

EXPLORING THE POTENTIAL OF MANAGED AQUIFER RECHARGE TO MITIGATE WATER SCARCITY IN THE LOWER JORDAN RIVER BASIN WITHIN AN IWRM APPROACH

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ABSTRACT

The Lower Jordan River Valley is a place of extreme water scarcity and constitutes an overexploited closed river basin. No surface runoff currently leaves the area and the water level of the Dead Sea, as the final sink, has already dropped by more than 20 m over the past fifty years as a result. This demonstrates, that even apart from water quality considerations, total inflows into the system do not match outflows, resulting in a continuous depletion of the available storage, i.e. all available water is already utilised. The only means of providing additional volumes of water to the area are water imports or reduction of evaporation from open water bodies or reduction of evapotranspiration from irrigated agriculture. Wastewater reuse and desalinisation would increase the amount of water fit for human demand but not affect the water balance in total. Increasing the amount of managed aquifer recharge (MAR) would be beneficial to the water availability of the region by reducing evaporation. In this background setting, the research initiative SMART (Sustainable Management of Available Resources with Innovative Technologies) has now been launched to include all available water resources of the Lower Jordan River, namely ground water, waste water, saline water, and flood water into an integrated management concept. This paper briefly explores the application of MAR technologies to the region and the barriers toward their implementation. Currently MAR technologies which aim at direct infiltration of water into the underground are not, or only at a very limited scale, implemented in the Lower Jordan River Valley. Dams and reservoirs which have been installed at the outlet of major wadis provide additional groundwater recharge but are characterised by high evaporation losses and progressive silting. Harvesting of rainwater in man-made subsurface structures (e.g. cisterns) is common in rural settings of both Palestine and Jordan. Soil aquifer treatment (SAT) concepts are successfully implied in Israel, although not in the Jordan River Basin. A significant contribution to groundwater recharge is provided through irrigation schemes with either freshwater or recycled water. Considering the prevailing aquifer characteristics (limestone and alluvial aquifers with sufficient hydraulic conductivity), MAR is considered feasible. Strong episodic rainfall runoff, especially from urban areas in the highlands, would be available to feed the MAR schemes. However, given the steep topography, often the karstic aquifers would not provide appropriate long term storage but discharge the water soon afterwards. A common concern is the quality of urban surface runoff which may require source control measures in the catchment. Due to rapid groundwater flow velocities and short residence time of contaminants in the aquifer system, karstic aquifers are particularly vulnerable to contamination. Careful site selection must take place to maximize the probability of success. At this point, major targets for managed aquifer recharge schemes could be the alluvial fan aquifers as well the carbonate aquifers in the western part of the study area. In conclusion, a series of detailed investigations on MAR applicability in the region is needed for future planning. Besides the screening for suitable aquifers, it is

recommended to use information from integrated water master planning tools, such as availability of source water and water demand for in depth feasibility studies of MAR.

KEY WORDS

Water resources, Jordan, Palestine, Israel, artificial recharge

INTRODUCTION

Project background and objectives

The German Federal Ministry for Research and Technology, considering the Resolution 58/217 of the United Nations dated 20 December 2000, is supporting a research program for the Integrated Water Resources Management (IWRM) “in regions with water shortages. The SMART project, *“Sustainable Management of Available Water Resources with Innovative Technologies”* in the lower Jordan Valley is one of these projects. The consortium comprises more than 17 partners from universities, research centers, companies and NGOs from Jordan, Israel and Palestine (www.iwrm-smart.org). IWRM is a process that aims to promote the coordinated development and management of water, land and related resources. The purpose is to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (GWP 2004).

The main idea of SMART is to include all water resources of the Lower Jordan River, namely ground water, waste water, saline water, and flood water into an integrated management concept. These issues are explored with a series of test sites along both sides of the Jordan Valley. Test sites are planned for infiltration of reclaimed wastewater, infiltration of water from flash floods, infiltration of urban surface runoff and irrigation of agricultural area with treated sewage. The test sites are embedded into several water balance studies and finally, a numerical groundwater flow model will be constructed for the entire Lower Jordan Valley. A separate team of socio-economists will assess the water demand in different sectors (e.g. agriculture, urban population) along with likely future trends. All information will then be integrated into a decision support framework (DSS). The DSS is based on the DPSIR approach (Drivers, Pressures, State, Impact, and Response). Together with key stakeholders from the three involved countries, scenarios of current and future water management strategies are set up. These scenarios are evaluated with special regard to their environmental, social and economical impacts on the region. Within this concept, SMART explores the role of MAR in the IWRM strategies of the Lower Jordan River.

Geographical Location/ Study Area

The investigation area covers the Lower Jordan River Valley from the southern shores of the Sea of Galilee (Lake Tiberias) to the northern part of the Dead Sea (Figure 1a). It comprises an area of about 8000 km². Three countries are neighbouring and sharing this basin and its margins: Jordan, the Palestinian Authority and Israel. The dominating tectonic element of the Jordan River Valley is the Dead Sea Transform (DST), a segment of the East African – Red Sea Rift System. At the northern shores of the Dead Sea the valley floor is at ca. -400 m below sea level whereas the surrounding highlands reach on average 800 m above sea level. The Jordan River flows along the valley from Lake Tiberias in the north to the Dead Sea in the south. The waters of the Jordan River are an extremely important resource to the dry lands of the area and are a politically sensitive issue between Lebanon, Syria, Jordan, Israel and Palestine.

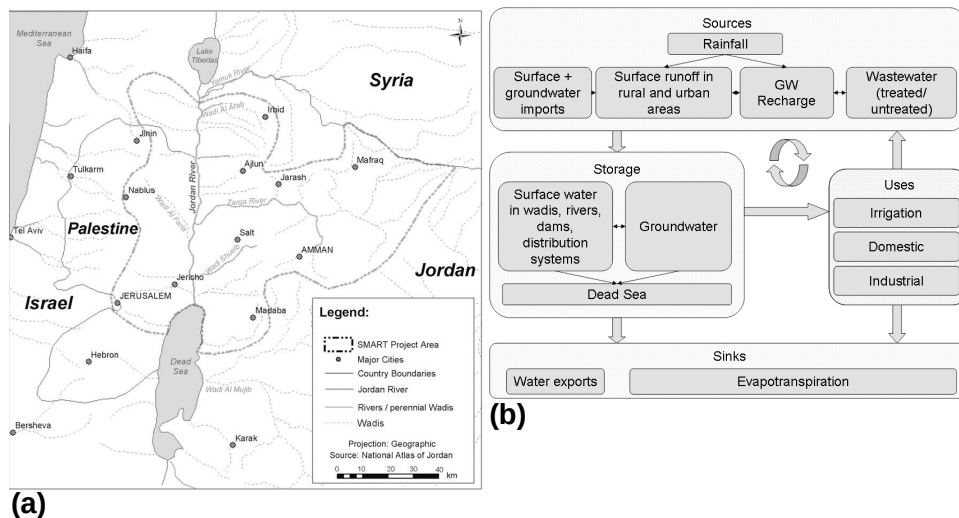


FIGURE 1. (a) Surface watershed of the Lower Jordan River Basin excluding Syrian parts. (b) Key elements of the water cycle in a closed river basin: the case of the lower Jordan River.

WATER RESOURCES STATUS IN THE LOWER JORDAN RIVER BASIN (LJRB)

General Situation in a Closed Basin

The study area constitutes a closed river basin with a pronounced water budget deficit. A progressive closure of the basin means in this case that almost no water is left to be mobilized and used while demand, notably in urban areas, keeps increasing (Venot, Molle et al. 2006). Figure 1b lists the key elements in the anthropogenic

modified water cycle of the LJRB. The final sinks of water in the LJRB are evaporation and water exports, there is no surplus water running to the open sea. The area is characterised by severe water scarcity. Aquifers are seriously overexploited and groundwater levels have been dropping in recent decades. For Jordan, the available renewable water resources decreased drastically to an annual per capita share of 160 m³/cap/y in 1997, compared to 3600 m³/cap/y in 1946 (population growth is a major driver for this). Owing to diversion of tributary waters and intensive mineral extraction, the level of the Dead Sea is dropping at a rate of up to one meter per year (Becker and Katz 2006). As a result, the surface area of the sea has already shrunk by one-third, springs around the sea are drying up and sinkholes (areas of severe land subsidence) are forming, threatening historical sites and infrastructure. (Salameh 2001a)

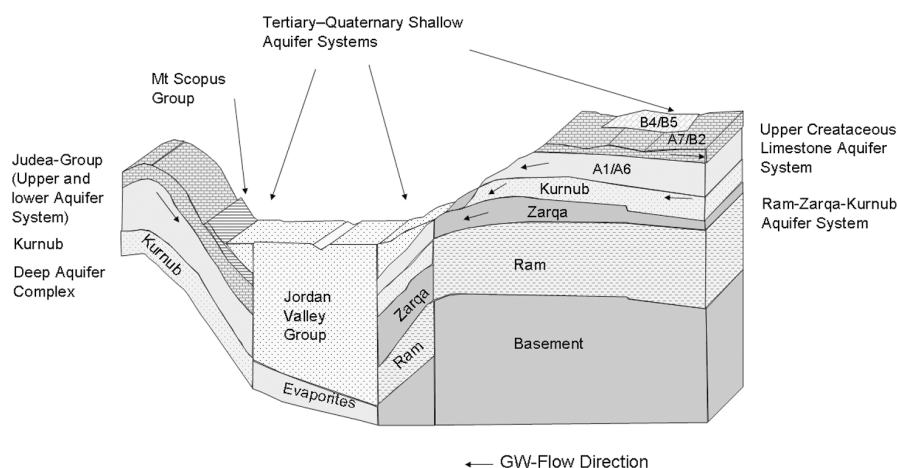


FIGURE 2. Schematic hydrogeologic profile of the Lower Jordan Valley. Assembled from various sources (Salameh and Udluft 1985; USGS 1998; The Hashemite Kingdom of Jordan 2004; Sauter 2006).

The quality of surface water is deteriorating due both to reduction in natural flow volumes but also due to the many known and unknown releases of sewage into surface water. The situation is pronounced at the Lower Jordan River, whose waters were also historically more saline than the waters north of the Lake Tiberias (Sea of Galilee) and of lower quality (Nissenbaum 1969 in Farber et al. 2005). While flows of untreated wastewater in the wadis obviously constitute a pollution hazard, they still provide an augmentation of the Lower Jordan River baseflow. If the sewage effluents are reduced as agreed in the Jordanian-Israelian Peace Treaty, the chloride concentrations in the Jordan River are expected to increase from up to 2600 mg/l at present to almost 7000 mg/l, due to the proportional increase of saline groundwater discharge into the river (Farber, Vengosh et al. 2005). Furthermore, intentional discharges of saline water into the Lower Jordan River are present. Around the Sea of Galilee, the so called saline

water is collected from several saline springs on the western shore and redirected into the Jordan in order to avoid salinisation of Lake Tiberias.

While governments of the region have expressed concern over the threats to the ecological and cultural heritage of the Dead Sea basin, they have traditionally seen the loss of the Dead Sea as an unavoidable consequence of rational economic policy (Becker and Katz 2006, Salameh 2001b). The diversion of water from the Yarmouk River and the Jordan River are the main drivers of this loss. In both cases, the majority of this water is dedicated to agriculture, which represents only 1.7 % of the gross domestic product in Israel (Central Bureau of Statistics Israel 2004), and 2.2. % of the gross domestic product in Jordan (World Bank 2005), and with only minor contribution to employment. Thanks to management efforts, freshwater demand for irrigation is now slowly decreasing in Jordan, while urban water demand is constantly on the rise. Irrigated agriculture in Jordan is the largest user of water, constituting 64% of the total water used in the country in 2002. Of the total renewable groundwater supplied for all uses estimated at 432 MCM/year, consumption of irrigated agriculture accounted for about 50%, or some 216 MCM in 2002 (The Hashemite Kingdom of Jordan 2004).

Groundwater

As groundwater is the major source of drinking water in the Lower Jordan River basin, hydrogeological aspects exert a dominant influence on the water management. Especially on the West Bank, groundwater is the most important source of fresh water supply in the area. The tectonically and sedimentologically complex setting in the LJRB produces a large number of local and regional aquifers. While major lithostratigraphic units were mapped in the region, hydrodynamic connections between aquifers and the borders of subsurface drainage basins are still a research topic, especially on the eastern side of the Jordan. While the geology east and west of the Jordan Valley shows a similar succession of lithostratigraphic units, a displacement of more than 107 km in the north-south direction is present. The various local aquifers may be grouped into three major aquifer systems:

1. Tertiary-Quaternary Shallow Aquifer System: Alluvial aquifers are present at the floor of the Jordan Valley and the fans of the incoming wadis, where the alluvium is in contact with the aquifers of Upper Cretaceous age (Ailun series). The alluvial aquifer extends from the northern shore of the Dead Sea in the south to the downstream part of the Yarmouk River in the north. The thickness of the alluvium in the Jordan Valley varies from zero along the eastern boundary to about 750 m in the deepest part of the basin near the Jordan River. An average thickness of 400 m may be reasonable for the purpose of hydrological considerations (The Hashemite Kingdom of Jordan 2004). The deposits on the eastern side of the Jordan Valley may be further grouped into JV1 (Ghor el Khattar Formation), JV2 (Ubeidiya and Samra Formation), JV3 (Lisan formation) and quaternary alluvial fans (Salameh 2001). In parts water quality of the shallow aquifer is impacted by

salts origination from the evaporitic parts of the Lisan formation (Al Kuisi 2006). Typical hydraulic conductivities are cited as 6.6 m s^{-1} (JICA 1995). In addition to the alluvial sediments, also chalk and limestone of tertiary age locally comprise important aquifers such as the B4/B5 in the area northwest of Irbid and Azraq, Sirhan, Jafr and the Hammad basins. On the western side of the Jordan Valley, the term Shallow Aquifer Hydraulic Complex is used. It comprises Pleistocene sedimentary and alluvial deposits of the Quaternary age which receive localized annual recharge from wadi flows. The extent to which this aquifer is recharged from lower aquifers has not been determined and may be a function of faulting and fracturing. Recent work in the Arava area on the western side of the wadi showed that the thickness of the permeable sediments deposits could be up to 550 meters in depth

2. Upper Cretaceous Limestone Aquifer System: This complex consists of an alternating sequence of limestones, dolomites, marl stones and chert beds. The total thickness in central Jordan is about 700 m. It can be divided in the Lower Ajlun aquitards/aquifers and in the Upper Ajlun A7/B2 Aquifer. On the western side of the Jordan, the aquifer system is known as the Judea Group (or also as Cretaceous Hydraulic Complex) and also here it is subdivided in at least an upper and a lower aquifer system. In terms of extracted volumes, this is the most important aquifer system in the region. It receives the major part of the groundwater recharge in the area, occurring mainly in the high mountain regions on both sides.
3. Ram-Zarqa-Kurnub Aquifer System: It includes the Ram aquifer, the Khreim aquitard, the Zarqa aquifer and the Kurnub aquifer (The Hashemite Kingdom of Jordan 2004). The Ram Group Aquifer (Disi) forms a large regional aquifer system, which underlies the entire area of Jordan and parts of Saudi-Arabia. It is also present west of the Jordan river in Israel and Palestine but not a major water source there to its depth below surface. It crops out only in the southern part of Jordan and along Wadi Araba – Dead Sea Rift Valley. Currently, the total existing abstraction, including that from Saudi Arabia, exceeds the safe yield of the aquifer and this source is generally considered as unreplenishible. The Palaeozoic sedimentary sequence consists mainly of sandstone interbedded with siltstone, mudstone, limestone and dolomite. The average thickness of the formation is about 1000 m and increases to 2500 m to the east. In general the Ram Group dips gently to the east and to the north at about 5 degrees. The aquifer can be characterized as a fractured-rock aquifer. Groundwater movement is primarily through secondary openings, such as joints, fractures, and bedding-plane openings. The Khreim overlies the Ram Group and consists of about 600 – 800 m of sandstone, siltstone, and shale which is dated to be of Middle Ordovician-Upper Silurian age. It has a low permeability and forms a confining layer to the Ram Group aquifer and is therefore regarded as an aquitard. On a regional scale, water in the overlying sandstone aquifers (Zarqa and Kurnub) is interconnected with that of the Ram by leakage. As a consequence, the Ram and the upper sandstone aquifers along with

the Khreim are considered to be one hydraulic system The Zarqa Group is limited to north and northeast of Jordan. In the southern part of the country the Zarqa Group is missing. Outcrops of this group are limited to the lower Zarqa River basin and along the escarpment between the Rift and the Highlands to the east. The Mesozoic sedimentary sequence consists mainly of sandstone interbedded with siltstone, limestone and dolomite. The thickness of the formation increases from the central part of Jordan to the north and west up to 1800 m. The Kurnub Group is of Lower Cretaceous age. It consists mainly of sandstone. For the movement of groundwater the intergranular porosity of the sandstones is of minor importance, because most of the intergranular space is filled with siliceous cement.

AVAILABLE MAR CONCEPTS AND THEIR CURRENT IMPLEMENTATION IN THE REGION

Introduction to MAR

Managed aquifer recharge (MAR) encompasses a whole suite of methods and describes intentional storage and treatment of water in aquifers. The term 'artificial recharge' has also been used to describe this, but adverse connotations of 'artificial', in a society where community participation in water resources management is becoming more prevalent, suggested that it was time for a new name. Managed aquifer recharge is intentional as opposed to the effects of land clearing, irrigation, and installing water mains where recharge increases are incidental (Gale 2005). Figure 3 shows the basic types for MAR but the actual implementation of schemes is varying widely with different concepts in many cultures. Typical goals of managed aquifer recharge perceived in the region are to maintain and increase the natural groundwater as an economic resource. (ii) avoid further salinization and salt water intrusion (iii) decrease losses due to evaporation (iv) create long-term or short-term water storage (v) provide treatment and storage for reclaimed wastewater for subsequent reuse). Table 1 lists the applications of MAR in the three riparian states of the LJR.

While there is more than a millennium of experiences of using rainwater and surface runoff in rural areas by various forms of rainwater harvesting, the use of treated wastewater is young in comparison. Nowadays intentional replenishment of aquifers by highly treated reclaimed waters is increasingly being practised in developed countries with the full support of communities, and health and environment regulators, for aquifers that are under stress through imbalances between rates of extraction and natural recharge (Dillon, Toze et al. 2004; Dillon and Jimenez in press). With strong population growth in many urban centres and reduction of agricultural water demand by use of innovative irrigation technologies, the need to set up more sustainable urban water systems becomes obvious.

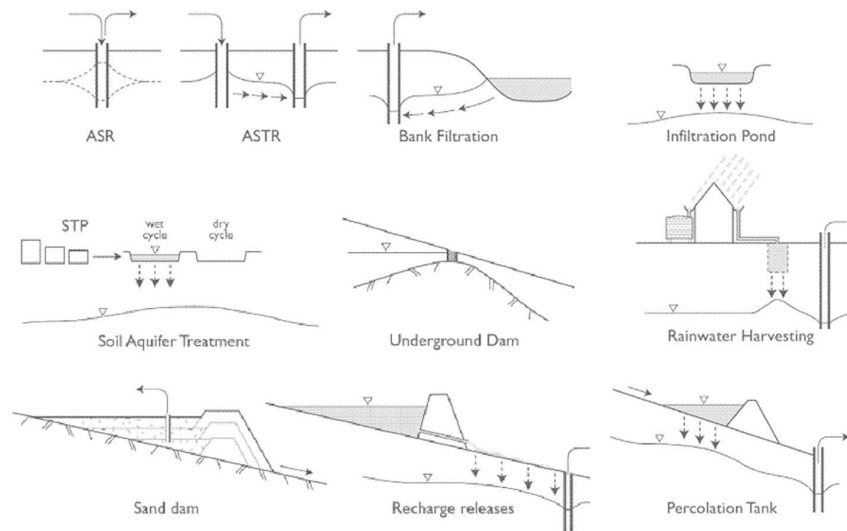


FIGURE 3. Schematic of types of management of aquifer recharge (Dillon 2005). Abbreviations: ASR=Aquifer Storage & Recovery, ASTR=Aquifer, Storage, Transfer & Recovery, STP = Sewage Treatment Plant.

Table 1. Methodologies for Managed Aquifer Recharge (adapted from Gale 2005) and their applications in the Jower Jordan River Basin.

	General methodologies for MAR	Applications in the LIRB
Spreading methods	Infiltration ponds and basins	Israel
	Soil Aquifer treatment	Israel (Dan region)
	Controlled flooding	
	Incidental recharge from irrigation	Jordan, Palestine, Israel
In-channel modifications	Percolation ponds behind check-dams, gabions, etc	Jordan, Israel
	Sand storage dams	
	Subsurface dams	
	Leaky dams and recharge releases	Jordan, Israel
Well, shaft, and borehole recharge	Open wells and shafts	
	Aquifer storage and recovery (ASR)	
	Aquifer storage, treatment and recovery (ASTR)	
Induced bank filtration	Bank filtration	
	Inter/-dune filtration	
Rainwater harvesting	Field bunds, agricultural ponds	Jordan, Palestine, Israel
	Roof-top rainwater harvesting	Jordan, Palestine, Israel

Examples for successful MAR applications at international level are numerous (Dillon and Jimenez in press). Runoff from urban areas, in particular, still provides a large potential of additional groundwater recharge. Besides roof runoff, also runoff from paved areas can be utilized successfully without health threats (Nolde 2007). Scenario simulations of the urban water balance using the AISUWRS approach (Wolf, Morris et al. 2006) showed how the city of Mt Gambier, Australia is effectively reducing surface runoff by injecting stormwater into a karstic aquifer: compared with three European cities Mt Gambier recharges 45 % of its total water input and discharges only 12 % via sewers and surface runoff, whereas the European counterparts discharge between 34 % and 70% of their total water input. The stormwater infiltration is ongoing since more than a century and the sustainability has been positively evaluated within a Hazard and Critical Control Point approach (Cook, Vanderzalm et al. 2006). In addition, long term evaluations (> 5 years) are documented for the pioneer site of Andrews Farm, South Australia, where urban stormwater is injected into a brackish limestone aquifer and used to generate an additional water resource (Pavelic, Dillon et al. 2006).

MAR EXAMPLES IN JORDAN

At this time, only a limited number of MAR applications are openly documented in Jordan. The major categories are rainwater harvesting in field bunds or at river beds, small check dams inside wadis and large reservoirs with an incomplete bottom sealing.

Rainwater collection and storage schemes are traditionally carried out in Jordan and continued especially in rural villages. One of the techniques involves the filling of excavations close to wadi beds with a clay liner at the bottom, coarse rocks in the middle and a cover at the top. This structure is then used as a reservoir with minimum evaporation in the dry months (Salameh 2004). New attempts to improve the systems by the use of capillary barrier systems are ongoing in the Karak area (A. Hamadeih, pers. comm.). For the future, some authors recommend that rain-water collection and storage schemes on large and/or small scale should be encouraged because in the long term these schemes would have an important role in securing sustainable water supplies in the Kingdom (Jaber and Mohsen 2001). In the year 1991 it was estimated that the developed quantities of water harvesting would reach 6 MCM by the end of the year 2000 (Pride Team 1992). Net additional water conservation gains for rainfall/runoff water harvesting from residential and industrial roofs was estimated to be around 4.3 MCM and 9.5 x MCM for the years 2005 and 2010, respectively (Jaber and Mohsen 2001).

A number of dams were built in Jordan, partly with the aim of groundwater recharge. A popular example for an effective recharge scheme is the Walah dam but also the Rail dam and the Siwaqa dam are described (Pavelic 2005). The first two are located

in the Mujib basin, the last one in the Azraq basin. *Sensu strictu*, none of them belongs to the catchment of the LJRB.

The Siwaqa dam is situated 70 km south of the capital, Amman and is recharging the Upper Cretaceous B2/A7 aquifer, belonging to the Aljoun Group. Groundwater levels in this area are in the range of 100m below surface. A rise of 15 m in the groundwater table in wells close to the dam has been reported. While the scheme was effective in the beginning, concerns are arising that the accumulating fine sediments in the reservoir are effectively sealing the bottom. The Wala dam is situated 45 km south of Amman in the Mujib basin. The dam was constructed in 2003 and has a capacity of 9.3 x MCM with a catchment area of 2000 km². The dam recharges the B2/A7 aquifer and contributes to the yield of the wadi Hidan well-field located west of the dam, which supplies water for the cities of Madaba and Amman Wellfields. Rates of recharge are dependent on the water level within the dam and can be up to 1 m/day when dam capacity is high, to <0.05 m/day at low capacity. The estimated volume of water recharged over the past 3 years is 30 MCM (Pavelic 2005).

In addition to the dams, a major recharge pond is reported at a plant near Aqaba where 1.91 MCM/y are infiltrated to an aquifer (The Hashemite Kingdom of Jordan 2002, Salameh 2002).

A different MAR strategy is the construction of several small dams along the wadi course to increase infiltration. In a desert location 25km northeast of Amman, a feasibility study on this was carried out (Chehata and Dal Santo 1997), which focused on the wadi's Madoneh and Butum. Direct infiltration tests in the wadi beds delivered promising results (Abu-Taleb 1999) and detailed design criteria based on hydrological studies in the area were reported (Chehata, Livnat et al. 1997; Abu-Taleb 2003). The amount of expected recharge from the structures was estimated as 0.075 MCM/y. The project is now supported by EXACT via UNESCO-IHE together with the MWI and the construction of the dams is foreseen in 2007 (de Laat and Al-Nsour 2007). The calculation of runoff coefficients and flow volumes was recently revised based on updated hydrological time series data (Dhakal 2006). The scheme in Wadi Madoneh is recharging the Wadi-Es Sir formation as part of the B2/A7 aquifer, partly also via more recent alluvial bodies in the wadi bed.

From an institutional viewpoint it is concluded that the water scarcity and the high demand on water for irrigation as well as the location of plants do not allow for planned recharge projects at the moment although studies indicated the possibility of recharging the aquifers in some areas (The Hashemite Kingdom of Jordan 2002)

MAR EXAMPLES IN ISRAEL

Managed aquifer recharge forms an integral part in the Israeli water management strategy with the main goals to (i) increase the available water resource, (ii) provide

aquifer management, (iii) utilize the storage capacity of the aquifer, (iv) reuse treated effluents (Guttman 2007). So far, only limited application exists in the LJR as the main focus areas of the aquifer recharge projects are the heavily used coastal aquifer and the surroundings of major urban centres.

One of the world largest Soil Aquifer Treatment plants is operated in the Dan region already since 1977, reclaiming some 110-130 MCM of secondary treated wastewater per annum (Idelovitch, Icekson-Tal et al. 2003). It is situated within the coastal plain aquifer, comprised mostly of Quaternary sands and calcareous sandstones with some alternating units of sandstone and clay. After 25 years of unproblematic operation high Manganese concentrations were observed in the recovered water. It is suggested that the Manganese is mobilized from the aquifer rocks as a result of the changed redox conditions (Oren, Gavrieli et al. 2007).

A successful project to use stormwater runoff in the Menashe artificial recharge plant at the northern part of the coastal aquifer about 3-4 km (Guttman 2007). With a catchment area of 189 km², and geology composed mainly of limestone and chalk, the plant manages to provide an artificial recharge of 17 MCM per annum to a heavily used sandstone aquifer. Recharge takes place via spreading ponds. Groundwater levels have risen significantly since the start of the operation, indicating the success of the scheme. As the system is driven by gravity, only minor costs arise from maintenance. The water pumped from the recharged aquifer is used for drinking purposes (Guttman 2007). Another example is the artificial recharge scheme of the Shikma river with a catchment area of approx. 750 km². The system is designed to cope with the strong seasonality of the rainfall. In this case a dam construction diverts the water into a sedimentation reservoir from which it is transferred to a recharge pond after settling. Around the ponds a series of wells is recovering the recharged water and ensures that water levels below the pond are low enough to allow further infiltration (Guttman 2007).

MAR EXAMPLES IN PALESTINE

Due to the ongoing, unfavourable political situation in Palestine, there has been little scope for the construction of artificial recharge sites in the last decades. Current systems centre on rainwater harvesting, looking back upon long tradition and experience. Within the local context, managed aquifer recharge examples are grouped under the section “non conventional technologies”. Popular methods are (i) covered, underground reservoirs (locally called wells or cisterns) or (ii) pools made from earth or steel, covered with black plastic sheets to prevent algae growth (Carlo and Ghanem 2007). The cisterns supply an estimated 6.6 MCM per year within the WestBank. Cisterns serve an essential purpose, meeting water needs left unfulfilled by the devastated infrastructure. In most cases, cisterns collect water from rooftops during the rainy season, which is then stored in subsurface containers, usually

ranging in size from 60-100 cubic meters. A large percentage of water collected in cisterns is used for domestic purposes. Tankers are also used to fill cisterns, especially in the summer months when the cisterns dry up due to the lack of rainfall (Shehabadeen and Ghanem 2007).

While these systems are effective in storing rainwater and securing the water supply during dry times, they are not recharging the groundwater directly. Direct recharge, however, is achieved through the numerous retaining walls on the agricultural fields. The retaining walls hinder surface runoff and enforce downward infiltration of water.

Incidental recharge occurs from a significant number of cesspits, but is associated with high nutrient and contaminant loads.

SUMMARY: POTENTIAL AND BARRIERS TO FUTURE MAR APPLICATIONS IN THE LJRB

In general, the overexploitation of all aquifers in the region calls for recharge enhancement. Even without a recovery of the injected water close to the recharge site, a major environmental benefit will be achieved. Aquifers with high transmissivities are available close to the surface and successful examples are already implemented in the region. A summary of aquifer characteristics and their influence on the potential for managed aquifer recharge was recently given (Dillon and Jimenez in press). Its application to the general aquifer types in the LJRB is listed in Table 2.

However, a range of implementation barriers is given. Beyond the hydrogeological constraints also the source of recharge water, the proximity to this source, the quality of the source and the availability of the source water must be evaluated. Within the LJRB, both surface runoff and wastewater are available as sources. While a significant amount of wastewater is produced in the urban areas, it is as far as possible used for irrigation following treatment. However, only between 50% and 80% of the population are already served by sewerage systems. The alluvial fan aquifers at the inlets of the wadis to the Jordan Valley offer a good potential for MAR due to their hydraulic conductivity, the gentle gradients and the long retention time. A major concern for the alluvial aquifers in the Jordan Valley is the mixing of the recharged water with saline groundwater. However, international studies have demonstrated that the mixing can be very low due to the slow groundwater movement and that efficient recovery of recharge water is possible (Pavelic, Dillon et al. 2006).

The Upper Cretaceous limestone aquifer system offers ample storage space but its use must be planned carefully due to the many fast discharge options via springs. Chances for successful recharge projects are given east of the water divide in the A7/B2 aquifer between Jordan Valley and the desert basins. Water recharged there will benefit the wellfields which supply the towns on the mountain ridge (e.g. Amman).

Table 2. Aquifer characteristics relevant for MAR: status and implications for the three major aquifer systems in the LJR.

Characteristics	Status & Implications		
	Tertiary-Quaternary Shallow Aquifer System	Upper Cretaceous Limestone Aquifer System	Ram-Zarqa-Kurnub Aquifer System
Confinement	Groundwater mostly occurs unconfined. >Surface infiltration methods viable, unprotected from surface contamination	The aquifer system contains confined and unconfined sub-aquifers. Depth to water table is very high. >Wide range of infiltration mechanisms possible	Generally confined aquifers, >Only well injection methods possible
Permeability	Moderate to high permeability >dispersion of recharged water, cheap recovery costs of pumped water	Moderate to high permeability > dispersion of recharged water, storage potential sometimes decreased due to quick discharge	Moderate to low permeability > recharged water more localized > higher recovery costs
Thickness	Sometimes limited thickness (e.g. B4/B5), sufficient thickness in Jordan Valley alluvium > storage volume is no major constraint	Thick (> 100 m). > high storage potential	Thick (> 400 m). > high storage potential
Unconformity of Hydraulic Properties	Homogeneous > minimal mixing > retention times do not vary significantly	Extremely heterogeneous due to karstification and fractures > fast discharge, insufficient retention time if aquifer is drained by springs close by	Moderate Heterogeneity, > moderate mixing > retention times do not vary significantly
Salinity of groundwater	Fresh with strongly increasing salinity toward the valley centre > limited recovery efficiency at parts with high salinity . less beneficial uses to protect	Dominantly fresh > unlimited recovery efficiency	Mostly saline > limited recovery efficiency > less beneficial uses to protect, so low treatment requirements of infiltration water
Lateral hydraulic gradient	Gentle > Recharged water contained closer to the point of recharge	Steep on the descent to the Jordan Valley, slightly more gentle in the uplands > Quick dispersion of injected water	Gentle > Recharged water contained closer to the point of recharge
Consolidation	Unconsolidated in the upper sections of the alluvial fans/ elsewhere consolidated.	Consolidated > easier well construction > less clogging problems	Consolidated > easier well construction > less clogging problems
Aquifer mineralogy	Unconsolidated conglomerates, carbonates > solution/dissolution should be considered	Carbonates, Sandstone > solution/dissolution should be considered	Sandstone, Carbonates, Shales > solution/dissolution should be considered

West of the Jordan, recharge is most sensible in the confined sections of the aquifer system. Several of the topmost aquifers are already contaminated with sewage water; the artificial recharge would enter a source which can not be used due to qualitative reasons. Regarding the Ram-Zarqa-Kurnub aquifer system the high drilling costs due to the large depth below ground might block off many attempts for recharging.

Planning for MAR must take the local circumstances into account, such as the strong seasonality of rainfall, and high intensity peak rain events which require large reservoirs to provide temporal storage for runoff during flash floods. High technology options like ASR require significant experience in set-up and maintenance, especially with regard to the prevention of clogging and may not be suitable at this point. Furthermore, surface runoff from urban areas may be strongly polluted as no effective source control measures are currently in place.

CONCLUSIONS & FUTURE WORK

This review showed that there is considerable potential in the Lower Jordan River Basin for managed aquifer recharge. However, MAR is not yet identified as a major goal in the national water master planning. Currently the main focus is on water demand management, water supply management and institutional reforms (Taha and Magiera 2006). Considering the currently limited depth of this review of MAR activities in the Lower Jordan River basin, it is essential to increase the coverage by incorporating more of the locally available grey literature. In order to unlock the potential for MAR in the region, a series of background and feasibility studies on the following topics are recommended:

- Increase of groundwater recharge from reservoir structures by removal/disturbance of low permeability reservoir sediments.
- MAR from open reservoirs into alluvial fan aquifers
- Use of urban surface runoff for groundwater recharge
- Holistic urban water balances and construction of sustainable water systems in the fast growing urban areas
- Quantification of the net benefit from MAR in terms of evaporation prevention
- Cost-benefit analysis of MAR within the IWRM framework under the consideration that all the recharged water volumes (irrespective of the recovery possibilities on spot) are effectively adding up to the total water availability in the Jordan River basin.

The mentioned studies are considered as a prerequisite for a representation of the potential of MAR schemes in water balancing tools like WEAP, Hydroplanner or Water Strategy Man which are used as a decision support for Integrated Water Resources Management. Despite the current implementation barriers, a boost of

MAR on regional scale is possible and recommended in order to mitigate water scarcity in the Lower Jordan River Basin. The successful case studies described in this paper may serve to encourage the development of MAR in the region.

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