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Implementation of Simple Strategies to Improve Wellfield Management in Arid Regions: The Case Study of Wadi Al Arab Wellfield, Jordan

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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. 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 four 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.

Keywords: groundwater management; wellfield management; decision support system (DSS); arid region; water supply; maintenance and operation (M&O)

1. Introduction

In many countries, especially those located in arid to semi-arid regions, precautions are taken against water scarcity [1,2]. Optimization of well field management practices and water quality protection received much attention in different regions in the world [3–11]. 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 [12,13]. 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 [14–22] and groundwater quantity [23–27].

Among the reasons for water scarcity in Jordan are climate change [28–35], population growth [36], geopolitical location as a downstream country, and refugee influxes due to political instability in the region [37]. In Jordan, water scarcity poses serious challenges for the wellbeing, security and economic development of the country [38]. 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 [39] and granting a more constant and reliable supply of water to the population [40]. According to [41], 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 [42], 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 [37], 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 [43]. 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 [44], most of them focused on either top level [45] or bottom level [46] 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 [47]. Usually, a top-down approach would not consider or plan for the priorities identified at the bottom level in their strategy [48]. Brown [49] mentioned that the knowledge culture varies at different stakeholder levels [47]. 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 [50] 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 [51,52].

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 [53]. Moreover, the strategy states that "deeper knowledge of the availability, quality, and protection of water is the foundation for effective decision-making" [53] (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 2 gives a general description of the study area. Section 3 describes the methodology that was implemented, including the operational decision support tool (ODST), measurement procedure and stakeholder engagement. Section 4 shows the quantitative results collected during the project. Section 5 depicts the discussion of the results. Finally, Section 6 presents our conclusions.

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 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.

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 [16,26,34,54,55]. 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 [55].

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 1 shows the location, elevation and completion date of all Wadi Al Arab wells.

In general, a cost-effective groundwater well design should last at least between 20 and 25 years [56]. Harter [57] 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.

Table 1. List of Wadi Al Arab wells with the Palestine Belt 1923 (PB) coordinates and 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 1982
AE1008	WA 2	32° 37′12.81401″	35°39′30.96736″	−35.36	Sep 1982
AE1009	WA 3	32° 37′26.67630″	35°39′52.15763″	−26.08	Nov 1982
AE3020	WA 3A	32°37′26.37884″	35°39′52.12241″	−25.87	Jun 2009
AE1010	WA 4	32°37′57.04019″	35°40′18.63580″	19.56	Sep 1982
AE1011	WA 5	32°35′48.60537″	35°40′01.84178″	47.00	Jan 1983
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 2003
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 2008
AE3042	WA 13A	32°36′34.52057″	35°40′04.92756″	104.87	Feb 2017
AE3021	WA 14	32°36′14.04827″	35°39′58.57560″	70.98	Jun 2009
AE3024	WA 15	32°36′57.18547″	35°39′35.25914″	32.58	Jul 2014
AE3027	WA 16	32°36′44.95781″	35°39′48.68497″	71.77	Sep 2014
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

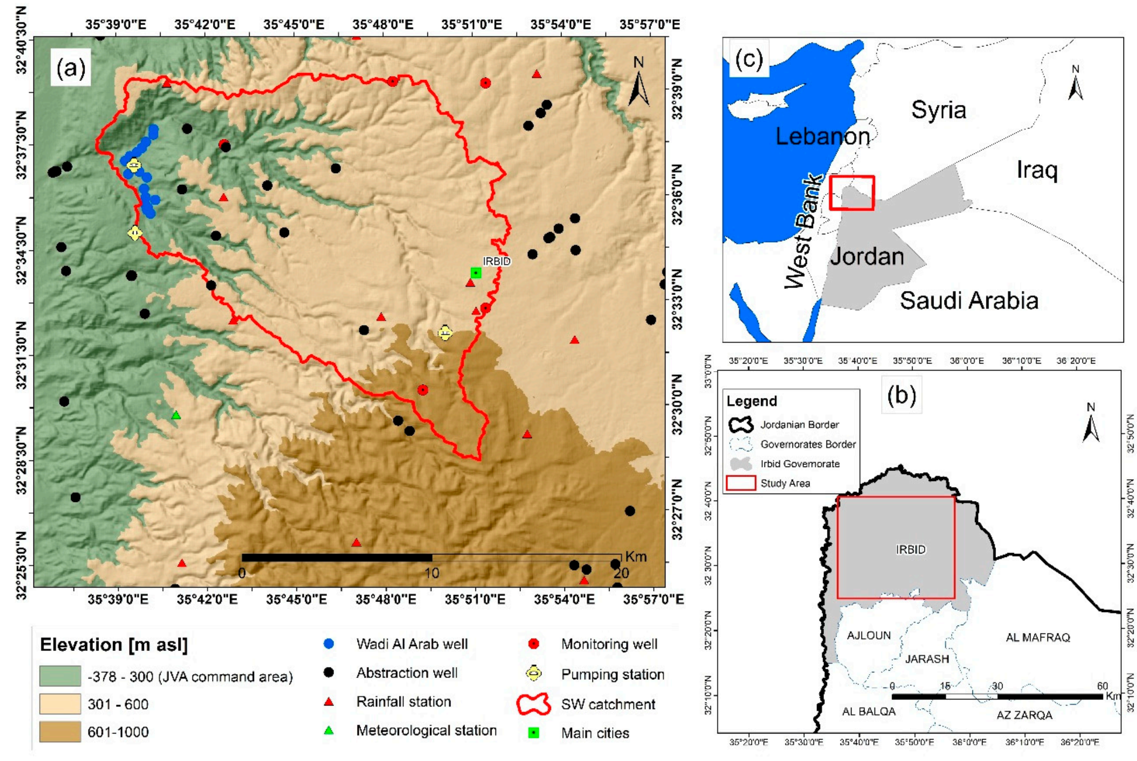


Figure 1. Overview map of the study area. (**a**) Shows the location the wells, rainfall stations, meteorological station, pumping stations and surface catchment area, it also shows the area topography. (**b**) Shows the area of Irbid governorate and the study area. (**c**) Shows the location of Jordan and surrounding countries.

2.1. Rainfall and Temperature

Daily rainfall data was collected from 13 stations located in the area (Figure 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 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 3).

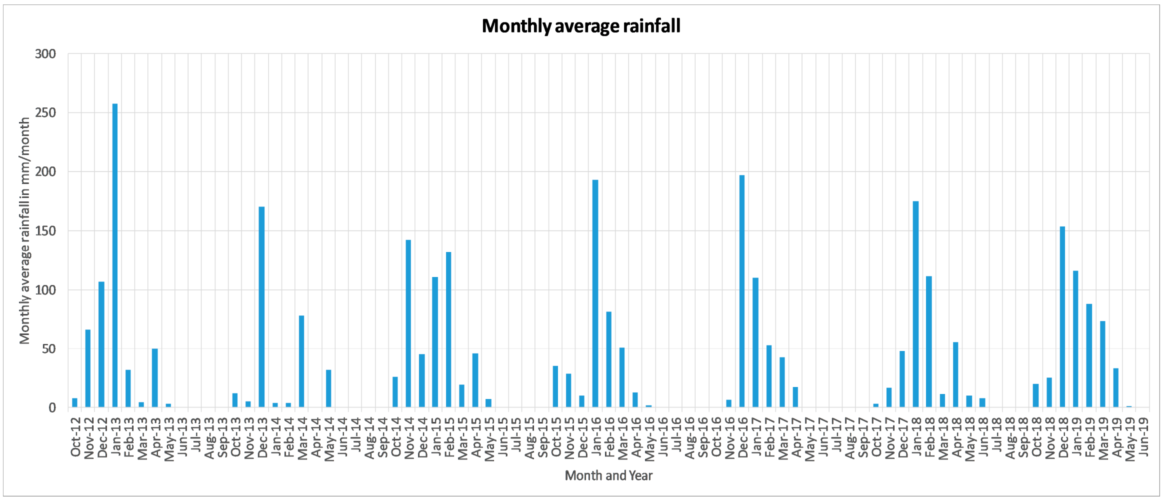


Figure 2. Average of monthly rainfall for the rainfall stations in the study area.

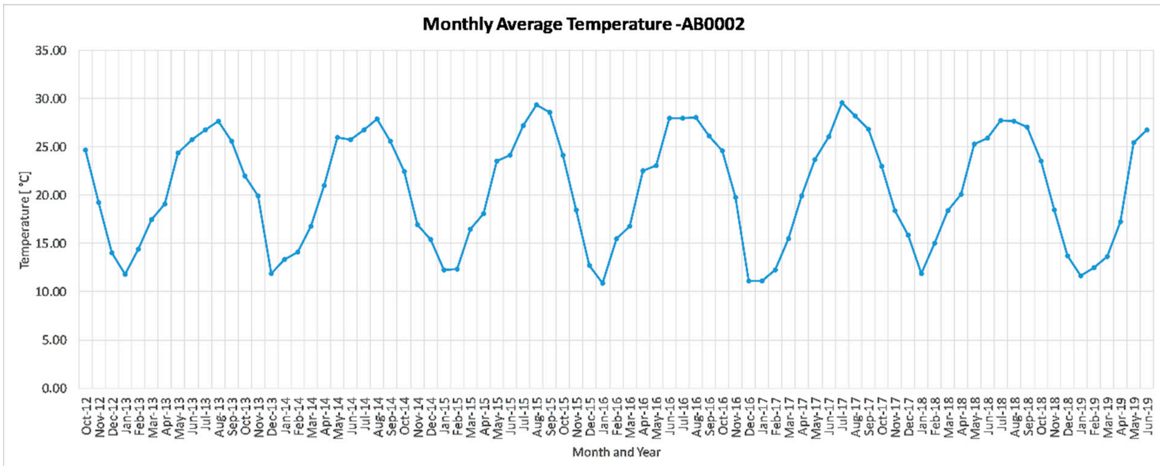


Figure 3. Average of monthly rainfall for the rainfall stations in the study area.

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 2) [58].

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). 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.

The water level in the Wadi Al Arab wellfield has decreased between 100 m and 150 m over the past 23 years (Figure 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.

Table 2. Description of the hydrogeological units in the study area (adopted from [55]).

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	
Muwaqqar	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	

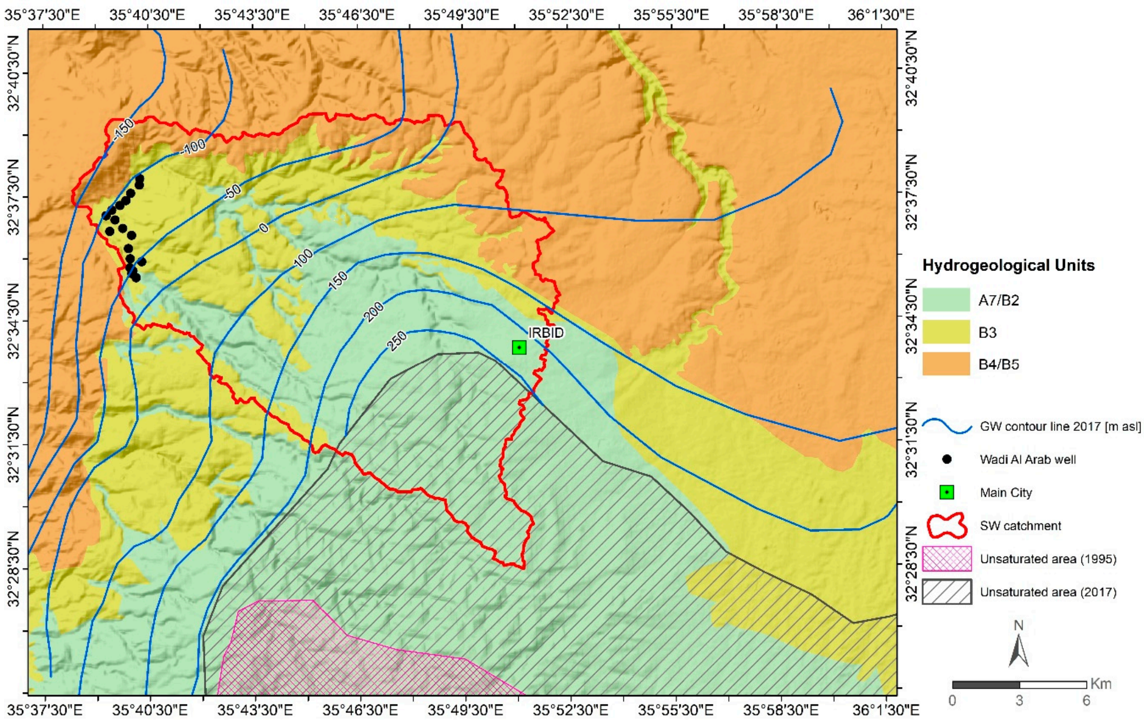


Figure 4. Groundwater contour map of the area of Wadi Al Arab.

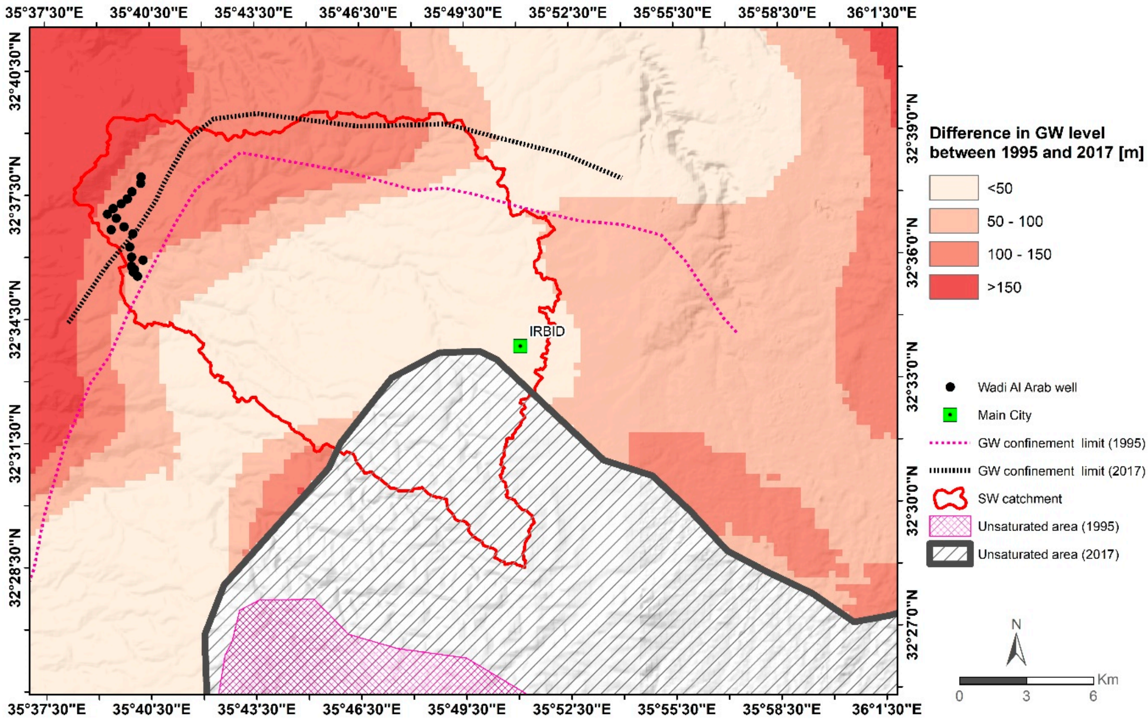


Figure 5. The decrease in the saturated thickness between the year 1995 and 2017.

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.

3. Methodology

3.1. Tools Development

Tools play a significant role in data management and in decision making process [59]. 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.

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 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).

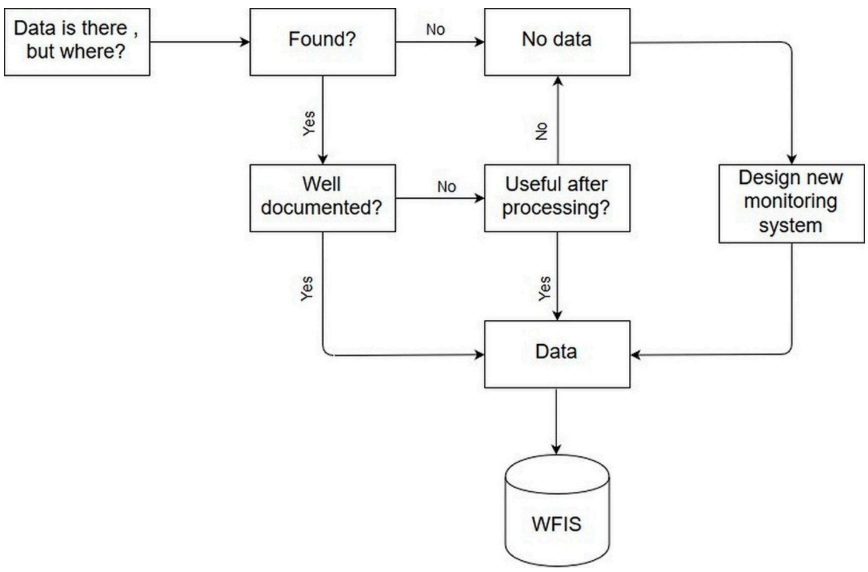
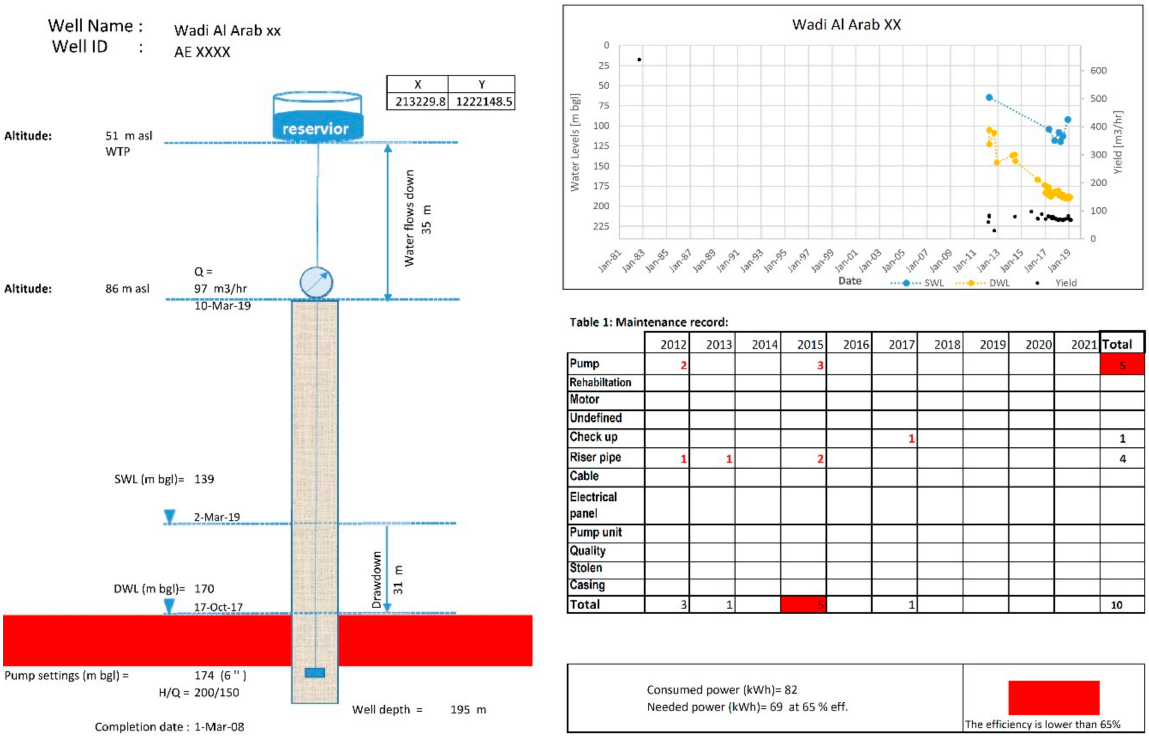


Figure 6. Schematic diagram for the followed processes to build the wellfield information system (WFIS).

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.

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 Excel dashboard (Figure 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 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.



	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 7. Operational decision support tool for wellfield management.

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 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.

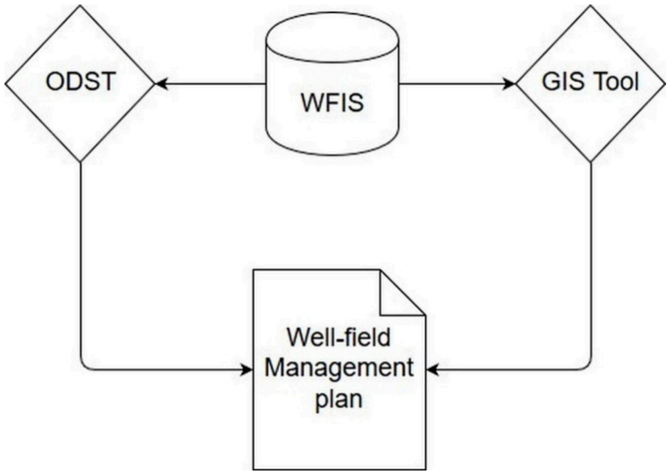


Figure 8. Wellfield management tools development flowchart.

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 [60]. 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 1 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 3).

Table 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

3.3. Stakeholder Engagement

Stakeholder participation was central to this research for the I-GWRM project team. Two of the methodological characteristics, presented by [50], 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 [50] 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" [50] (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. Results

Water pumping consumes around 15% of total electricity consumption in Jordan [61]. 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 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 10). It can be also noticed that the electricity consumption decreased by 5% between 2017 and 2018 (Figure 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 10). This cost increase has to also consider the increase of the electricity tariff, shown in Figure 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.

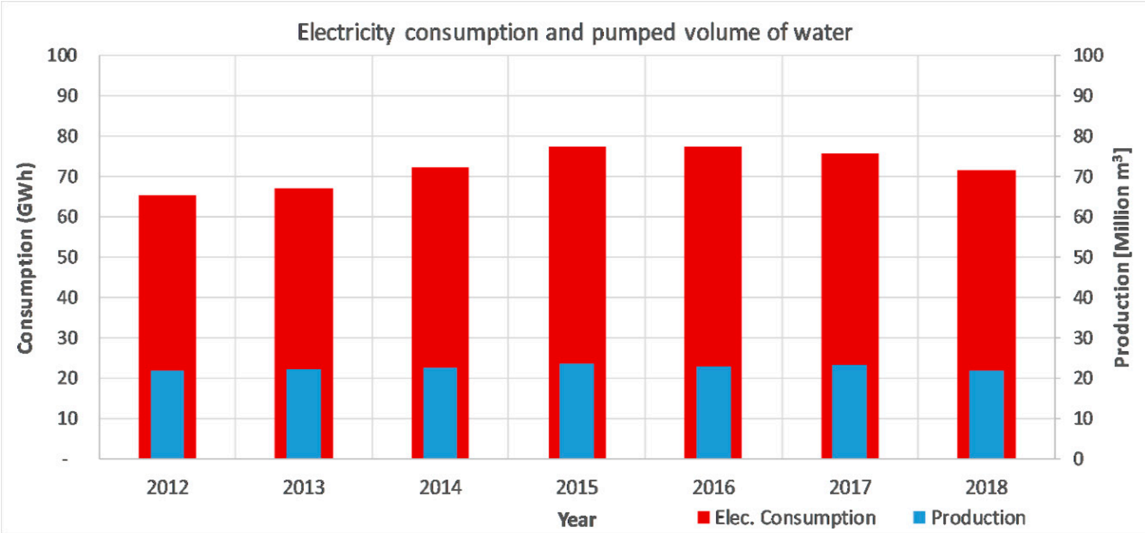


Figure 9. Total production (in the system) and Energy consumption of Wadi Al Arab wells and the three pumping stations 2012–2017.

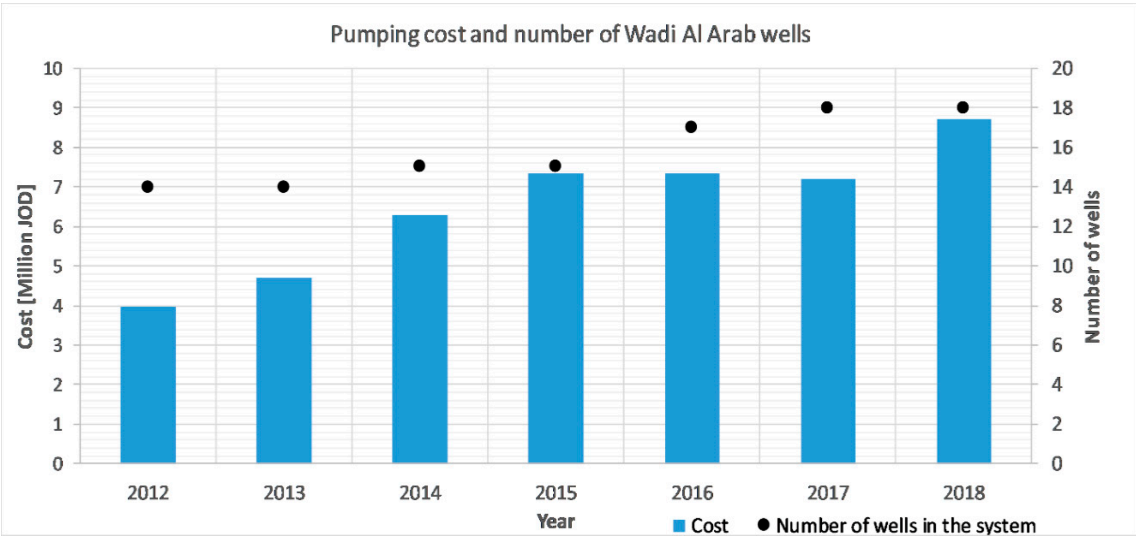


Figure 10. The cost of pumping the water from Wadi Al Arab wells and through the three pumping stations. The exchange rate during the mentioned period (1 JOD = 1.41 US dollar).

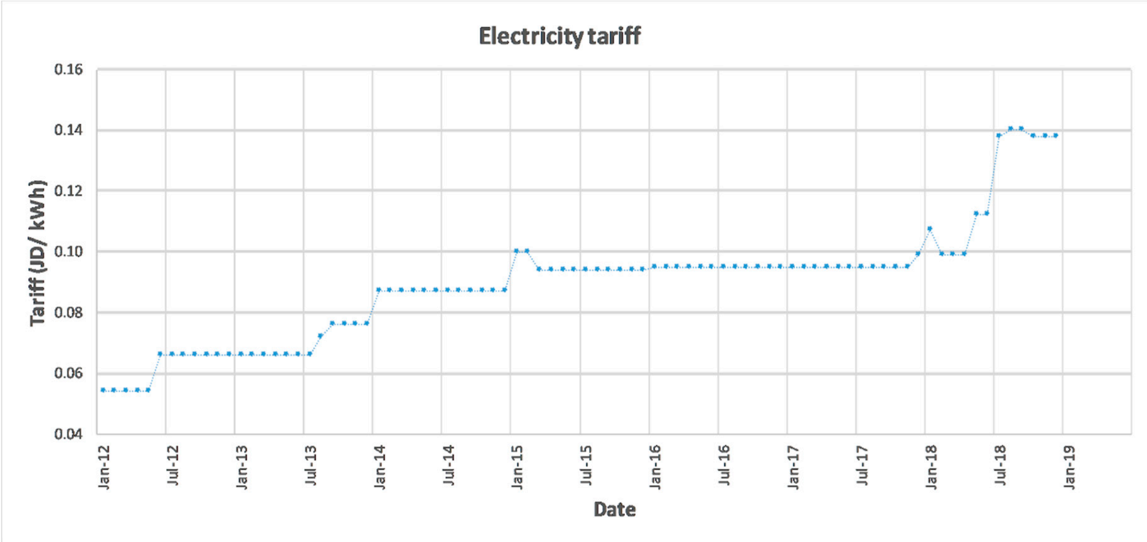


Figure 11. Average of the monthly electricity tariff for the water utility—Wadi Al Arab area (2012–2018).

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 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 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.

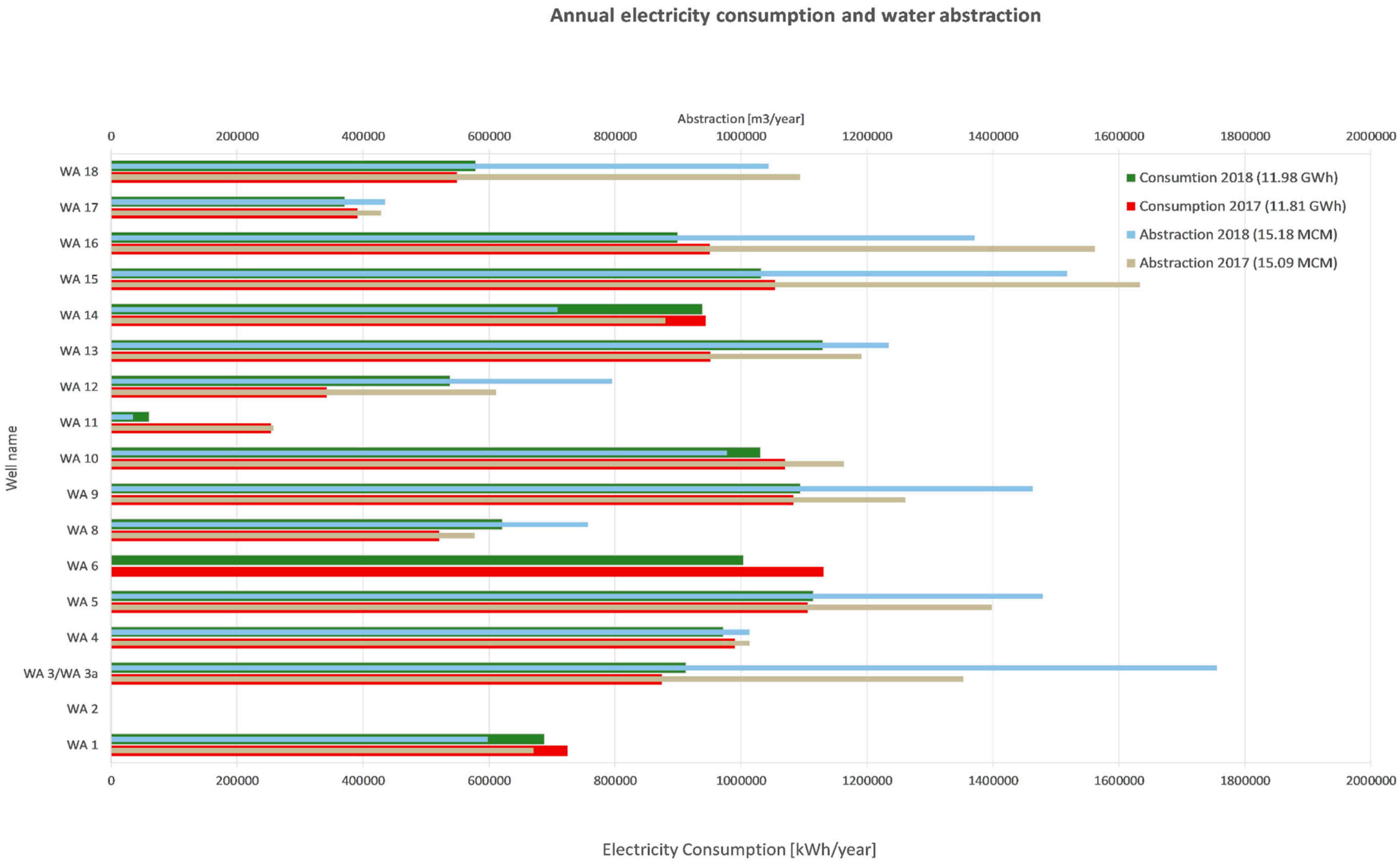


Figure 12. Electricity consumption and production in the wells of Wadi Al Arab (WA) wellfield in 2017 (no abstraction and electricity consumption as WA2. WA3 and WA3a had one electricity meter, no abstraction data was found for WA 6 as it doesn't pump water to the WA pumping station).

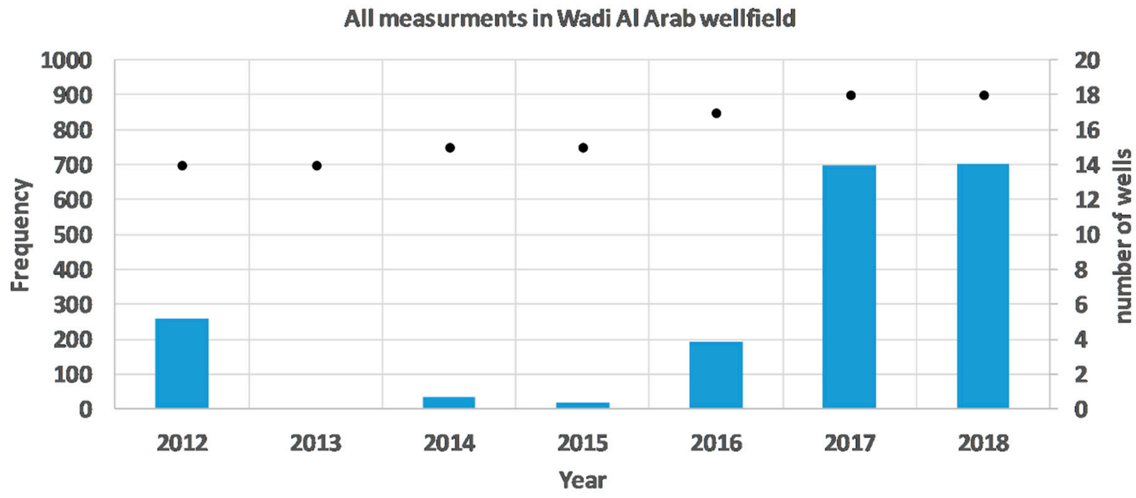


Figure 13. Number of annual field measurement between (2012–2018) (represented as columns) and number of wells (represented as scatter points).

The number of collected field measurements per month are shown in Figure 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.

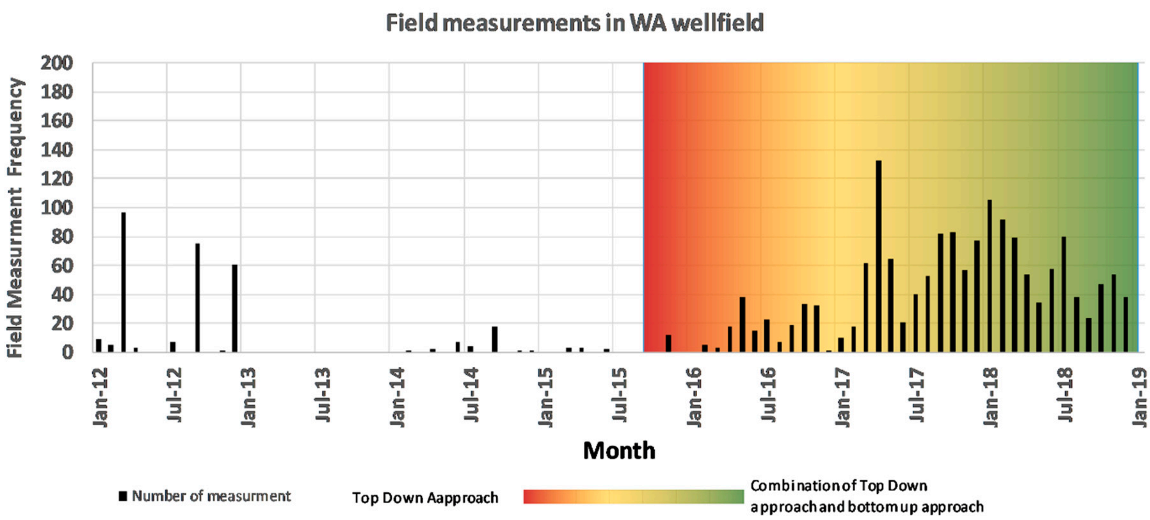


Figure 14. Number of monthly field measurements and the transaction period between top-down (red color) and the combination of top-down and bottom-up approaches (green color).

Figure 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 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.

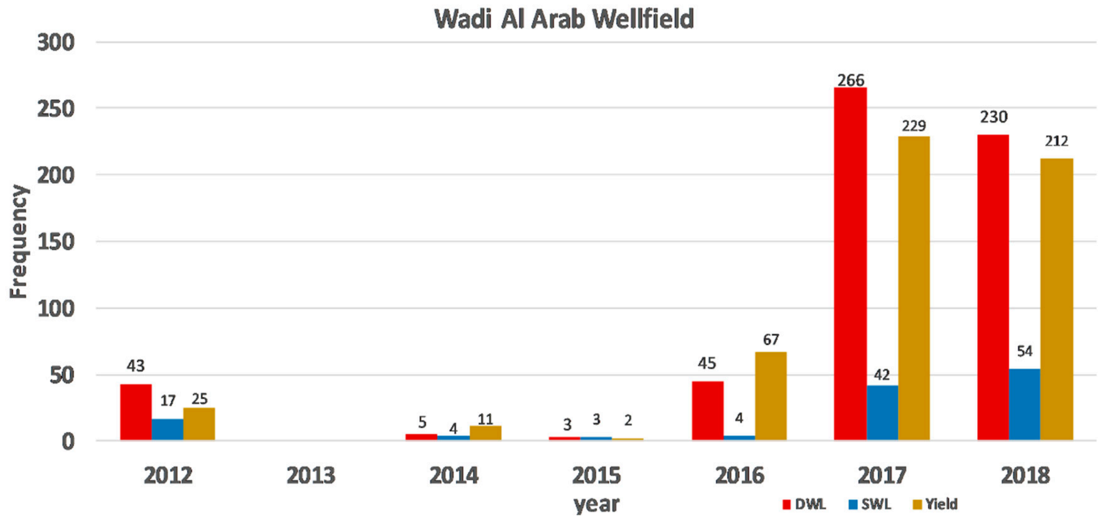


Figure 15. Number of field measurement frequency in Wadi Al Arab wellfield between the year 2012–2017 (2013 is missing).

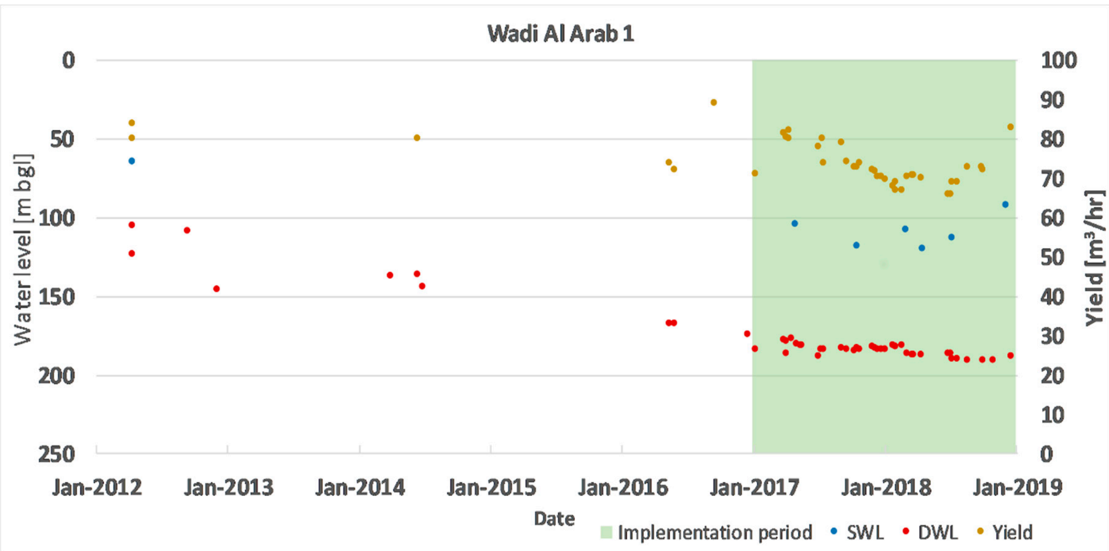


Figure 16. Improvement of field measurements (SWL, DWL and yield) before and during the implementation period of the tools, using WA-1 well as an example.

The maintenance intervals/periods mentioned in Table 4 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. 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**

5. Discussion

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.

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.

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.

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.

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