Hydrogeol J
DOI 10.1007/s10040-016-1427-6

REPORT

Spatial multi-criteria analysis for selecting potential sites for aquifer recharge via harvesting and infiltration of surface runoff in north Jordan

Anke Steinel[1,2] · Klaus Schelkes[1] · Ali Subah[3] · Thomas Himmelsbach[1]

Received: 26 June 2015 / Accepted: 6 May 2016

Abstract In (semi-)arid regions, available water resources are scarce and groundwater resources are often overused. Therefore, the option to increase available water resources by managed aquifer recharge (MAR) via infiltration of captured surface runoff was investigated for two basins in northern Jordan. This study evaluated the general suitability of catchments to generate sufficient runoff and tried to identify promising sites to harvest and infiltrate the runoff into the aquifer for later recovery. Large sets of available data were used to create regional thematic maps, which were then combined to constraint maps using Boolean logic and to create suitability maps using weighted linear combination. This approach might serve as a blueprint which could be adapted and applied to similar regions. The evaluation showed that non-committed source water availability is the most restricting factor for successful water harvesting in regions with <200 mm/a rainfall. Experiences with existing structures showed that sediment loads of runoff are high. Therefore, the effectiveness of any existing MAR scheme will decrease rapidly to the point where it results in an overall negative impact due to increased evaporation if maintenance is not undertaken. It is recommended to improve system operation and maintenance, as well as monitoring, in order to achieve a better and constant effectiveness of the infiltration activities.

Keywords Artificial recharge · Site selection · Arid regions · Rainfall/runoff · Jordan

Introduction

Arid regions like Jordan are characterised by high evaporation rates and high variability in precipitation in space and time leading to unpredictability in surface-water runoff; therefore, demand for agriculture and domestic use cannot be covered by available surface-water resources, and accordingly groundwater resources are used. However, natural groundwater recharge is also limited (commonly ranging between 0.1 and 5 % of long-term average precipitation) and occurs mainly through indirect recharge in wadi beds (Scanlon et al. 2006). Hence, groundwater resources have been overused in many arid countries resulting in a decline in water tables, which can lead to drying up of springs and shallow wells, as well as ingression of saline waters, and has been experienced in Jordan, for example around the Azraq Oasis (El-Naqa et al. 2007; Mesnil and Habjoka 2012). Demand is expected to increase further due to population growth and a rise in living standards, while supply is expected to decline due to climate change and pollution of available sources (MWI 2009).

In combination with demand reductions and other improved management options, managed aquifer recharge (MAR) can be an effective tool in reducing negative impacts of groundwater overdraft on a local scale. MAR is defined as intentional recharge in contrast to unintentional and unmanaged recharge and can occur with different water sources (stormwater, river base flow, treated wastewater etc.) and with different recharge methods (e.g. infiltration, injection). Advantages of MAR in arid regions are the availability of a large free storage space (which has been created by the overabstraction) and the reduction of problems associated with

---

✉ Thomas Himmelsbach
Thomas.Himmelsbach@bgr.de

[1] Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover, Germany

[2] Present address: Gesellschaft für Internationale Zusammenarbeit (GIZ), Km 4 Acostaville National Highway, Libertad, Butuan City 8600, Agusan del Norte, Philippines

[3] Ministry of Water and Irrigation, Shmeisani, Ibn Hayyan Street, P.O. Box 2412, Amman 11183, Jordan

surface storage like evaporation losses, large space requirements, algal blooms and potential contamination (Huisman and Olsthoorn 1983). There is also the added benefit of natural attenuation of a range of pollutants during recharge and storage (Bouwer 1996; Dillon and Toze 2005).

Worldwide, a range of different MAR techniques are implemented depending on site-specific conditions. For (semi-)-arid regions in developing countries, low cost schemes like recharge or recharge release dams and infiltration basins are more suitable than complex and costly injection or infiltration wells. MAR can provide a range of benefits to local communities like increased agricultural yields, drought resilience and improved livelihood, but does not come without challenges or constraints such as costs, ownership issues and environmental impact (Gale et al. 2002).

Nevertheless, MAR is considered an important technique for (semi-)arid regions with declines in groundwater levels worldwide. For example, India has been at the forefront of implementing small-scale community based recharge schemes supported by an artificial recharge master plan (CGWB 2002), guidelines (CGWB 2000) and manual (CGWB 2007). There are also a number of studies investigating MAR potential with multi-criteria analysis (e.g. Chowdhury et al. 2010; Machiwal et al. 2011).

Jordan suffers under chronic water scarcity due to the (semi-)arid climate. Highest demand comes from the agricultural sector (about 70 %) and groundwater abstractions have been above the safe yield for many years resulting in constantly declining water tables especially in the two basins investigated in this study (Margane et al. 2002). Therefore, the Jordanian National Water Master Plan and National Water Strategy both emphasise the need for an increase in water supply with MAR as one of the options (MWI 2009); hence, this study was initiated by the Jordanian Ministry of Water and Irrigation. The aim of this pre-feasibility study was to evaluate all available information for the two surface-water basins in north Jordan on a regional scale with respect to the potential for MAR sites. The study focuses on the option of retention of floodwater in mostly ephemeral streams followed by recharge via infiltration.

The technical issues that need to be addressed during a pre-feasibility study are:

1. *Source water availability*: In arid regions, rainfall is sparse and often occurs in short intense events leading to flood flows for only a few hours or days per year in otherwise dry wadis, which hinders effective harvesting of source water. Arid regions commonly do not produce sufficient runoff for economic harvesting; furthermore, water is frequently already committed for use and upstream harvesting leads only to a reallocation of water but does not generate any additional water resources. ‘Use’ also encompasses environmental demand as ephemeral wadis usually sustain the sparse vegetation and local habitats in arid regions. In addition, MAR is only beneficial if water is captured that would otherwise be evaporating or running off without recharging an aquifer further downstream. Although dissolution is no solution to pollution, another benefit of surface runoff is the “improvement” of water quality through the dilution of wastewater discharges in the Amman-Zarqa (AMZ) basin. Climate change may have a significant impact on source water availability and should thus be taken into consideration in the feasibility assessment (Kunstmann et al. 2007; Smiatek et al. 2011).
2. *Aquifer storage space*: A suitable aquifer with sufficient storage capacity is usually available in areas suffering from over-abstraction and groundwater level declines; however, underground storage space alone is not sufficient, if other prerequisites are not fulfilled.
3. *Effectiveness of transfer of harvested water to the aquifer*: For infiltration methods, which are the most cost effective option, permeable soils and unsaturated zones are needed to allow water to reach the aquifer. The first barrier is the soil surface that might be blocked due to bio-crusts or get clogged with fine sediments contained in the floodwater. Constant and regular maintenance and monitoring is therefore needed to prevent a recharge scheme turning into an evaporation pond. An even more likely barrier is an impermeable layer in the unsaturated zone that does not permit sufficient percolation down to the aquifer. These natural pedogenetic and geological heterogeneities are usually not known or measureable in detail but can severely reduce recovery efficiency.

This report addresses the aforementioned technical questions based on two separate assessments determining the ability of a sub-catchment to generate suitable runoff and the ability of a site to harvest and transfer the runoff to a suitable aquifer applying Boolean logic and linear weighted overlay methods of thematic maps using geographical information systems (GIS). Both methods have been proven to be useful for multi-criteria decision making in GIS (e.g. Malczewski 2006) and have been used in similar studies before (e.g. Al-Adamat et al. 2010; Jasrotia et al. 2007). In addition, further issues for implementation like socio-economic and environmental questions are addressed in the discussion.

Previously, two investigations looked at the potential for MAR in the area (Alraggad and Jasem 2010; Rapp 2008). Both studies used only a low number of criteria with a limited number of classifications and only thematic map overlay. The significance of this study is therefore the consideration of two aspects, i.e. catchment and site suitability, and the consideration of a high number of criteria and their overlay through weighted linear combination. The results of the study were to be used by the MWI for defining further efforts, for example, designing better monitoring and maintenance at existing schemes or undertaking detailed feasibility studies at the most promising sites. This case study also offers a methodology for assessing catchment and site suitability for artificial infiltration schemes using GIS and multi-criteria analysis at the basin level that could be employed for other study areas.

Study area

The study area encompasses two very different surface-water basins in north Jordan, namely the Amman-Zarqa (AMZ) and the Azraq basins. The Amman-Zarqa basin (3,592 km^2; note, this is the official size of the administrative AMZ basin, while in reality 81 km^2 discharges to the AMZ basin, but belongs administratively to the Azraq basin) is the most densely populated basin in Jordan accommodating about 4.5 million inhabitants (>65 % of the total Jordanian population) including the capital Amman and most of its industry. In contrast, the Azraq basin (11,720 km^2, including the catchment area of Qaa Khanna; note, this is the official size of the administrative Azraq basin from which 81 km^2 actually discharges into the AMZ basin, while 326 km^2, in the northeast, discharges to Syria) is only inhabited by about 30,000 people. The associated watersheds expand into Syria to the north (Fig. 1).

Topography

The topography is dominated by three main features: (1) in the north, the area is gently sloping towards the south from the highest point in the catchments, namely the volcanic cone of the Jebel el Druze/Jebel el Arab (1,750 m above sea level (asl)) in Syria (highest point in Jordan is about 1,150 m asl); (2) in the west, the Zarqa River and its tributaries have created steeply incised valleys into the north–south trending highland mountain range down to the lowest point in the catchments (−194 m relative to sea level); (3) in the middle of the Azraq basin, a very extensive flat depression without outflow (morphological feature called *qaa* in Jordan) has developed at around 500 m asl (Fig. 2). Accordingly, the morphology shows very steep slopes in the western part of AMZ, while more than 80 % of the total area is gently sloped (<5 % inclination). Especially in the basalt areas in the north, the flat topography results in a poorly connected drainage network and fosters the occurrence of internal depressions called *marabs* and *mini-qaas* (Allison et al. 1998).

Climate

The study area is characterised by cool winters (mean 8 °C) with rainfall between October and April and dry and hot summers (mean 27 °C) between May and September. In correlation with the topography, precipitation is highest (up to 450 mm/a) in the western mountains and decreases quickly towards the south-eastern desert (<50 mm/a) (Fig. 2). Based on the long-term average and the isohyetal method, the water budget would start with about 821 million m^3 per year (MCM/a) and 914 MCM/a of total rainfall with a standard variation of about ±45 % for AMZ and Azraq watersheds (including the Syrian part), respectively. Rainfall often occurs in thunderstorms with irregular intensity, duration and high spatial variations, but intensity records show that only about 2–10 % of all rainfall events have a total rainfall depth of more than 10 mm. Annual potential evaporation is high (2,500–3,700 mm/a) and exceeds the annual rainfall by far. Estimated actual evaporation ranges from 63 % of annual rainfall in the western highlands to around 99 % of annual rainfall in the eastern desert (Hammouri and El-Naqa 2007). Daily potential

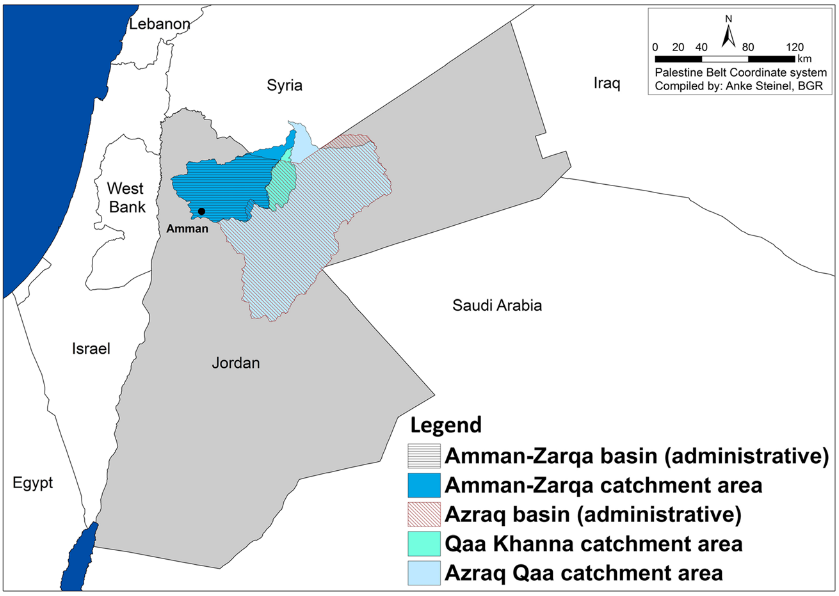


Fig. 1 Location of study area showing the administrative boundaries of the two basins and the delineation of the watershed areas (after US Geological Survey's HydroSHEDS (USGS 2008))

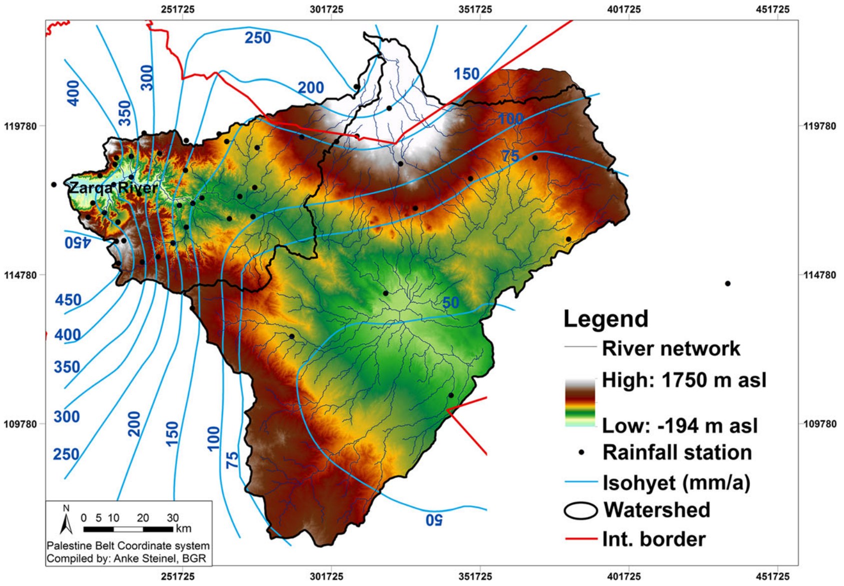


Fig. 2 Orohydrographical map (based on USGS-HyroSHEDS) and isohyetal map (based on long-term (min. 20 years) rainfall records from 47 stations) of the Amman-Zarqa and Azraq basins

evaporation values vary between 1 and 5 mm/day in winter and 15–25 mm/day in summer. According to the aridity index (UNDP 1992) most of the study area is, hence, characterised as arid to hyper-arid.

Land cover

About 50 % of the AMZ basin is covered by bare soils and rocks, 20 % is covered by fields with vegetables, grains and tree crops plus an additional 17 % with pastures. The urban areas have increased significantly over the last decades to currently about 16 % coverage (Fig. 3). In contrast, the Azraq basin is covered to 98 % by bare rocks, chert plains and alluvial deposits and is only very sparsely vegetated.

Surface-water resources

The Zarqa River is perennial in the lower catchment area due to groundwater discharges from the lower and deep aquifer systems. In addition to surface-water, runoff is also enhanced by treated and untreated wastewater discharges. The Azraq basin is only drained by ephemeral wadis with periodic surface-water runoff. Generally, runoff is negligible below 50 mm/a rainfall, and rises with an increase in annual precipitation. Evaluation of existing runoff data from 11 runoff stations in the ephemeral rivers showed that median annual runoff is between 0 and 2 % of annual rainfall. Using the measured rainfall-runoff relationship, estimations for total surface-water runoff in the basins are about 20 and 10 MCM/a for AMZ and Azraq basin, respectively. Estimations based on the

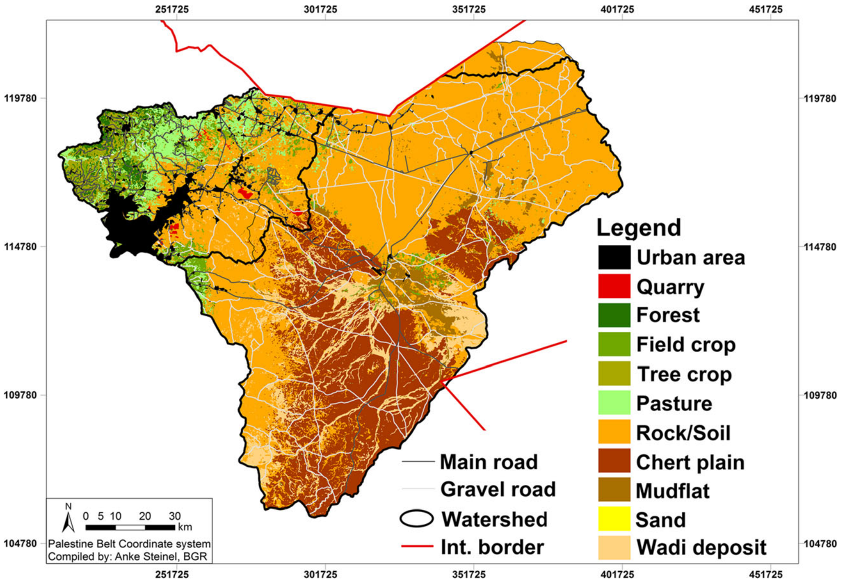


Fig. 3 Land cover map and road network for Amman-Zarqa and Azraq basins (modified from the land cover map (RJGC 2011))

curve number method (USDA-SCS 1985) lead to 33 and 22 MCM/a for AMZ and Azraq basin (Al-Kharabsheh 1995; Otova et al. 1989a, b), respectively, and are likely to overestimate runoff significantly (de Laat and Nonner 2011; Steinel 2012). Flood runoff events commonly last less than a day, and between 0.7 and 5 runoff events occur per year. The Zarqa River is intercepted by the King Talal Dam (designed storage capacity 75 MCM). A number of smaller water harvesting structures (like dams, dikes, lagoons, ponds and earth dams with an estimated total storage capacity of around 17 MCM) have been constructed already over both basins, including the largest structure in Azraq basin, the Wadi Rajil dam (designed storage capacity 3.5 MCM) (Fig. 4). Water quality data for ephemeral rivers are sparse, but it is estimated that floodwater contains around 500 mg/L suspended sediments (Obeidat and Abu Muheisin 1989) and about 1 % sediments as bed load, based on observed sedimentation behind existing dams (Shatnawi 2012). Water samples (mean values from 26 samples taken between 2010 and 2012 at Jerash Bridge available from the Water Authority of Jordan (WAJ)) from the downstream part of the Zarqa River commonly have elevated concentrations in dissolved solids (1,360 mg/L), nutrients (65 mg/L nitrate and 13 mg/L phosphate) and *E. coli* (2,000 MNP/100 ml) due to wastewater inflow and agricultural activities in the surrounding catchment area.

Hydrogeology

Above the terrestrial sandstones, siltstones and shales of the Zarqa and Kurnub group (Permian to Lower Cretaceous) follows a sequence of alternating marine limestones and marls (Upper Cretaceous to Eocene) (Fig. 5) namely the Ajlun group (consisting of the five formations Na'ur (A1/2), Fuheis (A3), Hummar (A4), Shueib (A5/6) and Wadi Es Sir (A7)) and the Belqa group (consisting of the five formations Wadi Umm Ghudran (B1), Amman (B2) Muwaqqar (B3), Umm Rijam (B4) and Wadi Shallala (B5); e.g. Bender 1974; Margane et al. 2002; Powell 1989). The Belqa group limestones contain a high amount of chert which is more resistant to erosion and hence accumulates on the surface resulting in widespread chert plains (Fig. 3). The Neogene and Quaternary basalts belong to the Harrat Ash Shaam basaltic supergroup stretching from Syria to Saudi Arabia (Ibrahim 1993) and are mainly composed of alkali-olivine basalt lava flows and pyroclastic sediments. Between the six phases of major eruptions, layers of tuff and up to 5-m-thick fossil clay soils can be found (Margane et al. 2002). On top are Quaternary sediments like alluvium, wadi sediments (sands and gravels), mudflat (silts and clays), and wind-blown sands as well as calcrete crusts and evaporites (Fig. 5). A number of structural faults with vertical displacement up to 3 km mainly striking NW–SE are present (Margane et al. 2002; Fig. 5).

This geological set up leads to the existence of a number of aquifer systems. The upper or shallow aquifer system consists of the basalt aquifer which is hydraulically connected to the underlying B4/5 aquifer and the overlying alluvium (Margane et al. 2002). Apart from the NE of the AMZ basin where the basalt is hydraulically connected with the A7/B2 aquifer system, the upper aquifer system is separated by the B3 aquitard from the underlying middle aquifer system consisting of the A7/B2 limestone aquifer. The B1 aquitard could hinder water movement in some parts of the system. The lower Ajlun formations form the lower aquifer system with intercalated aquifers (A1/2 and A4) and aquitards (A3 and A5/6) and lies on top of the deep aquifer system of the Kurnub and Zarqa sandstones (Fig. 5).

Data on aquifer characteristics are sparse. Transmissivity values are only recorded for about 5 % of all wells and show a

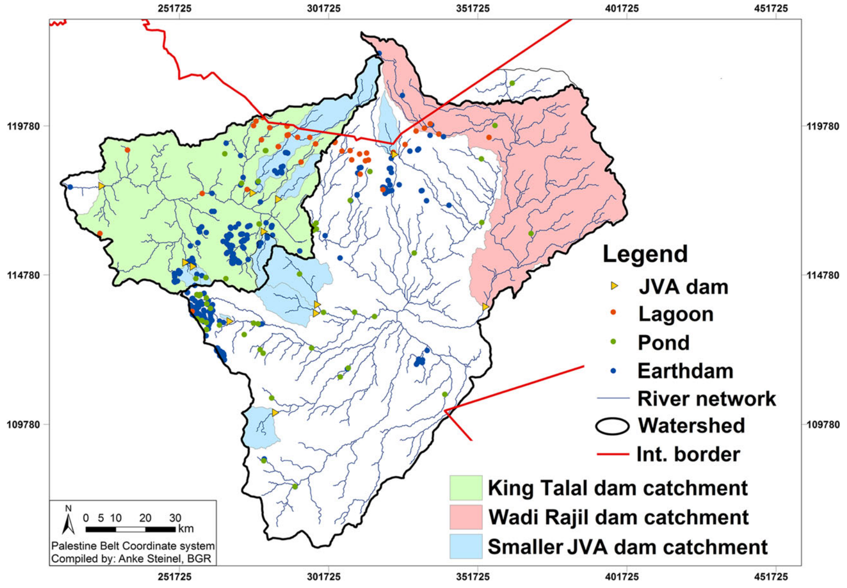
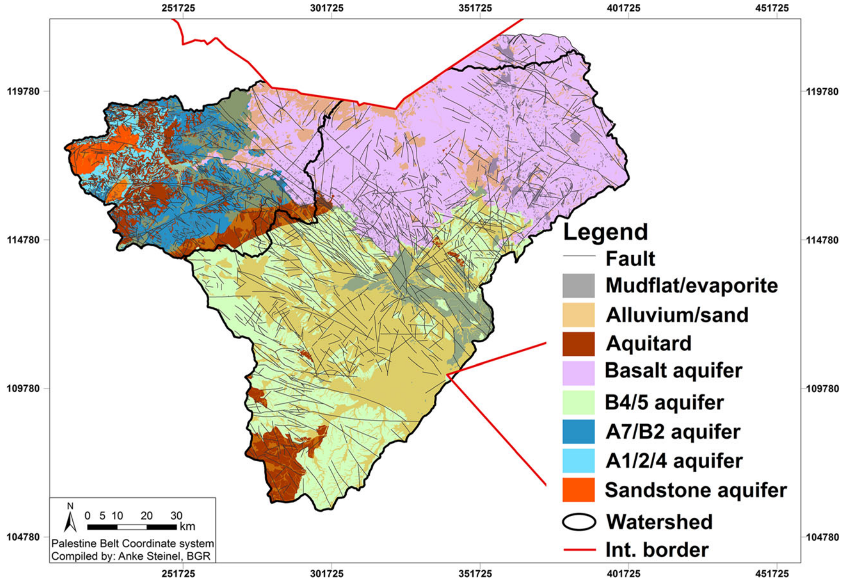


Fig. 4 Location of existing water harvesting structures and the catchments of larger structures under management of the Jordan Valley Authority (JVA) (arranged after JVA data and GoogleEarth survey)

Fig. 5 Simplified outcropping hydrogeology of Amman-Zarqa and Azraq basins showing aquifers and aquitards as well as overlying sediments (transparent) and faults (arranged after Hobler et al. (2001) and data from the National Resources Authority)



high heterogeneity of values, which does not allow for a meaningful regional interpolation. Average aquifer thickness is more than 200 m and only thins out at the edges of the aquifer systems or where vertical displacements along faults are large. For the upper aquifer system, flow is directed towards the topographic low in the centre of the Azraq basin (Fig. 6) and towards the Sirhan Graben (Alraggad and Jasem 2010; Hobler et al. 2001). For the middle aquifer system, flow is divided: towards the west in the middle part, towards the NW in the unconfined northern part and towards the Azraq Qaa in the confined eastern part (Fig. 6). The hydraulic gradient in the upper aquifer system is commonly low with about 0.1–0.2 % (El-Naqa et al. 2007). Groundwater age dating also suggests a low horizontal flow velocity (El-Naqa et al. 2007; Fröhlich et al. 1987). Locally flow directions and hydraulic gradients can be disturbed due to faults or abstraction cones (Borgstedt et al. 2007).

Groundwater level maps were created around 1995 and are based only on a limited number of observation wells especially in the Azraq basin. However, general patterns are visible showing that groundwater levels are more than 100 m below ground level (bgl) over large parts of the basins, but come closer to the surface near the former discharge area at Azraq Qaa (Fig. 7). As groundwater levels are generally declining (about 0.5–1 m/a), it can be assumed that current groundwater levels would be lower than depicted.

Groundwater salinity is generally good for domestic uses with over 80 % of sampled wells below 1,000 mg/L total dissolved solids (TDS) (Fig. 8). Increases in TDS occur with residence time along the flow path and with the age of the

Fig. 6 Groundwater-level contour lines (m asl), flow direction and limit of saturation for the upper or shallow aquifer (basalt and B4/5) and the middle aquifer (A7/B2) system before 1995 (arranged from Al-Kharabsheh 1995; Hobler et al. 2001)

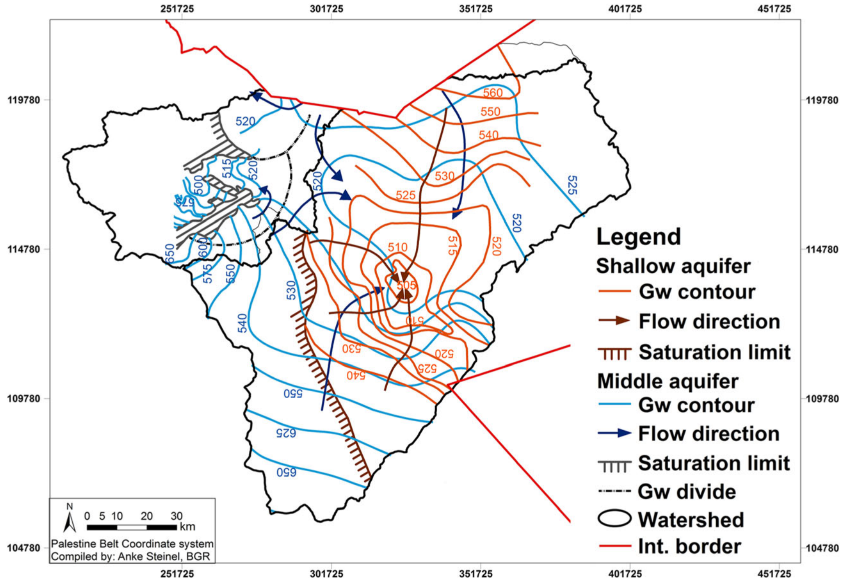
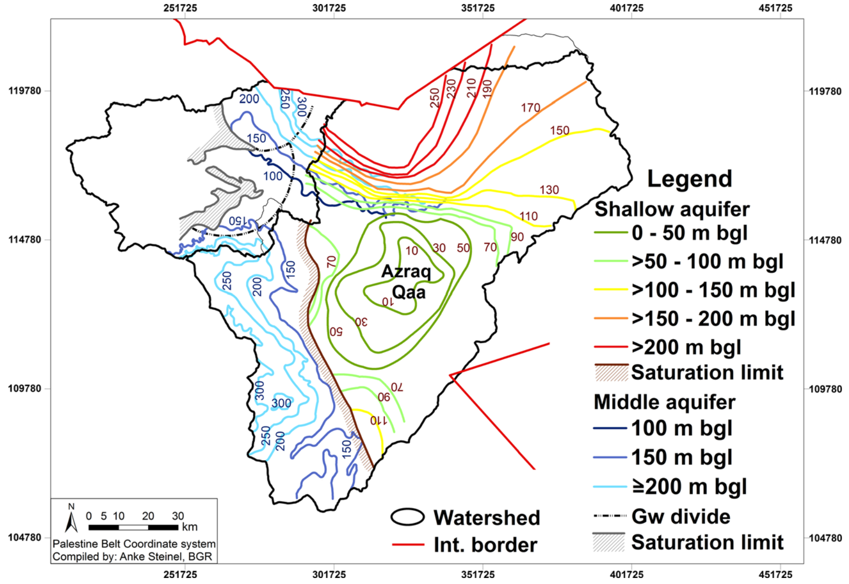


Fig. 7 Depth to groundwater (m bgl) and limit of saturation for the upper or shallow aquifer (basalt and B4/5) and the middle aquifer (A7/B2) system before 1995 (arranged from Al-Kharabsheh 1995; Hobler et al. 2001)



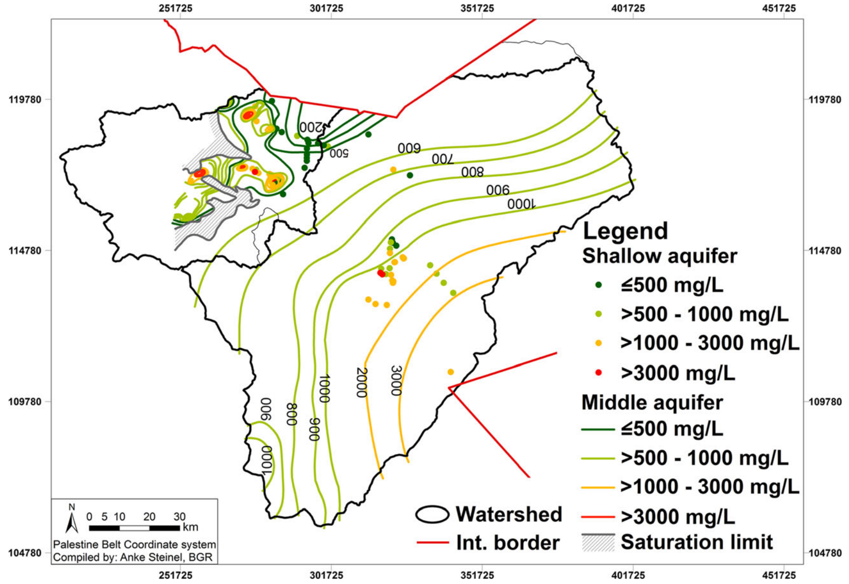
formation (El-Naqa et al. 2007). Strong increases in salinity can be found locally in the upper (Fig. 8) and middle aquifer system, where high groundwater abstraction rates have induced upward leakage of saline waters, for example around the Azraq Qaa (Fig. 8). A general trend of increasing salinity has been observed for the AMZ basin (Al Kuisi et al. 2009). Increases in salinity could also be due to agricultural return flows or dissolution of salic and gypsic soil horizons or rock strata.

An increase in nitrate concentrations mainly due to pollution from fertilizers and manure as well as wastewater has been detected across the AMZ basin (Al Kuisi et al. 2009). Taking into consideration that sampling points are biased towards contaminated wells and are largely clustered around urban and agricultural areas, still 105 wells sampled in AMZ basin between 2003 and 2010 showed nitrate levels above the drinking-water limit of 50 mg/L and 34 wells showed *E. coli* concentrations of >10 MPN/100 ml.

Soils

A regional soil survey was conducted in the 1990s mapping the soil associations within each "soil map group" (57 present in the study area) and giving the dominance of each soil within the association based on the physiographic position (HTS and SSLRC 1993). Information like soil thickness, texture and salinity are then available for representative profiles, but no data on soil permeability or field capacity are given (HTS and SSLRC 1993). In general, soils are thinner and more saline in Azraq basin compared to AMZ basin. The main soil textures

Fig. 8 Groundwater salinity (total dissolved solids in mg/L) for the A7/B2 aquifer system around 1995 (arranged after Hobler et al. 2001)



are clay, silt and loam with various percentages of gravels and stones and very low organic matter contents. Apart from the parent material, local variations in soil type are due to factors like erodibility, slope steepness and curvature (Ziadat et al. 2010). Sealing clay crusts combined with desert pavement covering vast areas hinder infiltration over large portions of the study area and cannot be described with simple pedotransfer functions. Therefore, transmission losses in wadi channels are generally assumed to be the main groundwater recharge source in arid regions (Lloyd 1986).

To get a better idea of infiltration capacity in the study area, basin infiltration tests (6 m^2) with drinking water were performed at five sites for 2 h. Observed infiltration rates ranged from 0 to 30 cm/d. Compared to the clean water used during the tests, actual recharge water with suspended solids would decrease infiltration rates by one or two magnitudes due to clogging (Schuh 1990). Consequently, infiltration rates during MAR operation are estimated to be around 0.3–3 cm/day in the best case compared to daily evaporation rates of around 0.5–1 cm/day. For more details on the study area, please refer to the full report (Steinel 2012).

Methodology

The aim of this study was to evaluate available data with respect to suitability for MAR through surface-water harvesting and subsequent infiltration to ultimately recommend suitable sites for further investigation. One has to distinguish between the suitability of the catchment for generating runoff to be harvested for MAR and the suitability of a specific site to construct a dam and to allow transfer of the harvested water into a suitable aquifer where it could be recovered from later. For both aspects, the same criteria might be evaluated differently (see Table 2). Previous MAR potential maps (Alraggad and Jasem 2010; Rapp 2008) have focussed mainly on the second aspect.

The approach of this study consisted of:

1. Defining criteria that affect surface-runoff generation and/or water infiltration and recovery potential for which spatial data are available to create thematic maps
2. Identifying constraint values that would completely hinder MAR implementation
3. Classifying each criteria into suitable (value 2), less suitable (value 1) and unsuitable (value 0) ranges
4. Determining the importance (weight) of each criteria in comparison to the other criteria (see Table 2)

This approach resulted in the creation of a number of thematic maps and eventually in a constraint map and a suitability map for both aspects, i.e. for catchment and site suitability. For a final evaluation, the visual overlay of both suitability maps should allow the ranking of suitable sites with associated suitable sub-catchments.

Obviously, it would not be necessary to assess the runoff generation of the catchments if a good record of runoff measurements was available; however, the existing spatial and temporal coverage and the reliability of runoff data (Fig. 9) were not sufficient to allow for a regional representation of runoff (especially for the Azraq basin). The conversion of rainfall into runoff depends on a number of factors such as rainfall intensity, rainfall duration, previous soil moisture condition, soil infiltration capacity, evaporation, slope and ground cover. In addition, losses occur during transport through infiltration in the wadi and through storage in depressions. Only a limited number of these factors were known and could be used for the creation of thematic maps.

Surface criteria

The main surface criteria for the generation of suitable runoff in the catchment were the amount of rainfall, the slope, the absence of existing dams and the absence of built up areas. The main surface criteria for site selection were land availability, the avoidance of conflicts of interest with local inhabitants and the presence of a soil allowing for infiltration.

Rainfall and sub-catchment size

Rainfall is obviously the most important parameter for runoff generation (Fig. 2). Regions with <50 mm/a could be neglected (Al-Kharabsheh 1995). Regions with <100 mm/a were not economically feasible, unless the catchment was very large and slopes were sufficiently high to actually allow most of the runoff to reach the MAR site (Sharda et al. 2006). In the study area, this situation was not available as the region between 50 and 100 mm/a has generally less than 5 % inclination. Commonly, water harvesting schemes start at rainfall of about 200 mm/a.

For the site assessment, however, rainfall was less critical as long as sufficient runoff reaches the site; however, if sites were located a long distance downstream from the area of sufficient rainfall the chances of runoff losses through infiltration in the wadi, soil moisture storage, storage in depressions and evaporation increased.

Topography

The slope influences runoff generation and runoff velocity (Fig. 2). For the catchment, moderate slopes were preferable. If the slopes were too high, the potential for erosion and increase in sediment load were a limiting factor. If the slope was too gentle, water would stagnate in small depressions rather than generate runoff. For the actual infiltration site, however, gentle slopes were needed to prolong the residence time of the

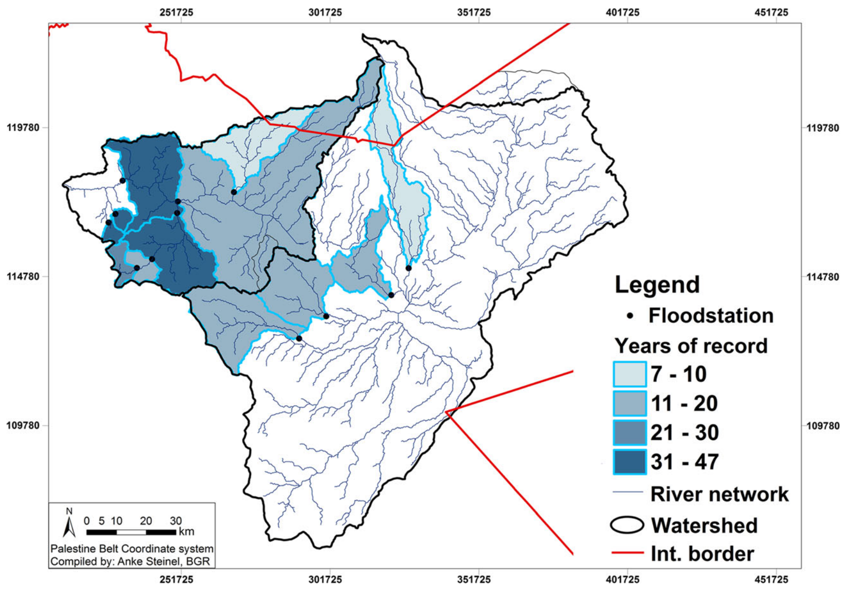


Fig. 9 Location of flood stations and the associated sub-catchments for Amman-Zarqa and Azraq basins, *colour graded* by the number of years of record

water to allow infiltration in the wadi or infiltration basin; however, it would be possible to modify the slope or to construct a suitable infiltration basin nearby.

Existing water harvesting structures

Obviously, catchments where the runoff was already collected by official or private water harvesting structures (see Fig. 4) were not suitable as the objective was to create new water resources rather than to relocate them. However, one focus of this study was to keep the water in the highland to reduce pumping costs from low-lying supply sites to elevated demand sites. Therefore, the upper catchment area of the King Talal Dam was generally considered suitable. The upper catchment of the Wadi Rajil Dam catchment was also generally considered suitable, as it was doubtful that the runoff would flow all the way to the dam due to the many flat areas. Other Jordan Valley Authority (JVA) dam catchments were considered unsuitable and included in the constraint map. Locations closer than 5 km up- or downstream of water harvesting structures like ponds, lagoons and earth dams with more than 10,000 m^3 storage capacity should be avoided to limit conflicts of interest with downstream users or allow for a sufficient catchment size below upstream structures, respectively. Smaller structures would not have a significant impact, unless there were many of them.

Soil

Soil texture influences the susceptibility to erosion and thus the sediment load in the runoff. In combination with soil thickness, it determines the moisture-holding capacity and the infiltration capacity. Accordingly, it was preferable to have thin soils with a limited content of fines to allow for fast infiltration and to improve runoff water quality. Saline soils should be avoided as this might lead to impaired water quality. As described in the preceding, sufficient information on infiltration capacity was not available, and hence the three available soil aspects were combined linearly to one soil score based on a weighting of 60 % for texture, 20 % for thickness and 20 % for salinity (Table 1).The resulting total soil score (Fig. 10) ranged between zero and 1.7. The soil score was used without further rounding for the combination with other thematic maps.

Land cover

Land use was a main factor for surface-water quality and for land availability. Urban areas and quarries should be excluded from the catchment as far as

Table 1 Classification, rating and weighting of soil aspects for a total soil score

Criteria	Classification	Rating	Weight
Soil thickness	Very shallow to shallow (<50 cm)	2	60 %
	Moderately deep (50–80 cm)	1	
	Deep to very deep (>80 cm)	0	
Soil texture	Silt + clay	0	20 %
	Loam	1	
	Sand	2	
	Gravelly or stony	+0.5	
Soil salinity	None to weak	2	20 %
	Moderate	1	
	Strong to very high	0	
Mudflats	Unsuitable	Constraint	–

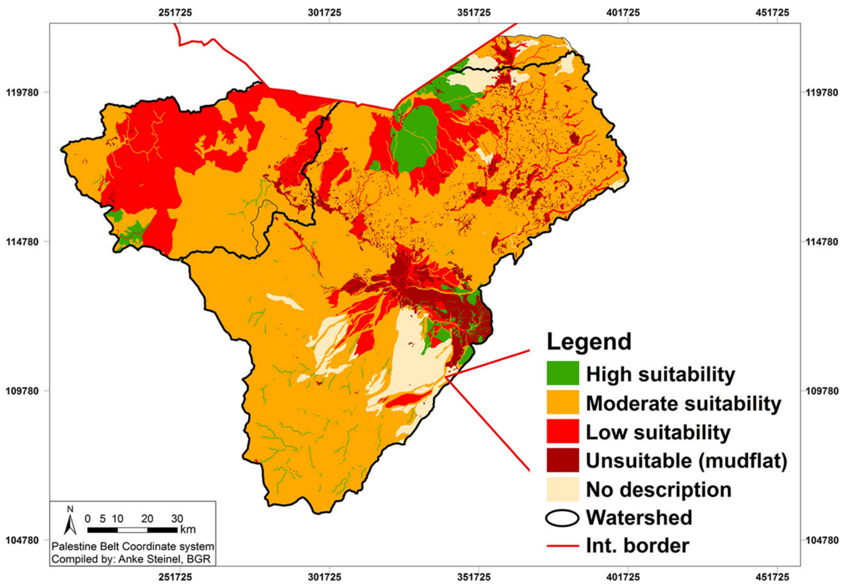


Fig. 10 Classification of total soil score based on a weighted combination of thickness, texture and salinity values (see Table 1)

possible and were not suitable for site selection. A buffer of 500 m was applied to account for further spreading of built up areas. The input of sediments, fertiliser and pesticides would be enhanced in agricultural areas. In addition, a conflict of interest and subsequent increase in vandalism might arise with farmers who prefer to store their water above ground. Agricultural areas were hence less preferable. Forest areas were likely to generate high amounts of organic material and evapotranspiration would be high, limiting the amount of runoff generated. Uninhabited areas with bare surface or pastures were most suitable. A catchment covered with surface crusts like chert plain was especially suitable as runoff generation is enhanced. Obviously, crusts would need to be removed at the infiltration site and were also less common in the wadi channels themselves. Mudflats were unsuitable for both runoff generating and infiltration. A further site assessment would need to address the availability of the land based on land ownership.

Site location

The location of a water harvesting site was obviously restricted to the wadi bed; however, it would be possible to transfer the water downhill from the harvesting site to an infiltration site. For the expected limited volumes of water, a transport over more than 2 km was not assumed to be economically viable. In addition, a distance of 2 km to the international borders should be observed for security reasons.

Sub-catchment size

As the runoff coefficient increases with rainfall, the minimum catchment size for an aspired mean annual runoff of about 50,000 m^3 increases non-linearly with rainfall range from about 25 km^2 in low rainfall regions (100–150 mm/a) to about 4 km^2 in high rainfall regions (400–450 mm/a). As most of the potential area was located in the lower rainfall range (100–250 mm/a) a mean value of 18 km^2 minimum catchment size was chosen. This was equivalent to a flow accumulation from 2,500 pixels of the digital elevation model (DEM) and was depicted by the extent of the river network.

Subsurface criteria

Apart from the near surface hydrogeology, runoff generation is not influenced by subsurface criteria. A MAR site, however, needs to be based on top of a suitable aquifer with sufficient aquifer storage space and an unsaturated zone allowing for infiltration to the aquifer.

Hydrogeology

A high permeability of superficial deposits and the underlying formation in the catchment was actually less preferable for runoff generation, while aquitards would allow more runoff generation and were favoured for the catchment selection (see Fig. 5). Obviously, the opposite was valid for the site selection. An underlying aquifer was essential and permeable superficial deposits were important for a fast infiltration. Accordingly, the presence of sandy deposits was given a bonus of 0.5 to the site suitability rate. As the permeability of unspecified alluvial deposits was not given but field visits showed often silty texture, it was assumed that they had higher permeability compared to underlying mixed aquifer/aquitard formations (+0.25) and lower permeability compared to underlying aquifers (−0.25; see Table 2).

Table 2 Criteria, classification, rating (*R*) weighting (*W*) for catchment and site assessment for constraint (*C*) and suitability mapping

Criteria	Classification	Catchment assessment		Site assessment	
		R[a]	*W*	*R*[a]	*W*
Surface criteria					
Distance to international borders	<2 km	–	–	C	C
Distance to wadis	>2 km	–	–	C	
Catchment size	<18 km^2	–	–	C	
Rainfall	<75 mm/a	C	5	C	1
	75–<100 mm/a	0		1	
	100–<200 mm/a	1		2	
	≥200 mm/a	2		2	
Land cover	Urban, quarries, mudflats	C	1	C	3
	Field and tree crops, forest	1		1	
	Bare rock, chert plains, sand, wadi deposits, pastures	2		2	
Slope	0–<2 %	0	4	2	4
	2–<5 %	1		1	
	5–<10 %	2		C	
	≥10 %	1		C	
Soil score[b] (60 % texture, 20 % thickness, 20 % salinity)	Score >67 %	2	2	2	4
	Score 33–67 %	1		1	
	Score <33 %	0		0	
	No description	1		1	
Existing dams	Other area	2	3	2	5
	Within 5 km of existing WH structure	1		1	
	Catchment JVA dam	C		C	
Subsurface criteria					
Hydrogeology and superficial deposits	Aquitard (B3, A5/6, A3)	2	1	C	4
	Mudflats, evaporites, calcrete	0		C	
	Aquifer/aquitard (B5, B1, K/Z)	2		1	
	Alluvium over aquifer/aquitard	1		1.25	
	Sand over aquifer/aquitard	1		1.5	
	Alluvium over aquifer	1		1.75	
	Aquifer (basalt, B4, B2, A7, A4, A1/2)	1		2	
	Sand over aquifer	0		2.5	
Thickness of aquifer	0–<20 m	–	–	C	2
	20–<50 m	–	–	1	
	≥50 m	–	–	2	
Depth to water table	10–<100 m	–	–	2	5
	100–>200 m	–	–	1	
	≥200 or <10 m	–	–	0	
Flow gradient	<0.2 %	–	–	2	1
	0.2–<0.5 %	–	–	1	
	≥0.5 %	–	–	0	
Distance to faults	<0.5 km (visible fault)	–	–	2	4
	<0.5 km (inferred fault)	–	–	1	
	Other area	–	–	0	
Groundwater salinity (TDS)	<1,000 mg/L	–	–	2	3
	1,000–<3,000 mg/L	–	–	1	
	≥3,000 mg/L	–	–	0	
Groundwater contamination (NO_3 > 50 mg/L or *E. coli* >10 MPN/100 ml)	<1 km from well	–	–	C	3
	1–<2 km from well	–	–	1	
	≥2 km from well	–	–	2	

Table 2 (continued)

Criteria	Classification	Catchment assessment		Site assessment	
		R^a	W	R^a	W
Infrastructure criteria					
Distance to roads	<1 km from main road	–	–	0	4
	<1 km from secondary road	–	–	1	
	<2 km from gravel road	–	–	2	
	Other area	–	–	1	
Distance to active government wells	<0.5 km	–	–	0	4
	0.5–<2 km	–	–	1	
	2–5 km	–	–	2	
	≥5 km	–	–	1	

[a] Values for *R* (rating): *C* constraint, *0* low suitability, *1* medium suitability, *2* high suitability

A1–A7, B1–B5 and K/Z abbreviations for geological units (see section "Hydrogeology"); *JVA* Jordan Valley Authority, *MPN* most probable number, *TDS* total dissolved solids, *WH* water harvesting

[b] Actual score (range 0–1.7) from combining the three soil aspects

Aquifer storage space

Aquifer storage space (Fig. 11) is dependent on the unsaturated thickness of the aquifer formation, i.e. is dependent on the total aquifer thickness and the depth to groundwater level. Therefore, regions with shallow groundwater levels were not suitable for aquifer recharge. In addition, the expected groundwater mount should not be too close to the surface, as this could lead to evaporation or interference with surface structures. Only the area around the Azraq Qaa fell into this category (see Fig. 7). Thin aquifer units were also not preferable for MAR. As no detailed thickness maps for the A1/2 and A4 aquifer were available, only the middle and upper aquifer complex could be assessed. Overall, there were only a few areas, where the aquifer thickness might be a limiting factor. In general, there was sufficient storage space and it is increasing every day through the decline in the water table.

Distance to faults

Fault lines (Fig. 5) provide preferential flow paths and could hence potentially be preferable for enhancing the vertical hydraulic conductivity for a faster infiltration. Higher transmissivity values associated with fault zones have been found (Al-Khatib 1999; Alraggad 2009). Faults were often only inferred or below superficial deposits and would need to be investigated in more detail at the site. A buffer of 500 m around the faults was used as maximum distance of positive influence.

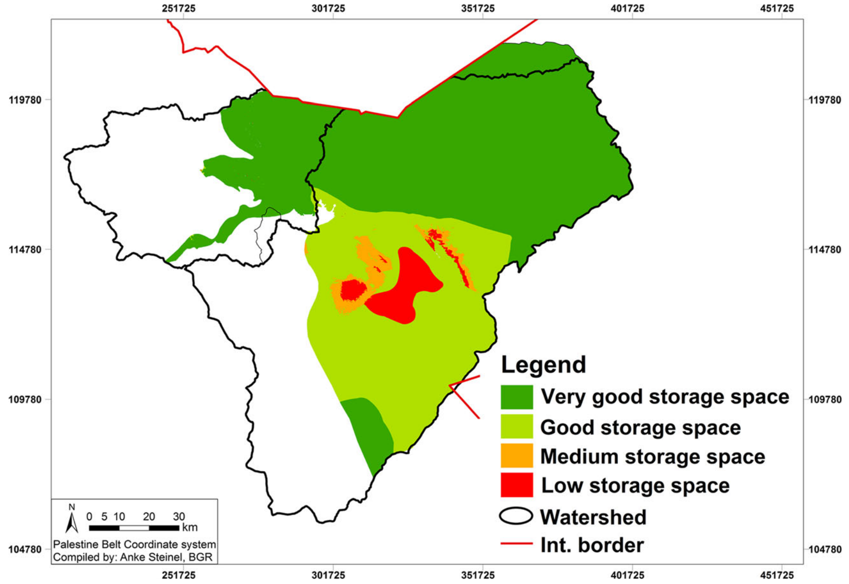


Fig. 11 Aquifer storage space availability in Amman-Zarqa and Azraq basins in areas with saturated zones of the aquifer (upper and middle aquifer system only) based on depth to water table and aquifer thickness

Economic/infrastructure criteria

As the main economic benefit is generated when the stored water is recovered, parameters affecting the recovery efficiency as well as other economic considerations like treatment costs before usage, accessibility and pumping costs also played a role.

Hydraulic gradient

The groundwater flow gradient was of interest for the recovery. A high hydraulic gradient limited the recovery efficiency as the recharged water would be dispersed over a large area and might mix with groundwater of unsuitable quality. The available water table contour lines (see Fig. 6) were used to calculate the flow gradient. The flow gradient was commonly quite flat leading to slow flow velocity; however, the flow gradient was likely to have increased locally around abstraction wells.

Groundwater salinity

Groundwater quality was also important for the recovery of the recharged water and suitability depends on the intended use. Groundwater salinity below 1,000 mg/L would be suitable for domestic uses, while salinity up to 3,000 mg/L could be acceptable for irrigational use and livestock watering. Salinity maps for the A7/B2 aquifer system showed suitable conditions in the outcropping areas and less suitable conditions in the confined regions that could not be used for MAR via infiltration anyway (Fig. 8). For the upper aquifer system, no detailed maps were available and available data did not cover the region equally to extrapolate reliable maps, but salinity in the upper aquifer system matched mostly with the range in the middle aquifer system; therefore, a regionalised map of the middle aquifer system salinity was used for the creation of the thematic map.

Groundwater contamination

Areas with known groundwater contamination should be avoided, as the recovered water should potentially be suitable for domestic use. A buffer of 1 km around all wells with nitrate >50 mg/L or *E. coli* values >10 MPN/100 ml was classified as unsuitable, while a buffer of 2 km was classified less suitable. This factor would be most important downstream of the MAR site, but could not be implemented graphically, as one well could be downstream of one potential site and upstream of another potential site. Therefore, the groundwater quality downstream of a selected MAR site should be investigated site specifically to assure that the recovered water is likely to meet the required standards. In addition, areas with groundwater contamination indicated that there might be a number of hazards in the catchment that could also have a negative impact on surface-water quality. These areas were commonly related to point contamination hazard sites (for which no regional map exists) or were related to diffuse contamination from urban or agricultural land cover. Limited groundwater quality could be overcome through adequate treatment of the recovered water before usage, but it would raise the price and decrease economic viability.

Depth to the water table

For the purpose of recovery, areas outside the limit of saturation of the aquifer were not suitable as recovery from the unsaturated zone would not be possible. Also, areas with a very deep water table (>200 m bgl) were less preferable as this would incur high pumping costs. In addition, infiltrated water might be lost in a thick unsaturated zone or be trapped above thin impermeable layers and hence lost for recovery purposes. The assessment was performed on the available older maps (see Fig. 7). Depth to water levels would have changed over the years and would need to be assessed site specifically.

Distance to roads

Site access should be reasonably easy for the construction and maintenance of the MAR site, but it should not be too easily visible from the main road or settlements, as this might increase vandalism. A short distance to main roads also increased the potential of surface-water pollution. Accordingly, the available road map (see Fig. 3) was classified into main roads, secondary roads and gravel roads.

Distance to active government production wells

Since the installation of new wells and conveyor lines can be very expensive, it would be an economic advantage if active production wells downstream of the MAR site would benefit from the recharged water. Preferably, recovery wells would be active government-owned wells and not private wells. However, the infiltration site should not be too close to any well to comply with groundwater protection guidelines. In Jordan, the groundwater protection zone 2 is delineated with a minimum of 150 m and a maximum of 2 km from the well to prevent potential bacteriological contamination from reaching the well (MWI-BGR 2011). As flow velocities were mostly unknown and seemed to vary considerably due to preferential flow paths, a limit of >2 km between the infiltration site and the well was preferable and a general buffer of 150 m around all existing wells was classified unsuitable. On the other hand, if the distance between the infiltration site and well became too large, the recharged water might take too long to reach the well within a reasonable time frame. So the optimal distance was estimated to be 2–5 km upstream from a production well (Fig. 12). The applied buffer included up- and downstream areas, as it was not possible to select only downstream areas for all possible sites. Accordingly, the groundwater flow direction and distance to the next well downstream would have to be assessed site specifically. If the well is further away, new water level measurements should be undertaken to estimate travel time based on a recent flow gradient.

Constraint mapping and multi-criteria analysis

Two principal overlay techniques for thematic maps were used. The Boolean logic allowed only a rating as suitable or unsuitable (0 and 1 value) and was used for creating the constraint maps, which meant that an area was regarded as potentially suitable if it fulfilled the minimum value for all the criteria, while the area was rated unsuitable if only one criterion value was below the minimum threshold. Completely unfeasible areas could be screened out with this technique.

The weighted linear combination (WLC) allowed the combination of classifications inside each criterion with different weights across all criteria and is commonly used to create suitability maps, which meant that areas that were unsuitable for one criterion could still get a high final score if all other criteria were valued suitable. The final score of the catchment and site suitability maps was based on the WLC formula, normalised by dividing by 2 (as the max. score is 2) and converted to percentage:

$$\text{Suitability score }(\%) = \left[\sum(R_i \bullet W_i)/\sum(W_i)\right]/2 \bullet 100$$

The flowcharts for catchment and site assessment are depicted in Figs. 13 and 14, respectively. All criteria applied (*i*), their classification (2 = max score), rating (*R*) and weight (*W*) are listed in Table 2.

Catchment assessment

The selection of a suitable catchment generating enough runoff of a suitable quality was constrained mainly by three criteria. Areas not fulfilling all of these minimum criteria were combined to a catchment constraint map (see Fig. 15):

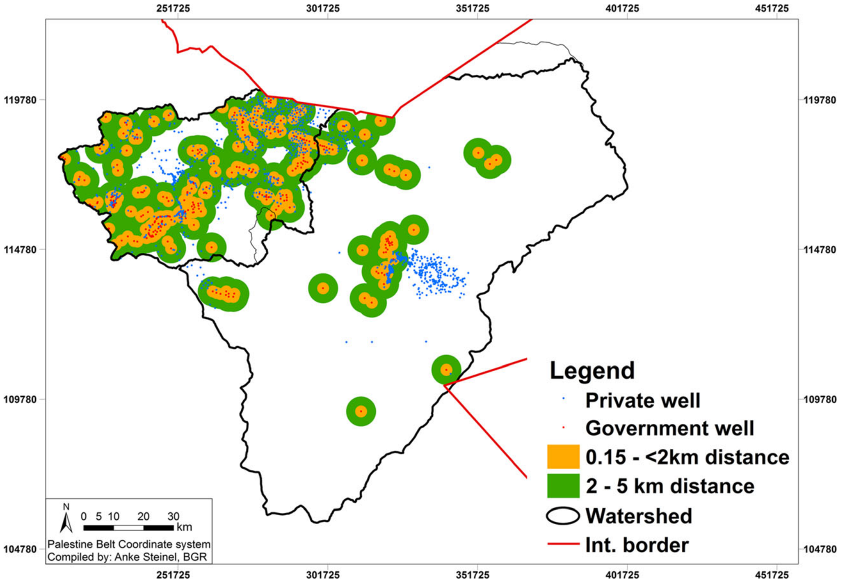
1. Rainfall <75 mm/a
2. Inside the catchment of existing dams (all small dam catchments and the lower part of the large dam catchments)
3. Land cover was built up, quarry or mudflat

The catchment constraint map served as a cover for the catchment suitability map (see Fig. 16). A number of combinations in weights were calculated to assess the sensitivity. Variations in final catchment score were within a limited range and the overall picture stayed the same.

Site assessment

As described in the preceding, the selection of a suitable dam and infiltration site was based on more criteria and

Fig. 12 Location of private and government production wells and a radius of 2 and 5 km around active government production wells



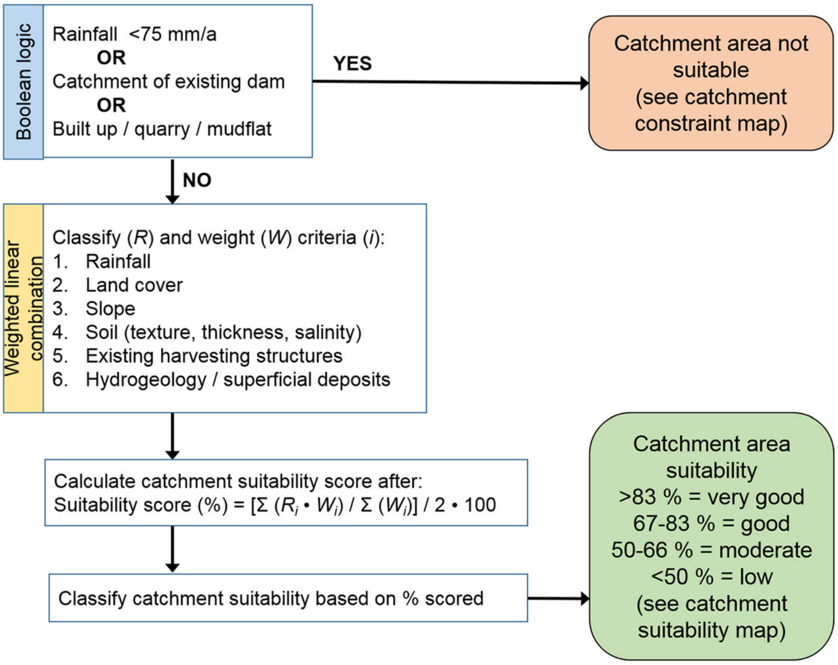


Fig. 13 Flowchart describing constraint and suitability mapping for catchment assessment

accordingly more constraint criteria were added. Areas not fulfilling all of these minimum criteria were combined to a site constraint map (see Fig. 17):

1. Rainfall <75 mm/a
2. Inside the catchment of existing dams (all small dam catchments and the lower part of the large dam catchments)
3. Land cover was built up, quarry or mudflat
4. Slope >5 %
5. Areas over aquitards
6. Aquifer thickness <20 m
7. Areas over unsaturated aquifer
8. Distance to contaminated well <1 km
9. Distance to international border <2 km

The site constraint map served as a cover for the site suitability map (see Fig. 18). In addition, two other criteria—distance to wadi >2 km and catchment size <18 km^2—were added as a second cover in case the assessment was to be used for other water resources like treated wastewater that would be available outside of the wadi system. Again, a number of

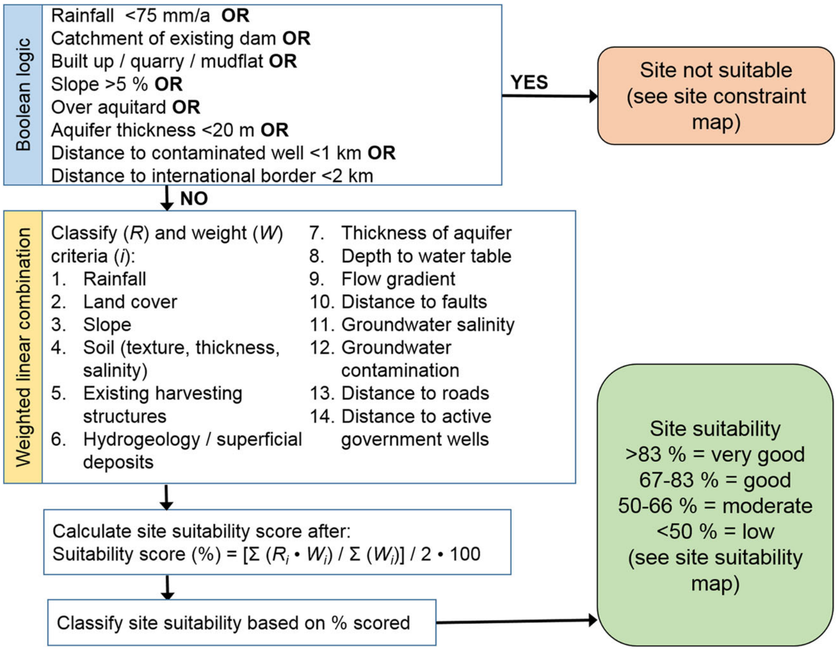


Fig. 14 Flowchart describing constraint and suitability mapping for site assessment

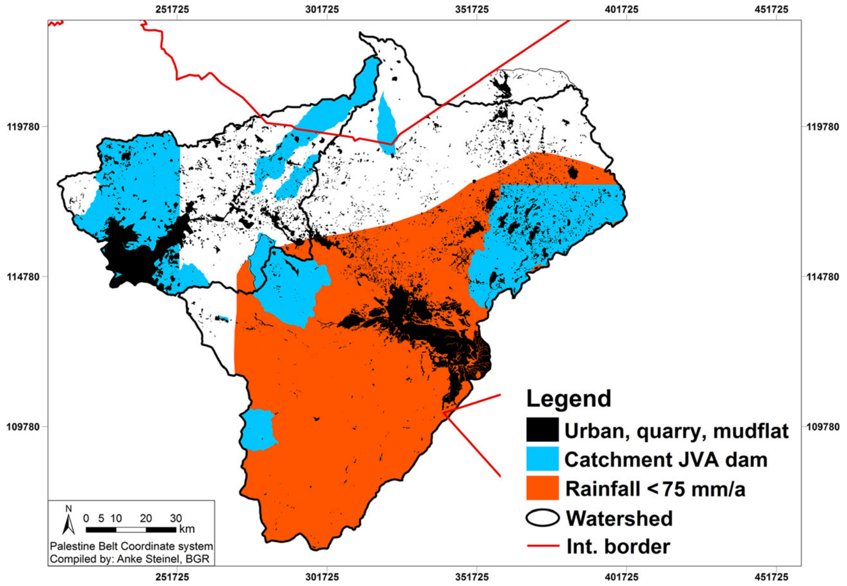


Fig. 15 Constraint map for catchment assessment of Amman-Zarqa and Azraq basins

combinations in weights were calculated to assess the sensitivity. Variations in final site score were within a limited range and the overall picture stayed the same.

Data availability and uncertainties

Due to the regional scale of the study and the resolution of input data, all maps represent simplification and have uncertainties attached to them. A specific assessment for all the criteria would have to be made during a following feasibility study to confirm catchment and site suitability.

The *topography* and derived values like slope, river network and (sub-)catchment areas were generated from the US Geological Survey's HydroSHEDS (USGS 2008). These are based on high-resolution elevation data obtained from NASA's Shuttle Radar Topography Mission (SRTM). The resolution of the DEM is about 90 × 80 m and is suitable for the regional scale of the study, but of course it is too coarse for selection of an individual dam site. Especially in Azraq basin, it is also uncertain whether the runoff from a larger sub-catchment actually flows down the entire wadi or stagnates due to the flat topography and the presence of smaller flat depressions. This cannot be fully identified with the resolution of the DEM. Catchment and site-specific topographic surveys would be needed to delineate the hydrologic boundaries of the catchment, find a suitable wadi cross section for dam construction and delineate the potentially flooded area.

The *land cover* map was provided as a shape file by the Royal Jordanian Geographic Center (RJGC 2011). It is based on satellite images from 2005, was verified by field inspections and released in 2011. As the built up area has significantly increased since 2005, all visible human constructions

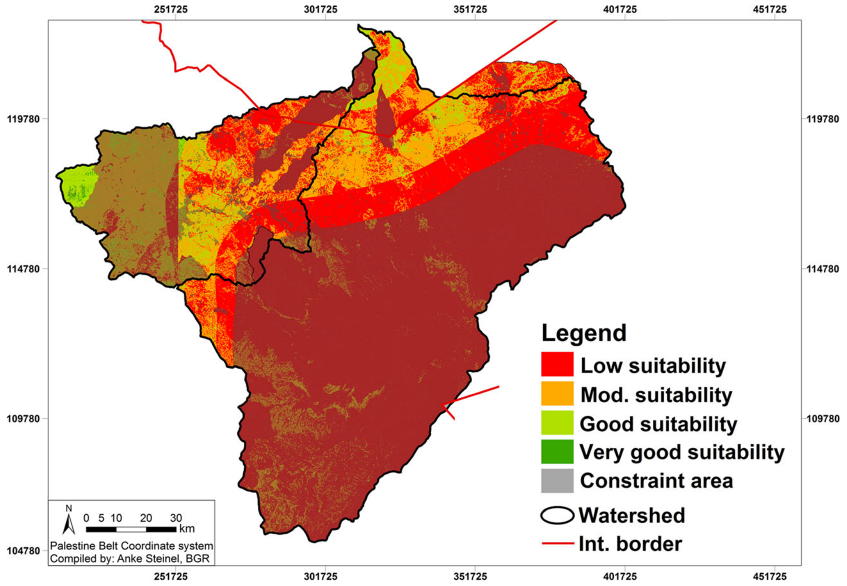
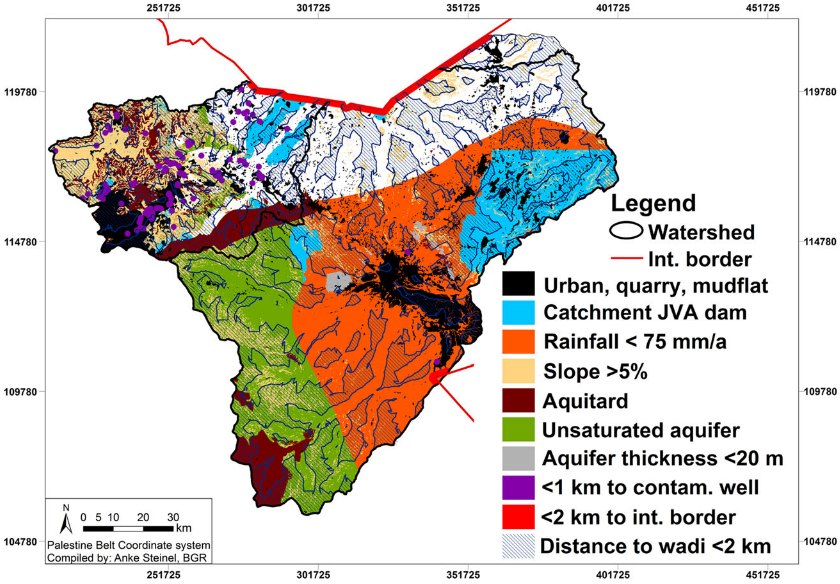


Fig. 16 Suitability map for catchment assessment of Amman-Zarqa and Azraq basins

Fig. 17 Constraint map for site assessment of Amman-Zarqa and Azraq basins

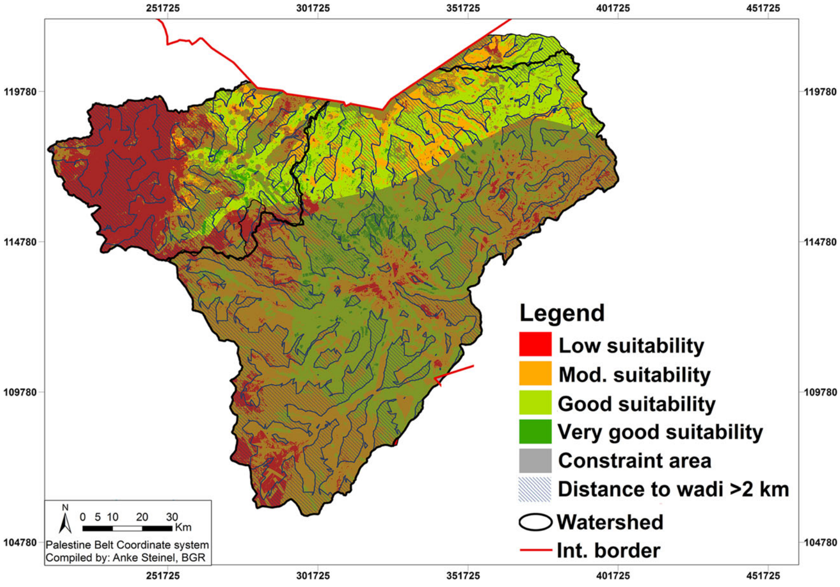


were mapped manually in GoogleEarth in April 2012 and added to the land cover class 'urban'. During field inspections in the catchment, potential hazards to groundwater and surface water should be mapped and potential conflicts of interest with existing land uses should be assessed.

Data on official *water harvesting structures* were provided by JVA, but there were no data on private water harvesting structures. These were mapped manually in GoogleEarth in April 2012. For a broad estimation of storage capacity, ponds were assumed to be about 2 m deep, and earth dams were assumed to hold around 1 m water depth over an idealised triangular area behind the dam (calculated by width and length of the visible storage area). The actual storage capacity, current status and number of harvesting structures would need to be assessed by a site-specific survey.

The regionalised *soil* data generated from the level 1 soil survey (HTS and SSLRC 1993) should be used with caution as they present a strongly generalised version using only the most dominant soil type characterised by one representative profile. Proper investigations into the hydraulic properties of the soil at the infiltration site would be needed. These should encompass basin infiltration tests, soil analysis, shallow drilling and geophysical surveys. As ring infiltrometer tests are often used to estimate infiltration capacity, ring infiltrometer tests (30 cm inner, 60 cm outer diameter) were undertaken at three sites for comparison with results from the basin infiltration tests (see section "Soils"). Compared to basin infiltration tests the mean of three ring infiltrometer tests gave at least double the infiltration rate due to lateral spreading. Therefore, ring infiltrometer tests have to be treated with

Fig. 18 Suitability map for site assessment of Amman-Zarqa and Azraq basins



caution (Youngs 1991). Soil sample tests should also determine the suitability of the material for dam construction.

The *hydrogeological map* and *faults* are based on the geological maps (1:50,000 and 1:100,000, purchased as shape files) from the national mapping program published with explanatory notes (e.g. Ibrahim 1996) by the Natural Resources Authority (NRA). A field survey should include a hydrogeological mapping of the area to assess if the regional data hold true at the specific site. It would also be necessary to investigate the foundation conditions for dam construction.

All *other data* (e.g. climate, rainfall, runoff, transmissivity values, groundwater levels, groundwater quality) were supplied by the Ministry of Water and Irrigation (MWI) and its subordinate divisions, the Water Authority of Jordan (WAJ) and the Jordan Valley Authority (JVA). In general, the spatial coverage of data in the Azraq basin is much lower than in the AMZ basin. Most records contain gaps in the timeline and the data had to be controlled for quality in the course of this study leaving some remaining uncertainty. The limited number of observation wells with reliable static groundwater level measurements leaves room for uncertainty in the groundwater level map and the subsequent calculation of flow gradient. These maps are also based on data from 1995, so groundwater levels are likely to have changed considerably in areas with high abstractions. All interpolated values are more uncertain along the edges of the interpolation, e.g. along the edges of aquifer outcrops. For more details on the data used, please refer to the full report (Steinel 2012).

Results and discussion

The outcome of this pre-feasibility study is twofold. Firstly, regional maps for Jordan assessing the potential for MAR via surface-water harvesting and subsequent infiltration are generated, and secondly, a potential blueprint for similar assessments in comparable regions is derived.

Technical aspects

This pre-feasibility study applied a number of technical criteria (Table 2) to generate constraint maps with Boolean logic and suitability maps with weighted linear combination for potential catchments and sites.

Catchment constraint and suitability maps

The catchment assessment showed that about 65 % of the total study area (including the Syrian catchment area) did not fulfil the minimum criteria (see section "Constraint mapping and multi-criteria analysis") and was hence combined to form the catchment constraint area (Fig. 15). The remaining area of interest is mainly in the northern basaltic area, where runoff is received through transboundary surface flows from the Jebel al Arab.

Applying the six catchment assessment criteria (i.e. rainfall, land cover, slope, soil, existing dams and hydrogeology) using WLC (see Table 2) showed that less than 5 % of the total area scored very good or good suitability (see all dark and light green areas in Fig. 16). This area was reduced to 3.7 % (0.1 % very good and 3.6 % good suitability) when subtracting the constraint area (see Table 3). The most suitable areas are located in the westernmost part downstream of the King Talal Dam outside of the highland area and hence are located outside the objective of the study. Smaller suitable areas are delineated inside Syria or close to the Syrian border where rainfall is higher.

Site selection constraint and suitability maps

The site assessment showed that about 87.5 % of the Jordanian study area did not fulfil the 11 minimum criteria (see section "Constraint mapping and multi-criteria analysis") and was hence combined to the site selection constraint area (Fig. 17). The main area of interest remains in the northern basaltic area of the Azraq basin.

Applying the 14 site assessment criteria using WLC (see Table 2) showed that about 40 % of the total area scored very good or good suitability (see dark and light green areas in Fig. 18). This area was reduced to 9 % (0.4 % very good and 8.6 % good suitability) when subtracting the constraint area (see Table 3). Some very suitable areas were scattered along the lower reaches of Wadi Zatari and Wadi Dhuleil in the AMZ basin for example.

Obviously, the availability of a good infiltration site is not enough without a suitable catchment upstream to provide sufficient water resources. To calculate the overall suitability of a sub-catchment at each possible site would require an algorithm to delineate the upstream sub-catchment and add up all catchment suitability scores over the sub-catchment in relation to sub-catchment size. Unfortunately, this calculation could not be conducted within the timeframe of this study. Therefore, only an overlay of the site suitability (Fig. 18) and the catchment suitability map (Fig. 16) was used for visual appraisal. Each potential wadi would need to be assessed individually and advantages and disadvantages considered.

Overall, in AMZ basin, urban and agricultural areas (including hazards like chicken farms and quarries) are enclosed in virtually all potential sub-catchments, which might lead to an impaired runoff and groundwater quality. It could also create conflict of interest with local inhabitants increasing the risk for vandalism. In addition, since 1995, when the data for the groundwater level maps were collected, over-abstraction might have resulted in unsaturated conditions or a higher flow gradient reducing the suitability of sites.

Table 3 Distribution of suitability score as percentage for the overall catchment assessment area (including Syrian area) and the overall site assessment area (Jordan only) without and with applying constraint area

Score	Suitability	Without constraint applied		With constraint applied	
		Catchment suitability	Site suitability (Jordan only)	Catchment suitability	Site suitability (Jordan only)
>83 %	Very good	0.1 %	1.7 %	0.1 %	0.4 %
67–83 %	Good	4.7 %	38 %	3.6 %	8.6 %
50–66 %	Moderate	26 %	43 %	14.3 %	3.5 %
<50 %	Low	69 %	17 %	16.8 %	0.0 %
Constraint	Unsuitable	–	–	65.2 %	87.5 %

Overall, in Azraq basin, only the northernmost areas encompass suitable sub-catchments. The main drawback in this region is the great depth to the water table which is commonly >200 m bgl and the limited number of potential recovery wells. In addition, catchment sizes might be overestimated due to the gentle slope and presence of flat areas and depressions, reducing the available water resources and the number of suitable dam construction sites.

Accordingly, no specific sites could be recommended for further investigation. Naturally, all data used are afflicted with uncertainty and inaccuracy due to the resolution and age of the data (see section “Data availability and uncertainties”). The highest uncertainty for catchment suitability is the amount of harvestable non-allocated surface runoff, which seems to be too low for viable MAR schemes. This is due to the fact that many harvesting structures are already in place and that low intensity rainfall events often do not generate appreciable amounts of runoff, while high intensity rainfall events often generate amounts of surface runoff that are too large to be captured and would mostly spill over harvesting structures. Constructing dams large enough to capture these rare flood events is usually not economically viable. Previous dam site investigations were based on runoff estimations using the curve number method (USDA-SCS 1985), which seems to considerably overestimate runoff in comparison to measured rainfall-runoff relationships (see section ”Surface-water resources”). Therefore, any further investigation into MAR should foremost be concerned in investigating the availability of water resources. It is highly recommended to increase the number of flood and rainfall monitoring stations. Placing a number of flood stations along the same wadi would also allow estimating transmission losses through the wadi bed, i.e. estimating natural groundwater recharge.

In addition, surface-water quality is commonly impaired by large sediment loads and by hazards like urban areas, large farms and quarries, but data on actual runoff water quality are very rare; for example, a better knowledge of sediment load and particle sizes would allow finding the most suitable pre-treatment and give a better estimation of maintenance costs. If surface-water harvesting is envisaged to increase, it is highly recommended that land-use planning incorporates the knowledge on potentially suitable surface-water catchments. These areas could be set aside as future water protection areas, so that the development of additional hazards could be avoided.

The highest uncertainty for the site selection is associated with the soil infiltration capacity. Based on basin infiltration tests undertaken with clean water during this study (Steinel 2012), maximum infiltration rates of 0.3–3 cm/day are expected for infiltration of turbid surface runoff. Taking into consideration evaporation rates of around 1 cm/day, considerable amounts of harvested water are likely to evaporate during infiltration. Proper construction of infiltration basins and settling basins for sediments, and regular maintenance is therefore paramount to keep infiltration rates as high as possible; also, recharge release dams could be an option if downstream wadi infiltration rates are high enough.

Previous MAR studies for the area (Alraggad and Jasem 2010; Rapp 2008) have neglected the assessment for the availability of non-allocated harvestable surface runoff and have only assessed the site suitability using the criteria slope, urban land cover, suitability of outcropping formation and distance to potential water resources (existing dams or wastewater treatment plants). The distance to fault lines was added as a criterion in Alraggad and Jasem (2010). Both studies used only successive intersection of thematic maps without weighting; thus, this study presents a more comprehensive assessment based on a large number of criteria and has considerably improved the assessment for MAR potential. The presented method is a potential blueprint transferable to other basins and regions as it is possible to adjust the number and type of criteria, and their classification and weights according to regional characteristics and data availability.

Socio-economic and environmental aspects

A complete feasibility study should encompass the environmental and socio-economic consequences of a MAR intervention as well as a cost-benefit analysis compared to other alternatives. This pre-feasibility study tried to address a number of important issues, but does not claim to be comprehensive.

Costs associated with a MAR scheme comprise capital costs and operational costs as well as social and environmental costs occurring before, during and after implementation. Often though, only capital costs before and during construction are considered. A proper MAR scheme should also include operation and maintenance (O&M) as well as monitoring (e.g. NRMMC, EPHC, NHMRC 2009). Including the costs of O&M into a lifetime cost analysis considerably increases the overall cost-effectiveness as recharge schemes might only be working for about 3 years without O&M due to the high sediment loads, but might last 20 years with O&M. More direct costs are accrued for the recovery of the water. These costs are highly dependent on the water table depth and energy source used for pumping. Contingency costs could occur, when polluted water was recharged or dam failure occurs.

Indirect costs are related to downstream impacts for example on consumptive allocations, environmental flows, groundwater recharge, loss of biodiversity or degradation of water quality. In general, downstream areas will be more affected than upstream areas, unless the ponding area is very large. The reduction of surface-water flow downstream of a water harvesting structure could not only create conflicts with downstream users, but is also likely to lead to a degradation of habitats in and along the wadi channels. Especially in Azraq basin, wadis and qaas are almost the only vegetated areas sustaining biodiversity and providing pastures for Bedouin livestock. For example, a fully flooded Azraq Qaa attracts many water birds. In AMZ basin, the reduction of stream flow is likely to lead to a reduction in water quality in the Zarqa River and King Talal Dam as the dilution of wastewater will be lower. It should also be taken into account that water harvesting structures prevent natural groundwater recharge downstream. This loss in natural recharge needs to be subtracted from the overall benefit of the recharge scheme. If recharged water contains contamination, the groundwater quality could deteriorate and groundwater users downstream might incur health problems. It is therefore important to monitor incoming water quality and to be able to shut down infiltration, if water quality is below certain thresholds.

Effectiveness of schemes depends not only on the costs but also on the *benefits* of a scheme, which is usually equated with the amount of recovered water and related increases in income and living conditions. The amount of recoverable water is obviously not equivalent to the amount of harvested water (or even the storage capacity of the dam). The highest losses occur due to evaporation during infiltration. Estimations vary between 20 and 75 % evaporation losses (e.g. Gale et al. 2006; Haimerl 2004; Kalantari et al. 2010; Sukhija et al. 1997; Zeelie 2002). A clogged recharge dam will result in negative impact and indirect costs, as the harvested water will not be available downstream for natural infiltration, environmental or human use. In addition to evaporation losses, water will be lost in the vadose zone as well as through transport in the saturated zone. There is also a time lag in benefits between recharging water and its potential recovery depending on the thickness and permeability of the vadose zone and groundwater flow velocity (Izbicki et al. 2008). If recharge occurs only every second year, it might also mean that this will only be enough to saturate the unsaturated zone and nearly no water would reach the groundwater. Data on the actual efficiency of recharge schemes in arid countries are limited and it is highly recommended to increase this knowledge, as it is vital for a meaningful cost-benefit analysis.

The *revenues* are also highly dependent on the water use. The earnings that can be generated through agricultural irrigation in arid regions are commonly lower than the costs associated with the real costs (i.e. non-subsidised costs) of water production. Providing additional water supply through recharge schemes often encourages unsustainable farming practices and increases the groundwater over-abstraction (Gale et al. 2006). The benefits that result from a lower pumping lift through an increase in groundwater level are negligible as recharge mounts quickly dissipate and regional groundwater level increases will be in the scale of mm, when only a few mm of annual rainfall could be harvested and recharged. Real benefits are the reduction of transport costs, when local demand can be covered by local supply, and the use of accumulated sediments for construction or soil fertilisation.

The concept of managed aquifer recharge through recharge release dams requires a certain hydrogeological understanding and a long-term thinking that is not necessarily in line with common perception. For example, local inhabitants blocked the release structures at the Wadi Madoneh dam (de Laat and Nonner 2011) and used it as surface-water storage; therefore, a successful MAR scheme would require intensive awareness campaigns and participation to create acceptance and ownership in the local population as well as the nomadic inhabitants passing through the area. Furthermore, clear legislation, regulations (including monitoring requirements), finance and distribution of responsibilities are needed for the planning, construction, operation and closure of MAR schemes to ensure sustainability.

Conclusions

This pre-feasibility study presents a comprehensive method for the assessment of MAR potential at a regional scale that is transferable and adaptable to other areas depending on available data. It defines and evaluates the fundamental technical requirements such as source water availability, aquifer-storage-space availability and effectiveness of transfer of harvested water to the aquifer for two basins in Jordan. While the site suitability assessment showed that there is ample storage space available and surface infiltration would potentially be suitable in many areas above the unconfined aquifers, unfortunately the assessment of catchment suitability indicated that the main limiting factor is the low amount of harvestable noncommitted surface runoff.

The effectiveness of MAR schemes is also highly dependent on a proper sediment management plan, especially for funding of operation, maintenance and monitoring. Cost-benefit considerations should be based on the actual amount of recoverable water rather than the expected amount of harvested water as has often been done in the past; furthermore, likely occurring negative downstream impacts should be considered, so water is not merely relocated. One should bear in mind, that MAR will not work everywhere as schemes may be neither socially acceptable nor economically feasible. MAR will not prevent groundwater level declines on a regional scale without demand management measures. Due to the high uncertainty associated with runoff water quantity and quality, it is therefore highly recommended to increase monitoring of these parameters before any MAR implementation takes place. During the operation of MAR schemes, monitoring must ensure that groundwater contamination is prevented and the effectiveness of the scheme is proven to justify replication. The sustainability of MAR interventions might also be increased through stakeholder participation.

Acknowledgements This study was funded by the GeoSFF (Study and expert fund for geoscientific sector schemes) of the German Ministry of Economic Cooperation and Development (BMZ) and undertaken in cooperation with the Jordanian Ministry of Water and Irrigation (MWI). In addition, we thank the Natural Resources Authority of Jordan, the Royal Jordanian Geographic Center, the Jordanian Water Authority and the Jordan Valley Authority for the supply of the data.

References

Al Kuisi M, Al-Qinna M, Margane A, Aljazzar T (2009) Spatial assessment of salinity and nitrate pollution in Amman Zarqa Basin: a case study. Environ Earth Sci 59(1):117–129. doi:10.1007/s12665-009-0010-z

Al-Adamat R, Diabat A, Shatnawi G (2010) Combining GIS with multicriteria decision making for siting water harvesting ponds in northern Jordan. J Arid Environ 74(11):1471–1477. doi:10.1016/j.jaridenv.2010.07.001

Al-Kharabsheh A (1995) Possibilities of artificial groundwater recharge in the Azraq Basin: potential surface water utilization of five representative catchment areas (Jordan). PhD Thesis, Selbstverlag des Lehr- u. Forschungsbereichs Hydrologie und Umwelt am Institut für Geologie, Würzburg, Germany

Al-Khatib MAMM (1999) Development of a groundwater model for the two upper aquifers (shallow and middle) of the Azraq basin, MSc Thesis, Jordan University of Science and Technology, Amman, Jordan

Allison RJ, Higgitt DL, Kirk AJ, Warburtoon J, Al-Homoud AS, Sunna BF, White K (1998) Geology, geomorphology, hydrology, groundwater and physical resources. In: Dutton RW, Clarke JI, Battikhi AM (eds) Arid land resources and their management: Jordan's desert margin. Kegan Paul, London, pp 21–44

Alraggad MM (2009) GIS-based groundwater modeling and hydrogeochemical assessment of the northern part of the Dead Sea groundwater basin: a tool for groundwater management. PhD Thesis, University of Jordan, Amman, Jordan

Alraggad M, Jasem H (2010) Managed aquifer recharge (MAR) through surface infiltration in the Azraq basin/Jordan. J Water Resour Prot 2(12):1057–1070. doi:10.4236/jwarp.2010.212125

Bender F (1974) Geology of Jordan. Bornträger, Berlin

Borgstedt A, Margane A, Subah A, Hajali Z, Almomani T, Khalifa N, Jaber A, Hamdan I (2007) Delineation of groundwater protection zones for the Corridor wellfield. Technical report no. 8, Federal Institute for Geosciences and Natural Resources, Amman, Jordan

Bouwer H (1996) Issues in artificial recharge. Water Sci Tech 33(10–11): 381–390. doi:10.1016/0273-1223(96)00441-6

CGWB (2000) Guide on artificial recharge to ground water. Central Ground Water Board, Ministry of Water Resources, New Delhi

CGWB (2002) Master plan for artificial recharge of ground water. Central Ground Water Board, Ministry of Water Resources, New Delhi

CGWB (2007) Manual on artificial recharge of ground water. Central Ground Water Board, Ministry of Water Resources, New Delhi

Chowdhury A, Jha M, Chowdary V (2010) Delineation of groundwater recharge zones and identification of artificial recharge sites in West Medinipur district, West Bengal, using RS, GIS and MCDM techniques. Environ Earth Sci 59(6):1209–1222. doi:10.1007/s12665-009-0110-9

De Laat P, Nonner J (2011) Artificial recharge with surface water: a pilot project in Wadi Madoneh, Jordan. Environ Earth Sci 65(4):1251–1263. doi:10.1007/s12665-011-1372-6

Dillon P, Toze S (2005) Water quality improvements during aquifer storage and recovery, vol 1. Water Quality Improvements Processes, CSIRO Land and Water, Australia

El-Naqa A, Al-Momani M, Kilani S, Hammouri N (2007) Groundwater deterioration of shallow groundwater aquifers due to overexploitation in northeast Jordan. Clean Soil Air Water 35(2):156–166. doi:10.1002/clen.200700012

Fröhlich K, Geyh MA, Verhagen BT, Wirth K (1987) Das Azraq-Gebiet, Jordanien. In: Isotopenhydrologische Methoden zur Begutachtung von Grundwasser in Trockengebieten: Entwicklung eines Instrumentariums für die Beurteilung gefährdeter Vorkommen [The Azraq Area, Jordan. In: Isotope hydrological methods for assessing groundwater in arid regions: development of an instrument for the evaluation of vulnerable resources]. Weltforum, Cologne, Germany, pp 29–44

Gale IN, Neumann I, Calow RC, Moench H (2002) The effectiveness of artificial recharge of groundwater: a review. Great Britain, British Geological Survey commissioned report, CR/02/108N, BGS, Keyworth, UK

Gale IN, Macdonald DMJ, Calow RC, Neumann I, Moench M, Kulkarni H, Mudrakartha S, Palanisami K (2006) Managed aquifer recharge: an assessment of its role and effectiveness in watershed management. Final report for DFID KAR project R8169, Augmenting Groundwater Resources by Artificial Recharge, BGS, Keyworth, UK. http://nora.nerc.ac.uk/7453/. Accessed 7 Feb 2012

Haimerl G (2004) Groundwater recharge in Wadi channels downstream of dams. PhD Thesis, Berichte des Lehrstuhls und der Versuchsanstalt für Wasserbau und Wasserwirtschaft, no. 99, TU München, München

Hammouri N, El-Naqa A (2007) Drought assessment using GIS and remote sensing in Amman-Zarqa Basin, Jordan. Jordan J Civ Eng 1(2):142–152

Hobler M, Margane A, Almomani M, Subah A (2001) Groundwater resources of Northern Jordan, vol 4. Contributions to the hydrogeology of Northern Jordan, Federal Institute for Geosciences and Natural Resources, Amman, Jordan

HTS (Hunting Technical Services Ltd.), SSLRC (Soil Survey and Land Research Centre) (1993) The soils of Jordan. Level 1 Reconnaissance Soil Survey, National Soil Map and Land use Project, Ministry of Agriculture, Amman, Jordan

Huisman L, Olsthoorn TN (1983) Artificial groundwater recharge. Pitman, Boston, MA

Ibrahim KM (1993) Geological framework for the Harrat As-Shaam Basaltic Supergroup and its volcanotectonic evolution. Natural Resources Authority, Amman, Jordan

Ibrahim KM (1996) The regional geology of Al Azraq area. Map sheet no. 3553 I, Ministry of Energy and Mineral Resources, Natural Resources Authority, Amman, Jordan

Izbicki JA, Flint AL, Stamos CL (2008) Artificial recharge through a thick, heterogeneous unsaturated zone. Ground Water 46(3):475–488. doi:10.1111/j.1745-6584.2007.00406.x

Jasrotia AS, Kumar R, Saraf AK (2007) Delineation of groundwater recharge sites using integrated remote sensing and GIS in Jammu district, India. Int J Remote Sens 28(22):5019–5036. doi:10.1080/014311698215018

Kalantari N, Rangzan K, Thigale S, Rahimi M (2010) Site selection and cost-benefit analysis for artificial recharge in the Baghmalek Plain, Khuzestan Province, southwest Iran. Hydrogeol J 18(3):761–773. doi:10.1007/s10040-009-0552-x

Kunstmann H, Suppan P, Heckl A, Rimmer A (2007) Regional climate change in the Middle East and impact on hydrology in the Upper Jordan catchment. In: Quantification and reduction of predictive uncertainty for sustainable water resources management 1 (Proceedings of Symposium HS2004 at IUGG2007, Perugia, Italy, July 2007), IAHS, Wallingford, UK, pp 141–149

Lloyd JW (1986) A review of aridity and groundwater. Hydrol Process 1(1):63–78. doi:10.1002/hyp.3360010107

Machiwal D, Jha MK, Mal BC (2011) Assessment of groundwater potential in a semi-arid region of India using remote sensing, GIS and MCDM techniques. Water Resour Manag 25(5):1359–1386. doi:10.1007/s11269-010-9749-y

Malczewski J (2006) GIS-based multicriteria decision analysis: a survey of the literature. Int J Geogr Inf Sci 20(7):703–726. doi:10.1080/13658810600661508

Margane A, Hobler M, Almomani M, Subah A (2002) Contributions to the hydrogeology of northern and central Jordan. Geologisches Jahrbuch, Reihe C, vol 68, Schweizerbart, Stuttgart, Germany

Mesnil A, Habjoka N (2012) The Azraq dilemma: past, present and future groundwater management. Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Jordanian Ministry of Water and Irrigation (MWI), Amman, Jordan

MWI (2009) Water for life. Jordan's water strategy 2008–2022. Ministry for Water and Irrigation, Amman, Jordan

MWI-BGR (2011) Water resources protection guideline no. 5106. Prime Ministry of Jordan, Amman, Jordan

Natural Resource Management Ministerial Council (NRMMC), Environment Protection and Heritage Council (EPHC) and National Health and Medical Research Council (NHMRC) (2009) Australian guidelines for water recycling: managing health and environmental risks (phase 2): managed aquifer recharge. National Water Quality Management Strategy, Document no. 24, NRMMC, EPHC, NHMRC, Canberra, Australia

Obeidat A, Abu Muheisin N (1989) Hydrometeorological data. Water year 1987/88 for Zarqa River Basin Project. Internal report, Water Authority of Jordan, Ministry of Agriculture, Amman, Jordan

Otova T, Ayed R, Condar E (1989a) Azraq basin water resources study. Draft final report. The North Jordan Water Resources Investigations Project Staff, Amman, Jordan

Otova T, Saad A, El Khaid S (1989b) Amman-Zarqa basin water resources study. Draft final report. The North Jordan Water Resources Investigations Project Staff, Amman, Jordan

Powell JH (1989) Stratigraphy and sedimentation of the Phanerozoic rocks in Central and South Jordan, part B: Kurnub, Ajlun and Belqa Groups, vol 11. National Resource Authority, Amman, Jordan

Rapp M (2008) Evaluation of potential sites for managed aquifer recharge via surface infiltration in NW-Jordan. Diploma Thesis, Part A, Universität Karlsruhe (TH), Karlsruhe, Germany

RJGC (2011) Land cover map of Jordan. Royal Jordanian Geographic Center, Amman. http://www.rjgc.gov.jo/RJGImages.aspx?lang=en&IID=9#!prettyPhoto[gallery1]/0/. Accessed 17 Apr 2012

Scanlon BR, Keese KE, Flint AL, Flint LE, Gaye CB, Edmunds WM, Simmers I (2006) Global synthesis of groundwater recharge in semiarid and arid regions. Hydrol Process 20:3335–3370. doi:10.1002/hyp.6335

Schuh WM (1990) Seasonal variation of clogging of an artificial recharge basin in a northern climate. J Hydrol 121(104):193–215. doi:10.1016/0022-1694(90)90232-m

Sharda VN, Kurothe RS, Sena DR, Pande VC, Tiwari SP (2006) Estimation of groundwater recharge from water storage structures in a semi-arid climate of India. J Hydrol 329(1–2):224–243. doi:10.1016/j.jhydrol.2006.02.015

Shatnawi A (2012) Siltation of Alghadeer Alabyadh reservoir. Jordan J Civ Eng 6(1):28–38

Smiatek G, Kunstmann H, Heckl A (2011) High-resolution climate change simulations for the Jordan River area. J Geophys Res-Atmos 116:D16111. doi:10.1029/2010JD015313

Steinel A (2012) Guideline for assessment and implementation of Managed Aquifer Recharge (MAR) in (semi-)arid regions. Pre-feasibility study for infiltration of floodwater in the Amman-Zarqa and Azraq basins, Jordan. Final technical report, Federal Institute for Geosciences and Natural Resources, Hannover, Germany. http://www.bgr.bund.de/EN/Themen/Wasser/Projekte/abgeschlossen/TZ/Jordanien/mar_guideline_part1.pdf;jsessionid=DACFADC6027A57EBE8E2388FADFE61C5.1_cid284?__blob=publicationFile&v=7. Accessed 15 Mar 2013

Sukhija BS, Reddy DV, Nandakumar MV, Rama (1997) A method for evaluation of artificial recharge through percolation tanks using environmental chloride. Ground Water 35(1):161–165. doi:10.1111/j.1745-6584.1997.tb00071.x

UNDP (1992) World atlas of desertification. Arnold, London

USDA-SCS (1985) National engineering handbook, section 4: hydrology. USDA-SCS, Washington, DC

USGS (2008) HydroSHEDS – data sources. http://hydrosheds.cr.usgs.gov/datasource.php. Accessed 2 May 2012

Youngs EG (1991) Infiltration measurements: a review. Hydrol Process 5(3):309–319. doi:10.1002/hyp.3360050311

Zeelie S (2002) Omdel Dam and recharge ponds to enhance recharge in Namib Desert. In: Dillon PJ (ed) Management of aquifer recharge for sustainability. Balkema, Dordrecht, The Netherlands, pp 387–392

Ziadat FM, Taimeh AY, Hattar BI (2010) Variation of soil physical properties and moisture content along toposequences in the arid to semi-arid area. Arid Land Res Manag 24(2):81–97. doi:10.1080/15324981003635396