpha \ln(1.78u_w))}{S}} \tag{6.1}$$

$$Relative\ threshold\ criterion\ (\alpha) = \frac{drawdown\ at\ the\ radius\ of\ influence}{drawdown\ at\ the\ well} \tag{6.2}$$

$$u_w = \frac{Sr_w^2}{4Tt} \tag{6.3}$$

6.4 Application of the DeMa

6.4.1 Data and Document Management for the Identification of Missing Information Concerning the Wellfield

From the operational point of view, the storage and access to documentation concerning the wellfield are of utmost importance for wellfield managers. However, very often, data and documents concerning the Wadi Al Arab wellfield are scattered among different authorities and even different departments within the water company. Therefore, DeMa aims to support the centralized storage and sharing of available information.

For example, the total number of documents focusing on water resources in the Wadi Al Arab area is 44. Among them, 16 documents were linked with the area/wellfield name, 18 with the individual wells, and 10 provided general guidelines for managing the wellfield, but they are derived from different sources, as indicated in Table 6.1.

Table 6.1 An overview of the included documents in DeMa and the sources of the documents.

Content of the Document	# of Documents	# of Sources	Linked to	Sources to Collect the Documents from
CCTV report	6	2	Well	Private drilling company, water utility
Completion report	9	3	Well	MWI, Private drilling company, water utility
General guidelines	10	2	-	Online, International cooperation projects in Jordan
Project report	7	2	Area/wellfield	MWI, International cooperation projects in Jordan
Pump curves	11	1	Well	Water Utility
Scientific article	11	1	Area/wellfield	Online

Centralized storage of the information, for example, improves the management of the wells. The 18 documents linked to individual wells, in fact, are the completion reports, CCTV reports, and the installed pump curve. Unfortunately, they do not contain specific information about the aging of the well structure. Table 6.2 shows an overview of the drilling completion documents associated with each relevant well. We can observe that less than 50% of the wells have an accessible completion report. It is essential to highlight that if a specific report is not available for a well, it does not mean that the report does not exist; instead, it is not accessible to the wellfield manager. Such information is of pivotal importance for adequate wellfield management. Its availability allows the user to quickly identify necessary actions to be taken in order to gather the missing documents and information, track which sources have already been utilized to collect available data, prioritize funding for further data collection, as well as to identify which possible data provider needs to be contacted. In other words, it helps users to efficiently manage their data collection process. Moreover, Table 6.2 presents an overview of missing data about the wells' casing, drilling, and lithology. Lacking such essential data on some wells prevents the wellfield manager from taking appropriate actions during well operation or in case of a well failure.

Therefore, DeMa, through the DMT, provides fast and easy access to documents related to the wellfield and presents an overview of the available and missing data. The DMT tool indicates to the wellfield manager the missing completion reports that need to be located and uploaded to the DMT. The completion reports usually include the drilling activities, pumping tests, and installed casing specifications for each well. Thus, including these reports is vital to fill in the missing data in Table 6.2. This approach was applied in the Wadi Al Arab case study to fill in the missing data of the wells AE1007, AE1008, AE1009, AE3027, AE3042.

Table 6.2. Availability of casing, drilling and lithology data and drilling completion reports of the Wadi Al Arab wells.

Well ID	**Casing**	**Drilling**	**Lithology**	**Completion Report Availability**
AE1007	Yes	No *	Yes	x
AE1008	Yes	No *	Yes	x
AE1009	Yes	No *	Yes	x
AE1010	Yes	No	Yes	
AE1011	Yes	No	Yes	
AE1012	No	No	Yes	
AE3005	Yes	Yes	No	
AE3006	Yes	Yes	No	
AE3016	Yes	Yes	No	
AE3017	Yes	Yes	No	
AE3018	Yes	Yes	No	
AE3019	Yes	Yes	No	
AE3020	Yes	Yes	Yes	
AE3021	Yes	Yes	No	
AE3024	Yes	Yes	Yes	x
AE3027	No *	No*	Yes	x
AE3030	Yes	Yes	Yes	x
AE3034	Yes	Yes	Yes	x
AE3035	Yes	Yes	Yes	x
AE3042	Yes	Yes	No *	x
AE3043	Yes	Yes	No	

* Data that were considered to be unavailable in the collected data, but were found in the completion reports when the document management tool DMT was used.

Not only were the documents related to the Wadi Al Arab wellfield organized and made easily accessible by DeMa, but also the data were collected, reorganized, and integrated into the DeMa database. The organization of data is of pivotal importance for the operational management of the wellfield, and dedicated tools to support wellfield managers in this action are generally not directly linked with post-processing tools (e.g., production of interactive graphics) as offered by DeMa.

Regarding the field measurements table, the total number of uploaded measurement data is 3187 in the period from 1982 to 2019. However, around 98.4% of these data were collected after 2012 because most of the data collected before 2012 were lost due to the termination of the signed agreement with the Veolia Aqua Company, as mentioned in Chapter4 (Alqadi et al., 2019). The economic and scientific loss caused by these missing data is challenging to quantify. Thus, the advantage of a software tool such as DeMa that allows for prompt storage and organization of relevant field data is evident. Figure 6.4 shows the different types of measurements collected. The amperage shows the highest number of recorded measurements in the graph with a value of more than 1400 records because the alternating current type is three-phase electric power, and actual amperage measurement is collected for all three wires each time. After amperage, the discharge and dynamic water level measurements have the highest collected measurements over time, with a value of around 700 measurements each. Besides the discharge and DWL, the pressure and shaft power should be frequently measured to calculate the pump efficiency and consequently detect possible performance issues (Cervera-Gascó et al., 2021), predicting failures and planning maintenance accordingly. Therefore, a recommendation that can be given to the wellfield managers by analyzing Figure 6.4 is to increase the budget and the effort to collect pressure and shaft power data.

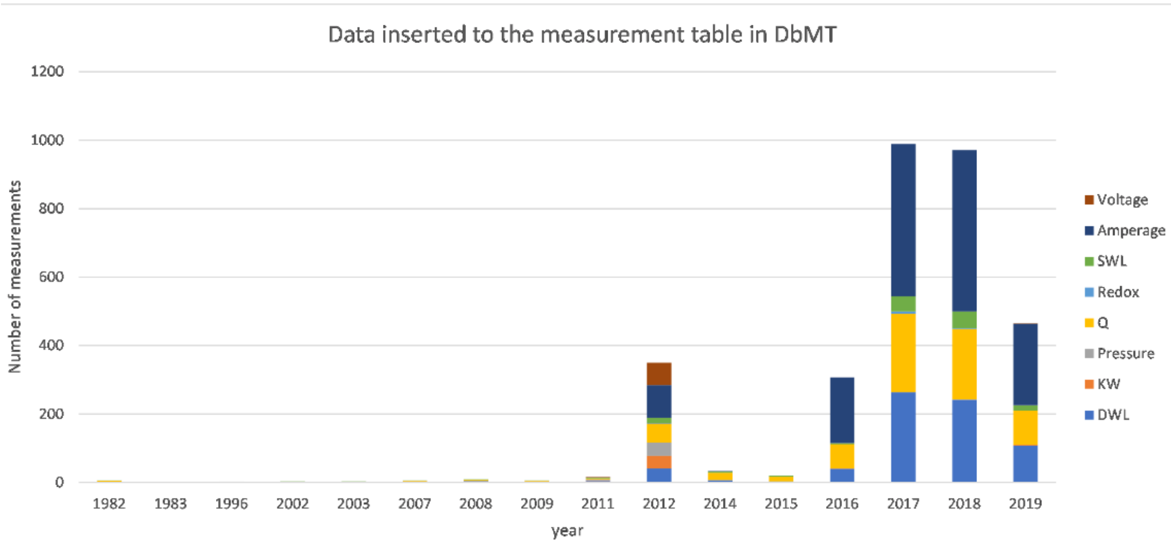

Figure 6.4. The collected and uploaded data to the measurement table in DbMT. List of abbreviation in the figure: SWL is static water level (m below ground level (bgl)); Q is discharge (m^3/h), KW is the power of motor (Kilowatt); DW is dynamic water level (m bgl).

6.4.2 Identification of Maintenance Needs

Figure 6.5 shows the status of AE3020 obtained through the OBT. As observed, the dynamic water level (DWL) gets closer to the pump depth, extending the riser pipe of this well to deepen the pump would be limited to only one segment of the riser pipe (6 m), when taking the pump length into consideration. This is because the pump should not be adjacent to the slotted section of the casing (from 165–175 m, after that open-hole). Otherwise, it will lead to sand pumping, gravel pack damage, and the pump breaking (Borch et al., 1993). Another observation can be detected from the figure; it can be seen that the section where the B3 oil-shale aquitard is not cemented, and the casing in the last 10 m of the formation is slotted; such an observation could justify the high concentration of heavy metals in this well (Alqadi et al., 2018; Dorsch et al., 2017). Therefore, DeMa brings the numerical and geological information of a well into a graphical representation. This process allows the wellfield manager to better grasp the maintenance needs.

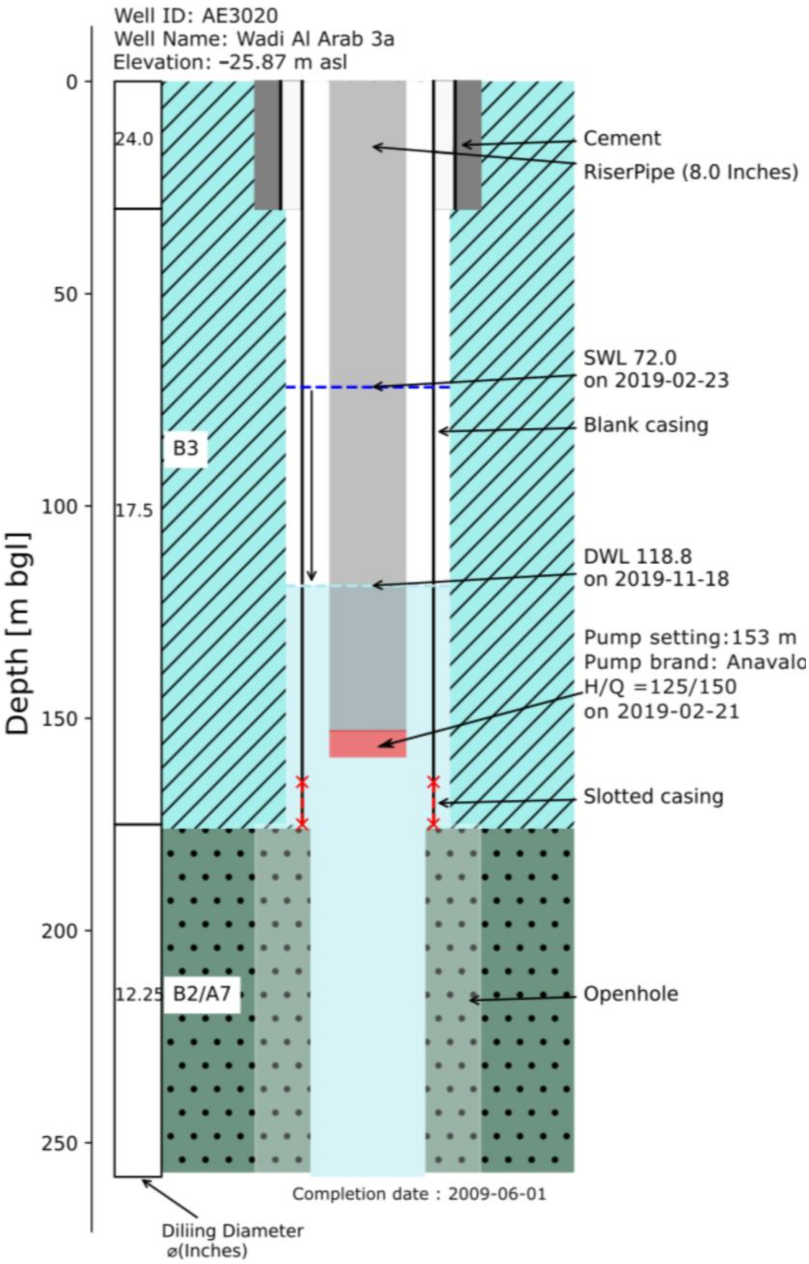

Figure 6.5. Well status of AE3020 as part of the OBT, a visualization of the recent collected data.

Moreover, a deeper understanding of the well's history can be obtained through a "well diary graph" in the OBT. This option provides a visualization of the lithology, the historical measurements of DWL, SWL, as well as the discharge, and links them with the maintenance actions and failure incidents that have been recorded in the well. For example, the diary graph of WA-04 produced automatically by DeMa is represented in Figure 6.6. The figure shows that after recording a rise in the DWL level between September and December 2012, the discharge rate did not decrease. This can be an indication of a malfunctioning of the riser piper which can be easily detected through the graphical output produced by DeMa. In fact, the riser pipe was checked afterwards, and a hole was found. The data shows that after fixing the problem, the discharge increased without changing the pump specification or depth.

Besides, the well's diary graph gives a general overview of the reasons behind interrupting the well's operation. For instance, in Wadi Al Arab 4, it is clear that the riser pipe (RP) was the reason for stopping the well seven times between 2012 and 2017 (three times because of holes in the pipe, four times for adding extra RP to deepen the pump setting). The graph also provides an overview of the frequency measurements of a particular parameter (SWL, DWL and discharge); this would draw the wellfield manager's attention if a particular parameter was not collected for a specific well so that actions could be taken accordingly. This figure is interactive and has built-in pan/zoom, change shape and color tools. These tools would help the user to implement the comparison between different measurements and have a closer look at a specific period. For instance, the user can observe the increase in the discharge after the riser pipe is repaired. Furthermore, the figure shows that the DWL dropped after repairing the RP; therefore, in the subsequent maintenance of the RP, the user could expect the behavior of the water level after the well operation.

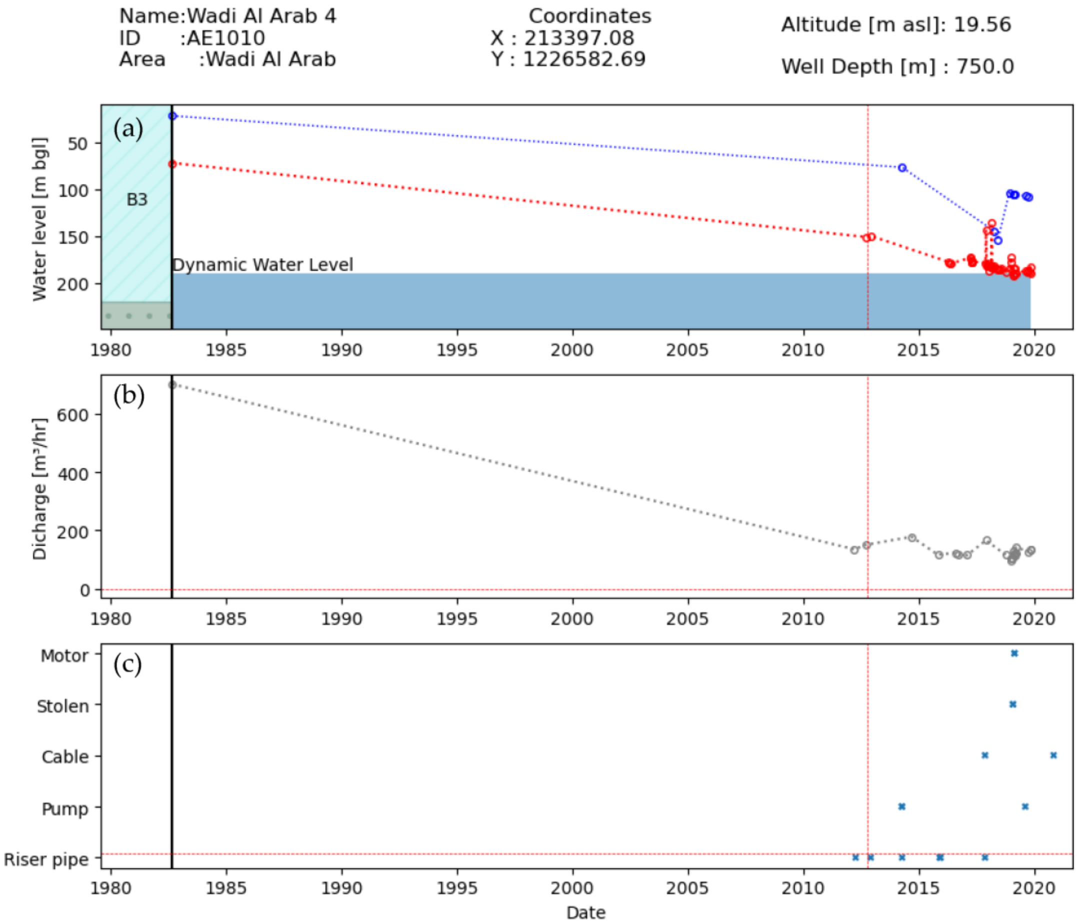

*Figure 6.6. Wadi Al Arab 4 (AE1010) diary graph as part of the OBT. (**a**) The change in groundwater level (blue dots represent the SWL and red dots represent the DWL) since the drilling of the well, the lithological units of the well, (**b**) the changes in the discharge (m^3/h) over the same period, and (**c**) the reasons behind interrupting the well's operation over time. The red cursor is to link the three figures (**a**–**c**) visually.*

6.4.3 Identification of a Suitable Location for a New Well

When the data availability checklist was applied to select the appropriate ROI method on the Wadi Al Arab wells, the results showed that any of the currently implemented ROI calculation methods in the RBT is applicable to the case study.

In this exercise, we can observe the importance of bridging together the different components of DeMa. The Wadi Al Arab wells did not pass the criteria mentioned above because the available lithological descriptions contained in the OBT tool indicate that the wells partially penetrated the B2A7 aquifer. To examine the confinement condition and the aquifer penetration extent of the wells lacking lithological description, they were plotted over the base of A7B2 and base B3 maps presented by Brückner (Brückner, 2018) and contained in the DMT tool. Moreover, the bases of the hydrogeological units were compared with the depth of the wells to check the aquifer penetration extent and with the water level to check the confinement conditions. This information is readily available for the wellfield manager since it is collected in the OBT tool. As can be noticed in Table 6.3, the two wells that might be fully penetrating the A7B2 aquifer are under unconfined conditions; therefore, this concludes that none of the existing wells is eligible to be applied with the methods presented in the current version of the RBT to calculate the ROI.

Table 6.3. Confinement condition and penetrating extent test for the Wadi Al Arab wells with no lithological description.

Well ID	Well Elevation	Well Depth	Elevation of Base of A7	Fully Penetrating the Aquifer?	Confinement Condition
AE3005	−14.89	243	−632	No	Confined
AE3006	79.29	260	−329	No	Unconfined
AE3016	85.63	195	−276	No	Unconfined
AE3017	74.65	230	−420	No	Confined
AE3018	−40.89	230	−597	No	Confined
AE3019	104.87	304	−469	No	Confined
AE3021	70.98	347	−219	Yes	Unconfined
AE3042	104.87	450	−469	No	Confined
AE3043	109.59	450	−287	Yes	Unconfined

Besides calculating the ROI of existing wells, the RBT supports the wellfield manager in assessing the location of proposed new wells to avoid significant interference with other existing wells based on the relative drawdown criterion equations (Equations (6.1)–(6.3)). We now assume that a hypothetical well is proposed to be drilled and fully penetrate the A7/B2 aquifer. The proposed location is to the east of Wadi Al Arab 4 (AE1010), where the hydraulic condition is confined; the wellfield manager would be able to define the minimum distance from the Wadi al Arab well by calculating the expected ROI of the hypothetical well shown in Figure 6.1d.

In the Wadi Al Arab confined area, the storativity is 0.001 (Al Manaseer & Ta’any, 2019; Rödiger et al., 2017), while the transmissivity is 9 m^2/day (Al Manaseer & Ta’any, 2019), and such information is easily accessible thanks to the DMT and OBT tools. According to Salameh et al. (2018), the rainy season in Jordan, which corresponds to the groundwater recharge, starts in October and ends in April. Therefore, we consider that the pumping time under stationary water level is during the summer (i.e., between May and September, 152 days). The typical diameter of the well in the wellfield is 17.5 inches (0.4445 m), and we assume that the maximum ROI acceptable by the water manager should not exceed 500 m, which would otherwise interfere with the ROI of Wadi Al Arab 4. The expected drawdown was considered 20 m in the proposed well according to typical drawdown values observed in the wellfield.

Figure 6.7 shows that after 152 days of pumping, the ROI of the proposed well is expected to reach 750 m, 1290 m, and 2480 m, where the drawdown at the ROI is 2 m, 1 m, and 0.2 m, respectively. After 60 days of pumping, the drawdown of 2 m would interfere with the Wadi Al Arab 4 ROI; such an observation will assist the wellfield manager in deciding whether the proposed location is suitable. For this hypothetical case, the wellfield manager will propose to shift the well toward the east by at least 250 m or to amend the pumping schedule to avoid significant interference between the ROIs. However, to correctly interpret the results, the assumptions for the application of the proposed analytical solutions mentioned previously should be carefully considered. To achieve better and more accurate results, the specialists could use more sophisticated models that consider the aquifer heterogeneity, geometry, topography, and boundary conditions (e.g., MODFLOW (McDonald & Harbaugh, 1988) and FEFLOW (Trefry & Muffels, 2007)). However, the provided solutions can be used as a simple-to-use estimate of the ROI.

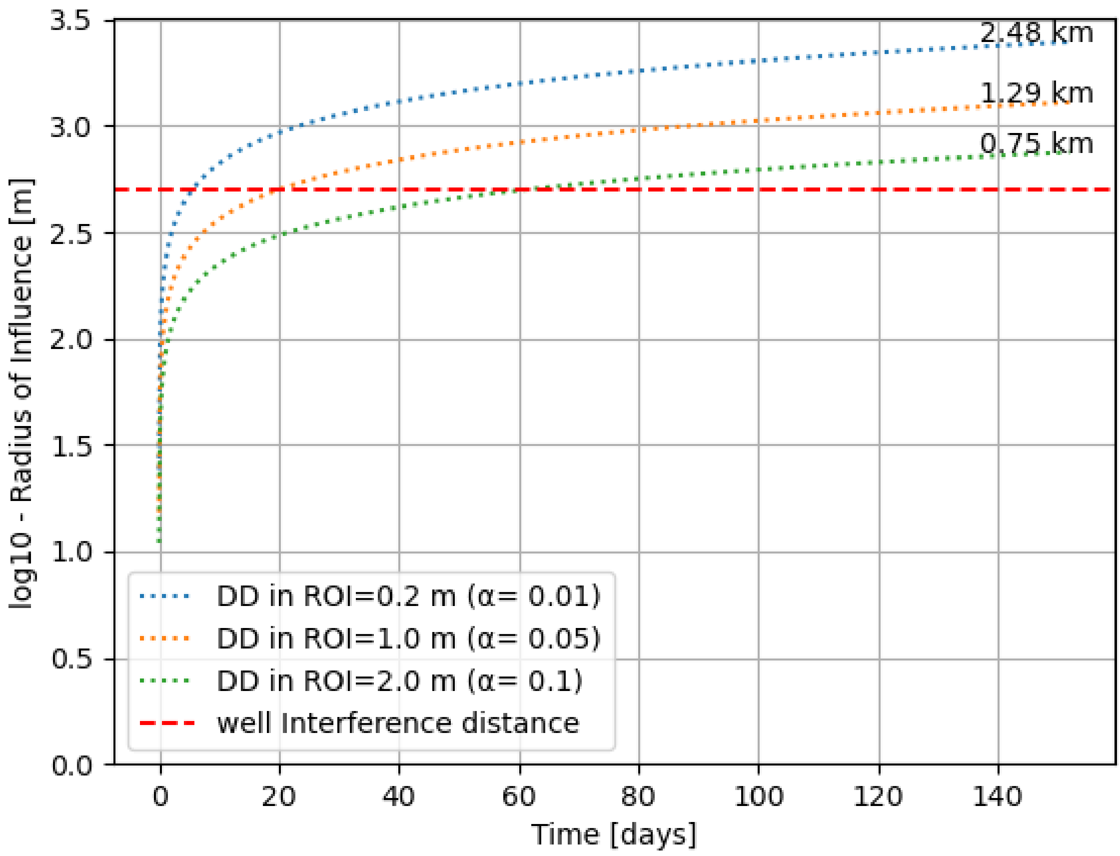

Figure 6.7. The application of the RBT for defining the ROI of the hypothetical well north of Wadi Al Arab 4.

6.5 Discussion and Outlook

A fundamental component of the software is the construction of the relational database. Indeed, the relational database is designed to ensure data consistency across different tables, allowing for quick retrieval of the well's data and aiding in automating the creation of user-friendly infographics and visualizations by the OBT. The produced graphics support the user in finding data gaps and provide an overview of the current status of a well within a wellfield, aiming to make data-driven decisions possible and simple (e.g., the pump in AE3020 cannot be further deepened due to the lack of blank sections in the lower part of the well in range of 165–304 m depth). The DMT assists in generating knowledge from the collected data. For instance, after uploading to the database the information collected by the water company in separated and unstructured Excel sheets, it was shown that four wells (AE1007, AE1008, AE1009, AE3027) lack some data related to "basic data table", so the database was updated through fast and easy access to the completion reports of the Wadi Al Arab wells. An overview of the missing data was reflected in the OBT by providing accurate visualizations of the current status of the well and the well's diary graph. The DMT also supports the research-based tool by providing a list of conducted research documents in the wellfield area (e.g., (Al Manaseer & Ta'any, 2019; Rödiger et al., 2017)), which can be used to identify the needed parameters (e.g., transmissivity, storativity) to calculate the radius of influence for a well in the area or any proposed wells. Accordingly, scientifically informed decisions are made.

Furthermore, we expect that providing a table of available and missing documents would encourage the user to fill in the gaps. For example, if the table presenting available CCTVs reports shows that the AE1007 has no CCTV report, although the wellfield manager is aware that a CCTV activity was conducted for this specific well, then, the manager can seek to locate and upload the report to the DMT. The previous discussion concluded that besides the benefits provided within each tool, DeMa presented that the interconnection between the four tools of DeMa are useful for data management, including the support for data availability, data accuracy and identification of missing data. For example, in the case application, we observed that certain data related to the wells (e.g., the installed motor models, riser pipe material) still need to be investigated and uploaded to the DbMT. The number of research project reports added to the DMT is probably less than the number of projects conducted in the area. It is expected that the application of DeMa by the end-users will improve data and document availability and accuracy in the study area.

Software enhancements are planned for future releases of DeMa. Mainly, (i) additional data frames related to water quality data will be added to the database, (ii) further features and analyses (e.g., water corrosivity graph) will be built into the OBT to support the wellfield manager with consideration of water quality data in the decision-making process, and (iii) the inclusion of big data analyses collected from the sensor-equipped monitoring systems of wells. Additionally, there is ample room for further development of the RBT by adding more research outcomes that support the user to determine the radius of influence in a partially penetrated aquifer (e.g., (Feng et al., 2021)) to define the best location of wells and water reservoirs for pumping cost minimization (e.g., (Katsifarakis et al., 2018; Nagkoulis & Katsifarakis, 2020, 2021)), and to analyze the pumping tests of a well (e.g., (Chang et al., 2021)). Furthermore, the future version of the software will include the option to calculate the ROI of the wells under unconfined conditions, and most probably, we will use the Dupuit formula and Thiem formula (Zhai et al., 2021).

6.6 Conclusions

This article presented DeMa (Decision Support Software and Database for Wellfield Management) and showcased its application for the Wadi Al Arab wellfield. DeMa is a comprehensive software for managing the information about a groundwater wellfield and hence supports the decision-making process of the wellfield manager. DeMa contributed to identifying missing documents and data for the wellfield, the wells' maintenance needs, and suitable locations for new wells. The DbMT provided a comprehensive database of all available data associated with the Wadi Al Arab wellfield, which can be updated and used by wellfield managers and technicians in various departments within the water company to improve the data flow.

The data and the results from the different analyses can be visualized by the OBT and linked with the documents (e.g., CCTV, completion reports, invoices) in the DMT. These features may be relevant for water companies, given that the software can be directly used to enrich the DbMT and DMT and prevent information losses in the future. Furthermore, the OBT assists well managers in identifying missing data and information by including all the project documents in one location and by grouping them by keyword tags. Hence, DeMa supports the transformation of data into information enabling the wellfield manager to sustainably predict and manage the well needs and identify areas with gaps. In addition, the RBT aims to facilitate the use of recent scientific outcomes by practitioners. The DeMa software provided a digital solution for (i) a better understanding of the data availability to support decision making for the wellfield and (ii) improved information and data management of the Wadi Al Arab wells. These are prerequisites to achieving improved groundwater management and moving towards data-driven decisions.

Some documents and data (e.g., financial-related data and information) were not shared as they contained sensitive and confidential information; therefore, we could not apply DeMa functions to conduct maintenance and operational cost analyses. Furthermore, the current version of DeMa does not provide features to include and analyze water quality data that aid the user in the water quality-related decision-making processes.

Chapter 7

Conclusions

Returning to the main questions posed at the beginning of this dissertation, it is now possible to state that although improving the management of groundwater resources in arid regions is challenging, it can be improved by (i) conducting demand-driven research, (ii) adopting an improved data and document management system, and (iii) deploying enhanced digital solutions in the operational system. The following subsections conclude the answers to the five sub-research questions.

7.1 Multilevel and interdisciplinary approaches in water management

Chapter 2 indicates that the average drop in groundwater levels in Jordan due to abstraction ranges from less than 1.0 m/year to more than 6.0 m/year. The chapter also highlights the different reasons behind this high abstraction and its diverse impacts in different areas of Jordan. Wadi Al Arab area has recorded the highest water level decline rate in Jordan, where groundwater resources were depleted because of the high abstraction from Wadi Al Arab wellfield for drinking water supply purposes. The significant drop of groundwater level had an impact on the hydrogeological characteristics of the area (i.e., the limit of confinement has shifted towards the north of the study area), where the hydraulic condition of the southern part of Wadi Al Arab became unconfined; this resulted in an increase in the heavy metals concentration in the wells of Wadi Al Arab. For instance, the molybdenum concentration for the Wadi Al Arab well (AE3021) increased from almost 0 mg/l to 0.4 mg/l between 2010 and 2017.

Furthermore, the high decline in water levels in the Wadi Al Arab area was found to have caused problems in the wellfield operation, where wells faced unexpected failures leading to unplanned maintenance. Therefore, the developed approach (Chapter 4) (a) increased the collected dynamic water level (DWL), static water level (SWL) and yield measurements of the wellfield from 85 to 496 recorded measurements between the years 2012 and 2018, respectively, (b) minimized the downtime of pumps from 141 times of 14 operating wells in 2012 to 11 times of 18 operating wells in 2018, and (c) shortened the needed period to reoperate the wells after maintenance from an average of 5.2 days/failure to 1.1 days/failure during the same time frame.

However, these results would not have been achieved without (i) building trust with the well technicians operating the wellfield by being present in the daily operations, (ii) enhancing the communication between different levels of stakeholders by conducting regular meetings to exchange information and knowledge that led to changing the previously followed approach from a top-down to a combination of both top-down and bottom-up approaches and, (iii) building a simple database and dashboard to organize and visualize the wellfield data using MS Access and Excel.

Another area that is undergoing an extreme groundwater level decline is the basalt plateau. The satellite images of this area detected an expansion of agricultural activities over the years; however, in some agricultural areas, no abstraction wells were registered, which indicates an illegal abstraction of groundwater, which might reach double the amount of registered abstraction by the MWI. The over-abstraction in this area has reversed the original groundwater flow regime; which, according to the groundwater flow map of 1995, groundwater was flowing towards the center of the Azraq Basin not toward the northern west of the Basin. In November 2021; the MWI started targeting deep aquifers by drilling the first well of a new wellfield for drinking water supply, called “The Basalt Wellfield”, which is located in the northern part of the Azraq Basin (i.e., eastern part of the plateau). The wellfield is located in the area where the marls of B3 separate the limestone and basalt aquifers. Due to the agricultural activities and abstraction from the Aqib wellfield for drinking water purposes, the unsaturated zone extends toward the east of the plateau area. Eventually, this will impact the upstream of the Azraq Basin; it may change the hydraulic conditions of the wells located in the western part of the basalt wellfield, to become unconfined. This could deteriorate the quality of the extracted water and might increase heavy metal concentration in the wells of the basalt wellfield, similar to the problem that appeared in the southern wells of the Wadi Al Arab wellfield.

The location of the basalt wellfield and the feasibility for groundwater extraction from the area was based on the results of Gropius & Dahabiyeh (2018) and Margane et al., (2015). It was not clear if the MWI or researchers had studied the possible impact of this wellfield on downstream of Azraq Basin or if previously existing studies on the deep aquifer of the Azraq Basin could help to anticipate this impact. Therefore, a rigorous literature collection of all available reports (e.g., published, and unpublished) in the MWI and peer-reviewed articles about the Azraq Basin was conducted to get a better overview of the available studies in the Basin, identify the needed research, and define whether or not the undertaken research in the Azraq Basin was demand-driven. No standard method was found that could facilitate accomplishing these research objectives. Therefore, a novel method was developed to identify the needed research for a specific basin, as presented in Chapter 3. The basic principle of this method references the goals that the MWI needs to achieve and identifies disciplines that did not contribute to a particular goal. For instance, no study investigated the topic of the deep aquifer in terms of quantity and quality to improve water supply in the Azraq Basin despite it being highlighted as necessary research within Jordan's water strategy 2008-2022. If such a topic within the Azraq Basin was addressed by research, then the consequences of the basalt wellfield on the deep aquifer of the Basin could be better predicted, and decisions could be improved to achieve the strategy goal 2a: "Uninterrupted safe and secure drinking water supply achieved including continuous flow in Amman, Zarqa, Irbid, and Aqaba". Such gaps are defined in this dissertation as "Water-Decision Research Gap", which is the inability to make decisions related to governmental water strategy goals through conducting a systematic peer and grey-literature review at the Basin level.

Besides defining the Water-Decision Research Gaps, the method defines the degree of contribution of different research focus areas (RFAs) to each of the strategy's goals at the Basin level, which consequently would enhance the multidisciplinary approach in water-related research and might lead to transforming the traditional research to become more innovative and imaginative within the Basin. For instance, as shown in Chapter 3 (Figure 3.9), there are no geophysical studies aligned with the "water for irrigation" goals; such observation would motivate researchers in the geophysics field to produce a new study that aims, for example, to evaluate the irrigation efficiency of farms in the basin by using soil electrical resistivity. Similarly, no study focuses on energy and "water supply" goals; such observation would encourage energy specialists to contribute to producing research that can aid the MWI in achieving the water supply goals at the basin level.

7.2 Digitalization and water management

Enhancing the collaboration between multilevel stakeholders and changing the existing management system was applied successfully in Wadi Al Arab wellfield. Additionally, storing data related to the wells, building relationships between them in the MS Access database, and visualizing in an MS excel dashboard assisted the wellfield practitioners in making decisions related to the maintenance and operation of the wells. Using such simple methods to store and visualize data improved the management process of wellfields substantially. This was represented by the reduced failure frequency and the downtime of pumps. However, in 2021, the users reported that they faced persistent connection problems between the MS Access database on the server and the MS excel sheet on the local computer, and the overall feedback was that the wellfield information system (WFIS) and operational decision support tool (ODST) could not be used for long term management of wellfields due to the connection problems. The overall experience confirms the need to move toward digitalization in the water sector as a strategy to improve wellfield management. In this situation, sophisticated software that includes a database and can run more complicated equations than an MS excel sheet was needed; the software would also be enhanced through options for better visualization to help the water utility in the management and decision-making processes. Therefore, **De**cision Support Software and Database for Wellfield **Ma**nagement (DeMa) was developed, the first software worldwide designed and developed for managing wellfields and individual wells.

In Chapter 4, obstacles to making data-driven decisions within a water utility are identified, including inconsistent and scattered data between different departments with missing metadata. The DeMa software introduces a built-in relational database that contains all groundwater-well-related data in one location. This database can be accessed through the user-friendly Database Management Tool (DbMT), which allows the user to add, remove, edit, and extract data while keeping the consistency of the data; using the DbMT will prevent any future loss of data, which previously occurred due to poor documentation processes. Furthermore, the DeMa software offers the Observation Based Tool (OBT), an enhanced version of the ODST that was introduced in Chapter 4. The OBT can display the stored data in graphs, visualizes the possible interaction scenarios between data, and solves equations, and performs statistical analyses that would help users form an overview of the status of individual wells or wellfields.

The other issue faced during the work presented in chapters 2, 3 and 4 is the mismanagement of reports and documents related to the wells (i.e., the documents are scattered and inaccessible). Such a problem exists at the wellfield level (i.e., water utility) and national level (i.e., the MWI); therefore, there was a need to develop the Document Management Tool (DMT), which reorganizes and manages all the documents related to a certain well or wellfield. In the DMT, the standard list of document types contains project reports, theses, completion reports, articles, guidelines, minutes of meetings, internal memos, invoices, and contracts. Different categories can be added by the user. Having easy and fast access to documents or scientific articles can help the manager make evidence-based decisions. Furthermore, the DMT provides a list of templates that all users can use to keep the consistency of standard procedures in the water utility or MWI settings.

To make good use of international research in wellfield management practices, the DeMa software introduces the research-based tool (RBT). The RBT is a graphical user interface (GUI) for scientific articles that is beneficial for the management of wellfields. Wellfield managers might need to apply specific methods or equations that are introduced in scientific articles to the wellfield’s management or operation; however, the managers may not have the technical skills (e.g., programming or mathematics) to run or test the new equations and methods presented in international research. The first paper added as GUI to this RBT tool is Bresciani et al. (2020), which presents nine different ways to calculate the radius of influence by using Python programing language, and can help the managers of wellfields to successfully locate new wells, define the optimal extractions of a particular well, and delineate the protection zones of wells.

DeMa shows the importance of digitalization in water utilities for (i) keeping data consistency and preventing future data loss, which is handled with the DbMT, (ii) automating the data analysis and visualization with the OBT, (iii) introducing fast and easy access to related documents and templates through the DMT, and (v) improving the impact of scientific research on wellfield management practices through both the DMT and RBT. By using the DeMa software, the wellfield manager can access all data, including data that is under the responsibility of other departments (via DbMT), visualize the relationship between data (via OBT), approach scientific research that is done within the area of jurisdiction (via DMT), and use scientific methods that were introduced by the global scientific community (via RBT). The DeMa software is expected to enhance wellfield management processes to become more interdisciplinary based, as it would enhance the chance to have a more comprehensive overview of a certain wellfield and might influence the decisions based on multiple disciplines other than only the manager’s experience.

DeMa was tested by uploading the collected data from Wadi Al Arab wellfield into the database using the DbMT; the software helped highlight the wellfield's missing documents and data. Moreover, via OBT, DeMa produced conceptual visualizations based on the most recent data. It includes routinely updated data (e.g., water level, pump settings) and invariable data (e.g., borehole design, lithology) of the individual wells. Also, the OBT generated temporal graphs for the data providing an overview of the reasons behind the well's operation interruption and the performed maintenance and its effect on the well’s water level and discharge rate. To test the RBT, a hypothetical well fully penetrating the A7/B2 aquifer is proposed to be drilled to the east of the Wadi Al Arab 4 well. The RBT was used to test the suitability of the well location. The needed information to calculate the radius of influence (e.g., storativity and transmissivity) was extracted from the documents in the DMT. The results indicated that the drawdown of 2 m would interfere with the ROI of Wadi Al Arab 4 after 60 days of pumping. In such a case, the RBT suggests to the wellfield manager to shift the well 250 m eastward to prevent interference.

7.3 Multidimensional digitalization in the water sector

Improving water management systems requires a thorough consideration since the water sector is multifaceted. Furthermore, presenting new aspects within this sector would also require an integral approach. Introducing digitalization to the water sector should involve the factors that might influence and be influenced by this transformation. Before introducing a technological transformation (i.e., introducing new technology, like a software) to an existing system, for example, it is crucial to enhance collaboration and communication between different levels (e.g., between the MWI and water utilities) and disciplines (e.g., between different departments within one water utility or between the water utility and the electricity company). Introducing “collaboration improvement” as a prerequisite step for digital transformation might be seen as an obstacle to moving toward digitalization in the water sector; on the other hand, the successful digital transformation of the water sector can be seen as an opportunity for maintaining collaborations, sustaining water data flow, and engaging in knowledge transfer processes Digital solutions, and multilevel and multistakeholder approaches complement each other and are part of the digital transformation process; together they shift the traditional management approaches of water resources into an integral approach.

Since collaboration and communication processes are already improved within Wadi Al Arab wellfield, as mentioned in Chapter 4, the DeMa can be directly introduced there as a digital solution as part of the digital transformation process of the wellfield. Assuming that changing an existing system is more complicated than establishing a new one, it is expected that applying participatory approach principles and introducing new digital solutions in the new basalt wellfield would be easier than applying it at a wellfield with an existing system such as the

Aqib wellfield, where the application of participatory approaches still needs to be improved (Hamdan et al., 2017). Therefore, using DeMa to manage the basalt wellfield from the beginning can ensure data availability for future decisions. To conclude this section, it is worth noting that the digitalization of the water sector does not only include introducing technology to the sector; rather, it is a multidimensional process that also includes understanding and transforming all the management approaches that might influence the decision-making process and the adoption process of new technological solutions.

7.4 Summary of the dissertation results

The results in Chapter 2 identified areas highly impacted by over-abstraction in Jordan, and highlighted the consequences of over-abstraction on the groundwater system. These results led to the pursuit of additional investigations and initiated new research questions regarding highly impacted areas by over-abstraction in Jordan (Chapter 3,4,5). Consequently, the research activities conducted in Chapters 2, 3, and 4 generated the data and documents managed via the DMT and DbMT in Chapter 5. The introduced monitoring procedures in Chapter 4 reduced the number of failures and the maintenance duration for groundwater wells. The results of Chapter 3 provided an overview of the topics that were covered about the Azraq basin and a list of topics that still need to be investigated. This could support the MWI and the researchers to redirect attention to these topics and optimize the available budget allocation for future studies.

Throughout the dissertation’s activities, historical records, documents, and data were gathered for Wadi Al Arab wellfield, and were integrated into the DeMa environment via the DbMT and tested by implementing OBT, DMT, and RBT. As presented in Chapter 6, (i) the OBT provided data visualization and identified the actions and maintenance needs of the wells, (ii) the DMT offered a comprehensive document management system providing easy and fast access to information which consequently improves the knowledge of the wellfield manager, and (iii) the RBT supported wellfield managers in locating new wells using scientific approaches. Thus, the results show that digital solutions aid in achieving data and evidence-based decision.

The results of Chapter 3 presented a methodology to identify the research gaps at the basin level by referencing the MWI’s strategy’s goals. Results showed that determining the research gaps is a preliminary step towards creating demand-driven research; the methodology defines which topics in the MWI water strategy have not yet been addressed by specific research disciplines. Furthermore, the findings demonstrated the importance of involving ministry actors as an entryway to inaccessible grey literature within the ministry's system. The methodology was applied to identify research gaps utilizing the MWI water strategy (2008 – 2022) and the research conducted in the Azraq Basin. The MWI water strategy states that the MWI plans to encourage research and facilitate cooperation between national and international research institutions. Nevertheless, none of the 99 investigated research documents explicitly addressed the goals of the MWI water strategy. Moreover, the distribution of these documents among the different strategy goals is heterogeneous, where most documents are aligned with the water supply goals.

7.5 Outlook and recommendation

This dissertation offers valuable insights into (i) the influence of adopting a participatory approach to a traditional water management process, (ii) the importance of new methods to improve the connection between researchers and decision-makers in the water sector, and (iii) the vital role of digitalization in moving forward towards an integrated approach of water management. The participatory approach was successfully applied in the Wadi Al Arab wellfield management system relatively quickly. However, the generalizability of this result is subject to limitations, as it might take a longer time to be applied at a different wellfield, as the time of implementation is based on the existing cooperation environment in the system and the background, diversity, and commitment of the actors working in a certain wellfield. Although, it would be an enriching exercise to repeat this experiment in multiple wellfields. Ideally, it is recommended to test the approach in the future "basalt wellfield" that has not yet been drilled and operated in the Azraq Basin.

As mentioned previously, increased heavy metal concentration is likely to appear in the basalt wellfield water. To overcome this risk, the cementation of the B3 aquitard must be applied to all wells of the basalt wellfield. Furthermore, the MWI should oblige the operator of the basalt wellfield to collect and share the operational data of the basalt wellfield with the ministry consistently and continuously from the first day of well operation. After testing and ensuring the performance of DeMa software, it is recommended to use the software for the management of the basalt wellfield.

Chapter 3 discussed the importance of defining research gaps and conducting demand-driven research for the water sector. Two of the reports conducted under the umbrella of the MWI for the Azraq Basin aimed to explore issues that were not included in the MWI water strategy goals

(2008 - 2022). This observation provides some preliminary evidence that the set of goals in the water strategy could be outdated. Therefore, it is recommended that the MWI produces a living document of the water strategy so that the researchers can continuously feed it with new research related to the specified goals. Simultaneously, the MWI can add more goals to be addressed by future research. However, further studies are needed to explore the concept of a living water strategy document that strengthens the connection between researchers and the MWI.

The dissertation's findings present several important implications for future research and practice. However, the implications will not be sustained unless the government adopts them. For instance, the MWI is recommended to further develop its cooperation with the Ministry of Higher Education and Scientific Research (MOHE) to develop a digital platform that can be used to archive reports and studies produced by research institutes and projects by following the method developed in Chapter 3 (i.e., matrix showing the contribution of RFAs to governmental goals), and a similar approach to the design of the DMT developed in Chapter 5, allowing for better connection to wells, wellfields, and basins. This will lead to a dynamic list of demand-driven research, ensuring the sustainable flow of new studies into the MWI, and enhancing the connection between the MWI and academia. It is also recommended to establish a national water knowledge translation committee within the organizational hierarchy of the MWI that includes members from research institutes and the MWI w that aims to make use of conducted research.

Besides the peer-reviewed research, the method introduced in Chapter 3 considers the unpublished reports within the MWI, and does not include those from other ministries. To overcome this limitation and achieve a higher level of multidisciplinary documents, it is recommended to also include the unpublished reports and governmental strategy goals of other ministers (e.g., Ministry of Environment, the Ministry of Agriculture, and the Ministry of Energy and Mineral Resources) related to the water sector. To further improve on this method, the RFAs that are considered in many studies can be branched into sub RFAs described in Table 3.3. For instance, the modeling RFA could be branched into the groundwater flow, solute transport, climate, surface water, erosion, geochemical model, decision support system, vulnerability mapping, and statistical analysis model. This would link each of the branched RFAs to one or more of the governmental water strategy goals, resulting in a more refined RFAs matrix, including RFAs that did not necessarily contribute to a particular water strategy goal and still need to be investigated.

It is essential to highlight that the method in Chapter 3 identifies the contribution of different disciplines to each of the governmental goals. If a specific RFA has multiple contributions to a particular goal, it does not necessarily indicate that there is no need to conduct further studies within that RFA. Due to time limitations, the dissertation was unable to identify research gaps across the entire country; therefore, it is recommended to conduct a cross-national study involving all the basins, which will provide an overview of the water situation and the required water-related research in Jordan. Moreover, researchers are also explicitly encouraged to state the goals of the MWI strategy targeted in their future work as it would help the MWI update that strategy; if the MWI adopts a living strategy document plan for its future water strategy.

As mentioned previously, improving data collection and cooperation among different levels and disciplines is part of the digital transformation process in the water sector. However, without the proper testing and design of the introduced digital solution, the digital transformation of the water management body would ultimately fail and, consequently, lead to the loss of the built channels of collaboration between the different levels and disciplines. To avoid this, the MWI should develop a tested and unified digital transformation approach for all water utilities to cover all groundwater wells for drinking supply purposes. Moreover, adopting comprehensive software that is designed explicitly for wellfield management, such as DeMa software, will enhance data flow from water companies to the MWI and improve the management of water resources in Jordan. Due to authorized access constraints, the dissertation cannot provide a comprehensive overview of official agreements between the MWI and water utilities. Nevertheless, based on the field observations during the research implementation and data collection activities and data transformation from water companies to the MWI still need to be improved. In official agreements, the MWI is recommended to provide a data governance guideline and a detailed standard operating procedure (SOP) to oblige water utilities/companies to collect operational data from the different water resources consistently and ensure a continuous flow to the MWI. MWI is highly recommended to also publish a guideline for water utilities to implement effective management and operation practices within the water utility. Representatives from water utilities and relevant research institutes should be involved in the different phases of developing this guideline.

Additionally, before DeMa software is introduced to water utilities, it is recommended to test the software with more data to ensure high performance and bug prevention. After implementing the software in water utility systems, user feedback should be continuously collected for further improvement. Furthermore, cyber security measures should be considered when establishing communication channels between the MWI and water companies. Finally, the future version of DeMa will include a water quality tool, and additional scientific research will be introduced in the RBT as GUI. Despite being initially developed and tested for wellfield management in arid regions, the DeMa software is designed to be applied to other wellfields elsewhere in the world to improve groundwater management on an international scale/or globally.

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Appendix

Table A 1. List of the analyzed documents, goals, and RFAs in Chapter 3

#	Reference	MWI Goals	Research Focus Areas (RFAs)
1	(Molle et al., 2017)	not align	Hydrogeological Field Measurement, Socio-Economy
2	(Verhagen et al., 1991)	2.f.	Laboratory Water Sample Analyses
3	(Bajjali & Al-Hadidi, 2006)	2.f.	Laboratory Water Sample Analyses
4	(Abu-Jaber et al., 1998)	2.f.	Hydrogeological Field Measurement, Laboratory Water Sample Analyses
5	(Salameh, Toll, et al., 2018)	2.c., 2.f.	Laboratory Water Sample Analyses, Modeling
6	(Abu-El-Shar & Rihani, 2007)	2.f.	Modeling
7	(F. Abdulla et al., 2000)	2.a.	Modeling
8	(Al-Kharabsheh, 2000)	2.f.	Modeling
9	(Al Qatarneh et al., 2018)	1.c.	Modeling
10	(Amro et al., 2001)	not align	Laboratory Soil Sample Analyses
11	(Al-Bakri, 2014)	1.b., 4.d.	Hydrogeological Field Measurement, Remote sensing
12	(Demilecamps & Sartawi, 2010)	4.d.	Agriculture, Hydrogeological Field Measurement, Remote sensing
13	(Al Eisawi, 2005)	1.a., 4.a.	Agriculture, Hydrogeological Field Measurement, Socio-Economy
14	(Rimawi & Udluft, 1985)	2.b.	Laboratory Water Sample Analyses, Modeling
15	(El-Waheidi et al., 1992)	2.b.	Geophysics, Hydrogeological Field Measurement
16	(Al-Tabini et al., 2014)	1.a., 4.a.	Hydrogeological Field Measurement, Modeling, Socio-Economy
17	(GIZ, 2015)	1.a., 4.a.	Agriculture, Energy, Hydrogeological Field Measurement, Socio-Economy
18	(Hamberger et al., 2009)	1.b.	Hydrogeological Field Measurement, Modeling, Socio-Economy
19	(Al Naber et al., 2017)	1.b., 4.e.	Agriculture, Hydrogeological Field Measurement, Socio-Economy
20	(Al-Bakri et al., 2016b)	1.b., 4.d.	Hydrogeological Field Measurement, Remote sensing
21	(Mesnil & Habjoka, 2012)	1.b., 4.d.	Agriculture, Hydrogeological Field Measurement, Remote sensing
22	(Consulting Engineers Salzgitter (CES) and Arabtech Consulting Engineers, 1994)	1.c.	Modeling
23	(Ayed, 1986)	1.c., 2.d.	Modeling

24	(Taany et al., 2014)	1.c., 2.a., 2.f.	Agriculture, Modeling, Socio-Economy
25	(Y. A. Al-Zubi, 2009)	1.c.	Modeling
26	(Gaj et al., 2015)	1.c., 2.f.	Modeling
27	(Shatnawi, R. & AlAyyash, S., 2014)	1.c.	Modeling
28	(Margane et al., 2017)	2.a., 2.g.	Hydrogeological Field Measurement, Socio-Economy
29	(Yogeshwar et al., 2013)	2.a.	Geophysics, Hydrogeological Field Measurement
30	(Aburub & Hadi, 2018)	2.a.	Modeling
31	(Al-Shabeeb et al., 2018)	2.a.	Modeling
32	(Y. Al-Zubi et al., 2002)	2.a., 2.g.	Agriculture, Modeling, Socio-Economy
33	(El-Naqa, 2010)	2.b., 2.c.	Geophysics, Hydrogeological Field Measurement, Laboratory Soil Sample Analyses, Laboratory Water Sample Analyses
34	(El-naqa et al., 2012)	2.b., 2.c.	Geophysics, Hydrogeological Field Measurement
35	(Abu Rajab & El-Naqa, 2013)	2.b.	Geophysics, Laboratory Water Sample Analyses
36	(Al-Momani et al., 2006)	2.b., 2.c.	Hydrogeological Field Measurement, Laboratory Soil Sample Analyses, Laboratory Water Sample Analyses, Modeling
37	(Jasem & Alraggad, 2010)	2.c.	Modeling
38	(Al-Adamat et al., 2003)	2.c.	Laboratory Water Sample Analyses, Modeling, Remote sensing
39	(M. Ibrahim & Koch, 2015)	2.c.	Laboratory Water Sample Analyses, Modeling
40	(Gassen et al., 2013)	2.c.	Hydrogeological Field Measurement, Remote sensing
41	(Worzyk & Hueser, 1987)	2.c.	Geophysics, Hydrogeological Field Measurement
42	(K. Ibrahim & El-Naqa, 2018)	2.c.	Modeling
43	(El-Naqa et al., 2007)	2.c.	Laboratory Water Sample Analyses
44	(Kaudse et al., 2016)	2.c.	Laboratory Water Sample Analyses, Modeling
45	(Baïsset et al., 2016)	2.c., 2.f.	Geophysics, Laboratory Water Sample Analyses, Modeling
46	(Baban et al., 2006)	2.c., 5.b.	Agriculture, Laboratory Water Sample Analyses, Remote sensing
47	(Al-adamat et al., 2006)	2.c., 5.d.	Laboratory Soil Sample Analyses, Laboratory Water Sample Analyses, Socio-Economy
48	(Obeidat & Rimawi, 2017)	2.c.	Laboratory Water Sample Analyses, Modeling
49	(Batayneh & Barjous, 2005)	2.c.	Geophysics, Laboratory Soil Sample Analyses
50	(Alraggad & Jasem, 2010)	2.d., 6.c.	Hydrogeological Field Measurement, Modeling
51	(Abu-Taleb, 1999)	2.d.	Hydrogeological Field Measurement
52	(Al-Adamat, 2008)	2.d., 6.c.	Modeling, Socio-Economy

53	(Al-Adamat, 2012)	2.d., 6.c.	Modeling
54	(Al-Amoush et al., 2015)	2.d.	Geophysics, Hydrogeological Field Measurement
55	(Al-Amoush et al., 2016)	2.d.	Geophysics, Hydrogeological Field Measurement
56	(Al-Shabeeb, 2016)	2.d., 6.c.	Modeling
57	(Taqieddin et al., 1995)	2.d., 6.c.	Modeling
58	(Al-Amoush, 2010)	2.d., 6.c.	Geophysics, Hydrogeological Field Measurement
59	(Steinel, 2012)	2.d., 6.c.	Hydrogeological Field Measurement, Laboratory Soil Sample Analyses, Modeling, Remote sensing, Socio-Economy
60	(Steinel et al., 2016)	2.d., 6.c.	Hydrogeological Field Measurement, Laboratory Soil Sample Analyses, Modeling, Remote sensing, Socio-Economy
61	(J. Al-Zubi et al., 2010)	2.d., 4.f., 6.c.	Modeling
62	(Shawaqfah et al., 2015)	2.d.	Modeling
63	(Saint-Jean & Singhroy, 2000)	2.d., 6.c.	Hydrogeological Field Measurement, Remote sensing
64	(Taany, 2013)	2.d., 6.c.	Modeling
65	(Yusra Al-Husban, 2017)	2.d.	Modeling
66	(Salameh et al., 2014)	2.d.	Laboratory Water Sample Analyses
67	(Al-Kharabsheh, 1996)	2.f.	Hydrogeological Field Measurement
68	(Abu-El-Shar & Hatamleh, 2007)	2.f.	Modeling
69	(Dottridge & Abu Jaber, 1999)	2.f., 2.g.	Modeling
70	(Moqbel & Abu-El-Sha’r, 2018)	2.f.	Modeling
71	(UN-ESCWA and BGR, 2013)	not align	Hydrogeological Field Measurement
72	(BGR/ESCWA, 1996)	2.f., 2.i.	Modeling, Remote sensing
73	(Leyronas et al., 2016)	3.a.,3.b.	Socio-Economy
74	(Octavio et al., 2008)	4.a.	Hydrogeological Field Measurement, Modeling, Socio-Economy
75	(Al-Naber, 2016)	2.g., 4.e.	Agriculture, Hydrogeological Field Measurement, Socio-Economy
76	(Sawarieh, 2008)	6.e.	Energy
77	(Mohsen & Jaber, 2001)	2.b., 6.e.	Energy, Modeling
78	(Shatnawi et al., 2014)	not align	Modeling
79	(Goode et al., 2013)	not align	Modeling
80	(Yogeshwar & Tezkan, 2017)	not align	Geophysics, Hydrogeological Field Measurement
81	(Al-Amoush & Rajab, 2018)	not align	Geophysics, Hydrogeological Field Measurement

82	(Batayneh et al., 2001)	2.c.	Geophysics, Hydrogeological Field Measurement
83	(United States Agency for International Development (USAID)/ISSP project, 2014b)	not align	Agriculture, Hydrogeological Field Measurement, Modeling, Socio-Economy
84	(United States Agency for International Development (USAID)/ISSP project, 2014a)	not align	Agriculture, Hydrogeological Field Measurement, Modeling, Socio-Economy
85	(Al Naber & Molle, 2017)	not align	Socio-Economy,Hydrogeological Field Measurment ,Agriculture
86	(Mesnil et al., 2014)	4.d.	Energy, Hydrogeological Field Measurement, Socio-Economy
87	(Almomani, 1996)	2.f.	Laboratory Water Sample Analyses
88	(Rawajfih et al., 2005)	not align	Laboratory Soil Sample Analyses
89	(Rawajfih et al., 2002)	not align	Laboratory Soil Sample Analyses
90	(Khresat & Qudah, 2006)	not align	Hydrogeological Field Measurement, Laboratory Soil Sample Analyses
91	(Ahmad & Davies, 2018)	not align	Laboratory Soil Sample Analyses
92	(Tansey et al., 1999)	not align	Laboratory Soil Sample Analyses, Remote sensing
93	(K. Ibrahim, 1996)	not align	Hydrogeological Field Measurement, Remote sensing, Socio-Economy
94	(Shawash & Al-Bakri, 2015)	4.d.	Agriculture, Hydrogeological Field Measurement, Remote sensing
95	(Shahbaz & Sunna, 2000)	2.g.	Hydrogeological Field Measurement, Remote sensing
96	(Essa & Detection, 2004)	not align	Modeling, Remote sensing
97	(Kloub et al., 2010)	not align	Modeling, Remote sensing
98	(Zanchetta et al., 2016)	not align	Hydrogeological Field Measurement, Modeling, Remote sensing
99	(Al-Adamat & Baban, 2004)	not align	Modeling