



**Development, Evaluation and Ranking of
Managed Aquifer Recharge (MAR) Planning Options
in Case Study Areas of the Lower Jordan Valley**

Special Deliverable
Consolidating Deliverables

D318 and D320

Editors

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0. Executive Summary

The Lower Jordan Valley (LJV) faces increasing pressures on the scarce water resources and water shortages. Especially the agricultural sector, as main water user, is suffering serious restrictions due to water scarcity. The present deliverable focuses on the potential and feasibility of Managed Aquifer Recharge (MAR) to improve the water supply reliability and to strengthen agricultural development, considering case study areas in Palestine and Jordan. The study shows that MAR is to be considered as obligatory IWRM measure for the region which should be implemented in a short term in order to improve the water supply situation. In order to study the viability of water storage and recovery in the shallow alluvial groundwater system as well as the performance of different MAR planning options, a numerical groundwater flow model has been applied. The results of the preliminary groundwater flow model show that the most promising MAR planning options in the valley refer to the infiltration of spring and surface runoff surpluses directly in the demand (irrigated) areas due to the high efficiency of water recovery and resulting groundwater level increase of the overexploited shallow aquifer. In the valley, the shallow aquifer system, as shown by case studies at Auja, Jericho and Deir Alla, is the only underground storage facility which guarantees the required control on the recharged water. MAR-implementation in the valley should mainly rely on water surpluses from springs and surface runoff. The Wadi Wala case study proves that under specific hydrogeological conditions, the Karst aquifer system may serve for Managed Aquifer recharge purposes, too. MAR-potential, water supply reliability and agricultural production may be further enhanced by direct irrigation of salt-resistant crops with treated effluents after mixing with brackish groundwater and installation of deep wells in the Karst aquifer system. All springs, due to their high water potential, are most important water sources for Managed Aquifer Recharge and require protection and careful exploitation. In order to ensure the recharge of large volumes of water in short time periods, preference should be given to infiltration structures for aquifer recharge. Their combination with infiltration wells, as so-called hybrid solutions, would further enhance the recharge potential but requires further studies. Since in the Palestinian areas, surface water reservoirs (e.g. Auja dam) suffer from high water losses (besides evaporation) from percolation into the Karst aquifer system, the water should be transferred to the recharge facilities directly after accumulation and sedimentation. In the valley, investments for the improvement of the existing hydro-infrastructure are urgently required in order to reduce the high water losses, especially due to poorly maintained old canals. The shallow alluvial aquifer system in the valley requires better investigation with regards to its hydraulic characteristics and long-term storage of surface water surplus in the demand areas. The impact of extreme hydrological variability on MAR planning and system operation need to be studied in more detail, providing a better understanding how Managed Aquifer Recharge may contribute to efficient adaptation strategies. Additional studies on groundwater flow and transport will be required in order to consolidate MAR-planning options, to study the freshening of the shallow brackish groundwater system and optimal groundwater management (pumping) strategies. Since the region around Jericho and Auja is part of the major shallow aquifer system in the valley, integrated solutions for MAR planning and management on catchment cluster level are required in order to proceed towards implementation. The decision making process should be strictly participative, following the suggested MAR-planning procedure.

1. Introduction

1.1 Contents

This document summarizes the work carried out in the frame of two deliverables of work-package WP3.2:

- **Deliverable 318:** Identification of the most suitable areas for the implementation of Managed Aquifer Recharge (MAR) in the Lower Jordan Valley;
- **Deliverable 320:** Development, evaluation, comparison and ranking of MAR-Planning options.

The reason for lumping these two deliverables stems from their deep inter-dependence and the conclusion of the editors that one integrated document has the potential to better contribute to the overall understanding of the methodologies and tools employed in the preparation of this document.

The document refers to three main case study areas on Managed Aquifer Recharge planning and implementation in the Lower Jordan Valley (LJV), namely the the case study Wadi Auja and Jericho in the Palestinian Territories in the West-Bank and the Deir Alla case study at the lower reach of the King Abdullah Canal in Jordan, providing some complementary results achieved at Wadi wala, too.

1.2 Importance of Managed Aquifer Recharge for the Region

The Lower Jordan Valley (LJV) faces semiarid to arid conditions and increasing pressures on the scarce water resources. Since drinking water supply has to be treated with highest priority, especially the agricultural sector, as main water user, is suffering serious restrictions due to water scarcity in spite of the need to increase food production for the growing local population and to extend the areas under irrigation. The region around the city of Jericho and Auja village is also known as the Palestinian Food-basket, due to its fertile soils, favourable climate and dominance of irrigated agriculture as main economic sector. Due to very low natural precipitation, crops require irrigation for agricultural production. The main limitation for the extension of irrigated lands is the amount of available sweet water during the irrigation season. During water scarcity conditions, agriculture mainly relies on the shallow alluvial groundwater system which contains partially brackish water.

Non-conventional water resources, such as treated wastewater, brackish water, water from flash floods, and imported water need to be considered in order to cover the increasing water demand and to provide sustainable development. Surface runoff appears in the form of so-called flash-floods. Most of this water is lost if not properly stored and managed. Some of the local sweet water springs from the regional Karst aquifer system present a great water potential but extremely high discharge fluctuation with significantly lower rates during summer time. In general, high water demand during summer coincides with the minimal available resources. Water storage facilities and adapted management concepts are required in order to match the supply with demand. Due to considerable water losses by evaporation from open water storage, the storage of water in the underground is an important management option for the region. Due to the need to control the recharged water for later recovery mainly for irrigation purposes, the shallow alluvial aquifer system in the valley gains a particular importance for Managed Aquifer Recharge. Therefore, MAR implementation would increase the water supply reliability and eventually permit the extension of irrigated lands. During the last decades, the water scarcity situation was resulting in groundwater over-exploitation, groundwater level decline and a salinity increase in the shallow alluvial aquifer system.

Managed Aquifer Recharge (MAR) permits the managed conjunctive use of surface- and ground-water resources and, therefore, is an important component of IWRM. The implementation of a MAR system requires careful planning in terms of achieving efficient integration into the water resources system and the overall water resources management objectives ([Rustenberg et al., 2008](#)). The roles that MAR may play within the framework of a water resources system are: short and long term storage for later recovery during dry seasons, recovery of groundwater level of over-exploited aquifers, provision of barriers to seawater intrusion in coastal areas, improvement of water quality, use of the aquifer as a water distribution system for individual users, and flood-prevention by deviating peak-flows.

MAR may be also applied for low-cost water reclamation and reuse in irrigated agriculture with low water quality requirements, especially if reused for restricted irrigation. Israel may be considered one of the pioneers of Soil-Aquifer-Treatment, a MAR technique which has been practiced over decades in Israel at various locations. Treated effluent of 124 MCM per year of the Dan region is recharged into the coastal aquifer by means of infiltration ponds, and is pumped after a residence time of at least six months. As based on the achieved water quality standard, the water is used for unrestricted irrigation in the Negev desert.

In the context of IWRM, MAR has to be understood as an optional measure, competing with other water resources planning and management solutions ([Rustenberg et al.; 2012](#)).

2. Research Objectives

The guiding research and development objectives of the deliverable are:

- Develop, evaluate, compare and rank different MAR-Planning options in selected case study areas in the Lower Jordan Valley;
- Select adequate sites and technologies for MAR in the LJV;
- Develop recommendations with regards to:
 - a. the methodological approach for MAR-Planning
 - b. adequate indicators for project planning
 - c. the application of numerical groundwater models
 - d. MAR Implementation in the LJV
 - e. continued research and data assessment

Altogether, this work will summarize the activities, achieved results, main conclusions and recommendations with regards to the potential and most promising alternatives for MAR implementation in the selected representative case study areas in the Lower Jordan Valley.

3. Overall Research Methodology

The planning of Managed Aquifer Recharge (MAR) is highly dependent on site specific parameters. Quality and quantity of the water source as well as their variation over the year, hydrogeology of the study area, operation and implementation costs, competing storage alternatives or social acceptance are of major importance but strongly depend on local characteristics. This brings up a problem in replicating other successful implementations. Especially the local hydrological and hydrogeological characteristics limit the applicability of elsewhere approved planning options (MWR, 2000). Thus, a generalized approach is required in order to develop suitable MAR Planning Options (MPOs) in the Lower Jordan Valley.

On the other hand, MAR implementation is not only a local or site specific task, which is restricted to the underground storage of water or to water quality improvement due to recharge, but should also be part of a regional IWRM approach on the basin level. MAR permits the joint management of surface water, groundwater, and wastewater resources and is therefore an important integrating element of IWRM. MAR implementation should contribute to the achievement of the overall water management goals of the river basin. The most promising MAR options will have to be studied in terms of environmental impact, socio-economic efficiency, as well as their contribution to the prevailing or future water resources problems as seen on the basin level. In the context of IWRM, MAR has to be understood as an optional measure, competing with other water resources planning and management solutions.

The planning of MAR systems is a non-straightforward decision making process. Numerous, mostly interdependent decisions will have to be taken, e.g. with regards to the selection of a source of water to be recharged, the identification of suitable recharge sites and adequate recharge technologies, the pre-treatment of water before recharge, the volume of water to be recharged and, the subsequent recovery of the recharged water. Therefore, the methodology for MAR-Planning here applied follows an engineering approach as suggested by [Rustenberg et al. \(2012\)](#). The flowchart in figure 1.1 presents the procedure. The process starts the analysis of the water resources system and the prevailing water resources problems. For specific attention to the water scarcity problem, a water budget study should be undertaken to provide information about the mean monthly water deficits to be mitigated by MAR.

Following this pre-analysis, a set of alternative MAR planning and management options is being defined. Decisions have to be taken with regards to the sources of water to be applied

for aquifer recharge, volumes of water to be recharged per month, the most appropriate MAR technology, best locations to infiltrate or to inject the water, required water treatment before recharge and, roughly, the design of the MAR plant, indicating e.g. the required area for the installation of infiltration ponds. Impact and performance of MAR options in socio-economic and environmental terms towards the main water resources management objectives is evaluated based on appropriate decision criteria.

Environmental and water related decision criteria, such as changes in groundwater level or mean nitrate concentration, are commonly determined by means of mathematical simulation models for underground flow and transport. MAR planning options may be ranked by Multi-Criteria-Analysis procedures, which permit to take socio-economic and environmental impacts and system performance into consideration. Any MAR planning options impacts on the overall management of the water resources systems. These implications need to be studied before closing the analysis on MAR implementation.

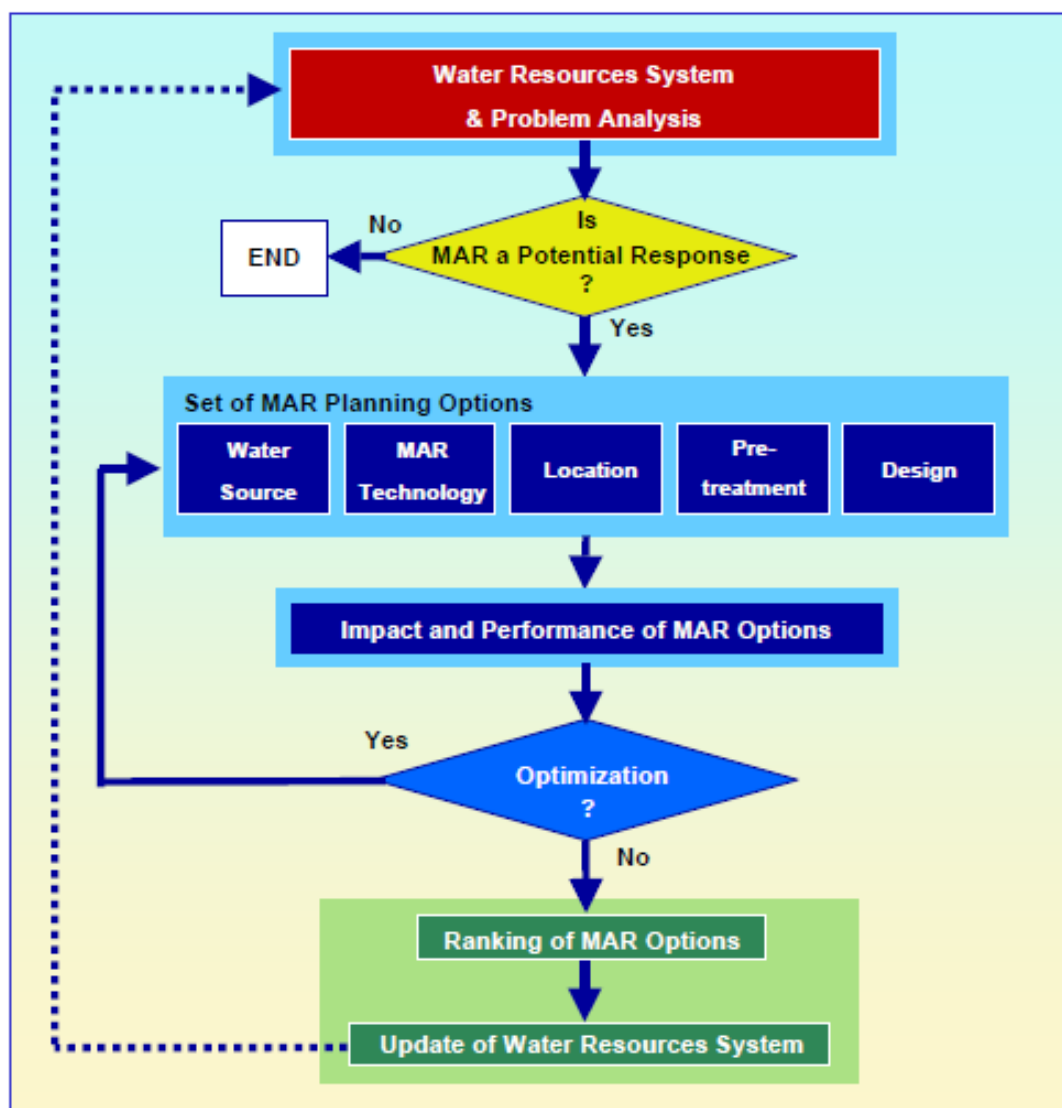


Figure 1.1: Flow-Chart for MAR Planning (Rustenberg et al.; 2012)

4. Case Study Auja

4.1 Introduction

The case study concentrates on Wadi Auja as a typical rural sub-catchment of the Lower Jordan Valley in the Palestinian-Israeli territory where people highly depend on irrigated agriculture. The lower areas of Wadi Auja in the valley are mainly classified as Area A under Palestinian administration. Nevertheless, hydro-infrastructure implementation on the ground should be considered as integrated effort which requires proper communication with the Israeli authority due its impact on water resources and their joint management.

Due to water scarcity, the agricultural area under irrigation is restricted to about 5000 dunam (500 ha) around the village. Irrigation mainly relies on Auja spring as main source of water and brackish groundwater from shallow wells. Due to missing water storage and management concepts, main part of these surface and spring water resources is lost. Furthermore, due to groundwater over-exploitation, the groundwater level of the shallow alluvial system is constantly decreasing during the last decades and suffering from salinization processes.

For the sustainable development of agriculture at Wadi Auja and extension of irrigated lands, the local water potential need to be better explored. This requires, besides other measures, the storage of surface water, including spring discharge surpluses during winter time and later recovery for irrigation purposes. According to figure 1.1, first of all, the question need to be answered if MAR is a potential and viable response to the prevailing water resources problems at Wadi Auja, before continuing with studies on the most appropriate MAR planning options as well as their performance and impacts.

4.2 Specific Research Objectives

Besides the main goals of research of the deliverables D318 and D320, the following specific objectives are linked to the case study of Wadi Auja::

- Study potential and viability of MAR implementation at Wadi Auja, taking alternative IWRM scenarios into account;
- Study the performance of alternative MAR Planning Options based on numerical groundwater flow modeling;
- Discuss economic viability and social dimension of MAR implementation to strengthen agricultural development;
- Develop recommendation for MAR-implementation at Wadi Auja.

4.3 Specific Research Methodology

The Wadi Auja case study follows the general methodology for MAR-Planning of figure 1.1 as suggested by Rusteberg et al. (2012). A focus is given on the environmental and operational performance of alternative MAR planning options, which is being studied by the groundwater flow modeling over a simulation period of 20 years, taking alternative IWRM scenarios into account. Economic and social aspects of MAR-Planning options are being discussed in this context.

4.4 Case Study Area

The study region at the Israeli-Palestinian territory comprises 3 watersheds, namely Al Qilt (189 km²), Al Nuemah (128 km²) and Al Auja (260km²), which are located in the south-eastern part of the West Bank. They extend from the central mountains of the West Bank in the west to the Jordan River in the east (Figure 4.1a). The lower parts of the 3 watersheds have considerable development potential with regards to trade and tourism. Furthermore, suitable climate and high land fertility result in a great agricultural potential. Therefore, the lower valley is of major importance for Palestinian crop production (JICA, 2007). Jericho city with 25000 habitants is the major urban center. The south-western parts near Ramallah-Al Bira present industrial and commercial potential. The difference in elevation between the lower and upper parts is around 1000m. The climate is arid to semi-arid with average annual rainfall from less than 100mm to 700mm and high evaporation of 2120mm/a in the LJV (Arij, 1998). The Eastern Groundwater basin of the West Bank is bounded by the major groundwater divide from the west, and the Jordan valley major fault from the east.

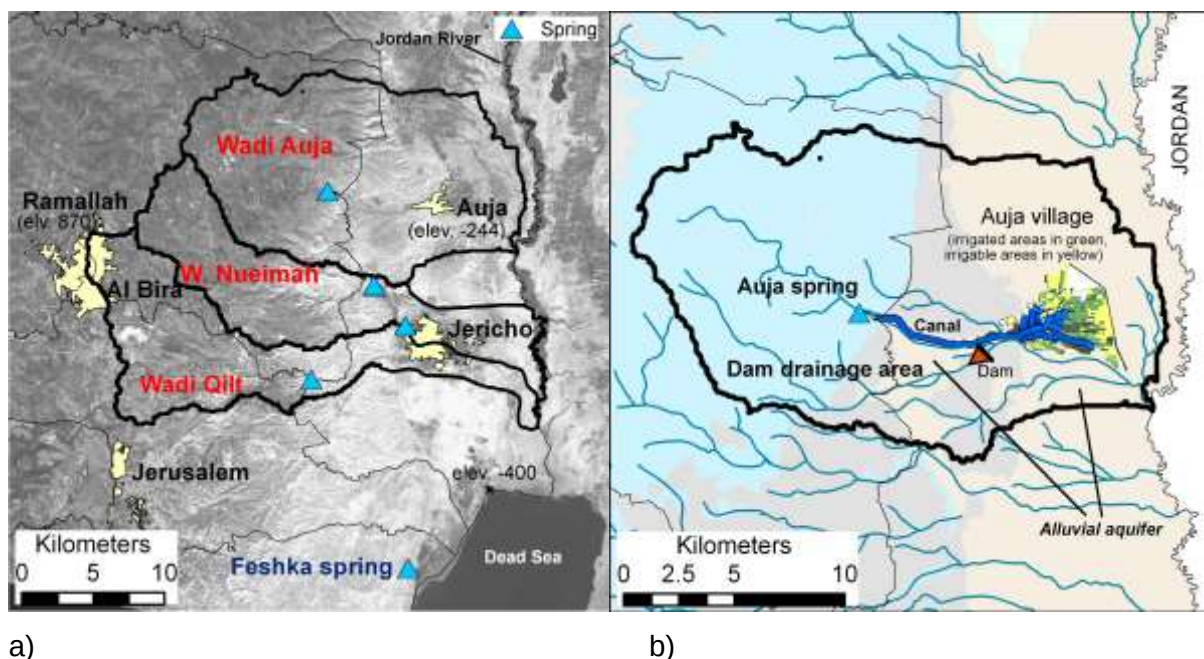


Figure 4.1: Study region (a) and case study area Wadi Auja (b)

4.4.1 Watershed and Basic Characteristics

Figure 4.1b presents the location of the Auja case study, a typical rural basin. Auja village (4550 habitants) strongly relies on agriculture and local water resources for socio-economic development (PCBS, 2010). Direct rainfall in the lower Valley area is about 156 mm annually (Shawahna, 2011), which is far below the average potential evapotranspiration rates of 2120.6 mm/a. Potential evapotranspiration rates outrange precipitation all over the year, with maximum rates during summer, reaching average values close to 300 mm in July. Temperatures in the study area range from 7.4 °C in January to 37.8 °C in July on the monthly average level. Mean annual temperature is 22.45 °C. Figure 4.2 shows the mean monthly data for temperature and direct precipitation of the climatic station at Jericho some 10 km in the south of the study area. The annual precipitation concentrates on the winter season between October and April, with its peak values during winter months at a maximum average of 53.7 mm in January while between the months of May and September practically no rainfall takes place. Rainfall mainly occurs in short events of very high intensity. These events periodically trigger storm floods with extremely high discharge rates, since precipitation in the mountainous areas in the upper Wadis is much higher than in the lower areas in the valley. Occasionally, precipitation height may reach XXX mm within few days. The dry soils in the valley are not able to take up the high volume of water within short time. Without proper flood retention structures most of the surface water discharge is lost towards the Dead Sea.

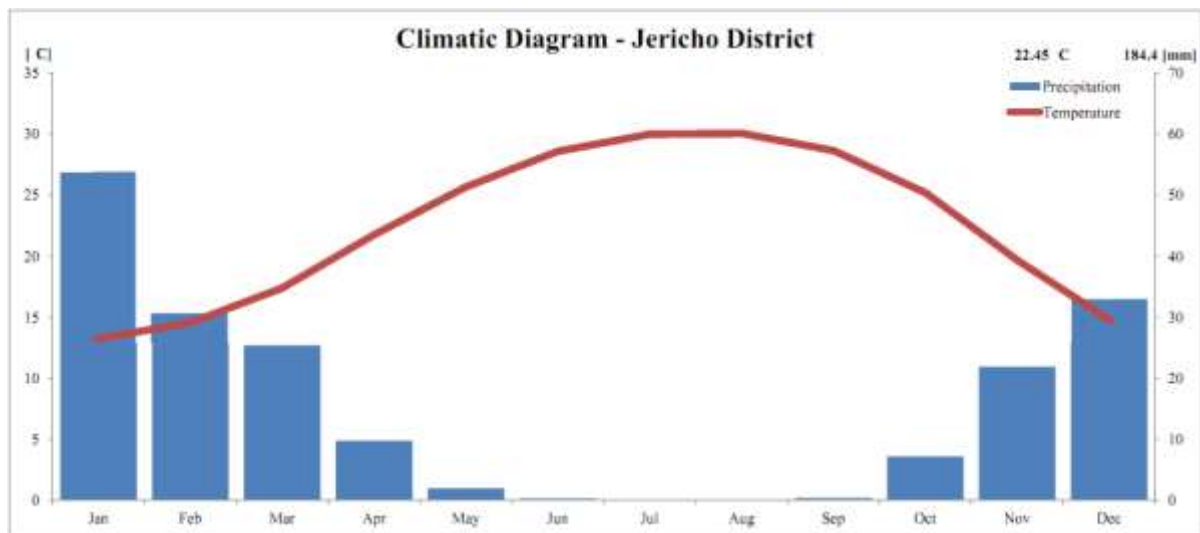


Figure 4.2: Climatic Diagram - Jericho District

The spring presents intermittent discharge behaviour and strong fluctuation during 40 years of available discharge series. Figure 4.3 presents the historical time series of discharge rates at Auja spring according to studies of Schmidt (2014) with a mean value of 9.7 MCM/a.

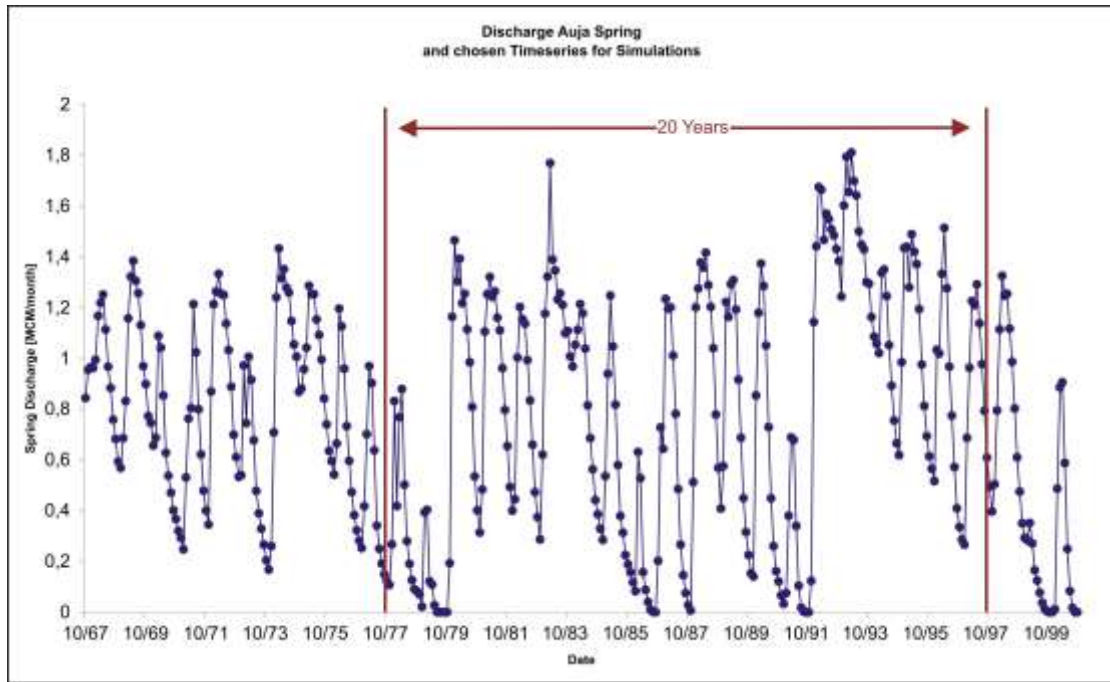


Figure 4.3: Historical time series of discharge rates at Auja spring (Schmidt, 2014)

4.4.2 Hydro(geo)logy, Aquifer Systems and Hydroinfrastructure

Figure 4.4 presents the local aquifer systems in a schematic and simplified way as required for later water resources system analysis. A deep carbonate aquifer system is present in the Mountain areas and underlying the shallow aquifer system in the valley.

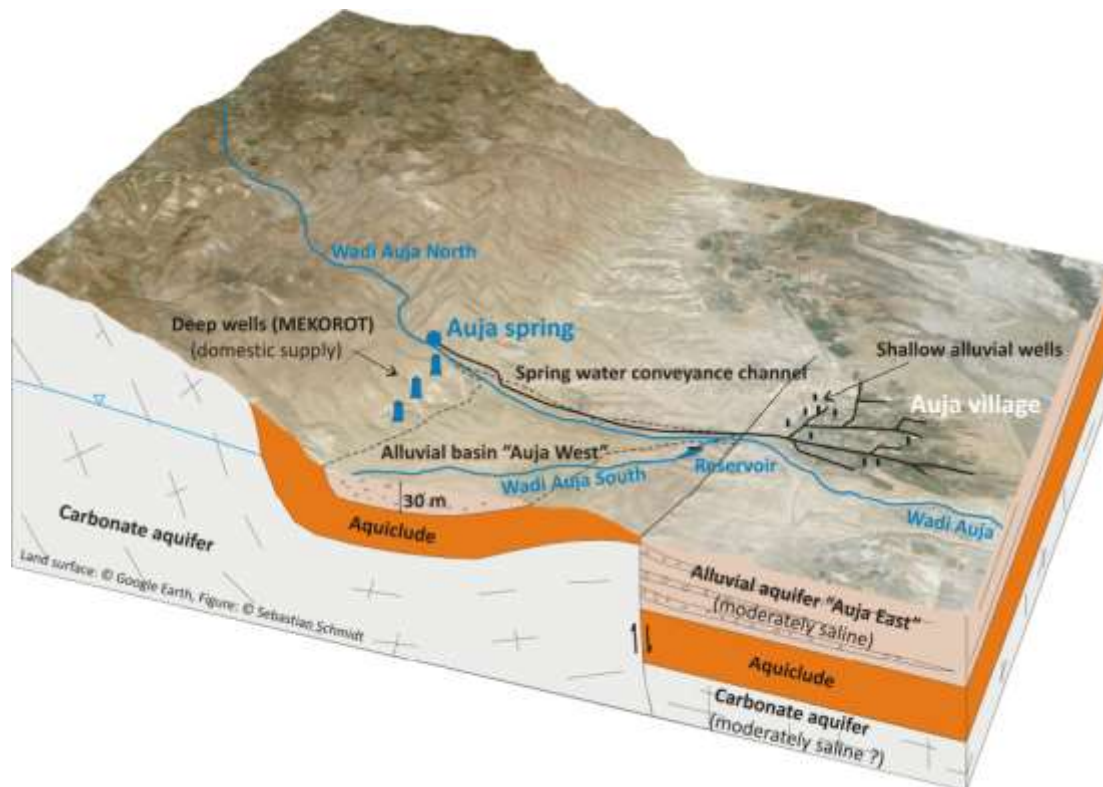


Figure 4.4: Groundwater systems and hydro-infrastructure at Wadi Auja (Schmidt, 2014)

The aquifers are recharging from the seasonal rainfall through outcropping area in the West Bank Mountains. The shallow alluvial aquifer in the valley is recharged through direct infiltrations from the surface runoff or by lateral flow from the mountain aquifers. The shallow alluvial aquifer may be classified in a western upper basin and the eastern part around Auja village (Fig.4.1,4.4,4.5). Besides outcrops of Cretaceous formations, Senonian and Turonian, the area is dominated by Quarternary sediments of the Holocene and Plio-Pleistocene. These include limnic silts and deposits of Dead Sea predecessors, the Lisan formation (Gropius, 1999). Both, the phreatic alluvial aquifer with partially high salt concentrations as well as the deeper fractured carbonate system with better quality water, suffer from groundwater level decreases during dry year conditions due to over-exploitation (Abdel-Ghafour, 2005).

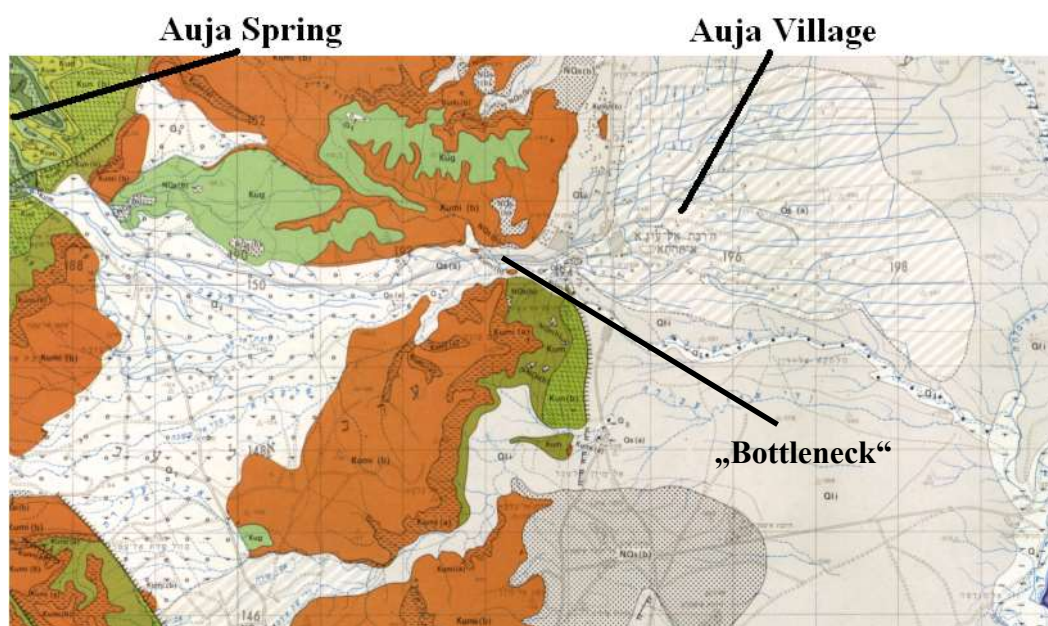


Figure 4.5: Geological formations at Wadi Auja (Geological Survey Israel, 1973, modif.)

The Lisan formation, in contrast to the coarse clastic alluvial sediments, shows very low hydraulic conductivity values. The Lisan covers the alluvial aquifer at the eastern part of the study area. General groundwater flow direction in Wadi Auja is west to east, downstream to the Jordan River and north to south, towards the Dead Sea (Ali et al., 2009).

4.4.3 Water Resources System and MAR Integration

Existing hydro-infrastructure: Figure 4.1b presents the Auja CS and some structural system elements. The dam with a designed capacity of 1.2 Million Cubic Meter (MCM) and 45 Km² of drainage area has been recently constructed. The water of the Auja spring is being conducted by an open canal to the irrigated areas around Auja village (PCBS, 2010). Poor canal maintenance results in water losses about 60% of the mean spring discharge (Sadah &

Tamimi, 2011, Aliewi et al, 2007). The present domestic water demand of around 0.3 MCM/a of Auja village is being supplied from deep wells in the mountain aquifer, operated by the Israeli water supply company MEKOROT.

Water Resources System Analysis. Figure 4.6 presents the results of the WRS-Analysis for the lower part of Auja Catchment, not considering the mountainous areas in the upper part of the Wadi. The available water resources, their water potential (no losses) in MCM/a, existing and further required hydro-infrastructure (dotted lines) for water potential activation as well as relevant water users and demand between 2010-2030 are given (Sadah & Tamimi, 2011). Freshwater resources (blue boxes) at Lower Wadi Auja consists of the carbonate aquifer system in the valley in the western part of the geological fault (fig. 4.4), Auja spring and surface runoff.

The potential of the deep carbonate freshwater aquifer in valley is estimated in about 8 MCM/a, but since the Israeli Authorities are abstracting up to 6 MCM of deep groundwater per year, Palestinian water availability with regards to this source is reduced to approximately 2 MCM/a. Therefore, the domestic demand of Auja village over the planning horizon may be covered from deep wells in the carbonate aquifer.

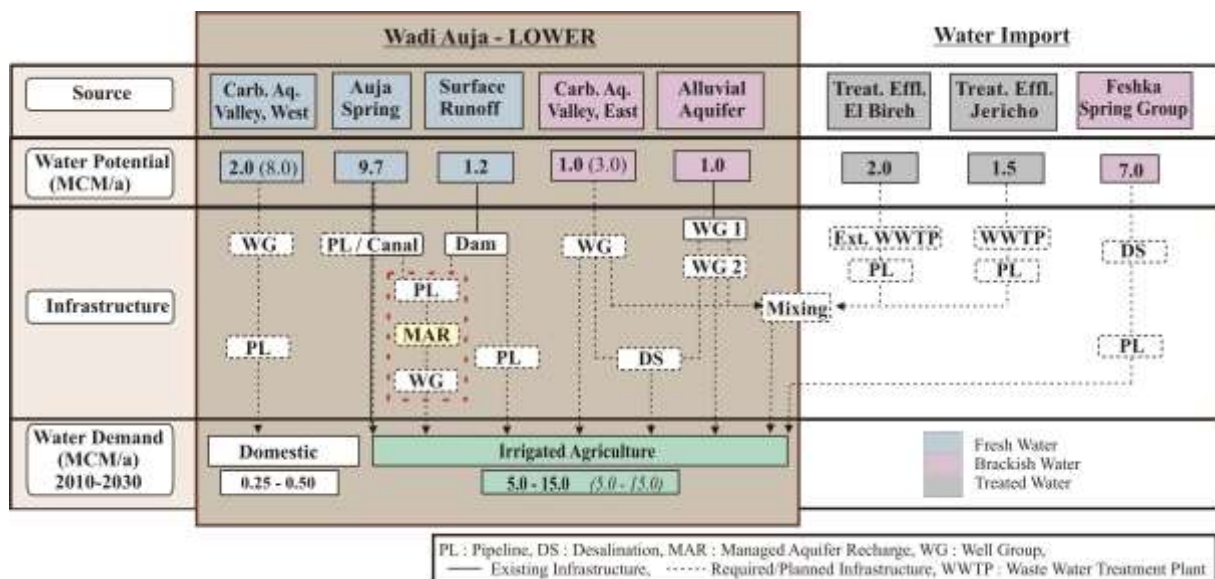


Figure 4.6: Integration of Managed Aquifer Recharge into WRS- Case study Auja

Auja spring presents a great water potential of about 9.7 MCM/a. The above mentioned high water losses in the old canal need to be reduced by rehabilitation measures or a new pipeline (PL) need to be installed. Auja spring discharge is directly supplied to the irrigated areas, but due to the highly variable discharge behaviour of the spring (Figure 4.3), within and over-the-year storage of spring water surplus will be required. According to figure 4.6, this requires the implementation of Managed Aquifer Recharge (MAR) and underground storage of water in the shallow alluvial aquifer. The porous aquifer system would permit the

controlled recovery of the recharged water by well groups (WG) during dry periods for irrigation purposes.

Surface runoff is stored in the new dam and should be supplied for irrigation with high priority in order to reduce evaporation and infiltration losses. It is recommended to install a pipeline between the dam and the irrigated lands, taking advantage of the improved hydro-infrastructure (canal or PL) between Auja spring and the agricultural land under irrigation. Due to the high temporal variability of surface runoff, the corresponding water potential is difficult to quantify (Moe et al, 1998). Based on precipitation-runoff studies (Abadi, 2006), it has been estimated that a mean runoff of 1.2 MCM/a may be stored in the dam. After attending the immediate irrigation demand, the remaining surface water surplus retained at the dam should be stored in the underground by means of Managed Aquifer Recharge in order to avoid evaporation and infiltration losses. In spite of the fact, that part of the infiltrated water would indirectly recharge again the shallow alluvial aquifer system, MAR should take place in the alluvial system in order to maintain control of the surface water surplus, to minimize water losses and guarantee the most efficient reutilization of these waters. According to figure 4.6, this may be achieved by the joint management of those MAR facilities which are required to store the spring discharge surplus.

Brackish groundwater (fig.4.6/red boxes) from shallow wells in the alluvial aquifer (1 MCM/a) and deep wells in the deep carbonate aquifer near to Auja village (1 MCM/a) may be used for direct irrigation to salt resistant crops or desalinated by small solar driven facilities and used for high quality crops and high-tech agriculture (greenhouses). This would require the installation of new wells in both aquifer systems. Optionally, brackish groundwater may be mixed with treated effluent (grey boxes) to reduce salt concentrations and directly applied for irrigation of salt resistant crops, such as palm trees. Due to insignificant effluent production at Auja village (0.15 MCM/a), additional effluents up to 2 MCM/a could be imported from El Bira waste water treatment plant (Fig.4.1a) by gravity pipeline or Jericho WWTP (<1.5 MCM/a). Auja effluents have not been considered in the WRS Analysis. Extraction of surface water from the Jordan river is not considered due to political restrictions.

As further external sources and potential water import, desalinated water from 20km distant Feshka spring may be imported by pipeline. The corresponding water potential linked to the case study are of Wadi Auja has been estimated in 7 MCM/a, which is around one third of the installed capacity of the desalination plant. Figure 4.1a shows the location of the Feshka spring near to the Dead Sea, offering a mean discharge of 60 MCM/a. The installation of a desalination plant with a designed capacity of 22 MCM/a is foreseen (PWA, 2009).

4.4.4 Irrigated Agriculture

Irrigated agriculture is the dominating water user in the Valley and main factor for social development. Main source of income is the local agriculture. According to the Palestinian Ministry of Agriculture (MoA), the irrigated area around Auja village is about 5,000 dunam (dn; 1dn = 0.1ha), while the total area of irrigable land with excellent agricultural potential amounts to approximately 15,000 dn. According to [Shawahna \(2013\)](#), further 15,000 dn could be made available for irrigated agriculture by means of rehabilitation measures in order to reduce soil salinity. Figure 4.7 presents a map of the today irrigated areas around Auja Village, together with available areas for the extension of irrigated land, according to different agricultural development scenarios, discussed by [Shawahna \(2013\)](#).

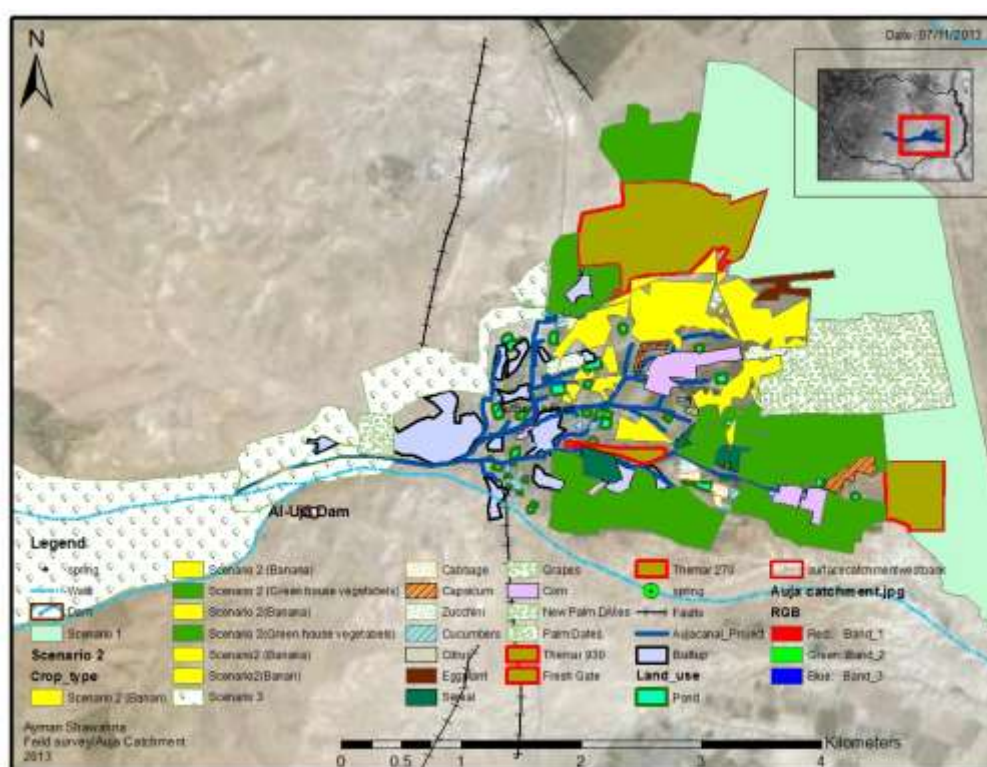


Figure 4.7: Irrigated area around Auja village and available irrigable land ([Shawahna, 2013](#))

Despite the irrigated areas around Auja Village, there is no proper land use in Wadi Auja. Most of the area is uncultivated land. Some areas at Auja village are possessed by private companies which produce medical crops (herbs) for export, using greenhouse technology. Local farmers and habitants of Auja village are employed by these firms to work on the land. Besides medical crops, palm trees, vegetables, grain, grapes and other citrus fruits are cultivated. Vegetables are cultivated in a traditional way by open drip irrigation schemes as regular agriculture (1,050 dn) as well as in greenhouses (280 dn). On 44% of the area (2200 dn), due to their robustness with regards to brackish water irrigation from shallow wells and economic value of dates, palm trees are cultivated. The average annual water demand for

irrigation is approximately 5 MCM, which leads to an average water demand of about 1,000 m³ ou 1,000 mm per dunam per year. Table 4.1 presents the mean monthly distribution of the Water Demand for irrigation (WDI) at Auja Village.

Table 4.1: Mean monthly Water Demand for Irrigation (WDI) at Auja ([Sadah & Tamimi, 2011](#))

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	SUM
WDI (MCM)	0.44	0.40	0.38	0.38	0.38	0.38	0.46	0.44	0.41	0.45	0.45	0.45	5.00
WDI (%)	8.8	8.0	7.6	7.5	7.6	7.6	9.2	8.8	8.2	8.9	8.9	8.9	100

According to the Palestinian Ministry of Agriculture, 11 wells with a mean depth of 100m are pumping annually about 1 MCM/a from the shallow alluvial aquifer system, while the total capacity of the wells is about 2 MCM/a. However, it is assumed, however, that an unknown number of illegal, minor wells is additionally being operated in the village.

4.5 MAR-Potential and Feasibility

4.5.1 Water Budgets

Today Situation

In order to analyse the potential and needs for the implementation of Managed Aquifer Recharge at Wadi Auja, different water budget studies have been conducted. According to figure 4.6, domestic demand is fully covered by freshwater from deep wells in the carbonate aquifer system and, has not been considered in the analysis. In the water resources system analysis, spring discharge together with surface runoff have been identified as main sources for Managed Aquifer Recharge.

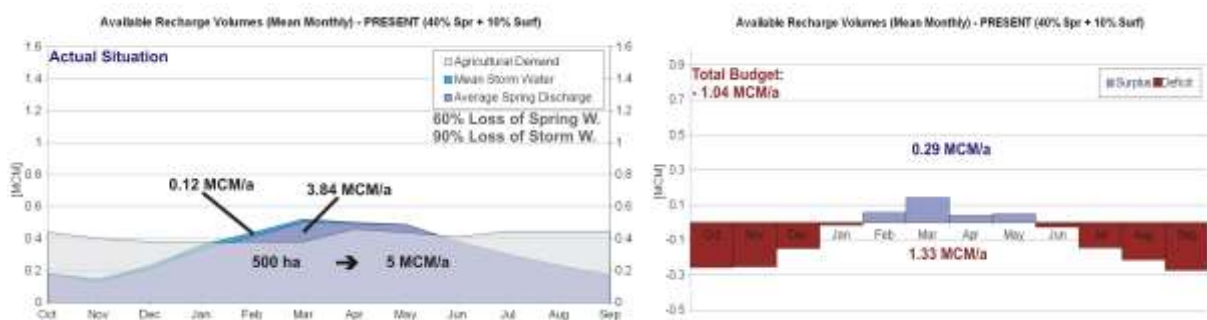


Figure 4.8: Today available surface water resources (Auja spring discharge and surface runoff) versus present water demand for irrigation

Therefore, the mean monthly water availability of these sources have been compared with the water demand of the today irrigated area of about 5,000 dunam. A mean water demand for irrigation of 1000 m³/dn/a has been assumed (MoA, 2013), resulting in an annual water demand of 5 MCM. For Auja spring, a historical time series of 34 years has been considered (fig.4.3). Figure 4.8 presents the today problematic situation with regards to irrigation demand and activation of the water potential. Around 60% of the spring water potential is being lost by infiltration from the old canal between the spring and the irrigated areas.

Some flood water retention take place at the irrigation ponds of the local farmer. Today, the water retained by the recently constructed dam at Auja is being lost by infiltration to the carbonate aquifer within few days (fig.4.9). Therefore, we assume that just 10% of the surface runoff is being used for irrigation purposes. According to the corresponding water budget calculation for mean hydrological conditions, presented in figure 4.7, there is a small water surplus during the months February to May, while during the rest of the year the irrigation demand cannot be satisfied. The overall water deficit of around 1 MCM/a is being covered by brackish water from the shallow wells of the alluvial aquifer system.



Figure 4.9: Auja surface reservoir on January 24th 2013. The arrows show the strong reservoir depletion after a rainfall-runoff event due to infiltration losses (photo: Muath Abu Sadah, HEC).

Reduction of Water Transfer Losses

The situation would be quite different, if water losses from spring discharge and surface runoff would be reduced to only 20% (fig.4.10). In this case, just the months of September to

November present a small water deficit. Practically all irrigation water demand could be covered by surface water resources, even leading to a considerable water surplus of about 3.8 MCM/a. This volume of water could be used for Managed Aquifer Recharge, storing the water for dry years and contributing to groundwater level recovery of the overexploited shallow alluvial aquifer system. The necessary hydro-infrastructural interventions refer to the installation of pipelines from the water sources Auja spring and surface reservoir (fig.4.9) to the irrigated lands around Auja village as well as to the MAR facilities, as studied in chapter 4.6.3. The water budget is based on a conservative approach, since water losses by pipeline may be considered to be less than 20%.

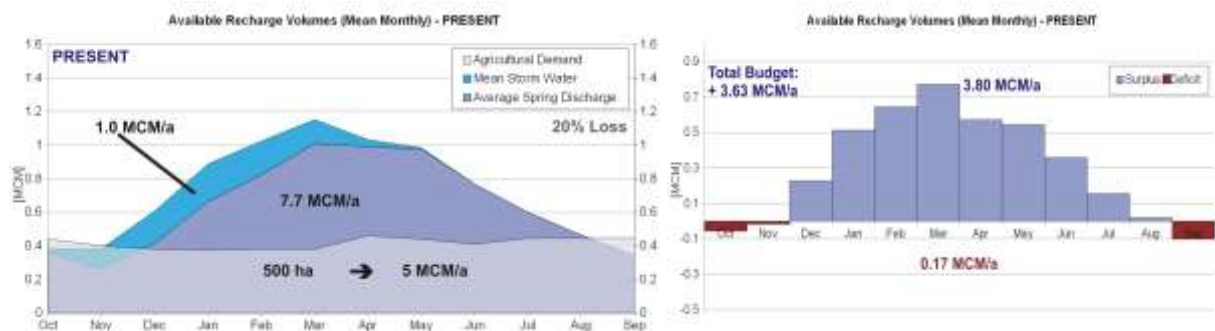


Figure 4.10: Surface water resources (spring discharge plus surface runoff), considering reduced water losses of 20%, versus present water demand for irrigation

Agricultural Development scenario for Future Water Budgets

The assessment of the future water budget relies on the scenario that the irrigated area around Auja has been duplicated from 5,000 to 10,000 dunam, maintaining the type of crops and irrigation schemes of the existing agricultural area and, therefore, the mean water demand per dunam.

Future Water Budget for MAR-Strategy A

The mean monthly water budget figure 4.11 compares the available surface water resources, taking again reduced water losses of 20% into account, with the water demand of the irrigated area after duplication. The water budget presents fresh water surpluses of 1 MCM during the period from January to May. The rest of the year, mainly due to decreasing spring discharge rates, a deficit of approximately 2.4 MCM is being accumulated.

The above defined agricultural development scenario results in an annual water deficit of about -1.4 MCM. This means that, even storing the surface water surplus during the first 5 months of the year in the underground and recovering the water during the water scarce period, the irrigation demand cannot be covered. On the other hand, the water budget shows

clearly that under mean hydrological conditions 1 MCM per year of surface water is lost if not properly stored by aquifer recharge. The total annual water deficit would have to be covered by groundwater resources.

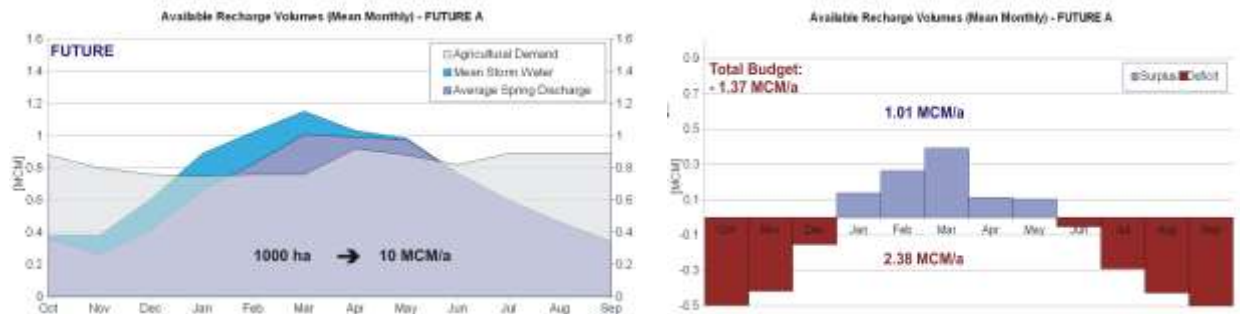


Figure 4.11: MAR-Strategy A – Available surface water after loss reduction versus future irrigation water demand for an area of 10,000 dunam

Future Water Budget for MAR-Strategy B (IWRM-Strategy)

Figure 4.12 presents an IWRM scenario with regards to the water availability and assumes that, additionally, 1 MCM/a of treated effluent from El Bireh or Jericho WWTP are transferred to Auja and 1 MCM/a of fresh ground water are pumped from the deep carbonate aquifer system to be directly applied to irrigated agriculture. The additional water volume of 2 MCM leads to a water surplus in the annual water budget of 0.6 MCM while the period of surplus extends for further 2 months. Since the focus of the water budgets studies is on the recharge potential, brackish water extraction by shallow wells has not been considered. The estimated annual natural recharge of the alluvial system around Auja village is about 1 MCM.

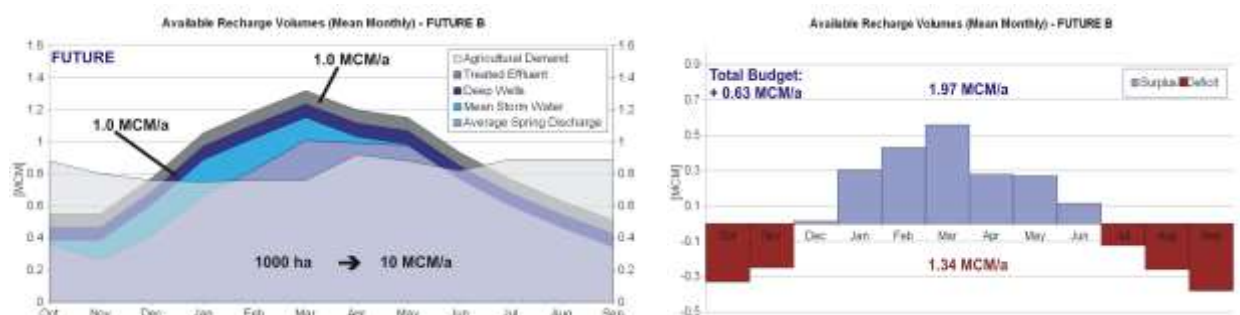


Figure 4.12: MAR-Strategy C (IWRM-scheme) - Available surface water after loss reduction versus future irrigation water demand, considering additional water production from deep wells and treated effluent import, 1 MCM/a each

This leads to the conclusion that, under mean hydrological conditions and the prevailing irrigation planning and management, the irrigated area may be extended to more than double the today existing area of 5,000 dunam. This conclusion is based on the assumption that the surplus of surface water from spring discharge and surface runoff may be stored and fully recovered later by pumping wells in the irrigated areas. In order to study this assumption, a numerical groundwater model has been applied to the shallow alluvial system. The results are presented in chapter 4.7.

4.5.2 Feasibility of Underground Storage

The alluvial aquifer system at the Lower Wadi Auja consists of mostly coarse gravel and sand formations. [Haaken and Kemna \(2012\)](#) conducted infiltration tests and geophysical measurements at several locations in the small alluvial basin “Auja West” (fig.4.4). The results of the geophysical surveys reveal a thickness of the alluvial sediments of 20 to 30m. The basin Auja West and the large alluvial eastern basin around Auja village present similar hydraulic conditions. While the small alluvial basin “Auja West” is shallow, the eastern system between the fault and the Jordan river presented a thickness of about 1000m (fig.4.4). According to the geophysical and hydrogeological studies by [Haaken and Kemna \(2012\)](#), the alluvial formation is suitable for subsurface storage of water. While double ring infiltrometer tests at “Auja West” showed just infiltration rates up to 0.24m/d at the surface, infiltration tests in laboratory with samples from different depths reveal, that the alluvial structures below the shallow soil should permit infiltration rates of around 1 m/d. Falling head tests in exploration boreholes revealed even very high hydraulic conductivity values in the range of 8.6m/d to 65m/d ([Haaken & Kemna, 2012](#)). Despite the overlaying Lisan formation east of the agricultural areas, the aquifer is unconfined. In order to guarantee high infiltration rates at the recharge facilities, the shallow soil layer with low hydraulic conductivity should be removed to a depth of about 2 m below surface by excavation.

The available agricultural land around Auja village as demand area or “Area of Interest” has a spatial extension of 15km². Based on an average groundwater depth of 45m, a mean porosity of 35% of the alluvial sediments ([Haaken & Kemna, 2012](#)), and the assumption that the recharged water could be retained in the demand area, some 180 MCM could be stored, resulting in a groundwater level rise of about 35 m.

4.6 MAR-Planning Options

4.6.1 Sources of Water

According to the water resources system analysis for Lower Wadi Auja (fig.4.6) and above water budget studies, Auja spring discharge and surface runoff are the sources of water, which are available for Managed Aquifer Recharge implementation. . Figure 4.3 presents the historical time series of discharge rates at Auja spring according to studies of [Schmidt \(2014\)](#) with a mean value of 9.7 MCM/a. The discharge of Auja spring presents excellent water quality. The analysis of the surface runoff showed further a water potential of about 1.2 MCM/a.

The above IWRM strategy (fig.4.12) ensures the extension of the irrigated area around Auja from 5,000 to 10,000 dn, taking mean hydrological conditions into account. A fresh water volume of 2 MCM is recharged to the shallow aquifer system in the months between December and June and should be recovered during the period with irrigation water deficits. This shows that the recharge volume depends on the use of complementary sources of water for direct allocation to irrigated agriculture, such as fresh or brackish water from the deep carbonate aquifer or treated effluent to be imported.

All water budget studies are based on the assumption that the recharged surface water will be fully recovered by pumping wells in the agricultural areas to cover water needs for irrigation.

4.6.2 Recharge Technology and Design

To recharge the water, different infiltration and injection technologies are available. The most common methods are: infiltration basins (spreading basins), sink-pits and canals, induced recharge by bank filtration, and injection wells. Use of these methods depends upon basic planning parameters, such as the type of water or effluent, the geological conditions, prevailing groundwater quality, water reuse purpose, and land availability. In case of water infiltration through ponds or ditches, the quality of the recharge water can be significantly improved due to filtration and other natural attenuation processes. MAR projects using surface waters are known to exist in many countries in Europe, USA, Latin America, former USSR, Mediterranean countries and the Middle East, South Africa, Australia and Southeast Asia, attending to different water management objectives.

The selection of an adequate MAR technology at the Lower Wadi Auja mainly depends on the characteristics of the unsaturated zone and the characteristics of the shallow aquifer system itself. The aquifer is unconfined in all the area around Auja Village area and to the

west. East of the village, towards the Jordan River, the Lisan formation is present near the surface with very low hydraulic conductivity, in contrast to the surrounding coarse clastic alluvial sediments. In these areas, the implementation of infiltration ponds is not possible. Some “fingers” of this formation are reaching the agricultural lands around Auja village. Since large volumes of surplus water of up to 1 MCM per month during wet years (fig.4.15) need to be recharged, infiltration ponds are indicated as recharge technology. While the alluvial underground presents high hydraulic conductivity, the shallow soils are characterized by low infiltration rates and should be removed by excavation (chapter 4.5.2). Mean depths to the alluvial groundwater table in the agricultural area is about 45m. In order to improve the efficiency of recharge, a hybrid system may be applied by combining injection wells with infiltration ponds. Assuming a mean infiltration rate of about 1 m/d at a excavated pond depth of 2m and a maximum water volume of 1 MCM per month to be recharged, the required area for the infiltration ponds is about 180mx180m (approx.. 33.300 m²). Due to clogging risk, two ponds should be installed in the area and operated in an intermittent manner. Excess surface runoff, which may contain low concentrations of contaminants due to untreated effluents, should just be infiltrated by ponds in hybrid systems, to take advantage of the natural attenuation capacity of the unsaturated zone.

4.6.3 Recharge Locations and Water Recovery

The selection of infiltration ponds as low cost recharge technology restricts the feasible region for MAR site selection to the alluvial areas in the eastern parts of the valley, which are not covered by the Lisan formation at the surface. For the determination of the feasible area, besides the underground characteristics, the following surface criteria have been considered: land use, topography, hydro-infrastructure, location of source of water and demand areas.

Figure 4.13 presents the feasible area for the installation of infiltration ponds and the position of 6 potential MAR locations which will have been delineated for further evaluation. Locations 1,2 and 3 are not located directly in the agricultural areas around Auja village. Their position considers the fact that the shallow alluvial deposits “Auja West” and the alluvial basin east of the fault are hydraulically connected by a alluvial “bottleneck” (fig.4.5) and that the prevailing groundwater flow direction is from west to east (Marej, 2013).

By infiltrating the surface water surplus at those locations, the aquifer could be used as water transfer system. The recharged water, reaching the phreatic groundwater table, will flow in direction to the demand areas around Auja village. Water recovery will take place by shallow pumping wells according to the irrigation demand, which has not been covered by surface water or other complementary water resources (deep wells, treated effluent). The water

transfer in the alluvial system will reduce the cost for pipeline construction due to shorter distances between the dam and the nearby infiltration facilities.

The infiltration facilities 4, 5 and 6 are directly installed in the “Area of Interest”, which is the demand area of agricultural land around Auja village. The performance of these alternative recharge locations has been studied by numerical groundwater modeling for an operational period of 20 years, taking the duplication of the today irrigated land into consideration (chapter 4.7).

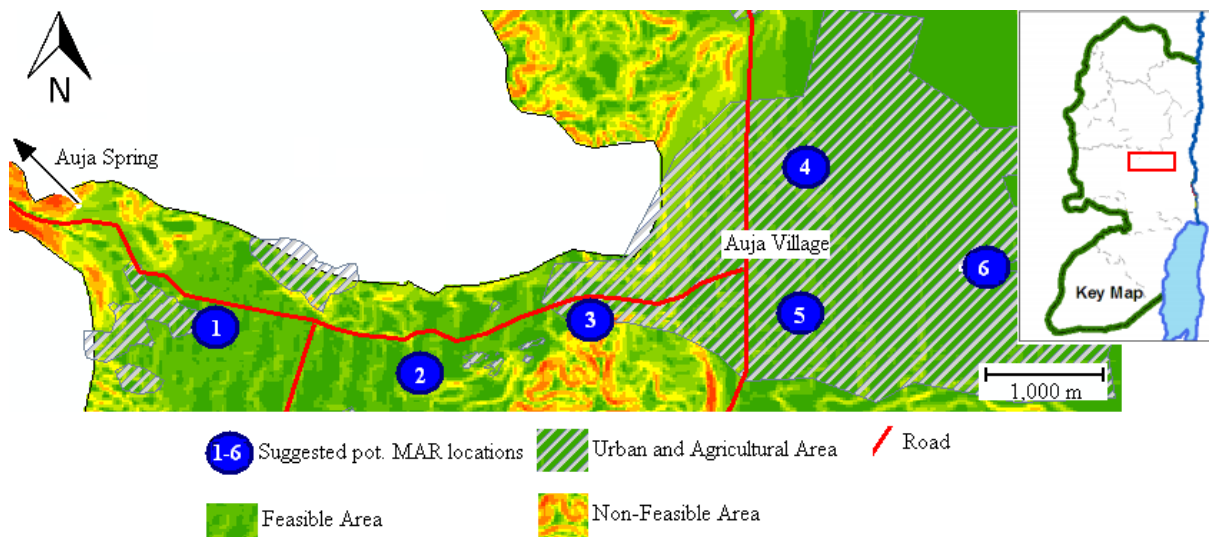


Figure 4.13: Feasible area for the installation of infiltration facilities and potential MAR locations.

Spring water and surface runoff are jointly recharged at these locations according to their availability, using the same infiltration structure. The extension of irrigated land and increased agricultural water demand requires the installation of additional wells in the shallow alluvial aquifer, doubling the existing pumping capacity of the wells. Figures 4.18 and 4.19 present the well groups which have been considered for the recovery of the recharged water.

4.6.4 Pre-Treatment

Due to the excellent water quality at Auja spring, there is no need for further treatment before recharge. The considerable sediment loads of the surface runoff will be accumulated at Auja dam which will serve as a natural sedimentation pond and may be transferred without any further treatment by pipeline to the recharge location, taking the natural attenuation capacity of the underground into consideration.

4.6.5 Operational MAR-Strategies

The water budget studies on mean monthly data to study the MAR-potential , as presented in chapter 4.5.1, were based on two distinct operational MAR-strategies:

Strategy A (fig.4.11) considers that the irrigation demand is first covered by surface water resources (spring discharge and runoff) and that the remaining surplus is being used for recharging the shallow alluvial groundwater system around Auja village. In case that the available amount of surface water is less than the total irrigation water demand, the remaining deficit will be covered by shallow groundwater from the alluvial system. No additional water resources for direct supply to irrigated agriculture are being considered.

Strategy B, also named IWRM strategy (fig.4.12), considers the activation of complementary water resources through deep wells from the carbonate aquifer with a production rate of 1 MCM/a and the import of 1 MCM/a of treated effluents from El Bireh or Jericho City. These water resources are applied for irrigation with high priority. The treated effluents will be mixed with brackish water from the alluvial groundwater system and applied for palm tree irrigation. The remaining irrigation water deficit will be covered by surface water from Auja spring and from runoff after rain events in the mountains (dam).

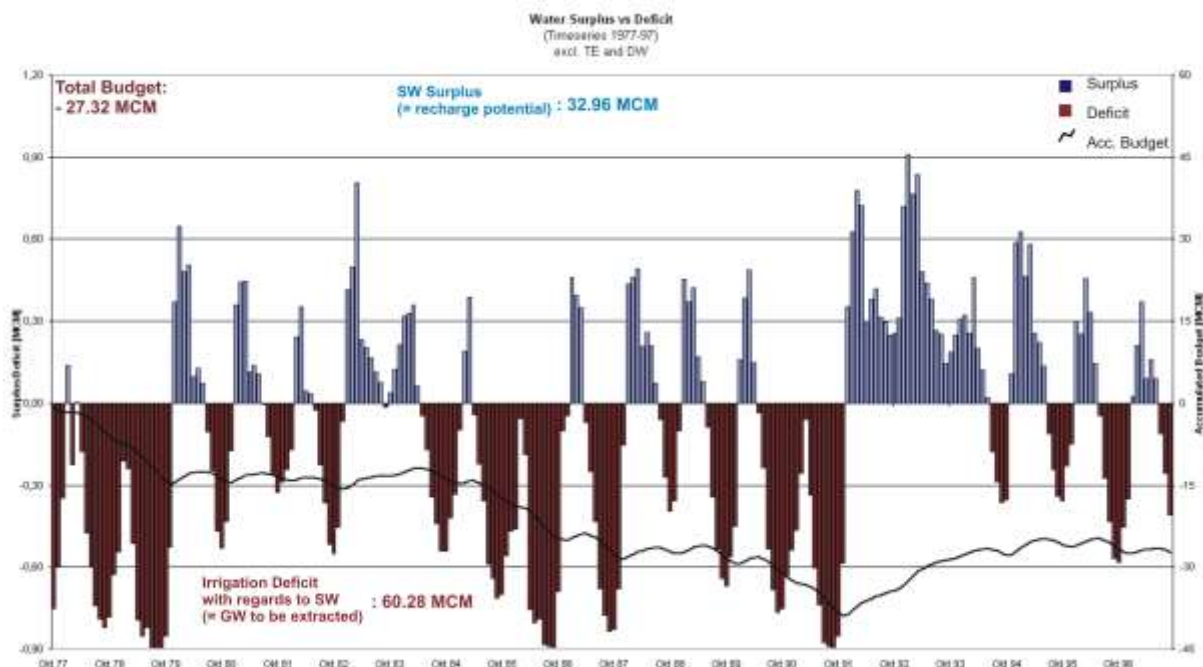


Figure 4.14: Monthly water budget between surface water surplus after irrigation and remaining irrigation deficit to be covered by the agricultural wells (1977-1997) – Strategy A: no complementary water resources for irrigation

The surplus of surface water again will be used for recharging the shallow alluvial system. In case that the available amount of surface water is still less than the total irrigation water demand, the remaining deficit will be covered by shallow groundwater from the alluvial system. Since the mean monthly water budgets are not representing the fluctuation of the surface water availability over time, a representative 20 years spring discharge period (1977-1997) has been selected for detailed MAR-operational and later simulation studies. The selected time period is represented in figure 4.3. The mean spring discharge of the partial time series is 9,7 MCM/a and equals to the mean discharge of the entire historical time series.

Figures 4.14 and 4.15 present a long-term budget of the above described operational strategies. The black line represents the accumulative budget between monthly recharge volumes (surplus/ blue columns) and pumped groundwater (irrigation deficit/ red columns). Figure 4.14 refers to strategy A without complementary sources of water for direct supply to irrigated agriculture. The available fresh water surplus for aquifer recharge is about 33 MCM for the entire 20 year time period, while the remaining irrigation deficit, to be covered by groundwater, amounts to 60.3 MCM. This results in a negative of MAR-Budget of -27.3 MCM after 20 years, represented by the accumulative budget line of the figure. Figure 4.15 presents the results of the strategy B, taking complementary water resources of 2 MCM per year into account. This results in a positive budget of +11 MCM. Due to the high recharge

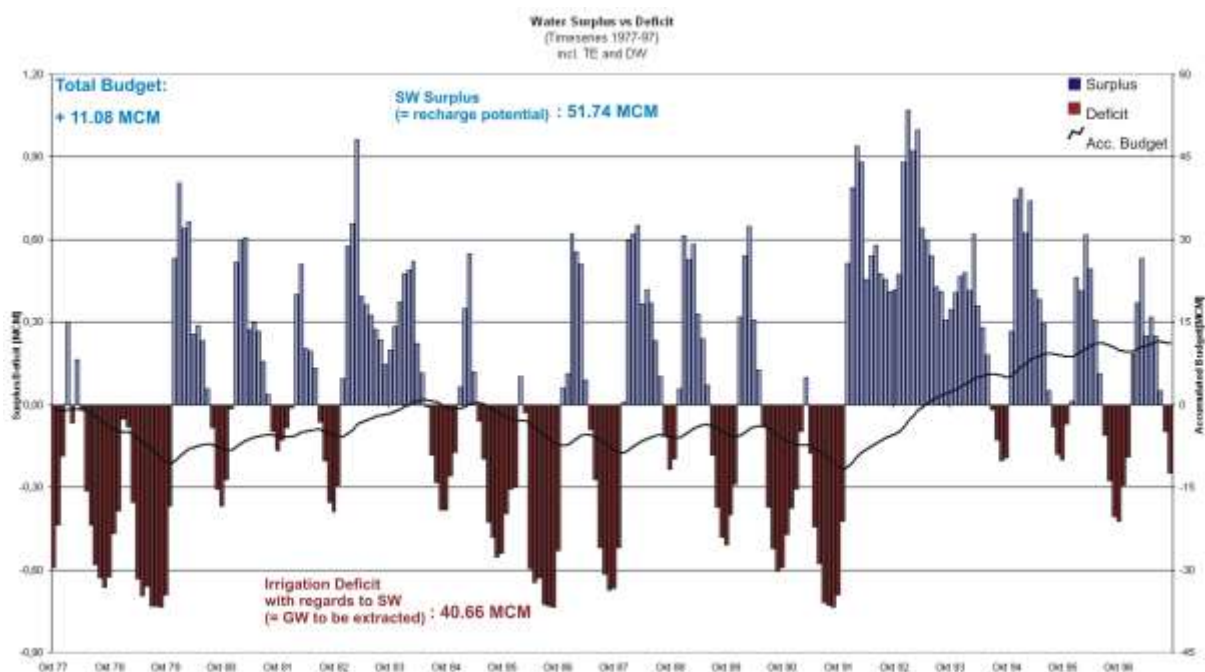


Figure 4.15: Monthly water budget between surface water surplus after irrigation and remaining irrigation deficit to be covered by the agricultural wells (1977-1997) – IWRM-Strategy B: with deep groundwater (1 MCM/a) & treated Eff. (1 MCM/a)

volumes in 1992 and 1993, the accumulative budget line shifts to positive values. Due to the IWRM-strategy, the total fresh water surplus for aquifer recharge increases to 51.7 MCM, while the remaining irrigation deficit to be covered by the recharged water decreases to 40.7 MCM. Based on the water budget results, it has been proved that the MAR-strategy B would permit the extension of the agricultural area under irrigation to 10,000 dunam.

The above budget studies assume that the surface water surplus may be temporally stored in the underground and later recovered for irrigation. This requires that the surface water will be recharged at a strategic location which permits the full recovery of this water in the demand areas by agricultural pumping wells. These assumptions require validation by numerical groundwater flow simulation, using historical spring discharge time series. Based on the simulation results, recommendations on recharge volumes and their recovery for irrigation purposes will be developed.

4.6.6 MAR Planning Options considered for further Analysis

Table 4.2 summarizes the 13 MAR planning options (MPO) to be further studied by numerical modelling. The first option refers to the so-called Do-Nothing-Approach (DNA) as reference scenario. Managed Aquifer Recharge is not implemented and the agricultural area under irrigation remains 5,000 dn.

Table 4.2: Summary of MAR-Planning Options (MPO) at Auja case study

MPO	Source	Technology	Location		Operational Strategy
			Recharge	Recovery	
0 (DNA)	-	-	-	6 wells	-
MPO A1	SD & SR	IP or HS	1	11 wells	A
MPO A2	SD & SR	IP or HS	2	11 wells	A
MPO A3	SD & SR	IP or HS	3	11 wells	A
MPO A4	SD & SR	IP or HS	4	11 wells	A
MPO A5	SD & SR	IP or HS	5	11 wells	A
MPO A6	SD & SR	IP or HS	6	11 wells	A
MPO B1	SD & SR	IP or HS	1	11 wells	B
MPO B2	SD & SR	IP or HS	2	11 wells	B
MPO B3	SD & SR	IP or HS	3	11 wells	B
MPO B4	SD & SR	IP or HS	4	11 wells	B
MPO B5	SD & SR	IP or HS	5	11 wells	B
MPO B6	SD & SR	IP or HS	6	11 wells	B

All other MPOs consider the recharge of both, Auja spring discharge (SD) and surface runoff (SR) from Auja dam as well as infiltration ponds (IP) for the recharge of up to 1 MCM water per month during wet years (fig.4.15). Optionally, a hybrid system (HS) may be applied (chapter 4.6.2) to enhance water passage through the unsaturated zone. All MAR planning schemes consider 11 recovery wells to ensure the required pumping volumes. The MPOs differ with regards to the recharge location (fig.4.13) and MAR-operational strategy, as presented in the before chapter 4.6.5.

4.7 Option Evaluation and Comparison based on Groundwater Modeling

4.7.1 Groundwater Model

Hydrogeological Setup

In order to evaluate the MAR Planning Options (MPOs) developed in the previous chapter, a groundwater flow model of the study area, including the region of Auja and Jericho, is utilized. Groundwater modelling is required to analyse the performance of the different MAR planning options and their impacts on local groundwater dynamics. The controlled recharge of the alluvial aquifer and water recovery by shallow pumping wells to attend to the delineated Agricultural Development Scenario (chapter 4.5.1, 4.6.3) are management measures with different impact on the groundwater dynamics for each MPO.

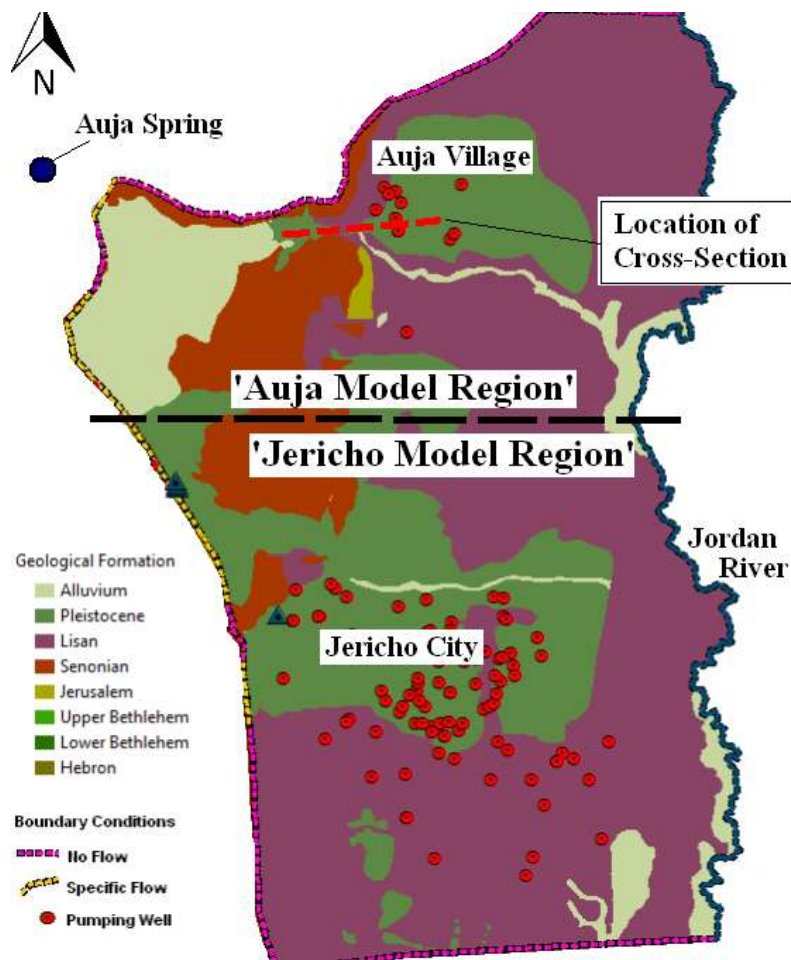


Figure 4.16: Modeling area with geology, wells and boundary conditions (Sadah, 2013, modified)

The transient groundwater flow model has been calibrated based on measured and interpolated groundwater level data of four observation wells, using monthly time steps. Due

to poor data availability in the study area, some of the input data, such as natural groundwater recharge rates, inflow from the mountain area or groundwater abstraction rates, is based on estimations and interpolation of the scarce data sets. For calibration, the time period of 2001 to 2009 was chosen.

The modelling approach allows a subdivision of the modelled aquifer in two groundwater flow regimes; the northern 'Auja Region' and the southern 'Jericho Region' (fig.4.16). The geological map was used for model calibration. For the simulation of deep groundwater flow towards the carbonate aquifer and vertical fluxes between the aquifers, an additional thin layer at the bottom of the deep alluvial system has been defined. The thickness of the main layers has a maximum depth of around 1,000 m at the eastern system boundary. In order to represent the low permeable Lisan formation at the eastern part of the model area, an additional layer has been introduced.

Natural Groundwater Recharge

Figure 4.17 gives an overview of the different recharge zones in the overall model region. This study, hence the following model description, concentrates on the northern part of model area, Wadi Auja.

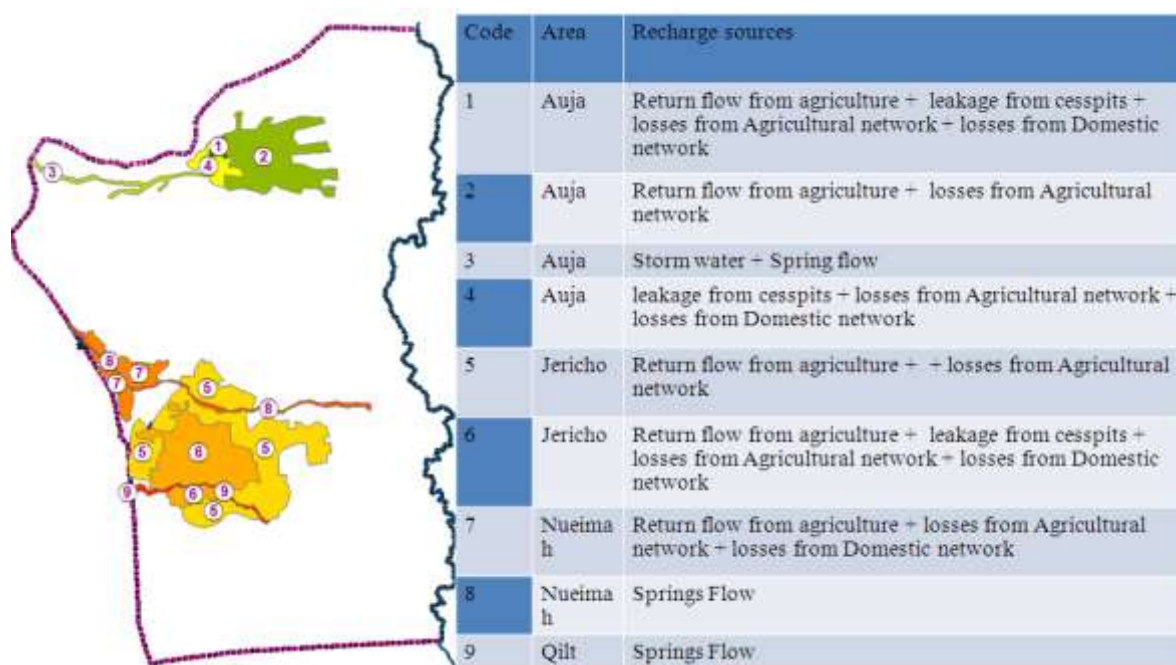


Figure 4.17: Zones of natural groundwater recharge (Sadah, 2013)

For the Auja model four zones of natural recharge have been considered in the model. These zones are directly correlated to six sources of recharge; Auja spring discharge, storm water, return flow from agriculture, losses from agricultural network, losses from domestic

network and leakage from cesspits. The recharge at zones 1,2 and 4 can be considered as insignificant. The recharge in zone 3 can achieve larger values in the Do-Nothing-Approach, but would be significantly reduced in case of the suggested pipeline construction between Auja spring, dam on the one hand and the irrigated lands on the other.

Model Boundary Conditions

Figure 4.18 concentrates on the model region Auja as focal area for MAR-implementation and presents the relevant boundary of that part of the system as well as the relevant agricultural pumping wells. System inflow of about 1.4 MCM/a through the underlying carbonate aquifer is provided at the transient flow boundary “Mountain North”. Some part of this water passes the geological fault and enters the shallow aquifer system around Auja village. The Northern boundary of Wadi Auja may be considered as No-Flow condition, while the Jordan river defines a river boundary in North-South direction, draining water towards the Dead Sea. Further to the south at the western model boundary “Mountain West”, a constant flow of 0.85 MCM/a is set. Model results showed that during aquifer recharge, this water flow does not enter the demand areas around Auja village (fig. 4.20), while strong pumping by a major well group around Auja may attract this water, contributing to the water budget of the “Area of Interest” (fig.4.19). It shall be kept in mind, that the total model area further extends to the south, including the region around Jericho city.

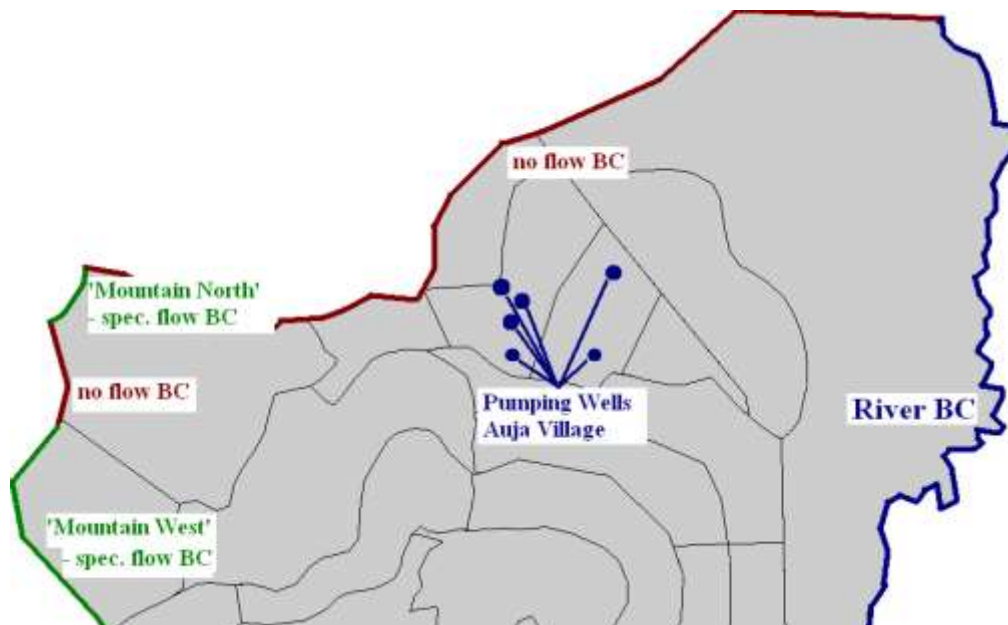


Figure 4.18: Model boundary conditions and pumping wells at the today irrigated area for the Do-Nothing-Approach /No MAR

Further information on the hydrogeological model set-up, boundary conditions and flows, model calibration and hydraulic parameters are presented in the SMART II deliverable D409 and [Walter \(2013\)](#).

4.7.2 Simulation of MAR Planning Options

The above MAR operational studies and water budget calculations assume that the recharged water is being strategically stored in the area of interest, which is the agricultural area around Auja village, and fully recovered during the demand periods by shallow wells. This assumption has been studied by the above described numerical model for the different MAR planning options. Figure 4.19 presents the 6 alternative recharge locations, as described in chapter 4.6.3, the Area of Interest (Aoi), which is the available agricultural land around Auja (15,000dn), as well as the position of 5 additional pumping wells, which had to be considered in the model in order to attend to the increased water demand for irrigation.

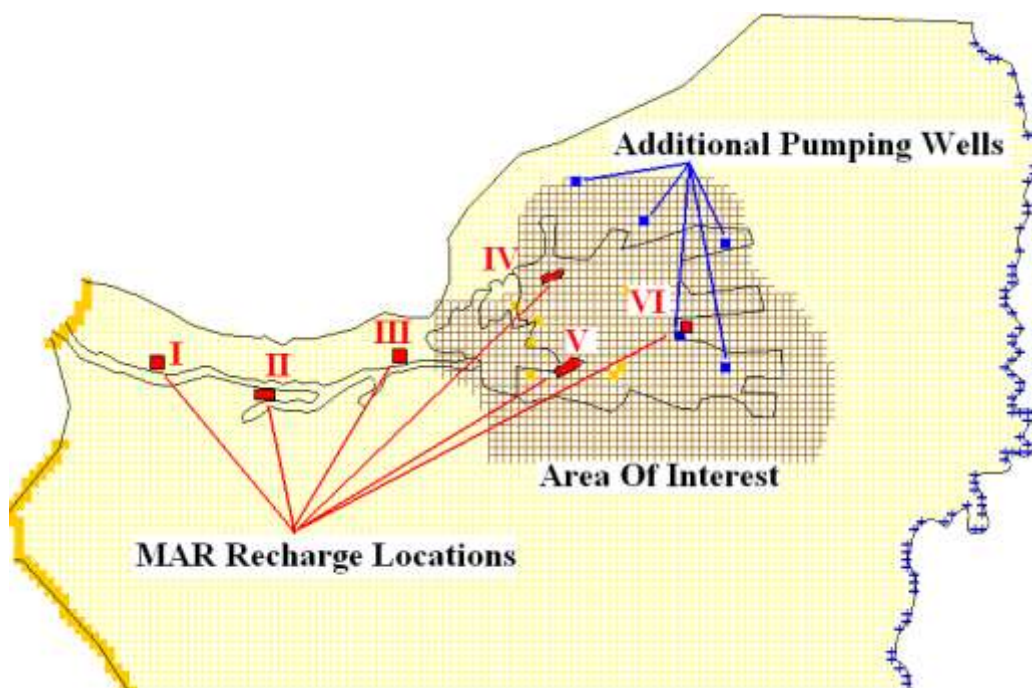


Figure 4.19: Delineation of Area of Interest (Aoi), Pumping Wells and MAR Locations

The below figures 4.20 and 4.21 are selected exemplary plots of the groundwater flow field for two different MAR situations. The area of interest is high-lighted. Different zones of hydraulic conductivity are classified.

Figure 4.20 represents MAR planning option 11, with recharge at location 4 and operational strategy B (table 4.2) in a typical recharge situation during the wet year 1993 (fig.4.15). Due to the hydrological surplus situation, the irrigated areas are mainly supplied by surface water,. The shallow pumping wells are not operating. The main flow direction is from west to east. Groundwater is leaving the area of interest to the east and south-east.

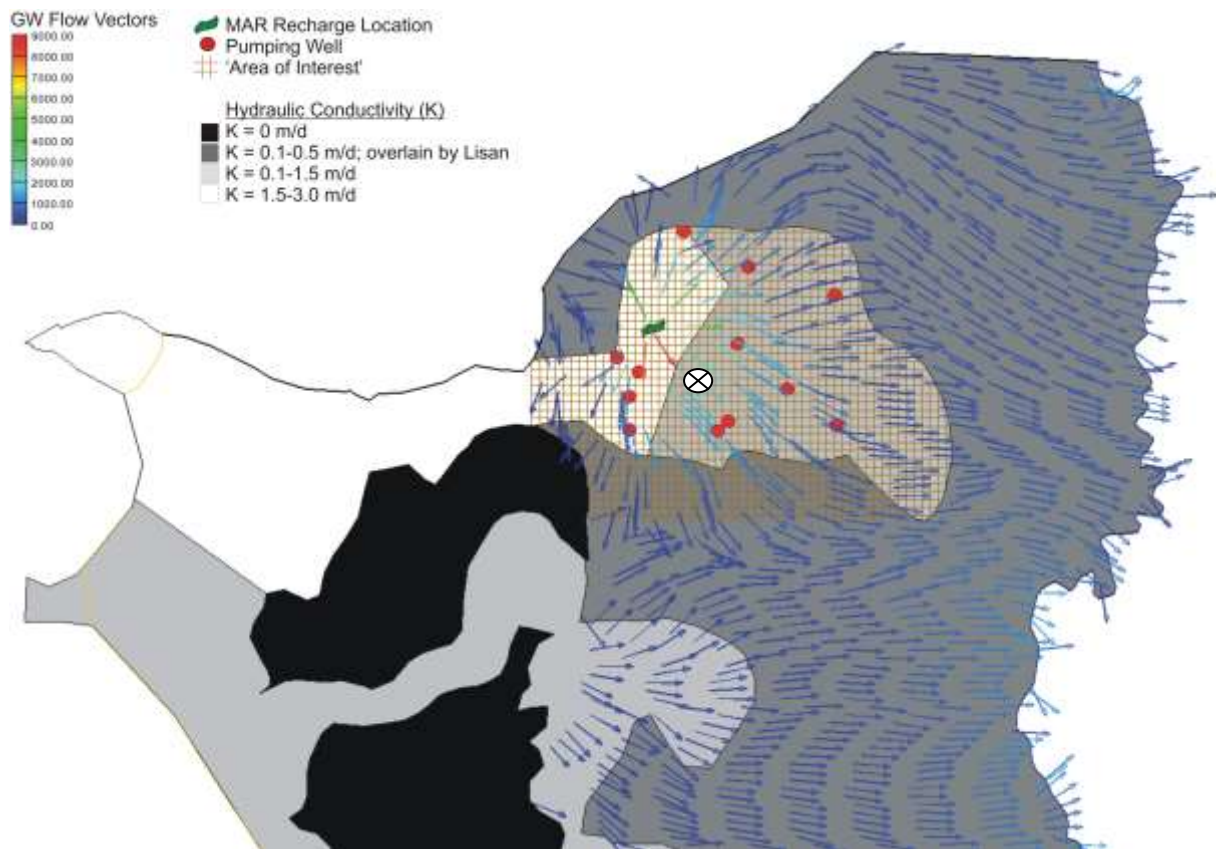


Figure 4.20: Groundwater flow field for recharge at infiltration pond IV

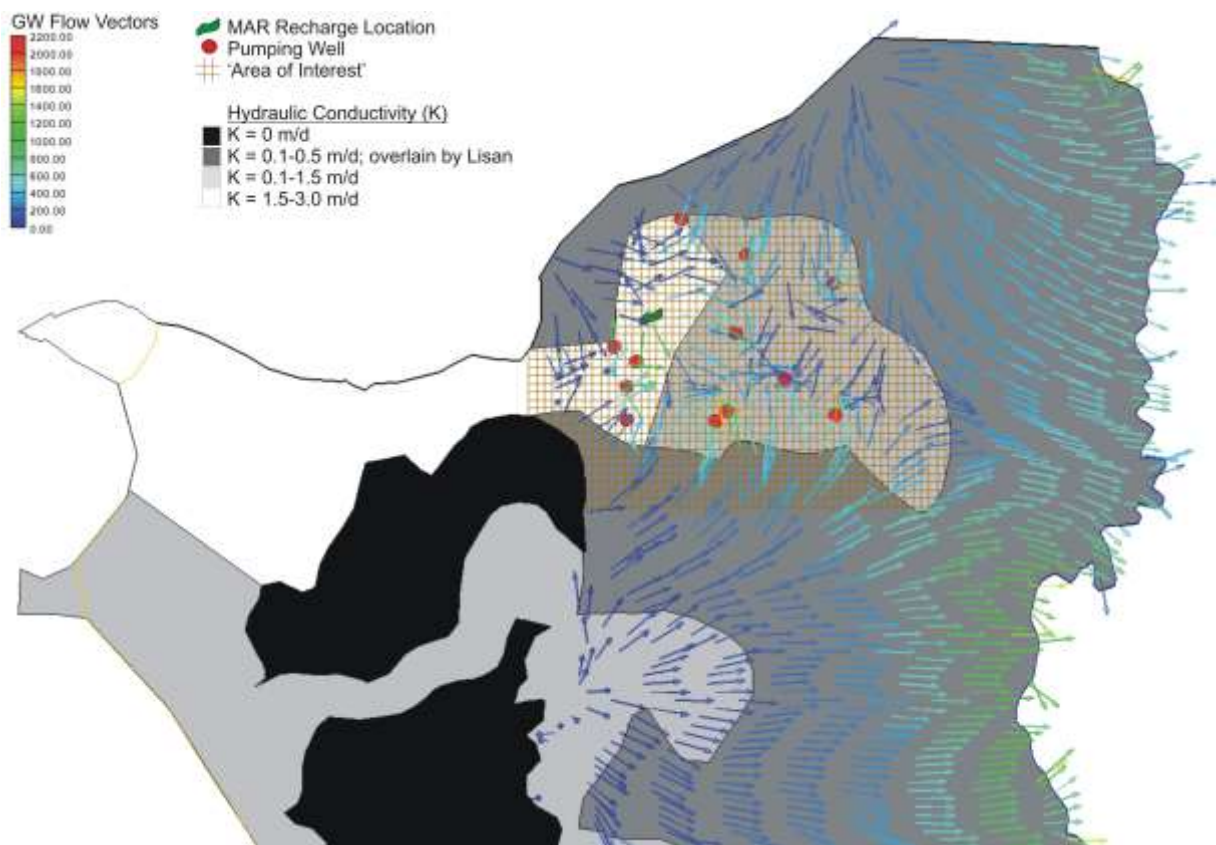


Figure 4.21: Groundwater flow field during pumping of the entire well group – no recharge

Figure 4.21 refers to the same MAR planning options, but represents a typical water recovery situation during the dry year 1991 without any recharge at location IV. The shallow agricultural wells attract water also from North, South and South-West. The groundwater in the South/South-East of the Area of Interest around Auja village is naturally recharged from the carbonate aquifer system at the geological fault and, therefore, definitely not related to any surface water recharge at Auja.

4.7.3 Analysis and Comparison of MAR Planning Options

Figure 4.22 presents the simulated groundwater heads over the selected period from 1977 to 1997 at a control point (fig.4.20) near to the center of the AoI for both, the Do-Nothing-Approach (MPO1) and the MAR planning option 11 with recharge at location IV and operational strategy B (table 4.2).

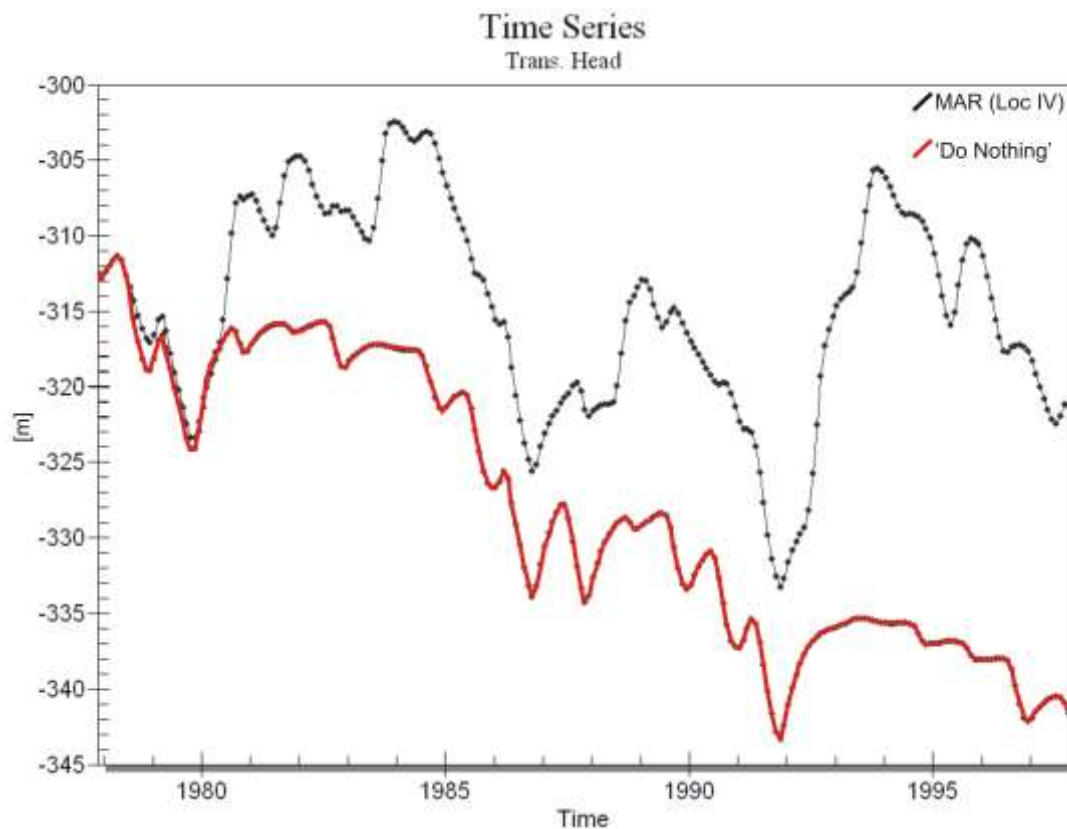


Figure 4.22: Simulated groundwater level at control point in AoI for MAR location IV and operational strategy B (MPO B4) versus Do-Nothing-Approach (no MAR)

The results show that under the Do-Nothing-Approach the groundwater table would decline further 30 m within 20 year, resulting in a mean groundwater decrease of 1.5 m per year. By implementation of MAR planning option B4 the groundwater table, at this control point, would have declined after 20 years about 10 m. Figure 4.22 shows the positive impact of the controlled recharge of surface water on the groundwater level of the shallow aquifer in the

area of interest. In general, changes in groundwater level follow the trend of the long-term water budget, as presented in figure 4.15. Both, figures 4.15 and 4.22, show the positive impact of the high recharge volumes during the years of 1992 and 1993. But while the MAR-budget (fig.4.22) remains positive, the groundwater level finally decreases below the initial level. This aspect will be further analysed and discussed below.

Figure 4.23 compares the different MAR planning options, operated according to strategy A, with the Do-Nothing-Approach, focusing on a water balance for the Area of Interest, with information about the total groundwater decline over the simulation period of 20 years. The simulated groundwater surface in the Area of Interest has been transformed to a mean groundwater level in order to calculate the decline for the entire area. The pumping volume from the shallow aquifer corresponds to the budgets values of the figures 4.14 and 4.15, being 60.23 MCM for strategy A and 40.7 MCM for strategy B. Figure 4.23 presents the same comparison for the operational strategy B. Without MAR-implementation the mean groundwater level in the Aoi would decrease more than 30m within 20 years, taking the historical time series into account.

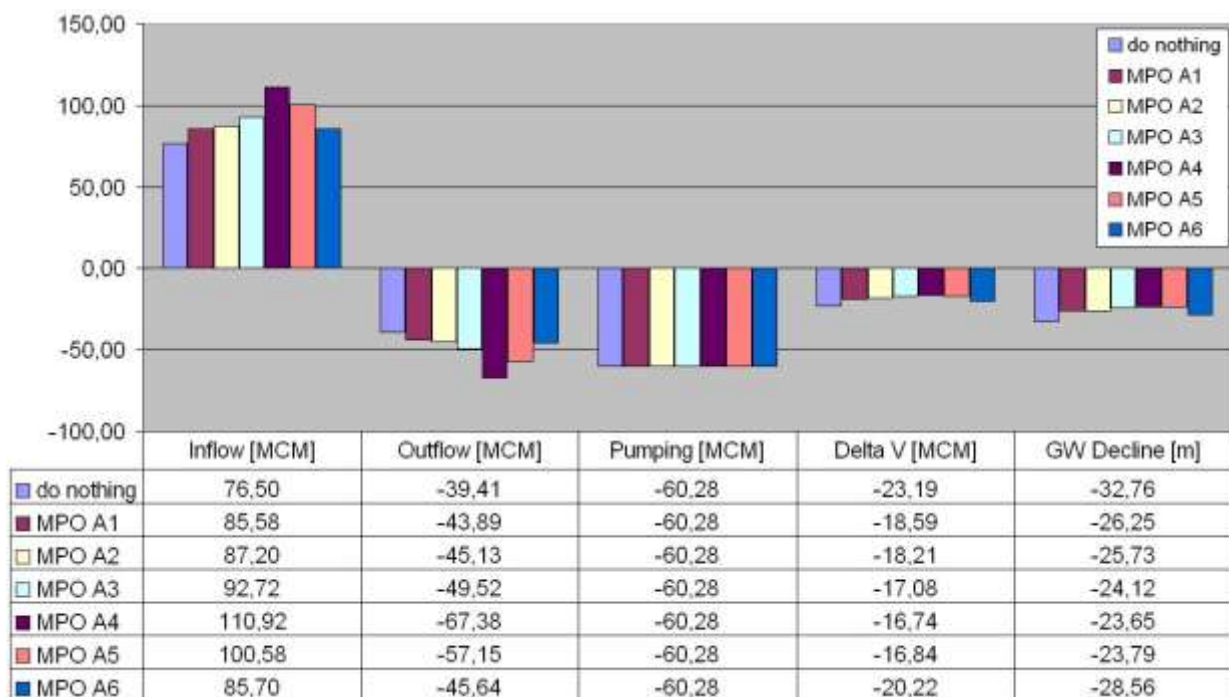


Figure 4.23: MAR-Strategy A - Simulated Water Flow Budget for the Area of Interest (Aoi) – no complementary water resources for direct irrigation – 20 years

In general, strategy B presents the better performance, requiring lower pumping rates from the shallow aquifer system and leading to a minor groundwater decline after 20 years. The MAR planning option with best performance is MPO B4, where surface water resources are recharged directly in the northern part of the Area of Interest (fig.4.13).

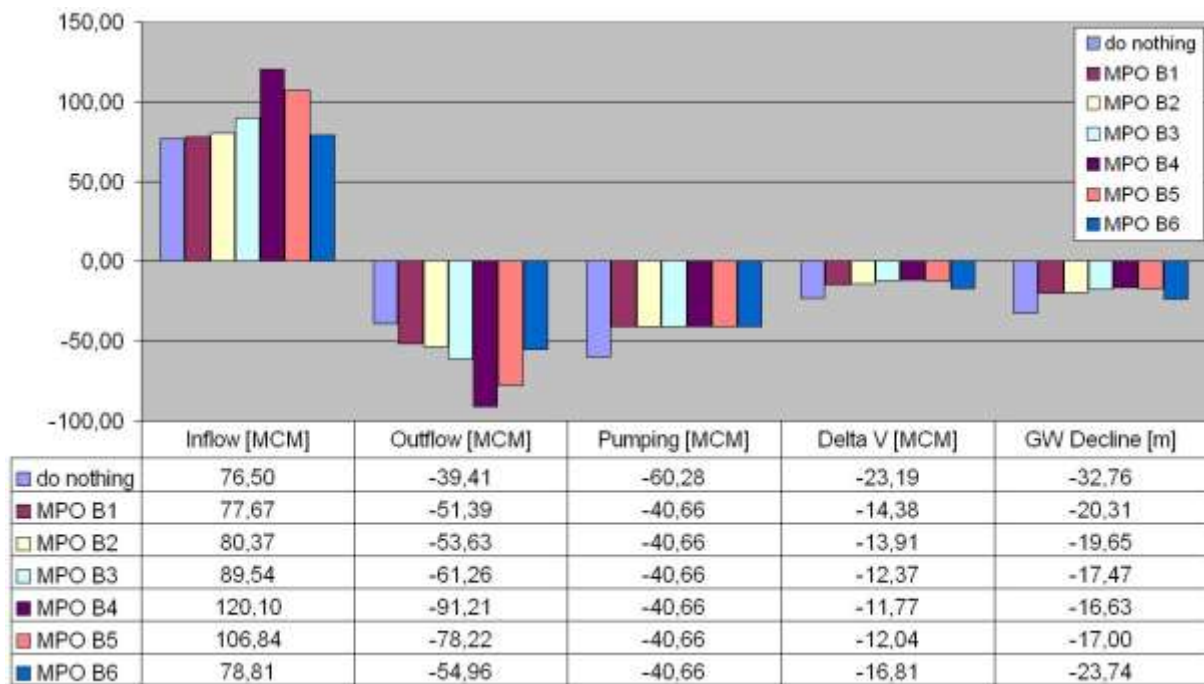


Figure 4.24: MAR-Strategy B (IWRM) - Simulated Water Flow Budget for the Area of Interest (AoI) – IWRM strategy: freshwater from carbonate aquifer and treated effluent import (1 MCM/a each) – 20 years

Figure 4.25 provides a comparison between the MAR water budget for the operational strategy B (IWRM) as presented in figure 4.15 (case A) and the zone water balance for the Area of Interest, both over the selected time period of 20 years. As discussed before, the MAR budget leads to a surplus of about +11 MCM, due to the fact that the total recharge volume exceeds total pumping volume for the shallow aquifer. In contrary, the zone budget for the AoI leads to a deficit of around 12 MCM, which actually corresponds with the groundwater level decrease presented in figure 4.22.

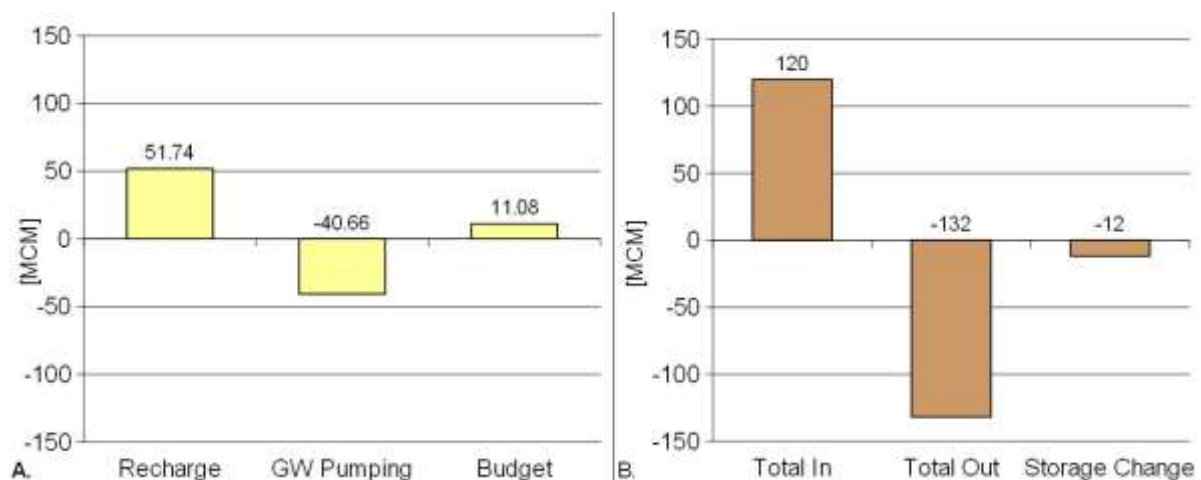


Figure 4.25: (A) MAR water budget for strategy B (IWRM), according to figure 4.15 and (B) simulated zone budget for the AoI and MPO B4, both over 20 years

The zone budget for MPO B4 states a total water inflow into the area of interest of 120 MCM and, additionally to the pumping volume of 40.7 MCM outflows from the area of about 91.2 MCM within 20 years. According to figure 4.21, groundwater is being attracted from south-west and north of Auja due to pumping activities of the entire well group, while groundwater is leaving the area during the months of aquifer recharge towards the east. This results in considerable inflow and outflow over the simulation period as presented in the zone budget of figure 4.25b. Therefore, the assumption that the recharged surface water may be temporally stored in the demand areas around Auja village and fully recovered during the dry seasons could not be confirmed by the simulation model.

4.8 Economic, Social and Environmental Considerations

The following considerations on economic, social and environmental viability of MAR implementation at Auja should be taken into account:

- All surface water surplus from Auja spring discharge and surface runoff is lost towards the Dead-Sea, if not properly recharged to the shallow alluvial aquifer system around Auja village and strategically recovered for irrigation purposes;
- Investments are required for pipeline installation between Auja spring and the irrigated land or, at least, canal rehabilitation in order to reduce the actual tremendous loss rate of about 60% to a maximum rate of 10 to 20%. Without this measure, further extension of the irrigated area at Auja village, based on local water resources, is not possible;
- This pipeline should be also connected to the existing Auja dam, since the surface reservoir suffers from huge losses to the below carbonate aquifer system. There is no further control on that amounts of surface runoff which infiltrates at the dam. Some part of the infiltrated water enters the shallow aquifer but flows mainly to the south. Therefore, the surface runoff stored at the dam should be immediately transferred by pipeline to cover irrigation deficits or to contribute to controlled recharge of the shallow alluvial aquifer;
- Since the above pipelines needs to be installed anyway, the specific recharge location has very little impact on the implementation cost of the different MAR planning options;
- The construction of infiltration ponds are low cost interventions. Hybrid systems, as combined infiltration through ponds and wells, would increase the implementation cost. Further groundwater modeling studies are required to judge the efficiency and necessity of hybrid MAR technologies under the prevailing local conditions;
- The most promising MAR planning option in economic and environmental terms refer to water infiltration directly within the demand area (Area of Interest) due to the high

efficiency of recharge and groundwater level recovery of the overexploited shallow aquifer in the demand area;

- Due to its contribution to sustainable groundwater management and groundwater protection, MAR implementation can be considered as obligatory in environmental terms;
- MAR implementation is also obligatory in social terms, due to the fact that the extension of the irrigated land, which is required for increasing family income and welfare, is just possible by MAR implementation with surface water surpluses;
- Detailed cost-benefit-analysis (CBA) for different MAR planning options will require further studies on the the most promising agricultural extension scenarios for the available land which will significantly impact on the expected benefits and future water demand.

4.9 Main Results and Conclusions

The main results are summarized as follows:

- Wadi Auja is a typical rural basin. The small domestic water demand is being covered by fresh water from deep wells in the carbonate aquifer, operated by Mekorot. The main water user is irrigated agriculture. Other uses area insignificant.
- According to the Ministry of Agriculture (MoA, 2013), the today irrigated area is approximately 5,000 dunam (500ha), while the available agricultural area at the lower Wadi Auja extends to about 15,000 dunam (1,500 ha). Taking the entire potential of the local surface water and groundwater resources of 23 MCM/a, 20% loss rate on the activation of surface water resources (2 MCM/a), actual Israeli groundwater abstraction of 8 MCM/a in the valley and a mean irrigation water demand of 1,000 m³/dunam into account, 13,000 dunam could be irrigated.
- By treated effluent import of 2 MCM from El Bireh and/or Jericho WWTP and mixing with brackish groundwater for direct irrigation of salt resistant crops, such as palm trees, the total available land may be irrigated.
- The main source of water is Auja spring with a mean discharge of 9,7 MCM/a. This water potential is not being used properly due to two reasons: (1) The high water transport losses of up to 60% by infiltration to the carbonate aquifer due to an old canal which is poorly maintained and (2) the strong discharge fluctuation of the spring during the year and in long-term. During wet years, the spring water surplus is lost towards the Dead Sea. This requires the efficient over-the-year storage of spring water surpluses.
- Since surface water reservoirs, such as Auja dam, suffer from huge evaporation and infiltration losses, the controlled underground storage of surface water surpluses in the shallow alluvial aquifer system in the valley and strategic recovery for irrigation purposes

during dry periods remains as only viable option. The water to be recharged consists by spring discharge surpluses and surface runoff which is being accumulated at Auja dam.

- A numerical groundwater flow model has been applied to the shallow alluvial system for two main reasons: (a) to validate the assumption that the recharged water may be efficiently stored in the shallow aquifer and recovered, according to the prevailing irrigation water deficits, and (b) to study the performance of 12 different Managed Aquifer Planning options (MPOs) in comparison with the so-called Do-Nothing-Approach.
- The performance of MAR planning options is evaluated based on the inflow of the recharge d water to the agricultural demand area (area of interest) and the total change of the mean groundwater table in the area of interest. All MPOs consider the duplication of the today irrigated land to about 10,000 dunam and full irrigation demand coverage.
- The model results show that the MAR planning option B4 with recharge location IV in the north-western part of the demand area, applying infiltration ponds or a hybrid system ensures high MAR performance. All MAR operational strategies which consider complementary water resources from deep wells and treated effluent import for direct supply for irrigation increase the surface water volume to be recharged as well as water supply reliability and, therefore, are superior solutions.
- It is expected that the different MAR planning options do not vary significantly with regards to their cost-benefit ratio.

Based on the above results, the following conclusions and recommendations may be drawn:

- Auja spring discharge, due to its high water potential, is the most important water source for the study area and requires protection and careful exploitation.
- In order to increase the surface water volume for aquifer recharge complementary water resources from deep well production and treated effluent import for direct supply in irrigation should be considered for integrated management.
- The shallow alluvial aquifer system requires better investigation with regards to its hydraulic characteristics and long-term storage of surface water surplus in the demand areas.
- Additional studies on groundwater transport and particle tracking will be required in order to study the freshening of the shallow brackish groundwater system and optimal groundwater management (pumping) strategies.
- Since agricultural development has a significant impact on the water budget situation, further studies on different agricultural development strategies and their impact on MAR planning and management are required.
- Potential, drawbacks and social acceptance of WWR through saline groundwater mixing with treated effluent for palm tree irrigation requires further investigations.

5. Case Study Jericho

5.1 Introduction

The case study concentrates on the city of Jericho and its location at the lower part of the Wadis Nueimah and Qilt, two sub-catchment of the Lower Jordan Valley in the Palestinian-Israeli territory where people highly depend on irrigated agriculture. The lower areas of Nueimah and Qilt in the valley are mainly classified as Area A under Palestinian administration. Nevertheless, hydro-infrastructure implementation on the ground should be considered as integrated effort that requires proper communication with the Israeli authority due its impact on water resources and their joint management.

Due to water scarcity, the agricultural area under irrigation is restricted to about 14,730 dunam (1,473 ha) around the city. Irrigation mainly relies on local spring groups, including Al-Sultan, Al Qilt, Al Fawwar, Al Farah, Ru'yan and Jumaiza spring in Wadi Qilt and Al Nueimah, Al Dyuk and Al Susah in Wadi Nueimah. In addition, brackish groundwater from shallow wells is utilized. Due to missing water storage and management concepts, main part of these surface and spring water resources is lost. Furthermore, due to groundwater over-exploitation, the groundwater level of the shallow alluvial system is constantly decreasing during the last decades and suffering from salinization processes.

For the sustainable development of agriculture at Jericho and extension of irrigated lands, the local water potential need to be better explored. This requires, besides other measures, the storage of surface water, including spring discharge surpluses during winter time and later recovery for irrigation purposes. According to the prior introduced MAR planning scheme (Figure 1.1), first of all, the question need to be answered if MAR is a potential and viable response to the prevailing water resources problems at Wadi Auja, before continuing with studies on the most appropriate MAR planning options as well as their performance and impacts.

5.2 Specific Research Objectives

The present Jericho case study focuses on the following specific objectives:

- Study potential and viability of MAR implementation for Jericho, taking Wadis Nueimah and Qilt as basin cluster and different operational scenarios into account;
- Apply an innovative procedure to support the evaluation of land suitability with regards to the implementation of recharge facilities and recharge site selection;
- Develop recommendations for MAR implementation at Jericho.

5.3 Specific Research Methodology

Like the prior case study, the Jericho case study follows the general methodology for MAR-Planning of figure 1.1 as suggested by Rusteberg et al. (2011). A focus is given on a site selection study, following a Spatial Multi Criteria Analysis (SMCA) approach and taking alternative IWRM scenarios into account.

The SMCA approach by [Rahman et al. \(2012\)](#) applied in this case study is illustrated in Figure 5.1. Problem definition is preliminary required in order to delineate whether MAR is a suitable response, before further analyses with regards to site selection for a potential MAR facility can be considered. Actual site selection is based on constraint and suitability mapping of the respective study area. The main objective of constraint mapping is to screen out a large number of alternatives, which have been deemed as being non-feasible. Sites, which are of prime interest to other planning projects or which are simply not available or completely non-feasible for MAR implementation are screened out in this step. The developed constraint map serves as a mask for suitability mapping.

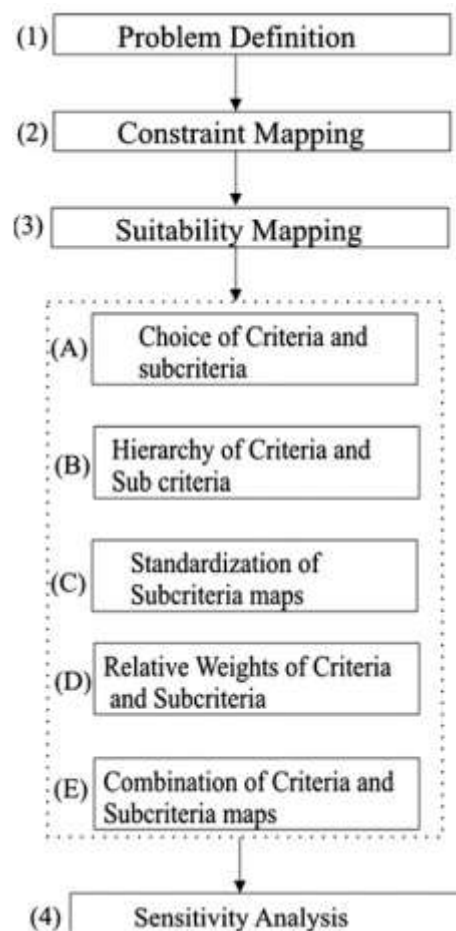


Figure 5.1: SMCA approach after [Rahman et al. \(2012\)](#)

For suitability mapping, a choice of site specific criteria and subcriteria needs to be made, selecting all relevant surface, subsurface, and regional characteristics. The Analytical Hierarchy Process (AHP) is used in order to decompose the ultimate goal into a three-level hierarchy of sub-criteria, which are presented by thematic maps or attributes. Standardization of these maps reduces dimensionality of the individual sub-criteria. The next step in the site selection procedure is assigning values of importance for all criteria and sub-criteria, which is done by assigning a weight to each criterion by means of pair-wise comparison. Finally, the overall suitability map is derived by aggregation of the developed maps. A sensitivity analysis should be undertaken in order to study the robustness of the suitability map with respect to the linguistic quantifier.

5.4 Case Study Area

The study area refers to the catchments around Jericho City. The city is located in the eastern part of the Westbank (Figure 5.2). Jericho City is the capital of the Jericho Governorate and has around 20,500 inhabitants according to the PNA (Palestinian National Authority, 2006). Two major watersheds delineate the case study area, Wadi Qilt (189 km²) and Wadi Nueimah (128 km²), with a topographic elevation difference of more than 1,000 m between the western mountain area and the eastern valley. The lower part has a great agricultural potential while the upper part has more industrial and commercial potential.

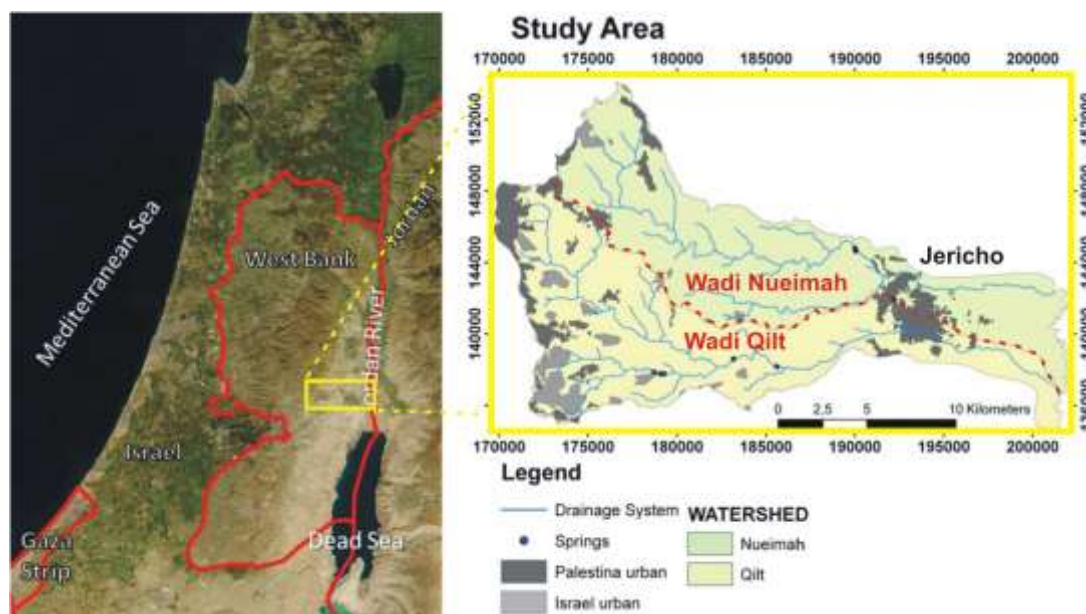


Figure 5.2: Location of the study area (yellow rectangle) within the West Bank and current boundaries (red lines) (left/a) and b (right) displays a map of the catchments (Lutz, 2011: Satellite image left: [NASA \(2006\)](#), modif.

5.4.1 Watersheds and basic Characteristics

The study area belongs to the arid and semi-arid climate zones. Therefore it has fluctuating and limited rainfall (Al-Jayyousi, 1999) as well as high evaporation rates. Table 5.1 shows average climatic data for the Jericho district in the south of the study area. The average annual precipitation of 184.4 mm is far below average potential evapotranspiration rates of 2120.6 mm/a. Rainfall is strongly limited to October till April, with its peak values during winter months at a maximum average of 53.7 mm in January. Rainfall mainly occurs in short events of very high intensity. These events periodically trigger storm floods, as high quantities of water discharge in short time and the dry soils are not able to take up much of the water. Potential evapotranspiration rates outrange precipitation all over the year, with maximum rates during summer, reaching average values close to 300 mm in July. Temperatures in the study area range from 7.4 °C in January to 37.8 °C in July on the monthly average level. Mean annual temperature is 22.45 °C (Walter, 2013).

Table 5.1: Average climatic values, Jericho District 1968-2004 (Shawana, 2010, modif.)

Month	Average Rainfall [mm]	Average pot. Evapo-transpiration [mm]	Minimum Temperature [°C]	Maximum Temperature [°C]
Oct	7.2	153.6	18.0	32.3
Nov	21.9	93.6	12.9	26.4
Dec	33.0	59.2	9.0	20.6
Jan	53.7	76.9	7.4	19.2
Feb	30.7	76.7	8.3	20.9
Mar	25.4	128.7	10.5	24.3
Apr	9.8	189.0	14.2	29.3
May	2.0	261.6	17.6	33.7
Jun	0.3	289.2	20.4	36.7
Jul	0.0	298.5	22.1	37.8
Aug	0.0	267.0	22.4	37.6
Sep	0.4	226.6	21.1	36.1
SUM	$\Sigma = 184.4$	$\Sigma = 2120.6$	$\bar{\Theta} = 15.3$	$\bar{\Theta} = 29.6$
	- 1936.2 mm/a		22.45 °C	

Water sources supplying Jericho City and the surrounding agricultural land today are springs and groundwater. The main spring systems in Jericho for domestic and agricultural purposes are the Wadi Qilt spring system including Ein Qilt, Ein Fara and Fawwar, the Nueimah spring system including the springs Ein Dyuk, Ein Nueimah and Shusha (Ali et al., 2009a), as well the Ein Sultan Spring system (Ali et al., 2009a; Lutz, 2011).

Spring discharge is relatively constant and presents very small fluctuation in its mean annual

rates. Figures 5.3 and 5.4 illustrate the historical time series of discharge rates at Al Dyuk and Al Sultan, being the most abundant springs of Wadi Qilt and Wadi Neuimah. As can be seen, despite few deviations, the mean annual discharge rates of the two representative springs are fairly constant.

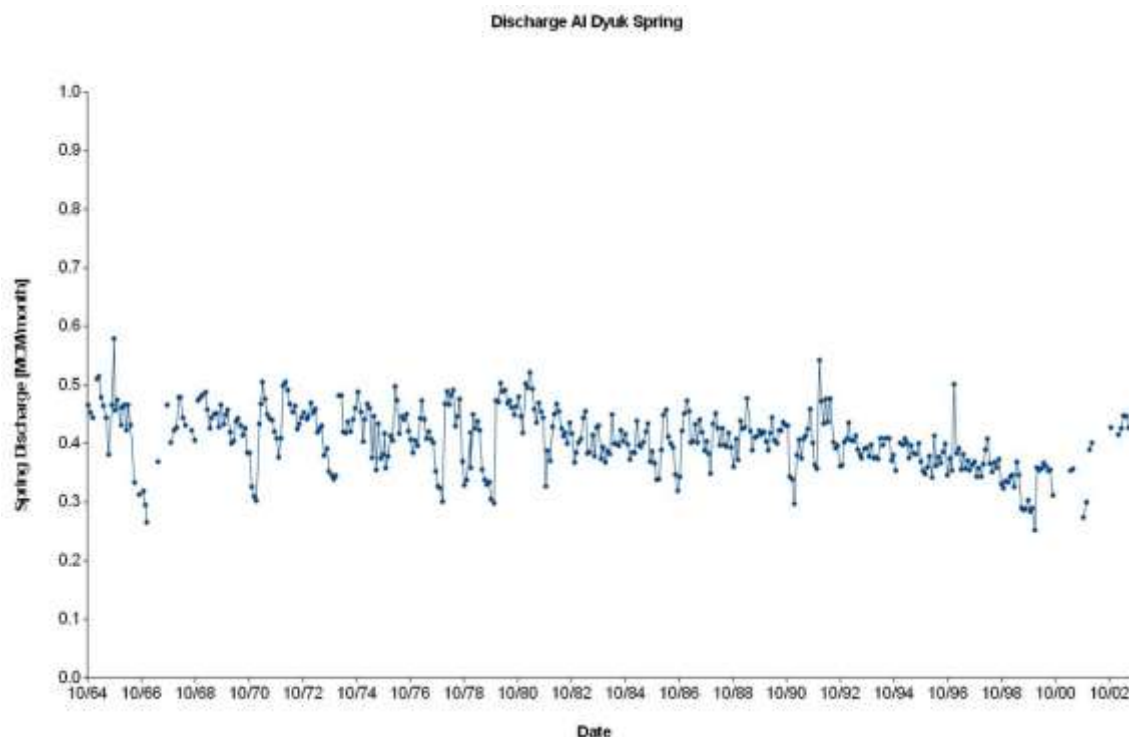


Figure 5.3: Historical time series of discharge rates at Al Dyuk Spring

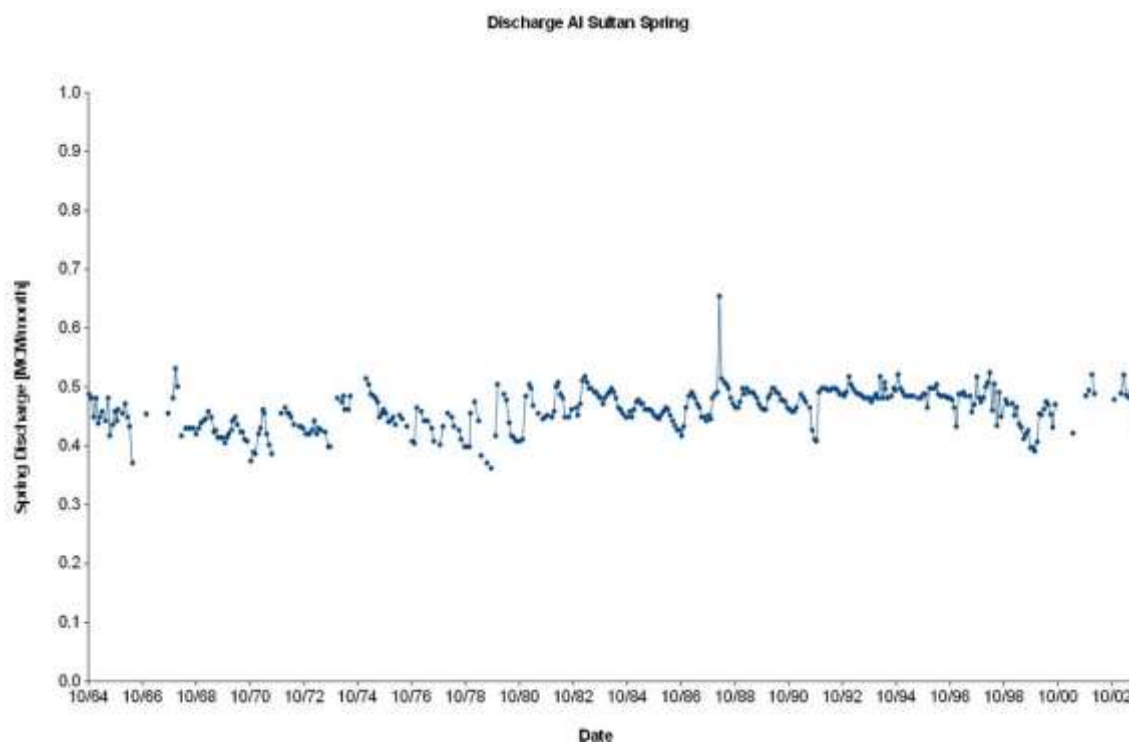


Figure 5.4: Historical time series of discharge rates at Al Sultan Spring

5.4.2 Hydro(geo)logy

The two surface drainage basins of the study area, Wadi Qilt and Wadi Nueimah, have their main catchment areas both in the Jerusalem Mountain west of Jericho. From there flood- and groundwater flows downstream to the Jordan Valley Floor (Jordan River and Dead Sea) (Ali et al., 2009a), but with no perennial flow. The direction of the groundwater main flow is primarily from west to east, which can in some parts change to southeast. The strong extraction of groundwater through mainly agricultural wells but also domestic wells in the Jericho area has a strong influence on the direction of the groundwater flow. (Lutz, 2011)

The most important aquifer in the area is located west of the Jordan Rift is the Cenomanian-Turonian Judea Group aquifer whose main components are carbonates (Anker et al., 2009). The aquifer in the Lower Jordan Valley floor consists of alluvial material, which is made up of limnic silts and evaporitic deposits of the different predecessors of today's Dead Sea (e.g. Lisan-Formation and Pleistocene Samara) (Gropius, 1999). The sub-basin is mainly fed by inflow of excess water from surface runoff in the wadis and from the adjacent aquifers such as the Lower Cretaceous Kurnub sandstone aquifer and the Albian to Turonian limestone and dolomite aquifer, also referred to as lower and upper aquifer (ARIJ, 1995; Lutz, 2011)

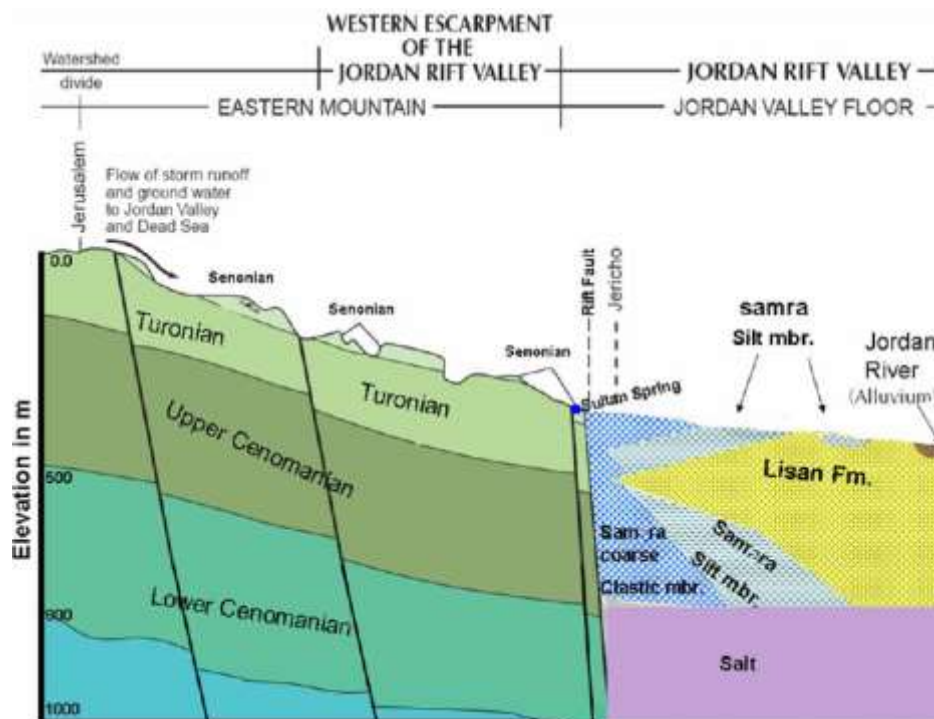


Figure 5.5: Schematic geological cross section in the study area (Lutz, 2011; Khayat, 2005, modified.)

All aquifers at the eastern side contain carbonate rocks and can be divided into two aquifers: Upper and Lower Cretaceous aquifer. Both aquifers have local sub-aquifers (e.g. the upper and lower aquifer of the Cenomanian-Turonian period). The thickness of the uppermost aquifer is about 150 m underneath Jericho. The aquifer system Cenomanian-Turonian is found in the eastern basin up to the rift fault just west of Jericho City with a confined behavior. West of the fault shallow unconfined aquifers are known made of clastic sediment deposits from the Pleistocene (Ali et al., 2009b; Lutz, 2011).

A new south-north fault was located in the eastern part of Jericho City as described by Al-Zoubi and Marej (2009). Saline groundwater bodies concentrated along the new fault system in the eastern part of Jericho City were recognized in depths of 120 and 160 m (Al-Zoubi and Marej, 2009). Furthermore, in the same study, a gravel deposit with 30 m thickness close to the surface was mapped, whereby the material is considered an indicator for the old wadi fan deposit (Lutz, 2011).

5.4.3 Water Resources System and MAR Integration

Existing hydro-infrastructure: The local spring systems are presently used for covering domestic, public, commercial and agricultural demand. A system of open canals, pipelines and water supply networks transports the spring discharge to the respective water users. Current loss rates resulting from water transport are varying between 25% and 35%. In addition, shallow wells in the alluvial aquifer in the lower Wadi Qilt catchment are installed. This brackish groundwater is currently directly applied for irrigation purposes.

Water Resources System Analysis: Figures 5.6 and 5.7 present the results for the lower part of each catchment, Qilt and Nueimah, not considering the mountainous areas in the upper part of the Wadi. The available water resources, their water potential (no losses) in MCM/a, existing and further required hydro-infrastructure (dotted lines) for water potential activation as well as relevant water users and demand between 2010-2030 (Sadah & Tamimi, 2011) are given. Freshwater resources (blue boxes) at Lower Wadi Qilt and Nueimah consist of the carbonate aquifer system in the western part of the major Jordan Valley fault, the Nueimah and Qilt spring groups, Al-Sultan spring and surface runoff.

The potential of the deep carbonate freshwater aquifer in valley is estimated in about 4 MCM/a at lower Wadi Nueimah and Qilt combined. But since the Israeli Authorities are abstracting up to 2.5 MCM of deep groundwater per year, Palestinian water availability with regards to this source is reduced to approximately 1 MCM/a in lower Wadi Nueimah and 0.5 MCM/a in lower Wadi Qilt.

The spring systems present a great combined water potential of about 20.7 MCM/a. Mean average discharge rates have been assessed by analysis of historical data as presented in chapter 5.4.1. With 4.9 MCM/a Al Dyuk is the most abundant spring in lower Wadi Nueimah, followed by Al Nueimah with 2.6 MCM/a and Al Susah with 0.6 MCM/a. At lower Wadi Qilt, Al-Sultan has the highest mean discharge rate with 5.5 MCM/a, the Qilt spring group, including Qilt, Fawwar, Fara, Jummaiza and Ruyan springs, discharges a cumulative quantity of 7.2 MCM/a.

The above mentioned high water losses need to be reduced by rehabilitation measures or a new pipelines (PL) need to be installed. Spring discharge is directly supplied to the irrigated areas, but over-the-year storage of spring water surplus will be required in order to improve the seasonal water deficit situation. According to figures 5.6 and 5.7, this requires the implementation of Managed Aquifer Recharge (MAR) and underground storage of water in the shallow alluvial aquifer. The porous aquifer system would permit the controlled recovery of the recharged water by well groups (WG) during dry periods for irrigation purposes.

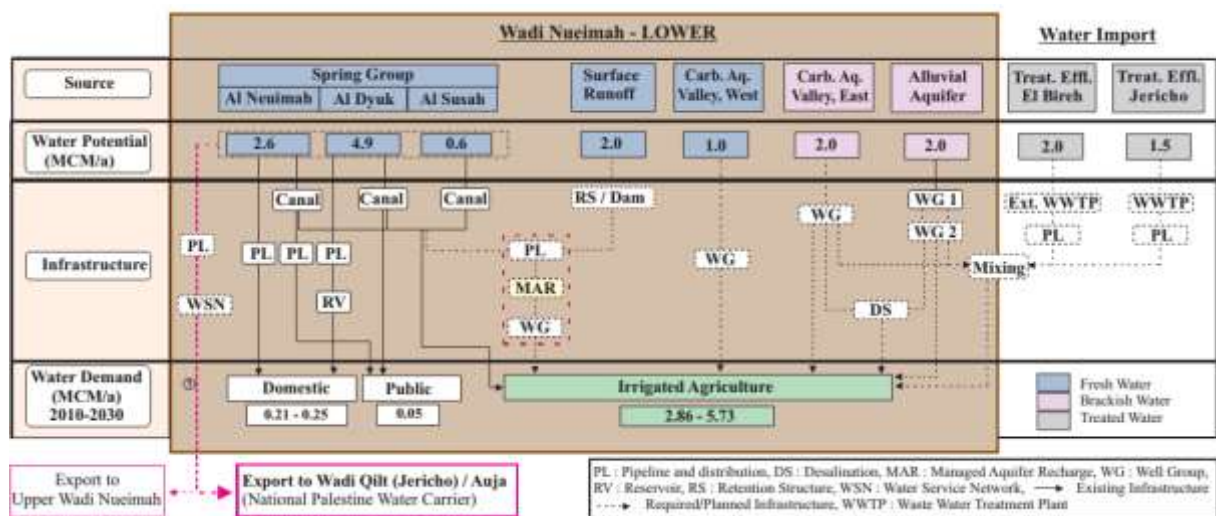


Figure 5.6: Integration of Managed Aquifer Recharge into the water resources system;
Case study Jericho – Wadi Nueimah

Surface runoff is currently not specifically utilized. It should be captured by new retention structures (RS) or dam constructions and should be supplied for irrigation with high priority in order to reduce evaporation and infiltration losses. It is recommended to install a pipeline between the dam and the irrigated lands. Due to the high temporal variability of surface runoff, the corresponding water potential is difficult to quantify (Moe et al, 1998). Based on precipitation-runoff studies (Abadi, 2006), it has been estimated that a mean runoff of 2 MCM/a may be stored at lower Wadi Nueimah and 1.7 MCM at lower Wadi Qilt. After

attending the immediate irrigation demand, the remaining surface water surplus retained should be stored in the underground by means of Managed Aquifer Recharge in order to avoid evaporation and infiltration losses. In spite of the fact, that part of the infiltrated water would indirectly recharge again the shallow alluvial aquifer system, MAR should take place in the alluvial system in order to maintain control of the surface water surplus, to minimize water losses and guarantee the most efficient reutilization of these waters. According to figures 5.6 and 5.7, this may be achieved by the joint management of those MAR facilities which are required to store the spring discharge surplus.

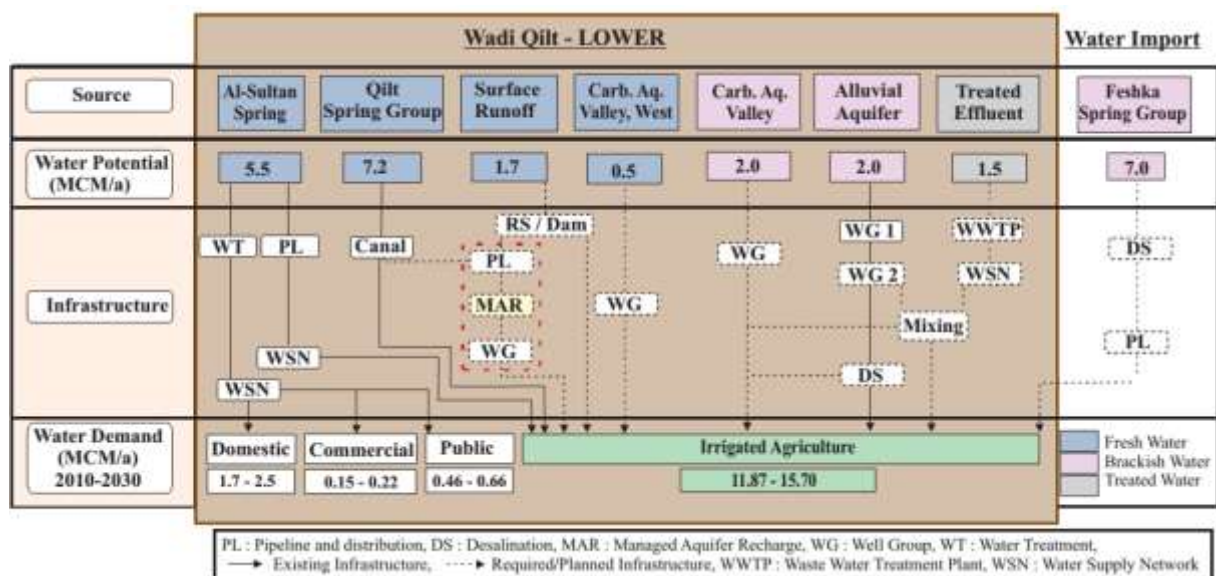


Figure 5.7: Integration of Managed Aquifer Recharge into the water resources system; Case study Jericho – Wadi Qilt

Brackish water resources (red boxes) at Lower Wadi Qilt and Nueimah consist of Brackish groundwater from shallow wells in the alluvial aquifer (2 MCM/a in each catchment) and deep wells in the deep carbonate aquifer (2 MCM/a in each catchment). They may be used for direct irrigation to salt resistant crops or desalinated by small solar driven facilities and used for high quality crops and high-tech agriculture (greenhouses). This would require the installation of new wells in both aquifer systems. Optionally, brackish groundwater may be mixed with treated effluent (grey boxes) to reduce salt concentrations and directly applied for irrigation of salt resistant crops, such as palm trees. In addition to effluent production at Jericho City (1.5 MCM/a), effluents up to 2 MCM/a could be imported from El Bira waste water treatment plant by gravity pipeline. Extraction of surface water from the Jordan river is not considered due to political restrictions.

As further external sources and potential water import, desalinated water from 20 km distant Feshka spring may be imported by pipeline. The corresponding water potential linked to the case study area of Wadi Qilt has been estimated in 7 MCM/a, which is around one third of

the installed capacity of the desalination plant. Feshka spring offers a mean discharge of 60 MCM/a. The installation of a desalination plant with a designed capacity of 22 MCM/a is foreseen (PWA, 2009).

5.4.4 Agriculture

Irrigated agriculture is the dominating water user in the Valley and main factor for social development. Agriculture is the main sector to provide food stock for the rest of the Palestinian areas (Mairie de Paris and PHG, 2010). According to Sadah and Tamimi (2011), the presently irrigated area around Jericho City is about 14,730 dunam (dn; 1dn = 0.1ha), while the total area of irrigable land with excellent agricultural potential amounts to approximately 21,430 dn.

Besides medical crops, palm trees, vegetables, grain, grapes and other citrus fruits are cultivated. Vegetables are cultivated in a traditional way by open drip irrigation schemes as regular agriculture as well as in greenhouses. Due to their robustness with regards to brackish water irrigation from shallow wells and economic value of dates, palm trees are cultivated. The average annual water demand for irrigation is approximately 14.8 MCM, which leads to an average water demand of about 1,000 m³ or 1,000 mm per dunam per year. Table 4.1 presents the mean monthly distribution of the Water Demand for irrigation (WDI) at Jericho City.

Table 5.2: Mean monthly Water Demand for Irrigation (WDI) at Jericho City (after Sadah & Tamimi, 2011)

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Ago	Sep	SUM
WDI (MCM)	1.30	1.18	1.12	1.11	1.12	1.12	1.36	1.30	1.21	1.32	1.32	1.32	14.8
WDI (%)	8.8	8.0	7.6	7.5	7.6	7.6	9.2	8.8	8.2	8.9	8.9	8.9	100

According to the Palestinian Ministry of Agriculture, XX wells with a mean depth of XXXm are pumping annually about 4 MCM/a from the shallow alluvial aquifer system. It is assumed, however, that an unknown number of illegal, minor wells is additionally being operated in the village.

5.5 MAR-Potential and Feasibility

5.5.1 Water Budgets

In order to analyse the potential and needs for the implementation of Managed Aquifer Recharge at Jericho City, different water budget studies have been conducted. In contrast to prior water resources analyses, these budgets cover water availability and demand for both, lower Wadi Qilt and lower Wadi Nueimah. The given demand values consider agricultural, domestic, commercial and public demand. In the water resources system analysis, spring discharge together with surface runoff has been identified as main sources for Managed Aquifer Recharge. Therefore, the mean monthly water availability of these sources have been compared with the water demand of the today irrigated area of about 14,800 dunam. For mean spring discharge rates, historical time series of 43 years and more have been considered, depending on available data for each of the springs. Figure 5.8 presents the today problematic situation with regards to irrigation demand and activation of the water potential. Around 25-35% of the spring water potential is being lost during the transport process.

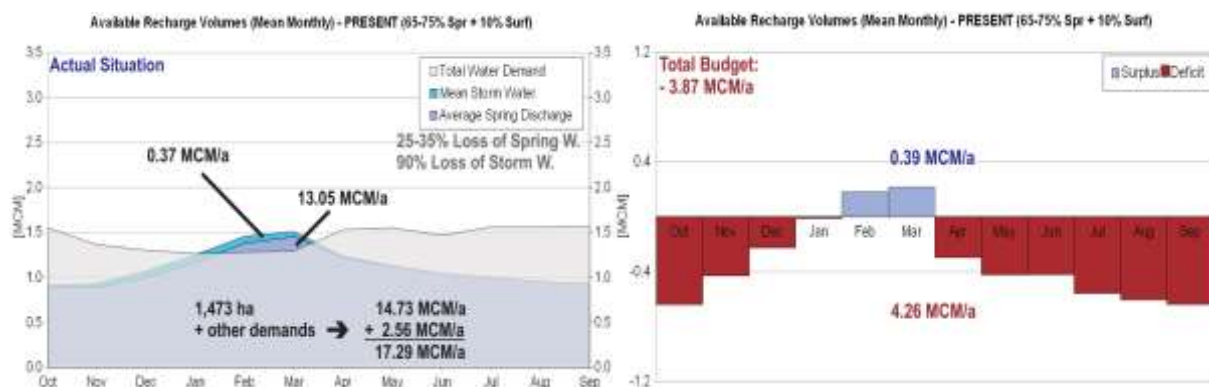


Figure 5.8: Today available surface water resources (accumulative spring discharge and surface runoff) versus present water demand for irrigation and public, domestic and commercial demand

Some flood water retention take place at the irrigation ponds of the local farmers. Therefore, we assume that just 10% of the surface runoff is being used for irrigation purposes. According to the corresponding water budget calculation for mean hydrological conditions, presented in figure 5.8, there is a small water surplus during the months February to March, while the rest of the year the irrigation demand cannot be satisfied. The overall water deficit of around 3.9 MCM is being covered by brackish water from the shallow wells of the alluvial aquifer system.

Figure 5.9 presents the today situation with regards to irrigation demand and activation of the water potential, though it already takes an improvement of the water loss rates into account, as could be achieved by modernisation of the transport system. Hence, loss rate is reduced to 20% here.

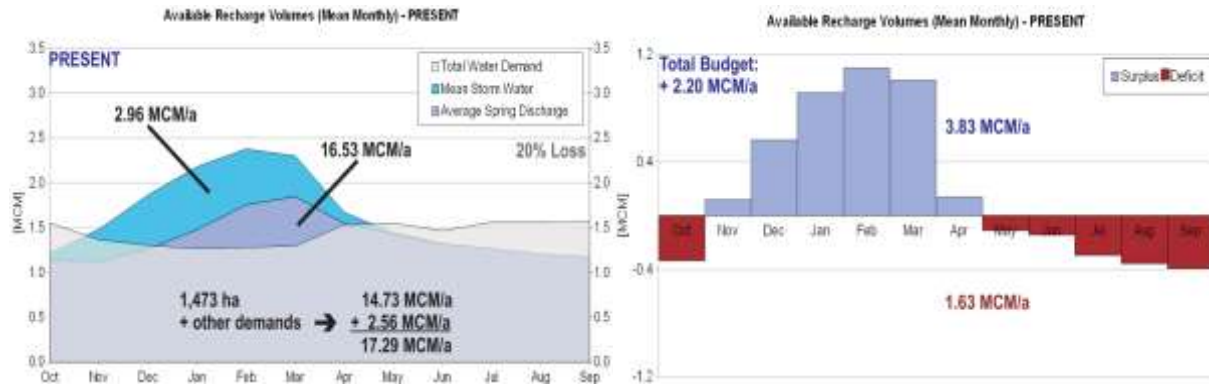


Figure 5.9: Surface water resources (spring discharge plus surface runoff) after loss reduction to 20% and average present pumping rate versus present total water demand for Jericho City

The months of May to October present a water deficit of 1.63 MCM. From November till April, water demand is not only covered, but a total surplus of 3.83 MCM would still be available for storage. This volume of water could be used for Managed Aquifer Recharge, storing the water for dry years and contributing to groundwater level recovery of the overexploited shallow alluvial aquifer system. The necessary hydro-infrastructure interventions refer to the installation of pipelines from the water sources to the irrigated lands around Jericho City as well as to the MAR facilities.

The water budget, presented in figure 5.10, considers the extension of the irrigated area to the maximum available land of 21,440 dunam, maintaining the type of crops and schemes of the existing irrigated area. The water budget presents fresh water surpluses of 1.28 MCM during the period from January to March. The rest of the year a deficit of approximately 6.9 MCM is being accumulated.

The above defined agricultural development scenario results in an annual water deficit of about -5.63 MCM/a. This means that, even storing the surface water surplus in the underground and recovering the water during the water scarce period, the irrigation demand cannot be covered. On the other hand, the water budget shows clearly that under mean hydrological conditions nearly 1.3 MCM per year of surface water is lost if not properly stored by aquifer recharge. The total annual water deficit would have to be covered by groundwater resources.

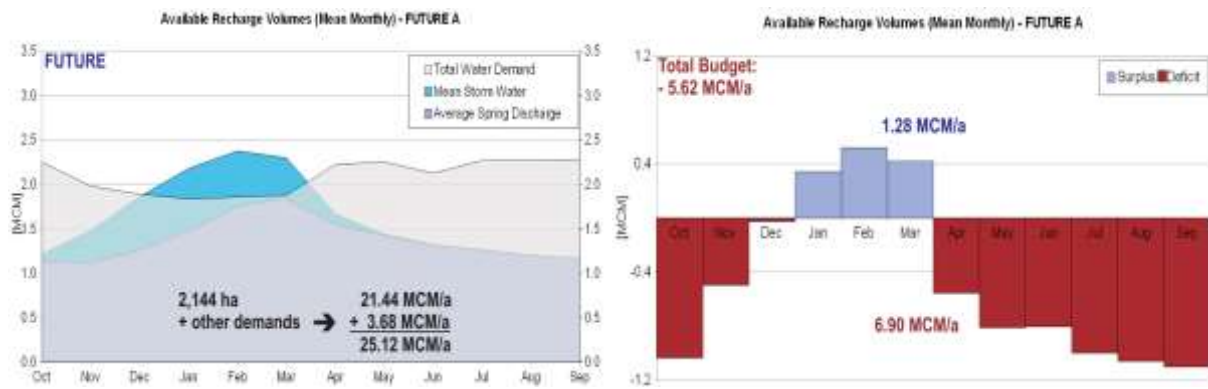


Figure 5.10: Surface water resources after loss reduction and average present pumping rate versus future total water demand for Jericho, taking an irrigated area of 21,400 dunam into account

Figure 5.11 presents an IWRM scenario with regards to the water availability. Additionally, 1.5 MCM/a of treated effluent from Jericho itself and another 2 MCM from El Bireh WWTP are activated.

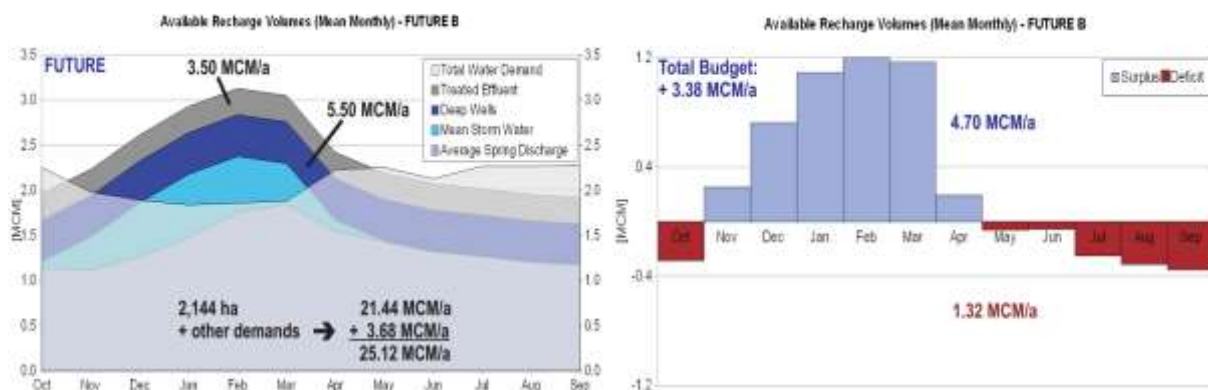


Figure 5.11: Surface water resources after loss reduction and average present pumping rate plus deep well installation and treated effluent utilization versus future total water demand for Jericho, taking an irrigated area of 21,400 dunam into account

Until today, there is no collection system for waste water in Jericho City or its vicinity. The waste water produced is still stored in cesspits (Lutz, 2011). Another 5.5 MCM/a could be pumped from the deep carbonate aquifer system, of which 1.5 MCM are fresh water from the western part of the aquifer, whereas the remaining 4 MCM would need to be extracted in the eastern part, representing brackish water. These additional sources should be directly applied to irrigated agriculture. The additional water volume of 9.5 MCM leads to a water surplus in the annual water budget of 3.38 MCM while the period of surplus extends to November till April.

Groundwater recharge rates were estimated by [Marei and Subeih \(2009\)](#) to be around 3.5 MCM/a in high recharge sections ([Lutz, 2011](#)). This leads to the conclusion that, under mean hydrological conditions and the prevailing irrigation planning and management, the irrigated area may be extended to its maximum threshold of 21,440 dunam. This conclusion is based on the assumption that the surplus of surface water from spring discharge and surface runoff may be stored and fully recovered later by pumping wells in the irrigated areas.

5.5.2 Feasibility of Underground Storage

The alluvial aquifer at Jericho City resembles the same material as in Wadi Auja and consists of mostly coarse gravel and sand formations. Thus, hydraulic conductivity and storage capacity are high. Figure 5.12 shows the outline of the quarternary alluvial aquifer in the case study area and corresponding infiltration rates in the range of 0.25-1m/d, representing the uppermost soil layer ([Lutz, 2011](#)).

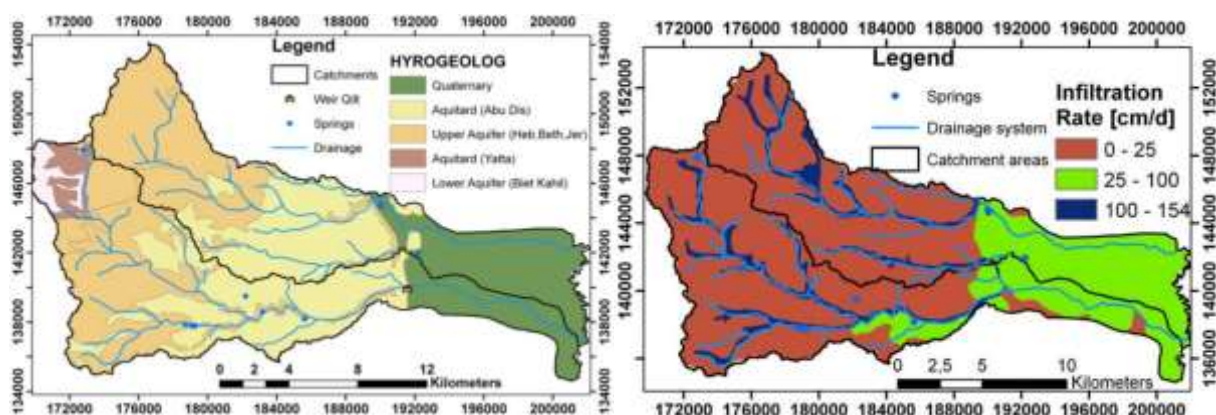


Figure 5.12: hydrogeology map of the region and infiltration rate map ([Lutz, 2011](#))

As only estimated data of the local aquifer's hydraulic characteristics is available, [Lutz \(2011\)](#) calculated approximate values of hydraulic conductivity and flow velocity. Based on an estimated average aquifer thickness of 80m and available transmissivity data, a mean hydraulic conductivity of 6.25 m/d and groundwater flow velocities of 0.15 m/d were calculated ([Lutz, 2011](#)).

The Storage capacity of the respective area of interest is estimated based on the average groundwater table of 17m (Gropius, 1999) and an assumed mean porosity of 35%. Assuming an area of interest of about 25 km², representing the area of potential agricultural extension, a storage capacity of more than 100 MCM can be estimated.

5.6 MAR Planning Options

5.6.1 Sources of Water

According to the water resources system analysis (Fig. 5.6 and 5.7) and above water budget studies, local springs and surface runoff are the sources of water, which are available at Jericho City for Managed Aquifer Recharge implementation.

The above IWRM strategy (Fig. 5.11) ensures the extension of the irrigated area around Jericho City from 14,730 to 21,430 dn, taking mean hydrological conditions into account. A fresh water volume of 4.7 MCM is recharged to the shallow aquifer system in the months between November and April and should be recovered during the period with irrigation water deficits. This shows that the recharge volume depends on the use of complementary sources of water, such as fresh or brackish water from the deep carbonate aquifer or treated effluent.

All water budget studies are based on the assumption that the recharged surface water will be fully recovered by pumping wells in the agricultural areas to cover water needs for irrigation.

5.6.2 Recharge Technology

As basic characteristics of the local alluvial aquifer are similar to those in the case study area of Auja, infiltration ponds are the recommended choice of MAR technology. Infiltration rates in the respective area of potential MAR implementation are found to range between 0.25 m/d and 1.54 m/d at the top soil layer (Fig. 5.12). Shallow soils with lower infiltration capacity may be removed by excavation. Mean depth to the alluvial groundwater table in the agricultural area is about 17m. In order to improve the efficiency of recharge, it is recommended to apply a hybrid system by combining injection wells with infiltration ponds.

For runoff harvesting, different methods of capturing can be achieved. Possibilities are a storage dam or retention dam construction as well as dividing the riverbed. Retention dams are used to increase infiltration in streambeds. The traps are earthen dams of variable height, normally below 3 m, that are constructed of local available materials ([UNEP, 1997](#)). The storage dam stops the water at once. The water stored in a basin beyond can be transported to the needed location via channel or pipeline ([Lutz, 2011](#)).

When constructing a single dam (storage dam) as harvesting structure, high evaporation rates have to be taken into account due to the climate situation. This method would mainly

serve as first stop of the water, which will lead for infiltration to another location. Another possible harvesting method is the latter diversion technique, where the flood water will be let down into the recharge basin through the connecting channel by gravity flow (JICA, 2007). A further possibility would be to divide the riverbed and guide the main part of the water to a row of infiltration ponds (Lutz, 2011). Due to expectedly high sediment loads, each of these technologies requires further pre-treatment measures in order to prevent clogging.

5.6.3 Recharge Location – MAR Site Selection

Constraint Mapping

The search of a feasible site starts by defining the data maps. Within this step the thresholds of each criteria map (constraint mapping) are described. Using the Boolean overlay method, a first site selection is done. The simplest type of the aggregation is the intersection or logical AND, which is used only when maps have been classified into suitable and unsuitable images by values 1 and 0 (Drobne and Lisec, 2009). By this method non-feasible areas, which receive a value of 0, are excluded. An overall constraint map is produced by overlaying the chosen maps after the non-feasible areas were excluded (Lutz, 2011).

Table 5.3 presents the site specific thresholds used for the study area (Lutz, 2011). In the table the criteria are classified according to their use for the two mapping processes. The land use criterion is the only one which is just used for constraint mapping. Urban areas, military and refugee camps as well as existing forests will be excluded from the study area, as no MAR can be implemented in such a region without pulling down buildings or deforestation. Agricultural land, waste lands and natural vegetation areas can be used for suitability mapping. Steep gradients are not feasible for MAR. Slope values greater than 8 % were excluded using the Boolean overlay method (Feiznia et al., 2007). During suitability mapping the best values of the slope will have a value of 0 %, as they are most suitable for infiltration ponds. Infiltration rate should have at least a value of 0.25 m/d in order to operate the facility efficiently under the prior delineated potential recharge values. In the suitability process the highest saturated hydraulic conductivity will receive the number 1. The vadose zone has to be thick enough so that the percolating water can be admitted. Therefore depth to the groundwater table should be at least 10 meters. In the following process of weighting, a minimum depth of 30 m from the surface is declared best. The thresholds are defined using the values used in the paper of Feiznia et al. (2007). The health risk value for chloride concentration in drinking water lies by 250 mg/L (USEPA, 1996). That is why the lower limit was also adapted to that value given. As the water quality should improve especially in the case of salinity, higher concentrations are more feasible. The same logical step was

performed when defining the values for electrical conductivity (EC). A rate of 3 mS/cm is still suitable for medium salt sensitive plants can still exist (Feiznina et al., 2007). Therefore the limitation for the EC item was set equal. The distance to the Jordan River is a necessary criterion, because if the recharged groundwater gets too close to the river this water will be lost into the river (Lutz, 2011).

Table 5.3: Used thresholds for the site selection in case of constraint and suitability mapping (Lutz, 2011)

Items	Thresholds	
	Constraint mapping	Suitability mapping
Land Use	Urban areas and forests will be excluded (set to zero).	-
Slope	$\geq 8\% = 0$ $< 8\% = 1$	$0\% = 1$ $4\% = 0.4$ $8\% = 0$
Infiltration Rate	$\leq 0.25 \text{ m/d} = 0$ $> 0.25 \text{ m/d} = 1$	$1.54 \text{ m/d} = 1$ $1.00 \text{ m/d} = 0.5$ $0.25 \text{ m/d} = 0$
Depth to GW Table	$\geq 10 \text{ m} = 0$ $< 10 \text{ m} = 1$	$30 \text{ m} = 1$ $10 \text{ m} = 0$
Transmissivity	-	$600 \text{ m}^2/\text{d} = 1$ $300 \text{ m}^2/\text{d} = 0$
Chloride	-	$1718 \text{ mg/L} = 1$ $250 \text{ mg/L} = 0$
Electrical Conductivity	-	$6 \text{ mS/cm} = 1$ $3 \text{ mS/cm} = 0$
Distance to Jordan River	$500 \text{ m} = 0$ $501 \text{ m} = 1$	$4000 \text{ m} = 1$ $501 \text{ m} = 0.5$ $500 \text{ m} = 0$

After producing individual constraint maps for each threshold, these are overlain to achieve one single combined map. This final overall constraint map is shown in Figure 5.13. It can be seen that a great part (white) is defined as not feasible for the purpose of MAR. Only the blue areas are used for the suitability mapping in the next step as these are indicated as appropriate. It can be seen that only the eastern part (the Lower Jordan Valley Floor) of the study area is classified as feasible. This results from the steep mountain region in the western part of the study area. The part of feasible sites in the study area has been narrowed from 296.61 km² in total to 41.78 km². This decreases the suitable region for MAR to about

14 % of the total area (Lutz, 2011).

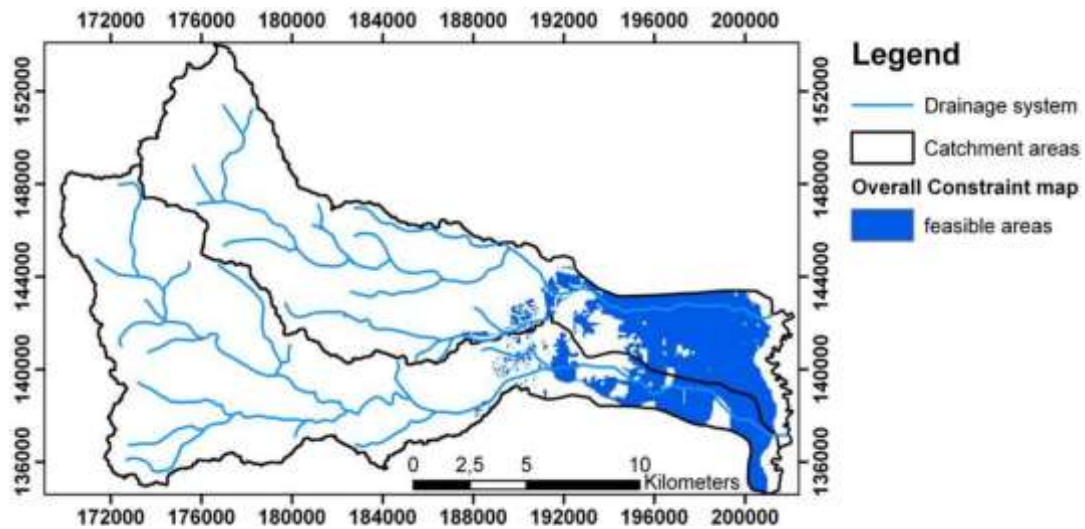


Figure 5.13: Overall constraint map for the catchments of Jericho city (Lutz, 2011)

Suitability Mapping

The prior introduced and standardized sub-criteria (Table 5.3) are categorized in four main criteria; 'Surface Characteristics', 'Underground Characteristics', 'Groundwater Quality' and 'Further Characteristics'. By pair-wise comparison, global weights of the main criteria are derived (Table 5.4). Direct weighting of the individual sub-criteria results in final weights for each sub-criterion as illustrated in Figure 5.14 (Lutz, 2011).

Table 5.4: Pair-wise comparison weighting for the resulting weighting scheme (Lutz, 2011)

Main criteria	Surface Ch.	Underground Ch.	GW Quality	Further Ch.	Relative Importance
Surface Ch.	1	$\frac{1}{5}$	$\frac{1}{3}$	2	0.121
Underground Ch.	5	1	2	5	0.513
GW Quality	3	$\frac{1}{2}$	1	3	0.281
Further Ch.	$\frac{1}{2}$	$\frac{1}{5}$	$\frac{1}{3}$	1	0.085

The underground characteristics were defined as most significant, as the storage capacities of the aquifer (transmissivity and depth to groundwater level) are the most relevant criteria for the construction of the aquifer recharge basins. Second comes the groundwater quality. The surface characteristics are placed third, due to small elevation differences in the area after exclusion by constraint mapping. Further characteristics were ranked as least important.

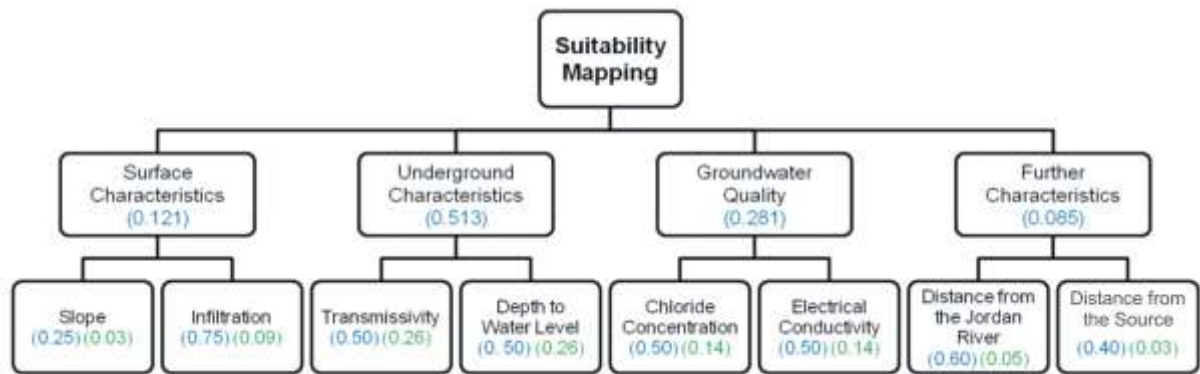


Figure 5.14: Hierarchy for the suitability mapping; blue: local weights, green: global weights (Lutz, 2011, modif.)

There is already a buffer of 500 m to the Jordan River excluded by constraint mapping, so that no recharged water will be lost by groundwater flow to the river. Based on the developed weighting scheme, the final suitability map is generated. (Lutz, 2011):

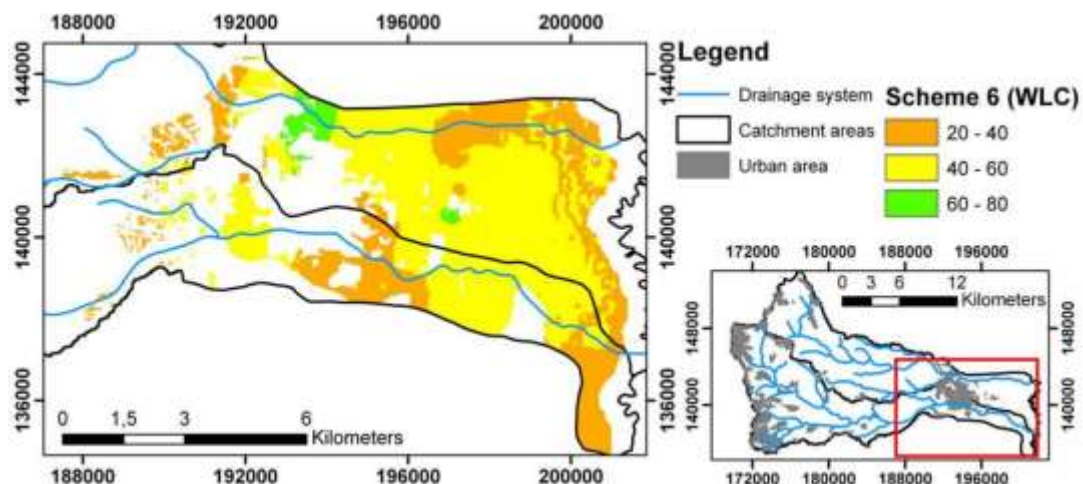


Figure 5.15: Final suitability map for MAR site selection (Lutz, 2011).

Sensitivity Analysis

A final sensitivity analysis is performed by adjustment of the linguistic quantifier (α). Figure 5.16 exemplarily shows the results for an α -value of 1, meaning half of the criteria should be satisfied. It is similar to the final suitability map (Figure 5.15). For reasons of good comprehension, the same scale for the legend is used. In total, the sensitivity analysis verifies the robustness of the made calculations (Lutz, 2011).

5.6.4 Pre-Treatment

Quality measurements of the flood waters are very raw in the West Bank area. Data on the water quality of flash floods were only found for the Wadi Qilt but not for Wadi Nueima. It can be concluded from the master thesis by [Daghrah \(2005\)](#) that most trace elements were classified to be under the maximum allowable limit of existing guidelines (e.g. [USEPA, 1996](#)). Still, the Wadi Qilt is microbially contaminated. When recharging the harvested surface runoff by infiltration ponds, the respective quality requirements for irrigation need to be achieved. However due to the high material transport in the surface water, some kind of sedimentation pond/dams have to be built as pre-treatment method. As known today, no sediment load measurements were made. Only observations from authors of the [JICA report \(2006\)](#) indicate high sediment loads. Measurements in terms of the magnitude of material transport need to be done before the construction of the sedimentation ponds can start. The ponds have to be constructed appropriately with a sufficiently large volume ([Lutz, 2011](#)).

5.6.5 Operation

A potential MAR facility requires operational management with regards to the temporal variation of available recharge water and deficits. Surplus of water, after the water demand is satisfied, should be used for artificial groundwater recharge, whereas in dry periods deficits need to be covered by groundwater pumping. In general, further and more detailed studies of the local aquifer system, the highly variable surface runoff and the temporal distribution and quantities of surplus and demand are required to establish efficient operation of the MAR facility.

5.7 Main Results and Conclusions

The main results are summarized as follows:

- Irrigation of all appropriate areas could not be covered by local water resources without MAR implementation and would result in water deficits of 6.9 MCM/a in the Jericho region, taking modernization of the hydro-infrastructure into account;
- The study shows that an extension of the irrigated areas around Jericho City of up to 21,440 dn could be sustained through MAR implementation, assuming that spring water and surface runoff surpluses during wet and mean hydrological years could be used for over-the-year storage in the alluvial aquifer and efficiently recovered during dry periods;
- The applied Spatial Multi Criteria Analysis Tool proved to be a practical support system for evaluating land suitability for MAR implementation as well as MAR site ranking.

Based on the above results, the following conclusions and recommendations may be drawn:

- The shallow alluvial aquifer system requires better investigation with regards to its hydraulic characteristics and long-term storage of surface water surplus in the demand areas;
- Additional studies on groundwater transport and particle tracking will be required in order to study the freshening of the shallow brackish groundwater system and optimal groundwater management (pumping) strategies;
- Potential, drawbacks and social acceptance of WWR through saline groundwater mixing with treated effluent for palm tree irrigation requires further investigations.

Further studies on different agricultural development strategies and their impact on MAR planning and management are required.

6. Case Study Deir Alla

6.1 Introduction

The Jordan Valley is the base level for all the natural water courses of the northern highlands. It is built of recent clastic sediments forming local aquifers. These aquifers are not filled with water, but are even overexploited. According to ongoing geologic and geophysical investigations rechargeable aquifers which can serve as storage reservoirs are found in the JV. They can accommodate several tens of millions of cubic meters of recharge water.

Flood waters of inter catchments and wadis downstream of dams in addition to treated waste water, especially during the rainy season still flow unutilized and can be used as recharge water. Water /water and water /rock interactions show that the recharge water will not have any adverse impacts on the groundwater quality or on major dissolution precipitation processes in the aquifers.

Therefore, countries sharing the Jordan Valley area should utilize its recharge potential during the rainy season and in times when there is no need for water use, to store any excess water in the underground for times of need. This seems a more appropriate way of storing water than surface reservoirs with all their problems of evaporation, eutrophication and pollution.

King Abdullah Canal (KAC) (The East Ghor Canal) and its irrigation network is considered the most important water project in Jordan, it is a concrete lined gravity canal 110 km long fed by 1 km diversion tunnel running underneath the mountain between Yarmouk River and the village of Adassiya. The water sources of the KAC are from Yarmouk River, at the international Jordan border with Syria, Mukheiba wells, the peace conveyer water from Israel, and the southern tributaries, which flow within Jordanian territories. In many years since its operation the KAC was not able to supply the necessary water amounts due to decreased flow, especially during the summer months when drinking water is badly needed. The risks of contamination and drought are still present and can at any time negatively affect the water supply of Amman and the other cities, which partly depend on Deir Alla-Zai scheme for their drinking water In general storing surface water underground has many advantages over storing it in surface reservoir dams or Canals such as KAC. The water of the KAC according to the suggested scheme sees for to store water in the aquifers along the Canal when water is in excess (winter times) and pump it when need arise or when the Canal water can not be used directly as a source of drinking waters due to pollution. ([Al-Amoush et al., 2012](#))

In the course of SMART II project Managed Aquifer Recharge (MAR) studies were carried out for various parts on the eastern parts of the JV but they concentrated on Deir Alla –Suleikhat area, where MAR can really contribute to solve the major problem of drinking water supply of the city of Amman.

6.2 Specific Research Objectives

Besides the main goals of research of the deliverables D318 and D320, the following specific objectives are linked to the case study of Deir Alla:

- Study potential and viability of MAR implementation at Deir Alla;
- Study the suitability of the local aquifer in terms of feasibility for underground storage and finding potential locations for MAR implementation;
- Discuss economic viability and social dimension of MAR implementation to strengthen agricultural development;
- Develop recommendations for MAR-implementation at Deir Alla.

6.3 Specific Research Methodology

The Wadi Deir Allah case study follows the general methodology for MAR-Planning of figure 1.1 as suggested by Rusteberg et al. (2012). A focus is given on the suitability of the local aquifer as underground storage and the delineation of feasible recharge locations, based on geological mapping, vertical electrical soundings and hydro-geochemical investigations ([Al-Amoush et al., 2012](#)).

6.4 Case Study Area

The Case Study Area is located in Jordan and lies in the middle eastern part of the Lower Jordan Valley (Figure 6.1). It extends from Deir Alla in the south to Suleikhat in the north, while its eastern and western boundaries are defined by the Jordan River and the mountain foothills ([Salameh, 2012](#)), covering an area of 110 km². Within the study area runs the King Abdullah Canal (KAC, or: The East Ghor Canal) which, together with its irrigation network is considered the most important water project in Jordan ([Al-Amoush et al., 2012](#)).

6.4.1 Local Climate

Local climate is classified as semi arid type with a mean annual precipitation of 235 mm (Salameh, 2012). Mean annual temperatures between slightly above 0°C and 30°C, while

relative humidity ranges between 30% and 70% (Salameh, 2001; DOM, 2011). As a result of temporal strongly accumulated precipitation events resulting in storm floods, the area is characterized by several major Wadis; Rajib, Kufranja and Sulikhat, and Zerqua River, discharging to Jordan River (Al-Amoush et al., 2012).

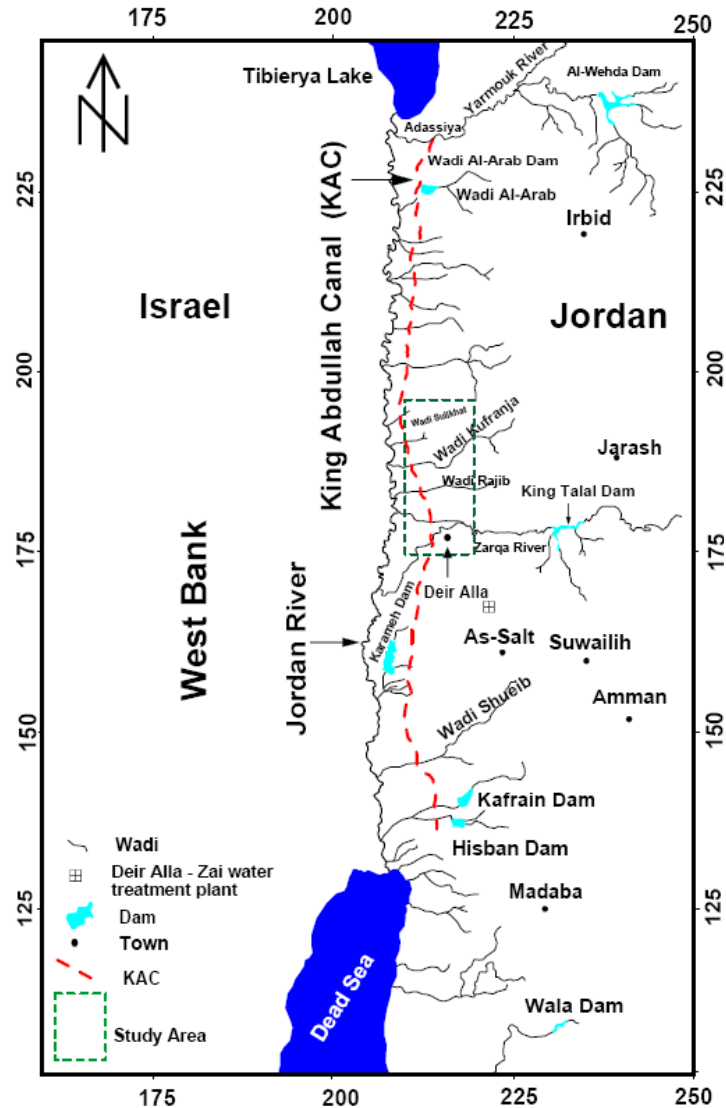


Figure 6.1: Location map of the case study area and KAC route (Al-Amoush et al., 2012)

6.4.2 Geology and Hydrogeology

Within the study area, the following lithofacies are predominating (Al-Amoush et al., 2012):

- Top soil layer (20 - 200 Ω m)
- Unconsolidated alluvial deposits of gravel and dry sand ($> 60 \Omega$ m)
- Two Lisan marl and clay layers ($\leq 10 \Omega$ m)
- Water saturated alluvial sandy gravel layer (10 - 60 Ω m)

The top soil layer is up to 2 m in thickness. To the east, Rendzina and Lithosol with their parent rocks of carbonate are dominating the study area. The most western part is occupied by soil developed on loss-like sediment ([Al-Amoush et al., 2012](#)). These soils are silty and loamy with moderate humus in addition to granular and friable gravel ([MoA, 1993](#)). Overlaying gravel and stony horizons, Rendzina soils are pre-dominant ([Hamadeh, 2000](#)).

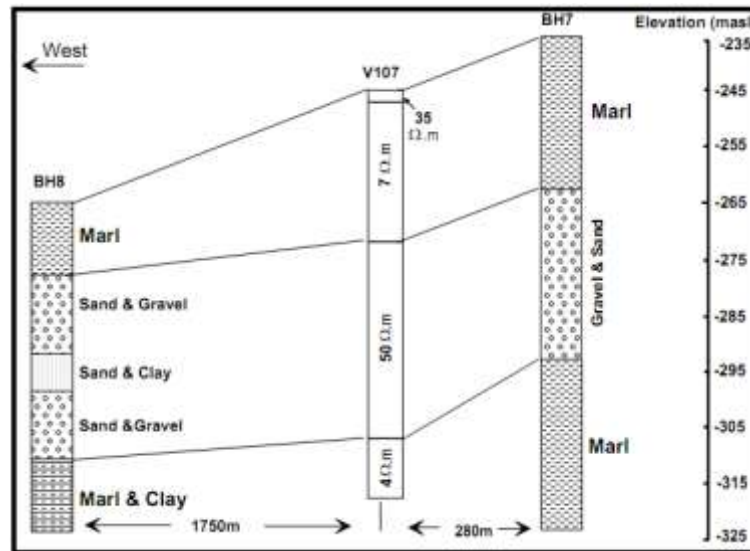


Figure 6.2: Correlation of the interpreted resistivity sounding ([Al-Amoush et al., 2012](#))

An unconsolidated sandy gravel layer of about 5 to 30 m is found underlying the soil profile at different sites along the geo-electrical cross-sections in the study area. It is composed of lenticular beds of gravels, sands and calcareous clay ([Al-Amoush et al., 2012](#)).

Two principle marly, clayey layers of the Lisan formation have been identified (Figure 6.2). The first layer lies beneath the unconsolidated deposits, gravel dry sand layer and above the water saturated sandy gravel layer, while the second layer lies beneath the water saturated sandy gravel layer and forms the most bottom layer of the whole Jordan Valley ([Al-Amoush et al., 2012](#)).

The saturated sandy gravel layer forms the major water bearing layer in the Jordan Valley ([Al-Amoush, 2006](#)). This layer was found along all geoelectrical cross sections. The gravels are predominantly composed of limestone, dolomites, chert, basalt boulders and pebbles with a matrix of sand, silt and clay ([Bender, 1974](#)). The gravel beds are generally very pervious, the calcareous clays and clay beds are fairly impervious, the gravel beds are more abundant near the side wadis of the foothills, while the silt and sands occur more abundantly at the fringes of the fans towards the Jordan River course ([Al-Amoush et al., 2012](#)). The

thickness of alluvial fans as encountered by drilling and geo-electric sounding may exceed 100 m (Al-Amoush, 2006). More than 80% of the available fresh groundwater in the Jordan Valley occurs within these alluvial fans of the major side wadis (Salameh, 1996).

6.4.3 King Abdullah Canal

The King Abdullah Canal (KAC) is a concrete lined gravity canal of 110km length, fed by a 1km diversion tunnel running underneath the mountain between Yarmouk River and the village of Adassiya (Al-Amoush et al., 2012). Water sources are Yarmouk River, at the international Jordan border with Syria, Mukheiba wells, the peace conveyer water from Israel, and the southern tributaries which flow within Jordanian territories (Salameh et al., 2009). Water is transferred to the south, the city of Amman, the Zai water treatment plant and at the shores of the Dead Sea (Al-Amoush et al., 2012). The KAC irrigation network supplies water to 230,000dn of agricultural area (MWI, 2011). In addition, 60 to 70 MCM/a are presently pumped from the KAC to Amman (Al-Amoush et al., 2012).

Water supply by the KAC is strongly influenced by water shortage during the dry season and reoccurring pollution events lasting for days, during which a major drinking water supply in Jordan is interrupted with no substitute (Al-Amoush et al., 2012).

6.5 MAR-Potential and Feasibility

6.5.1 Aquifer

To further investigate the potential of the local aquifer as subsurface water storage by means of Managed Aquifer Recharge Within the study area, Vertical Electrical Resistivity Soundings (VES) were conducted along N-S and E-W profiles of the study area (Figure 6.3). The selection of sounding locations was governed by the geologic findings, the site conditions, geophysical noise level, accessibility through cultivated farms and road availability. Interpretation was based on available information from surface geology and from the few wells drilled in the area and its surroundings, as well as geological, hydrological, hydrochemical and geoelectric surveys. In addition, 9 investigation boreholes have been drilled (Salameh, 2012).

Figures 6.4 and 6.5 show two representative geo-electrical cross sections J-J' and E-E' derived from VES investigations. Cross section J-J', running from east to west, shows apparent resistivity values of 15- 50 Ω m extending over the entire cross section and in average following the topography of the surface layer, beginning at 220 m b.s.l. in the east

and 270 m b.s.l. at western end of the cross section. This area is identified as the water saturated alluvial sandy gravel layer introduced before. Overlaying to the east, slightly higher resistivities of 30-70 Ωm can be found, indicating fans of unconsolidated alluvial deposits of gravel and dry sand, interfingering with very low resistivity areas to the west, which can be identified as marl and clay layers of the Lisan formation. The Lisan increases in thickness towards the west and overlies the water saturated alluvium.

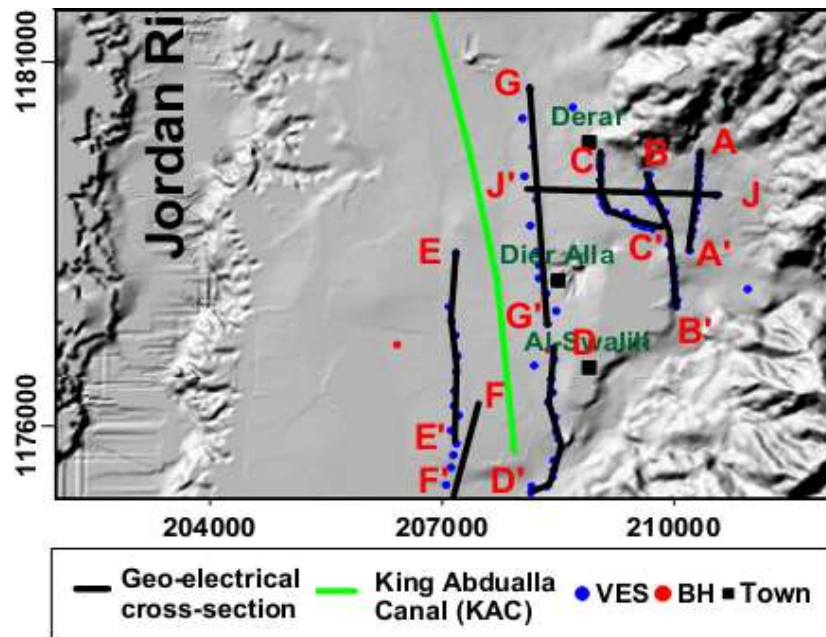


Figure 6.3: Geoelectrical cross-sections overlying shaded relief map of the study area (Al-Amoush et al., 2012, modif.)

Cross section E-E', running north to south, is located further westwards towards the Jordan River. In addition geological data from a borehole, located another 750 m to the west, is illustrated in Figure 6.5. Both data, of VES and the borehole, show that the water saturated alluvium is confined by two major Lisan layers above and below. Also, it appears to be decreasing in thickness, as the borehole data indicates.

The geologic, geomorphologic and geo-electrical studies revealed that an aquifer is present in the case study area between Zarqa River and Suleikhat (Figure 6.6). The wedge shaped aquifer persists of fine to coarse grained gravely sand, fining up and diminishing westwards towards the Jordan River, where it interfingers with marls of the Lisan formation. Geoelectric soundings revealed an underground flow channel containing a fresh water body (60-220 Ωm) within a slightly brackish groundwater environment (1500 $\mu\text{S}/\text{cm}$). General groundwater flow direction is to the west. The salt content along the flow path increases especially when coming closer to the Jordan River due to the effects of the salty Lisan Marls, reaching 2500 $\mu\text{S}/\text{cm}$ (Salameh, 2012).

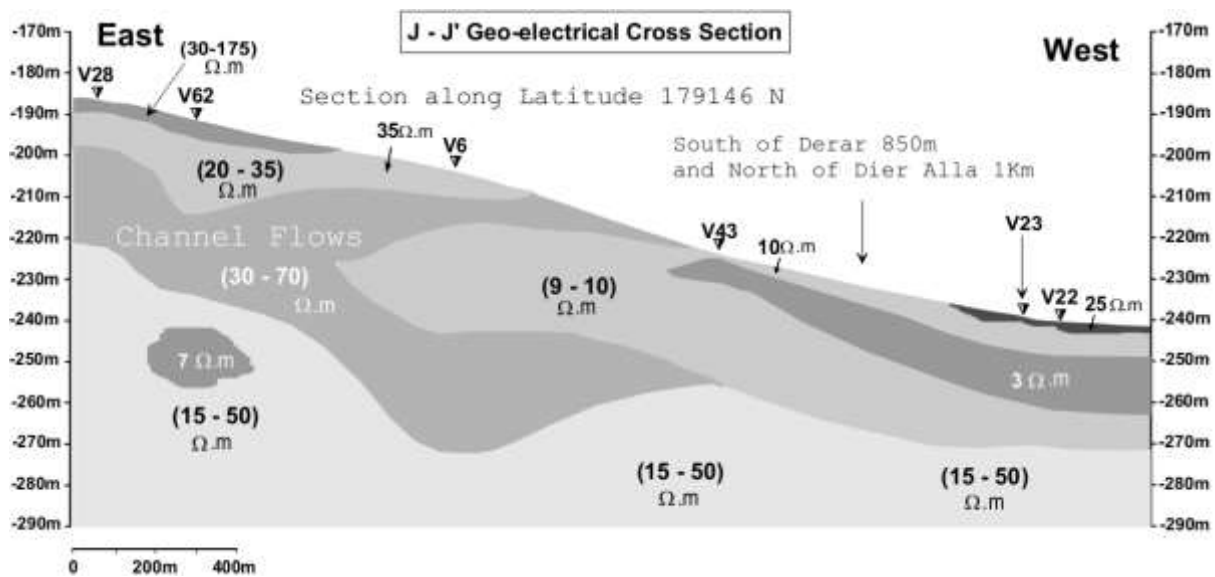


Figure 6.4: Underground resistivities along Geoelectrical cross section J-J' (Al-Amoush et al., 2012)

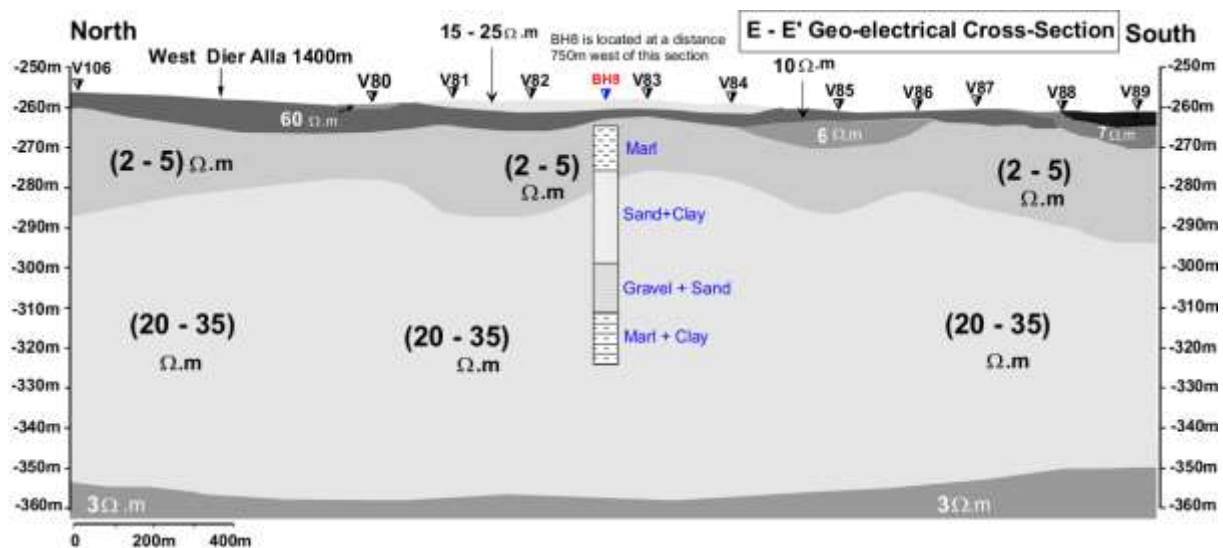


Figure 6.5: Underground resistivities along Geoelectrical cross section E-E' (Al-Amoush et al., 2012)

The aquifer is not filled and possesses a potential to be recharged. Porosity resembles that of fine sand with some silt components of around 15%, with a drainable porosity of about 7%. The geologic set up will allow to store up to 10 MCM of reclaimed water, in addition to the stored quantities in the aquifer of some 15 MCM (Salameh, 2012). Permeability in the eastern part is around 10^{-5} m/s (0.86 m/d) decreasing westwards to about 10^{-6} m/s (0.086 m/d) (Salameh, 2012). Specific Capacity of Sand/Gravel aquifer ranges from 100 to 300 m²/day in average (JICA, 1965).

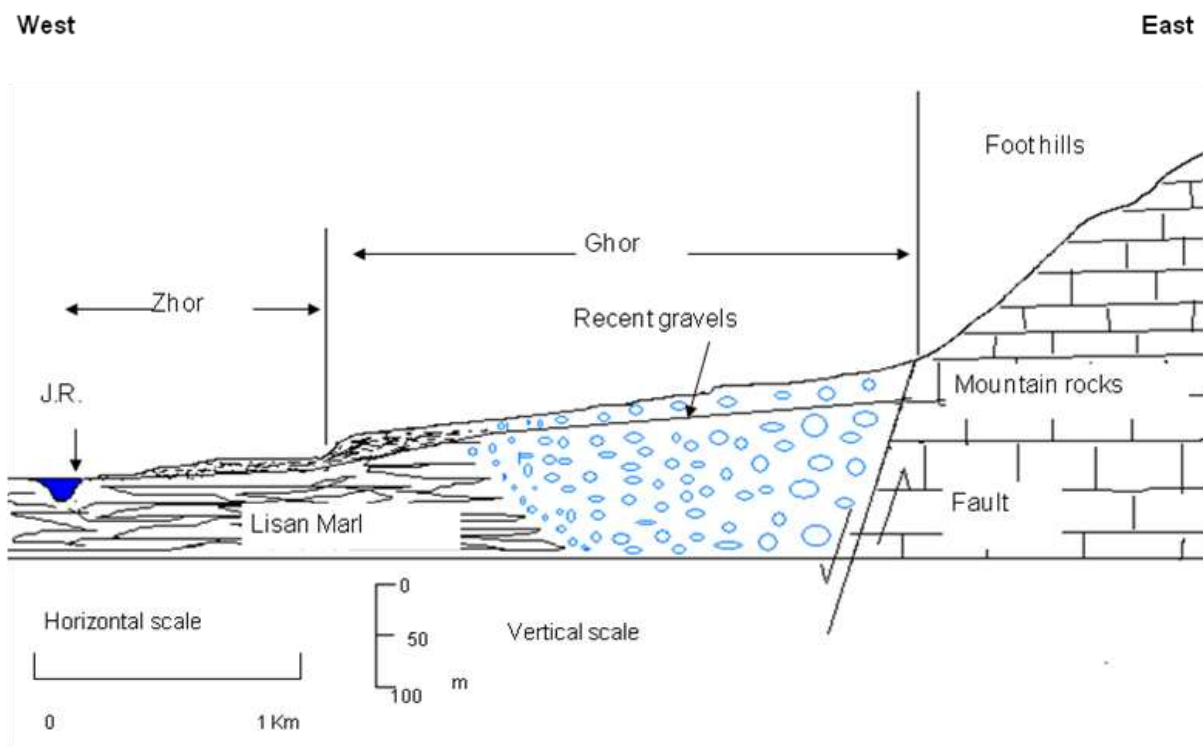


Figure 6.6: Geologic cross-section in the Northern Jordan Valley (Suleikhat area) (Salameh, 2012)

The capacity of the empty part of the aquifer is estimated at 5-10MCM. Recharging this amount in addition to the water stored in the recharge pool of about 2.5 MCM represent a safe large storage for drinking water, equivalent to a pumping amount for dinking purposes of at least 6 weeks.

6.5.2 Water Quality

To evaluate potential mixing processes of the Canal water and the existing groundwater bodies and the water/rocks interaction, chemical saturation states of minerals in the groundwater of the study area were calculated using the equations of thermodynamic equilibrium states to assess the dissolution/precipitation of the groundwater (Al-Amoush et al., 2012).

Temporarily, water/water and water/rock interaction may cause a slight increase in water salinity from an average of 950 $\mu\text{S}/\text{cm}$ in KAC water, when that water is used for recharge to about 1050-1100 $\mu\text{S}/\text{cm}$. The water will still be within the Jordanian standards for drinking water. With time of operation the salinity will stabilize and the salinity of the recharged water will not increase, but will remain at its original salinity. Winter flood water has a salinity of 500 to 600 $\mu\text{S}/\text{cm}$ (mixture of flood and base flows). Therefore, the salinity of that water after recharge will most probably increase to 600-750 $\mu\text{S}/\text{cm}$. This means that the groundwater salinity will be lower than that of KAC water during the dry periods of about 950 $\mu\text{S}/\text{cm}$ (Salameh, 2012).

Chemical analyses show that the groundwater is under-saturated with respect to Calcite, Dolomite, Gypsum and Anhydrite and strongly under-saturated with respect to Halite. This means that the water is capable to dissolve these minerals. Analyses of mixing KAC water with the average groundwater type of different ratios, indicate that the water after mixing will be still under-saturated with respect of the mentioned minerals. But since the alluvial aquifer does not contain in its matrix Gypsum, Halite or Anhydrite, no dissolving will occur and no major dissolution/ precipitation reactions are to be expected within the rock matrix when artificially recharging the aquifer, utilizing the KAC as water source ([Al-Amoush et al., 2012](#)).

6.6 MAR-Planning Options

6.6.1 Water Source

The only water source in the study area that can be used for a potential MAR implementation is delivered by the King Abdullah Canal, supplying water from the northern Yarmouk River, Mukheiba wells, the peace conveyer water from Israel, as well as several minor tributaries within the Jordan territories ([Salameh et al., 2009](#)).

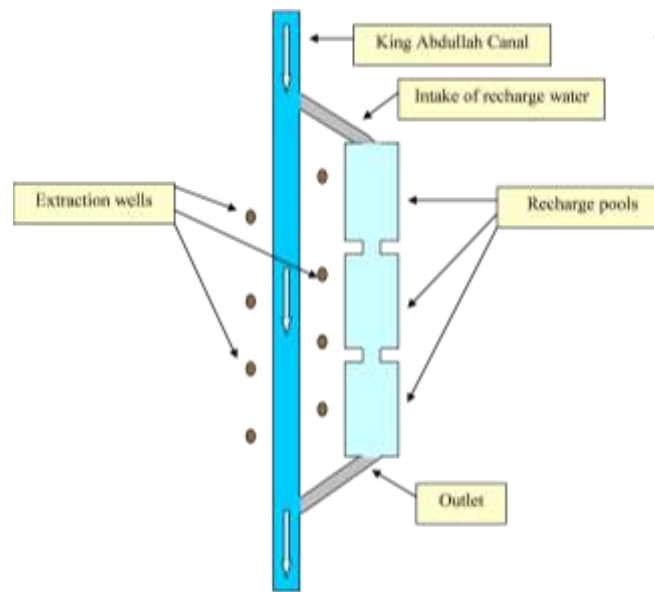
6.6.2 Technology

In order to derive water from the KAC, recharge pools parallel to the canal are suggested (fig. 6.7). With sufficiently high potential infiltration rates, recharge by means of infiltration ponds is possible. Additional hydro-infrastructure is required in order to divert recharge water from the KAC to the infiltration ponds. New extraction wells downstream the groundwater flow direction (East-West) need to be implemented for water recovery.

6.6.3 Location

Recharge to the aquifer is suggested to be implemented utilizing an abandoned gravel quarry in Suleikhat area with an N-S extension of about 800m, an E-W extension of 150 to 300m and a depth of 10 to 20m. Groundwater will then be extracted from wells drilled for that purpose in the down-gradient areas further west from the recharge site ([Salameh, 2012](#)).

The recharge area lies upstream of the intake site for drinking water and therefore pumping heads are moderate and relevant from an economic point of view. In addition the area is very sparsely populated and land use is restricted to some controllable agricultural activity with high potential of applying groundwater protection zones.



Groundwater recharge scheme along King Abdullah Canal

Figure 6.7: Recharge and extraction scheme in Suleikhat area ([Salameh, 2012](#))

In general, land at the foothills of the eastern mountains of the Jordan Valley is not used and MAR facilities can easily be implemented. Infiltration tests in local gravel outcrops revealed possible recharge rates of more than 8.44 m/d ([Salameh, 2010](#)). The advantage of utilizing the abandoned gravel quarry is that no top soil layer is present, which would negatively affect the recharge rates. Extraction of recharge water is recommended to be accomplished in areas in between the recharge areas and the Jordan River, before the groundwater enters the Lisan formation regimes and becomes saline. In the suggested area of MAR implementation, this is favored by geological conditions, as the clastic alluvial deposits fine up towards the Jordan River which limits the groundwater flow to the west due to decreasing hydraulic permeability ([Salameh, 2010](#)).

6.6.4 Pre-Treatment

Water quality analyses show that no pre-treatment measures need to be implemented. Self-purification during infiltration and recharge is expected ([Salameh, 2012](#)). Sediment loads of the KAC water are low. In order to reduce maintenance costs associated with anti-clogging measures at the recharge location, the implementation of an additional settling pit should be considered to mechanically reduce sediment loads before infiltration. The water which contains high turbidity during floods and therefore, at present, cannot be used for direct drinking water supply.

6.6.5 Operation

The operation of the project will be taken over by the Ministry of Water and Irrigation. The stored groundwater will be extracted when qualitative or quantitative problems arise, especially when the amount of water in the Canal is not enough to satisfy drinking water and irrigation water needs. This is expected to happen during the dry season, when the Canal water suffers of eutrophication processes and the treatment at Zai becomes a dilemma. The Canal water suffers of pollution accidents, and the water suffers of high turbidity during floods and there is no need for it in irrigation (it is raining).

6.8 Main Results and Conclusions

The geologic, geomorphologic and geoelectric studies about the area shows that in the area north of Zerka River course (Latitude 175000N) to Suleikhat area, 194000 N and between longitudes, E 206.000 and 209.500 an aquifer is present. Its thickness as revealed from geoelectric soundings is about 80m in the east decreasing gradually to the west due to fining up of grain sizes and diminishing at longitude 206.000. Nevertheless, at latitude 178.000 to 179.000 and longitude 206.000-207.000 an underground flow channel was revealed by geoelectric soundings, with a resistivity of 60-220 Ω m indicating a fresh water body in this channel.

This aquifer extending between 175.000-193.000 N and 206.000 to 209.500 E contains fresh to slightly brackish (1500 μ S/cm) ground water. The aquifer is not filled and possesses a potential to be recharged.

The study concludes that between coordinates N: 170.000 to 195.000 and E: 205.000 to 210.000 a fine to coarse grained gravelly sand aquifer underlies the area. It has a wedge shape in its vertical cross-section with a thickness of around 80m at the mountain foothills along longitude 209.500 E decreasing westward to interfinger with the Lisan Marls along longitude 206.000 E east of the Jordan River. In its north south extension this aquifer starts at the northern bank of Zarqa River at latitude 175 N to about 185 N. Further north alluvial fan deposits are found.

The aquifer in the Jordan Valley is saturated at depth with fresh water in its eastern parts in the mountains foothills. The salt content along the flow path increases to the west especially when coming closer to the Jordan River course. The middle reaches; 207-208 E show groundwater salinities of 1500-2500 μ S/cm. In its western parts the salinity of the groundwater increases further due to the effects of the salty Lisan Marls.

The porosity of the aquifer resembles that of fine sand with some silt components of around 15%, with a drainable porosity of about 7%. The permeability in the eastern part is around 10^{-5} m/s decreasing west wards to about 10^{-6} m/s.

The geologic set up will allow to store up to 10 MCM of regain-able water, in addition to the stored quantities in the aquifer of some 15 MCM.

The water quality of the recharged water will improve due to self-purification during infiltration and flow into existing groundwater body.

Temporarily, water/water and water/rock interaction may cause a slight increase in water salinity from an average of 950 $\mu\text{S/cm}$ in KAC water, when that water is used for recharge to about 1050-1100 $\mu\text{S/cm}$, but the water will still be within the Jordanian standards for drinking water.

With time, in a few years of operation the salinity will stabilize and the salinity of the recharged water will not increase, but will remain at its original salinity. None-the-less the water quality itself will improve, due to self-purification during infiltration and recharge.

Most probably winter flood water in KAC will be recharged into the aquifer. That water has a salinity of 500 to 600 $\mu\text{S/cm}$ (mixture of flood and base flows). Therefore, the salinity of that water after recharge will most probably increase to 600-750 $\mu\text{S/cm}$. This means that the groundwater salinity will be lower than that of KAC water during the dry periods of about 950 $\mu\text{S/cm}$.

Storing KAC water in the delineated aquifer as groundwater has the following advantages:

1. Guaranteeing an additional stored amount of up to 10 MCM of water in the aquifer.
2. The stored water will have a superior quality compared to KAC water during summer times.
3. In the case of diminishing flows in KAC, the water supply of Zai to Amman will not be interrupted, because the stored groundwater will then be used for that purpose.
4. In the case when the canal water becomes highly eutrophic (as in 1987 and 1998) or contaminated (as for example in 2007 and 2009) the stored groundwater will be used to supply Zai with the required amounts of water, without interruptions.

7. Complementary Experiments

7.1 Case Study Wadi Wala

7.1.1 Introduction

The Wadi Wala is located at the eastern shore of the Dead Sea around 16 km south of Madaba, Jordan. Its surface drainage basin is part of the Mujib surface water sheet and Dead Sea groundwater basin (Figure 7.1). Intensive rainfall events during winter season generate large amounts of surface runoff, which flows along numerous tributaries until it is collected in wadi Wala. From there it flows into wadi Hidan around 20 km before discharging into the Dead Sea. The largest proportion of precipitation is lost by evaporation and smaller parts are infiltrating into the ground. Surface and groundwater flow is almost east to west oriented.

Natural recharge of the upper aquifer system B2/A7, within the Dead Sea basin, is taking place at the outcrops of Wala catchment. The groundwater flow provides Hidan well field (Figure), which are mainly used for drinking water supply of Amman, Madaba and communities in the surrounding area. Abstraction yields of the aquifer system exceeded the natural recharge in the past decades and caused groundwater level decrease at Hidan well field.

To counteract this water level drop, Wala reservoir was constructed (1999-2002) to store the flood water and recharge it to the underlying karst aquifer by natural seepage from the reservoir but also through recharge wells. Since the first inflow in October 2002, a total amount of around 74 MCM was infiltrated into the ground until 2012, which facing a total abstraction at Hidan well field of around 128 MCM in the same period. The proportion of infiltrated water on the abstracted groundwater is almost 58 % in the period 2002-2012 ([Xanke et.al 2014](#)). Original storage capacity of around 9.3 MCM has been reduced through sedimentation to about 7.7 MCM in 2012 and also affected the infiltration rates tremendously by clogging the reservoir bottom.

Overflow of the Wala dam in the past years, due to intensive floods that exceeded the storage capacity of the reservoir, led to turbidity events in Hidan wells. Additionally, lateral surface runoff along the wadi, downstream of Wala reservoir, carried waste water and fertilizers from the adjacent agricultural areas and settlements into the wadi from where it infiltrates into the ground. Consequently, high contents of fecal bacteria occurred in the wells and induced the cessation of pumping activities.

Reservoir inflow is carrying fine sediment, which is eroded in the catchment. The accumulation of these silt, clay and sand intake is clogging the infiltration paths and reducing

the storage capacity of the reservoir. This led to a remarkable decrease of infiltration rate but also increases the overflow events of the reservoir.

Wala reservoir and Hidan well field have been investigated in the SMART project in order to achieve detailed information about the impact of the reservoir water on the groundwater. This considered hydro-chemical aspects but also the water balance of the MAR system.

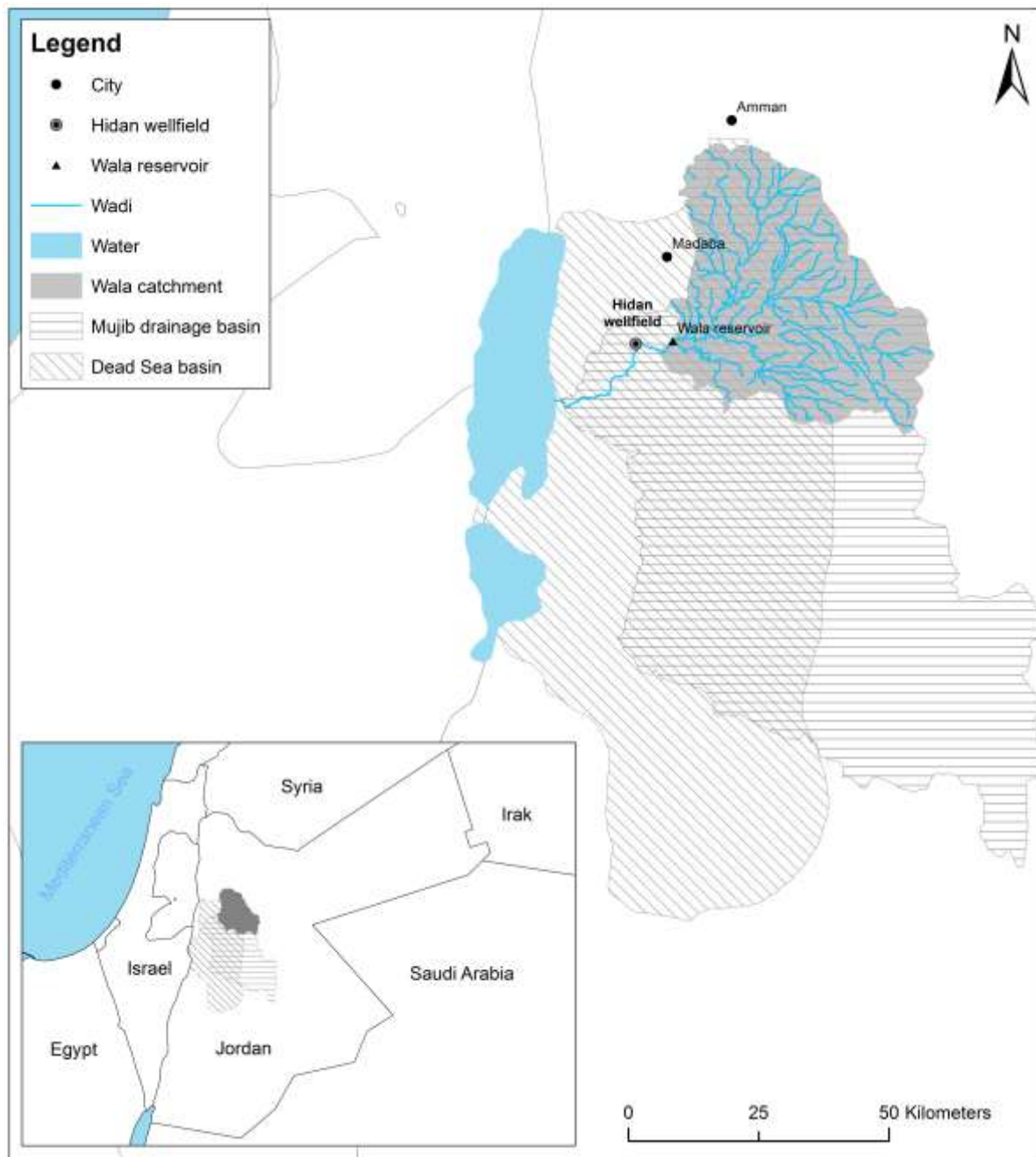


Figure 7.1: Map shows the location of Jordan with the Dead Sea groundwater basin, the Mujib surface drainage basin and the Wala surface catchment. Wala reservoir is situated around 40 km south of Amman and around 8 km east of Hidan wellfield.

7.1.2 Methodology

Recharge technics

Recharge of water from the reservoir to the aquifer comes along with two technics. The seepage from the reservoir into the ground is driven by natural gravitation and depends on the height of the water level. Here, infiltration is taking place mainly along joints and fractures at the lateral lakeside. Furthermore, water is injected through eight recharge wells (fig. 7.2) into the ground, where water is flowing from the reservoir via a pipeline and through sand filter into the wells. The wells provide water almost along a filtered section of 100 meter, while their total depth is 175 meter. The proportion of artificially injected water on naturally seeped water is small (Sawarieh and Xanke, 2013)

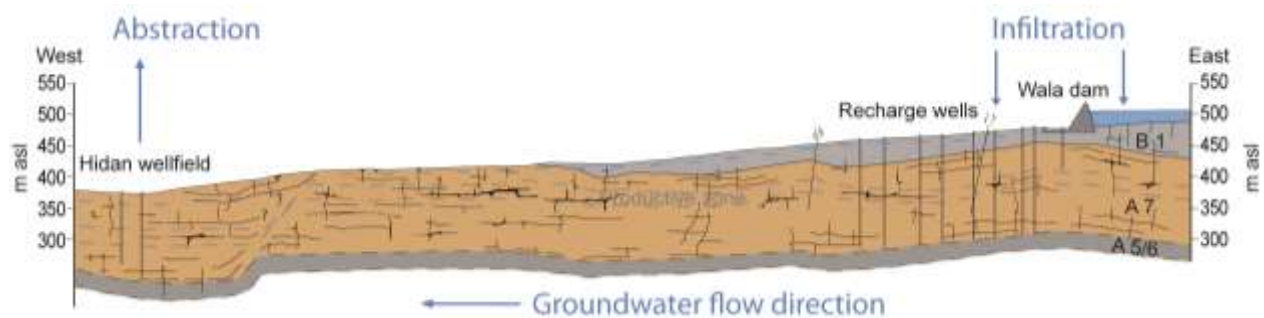


Figure 7.2: Schematic profile along wadi Wala showing the location of Wala reservoir, recharge wells and Hidan wellfield. Groundwater flow is flowing from east to west (modified after Humphreys, 1991).

General observation methods

To observe the impact of artificial recharge on the aquifer, the water level in the reservoir and the groundwater is observed regularly. Here, the daily water balance of the reservoir is calculated by the water level change, the related reservoir volume and the evaporation records. Measurements of groundwater fluctuations in the recharge wells document the direct surrounding of the reservoir, whereas observation wells in Hidan well field showing the impact on a larger distance.

Spatiotemporal distribution of reservoir water is documented by analyzing physico-chemical parameters such as electrical conductivity, temperature, major ion content and isotopic signature of deuterium, oxygen-18, tritium and carbon-14.

Water quality observations are mainly conducted during the winter season, where surface water carrying waste water and fertilizers from surrounding areas into the reservoir and the wadi. This includes turbidity and *E.coli* bacteria measurements.

7.1.3 Specific research in SMART II

From 2011 to 2013 several field investigations has been conducted at Wala reservoir and Hidan well field. The findings of the studies are completed by the evaluation and interpretation of previous data from the Ministry of Water and Irrigation, Jordan. The field work comprises:

- Sampling and analyzes from sediment of Wala reservoir regarding grain size distribution, carbonate content and polycyclic aromatic hydrocarbon (PAH).
- Measurement and calculation of sedimentation rate and total sediment income.
- Observation of water level fluctuations on high time resolution in certain wells.
- Measurement of turbidity and E.Coli of groundwater samples. Results were related to rainfall events in 2012.
- Tracer test with sodium-naphthionate to identify flow time and path of groundwater near Hidan well field.
- Tracer test with sodium chloride in the well field to prove flow time and path of surface water infiltration to the wells.

Detailed information to the investigation results are described by [Sawarieh and Xanke \(2013\)](#), [Xanke et al., \(2014\)](#), [Xanke and Gassen \(2014\)](#).

7.1.4 Conclusions

Managed aquifer recharge at Wala reservoir is a very successful approach and a promising example for other MAR projects in Jordan and the region. The combined measurements of water level and physico-chemical parameters are a valuable approach to document the spatiotemporal impact of artificial recharged water on the groundwater of a karst aquifer.

The main challenges are posed by the sedimentation in the reservoir and reoccurring contamination of groundwater. Thus, check dams would be a possible solution to minimize sediment income and / or sediments have to be removed from the reservoir ([Sawarieh and Xanke, 2014](#)).

A continuous surveying of water quality is required to identify possible contamination source and path. Herby, turbidity and E.coli measurements are good indicators for contamination. In this context, also tracer tests are proposed.

Tracer tests are very important tools in order to get information about hydraulic characteristics of the underground. Especially in the case of karst aquifers, tracer test give valuable information of flow path and time of surface and groundwater and can help to identify possible contamination sources. With regard to MAR, tracer tests are recommendable approaches because infrastructure for their input and measurement is already given by surface ponds, injection wells and abstraction wells. There are numerous artificial and natural tracers that pose no health concern for consumers and can be applied also in drinking water reservoirs.

8. Main Results

8.1 Palestine

The main findings of the Wadi Auja case study may be summarized as follows:

- The main source of water is Auja spring with a mean discharge of 9.7 MCM/a. This water potential is not being used properly due to two reasons: (1) The high water transport losses of up to 60% by infiltration to the carbonate aquifer due to an old canal which is poorly maintained and (2) the strong discharge fluctuation of the spring during the year and in long-term. During wet years, the spring water surplus is lost towards the Dead Sea. This requires the efficient over-the-year storage of spring water surpluses.
- Since surface water reservoirs, such as Auja dam, suffer from huge evaporation and infiltration losses, the controlled underground storage of surface water surpluses in the shallow alluvial aquifer system in the valley and strategic recovery for irrigation purposes during dry periods remains as only viable option. The water to be recharged consists by surface runoff which is being accumulated at Auja dam and spring discharge surpluses.
- Taking the reduction of water transfer losses into account, there are considerable surpluses of spring discharges and surface runoff under mean and wet hydrological conditions which should be stored in the shallow alluvial aquifer system in the valley as only place which guarantees the over-the-year and controlled storage of this water;
- A numerical groundwater flow model has been applied to the shallow alluvial system for two main reasons: (a) to validate the assumption that the recharged water may be efficiently stored in the shallow aquifer and recovered, according to the prevailing irrigation water deficits, and (b) to study the performance of 12 different Managed Aquifer Planning options (MPOs) in comparison with the so-called Do-Nothing-Approach.
- The performance of MAR planning options has been evaluated based on the inflow of the recharged water to the agricultural demand area (area of interest) and the total change of the mean groundwater table in the area of interest. All MPOs consider the duplication of the today irrigated land to about 10,000 dunam and full irrigation demand coverage.
- The model results show that the MAR planning options with recharge in the north-western part of the demand area, applying infiltration ponds or a hybrid system ensures high MAR performance. All MAR operational strategies which consider complementary water resources from deep wells and treated effluent import for direct supply for irrigation increase the surface water volume to be recharged as well as water supply reliability and, therefore, are superior solutions.

- The most promising MAR planning option in economic and environmental terms refer to water infiltration directly within the demand (irrigated) area due to the high efficiency of recharge and groundwater level recovery of the overexploited shallow aquifer in the demand area;
- The study shows that the today irrigated area of about 5,000 dunam (500ha) may be more than doubled by means of MAR implementation with groundwater recharge by spring discharge and surface runoff and water recovery from shallow pumping wells at strategic locations;
- Water supply reliability and agricultural production may be enhanced by treated effluent import from El Bireh and/or Jericho WWTP and mixing with brackish groundwater for direct irrigation of salt resistant crops, such as palm trees.

The main results of the Jericho case study are:

- Irrigation of all appropriate areas could not be covered by local water resources without MAR implementation and would result in water deficits of 6.9 MCM/a in the Jericho region, taking modernization of the hydro-infrastructure into account;
- The study show that an extension of the irrigated areas around Jericho City of up to 21,440 dn could be sustained through MAR implementation, assuming that spring water and surface runoff surpluses during wet and mean hydrological years could be used for over-the-year storage in the alluvial aquifer and efficiently recovered during dry periods;
- The applied Spatial Multi Criteria Analysis Tool proved to be a practical support system for evaluating land suitability for MAR implementation as well as MAR site ranking.
- Nevertheless, the today available information about the shallow alluvial aquifer system is not enough to study the viability of over-the-year storage and to consolidate the spatial analysis with regards to most appropriate recharge locations.

8.2 Jordan

The main findings of the Deir Alla case study are summarized as follows:

- According to a preliminary assessment, MAR-implementation would guarantee an additionally stored amount of up to 10 MCM of water in the aquifer;
- The stored water will have a superior quality compared to the water in the King Abdullah canal (KAC) during summer times;
- In the case of diminishing flows in KAC, the water supply of Zai to Amman will not be interrupted, because the stored groundwater will then be used for that purpose;
- In the case when the canal water becomes highly eutrophic (as in 1987 and 1998) or contaminated (as for example in 2007 and 2009) the stored groundwater will be used to supply Zai with the required amounts of water, without interruptions.

From 2011 to 2013 several field investigations has been conducted at Wala reservoir and Hidan well field. The findings of the studies are completed by the evaluation and interpretation of previous data from the Ministry of Water and Irrigation, Jordan. The field work comprises:

- Sampling and analyzes from sediment of Wala reservoir regarding grain size distribution, carbonate content and polycyclic aromatic hydrocarbon (PAH).
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Detailed information to the investigation results are described by [Sawarieh and Xanke \(2013\)](#), [Xanke et al., \(2014\)](#), [Xanke and Gassen \(2014\)](#).

9. Conclusions

The main conclusions of the present aggregated deliverable D318/320 are summarized as follows:

- All surface water surplus in the valley, consisting in spring discharge and surface runoff, is lost towards the Dead-Sea, if not properly stored in surface water reservoirs or recharged to the local aquifer systems and strategically recovered;
- Due to the extreme hydrological variability, where wet years are frequently followed by dry periods, over-the-year water storage facilities are needed to take advantage of the local water potential. On the other hand, surface water reservoirs for the storage of spring discharges and flood water retention suffer from huge evaporation losses;
- Due to these reasons, MAR is to be considered as obligatory IWRM measure which should be implemented in a short term in order to improve water supply reliability and to strengthen agricultural development;
- Due to its contribution to sustainable groundwater management and groundwater protection, MAR implementation can be considered as obligatory in environmental terms, too;
- MAR implementation is also obligatory in social terms, due to the fact that the extension of the irrigated land, which is required for increasing family income and welfare, is just possible by means of MAR implementation with surface water surpluses;
- As sources for aquifer recharge, surface water surplus from runoff and local springs should be used, which is available under mean and wet hydrological conditions;
- The studies show, that the volume of surface water to be recharged can be increased, if groundwater from the deep Karst aquifer system and treated effluents are considered for direct supply to irrigation as part of an integrated water management concept;
- Water supply reliability and agricultural production can be enhanced by waste water reuse in irrigated agriculture and mixing with brackish groundwater for direct irrigation of salt resistant crops, such as palm trees;
- In the valley, the shallow aquifer system, as shown by case studies at Auja, Jericho and Deir Alla, is the only underground storage facility which guarantees the required control on the recharged water. Groundwater flow and transport models are required to for integrated MAR system planning and operation;
- Under specific hydrogeological conditions, the Karst aquifer system may serve for Managed Aquifer recharge purposes, too. Managed aquifer recharge at the Wala reservoir proved to be a successful approach and a promising example for other MAR projects in the region. The combined measurements of water level and physico-chemical

parameters are a valuable approach to document the spatiotemporal impact of artificial recharged water on the groundwater of a karst aquifer.

- The studies showed that a continuous surveying of water quality is required to identify possible contamination source and path. Herby, turbidity and E.coli measurements are good indicators for contamination. In this context, also tracer tests are proposed.
- Tracer tests are very important tools in order to get information about hydraulic characteristics of the underground. Especially in the case of karst aquifers, tracer test give valuable information of flow path and time of surface and groundwater and can help to identify possible contamination sources. With regard to MAR in Krast aquifer systems, tracer tests are recommendable approaches because infrastructure for their input and measurement is already given by surface ponds, injection wells and abstraction wells. There are numerous artificial and natural tracers that pose no health concern for consumers and can be applied also in drinking water reservoirs.
- Finally, it can be concluded that the MAR-planning concept, suggested by Rusteberg et al. (2012), could be successfully applied under the conditions of the Lower Jordan Valley.

10. Recommendations

10.1 MAR-Planning and Implementation

With regards to the planning and future implementation of Managed Aquifer Recharge in the Lower Jordan Valley the following recommendations are given:

- All springs, due to their high water potential, are most important water sources for Managed Aquifer Recharge and require protection and careful exploitation;
- MAR-implementation in the valley should mainly rely on water surpluses from springs and surface runoff;
- Since in the Palestinian areas, surface water reservoirs (e.g. Auja dam) suffer from high water losses (besides evaporation) from percolation into the Karst aquifer system, the water should be transferred to the recharge facilities directly after accumulation. The flood water retention structures will serve as sedimentation facilities, too. No further treatment of the water is required before recharge;
- In order to ensure the recharge of large volumes of water in short time periods, preference should be given to infiltration structures for aquifer recharge. Their combination with infiltration wells, as so-called hybrid solutions, would further enhance the recharge potential but requires further studies;
- The results of the preliminary groundwater flow model in the Palestinian areas show that the infiltration structures and water recovery wells should be strategically located in the irrigated area to guarantee a sustainable groundwater yield for irrigation purposes and to avoid further groundwater level decrease in the area;
- In the valley, investments for the improvement of the existing hydro-infrastructure are urgently required in order to reduce the high water losses, especially due to poorly maintained old canals;
- In order to increase the available surface water for aquifer recharge, groundwater from the deep Karst aquifer system and treated effluents import should be activated for direct supply to irrigation as part of an integrated water management concept. This requires the installation of deep wells in the area as well as hydro-infrastructure for waste water treatment and transfer of treated effluents;
- Since the region around Jericho and Auja is part of the major shallow aquifer system in the valley, integrated solutions for MAR planning and management on catchment cluster level are required in order to proceed towards implementation. The decision making process should be strictly participative, following the suggested MAR-planning procedure.

10.2 Further Research Activities

- The impact of extreme hydrological variability on MAR planning and system operation need to be studied in more detail, providing a better understanding how Managed Aquifer Recharge may contribute to efficient adaptation strategies;
- The shallow alluvial aquifer system in the valley requires better investigation with regards to its hydraulic characteristics and long-term storage of surface water surplus in the demand areas. The Lisan formation in the valley with low hydraulic conductivities requires better characterization in order to choose the best location for the recharge facilities to be implemented;
- Additional studies on groundwater flow and transport will be required in order to consolidate MAR-planning options, to study the freshening of the shallow brackish groundwater system and optimal groundwater management (pumping) strategies;
- Since agricultural development has a significant impact on the water budget situation, further studies on different agricultural development strategies and their impact on MAR planning and management are required;
- Potential, drawbacks and social acceptance of waste water reuse through saline groundwater mixing with treated effluent for the irrigation of salt resistant crops, such as palm trees, requires further investigation;
- In general, the use of brackish groundwater for irrigation purposes including pre-treatment requirements, such as desalination or mixing, require further studies in order to optimize the integrated management of water of different qualities.
- The reuse of treated effluent in irrigated agriculture requires the development of a comprehensive implementation concept for integrated waste water management in the valley;
- Further groundwater modeling studies are required to judge the efficiency and necessity of hybrid MAR technologies under the prevailing local conditions;
- It is expected that the different MAR planning options do not vary significantly with regards to their cost-benefit ratio. Nevertheless, cost-benefit-analysis (CBA) for different MAR planning options and agricultural development scenarios should be conducted, since the latter may significantly impact on the expected benefits and future water demand.
- For Deir Alla, the water budget situation together with impact and performance of different MAR-planning options need to be assessed in detail in order to provide clear recommendations for MAR implementation in the area;

- The set of performance and impact indicators to be applied for the comparison and ranking of alternative MAR planning options in the context of IWRM implementation need to be further consolidated together with stakeholder and decision makers;
- Further studies are required in order to develop strategies for the joint management of flood water retention structure and shallow alluvial aquifers by means of Managed Aquifer Recharge.

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