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

Hannover, Dec. 2012

HASHEMITE KINGDOM of JORDAN
Ministry of Water and Irrigation

BGR Bundesanstalt für Geowissenschaften und Rohstoffe

On behalf of:

BMZ Federal Ministry for Economic Cooperation and Development

FINAL REPORT

Guideline for assessment and implementation of Managed Aquifer Recharge (MAR) in (semi-)arid regions

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German-Jordanian Technical Cooperation, GeoSFF Study

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Summary

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Title: 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

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In (semi-)arid regions available water resources are scarce and commonly overused necessitating the need to look for unconventional water resources or for better use of available resources. Managed aquifer recharge (MAR) of floodwaters has been practiced internationally and in Jordan and can be successful if undertaken properly (e.g. proper siting, operation and maintenance as well as monitoring and reporting). General technical and socio-economic questions are addressed in the report as well as specific issues relating to Jordan.

A MAR potential map addressing water availability and site suitability has been developed for two surface water basins in Jordan. The evaluation of existing data and experiences from existing structures showed that source water availability is the most restricting factor in regions with less than 200 mm/a rainfall. Another important restriction is the high sediment load of the runoff waters requiring regular maintenance. If maintenance is not undertaken, the effectiveness of MAR schemes can decrease dramatically to the point where they result in an overall negative impact. It is recommended to improve operation and maintenance as well as monitoring at existing MAR sites in Jordan to be able to assess the actual effectiveness and to increase the involvement of the local community in MAR activities.

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Foreword

This report is the output of a short term (1.9.2011 – 31.12.2012) bilateral German – Jordanian technical cooperation project funded by the GeoSFF (Study and expert fund for geoscientific sector schemes) of the BMZ. In this study, the BGR supported the Jordanian Ministry of Water and Irrigation (MWI) in its potential to successfully use managed aquifer recharge via infiltration of stormwater runoff and its work in selecting suitable recharge sites by exemplarily evaluating the potential for MAR in two basins (Amman-Zarqa and Azraq basins). The main tasks comprised (1) the development of a map for MAR potential leading to the subsequent identification of suitable sites for potential pilot projects or measures to increase recharge effectiveness from existing structures and (2) the preparation of a guideline for the implementation and regulations of MAR in (semi-)arid regions like Jordan.

This guideline was prepared for decision makers, funding agencies, interested stakeholders and the scientific community involved with managed aquifer recharge in (semi-)arid regions. Part I contains a literature review with international examples addressing technical requirements and investigations as well as aspects of implementation and regulations. Part II describes the situation in Jordan with focus on two basins. The more technical chapters 10 and 11 illustrate the available data and demonstrate the development of a MAR potential map. The following chapters describe steps for further implementation and discuss socio-economic aspects relevant for Jordan leading to final recommendations (chapter 16) mainly for the MWI, but they might be applicable for other countries as well.

In this report, the term guideline is used in the sense of recommendation or orientation guide but not in the sense of a legally binding directive, regulation or policy (unless it refers to an international regulation document called 'guideline'). However, it would be highly recommended to use this report as starting point for discussion leading to the development of a policy and/or by-law for MAR in Jordan.

This guideline could be used to transfer the MAR mapping method to other promising basins within Jordan or other countries. Catchments that are recognised to be of future potential for water harvesting for groundwater recharge could be set aside in the land use planning to prevent further development. If these catchments become groundwater protection zones even before a MAR scheme is implemented, it could allow for high runoff water quality in the years to come.

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Abbreviations, acronyms and units

Units and symbols used (SI units of metric system and chemical symbols not listed)

a	annum = year
bar	unit of pressure; 1 bar = 10^5 Pa
BCM	billion cubic meters = 10^9 m³
°C	degree Celsius
CFU	colony forming units
d	day
D_{xx}	xx percentile diameter, e.g. D_{50} = median diameter
ha	hectare; 1 ha = 100 m²
h	hour; 1 h = 3600 s
inch	1 inch = 0.0254 m
JD	Jordanian Dinar (equivalent to about 1.07 € or 1.41 US$ on 19.10.2012)
Kf	hydraulic conductivity
L	litre; 1 L = 10^{-3} m³
m asl	meter above sea level
m bgl	meter below ground level
MCM	million cubic meter = 10^6 m³
meq	milli(molar)equivalent; e.g. 1 meq = 1 mmol for monovalent ions, 1 meq = 0.5 mmol for divalent ions
mg	milligram; 1 mg = 10^{-6} kg
min	minute; 1 min = 60 s
mm	millimetre
MPN	most probable number
NTU	nephelometric turbidity unit (turbidity measurement unit)
P	precipitation
PBE	Palestine Belt Easting
PBN	Palestine Belt Northing
pF	decimal cologarithm of soil water content; pF 1 = -10 hPa, pF 2 = -100 hPa
Q	runoff
µS/cm	microsiemens per centimetre (unit for electrical conductivity); 1 µS/cm = 10^{-4} S/m
S	potential maximum soil moisture retention after runoff begins

Abbreviations

avg.	average
coeff.	coefficient
et al.	et alii = and others
Fig.	figure
gw	groundwater
max.	maximum
min.	minimum
Mio.	million (10^6)
p.	page
temp.	temperature

General acronyms

AF	aridity factor
AHP	analytical hierarchy procedure
ASR	aquifer storage and recovery
ASTER	advanced spaceborne thermal emission and reflection radiometer
ASTR	aquifer storage, transport and recovery
AWC	average water holding capacity
CEC	cation exchange capacity
CN	curve number
CROPWAT	crop water and irrigation requirements program

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DAFF	dissolved air flotation and filtration
DEM	digital elevation model
DO	dissolved oxygen
DPSIT	driver, pressure, state, impact and response
E.coli	*Escherichia coli*
EC	electrical conductivity
GAC	granular activated carbon filtration
GCM	global climate model
GSD	grain size distribution
GWD	Groundwater Directive (Directive 2006/118/EC of the European Parliament and the Council)
HACCP	hazard analysis critical control point
IPCC	Intergovernmental Panel on Climate Change
LAI	leaf area index
MABIA	MAîtrise des Besoins d'Irrigation en Agriculture (Control of Agriculture Irrigation needs)
MAR	managed aquifer recharge
MF	microfiltration
MFI	modified fouling index
MTBE	methyl *tert*-butyl ether = $(CH_3)_3COCH_3$
NDVI	normalised difference vegetation index
O&M	operation and maintenance
RO	reverse osmosis
RRMT	Rainfall-Runoff Modelling Toolbox
SAR	sodium adsorption ratio
SAT	soil aquifer treatment
SRTM	shuttle radar topography mission
SWAP	Soil Water Atmosphere Plant
TDS	total dissolved solids
T-N	total nitrogen
TOC	total organic carbon
TRMM	tropical rainfall measuring mission
TSS	total suspended solids
WEAP	Water Evaluation and Planning System
WFD	Water Framework Directive (Directive 2000/60/EC of the European Parliament and the Council)
WWTP	wastewater treatment plant
XRD	X-ray diffraction

Specific abbreviations and acronyms

A1/2	Na'ur formation (Ajlun group)
A3	Fuheis formation (Ajlun group)
A4	Hummar formation (Ajlun group)
A5/6	Shueib formation (Ajlun group)
A7	Wadi Es Sir formation (Ajlun group)
AL	code of MWI for Amman-Zarqa basin
AMZ	Amman-Zarqa
B1	Wadi Umm Ghudran formation (Belqa group)
B2	Amman formation (Belqa group)
B3	Muwaqqar formation (Belqa group)
B4	Umm Rijam formation (Belqa group)
B5	Wadi Shallala formation (Belqa group)
CD	code of MWI for Mujib basin
F	code of MWI for Azraq basin
JS	Jordanian Standard

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K	Kurnub group
S	code for Syrian rainfall stations
(R)WH	(rain) water harvesting
W.	Wadi
WDC	Water Document Center (of WAJ)
WIS	water information system (of MWI)
Z	Zarqa group

Institutions, organisations, consultants and programs

ACSAD	Arab Center for the Studies of Arid Zones and Dry Lands
ADB	Asian Development Bank
AFD	French Development Agency (Agence Française de Développement)
AHT	Agrar- and Hydrotechnik GmbH, Germany
AMHC	Australian Health Ministers' Conference
ANZECC	Australian and New Zealand Environment and Conservation Council
Arabtech CE	Arabtech Consulting Engineers, Jordan
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
ASCE	American Society of Civil Engineers
BGR	Federal Institute for Geosciences and Natural Resources, Germany
BMZ	Ministry of Economic Cooperation and Development, Germany
CDPH	California Department of Public Health, USA
CES	Consulting Engineers Salzgitter, Germany
CGWB	Central Ground Water Board, India
DoM	Department of Meteorology. Jordan
DoS	Department of Statistics, Jordan
DWA	Department of Water Affairs, Namibia
EPHC	Environment Protection and Heritage Council, Australia
GIZ	German Agency for International Cooperation (Deutsche Gesellschaft für Internationale Zusammenarbeit
GTZ	German Agency for Technical Cooperation (Deutsche Gesellschaft für Technische Zusammenarbeit); now merged into the GIZ
HTS	Hunting Technical Services Ltd., Canada
IETC	International Environmental Technology Centre, Japan; branch of UNEP
IGRAC	International Groundwater Resources Assessment Centre, The Netherlands
IUCN	International Union for Conservation of Nature, Switzerland
JCE	Jordanian Consulting Engineers
JICA	Japan International Cooperation Agency
JISM	Jordanian Institute for Standards and Metrology
JVA	Jordan Valley Authority
MIWR	Ministries of Irrigation and Water Resource of the Government of National Unity (GoNU), Sudan
MoA	Ministry of Agriculture, Jordan
MoMA	Ministry of Municipal Affairs, Jordan
MWI	Ministry of Water and Irrigation, Jordan
MWRI	Ministry of Water Resources and Irrigation of the Government of Southern Sudan (GOSS):
NCARE	National Center for Agricultural Research and Extension
NGO	non-governmental organisation
NHMRC	National Health and Medical Research Council, Australia
NRA	Natural Resources Authority, Jordan
NRC	National Research Council, USA
NRMMC	Natural Resource Management Ministerial Council, Australia
OCWP	Oklahoma Comprehensive Water Plan
ODA	Overseas Development Administration, UK; now DFID (Department for International Development)
Orient ECD	Orient Engineering Consultancy and Design, Jordan

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RAIN foundation	Rainwater Harvesting Implementation Network foundation
RJGC	Royal Jordanian Geographic Center
SAIC	Science Applications International Corporation, USA
SSLRC	Soil Survey and Land Research Centre, Jordan
TECHNEAU	Technology Enabled Universal Access to Safe Water
TEEB	The Economics of Ecosystems and Biodiversity
UFZ	Helmholtz Centre for Environmental Research, Germany
UNDP	United Nations Development Programme
UNEP-DTIE	United Nations Environment Programme - Division of Technology, Industry and Economics
UN-ESCWA	United Nations Economic and Social Commission for Western Asia
US EPA	United States Environmental Protection Agency, USA
USDA-SCS	United States Department of Agriculture - Soil Conservation Service, USA
USGS	Unites States Geological Survey, USA
WAJ	Water Authority of Jordan
WHO	World Health Organisation

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Glossary

Arabic words

hafir	in Jordan the term 'mahafir' or 'hafir' is used for crescent and rectangular shaped excavations dug into the playa surface for water harvesting and storage; in Sudan it is a local name for a water reservoir dug in the ground designed to store water runoff after a rainy season
marab	flat or slightly sloping depression with clayey sediments fed and drained by wadis, seldom saline
playa	flat depression with no outflow periodically fills with runoff to form a temporary lake; also known as qaa
qaa	very extensive flat depression with clay surface without outflow fills with runoff to form a temporary lake, often saline; word used in Jordan
shabkhas	salt flat either supratidal (inundated by very high tides) or fed by salty groundwater; word used on the Arabian Peninsula
takyr	flat or slightly sloping dense clay surfaces, which act as natural catchment areas; similar to qaa; word used in Turkmenistan
wadi	valley; it commonly refers to a dry (ephemeral) riverbed that contains water only during times of heavy rain

other definitions

artificial recharge	recharge of groundwater encompassing unintentional recharge (e.g. from leaking network pipes, irrigation return flow, land use changes) and unmanaged recharge; in older publications and in Arabic countries often used interchangeably with managed aquifer recharge
guideline	for this report the term is used in the sense of recommended practices or procedures; in other circumstances the term is also used in the sense of a legally binding directive, by-law or policy
hydraulic conductivity	also called permeability, describes the rate at which a fluid can move through the pores/fractures of an layer; depends on the effective porosity, degree of saturation, viscosity of the fluid, and varies largely with direction
managed aquifer recharge (MAR)	intentional recharge of groundwater for recovery or environmental purposes including the monitoring of recharge water quality and resulting impacts
pedo-transfer function	predictive function for certain soil properties based on easily measurable other soil properties filling the gap between available soil data and required soil data
rainwater harvesting	commonly and in this report used for harvesting of roof runoff with subsequent storage in rainwater tanks; in Arabic countries also used for surface water harvesting and might include the leakage from storage dams to the groundwater
transmission loss	drop in hydrograph and flood volume during downstream movement mainly due to infiltration of runoff during flow in the wadi channel and bank storage
transmissivity	describes the quantity of water transported horizontally through the aquifer; product of hydraulic conductivity and saturated thickness summed up over all layers of the aquifer; commonly measured with pumping tests

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Extended Summary

The first part of this report outlines international examples and it reviews some lessons learned and steps to be taken for a sustainable MAR scheme implementation, thus providing a guideline for MAR projects. The second part is a case study on two heavily overabstracted watersheds in Jordan, the Amman-Zarqa and Azraq basins. Here, the climatic, hydrological, hydrogeological and other factors potential are described in detail and used as criteria in a pre-feasibility study on their MAR. This is followed by recommendations for a feasibility study, implementation and necessary activities afterwards. To guide the reader, crucial statements of each section are summarised in grey boxes. Blue boxes illustrate special topics in more detail, while orange boxes are direct citations emphasising existing vital knowledge.

Managed aquifer recharge (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 sewage etc.) and with different recharge methods (e.g. infiltration, injection). This report focuses mainly on the retention of flood water in ephemeral streams followed by recharge via infiltration.

Any pre-feasibility study should answer the main **technical questions** about:

 (a) **Source water availability**: In (semi-)arid regions, rainfall is sparse and often occurs in short intense events leading flood flows for only a few hours or days per year in otherwise dry wadis. This hinders effective harvesting of source water. Arid regions (<200 mm) commonly do not produce sufficient runoff for economic harvesting (see section 2.6). Furthermore, water is frequently already committed for use and upstream harvesting leads only to a reallocation of water but does not generate additional water resources. 'Use' also encompasses environmental demand as ephemeral wadis usually sustain the only vegetation and habitat in arid regions. MAR is only beneficial if water is captured that would otherwise be evaporating or running off unused without being adequately recharged to an aquifer. Climate change may have a significant impact on source water availability and should thus be taken into consideration in the feasibility assessment.

 (b) **Aquifer storage space**: A suitable aquifer with sufficient storage capacity is usually available in areas suffering from overabstraction and groundwater level declines. However, underground storage space alone is not sufficient, if other prerequisites are not fulfilled.

 (c) **Effectiveness of transfer of source 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 possess crusts or get clogged with fine sediments contained in the floodwater. Regular maintenance and monitoring is needed to prevent the creation of an evaporation pond instead of a recharge scheme. A second barrier could be an impermeable layer in the unsaturated zone that does not permit sufficient percolation down to the aquifer. These natural heterogeneities are usually not known in detail and can severely reduce recovery efficiency.

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Another vital aspect is the choice of the most appropriate **technique**. For semi-arid regions with high sediment loads in wadi runoff, recharge release dams are more effective than recharge dams and low cost surface infiltration is preferred over infiltration or injection wells.

In addition a range of **socio-economic questions** should be addressed:

(d) **Demand**: Usually there is a clear demand for groundwater recharge, as groundwater is commonly the only reliable water source in (semi-)arid regions and is often overabstracted. However, if recovery is intended for agricultural reuse, which is heavily subsidized or provided free of charge, revenues might be lower than invested capital. Also, MAR schemes may encourage investment in even more unsustainable agricultural activities as now more water seems available in an area. It would thus intensify the problem of unsustainable water use, while demand reduction management would be necessary instead.

(e) **O&M**: The success of any recharge scheme depends on a proper operation and maintenance (O&M). Especially clogging management is of utmost importance. If funding or labour is not available for this activity, MAR schemes should not be implemented.

(f) **Monitoring**: Monitoring is vital to assess the effectiveness of a MAR scheme and to make the right management decisions. Especially pilot projects in a new region should be monitored well to improve schemes during up-scaling or to help decide that up-scaling is not feasible. It is important to establish solid baseline monitoring for a comparison of the situation before and after implementation. MAR schemes may cause unwanted changes in the unsaturated zone or aquifer. Therefore, monitoring of water quality at both, source water and aquifer, must be an integral part of the program. Monitoring requires additional funding (and staff) which must be part of any proposed MAR scheme.

(g) **Economics**: An economic analysis has to incorporate all costs and benefits over the lifetime of a scheme including indirect and downstream impacts. Depending on the source water quality and volume as well as recharge methods, the pre-treatment required might exceed the benefits of the scheme. Such projects should not be executed. Implementation of schemes should also not be considered, if management capabilities and funding are insufficient to guarantee a proper maintenance and monitoring.

(h) **Institutions and management capability**: The most sustainable MAR schemes worldwide are either highly sophisticated, well monitored schemes undertaken by government or water suppliers in developed countries or are small scale, low technology schemes in developing countries undertaken in a decentralised participatory approach involving local stakeholders.

For the **Jordanian case study,** two assessments (each comprising a constraint and a subsequent suitability map) were undertaken to determine feasibility:

    a) the ability of the <u>catchment</u> to generate suitable runoff, and

    b) the ability of a <u>site</u> to harvest and transfer this resource to the aquifer.

The **catchment** constraint mapping was based on the minimum criteria of 75 mm rainfall, the absence of existing large dams and the absence of urban areas, mudflats or quarries. The following catchment suitability mapping assessed the potential for runoff generation based on

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rainfall, slope, existing water harvesting structures, soil, hydrogeology and land use. 69 % of the total area located in the Jordanian part of the two basins (parts of the watershed is actually located in Syria) are unsuitable due to catchment constraints. Only 3 % of the area scored more than 67 % of potential full score for suitability (see section 11.3 for details), 25 % of the area scored between 33 - 67 % and 3 % of the area scored less than 33 %. The most suitable sites are found downstream of the largest dam (King Talal) and not in the highlands, where the water demand is highest.

The **site** constraint mapping was based on the same minimum criteria as the catchment constraint map plus the additional criteria of slope <5 % for infiltration (either in the wadi downstream of the dam or in infiltration basins), absence of aquitard, aquifer thickness >20 m, saturated aquifer, distance to contaminated well >1 km, distance to international border >2 km, distance to wadi <2 km, and catchment size >18 km². The following site suitability assessment was based on rainfall, slope, existing water harvesting structures, soil, hydrogeology, land use, aquifer thickness, depth to water table, hydraulic gradient, groundwater salinity and distance to faults, roads, governmental production wells and contaminated wells. About 88 % of the total area located in the Jordanian part of the two basins is unsuitable due to site constraints. In terms of site suitability, 3.5 % of the area score between 50 - 67 % of a possible 100 % full score, 8.6 % of the area score 67 - 83 % and only 0.4 % of the area score >83 %.

The assessment of catchment and site suitability showed that the main technical constraints in Jordan are the availability of non-committed surface runoff, impaired surface water quality due to high sediment loads and in some areas also hazards like animal farms, settlements or industry, as well as a deep groundwater table. Necessarily, this assessment contains a number of uncertainties mainly due to the limited availability and reliability of data especially concerning runoff quantity and quality, detailed lithological logs and filter depths, hydraulic conductivity, water levels, surface water usage and transmission losses.

The analysis of institutional and socio-economic constraints in Jordan showed that previous projects failed mainly due to a lack of funding for maintenance and monitoring. In addition, there is limited institutional capacity to manage MAR projects in all three institutions of the Ministry (MWI, WAJ, JVA). In none of the previous and mostly unsuccessful attempts to establish MAR sites in Jordan a participatory approach has been tried.

Based on this investigation, the potential for additional MAR schemes and their ability in resolving impacts from groundwater overabstraction seems limited. Demand reduction management measures would be more effective to mitigate the effects of regional groundwater overabstraction.

It is recommended to retrofit and rehabilitate existing sites into recharge release dams, to establish and fund maintenance procedures, to operate sites properly and to monitor existing sites to prove effectiveness. It is highly recommended to involve local stakeholders (e.g. tribal leaders, farmers, residents, nomad Bedouins, regional water authority personnel, NGO representatives) in this process and educate them about MAR schemes to increase local acceptance, decrease vandalism and potentially involve local beneficiaries in operation and maintenance of schemes.

Part I: Aspects for assessing MAR potential and site selection

Definition: Managed aquifer recharge is the intentional recharge of water to aquifers for subsequent recovery or environmental benefit assuring adequate protection of human health and the environment.

In this report the term 'managed aquifer recharge (MAR)' will be used for intentional recharge in contrast to the often used term 'artificial recharge', which encompasses also unintentional recharge (e.g. from leaking network pipes, irrigation return flow, land use changes) and unmanaged recharge, which is not focussed on recovery or environmental health (e.g. disposal of sewage, stormwater drainage wells) (NRMMC-EPHC-NHMRC, 2009b).

1 Introduction

(Semi-)arid regions 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 groundwater resources are used. As natural groundwater recharge is limited (commonly ranging between 0.1 - 5 % of long-term average precipitation) occurring mainly through indirect recharge in wadi beds (Scanlon et al., 2006), groundwater resources have been overused in many (semi-)arid countries resulting in a decline in groundwater tables. This can lead to drying up of springs and shallow wells, as well as ingression of saline waters (Miller, 2005). Further demand increases are expected due to population growth, and increase in living conditions. Further supply reductions are expected due to climate change and pollution of available sources. The consequences are an overall increase in costs for water supply (e.g. drilling of deeper wells, higher pumping lift, developing of new resources like water desalination or long distance transport of water) and deterioration of groundwater dependent ecosystems.

In combination with demand reductions and other management options, MAR can be an effective tool in reducing these negative impacts on a local scale. The main benefits of MAR in these regions are the availability of a large free storage space (which has been created by the overabstraction) and the reduction of problems associated with surface storage like evaporation losses, large space requirements, algal blooms and potential contamination (Asano, 1985; Pyne 1995). There is also the added benefit of natural attenuation of a range of pollutants during recharge and storage (Dillon and Toze, 2005).

The main pre-requisites for MAR are: (a) available non-committed water supply, (b) a suitable aquifer, and (c) an effective technique allowing the transfer of the water into the aquifer.

Apart from the problem of availability of non-committed water resources, implementation of MAR schemes could also be hindered by a lack of detailed hydrogeological knowledge, lack of well monitored projects providing long-term performance data, insufficient legislation and regulations as well as lack of experience and knowledge in the relevant authorities (Dillon, 2005; Hatt et al., 2006; Maliva et al., 2006). Especially if recovered water should be used for potable supply or aquifers with drinking water quality groundwater are used for storage, the long-term sustainability of MAR schemes has to be proven.

2 MAR techniques

MAR can be undertaken with a range of diverse source waters into several aquifer types using a variety of techniques, which will be selected depending on the site-specific conditions.

A number of publications give a general overview of MAR techniques and issues related to different sources of water (stormwater, treated wastewater, desalinated drinking water, river runoff etc.), hydrogeological set ups (unconfined or confined; porous or fractured/karstic) and operation (e.g. Asano, 1985; Pyne, 1995; ASCE, 2001; Bouwer, 2002; Gale et al., 2002a; Gale, 2005; Bouwer et al., 2008; NRC, 2008). This report will mainly focus on recharge of stormwater via infiltration, and only briefly introduce other options. Typical components of MAR projects are summarized in Fig. 1.

Water source	① Capture	② Water treatment before recharge	③ RECHARGE ④ AQUIFER STORAGE ⑤ RECOVERY	⑥ Post treatment	⑦ End use
Mains water	Tap into mains pipe	None or filter		Disinfection	Drinking water
Rain water	Tank	Filter		None	Industrial water
Stormwater	Wetland or basin	Wetland, MF, GAC		None	Irrigation
Reclaimed water	Pipe from water reclamation plant	DAFF, RO		None	Toilet flushing
Rural runoff	Wetland, basin or dam	Wetland		None	Sustaining ecosystems
A different aquifer	Pump from well	None			

Fig. 1: Typical sources of water, methods of capture and pre- and post-treatment for MAR (Dillon et al., 2009). All sources of water, in combination with the appropriate treatment, can be recovered from the aquifer for any end use. This applies for all methods of recharge (see Dillon, 2005). Note actual pre-treatments and post-treatments will be project-specific to achieve effective management of risks and clogging (MF is microfiltration, GAC is granular activated carbon filtration, DAFF is dissolved air flotation and filtration, RO is reverse osmosis).

2.1 Water source

Stormwater/Floodwater is highly variable and unpredictable in quantity. The quality is mainly impaired by high sediment loads leading to physical clogging and potentially also by hazardous substances (fuel, oil, wastewater).

> **Reclaimed wastewater is predictable and less heterogeneous in quantity. The quality is mainly impaired by nutrients, pathogens, TOC and salinity leading to biological clogging.**
>
> **Water quality of both sources can be improved with pre-treatment.**

A range of diverse water sources have been used for MAR, but the most common are surface water from base and/or flood flow and treated or reclaimed wastewater. The sources vary in their availability, volume and water quality. Source water quality might need to be treated depending on groundwater quality and reuse.

2.1.1 Stormwater or floodwater

In many (semi-)arid regions baseflow is usually limited or already committed for use. Commonly rivers are ephemeral and runoff is only generated when precipitation intensity and duration overcomes a certain threshold, usually in the range of 10 - 15 mm/d. Rainfall that does not generate runoff is attributed to evapotranspiration, soil moisture storage, direct recharge, transmission losses/indirect recharge or localised ponding (Lloyd, 1986). The highest percentage (around 80 - 95 %) of rainfall evaporates either directly from the surface or after the rainfall event out of the soil, from puddles or ponded water bodies. Direct recharge is negligible for regions with <200 mm/a of rainfall (Lloyd, 1986). Apart from rainfall characteristics, the most important parameters for runoff generation are land use including vegetation, slope, soil characteristics and antecedent moisture conditions (e.g. Chow, 1988; Anderson and Burt, 1990; Fetter, 2001). Sandy soils are limiting to water harvesting as their infiltration rate is high and hence runoff generation is limited (Practical Action, 2005). In general, runoff increases with changes in land cover from forest < pasture < cropland < bare soil < urban, while recharge decreases roughly in the same order when not accounting for irrigational return flows (van Steenbergen et al., 2011). Highest runoff rates will occur on bare soils with surface crusts or sealed surfaces and on steep slopes. Runoff can be separated in infiltration excess flow (Hortonian overland flow) and saturation excess flow. The former is more common in arid areas.

Due to their high variability and potentially destructive force, runoff of ephemeral rivers is seldom measured. If Stevens recorders are not placed correctly or the cross-section on which the rating curve is based is changed by scouring or sedimentation effects of floods, flow volumes can be over- or underestimated. Accordingly, runoff quantities are commonly modelled (see section 4.1).

Runoff quality is also highly variable depending mainly on land use and soil characteristics, but is commonly low in salinity (Eriksson et al., 2007). Rural runoff might be elevated in nutrients, pesticides and pathogens, while urban stormwater could also be elevated in heavy metal and organic contaminants (Makepeace et al., 1995; Pitt et al., 1999). Roof runoff contains the lowest levels of pollutants and is therefore the best source water especially if the first flush is diverted (Thomas and Greene, 1993; Zobrist et al., 2000). The main problem for water quality is the sediment load, as (a) many priority pollutants are not dissolved, but are attached to particles (e.g. Marsalek, 1991; Mikkelsen et al., 1994; Sansalone et al., 1995; Characklis et al., 2005) and (b) accumulation of sediments leads to physical clogging and an associated decrease in infiltration rates. Even if contaminant loads are low in sparsely populated areas, sediment loads are high as the vegetative cover is commonly sparse in arid

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region and soil erosion is a major problem. Common suspended loads of 350 - 5000 mg/L were measured in Namibia (Crerar et al., 1988). Total sediment loads including bed load varies between 1 - 5 % of total runoff volume (Shahin, 2007; van Steenbergen et al., 2011).

2.1.2   Reclaimed wastewater

If a WWTP is running properly, similar effluent quantities are supplied each day of the year. Variations between summer and winter could occur with changes in population numbers due to tourism and with changes in habits. However compared to stormwater, quantities are reasonably constant and predictable depending on the size of the WWTP. In (semi-)arid regions treated wastewater (or even untreated wastewater) is commonly used directly for agricultural use and might hence not be available for managed aquifer recharge, but will unintentionally add to groundwater recharge (McIlwaine and Redwood, 2010; Maliva et al., 2011).

Treated effluent quality is highly variable dependent on the source water (e.g. industrial or only domestic sewage) and the treatment processes applied, but is reasonably constant for one specific WWTP. Compared to stormwater it usually contains much higher amounts of nutrients, organic matter, trace organic contaminants (e.g. pharmaceutically active compounds, endocrine disrupting components) and dissolved solids, but lower values of suspended solids (Tredoux et al., 2002; Idelovitch et al., 2003). The presence of nutrients and organic carbon favours biological clogging (Rinck-Pfeiffer, 2000; Bahr et al., 2002; Pavelic et al., 2007). Organic matter and nutrients are also the major factor for changes in the redox state and associated reactions like degradation of organic contaminants or mineral dissolution/precipitation (Stumm and Morgan, 1996).

Recharge scheme can hence work all year round and operation can easily be designed to the available quantity and quality.

2.1.3   Other sources

In the USA most recharge schemes use water treated to drinking water quality (Asano, 1985; Pyne, 1995). The main quality issues here are the development of disinfection by-products during storage (McQuarrie and Carlson, 2003; Pyne, 2006) and potentially the dissolution of minerals resulting in elevated heavy metal and metalloid concentrations (Arthur et al., 2002; Bahr et al., 2002; Jones and Pichler, 2007).

Some Gulf countries are even considering aquifer recharge with desalinated sea water to create an emergency storage (Schott, 2010; Koziorowski, 2012). Due to the low mineralisation, mineral dissolution during storage might decrease water quality and impact on the stability of the aquifer (Johnson et al., 1999; Pavelic et al., 2006).

2.1.4   Treatment

If the source water is impaired in quality, a variety of treatment options are available. For the reduction of sediments in runoff it is advisable to build a number of retention structures in a row, so the upstream structures (pre-dams) can be used for settling and sediment retention. Silt traps or desilting basins can be installed before infiltration basins or between detention structures (Fig. 2). Further treatment could involve sand filters of variable design and pore

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size depending on sediment and water loads and required final sediment concentration (Fig. 3).
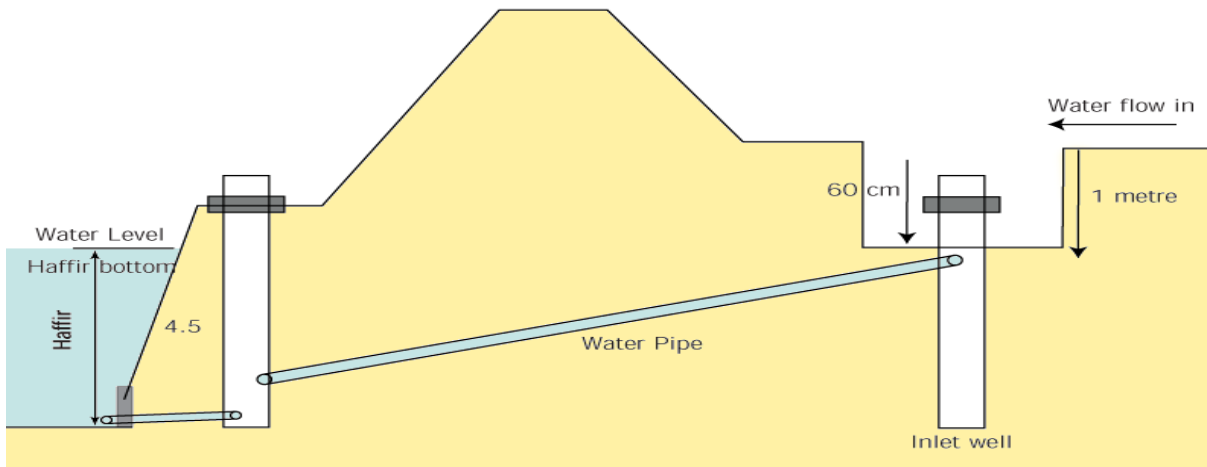
Fig. 2: Silt trap at the mouth of a hafir to reduce sediment input to the hafir (practicalaction.org).
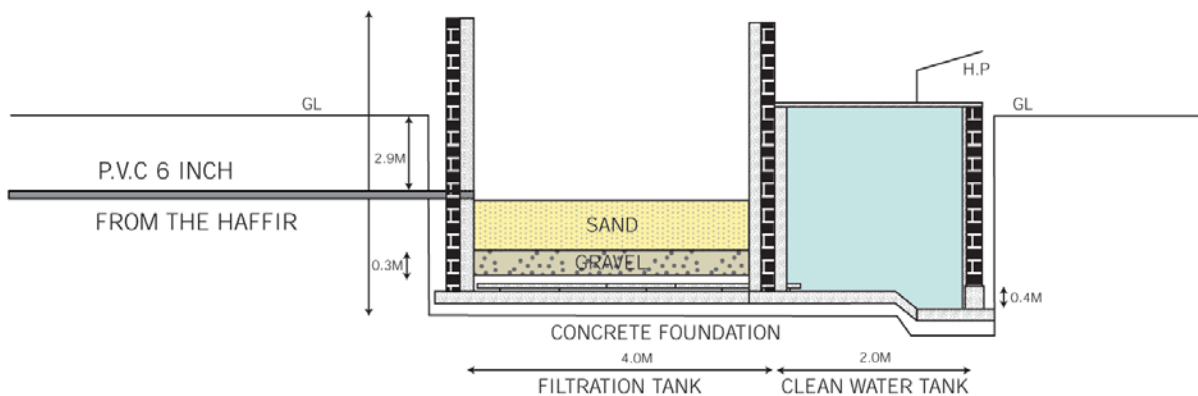
Fig. 3: Slow sand filter at the outlet of a hafir creating drinkable water (practicalaction.org).

For reclaimed wastewater the WWTP could be equipped with a further treatment step. Possible treatment options are wetlands, sand filters, activated sludge, flocculation, activated carbon filtration, disinfection etc. (e.g. US EPA, 1990; Tchobanoglous and Burton, 1991; Binnie et al., 2002; Crittenen et al., 2005).

2.2   Interception/harvesting techniques

> **Retention structures are needed to harvest available runoff water and should be designed based on estimated flood volumes or harvesting objectives.**
>
> **In (semi-)arid regions with high sediment loads settling facilities should be constructed.**

While treated wastewater arrives at the WWTP via the sewage network and might have to be transported from the WWTP to a suitable infiltration site, runoff needs to be harvested first. It is common practice in many (semi-)arid regions to construct either many very small scale structures or larger structures for the whole catchment built inside the runoff channel.

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2.2.1   In-channel modifications

Many different names and designs for in-channel modifications are being used worldwide e.g. check dam, gabion dams, dikes, earth dams, rock dams, water spreading weirs, hafirs (e.g. Hudson, 1987; Gale, 2005; Practical Action, 2005; van Steenbergen and Tuinhof., 2009; MIWR and MWRI, 2009; Stephens 2010; BMZ, 2012). (In the following text 'dam' will mostly be used as synonym to incorporate different kinds of retention/harvesting structures). They are placed across the channel to intercept runoff and detain the water in a reservoir behind the retention structure and can be built from different material including clay, earth, rocks, concrete. Depending on the size of the dam further structures like spillways, emergency release gates etc. might need to be constructed to prevent damage to the dam during large flood events (USDA-SCS, 1990; CGWB, 2000).

Where no suitable aquifers are available, sand storage dams can be constructed that allow the retention of bed load sediments, while suspended loads are flowing over the dam structure. With successive heightening of the dam wall, an alluvial aquifer for storage can be created behind the dam (Nissen-Petersen, 2006a; RAIN Foundation et al., 2009). Another special technique are subsurface or underground dams that can make use of shallow alluvial aquifer perched on the basement or aquitard that reach close to the surface. The subsurface dam hinders the shallow groundwater from flowing downstream (Nissen-Petersen, 2006a; Raju et al., 2006).
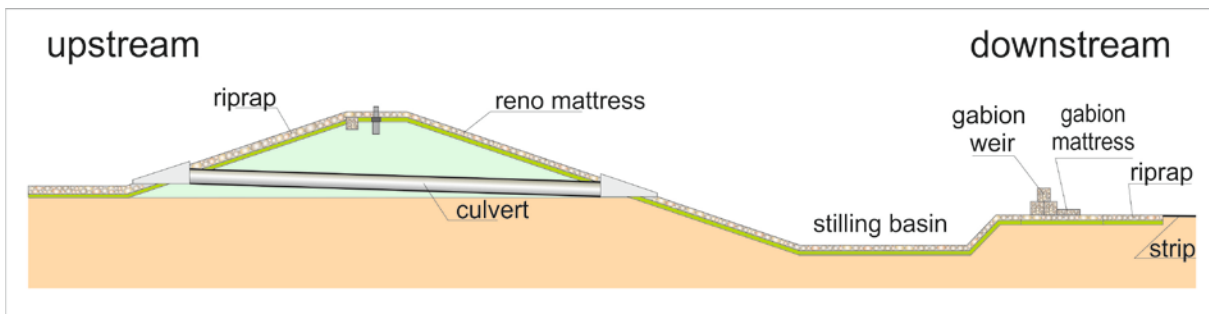
Fig. 4: Schematic design for Wadi Samail Flood Protection Dam. (after Omani Ministry of Regional Municipalities and Water Resources).
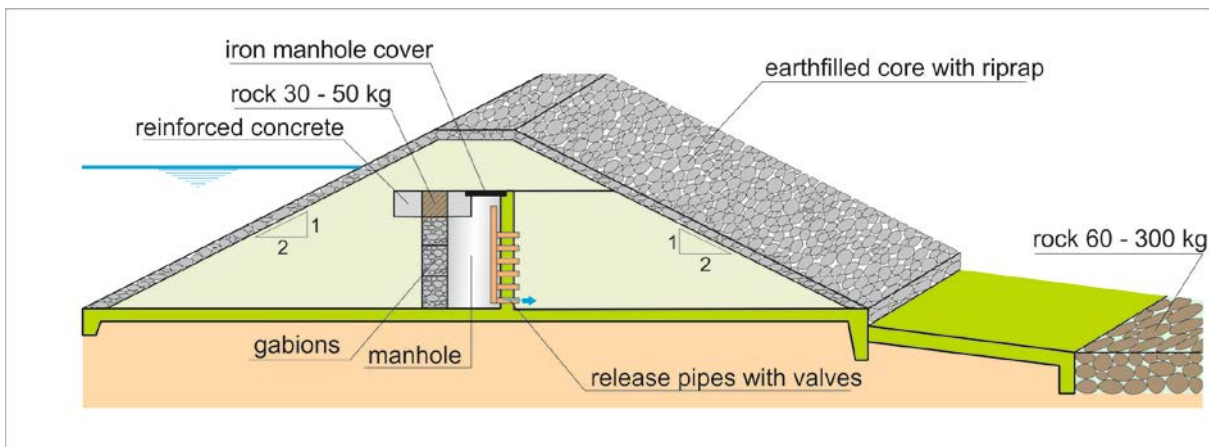
Fig. 5: Schematic cross section of the Madoneh recharge release dams (after de Laat and Nonner, 2011).

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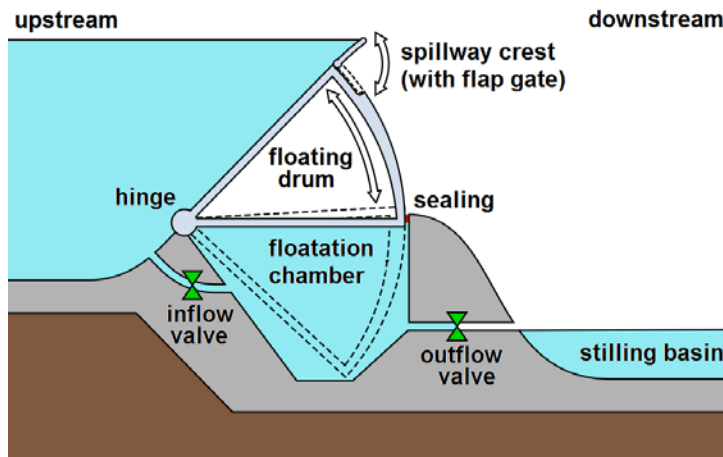
Fig. 6: Schematic cross section of a drum gate. Water is allowed in or out of the floatation chamber to adjust the dam's crest height.

Infiltration to the groundwater can occur directly from the dam reservoir (so-called percolation tanks or recharge dams), but due to high sediment loads it is preferable to release the water out of the retention structure for infiltration downstream. Various designs of recharge release dams are possible like simple culverts (example Oman, Fig. 4), release pipes with valves (example Wadi Madoneh, Jordan, Fig. 5) or weirs with moveable flap or drum gates (Fig. 6).

Water could also be released from the dam via pumps mounted on floating pontoons to extract water from the top of the water column, where sediment concentrations are lowest.

2.2.2   Rainwater harvesting

Runoff harvesting can also encompass many small scale harvesting structures commonly referred to as 'rainwater harvesting techniques'. Roof-top runoff can be harvested in rural and urban areas and directly be used at household level or for local aquifer recharge. Especially in urban areas, where runoff generation is increased through sealing of surfaces, runoff should be recharged to the groundwater. To prevent groundwater contamination suitable treatment has to be provided. Water sensitive urban design uses grass swales, wetlands, infiltration trenches, biofilters, filter strips etc (Barr Engineering Company, 2001; Hatt et al., 2006; Hatt et al., 2007).

Ground surface runoff collection from micro-catchments can be undertaken with barriers like earth bunds, terraces or ridges constructed from earthen material or rocks usually along the contour lines or with the creation of small depressions like trenches, ditches or pits (Boers et al., 1986; Hudson, 1987; Critchley and Siegert, 1991; Abu-Zreig, 2004; UNEP-DTIE-IETC sourcebooks). The main aim of these structures is the retention of soil moisture for plant growth rather than aquifer recharge and is hence also called dry land farming.

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2.3   Transfer techniques

> **Infiltration basins are suitable for unconfined aquifers and can handle low quality recharge water. Injection wells are needed for confined aquifers, but require high quality recharge water. Infiltration trenches/wells can be used if the surface layers are impermeable, but also require high quality recharge water as backflushing is not possible.**
>
> **In (semi-)arid regions with a harsh environment, sparse population, limited financial strength but abundant land availability, infiltration basins are the preferred method.**

If sufficient volumes of runoff can be harvested, water has to be transferred to the suitable aquifer. The choice of transfer technique depends on the hydrogeological conditions and can be categorised into surface spreading methods for unconfined aquifers and well injection for confined aquifers. Infiltration wells and trenches can be considered if there is an impermeable layer close to the surface (Table 1). The source water may be transferred by canals or pipelines from the surface water stream to the area where infiltration is most suitable.

2.3.1   Infiltration or spreading techniques

For unconfined aquifers, infiltration or spreading techniques are commonly used as they are the most cost-efficient and can handle the highest sediment loads. The prerequisites are a larger surface area with only gentle slopes (<5 %), soils with sufficient hydraulic conductivity, the absence of saline horizons and of impermeable layers between the surface and the groundwater table (Asano, 1985). Depth and size vary depending on hydraulic loads. Deeper basins are preferable as they make use of horizontal permeability as well as vertical permeability. The basin floor can be filled with gravel and sand media to increase hydraulic conductivity and prevent the penetration of fines into the deeper underground (Bouwer, 2002). Long narrow basins are more active than wide basins (Al-Kharabsheh, 1995).

Very shallow flooding over large areas is the opposite strategy to overcome potential clogging and requires slopes of 1 - 3 % (Asano, 1985). Conveyance spreader canals and level-silled channels can be used for providing an even thin sheet flow. While evaporation is significantly increased, flooded areas can be built up into fertile lands due to the accumulation of fines (van Steenbergen and Tuinhof, 2009).

The wadi channel downstream of the dam can be used for infiltration if the wadi sediments are permeable enough. The wetted area can be increased through smaller stream channel modification like dikes, berms, ditches, T-levees etc to decrease water velocity and spread the water over the whole wadi channel (Asano, 1985; Bouwer, 2002).

If the surface layer is impermeable or surface crusts are present over an unconfined aquifer, these layers can be overcome by constructing infiltration ditches, drains, seepage trenches, infiltration galleries or infiltration wells (also called vadose zone wells, dry wells, recharge tube wells or recharge shafts). Though varying in depth and width, they are all backfilled with coarse sand or fine gravel with finer material or geotextiles on top to prevent sediment penetration and could be covered to limit evaporation. Recharge water must have a very low total suspended solid (TSS) content as rehabilitation requires replacement of the filter media

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as no backflushing is possible (Bouwer, 1996; Bouwer 2002). Due to higher construction costs, higher treatment and maintenance costs, these options are much more expensive than infiltration basins.

Where there is a thick vadose zone (i.e. where groundwater levels are deep), recharged water may never reach the regional groundwater table, but could create a localised saturated zone (Izbicki et al., 2008; Heilweil et al., 2009). Unsaturated flow will not be possible to recover. This could be overcome by deep vadose zone wells.

2.3.2 Injection techniques

If the aquifer is confined, recharge wells or injection wells have to be used to penetrate into the permeable aquifer formation. The scheme uses either one well for recharge and recovery (ASR - aquifer storage and recovery) or a different well downstream for recovery (ASTR - aquifer storage, transport and recovery). The latter is used if groundwater flow velocities are high or if a certain residence time for attenuation processes needs to be guaranteed. As there is no attenuation in the unsaturated zone and clogging is a major issue, water quality needs to be high. The recharge water should not contain more than 10 mg/L TSS, total organic carbon (TOC) or total nitrogen (T-N) (NRMMC-EPHC-NHMRC, 2009b). Drinking water quality might be required if the recharged aquifer is used for potable supply (Tredoux et al., 2009). Disinfection of recharge water might be needed to avoid the development of biofilms, but could also lead to the development of hazardous disinfection by-products (Pyne, 1995; McQuarrie and Carlson, 2003).

While this method can effectively recharge groundwater, the disadvantages are higher costs related to water pre-treatment, pumping and technical equipment. It also requires skilled personal and good maintenance practice like regular backflushing to prevent well clogging as well as continuous quality monitoring to prevent groundwater contamination.

2.3.3 Indirect recharge

Bank filtration is a special case of groundwater recharge, where abstraction wells are placed in the vicinity of surface water bodies (mainly perennial rivers). Due to the lowering of the water table the hydraulic gradient is increased and more surface water can infiltrate through the river bed. Compared to direct use of river runoff, the passage through the aquifer provided purification (Massmann, 2002; Grünheid et al., 2005; Greskowiak, 2006). The distance of the wells should therefore be placed to ensure sufficient travel time. This method requires a perennial river, permeable bed sediments and an acceptable surface water quality (Huisman and Olsthoorn, 1983; Tufenkji et al., 2002; Hubbs, 2006).

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Table 1: Summary of typical advantages and disadvantages or constraints of different techniques.

technique	scale	costs	maintenance	land requirements	attenuation of pollutants	unconfined aquifer and permeable soils	potential evaporation	complexity of construction and operation	potential for source water contamination	source water quality requirements
recharge dam, percolation tank	variable	1	simple, but essential	1	yes	yes	3	1	2	1
recharge release dam, leaky dam	variable	1	simple, but essential	1	yes	yes	1	2	2	1
sand storage dam	small	1	low	1	limited	no	2	1	3	1
	coarse sediments, high groundwater table or impermeable layer needed									
water spreading weirs	medium	1	low	2	yes	yes	3	1	3	1
	reduces degradation of river course, allows runoff downstream, requires wide valley									
infiltration ponds/basins	variable	1	simple, but essential	3	yes	yes	3	1	3	1
	requires flat area									
ditch, drain, trenches, infiltration galleries	small	2	costly	2	yes	yes,	1	2	1	2
	can be installed underground; impermeable surface layer possible									
infiltration wells/shafts, vadose zone wells	medium	2	costly	1	variable	yes	1	2	1	3
	land for pretreatment needed; impermeable layer possible									
injection wells, deep wells	large	3	essential	1	limited	no	1	3	1	3
	can be used for recovery; land for pretreatment needed; intensive monitoring needed									
bank filtration	large	3	limited	1	variable	yes	1	3	3	2
	requires perennial stream or surface water body; intensive monitoring needed									

1= low, 2 = medium, 3= high

2.4   Aquifer characteristics and groundwater quality

> **A suitable aquifer provides enough storage capacity, allows high recovery efficiency and does not lead to a significant deterioration of recovered water quality.**
>
> **Porous aquifers are more favourable than fractured/karstic aquifers; recharge to unconfined aquifers will be less costly than to confined aquifers, and even saline aquifers can be used by creating a fresh water lens.**

The hydrogeological considerations are based around the questions: (a) can water enter the aquifer quickly enough, (b) does the aquifer have enough space for storage of recharged water, and (c) can the water be recovered in suitable quantity and quality?

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2.4.1 Hydraulic considerations

Infiltration rates depend on the vertical permeability and degree of saturation of the soil and can be significantly reduced due to surface clogging. Infiltration rates are decreased as a result of clogging by two to three orders of magnitude (Table 2) resulting in unsaturated conditions below the recharge basin (Schuh, 1990; Bouwer et al., 2001). Even thin horizontal layers of low permeability can effectively hinder downward movement. Biological clogging through cyanobacterial mats on the basin bottom can also reduce infiltration rates (Bouwer, 2002). Typically infiltration rates vary from up to a few m/d on gravel/sand, to tens of cm/d on loamy soils to a few mm/d if the basins are clogged. An infiltration rate >1 m/d is suitable; <0.5 m/d it becomes unsuitable (Zeelie, 2002; Haimerl., 2004; Ghayoumian et al., 2007). Mostly infiltration follows preferential flow paths rather than the piston flow concept, especially after a clogging layer has formed. Preferential flow can occur e.g. through mudcracks, along faults, roots or dissolution voids. Karst areas with high permeability can be favourable for MAR if water quality is good enough not to compromise the groundwater quality (Murray, 2009).

Table 2: Selected compilation of decrease in infiltration rates due to clogging.

reference	site	infiltration rate (m/d)		comment
		unclogged	clogged	
Agnew et al., 1995	Badia, Jordan	0.57	0.048	wadi vs. playa
Al-Muttair et al., 1994	Saudi Arabia	3 - 13	0.280	wadi vs. reservoir
Bouwer, 1988	USA	3	0.300	
Bouwer et al., 2001	column study	10	0.010	20 cm clogging layer
Gale et al., 2006	India	na	0.007	
Izbicki et al., 2008	California, USA	0.85	0.330	
Pedretti et al., 2012a	Spain	0.2 - 13	0.17 - 3	after one event
Racz et al., 2012	California, USA	>1	0.100	
Rahman, 2011	Portugal	5	0.250	limit for maintenance
Warbuton, 1998	Jordan	750	0.072	wadi vs. qaa
Zeelie, 2002	Omdel, Namibia	1.2	0.500	limit for maintenance

Injection rates depend mainly on the horizontal permeability of the aquifer, the hydraulic head and well clogging effects. Lateral permeability is commonly about ten times higher than vertical permeability. Well clogging decrease injection rates significantly and is commonly a combination of biological, chemical and physical clogging (Asano, 1985; Pyne, 1995).

Storage capacity depends on the permeability of the aquifer formation, the thickness of the formation, groundwater level and the confinement. Thick, unsaturated, permeable formations would provide high storage capacity and are often found in (semi-)arid regions. Unconfined unconsolidated porous aquifers generally have the highest storage capacity. If unconfined groundwater levels are too close to the surface, storage space is limited as discharge to the surface is usually unwanted and could impact on building foundations. In confined aquifers storage capacity is limited by the increase in hydraulic head and the stability of the overlying confining layer (NRMMC-EPHC-NHMRC, 2009b). If permeability is low this reduces the storage capacity as well as the velocity of recharge and increases the risk of clogging. Limestone aquifers have been favoured in many regions as calcite dissolution increases storage capacity and counteracts clogging (Pavelic et al., 2007).

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Recovery efficiency (defined as the percentage of water volume injected compared to recovered within the target water quality criteria) depends on the hydraulic gradient (i.e. groundwater velocity), on the uniformity of hydraulic characteristics and the salinity of the groundwater. Fractured and dual porosity aquifers generally have lower recovery efficiency as subsurface flow paths are often unknown, even though storage capacity might be high (NRC, 2008). In contrast, homogeneous porous aquifers allow reliable predictions of groundwater movement and allow for high recovery efficiencies. If saline aquifers are used, a buffer zone has to be created to build a barrier between native groundwater and recharged water (Pyne, 1995). Recovery efficiency can also be reduced due to leakage to over- or underlying aquifers or if groundwater velocities are high. The latter case would require recovery wells downstream of the recharge site.

2.4.2   Quality considerations

> **In (semi-)arid regions with limited vegetation and population, infiltrated concentrations of TOC and nutrients are commonly low and only limited reactions are expected in fresh water aquifers. The opposite is valid for treated wastewater.**

Quality changes during storage resulting from interactions of recharged water with aquifer matrix and native groundwater are mainly dilution, filtration, ion-exchange, dissolution / precipitation processes and degradation of organic compounds. A major driver of the latter two processes are redox changes induced by the recharge of oxygenated, nutrient and organic carbon containing water (Greskowiak et al., 2005). The larger the difference in native groundwater and recharged water the more quality changes will occur. In general, water quality changes are maximal during the initial recharge periods and below the infiltration basin or around the recharge well. Low permeability layers or lenses might require longer for 'flushing' the native groundwater out of small pores (Pavelic et al., 2006). While improvements of recharged water quality due to biodegradation, pathogen die-off, adsorption of contaminants and ion-exchanges are predominant (Bouwer, 1988; Dillon and Toze, 2005; John and Rose, 2005), some negative reactions have been observed. These include the formation of disinfection by-products (if recharged water is disinfected with chlorine) (Pyne, 1995; McQuarrie and Carlson, 2003) and the dissolution of trace minerals leading to elevated heavy metal concentrations. Both reactions are mainly driven by redox reactions.

2.5   Recovery and reuse options

> **In (semi-)arid regions groundwater is often the main water resource used for irrigation (commonly 60 - 90 %), domestic and industrial uses. Most MAR projects are implemented to increase agricultural revenues (van Steenbergen et al., 2011), while the use for municipal or industrial supply would give higher returns.**

The decision if recharged water can be used for drinking water purposes depends mainly on the quality of the native groundwater.

If the native groundwater is of potable quality, the recharged water should be of such a high quality that a deterioration of groundwater quality does not occur taking natural attenuation

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processes in the aquifer into account. Therefore, recovered water should be fit for drinking purposes as well or might require minor post treatment like filtration and disinfection as would be undertaken with the native groundwater as well. Obviously, reuse for lower beneficial uses like irrigation is possible too.

If the native groundwater is of higher salinity, the recharge with lower salinity water would result in the creating of a low salinity lens and a mixing / buffer zone. Accordingly the first recharge phases would need to be used for creating the buffer zone and to flush the native groundwater out of the recharge storage space. The use of brackish groundwater works best if groundwater velocity is low or larger and constant recharge volumes are available to be able to recover most recharged water. Reuse option depend mainly on the quality of the recharged water, but commonly reuse for irrigation is advised, as irrigation water can be of higher salinity than drinking water purposes. Successful examples of small scale brackish aquifer reuse can be found in Paraguay (van Steenbergen and Tuinhof, 2009) or Bangladesh (Tuinhof et al., 2012).

If the native groundwater is impaired due to contamination, recharged water could lower contamination levels due to dilution. It would most definitely require post treatment of recovered water to ensure suitability for reuse. MAR schemes in contaminated aquifers are generally not undertaken for recovery, but for the creation of a hydraulic barrier.

If the main purpose of MAR projects is to increase availability of water resources for agricultural purposes, the additional costs should be recovered by implementing adequate water tariffs for the agricultural sector profiting from such projects.

2.6 Selected international examples of MAR schemes

Even though MAR is conducted in many (semi-)arid countries, monitoring is often lacking or information is not published. Accordingly the success of these schemes cannot be evaluated.

In (semi-)arid regions the main problem is the availability of source water if flood water is to be used. A compilation of published MAR schemes shows that most schemes are located in regions with higher precipitation (Table 3). Examples from North India show that of 100 mm/a rainfall about 1 mm could potentially be infiltrated (Sharda et al., 2006).

Harvesting of runoff in earthfill dams is practised in Israel, Syria, Iran, India, Jordan, Saudi Arabia, China, Yemen, etc. but harvesting schemes are used for surface storage or direct irrigation rather than aquifer recharge.

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Table 3: Selected compilation of mean annual rainfall for implemented or investigated MAR schemes using flood water.

reference	region	mean rainfall (mm/a)	MAR scheme
van Steenbergen and Tuinhof, 2009	Niger	50	infiltration basin in river bed
Boers, 1994	Niger	90	micro-catchments (soil moisture storage)
Al-Muttair et al., 1994	Saudi Arabia	115	recharge dams
Mousavi and Rezai, 1999	Iran	120	infiltration basins
Fleskens et al., 2007	Turkmenistan	110 - 200	takyr usage (no cost for water harvesting)
DWA, 1994	Namibia	100 - 200	recharge release dam with infiltration basins (catchment 14 600 km²)
Margane et al., 2009a	Jordan, Wala dam	180	recharge dam (catchment 1788 km²)
van Steenbergen et al., 2011	Yemen	250	check dam cascades
Practical Action, 2005	Sudan	250	check dams, hafirs
Ghayoumian et al., 2007	Iran	260	feasibility study
Zammouri and Feki, 2005	Tunisia	300 - 400	recharge release dams
van Steenbergen and Tuinhof, 2009	Kenya	semi-arid	sand dams
Saleh, 2009	Palestine	470 - 660	feasibility study
Anbazhagan et al., 2005	India	500 - 790	feasibility study
Kalantari et al., 2010	Iran	640	floodwater spreading
van Steenbergen et al., 2011	India	710	retention weirs
van Steenbergen and Tuinhof, 2009	Paraguay	800 - 900	tajamar infiltration
CGWB, (2000)	India	<1000	check dams
Padmavathy et al., 1993	India	1000	feasibility study
Das, 2007	India	1200	feasibility study
Chowdhury et al., 2010	India	1500	feasibility study

Australia appears to be at the forefront of non-potable water recycling and has focused on water reuse in urban areas. A number of MAR schemes have been implemented that are usually well monitored (Fig. 7). These schemes inject mostly stormwater or reclaimed wastewater into brackish limestone aquifers. Through the use of brackish aquifers the beneficial use of these aquifers is not compromised. Treatment is often done through a number of detention ponds and wetlands. Examples are Bolivar (reclaimed wastewater), Andrews farm (stormwater) or Parafield (stormwater) (e.g. Greskowiak et al., 2005; Marks et al., 2005; Pavelic et al., 2006; Vanderzalm et al., 2006; Page et al., 2010). A long running infiltration basin scheme is the Burdekin Delta, where up to 45 MCM/a of river water are recharged for irrigational use and to prevent seawater intrusion, but has a tropical climate (>1000 mm/a) (Charlesworth et al., 2002).

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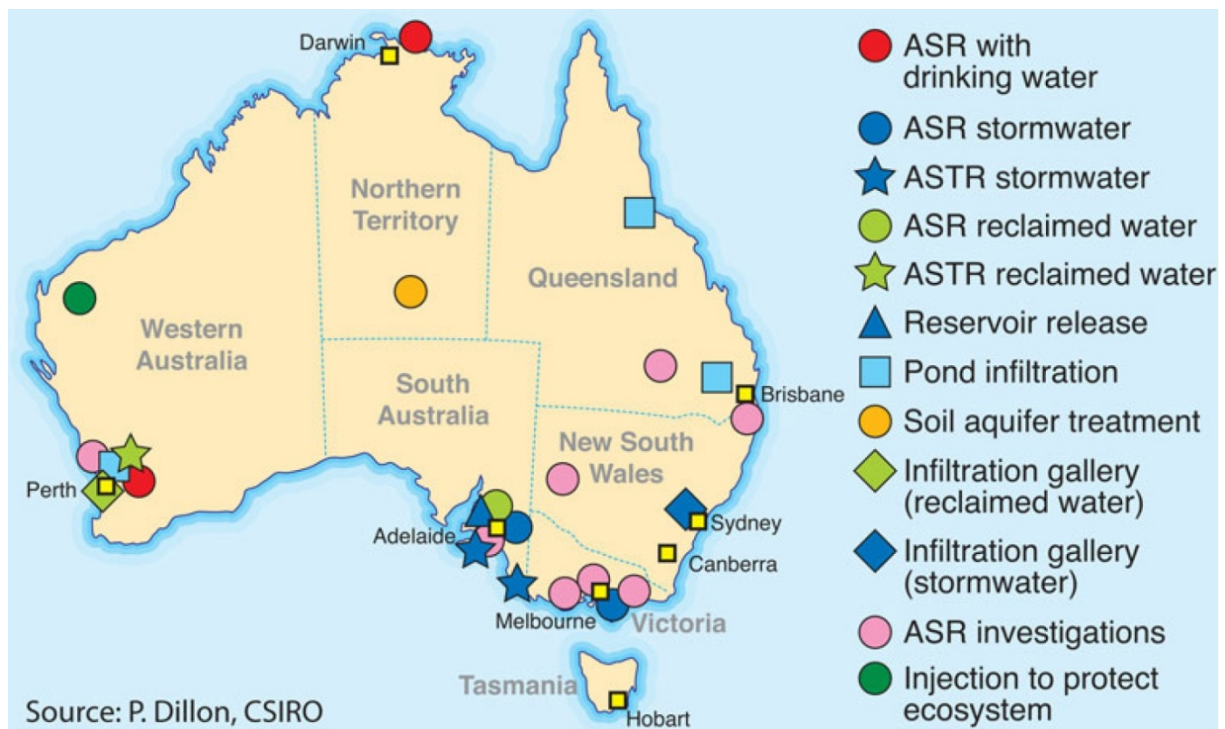
Fig. 7: Map of managed aquifer recharge in Australia in 2011. ASR = aquifer storage and recovery, ASTR = aquifer storage transport and recovery (Ward and Dillon, 2012).

In **Europe** MAR schemes are often bank filtration schemes (indirect reuse of treated wastewater as well; e.g. Germany (Jekel and Gruenheid, 2008)) or applied to prevent seawater intrusion (e.g. Netherlands). Some reclaimed wastewater schemes are operational using infiltration basins (e.g. Braunschweig (Eggers, 2008); Granada (Moreno et al., 2008); Mediterranean area (MED-EUWI, 2007)), but no ephemeral rivers are used.

India has experienced a large increase in groundwater abstractions due to population growth and has focused on watershed management in rural areas including runoff harvesting and aquifer recharge. Main methods are percolation tanks, cement plugs, check dams, groundwater weirs and roof water harvesting as well as infiltration basins and recharge wells (Kaledhonkar et al., 2003; CGWB, 2007). Due to higher rainfall and vegetation, sediment loads are often lower than in desert areas. Maintenance and operation is often done by the community providing local employment. While many schemes are working successfully (CGWB, 2011), some projects show low benefits as site-specific aspects were neglected (Gale et al., 2006).

Iran practices aquifer recharge via a cascade of basins including settling basins or floodwater spreading systems (Kalantari et al., 2010; van Steenbergen et al., 2011; Hashemi et al., 2012). Removal of accumulated sediments is vital for maintaining infiltration rates in the infiltration basins (Mousavi and Rezai, 1999). In the flood spreading systems the accumulation of sediments is used as improvement to the soil for agriculture.

Israel has a long-running treated wastewater infiltration scheme (Dan region (Kanarek and Michail, 1996)) and also recharges stormwater runoff after sedimentation basin via recharge ponds (Nahaley Menashe project). Runoff from the Shikma river is diverted after settling from the dam to recharged ponds (Wolf et al., 2007). Lake water is also injected into a limestone aquifer (Murray, 2009).

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Jordan has one large recharge dam, Wala dam, where surface runoff is infiltrating via the side walls to recharge production wells downstream, but sedimentation has decreased storage volume and infiltration rates considerably as no sedimentation dams are installed upstream, necessitating the use of recharge wells (see section 9.1.1 for details).

Namibia has one large recharge release scheme, the Omdel dam, where storm runoff from a 14 600 km² catchment with a precipitation range from 50 - 300 mm is harvested in a dam with 40 MCM storage capacity. While the mean runoff is 15 MCM/a only about every 5 years is runoff occurring and every 15 years large floods of >100 MCM can occur. Sediment loads are very high with about 7.5 % of runoff volume. Infiltration is through two or four infiltration basins after settling in the dam and release is turbidity controlled (DWA, 1994). Regular removal of sediments in the infiltration basins is undertaken. Efficiency is around 50 % due to evaporation and technical constraints (Zeelie, 2002). Optimisation of release flow has been undertaken with a hydrogeological model (Dorsch International Consultants, 2012). Another large recharge scheme in Namibia is the emergency storage created in the Windhoek quartzite using treated reservoir water, which is more expensive than current water costs, but less expensive than other alternatives (van der Merwe et al., 2008; Tuinhof et al., 2012).

Niger is an example for an arid region where a shallow alluvial aquifer is recharged by diversion of low floods (about 13 % of flow) into an infiltration basin, while high floods with high sediment loads are not diverted (van Steenbergen and Tuinhof, 2009). It required considerable expert investigations and a highly permeable sandy aquifer.

Oman has 15 recharge release dams that capture runoff from the mountains in the plain with high sediment loads (5 - 6 % of runoff volume) and infiltrate runoff downstream to prevent seawater intrusion and for irrigational reuse (Haimerl, 2004; Abdalla et al., 2010; Prathapar, 2012). Socio-political reasons and a lack of regulations are the main limiting factors and recharge scheme do not generate economic benefit for irrigational reuse (Prathapar, 2012). It has even been investigated to drill underground storage tanks in the mountainous areas to store surface runoff after purification (Hahn et al., 2010).

Pakistan has implemented a small leaky dam (11 000 m³) from local materials with pipes for release allowing for downstream infiltration (Kahlown and Abdullah, 2004). The retention time of the flood water can be prolonged with an adjustable gravel filled sheet on the upstream site of the dam (Gale, 2005). Spate irrigation is also practiced with recharge as a by-product.

Saudi Arabia has constructed a number of recharge dams, which are experiencing clogging problems and sediment removal or release to downstream infiltration basins or the downstream wadi channel need to be undertaken (Sendil et al., 1990; Al-Muttair et al., 1994). There are investigations to use treated wastewater in fully engineered artificial recharge and recovery systems in alluvial wadi aquifers (Missimer et al., 2012).

South Africa has a holistic water reuse project in Atlantis, where stormwater, industrial and domestic treated wastewater are reused. Low quality water is used via dune recharge to prevent seawater intrusion and high quality water is recharged via infiltration basins for domestic and industrial reuse (Wright and du Toit, 1996). Small scale runoff harvesting (around 1000 m³/a) from ephemeral streams in Kharkam is injected into a fractured aquifer for general reuse (Murray, 2009).

Sudan is practicing water harvesting with improved hafirs providing potable water for human consumption (MIWR and MWIR, 2009) and uses permeable rock check dams for spreading and slowing down flood water (Practical Action, 2005).

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Tunisia recharges surface water for agricultural and domestic purposes after retention in small earth dams via basins and recharge wells. In upland areas the reservoir area with collected sediments is often used for farming and further retained water is hence used for irrigation and not for recharge. Profitability of the schemes is relevantly low (Ouessar et al., 2004). The release of captured flood water for downstream percolation in the wadi is also practiced (Nazoumou and Besbes, 2000; Ketata et al., 2011) and simulations showed much higher recharge rates especially when first flush release for silt removal was undertaken (Zammouri and Feki, 2005). In coastal regions seawater intrusions are controlled by recharge of reservoir water via wells (Bouri and Dhia, 2010). The infiltration of treated wastewater has also been investigated in coastal regions (Kallali et al., 2007).

Turkmenistan uses the runoff collected in natural 'takyrs' (flat areas with clay surface similar to a qaa) to store for later use either in open reservoirs, closed cisterns, or in the sandy shallow aquifer underneath the takyr or off-site (Fleskens et al., 2007).

The **USA** have practiced MAR for many decades with injection wells and infiltration basins often using highly treated source water and alluvial aquifers to meet seasonal/peak demands or for seawater intrusion control (Asano, 1985; Pyne, 1995; Brown et al., 2006). The Phoenix 23rd avenue project recharges reclaimed wastewater through spreading basins (Bouwer et al., 1984). The Everglade projects are mainly for wetland conservation and seawater intrusion control rather than recovery (Brown et al., 2008).

Yemen uses spate irrigation or flood spreading in many areas combining groundwater recharge with direct agricultural use (van Steenbergen and Tuinhof, 2009). Cascades of check dams have been built to divert flood water to the fields and increase recharge through the riverbed (van Steenbergen et al., 2011).

For further reading, a number of international MAR and related schemes are compiled in Gale, 2005; van Steenbergen and Tuinhof, 2009; van Steenbergen et al., 2011, Tuinhof et al., 2012.

> **The examples demonstrate the need for sediment retention and maintenance to manage clogging for successful recharge.**

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3 MAR potential maps as part of the pre-feasibility study

Apart from demand and supply questions, the availability of a suitable catchment and aquifer are one of the first questions to be addressed and is the main focus of the case study in Jordan (see part II).

A possible methodology for finding a suitable MAR site (Rahman, 2011):

1) **Definition of problem**

2) **Constraint mapping**

3) **Suitability mapping (spatial multi-criteria decision analysis)**

4) **Sensitivity analysis**

5) **Site ranking based on environmental, economic and social considerations**

In recent years the use of GIS and remote sensing techniques for large scale investigations has increased. The usefulness of this approach depends on the selected scale and of course on the available detail and scale of input data. It will give a general idea what knowledge gaps exist, where to undertake more monitoring and which zones are favoured or discarded for further investigation.

The approach deploys the preparation of different thematic maps based on the available data or best estimations. Each parameter or criterion is classified based on numerical values or linguistic quantifiers and each class is rated based on its suitability. Afterwards the different thematic maps are overlaid. This can be done only qualitatively with a small number of thematic maps (e.g. Alraggad and Jasem, 2010) or quantitatively giving after weights are assigned for each thematic map. There are two main overlay techniques. The Boolean logic allows only a rating as suitable or unsuitable (0 and 1 values) and is commonly used for creating constraint maps. It means that an area will be regarded as suitable if it fulfils the minimum value for all thematic maps, while the area will be rated unsuitable if only one parameter is below the minimum threshold. Completely unfeasible areas will be screened out in this process. The weighted overlay allows the combination of classification inside each thematic map with different weights across all thematic maps based on their importance and is used to create suitability maps (Malczewski, 2004; O'Sulllivan and Unwin, 2010). It means that areas that are unsuitable for one parameter can still get a high class if all other criteria are valued suitable. Different ratings and weights can be assigned to assess the sensibility or to evaluate different aspects of the MAR scheme. Based on expert input or risks accepted, rates and weights can be varied to rank sites (Rahman, 2011).

Many MAR suitability assessments are a mixture of catchment suitability for runoff generation, aquifer suitability and site suitability for retention and transfer to the underground. However, it would be preferable to clearly separate these issues as the same parameter can be unsuitable for runoff generation but highly suitable for infiltration (i.e. sandy soils or gentle slope). MAR schemes using flood water have to find a suitable catchment and site for water retention and a suitable site for recharge. With respect to surface water runoff generation, the evaluation for water harvesting structures used for domestic, agricultural and livestock watering is similar to assessing the potential for retention structures for later recharge, but it differs widely in many other parameters. For simple water harvesting structures impermeable soil and distance to faults is necessary to prevent harvested water from infiltration, and

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vicinity to settlements and infrastructure is preferred to limit the costs of water transport (e.g. Al-Adamat et al., 2010). Recharge structures on the other hand should specifically be built on permeable soils, preferably near fault lines and be away from human interference. Hence the technique used and parameters evaluated are similar, but the ratings are very different.

3.1   Data acquisition

> **Existing monitoring data and regional maps as well as remote sensing data should be combined for best results.**

Data acquisition and evaluation is the most important part, as uncertainties will add up with each layer. For some criteria remote sensing data can be a valuable source (Schultz, 1994). For example slope, watershed size, drainage density, geomorphology and land use/cover can commonly be derived from digital elevation models (DEM) and satellite/radar data. Some lineaments/faults can also be assessed. The amount of detail available depends on the resolution and should be suited to the scale of the assessment. For example freely available Landsat data do not allow land use differentiation on a single dwelling scale especially if the building material is taken from local material. GoogleEarth data have different resolutions and dates for each grid segment, but can also give an idea about temporal land use changes. DEM data free of charge are available in 90 m * 90 m resolution from the Shuttle Radar Topography Mission (SRTM) or in 30 m * 30 m from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) system (ASTER GDEM Validation Team et al., 2009; Jacobsen, 2010). At this resolution the selection of actual dam construction sites that require a narrow cross section and deeper incision is limited and cannot be done without a field survey.

Regional maps for geology, soil, roads, settlements or topography are commonly available at different scales. If regional groundwater models are available these can be used to extract regional maps on depth to groundwater and aquifer characteristics like thickness, transmissivity, impermeable layers, etc. Sometimes hydrogeological maps are available with groundwater level depth, flow gradient information and spatial distribution of hydrochemical parameters. More often though only point data are available for groundwater and aquifer characteristics. If the coverage of the points is dense enough and heterogeneity is low, interpolation methods can be used to generate regional maps. If information density is too low, general trends might be visible and used with a higher uncertainty attached. Maybe only point data can be used or the thematic map cannot be created without further investigation.

Soil maps do usually not encompass infiltration capacity values, but might give soil texture or grain size distributions, soil density, soil thickness or soil quality data like cation exchange capacity, organic matter content, etc. These data can be used for the estimation of hydraulic conductivity using pedo-transfer functions (Vereecken et al., 1990; Tietje and Hennings, 1996), but uncertainty to actual infiltration capacity at a specific site is high and even with very good analysis easily vary between a third and three times the calculated value (Chapuis, 2012). Sometimes a number of soil groups are characterising a certain area and their distribution depends on the toposequence and parent material (Ziadat et al., 2010; Schulz, 2011) necessitating more analysis work and increasing uncertainty.

3.2 Selected international examples of MAR potential mapping

> The study for two basins in Jordan (part II) is comparable to other international research including a large number of thematic maps and combines the assessment of constraint and suitability maps for catchment and site selection.

A number of GIS and remote sensing based assessments for MAR suitability or site selection of water harvesting structures have been published (Table 4). Depending on the availability of data and the scale, different thematic maps were created and overlaid. Some studies have incorporated distance to supply and demand or the availability of source water, while other mainly looked at the aquifer characteristics. Most studies use 2 - 4 classes for each parameter. It is also possible to use linear or other functions to create a rating for a parameter (Rahman, 2011). Some studies just performed a qualitative overlay without assigning weights, but most studies use some criteria with Boolean overlay to exclude unsuitable areas. Weighing could also be done using an analytical hierarchy procedure (AHP) by weighing the importance of main and sub-criteria (Fig. 8).
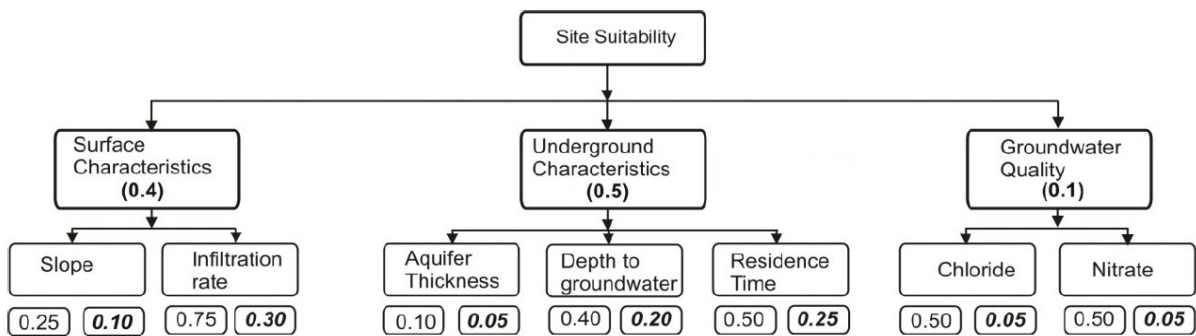
Fig. 8: Criteria for suitability mapping and hierarchical structure (in brackets the local and global weights, bold and italic number to indicate the global weights) (Rahman, 2011).

The comparison with other studies shows that this study (see part II) included more aspects than most studies looking at source water availability by assessing the catchment as well as distance to supply and demand sites for site selection.

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Table 4: Compilation of selected references using GIS/remote sensing for assessment.

	parameter	Alraggad and Jasem, 2010 (Jordan)	Rapp, 2008 (Jordan)	Al-Adamat et al., 2010 (Jordan)	Ghayoumian et al., 2007 (Iran)	Jasrotia et al., 2007 (India)	Kallali et al., 2007 (Tunisia)	Mukhopadhyay and Fadlelmwala, 2010 (Kuwait)	Rahman, 2011 (Portugal)	this study (Jordan)
no of classes for each parameter	slope	2	2	4	4	6	2		L	3
	land use/cover	3	2		2	8			2	3
	geomorphology					8				
	superficial deposits	2	2							3
	soil texture			4		6	2			6
	infiltration rate				4	9			L	
	aquifer type/lithology	2	3			8	2			3
	aquifer thickness								L	3
	aquifer permeability					9				
	aquifer storativity					8				
	aquifer transmissivity					8		2		
	aquifer specific capacity					8				
	depth to water table				4	5	2	3	L	3
	flow gradient							2		3
	residence time								4	
	gw salinity				4		2	2	L	3
	gw contamination								L	3
	rainfall			4						3
	distance from supply	2	2	4			2			3
	distance from faults	2		2						2
	distance to urban areas			4			2			2
	distance to roads			4				2		3
	distance to wells			2						3
	distance to int. borders			2						2
overlay	qualitative	x	x							
	boolean			x	x	x	x	x	x	x
	weighted			x	x	x			x	x
aspects assessed	aquifer suitability	x	x		x	x		x	x	x
	water harvesting			x		(x)				x
	transfer	inf	inf	no	inf	inf	SAT	inj	SAT	inf
	demand			x			x		x	x
	supply			x			x		x	x

inf: infiltration, SAT: reclaimed wastewater use, inj: injection; L = linear rating

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4 Feasibility study before implementation

"It is not an overstatement that the single most important process for the successful implementation of an ASR [aquifer storage and recovery] project is planning". (Maliva and Missimer, 2010)

A number of technical criteria need to be fulfilled for a successful MAR scheme. During the pre-feasibility stage existing data are evaluated and potential sites are selected based on the MAR potential map. Any found knowledge gaps need to be filled in the feasibility study and site specific data will have to be collected even if a good regional data base is available (see also chapter 13).

4.1 Supply analysis or runoff estimation

Long-term runoff measurements give the best indication for available source water. Rainfall-runoff models of different complexity are available but their use is often hindered by a lack of data. Uncertainty of input data should be considered as well as downstream impacts. Water quality decides about the value of the supply.

If no flood station is installed at the site of investigation the most reliable measure would be to install a flood station and measure runoff for a number of years (minimum 3 years, better 5 years). Rainfall measurements of the catchment are used to judge if the measured years represent dry, normal or wet years. If no rain gauges are located in the catchment, it is advisable to also install new rain gauges or use Tropical Rainfall Measuring Mission data (TRMM; see section 13.1). The number of rain gauges for a representative coverage depends on topography and size of the catchment. The evaluation of actual rainfall and runoff data will allow a reasonably good estimate of available surface runoff over the long-term.

Commonly time for monitoring is limited and runoff estimations are made from existing data. For the estimation of potential runoff, there are numerous **rainfall-runoff models** available (Beven, 2012) ranging from models based on the SCS-CN method sometimes in combination with the Green-Ampt infiltration equation (e.g. WinTR55, WinTR20, HEC-HMS, EPA-SWMM, SWAT, GLEAMS, EPIC, NLEAP, and AGNPS (Peugeot et al., 1997; Eli and Lamont, 2010; Grimaldi et al., 2012; Perrin et al., 2012), physically based models (e.g. J2000, TRAIN-ZIN, MIKE-SHE (Abbott et al., 1986a,b; Krause, 2001; Alkhoury, 2011), stochastic models (e.g. Hsu et al., 1995; Shamseldin, 1997; Sajikumar and Thandaveswara, 1999; Tokar and Johnson, 1999) and conceptual models (e.g. RRMT toolbox (the Rainfall-Runoff Modelling Toolbox RRMT; Hsu et al., 1995; Tokar and Johnson, 1999; Wagener et al., 2001, 2002; Wu and Chau, 2011). The regionalisation approach uses models calibrated for gauged catchments to similar ungauged catchments (Lee et al., 2005; Wagener and Wheater, 2006). However, even nearby catchments can vary significantly with respect to their hydrological behaviour (Wagener and Wheater, 2006). Artificial neural networks are another approach to model rainfall-runoff (Hsu et al., 1995; Tokar and Johnson, 1999; Zhang and Govindaraju, 2003; Kumar et al., 2005; Wu and Chau, 2011).

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The more sophisticated a model, the more input data are commonly required. Due to lack of data the **Soil Conservation Service Curve Number (SCS-CN) method** is still widely used, even though it has a number of disadvantages. It was developed in 1954 from gauged watersheds and infiltration tests in the USA without peer-review (Ponce and Hawkins, 1996). Based on soil type (4 classes), land use + treatment (many classes), hydrologic surface conditions (3 classes) and antecedent moisture conditions (3 classes) a single CN is selected (USDA-SCS, 1985). This lumped model does not account for spatial or temporal variability and does not replicate infiltration mechanisms. In addition, it is further simplified by using an initial abstraction value of 20 % (even though variations between 10 - 38 % were recorded in the method development) which leads to the final formula (see also section 10.2.1):

$$Q = \frac{[CN * (P + 2) - 200]^2}{CN * [CN * (P - 8) + 800]}$$

with Q = runoff (inch), P = precipitation (inch), multiply by 254 for mm

Although a list of CNs corresponding to dry and wet antecedent moisture conditions is available, typically only the medium antecedent soil condition is applied. In the natural system infiltration rates and runoff coefficients vary with rainfall intensity and duration, microtopography leading to surface ponding, sealing patterns and plant cover (Langhans et al., 2011).

Due to its limitation the CN method needs to be modified for long-term hydrologic response modelling of a catchment (Ponce and Hawkins, 1996). As it was developed from vegetated agricultural sites, it cannot account for surface phenomena like crusts typical for (semi-)arid regions, where infiltration is severely hindered (Le Bissonais and Singer, 1993; Chamizo et al., 2012). Higher uncertainty for (semi-)arid catchments results also from the fact that CN is very sensitive at low rainfall depth. Transmission losses are not accounted for (Simanton et al., 1996) and can be as high as 95 % (Sorman and Abdulrazzak, 1997). The underlying geology is also not considered, so effects of impermeable layers or faults are not described (Margane et al., 2009b). Accordingly, the SCS-CN model might show infiltration where in fact there is none. For large catchments sizes subdivisions need to be made to lower spatial scale effects. The CN method was found to overestimate runoff by 100 % for a catchment in Jordan (de Laat and Nonner, 2011).

In addition to the uncertainty related to the applied model, all input data are accompanied by **uncertainty** due to spatial and temporal heterogeneity (e.g. Chamizo et al., 2012; Quintero et al., 2012). For example in very flat regions, uncertainty attached to watershed sizes and drainage pattern is much higher than in mountainous areas and should be double checked in the field. The existence of flat depressions like playas, qaas, shabkhas, marabs etc can result in a significant reduction of watershed area that might not be depicted in the DEM.

The uncertainty related to rainfall data as the main input is high in (semi-)arid regions as rainfall often occurs in local and intense thunderstorms that are not well depicted by rain gauges. Even rain gauges a few meters apart can result in very different numbers (see Box 5).

Climate data like **evaporation** data from Class A pan measurements are afflicted with errors due to possible accumulation of windblown dirt in the pan, loss of water by wave action,

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drinking of water by animals, inaccurate reading method and the storage of heat in the large volume of pan water resulting in slow response to heat changes. Rainfall will also fall into the pan[1] (Messing, 1998). For the estimation of reservoir evaporation Class A pan measurements are reasonably representative as the same influences apply to the reservoir. Piche atmometers are much smaller with a fast response time and measure the aerodynamic component in the Penman-Montheith equation (van Zyl et al., 1989; Messing, 1998). They need to be shaded from direct radiation and the membrane needs to be cleaned regularly to avoid wrong measurements. In order to relate Penman evaporation values to pan evaporation a correction factor of 2.5 times the psychrometric constant (it relates the partial pressure of water in air to the air temperature) was suggested (Kohler et al., 1955).

Supply would also be diminished if **existing water harvesting structures** are in place. As small scale dikes or diversions are often constructed by private farmers without any record, a survey of existing structures and their storage capacity should be part of the supply estimation. This should extend to downstream areas to avoid conflict with current users. The amount of environmental flow needed to sustain potential downstream ecosystems should also be taken into account. To calculate excess supply it should also be considered that water harvesting will prevent natural transmission losses in the wadi further downstream and hence this amount should be subtracted in the overall water balance. Unfortunately transmission losses are very site specific varying also with flood volumes (Sorman and Abdulrazzak, 1997). Monitoring of changes in flood volume at a number of stations along the wadi and the additional flow from tributaries would be required.

The supply analysis should also consider **water quality** questions. During the initial investigation surface water samples should analysed especially for TSS, TOC and nutrients to assess pre-treatment requirements. TSS loads could also be estimated from sedimentation rates of existing structures. The potential for water contamination could be complemented by a hazard survey of the catchment. If water quality is impaired and treatment costs would be excessive, the available supply that can be used economically feasible might be reduced considerably.

4.2 Demand analysis or reuse evaluation

> **Objectives for each MAR scheme should be clearly outlined before implementation and encompass a water resources management plan for the whole catchment.**

The demand analysis should include the evaluation of current groundwater abstractions and projected future increases by use category. Environmental and downstream demand should not be disregarded. If demand cannot be fulfilled with a small scale MAR scheme, other solutions like demand reduction measures or alternative supplies to MAR should be contemplated and evaluated in conjunction with stakeholders. MAR might be possible, but not necessarily the best or only solution and is mostly only one small piece of the solution. A sustainable water resources management plan for the whole catchment should be developed.

Reuse options depend mainly on water quality considerations of both the source water and the groundwater. Recovered water quality will also be affected by interactions with the

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[1] It is not clear, if rainfall is commonly subtracted for the data in the WIS.

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aquifer matrix and be dependent on the retention time. If quality is slightly impaired, irrigational reuse is more appropriate. The cultivation of salt tolerant plants is recommended if salinity is an issue. Higher use categories and safe water supply can be achieved by pre- or post-treatment, but cost effectiveness would need to be assessed.

Beneficial use is also often limited by the scale. Small scale projects, which are more expensive, are usually used for drinking water supply to maximise the benefits.

Beneficiaries of the envisaged MAR scheme will be existing groundwater well owners. If these constitute only private wells, the government might want to transfer responsibilities for management of the scheme to these private beneficiaries and involve them in all planning and implementation stages.

If no abstractions wells are currently in place, additional costs for recovery wells and water transport to demand sites will decrease economic viability and might preclude some areas from further assessment.

4.3   Field investigations

> **Field investigations are needed to get site-specific information on soil, geology, hydrology, climate, water quality, topography for retention structures, land ownership and access as well as catchment information on up- and downstream users and hazards to water quality.**

For obtaining site specific or generally missing data, sampling of groundwater, shallow drilling, shallow geophysical investigation, infiltration tests and the installation of flood gauges and rain gauges could all be part of the field investigations.

Commonly a **topographic survey** is conducted to find a suitable cross section in the water course for creating a harvesting structure and to calculate potential storage capacity. Inspections of the catchment would also be established the actual catchment size, land use that might interfere with MAR, existing harvesting structure and land ownership. Accessibility and infrastructure for construction and maintenance will also be incorporated. **Field surveys** of the local geological formation and structural features could point to areas of higher infiltration potential (e.g. de Laat and Nonner, 2011). Local long-term knowledge from residents about rainfall, flow and infiltration pattern should not be disregarded.

Soil samples are taken to assess the suitability as construction material to reduce material costs. Grain size analysis will also give an indication about the erodibility of the soil and the expected sediments input to the harvesting structure (Ziadat et al., 2010). The estimation of hydraulic conductivity from grain size distribution and other soil parameters (see also section 10.4.1) varies largely (2 - 4 magnitudes) with the pedo-transfer function used (Chapuis 2012; Matthes et al., 2012).

One of the most important parameters for a successful aquifer recharge is the **permeability assessment** at the selected site (see also section 10.4). It incorporates the infiltration (transition from the surface to the soil, controlled by surface conditions) and the percolation or transmission (transition through the vadose zone to the aquifer controlled by horizons) (USDA-SCS, 1985; Warburton, 1998). In unconsolidated sediments, vertical permeability is smaller than horizontal permeability due to heterogeneities from sediment deposition. Minor

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changes in soil grain size distribution (including clogging) or the existence of preferential flow paths can lead to significant changes in permeability (e.g. Pedretti et al., 2012a).

As they are easy and cheap, **infiltration tests** are commonly undertaken to assess the infiltration capacity. The larger the wetted area during the test and the longer the infiltration time, the more reliable are the results as spatial heterogeneities are evened out. As infiltration rates increase with decrease in ring infiltrometer diameter due to the larger effect of lateral spreading, infiltration rates are commonly overestimated (Bouwer, 1986; Youngs, 1991). A minimum diameter of 40 cm for homogeneous soils and 80 cm for heterogeneous soils is recommended (Lai and Ren, 2006). Basin infiltration tests are the most preferred option and actual infiltration rates during flooding vary commonly about 1/3 lower than measured (Bouwer, 1988) (see also Table 2 and Table 29).

However, they will not allow the assessment of percolation as they are usually not undertaken with large quantities and over long time scales and hence do not give evidence that the infiltrated water will ever reach the groundwater table. Instead infiltrated water could be perched on an impermeable layer above the groundwater table or it could be stored in the vadose zone and potentially evaporate later (e.g. Haimerl, 2004). The diffusive loss extinction depth depends on the soil texture and was estimated to be around 1.5 m for silty sand (Sorman and Abdulrazzak, 1997), about 3 m for alluvial in Oman (Haimerl, 2004), 4 m for sandy alluvial Paraguay (Tuinhof et al., 2012) and up to 12 m for clayey soils at Azraq Qaa[2].

Shallow drilling, auger tests and geophysical investigations help to assess the spatial heterogeneity at the site and allow for the detection of impermeable layers in the subsoil that would hinder percolation. In-situ permeability testing in the subsoil can be undertaken via air-entry permeameter, double-tube method, infiltration gradient technique, and reverse auger hole or well pump-in method (Bouwer, 1978).

Depending on the scale of the recharge scheme and the density of existing wells, it might be necessary to drill new **wells** either for recovery or for monitoring. It will also allow getting a detailed lithological description and material from deeper unsaturated layers for permeability assessment as well as analysis of geochemical components to judge possible interactions between the recharged water and the aquifer matrix. If reclaimed wastewater is used, lab tests or geochemical modelling with supply water, groundwater and aquifer matrix could help to identify possible reactions (especially precipitation or dissolution) that might pose a risk to the MAR scheme. Bore log **geophysics** and pump tests will give even more information on hydrogeological characteristics. The installation of heat dissipation probes and tensiometers in wells close to the infiltration site would allow the assessment of water percolation in the unsaturated zone (Izbicki et al., 2008).

Groundwater level measurements over a larger region should be repeated over one year to assess groundwater flow direction and seasonal variations if available data are scarce. If flow paths are unknown, tracer tests could help in identifying flow direction and velocity (e.g. Käss, 1998; Kalbus et al., 2006; Luhmann et al., 2012). This will allow determining the best recovery location for highest recovery efficiency after the required retention time. Groundwater samples should be taken at a number of wells over the year in the upstream and downstream area to assess the beneficial use potential.

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[2] A. Subah (MWI), 2012, personal communication

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4.4   Impact assessment

> **Impact assessment for environmental, health and socio-economic aspects is an essential planning step to adequately evaluate hazards and associated risks and is often required by MAR regulations.**
>
> **Education of local communities about processes and benefits and their involvement during planning and design is the key to increase acceptance and success of MAR schemes.**

As has been mentioned previously MAR schemes might not only have positive impacts but might also have negative **environmental impacts** mainly on downstream areas (see also section13.3). Environmental impact assessment (EIA) and environmental risk assessment (ERA) are common methods to evaluate severity and likelihoods of adverse effects to humans and ecosystems (Lohani et al., 1997). They can be based on different approaches depending on the scale of the project and information availability. The main environmental impacts are related to the decline in runoff and sediment for downstream areas. Especially in (semi-)arid regions wadis are often the only area sustaining some vegetative cover providing habitat. If recharged water provides discharge to ecosystems, water quality might also be an issue.

If water is recovered for drinking water purposes or irrigation **human health** should be protected from negative impacts and recovered water should adhere to drinking water or irrigation water standards otherwise post-treatment is needed. The hazard analysis and critical control point (HACCP) approach might be used to control hazards (NRMMC-EPHC-NHMRC, 2009b). Due to attenuation processes during MAR, risks will be reduced. When using reclaimed wastewater the impacts of pathogens and resistant micropollutants should be considered among other factors.

The **social** acceptance of MAR varies depending on country, regions, social status, economic welfare, traditional believes, dependence on the environment and quality of life. The location of a person either upstream or downstream of the MAR scheme as well as the perceived distribution of economic benefits among different stakeholders will also influence acceptance. If water has traditionally been stored in surface impoundments, the release of water out of dam might seem like a loss of water. Commonly, the understanding of underground processes and groundwater recharge is limited and acceptance will hence be limited. Education of local communities about processes and benefits and their involvement during planning and design is the key to increase acceptance and success of MAR schemes.

Decision support systems, sometimes coupled with hydrogeological models, can help in modelling different scenarios and assess the variation in impact. For example, an analysis of the overall water budget including future scenarios could be analysed with WEAP (Water Evaluation and Planning System). Another tool to help with impact assessment is the DPSIT (driver, pressure, state, impact and response) module (Rahman, 2011). Possible criteria for assessment could involve the change in groundwater level, the change in salinity and nitrate concentration overall and in domestic wells, the level of convenience, satisfaction with available water quantity and quality, contribution to employment, contribution to income and

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willingness to pay (Rahman, 2011). Obviously the quality and quantity of available water is difficult to assess before the implementation and might change with time.

> *"MAR schemes may neither be socially acceptable nor economically feasible and before implementing any MAR scheme, proper assessment of environmental, health and socio-economic impacts should be undertaken to ensure a beneficial performance." (Rahman, 2011)*

4.5 Economic considerations

How to conduct a cost-benefit analysis or cost-effectiveness analysis has been described in detail elsewhere (e.g. ADB, 1998; Interwies et al., 2004; TECHNEAU, 2008; US EPA, 2010). It should evaluate all relevant costs and benefits of a MAR scheme, which are expressed in monetary terms for a particular lifetime (TECHNEAU, 2008). Costs and benefits of recharge schemes vary largely depending on the technique, operation and maintenance (O&M) requirements, water availability and scale. They can be direct or indirect over spatial (on/off-site) and temporal (short/long-term) scale.

The main direct costs are expenditures for feasibility studies, stakeholder consultation, construction, O&M and monitoring (Box 1). Indirect costs accrue due to the negative impacts like reduction in environmental flows and sediments downstream affecting ecosystems or other communities. In addition reduced flows result in a reduction in natural recharge downstream and reduced dilution of impaired surface water quality (e.g. discharge of wastewater) (Box 2). If recharge schemes are not properly maintained they will result in an increase in evaporation rather than the anticipated decrease.

The main benefits are the potentially higher availability of water at the location and the resultant usage, e.g. higher agricultural yield, more livestock, shorter distance to water source. Other benefits are the higher resilience to droughts and downstream flood protection. The slowing of flash floods due to retention structures also decreases erosion (Box 2). The beneficiaries of the scheme should be involved in covering the costs (Gale, 2005).

Source water availability and effectiveness of recharge is crucial, as no MAR scheme will accrue any benefits, if no water is recharged. Commonly economic analyses are using the design storage potential or projected flood volumes as input value rather than actually measured recharged volumes resulting in an overestimation of benefits. Moreover, most assessments are based on the status quo and not on climate change projections. Therefore future changes in the climatic conditions, i.e. even during the planning horizon, could have a significant impact on source water availability.

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Box 1: Selection of cost generating activities during the implementation of MAR projects via recharge release dams

1) **hydrological and hydrogeological prefeasibility study**
   - evaluation of existing meteorological, hydrological and hydrogeological data
   - installation of flood station and rainfall gauges at potential sites for measuring flood amounts for at least 3 years to design dam storage capacity correctly
   - sampling of flashfloods for analysis on sediment concentrations and particle sizes to determine expected sediment accumulation and potential pretreatment measures
   - collection and analysis of groundwater samples to assess potential contamination problems
   - consultation with local stakeholders

2) **site assessment**
   - topographic survey to find suitable cross section
   - soil sampling and testing
   - geophysical and geotechnical investigation: assessment of permeability of wadi channel via infiltration tests, shallow geophysical investigations (electrical soundings), drilling of shallow wells and permeability tests
   - impact assessment
   - cost-benefit analysis

3) **construction**
   - engineering design
   - land acquisition (potentially)
   - potentially drilling of extraction and monitoring wells (if not already existing)
   - dam construction (dam, spillway, water release structures)
   - potentially construction of pre-treatment facilities like sedimentation dams, infiltration basins, infiltration trenches etc.
   - installation of water level meters in dam to monitor actual flood volumes stored and infiltration rates

4) **operation, maintenance and monitoring**
   - cleaning of release structures and removal of silt accumulation in dam and basins during each dry season to prevent clogging
   - repair to structures caused by natural forces and vandalism
   - monitoring of groundwater levels in monitoring wells
   - evaluate water level meters and rain gauge records
   - regular inspections (e.g. every month) in wet season to see if there are any problems
   - awareness raising with local stakeholders

5) **contingency cost, decommissioning costs**
   - contingency costs (about 10 – 15 % of project costs) to cover eventualities including legal challenges
   - decommissioning costs for restoring surface conditions, backfilling etc.

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Box 2: Potential benefits/positive impact versus potential negative impacts

positive

- employment due to construction and maintenance
- increase in water availability for various uses
- increase in groundwater table
- flood and erosion protection

- higher resilience to droughts
- decrease in evaporation

- potential dilution of brackish groundwater
- shorter transport from supply to demand site
- collection of fertile sediments for further use

negative

- reduced water and sediment downstream for human use
- potentially only relocation of water

- reduction in natural recharge downstream
- less dilution of impaired surface water downstream
- impacts on downstream ecosystems
- increase in evaporation if not maintained properly
- potential groundwater contamination

- not effective if source water availability is limited (e.g. due to climate change)

Quantitative assessment of MAR schemes including all aspects are rare, especially as indirect and intangible social benefits are often hard to give a price tag and hardly any infiltration scheme actually measures recharged volumes (Gale, 2005). A compilation of case study cost-benefit assessment has recently been published with some cases from semi-arid regions, but none from arid regions (Tuinhof et al., 2012). Main benefits are the increase in agricultural production and drought resilience, but downstream costs are hardly measured.

"Improved understanding of how recharge structures actually work and the impacts they have on water availability, water quality, social and economic sustainability as well as the local and downstream environment, needs to be gained and disseminated to promote widespread cost-effective implementation." (Gale, 2005)

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5 Implementation, operation and monitoring

If MAR has been found a viable, possible and accepted option, implementation can proceed. This step involves not only the actual design and construction, but also the layout for the following O&M procedures, emergency plans, monitoring needs, the fulfilment of all regulation and the acquisition of all needed permits. Rights and responsibility for the MAR scheme need to be defined by the stakeholders. Generally it is advisable to start with a small scale pilot project and then improve the design and management plan for a full-scale project.

5.1 Design and construction

> **Design should respect site-specific conditions, be functional but as simple as possible and be optimal in size. Vandalism can be kept to a minimum by transferring responsibility to the beneficiaries of the scheme.**

The appropriate **design** at a selected site depends on many site specific characteristics. The runoff characteristics, demand and topography determine the optimal size of the harvesting structure, the source water quality determines the needed pre-treatment installations, and the permeability of the subsurface determines the transfer method. As outlined in chapter 2 various options and combination of techniques are available. A number of manuals on design and construction have been published (e.g. Critchley and Siegert, 1991; Practical Action, 2005; Nissen-Petersen, 2006b; CGWB, 2007; MIWR and MWRI, 2009; BMZ, 2012; Maddrell and Neal, 2012)

The right dimensioning of the retentions structure is based on runoff data or estimations. Without appropriate measurements, storage capacity might be largely overdesigned emphasizing the need for a feasibility study including runoff measurements for a number of years (de Laat and Nonner, 2011). Variability of rainfall and runoff due to climate change adds additional uncertainty to the optimal design size, but overall smaller sizes are more cost effective (Nassopoulos et al., 2012). Design also needs to consider potential pre-treatment options and allow for easy maintenance.

Design should take local **constraints** into account. Simpler designs are preferable over complex designs to reduce maintenance and repair costs as well as theft. Special care should be taken to avoid designs with many metal parts or the need for reliable electricity. Access to monitoring equipment, release valves etc should be restricted and secured. The best insurance against vandalism is the transfer of responsibility to and bearing of maintenance costs by the stakeholders, so they have a vested interest in keeping the structure running.

For many projects **construction** is undertaken by labour through the community or employment of local workers. Accordingly design needs to be simple and possible without the need for large machinery. If construction is tendered and carried out by a constructor, oversight about the compliance with construction specifications might be needed to avoid the use of low quality material and later high repair costs (de Laat and Nonner, 2011). In some cases land might need to be purchased or permission for construction might need to be acquired. Ownership issues should be resolved before implementation.

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5.2 Operation, maintenance and monitoring requirements

Implementation of a MAR scheme does not finished with construction, but actually starts and O&M operations decide about success or failure (see also section 15.1).

5.2.1 Clogging

Clogging appears to be the most limiting technical problem in artificial recharge and can only be managed with regular maintenance and pretreatment.

Clogging can be caused by various mechanisms like physical clogging by suspended solids, chemical clogging due to precipitation or clay dispersion, mechanical clogging due to entrapped air or biological clogging due to microbial growth (Pyne, 1995; Pérez-Paricio and Carrera, 2001; Bouwer, 2002). Clogging leads to the decrease in porosity and hydraulic conductivity and is experienced at the bottom of infiltration basins as well as around injection wells. There are two basic principles for the management of clogging: (a) pretreatment of recharge water and (b) redevelopment (Brown et al., 2006).

The pretreatment can include settling, filtration/coagulation of suspended particle and microorganisms, addition of pH elevating substances to reduce iron precipitation and disinfection to avoid microbial growth (Pyne, 1995; Stuyfzand et al., 2006). Settling basins are a common and cheap method for increasing water quality of recharged water. The time required for settling depends on the particle sizes and density. Clay particles (<2 μm) need about 4.6 days to fall 1 m in an undisturbed water column, while silt particles only need a few minutes. Due to the formation of flocs with larger diameter but lower density, settling velocities can also decrease with size (Semadeni-Davies, 2008). Undisturbed settling for a number of days is recommended if clay concentrations are high. Smart release systems could be coupled to a turbidity meter (DWA, 1994). TSS concentrations of <10 mg/L (NRMMC-EPHC-NHMRC, 2009b) or turbidity <10 NTU (ASCE, 2001) are recommended and TSS concentrations >50 mg/L quickly lead to a decrease in infiltration rate by two to three magnitudes (Schuh, 1990).

Redevelopment for recharge basins is done by regular removal of the accumulated sediments. Raking, disking or ploughing of the clogging layer is not recommended as it allows for deeper penetration of fine particles and has only very short term effects (Bouwer, 1996). To prevent biological clogging recharge basins are commonly used cyclic with drying and wetting periods (Bouwer, 1988; Maliva and Missimer, 2010). During the dry period the removal of sediments can then be undertaken as well and filter sand might be added. If scraped sediments are free of contamination they might be reused for construction or soil amendment. Otherwise they need to be disposed of correctly. If release to downstream wadi channels is practiced a first flood wave should be high enough to remove the developed surface crust layer as this natural process is obviously disrupted (Crerar et al., 1988; Zammouri and Feki, 2005).

Backflushing or purging of wells can recover most of the injection capacity and treatment with disinfection or acid in the well can decrease biological clogging and increase dissolution in limestone aquifers (Gerges et al., 2002). The disposal of these backflushed waters that are usually of low quality have to be accounted for in the planning stage of ASR schemes

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(NRMMC-EPHC-NHMRC, 2009b). Precipitation of iron and manganese oxyhydroxides can be a problem during injection into anoxic groundwater (Moormann and Colin, 2002).

A number of clogging models and indexes have been used to predict the clogging behaviour, but not all processes are fully understood yet and clogging is variable in time and space (Brun and Jensen, 2001; Racz et al., 2012). For example the modified fouling index (MFI) could be used to estimate clogging potential (Dillon et al., 2001). Models are sensitive to initial conditions and require detailed information on soil properties, which is often limited by the intrinsic heterogeneity (Xiao, 2001; Siriwardene et al., 2007).

5.2.2   Other O&M

Apart from maintenance related to clogging regular inspections of the facility are needed to assess if any repair works or cleaning is needed. This could include the cleaning of any screens, change of batteries, lubrication or replacement for equipment prone to wear and tear, repair of damage done by natural forces or vandalism. If mechanical or electrical parts are involved their proper functioning needs to be tested.

Models can also help in optimising current operations. For example a Hydrogeological Model based on Visual C++2010 has been developed for the Omdel recharge dam (see section 2.6) (Dorsch International Consultants, 2012). With a monthly record of inflow data and the mean rainfall and evaporation for the catchment, stochastically generated sequences of monthly inflow to the dam are simulated. To calculate infiltration at the dam reservoir, along the river section towards the basins and inside the infiltration basins, estimations for infiltration rates are needed. The estimated sediment load allows for defining scouring and recharge release based on the appropriate settling period. This model could be adjusted to other infrastructure settings.

5.2.3   Monitoring

> **Monitoring is an integral part of the risk assessment of MAR and should be undertaken to both determine the effectiveness of the recharge scheme and to investigate the sustainability with respect to human and environmental health. Due to site-specific characteristics each scheme will be different.**

Monitoring (see also section 15.2) starts with baseline monitoring i.e. the investigation of the current situation before the MAR scheme is implemented and should cover spatial and temporal variability. Validation monitoring determines the actual performance of the MAR scheme and is essential if the natural attenuation processes are part of the treatment scheme. For quality monitoring, mean concentrations in source water rather than peak values are needed. Commonly surrogate parameters are monitored. If pathogens are of concern, *E.coli*, coliphage and clostridium spores (NRMMC-EPHC-NHMRC, 2009b) or rotavirus, *Cryptosporidium parvum* and *Campylobacter* (WHO, 2004) could be measured as pathogenic indicators. Typical herbicide parameters could be simazine and chloripyrifos (Swierc et al., 2005). Conservative tracers in source and groundwater can help determine the amount of mixing. More than one monitoring well is required in fractured or karstic aquifers. They should be placed at the margin of the attenuation zone. Determining quantitative recharge aspect helps to undertake a better cost-benefit analysis and make informed

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decisions. Operational monitoring is required for sophisticated MAR schemes that shut down if certain quality parameters are not fulfilled. Verification monitoring is often necessary for regulatory agencies assessing the whole performance. The review of monitoring results allows the adjustment of parameters and sampling frequencies (NRMMC-EPHC-NHMRC, 2009b). It is vital that monitoring results are collected, evaluated and distributed to interested stakeholders. As many different parameters determine the performance of a MAR site, each site is unique and requires site assessment and monitoring (NRMMC-EPHC-NHMRC, 2009b).

Recommended preventive maintenance and monitoring requirements for surface recharge operations in the USA include daily changes in water level and water quality sampling of inflow water; weekly calculation of water budget including evaporation, calculation of recharge rate, check on conditions of dam, levees etc,; and monthly maintenance of pumps, gates, valves and groundwater level monitoring (ASCE, 2001).

Most schemes in developing countries are not or only sparsely monitored to reduce costs. However, without controlling the effectiveness, costs spend on implementation might be wasted, and without monitoring of impacts to environment and health, long-term costs due to groundwater contamination might largely outweigh saved monitoring costs. Especially pilot projects should be monitored properly to assess the viability before up-scaling.

A number of reports on the topic of monitoring well installation and networks for characterizing subsurface processes have been published (e.g. NRC, 1994, 2000; Margane, 2004; IGRAC, 2006).

> **Long-term monitoring of actual flood volumes should be undertaken before dam construction. Monitoring of recharge volumes should be undertaken after construction.**

5.3 Institutional issues

> *"Projects which devote time to community mobilisation and user group formation, and that clearly define their rights and responsibilities, are likely to be more sustainable." (Gale, 2005)*

The institutions involved in the implementation of MAR schemes depend mainly on the scale. As water availability is often limited in (semi-)arid regions small scale schemes are more common. For these, the participation of the local stakeholders and beneficiaries is the key to success, and many published MAR schemes in the developing world are based on a decentralised and participatory approach. Many schemes are implemented and managed through the labour and partial monetary investment by the local community creating a sense of ownership and responsibility. Technical and financial help from governmental institutions, technical experts and NGOs would be needed for creating knowledge about MAR technologies, water right issues and management issues. Site selection should be based on expert analysis and local knowledge about water flow pattern. Guidance should also be given in organising and regulating the MAR schemes. Cost and labour sharing arrangements as well as rights and responsibilities have to be defined at the start of the project and a review process should be clearly outlined (Gale, 2005) (see also section 13.6).

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Large scale schemes with a higher degree of technical complexity on the other hand should involve the education and consultation of the affected community, but would be managed and implemented by regional or national authorities (Tuinhof et al., 2012).

If there is a history of government based implementation, the local community might require some incentives and knowledge as well as time to adapt to the new approach. Published handbooks (e.g. Jeffrey and Russel, 2006) might provide some guidance. A partnership between the public administration and local communities, potentially facilitated by local authorities could be the preferred model (Gale et al., 2002a).

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6 Strategies, regulations and legal issues

Apart from the technical considerations and economics, legal issues and institutional arrangements are important for a successful MAR scheme.

As socio-economic and political aspects are usually more critical than technical aspects, any new national strategy and implementation scheme should be developed with all stakeholders and cannot be written overnight. Only with a consistent and transparent support from the government and knowledge about MAR potential will local user groups and NGOs be able to create a significant impact. Up-scaling of pilot initiatives can only be undertaken with a concerted effort from all sites and can be done via replication, via diversification or by a large intervention (Tuinhof et al., 2012). Without a clear strategy from the government and legal security, MAR schemes might remain small, local and ineffective. Without clear regulations, MAR arrangements are often ad hoc and arbitrary, resulting in uncertainty.

The main objectives of MAR regulations should be the protection of groundwater from pollution and the insurance of public health. Topics covered in a regulatory framework include technical issues, water quality requirements to protect groundwater and human health, regulations on the authorization to recharge and to recover water and institutional arrangements (NRC, 2008). Allocation and water quality issues are of high relevance and it is advisable to have one operator for one aquifer to decrease complexity (Dillon et al., 2007). It is advisable to tailor the level of protection to the ambient conditions of the aquifer to achieve a higher efficiency (Dillon et al., 2007). For example, recharge water would not need to be treated to highest quality if the recharged aquifer is highly saline.

Regulations should ensure that appropriate investigations are performed for site selection, design and operation. The existence of a management and monitoring system as well as reporting needs should be demanded and the purpose clearly outlined (Dillon and Molloy, 2006).

One strategy could be to make stormwater recharge basins and roof-top harvesting mandatory for new developments. Another strategy could also to set aside uniquely suitable areas for MAR for later implementation and invest in water quality protection in the catchment (Murray et al., 2007).

Liability issues need to be outlined related to possible drowning in retention structures or downstream damage, if retention structures collapse resulting in a larger flood. A local community or NGO will not be able to indemnify victims for their losses.

6.1 Selected international examples for MAR regulations

There are only a few planning documents that clearly incorporate MAR as part of the water resources management.

6.1.1 Australia

The Australian MAR guideline forms part of the guidelines for water recycling (NRMMC-EPHC-AMHC, 2006) which is subdivided into water recycling for augmentation of drinking water supplies (NRMMC-EPHC-NHMRC, 2008), managed aquifer recharge (NRMMC-EPHC-NHMRC, 2009b) and stormwater harvesting and reuse (NRMMC-EPHC-NHMRC, 2009a). Altogether they form part of the broader national water quality management strategy

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(ARMCANZ-ANZECC, 1994) comprising guidelines for fresh and marine water quality (ANZECC-ARMCANZ, 2000a), for groundwater protection (ARMCANZ-ANZECC, 1995) and for water quality monitoring and reporting (ANZECC-ARMCANZ, 2000b) as well as the drinking water guidelines (NHMRC-NRMMC, 2004).

The MAR guideline applies to all aquifer types (unconsolidated, fractured, karstic), but does not cover allocation or water governance issues and is not binding. Allocation and water governance is recommended to be based on a strict separation of rights for water harvesting, aquifer recharge, for recovery and for use, but implementation is yet to come (Ward and Dillon, 2009, 2011, 2012).

The protection of the environment especially groundwater dependent ecosystems and human health are the main objectives and the risk management plan is based on 12 main elements (Fig. 9).The approach is risk based and uses the HACCP approach adopting preventive measures and operational procedures rather than strict values for each parameter. Accordingly the approach is flexible and poorer quality water can be used if native groundwater quality is brackish and reuse beneficial use is not drinking supply. Monitoring forms the component of the risk management framework and encompasses baseline, validation, operational and verification monitoring.
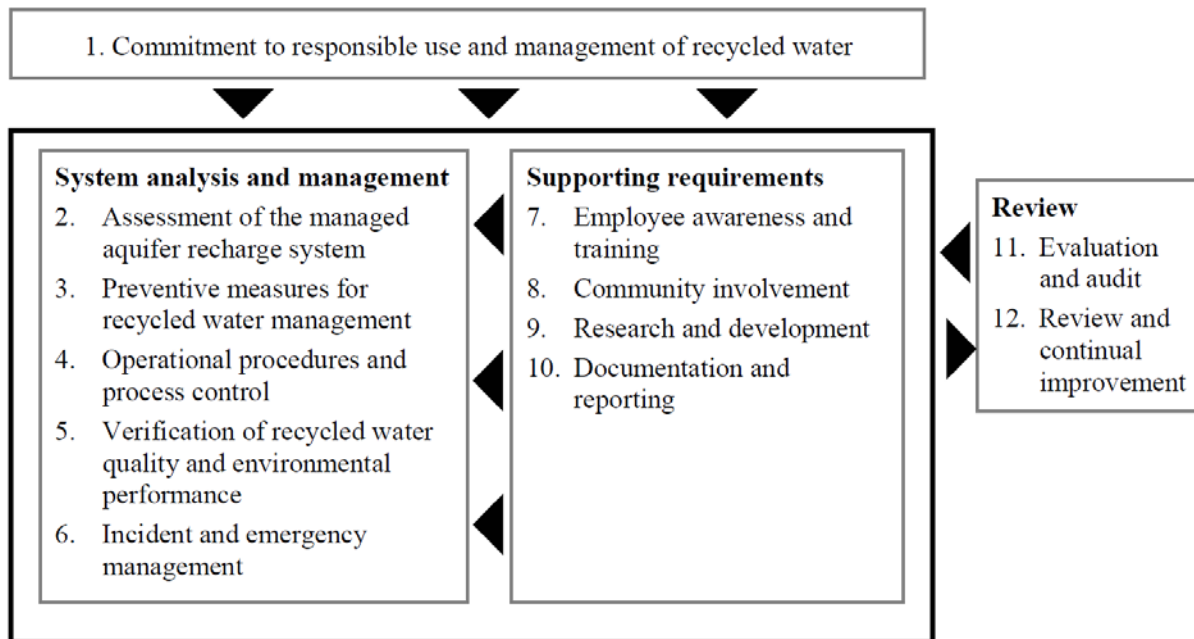
Fig. 9: The 12 fundamental elements for the development of a risk management plan for MAR (NRMMC-EPHC-AMHC, 2006).

The entry level assessment assesses the viability of the scheme (part 1) based on five main factors: demand, supply, aquifer characteristics, land requirement and the management capability and at the degree of difficulty (part 2) based on 14 questions relating to source water quality, groundwater quality, current use etc (see section 13.7 for an example assessment and Page et al. (2010)). The next stage a baseline investigation collects information in the field and through modelling to allow for a maximal risk assessment in the absence of preventive measures, followed by a residual risk assessment in the presence of preventive measures for precommissioning. Main hazards discussed in the framework are chemical (pathogens, inorganic chemicals, salinity, nutrients and organic carbon, organic

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chemicals, turbidity/particulates, radionuclides), physical (pressure and groundwater levels, contaminant migration, aquifer dissolution and stability) and environmental (groundwater-dependent ecosystems, greenhouse gas considerations).

6.1.2   Europe

European regulations are based on the Water Framework Directive (WFD, 2000/60/EC (European Commission, 2000)) and the Groundwater Directive (GWD, 2006/118/EC (European Commission, 2006)) which prescribes the imperative of non-deterioration of current water status and the aim of achieving a 'good' water status. These directives do not specify MAR regulations, but it is generally permitted. To guarantee the protection against pollution and deterioration the input of hazardous substances should be prevented, but natural attenuation processes are taken into consideration (Hochstrat et al., 2010). A guiding European document should be developed and decision support systems could help in a sustainable MAR planning (Hochstrat et al., 2010).

French water policy relies on regulatory and planning instruments on three levels: European Union, national and hydrographic basin. The Water law from 1992 is the basis and has subdivided regulations into 'declaration' for a harvesting surface area from 1 - 20 ha and 'authorisation' for <20 ha. Smaller schemes are accordingly less restricted, both schemes require a water harvesting approval, and larger schemes also require an environmental impact assessment and need to comply with a set of water quality standards (Ward and Dillon, 2009).

The **Spanish** government issued the Royal Decree 1620/2007 which prescribes a number of water quality standards for reuse of reclaimed wastewater and excludes reuse for human consumption (Hochstrat et al., 2010).

In the **UK**, the authorization or licensing of the source water extraction, the quality of the recharged water and potential environmental impacts are addressed in the groundwater regulations reflecting the European groundwater directive and are overseen by the Environment Agency. Drinking water standards are used as benchmark (Gale et al., 2002b). The UK is undertaking pilot investigations and has done a national assessment of aquifers (Gale et al., 2002b).

6.1.3   India

The Indian Central Ground Water Board (CGWB) has published a guide on artificial recharge (CGWB, 2000), created a master plan (CGWB, 2002) and released a manual (CGWB, 2007) and selected case studies (CGWB, 2011). The Indian MAR strategy is based on the main requirements of source water availability and aquifer storage space and offers a range of techniques from spreading and percolation tanks to wells and roof-top harvesting. More than 225 000 recharge structures and 3.7 million rainwater tanks have been implemented already as roof water harvesting was made mandatory in urban areas. The guidelines emphasise the need for participatory decentralised decision making and projects are commonly organised through state/government - NGO partnerships and include a high level of community participation in planning, rehabilitation and management.

The technical aspects of the guideline describe the needed information and investigation (hydrometeorological, hydrological, soil infiltration, hydrogeological, geophysical and water

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quality studies) and possible techniques. Monitoring (water level, zone of benefit, water quality), impact assessments and economical analysis should be part of any project and finalise the application that should be submitted to the CGWB for each new MAR project. A checklist for implementation has been developed (Box 3).

Box 3: Check list for planning artificial recharge projects in India (CGWB, 2000)

1. Has the need for Artificial Recharge been properly established?
2. Have the issues concerning clearance of the scheme by competent authority been cleared on the following points? a) Economic viability, b) Subsidy if proposed, c) Sharing of costs, d) Sharing of benefits, e) Acceptance of submergence area, f) Compensation of land required to be paid for procurement, g) Any other issue.
3. Meteorological & hydrological Surveys: Have the following factors been taken into account? a) Rainfall and rainy days intensity, b) Evaporation, c) Availability of surplus water, d) Yield of basin and flood for designing spillways, e) Sediment load
4. Field Surveys: Have the following surveys been carried out? a) Regional Hydrogeological Survey, b) Detailed site hydrogeological survey, c) Soil survey, d) Infiltration studies
5. For construction of structures:
    A. Have the following investigations been carried out? a) Foundation conditions of percolation tanks, bunds, reservoirs, nala bunds, b) Sub-surface strata conditions for Recharge wells, underground dams (bandharas), c) Spill way design;
    B. Material Survey: a) Soils for impervious, semi-pervious, pervious zones of surface/sub-surface bandharas, b) Sand/rocks/bricks & tiles/Pea (for wells), c) Cement, d) Steel/Steel pipes/Slotted pipes/well screens
6. Land Acquisition: a) Have the land acquisitions required for structures, inundation, and source water supply channel/pipe line been decided? b) Has the mode of acquisition of land been discussed?
7. Design: a) Has the final location of each structure been decided? b) Has the layout of structures been marked out? c) Have the design details of individual structures been finalised?
8. Construction Programme schedules: a) Has the proposed construction programme been prepared and synchronised for timely construction? b) Have the agencies undertaking the work been identified?
9. Financial Resources: a) Have the year wise requirement of funds been worked out? b) Has approval of Finance Department been obtained? c) Has the expenditure approval been obtained and budget provision made?
10. Ecological Aspects: Is the area going to experience any of the following environmental/ecological problems? a) Inundation of habituated land, b) Creation of water logging, c) Deterioration of quality of groundwater
11. Public Participation, Cooperation: a) Have the implications of the scheme been explained and discussed with the local population? b) Have the aspects of the scheme involving people's active participation been worked out?

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6.1.4   South Africa

South Africa developed the Artificial Recharge Strategy in 2007 as part of IWRM (Murray et al., 2007). The national strategy is supposed to create an enabling environment for implementation of MAR and describes 7 themes (knowledge, legislation and regulation, planning, implementation, management, research and strategy implementation). Possible constraints and risks like clogging and uncertainty about the aquifer hydraulics as well as efficiency drops without basic maintenance are pointed out.

The pre-feasibility study check list encompasses 10 success criteria assessing demand, supply, aquifer characteristics, water quality, applicable method, environmental and regulatory issues as well as economic, technical capacity and institutional arrangements to screen areas for their suitability (Table 5). Afterwards the feasibility study assesses the same 10 criteria, but with more detail and more site-specific questions (Table 6). If an area is found to be technologically, economically, environmentally and socially feasible, an implementation and authorization process is recommended. A national study delineated about 20 priority areas for MAR based on bore yields, storage area, source water supply and areas with high abstraction signifying high demand. Further adjustment of the legal framework to clarify the authorization process for MAR projects was presented in 2009 (Table 7) (Murray, 2009).

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Table 5: The pre-feasibility study check list (Murray, 2009).

SUCCESS CRITERIA	CHECK LIST
1. The need for an artificial recharge scheme	1. What are the primary and secondary objectives? (Eg Primary: increase security of supply by ensuring aquifers are full prior to the onset of the dry season; secondary: water treatment) 2. Is artificial recharge the best option to meet the primary objective? (Better options may be, for example, to expand the existing wellfield, develop a new aquifer or introduce better water conservation measures). 3. Will artificial recharge meet the primary objective? (Eg If the aquifer is full prior to the onset of the dry season, will it provide the envisaged security?)
2. The source water	1. Roughly what volume of water is available for recharge? 2. When is it available?

3. Aquifer hydraulics	1. Will the aquifer receive the water?
	   a) Is there sufficient space in the aquifer to receive the water? (Eg. If you need to store $1 Mm^3$ before the onset of the dry season, will the aquifer be able to receive that volume?).
	   b) Is the aquifer permeable enough to receive it at the planned supply rate? (Eg If you need 10 x 10L/s injection boreholes, are there enough drilling targets or existing boreholes that will allow for these rates?).
	2. Will the water be retrievable when you want it? Or will it flow down gradient and away from the planned abstraction area?

4. Water quality	1. Is the source water quality suitable for recharge? Eg. Is the water not too turbid, saline or rich in organic material? Are there any particular worrying determinands, like heavy metals, disinfection by-products, etc, that could affect the final water quality? 2. Describe the natural groundwater quality. 3. Will *in situ* blending likely improve the natural groundwater quality or make it worse? Estimate the concentrations of key determinands in the final water quality. 4. Comment on clogging concerns.
5. The artificial recharge method and engineering issues	1. How will the water be transferred into the aquifer? 2. What infrastructure will be needed to treat, recharge and extract the water? 3. What are the engineering challenges and how significant are they?
6. Environmental issues	1. What are the potential environmental benefits, risks and constraints?
7. Legal and regulatory issues	1. Are there legal constraints? Eg Securing source water rights, etc. 2. Is there an existing groundwater licence and what are the conditions regarding use? 3. What type of authorisation is required from DWA to do the feasibility tests?
8. Economics	1. How much will the feasibility study cost? 2. Roughly, how much will the scheme cost? 3. Roughly, how much will $1 m^3$ of supplied water cost and how does this compare to other options for water supply?
9. Management and technical capacity	1. What skills will be necessary to manage, operate and maintain the scheme and are they available or obtainable?
10. Institutional arrangements	1. Who will be responsible for supplying the source water? 2. Who will pay for the source water? 3. Who will ensure that it's quality is suitable for recharge? 4. Who will regulate the scheme?

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Table 6: The feasibility study check list (Murray, 2009).

Success Criteria	Check list
1. The need for an artificial recharge scheme	1. List the primary and secondary objectives. 2. Describe how the scheme will work to meet the primary objective. Describe the artificial recharge and abstraction cycle in relation to expected source water availability and recovered water needs. 3. Define the minimum (annual) injection volume that would make the project worthwhile. 4. Quantify the additional assured yield of the aquifer with AR.
2. The source water	1. Quantify the source water's assured yield (per month). Discuss risks of under-supply.

3. Aquifer hydraulics	1. Will the aquifer receive the water?
	   a) Quantify the volume of water the aquifer is able to receive when water is available for recharge. This should be based on historical water level and abstraction data.
	   b) Quantify the artificial recharge rates. Depending on the artificial recharge method, this should be done by soil infiltration tests or borehole injection tests. If injection tests are not possible (because of the logistics of getting source water to boreholes), then pumping tests should be done. The purpose and method of all tests must be clearly defined.
	2. Describe the groundwater flow regime and comment on envisaged losses down-gradient of the wellfield.

4. Water quality	All aspects that define water quality need to be assessed, including chemistry (organic and inorganic), microbiology and physical characteristics such as turbidity, etc. 1. Describe the source water quality. 2. Describe the groundwater quality. 3. Discuss whether there are concerns around the expected blended water quality, and if so, assess them. 4. Discuss whether there are concerns around water-rock interactions, and if so, assess them. 5. Estimate the concentrations of key determinands in the final water quality. 6. Describe expected types of clogging and prevention and management considerations. 7. Establish whether pre-treatment is necessary and if so, what form. 8. Describe whether post-treatment will be required and if so, what form. 9. The purpose and method of all tests must be clearly defined.
5. The artificial recharge method and engineering issues	1. Identify the project implementation phases if a phased approach is necessary. 2. Develop a preliminary infrastructure design for the treatment and conveyance infrastructure, and for the recharge facility. 3. Describe how the design will minimise clogging. 4. Compile a detailed project implementation plan.
6. Environmental issues	1. Identify environmental benefits, risks and constraints. Certain tests may need to be designed specifically to establish environmental impacts. 2. Discuss unforeseen risks, such as the use of reclaimed water for any purposes that were not intended, discharge of a recharged, full aquifer into the environment, etc.
7. Legal and regulatory issues	1. Describe the current legal status and new requirements for an artificial recharge scheme. 2. Obtain authorisation, if needed, from DWA to do the feasibility tests. 3. Establish authorisation requirements for full-scale operation.
8. Economics	1. Cost the project based on the preliminary infrastructure design. 2. Establish the cost per 1 m^3 of supplied water. 3. Compare these costs to those of other supply options. 4. Describe (or cost) other quantifiable and non-quantifiable economic benefits that relate to the secondary objectives.
9. Management and technical capacity	1. Describe the skills needed to operate the scheme. Include management, scheme maintenance, hydrogeological, etc. 2. List the available skills and shortfalls. 3. Articulate the outstanding skills needed to operate a successful scheme.
10. Institutional arrangements	1. Describe the institutional arrangements and include: 2. Who will be responsible for supplying the source water. 3. Who will pay for the source water. 4. Who will ensure that it's quality is suitable for recharge. 5. Who will do the necessary monitoring (water levels and quality). 6. How the scheme will be regulated in terms of the licence conditions (particularly relating to source water quality, final water quality, water levels, recharge rates and environmental monitoring requirements).

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Table 7: Artificial recharge project stages, key activities and authorisation requirements (Murray, 2009).

Project Stage	Key Activities	Authorisation requirements
Pre-feasibility Stage	• Identify the potential AR project and describe the information currently available. • Based on existing information, comment on the feasibility of the project. • Describe the work required for the Feasibility Stage and estimate the cost of undertaking the feasibility study. • Establish existing water use licence conditions and authorisation requirements from DWA.	None
Feasibility Stage	• If needed, obtain a water use licence and environmental authorisation for the recharge tests. • Conduct the feasibility study. This should include AR testing (eg injection tests, infiltration tests, pumping tests, water quality assessments, etc) • Develop a preliminary infrastructure design. • Identify the project implementation phases if a phased approach is necessary (eg starting small and expanding after successive recharge cycles). • Estimate the costs of the project. • Identify funding sources • Compile a detailed project implementation plan.	None, or a short-term water use licence for AR testing and possibly environmental authorisation for AR testing
Implementation Stage	• Obtain the necessary water use licence and environmental authorisation for the AR scheme. • Drilling and testing new injection and abstraction boreholes or infiltration basins • Set up the groundwater and recharge water monitoring system • Develop the detailed infrastructure design, carry out the tendering processes, and construct the project. • Compile monitoring, operation & maintenance procedures.	Water use licence and possibly environmental authorisation
Operation and Maintenance Stage	• Carry out performance monitoring during production. • Modify operation & maintenance procedures based on scheme performance. • Develop final monitoring and reporting system.	Compliance monitoring and reporting.

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6.1.5   USA

The USA has a long history of MAR schemes with many projects under operation. The standard guideline for artificial recharge was introduced in 2001 (ASCE, 2001), but legislation lies with each state and hence regulations are fragmented (Maliva and Missimer, 2010). Many schemes are for potable reuse resulting in water right issues and contamination risks that have to be assessed. Accordingly feasibility studies have to be sufficiently comprehensive to allow for viability assessment. Recharge of reclaimed wastewater for potable recovery is possible after a minimum residence time of 60 days (CDPH, 2011). Good results have been achieved in alluvial aquifers, but more schemes also consider fractured or karstic aquifers. Many assessments comprise qualitative geochemical modelling of source and aquifer/groundwater interactions and quantitative hydrogeological modelling. Adequate monitoring and environmental impact assessment are usually required. The operation is commonly undertaken by the water agencies and subsidizes are limited. Groundwater laws cover property issues and authorisation regarding source water and recovered water and interaction between different users as well as the use of the aquifer (Ward and Dillon, 2009).

The recommended procedure for MAR implementation could be summaries in the following steps and include the involvement of the public from step 1 (ASCE; 2001):

1. **determination of demand, statement of objectives**

2. **data collection and organisation including physical and non-physical data**

3. **long-term resource evaluation (quantity and quality), legal restraints and cost estimations leading to first inventory of possible sites**

4. **site-specific studies including field testing for hydrogeology, geochemical interactions etc. leading to a conceptual hydrogeological model**

5. **design of scheme including conceptual plan, O&M plans, contingency plans, alternative plans**

6. **assessment for environmental issues, legal issues and social issues**

7. **cost-benefit analysis including O&M costs, contingency costs, and decommissioning costs**

8. **construction with detailed logging of bores, pump tests, sampling and record keeping**

9. **operation and maintenance including training for operators, preventive maintenance, monitoring and record keeping**

10. **decommissioning including monitoring and prevention of groundwater pollution**

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7 Conclusions (part I)

Managed aquifer recharge can be one component in an integrated water and catchment management strategy. It is likely to increase in importance in the future with increases in demand due to population growth and increases in water resource variability due to climate change. MAR can overcome some drawbacks of surface storage like high evaporation loss and water pollution risks. Worldwide, a range of different MAR techniques are implemented. The appropriate MAR design and management are selected based on site specific conditions. For (semi-)arid regions in developing countries low cost schemes like recharge (release) dams and infiltration basins are more suitable than complex and costly injection or infiltration wells. In such areas climate change impacts may result in lower source water availability, rendering schemes non-beneficial, a fact which is often not accounted for in feasibility studies.

MAR can provide a range of benefits to local communities like increased yields, drought resilience, improved livelihood and increase in habitats, but does not come without challenges or constraints such as costs, ownership issues and environmental impact. Lessons learned from worldwide examples show that technical and socio-economic constraints need to be considered (Gale et al., 2002a).

Technical feasibility can be limited by:

(a) the availability of source water. Especially in (semi-)arid regions with low rainfall, available water resources might already be utilised and its capture may only result in a reallocation between users but in no added benefit. In addition, mean precipitation is often not meaningful as rainfall occurs in infrequent, high intensity events. The results in the retention structure being dry most of the time, while the rare high runoff leads to overspilling, further reducing efficiency. In rural areas, where human demand already exceeds supply and environmental flow needs, the establishment of MAR might lead to increased degradation downstream.

(b) loss of harvested water through evaporation. If sediments clog the recharge structure and maintenance is not frequent enough, high levels of evaporation may actually result in reduced water availability. As actual recharge volumes are often not monitored, appropriate management decision cannot be achieved.

(c) water quality either through contamination of the source water or high salinity in the groundwater. The former requires expensive pre-treatment, the latter might result in low recovery efficiency, both possibly rendering the scheme unprofitable.

> **Underground storage space alone is not sufficient, if there is no water to fill it with.**

Socio-economic constraints could include:

(a) the inability of generating concrete benefits over a reasonable time and spatial scale. MAR scheme might not result in a significant increase in groundwater level and might have a longer lag time if vadose zones are thick. Recharged water might spread considerably and flow away scattering benefits over a larger area.

(b) economics. For example where water or energy prices are subsidised and an increase in water availability does not result in tangible benefits for the local community or if the pre-treatment and O&M costs outweigh the benefits. In addition,

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local stakeholders might not have incentives to invest in MAR, if they have short-term goals or their income is not affected by water scarcity.

(c) increase in demand. The implementation of MAR schemes displays an increase in water availability that commonly stimulates an intensification of agricultural activities often leading to an increase in abstraction rather than solving the original objective.

Accordingly, investigations for new MAR scheme should be based on solid baseline monitoring, site specific field investigation and demand analysis and should be accompanied by an impact assessment and economic analysis. If uncertainties about aquifer hydraulics and water quality are high, the required investigations will increase the costs of a MAR scheme. The development of multi-criteria GIS based MAR constraint and suitability maps could be a first step to identify viability and potentially suitable areas.

> **Baseline monitoring before and verification monitoring after implementation is needed to get comprehensive and reliable information on the rentability of MAR schemes. This will help to make informed decisions.**

However, success or failure hinges on a proper and economically viable management plan. The management of clogging is the single most important factor, followed by monitoring of effectiveness and protection of environmental and human health.

From an institutional point of view international examples show that the most sustainable projects engage local stakeholders and have clearly defined objectives, responsibilities and processes. Genuine participation combined with sound technical input will perform best (Gale et al., 2006). It is recommended to develop a holistic MAR strategy and to implement transparent and comprehensive regulations specifying maintenance, monitoring and reporting requirements. Regulations should also address water allocation, ownership issues and demand management.

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Part II: Jordan case study

8 Introduction

> **Available water resources are limited, while demand is steadily rising. MAR could help to increase available groundwater resources, decrease pumping costs and decrease groundwater salinity by dilution.**

Jordan is a country with chronic water scarcity (water availability in 2007: 140 m³/cap/a) due to its semi-arid to arid climate and growing water demand (Abdel Khaleq, 2008). The general population growth (2.2 - 2.5 % growth/year, total >6.5 Mio) is amplified due to migration from politically unstable neighbouring countries, e.g. 2 million people fled from Iraq to Jordan since 2003 (Hayek, 2009; Mesnil and Habjoka, 2012). Water demand could increase further for cooling of an envisaged nuclear power plant and processing of oilshale (Margane et al., 2010).

Estimations of the available renewable water resources vary. The long-term water budget states that 91.8 % of the total precipitation of 8.2 BCM evaporates, while about 4.8 % is infiltrating to recharge the groundwater (390 MCM/a) and the remaining 3.4 % occur as surface runoff (280 MCM/a) (MWI-GTZ, 2005). Another source states that Jordan's water resources consist of usable surface water (505 MCM/a), safe yield of groundwater resources (275 MCM/a) and treated wastewater (80 MCM/a), as well as fossil groundwater resources (143 MCM/a) and desalinated groundwater (50 MCM/a) (Hayek, 2009). The National Water Strategy (MWI, 2009) is based on the estimation of about 280 MCM/a of groundwater as renewable groundwater (baseflow) and a direct runoff of around 330 MCM/a (Fig. 10) (Margane et al., 2002a).

The current water use is about 1.5 BCM with the highest demand from the agricultural sector (71 %), followed by the municipal (23 %) and industrial sector (6 %) (AFD, 2011). As a consequence of a higher demand than supply, groundwater resources have been overabstracted for many years (about 50 % above safe yield in 2005). This has led to declining groundwater tables (Margane et al., 1995a, b) and drying up of springs and rivers (with Azraq Oasis being a prominent example) (Abu-Sharar and Rimawi, 1993; World Bank, 2009). In addition to groundwater quantity issues this has also led to groundwater quality issues with an increase in groundwater salinity in a number of wells. Groundwater and surface water quality is also deteriorating due to an overuse of fertilizer and pesticides, inappropriate solid waste disposal and discharge of untreated municipal, agricultural and industrial wastewater into the environment (World Bank, 2009).

Apart from the long standing recommendations for water demand reduction, the National Water Master Plan and National Water Strategy both call for an increase in water supply that could be achieved - besides large scale schemes - with an increase in reuse of treated wastewater as well as stormwater harvesting (MWI, 2009). Hence, investigations into managed aquifer recharge are seen as an option to increase water supply and reduce the effects of groundwater decline. Therefore, this study was initiated by the MWI and is concerned with the two most overabstracted basins in the highlands of Jordan: Amman-Zarqa (AMZ) (overabstraction 71.5 MCM in 2010) and Azraq basins (overabstraction 29 MCM in 2010) (MWI, 2010).

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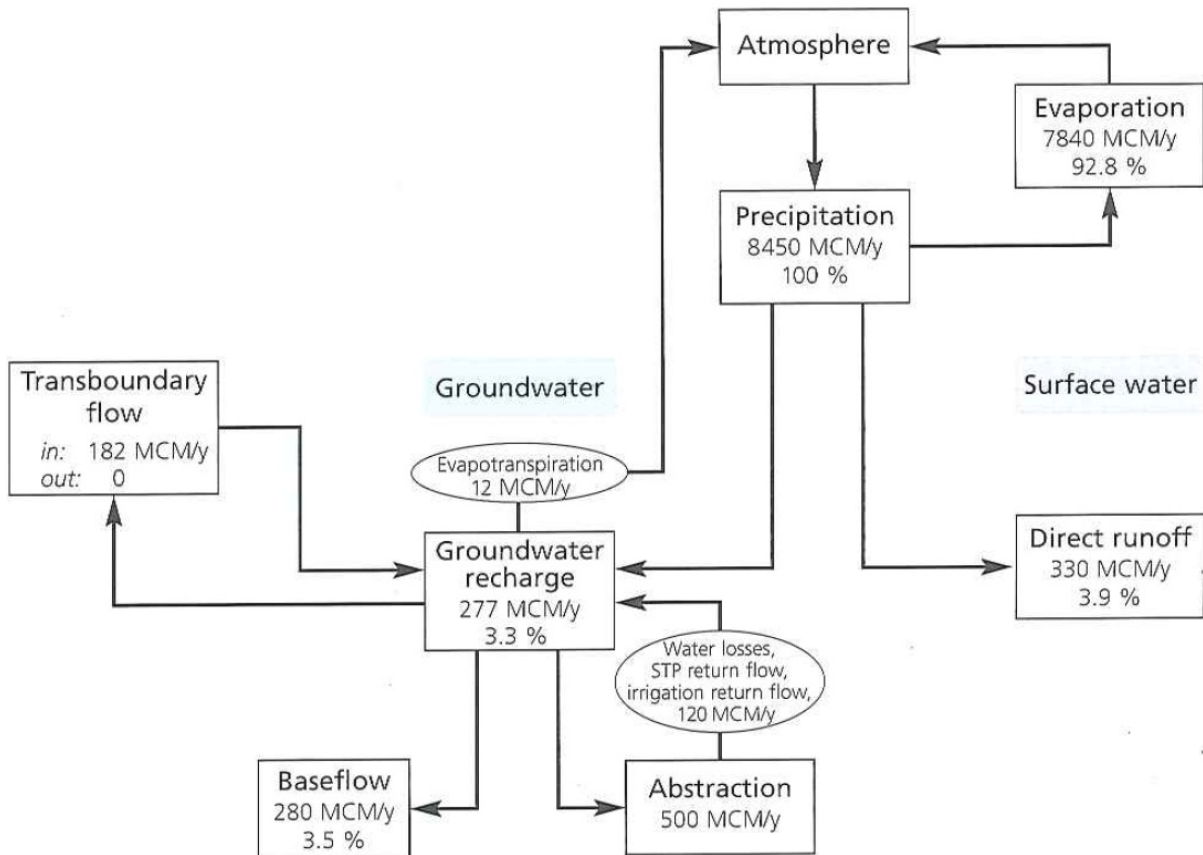
Fig. 10: Estimations of Jordan's water budget for Northern Jordan groundwater model (Margane et al., 2002a).

The purpose of recharge enhancement would be to alleviate the current groundwater level decline, store water in winter for use in summer and increase overall groundwater storage. Through the anticipated increase in groundwater level a decrease in pumping costs is also envisaged. In addition, groundwater recharge should improve poor groundwater quality by diluting it with fresh water. Even without a recovery of the recharged water close to the recharge site, a major environmental benefit could be achieved (Wolf et al., 2007).

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9 Previous studies and existing MAR sites

> **The hydrogeological setting is mostly favourable for MAR and a number of dams have been built already. However, considerable deposition of silt and clay at recharge dams hinders vertical infiltration; mainly lateral infiltration is occurring at sites with steep side walls. In addition, vandalism due to conflict of interests decreases the effectiveness of schemes and extra maintenance costs have to be anticipated, especially for small scale desert sites.**

In Jordan, water harvesting structures dating back to the Bronze Age have been found (Agnew et al., 1995) and the concept of managed aquifer recharge via recharge dams is not new either. A number of investigations have already been undertaken and a number of dams have already been built along the Jordan Valley and in the Highlands (Fig. 11), but documentation is often not available (Pavelic, 2005). Some of these dams where constructed for water harvesting and afterwards turned out to be leaking to the groundwater[3] (Al-Hamoud et al., 1995).
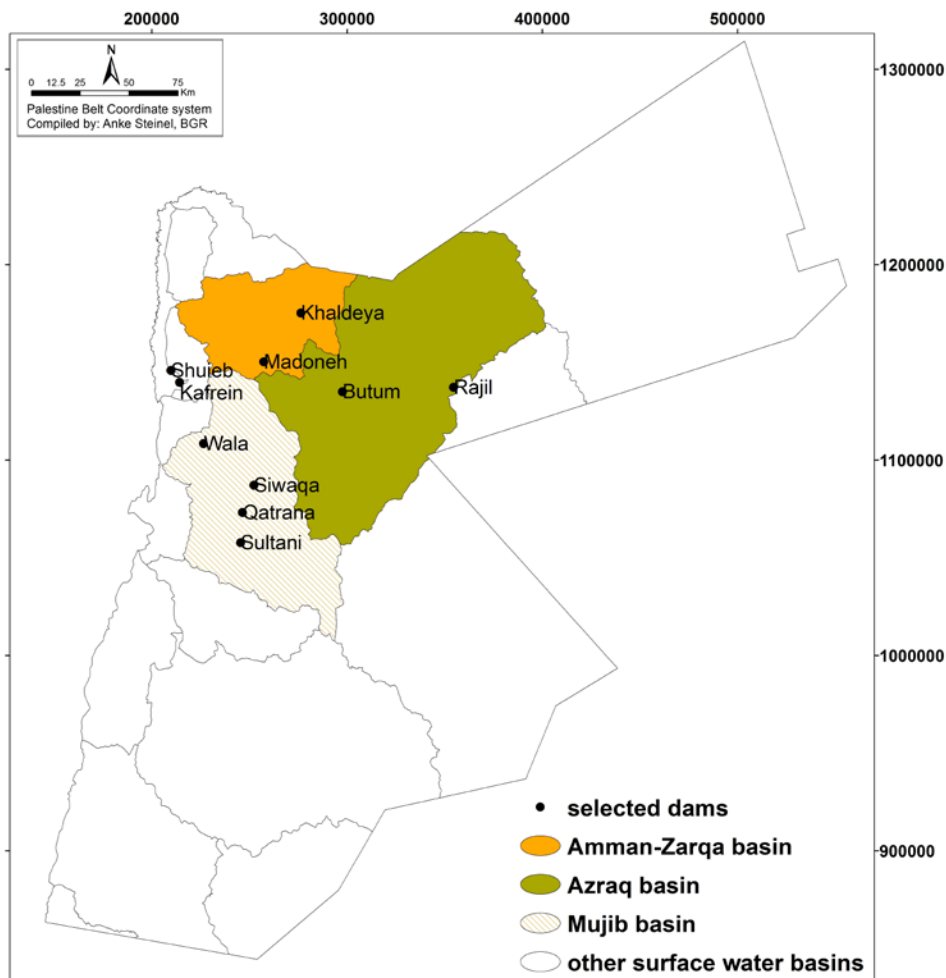
Fig. 11: Location of selected existing dams in Jordan.

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[3] e.g. Wadi Wala dam designed calculation were based on water storage for domestic use (Ismail, 1986); Kafrein dam: leakage was tried to stop with injections of cement and bentonite (Lenz, 1999)

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9.1 Jordan Valley

A number of water harvesting dams e.g. Wadi Shueib (constructed 1968, design capacity 2.5 MCM, catchment 185 km²), Wadi Kafrein (constructed 1968, raised 1996, design capacity 7.5 MCM, catchment 161 km²) have been built along the side wadis of the Jordan Valley, where catchments receive about 300 - 400 mm of rainfall, and are characterised by high evaporation losses and progressive silting (Wolf et al., 2007). They showed initially high leakage losses to the alluvial sands and gravel overlying the fractured limestone (at Wadi Shueib 30 000 m³/d in initial 3 months) and depending on the water level these dams can still recharge up to 20 000 m³/d (Lenz, 1999; MWI, 2001). While these dams provide enough water for recharge, a general problem with MAR schemes along the Jordan Valley is the short residence time of the recharged waters of only a few months due to the fractured nature of the aquifer and the location at the foot of the steep valley (Wolf et al., 2007).

9.1.1 Wadi Wala

Wadi Wala (Mujib basin, constructed 2002, design capacity 9.3 MCM, catchment 2000 km²) is commonly showcased as the most successful recharge dam in Jordan with a recharge volume of about 8 MCM/a (Sawarieh et al., 2011). Recharge rates into the A7/B2 aquifer vary between <0.5 to 1 m/d with water level in the reservoir, and the water is recovered at the downstream Heedan wellfield, where monitoring wells are directly responding to the reservoir storage level (Pavelic, 2005). The recharge occurs mainly through lateral movement in the steeply incised wadi walls and is not a possible scenario in the highlands, where the topography is generally much gentler. The evaporation from this reservoir is around 0.8 MCM/a and the siltation reached about 1.3 MCM in 2008, covering the lower draw off pipe (Margane et al., 2009a; Sawarieh et al., 2011).

This dam was actually designed as a recharge dam and dam water taken from the upper intake pipe passes through 6 sand filter units (capacity 1800 m³/h, 80 µm, recharge water turbidity <5 NTU) and is then infiltrated via 8 recharge wells (gravity flow) downstream of the dam. As the natural recharge rates has been decreasing and the reservoir does not empty enough for the next rainy season, the recharge wells are being used since June 2011. Since then recharge has taken place through a varying number of wells and rates varying from 1000 to >10 000 m³/d per well[4]. The resulting increase in groundwater level is dissipating quickly and no clogging effects have been experienced yet[5].

The heightening of the dam wall would most likely not have the effect of increasing recharge in the dam, as the overlying geological formations B1 is not conductive to lateral infiltration and further overlying B2 formation might direct the flow away from Heedan wellfield[6] (Margane et al., 2009a). It should be investigated, if it would not be cheaper to pump the water straight out of the reservoir to the next water treatment plant instead of increasing costs for filtering, recharging, pumping it a few hundred meters further uphill and then treat it, especially since there have been problems with elevated concentrations of nitrate, pathogens and turbidity in the Heedan well field (Margane et al., 2009a). Currently investigations are underway to determine the flowpath to the Heedan wells by tracer tests.

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[4] E. Hababsah (JVA), 2012, personal communication
[5] J. Xanke (KIT), 2011, personal communication
[6] H. Hötzl (KIT), 2011 personal communication

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9.1.2   Alluvium in Jordan Valley

The alluvium aquifers in the Jordan Valley deposited by the side wadis (Tertiary and Quaternary) are under investigation to be used for emergency storage of water supplied from the King Abdulla Canal or side wadi reservoirs. The potential storage capacity of all alluvial fans was estimated at about 115 MCM, but in some areas the underlying highly saline Lisan formation (aquitard) might lead to an undesirable increase in salinity (Salameh, 2001). Infiltration rates in the gravel beds of around 4 cm/d after some accumulation of silt seem to be possible (Dillon and Jiménez, 2008; Al-Amoush et al., 2012), but no recharge scheme has been implemented yet.

9.2   Desert Dams

For most of the older dams the documentation or monitoring is very limited and known details are hence very few. In the 1990s the 'Water Quality Improvement and Conservation Project' investigated the possibility for groundwater recharge in all of Jordan with a detailed feasibility study for Wadi Madoneh and Wadi Butum (Chehata et al., 1997; Abu-Taleb, 1999). In both areas recharge structures have been implemented since. The Wadi Madoneh case is the only well documented and monitored site (de Laat and Nonner, 2011). For the most recently constructed site at Wadi Butum a newer feasibility study (Orient ECD, 2010) and design drawings are available, but no monitoring has been implemented.

For Azraq basin an assessment based on hydrogeology and runoff calculations using the CN method selected five suitable MAR sites (Wadi El Maghayer, Wadi Butum, Wadi Kleita, Wadi Erratam and Wadi Aritain) (Al-Kharabsheh, 1995). Only the Wadi Butum site has been implemented.

9.2.1   Various older sites

The main issue commonly noticed at existing recharge dam sites (e.g. Sultani dam (Mujib basin, constructed 1962, design capacity 1.2 MCM), Qatrana dam (Mujib basin, constructed 1964, design capacity 4 MCM), Rajil dam (Azraq basin, constructed 1992, design capacity 3.5 MCM, catchment ~3000 km²), Siwaqa dam (Mujib basin, constructed 1993, design capacity 2.5 MCM, catchment 189 km²)) is the accumulation of fine sediments at the dam. Most of these dams have silted up and now basically act as large evaporation ponds (Chehata et al., 1997; Pavelic, 2005; van Steenbergen and Tuinhof, 2009). One monitoring well near Siwaqa dam (CD3305) showed annual peaks in groundwater level slightly higher than usual for the first years after construction (Almomani and Subah, 2005). This would imply that recharged water infiltrated 80 - 100 m vertically and 100 m horizontally in the same year and recharge mounds would not dissipate too quickly. Alraggad (2009) attributed a rise in groundwater levels in 2002 - 2006 to the same recharge dam, which could mean that the main recharge front needed 8 years to reach the monitoring well (Fig. 12). However, it seems unrealistic that noticeable water level increases would be measurable in comparison to the natural fluctuations (Gale et al., 2006).

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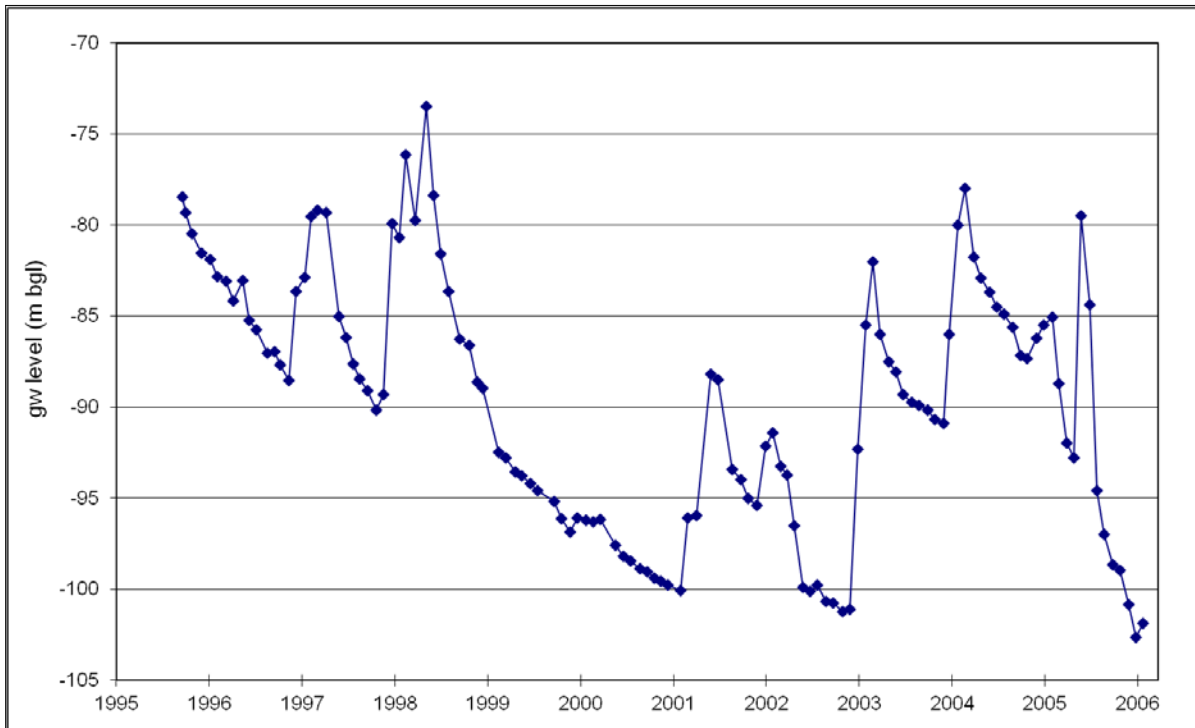
Fig. 12: Groundwater level (m bgl) at well CD3305 (Siwaqa dam observation well no.1), total depth 208 m, aquifer A7/B2.

Khaldeya dam (AMZ basin, also called Aqib dam, constructed 1983, design capacity 1.4 MCM, catchment 395 km²) was designed for local recharge and recharge wells have been constructed, but were never used and recharge from the dam was unsuccessful due to rapid siltation (MWI, 2001) (Box 4). Wadi Rajil was only filled once in the first 5 years after construction (Dottridge, 1998) and recharge has not been monitored.

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Box 4: Evaluation of impact of Khaldeya recharge dam on groundwater level

The monitoring well AL1926, which is about 780 m SSE of Khaldeya dam, shows no significant drawdown until 1988, which might be due to recharge from the dam, but could also be due to three years of reasonably good rainfall. Later the drawdown is about 1.3 m/a. It is also noticeable that years with rainfall <100 mm/a show only a very small to no peak in water level. This is due to reduced groundwater recharge and an increase in abstraction at the nearby Hallabat wellfield. The graph (Fig. 13) also shows that infiltration through 100 m of unsaturated zone and flow along 780m of saturated aquifer occurs within a few weeks due to the karstic nature of the limestone aquifer A7/B2 and the accordingly high hydraulic conductivity (see Table 23).
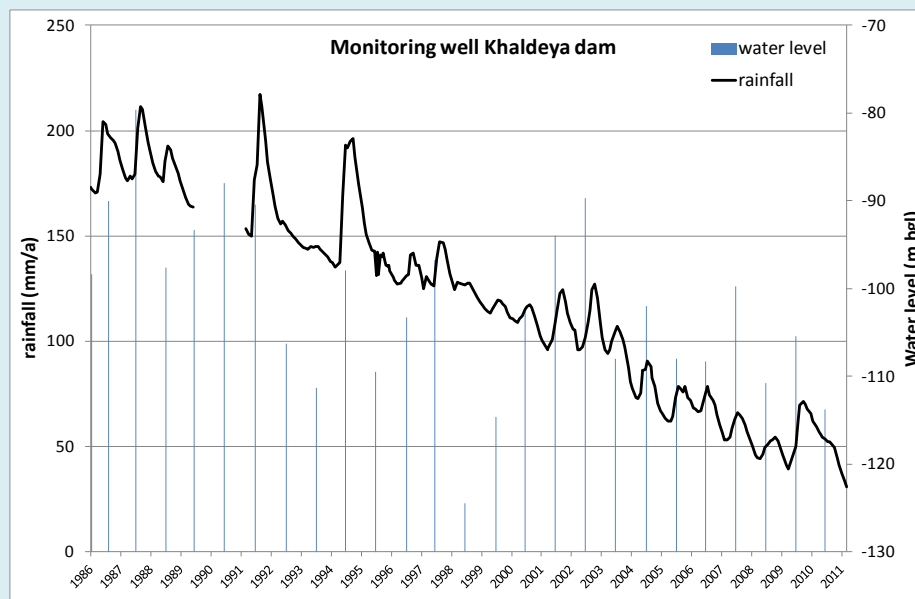
Fig. 13: Water level at monitoring well AL1926 in aquifer A7/B2 about 780 m SSE of Khaldeya dam compared to weighted average annual rainfall over catchment from rainfall stations AL0048, AL0058, AL0059 and F0001 (arranged from WIS data, MWI, 2011).

9.2.2   Wadi Madoneh

The Wadi Madoneh scheme consists of 4 dams (AMZ basin, constructed 2007, total design capacity 0.093 MCM, total catchment 34 km²) recharging the A7 aquifer. These are the first recharge release dams in Jordan with a simple design of a vertical line of release pipes that allow the stored water to be released from the dam in about 14 days and to slowly infiltrate in the downstream wadi (de Laat and Nonner, 2011). A prefeasibility study consisted of measuring rainfall (average 160 mm/a) and runoff over three years (avg. 0.2 MCM/a). It showed that about three runoff producing events per year occur with a runoff coefficient of about 3.5 % (de Laat and Nonner, 2011). It was also implied that runoff calculations (0.38 MCM/a) using the CN method (see Chehata et al., 1997) largely overestimated actual flood volumes (de Laat and Nonner, 2011). Infiltration tests gave an infiltration rate of around 0.44 m/d (Abu-Taleb, 1999).

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Fig. 14: Wadi Madoneh: left) dam M2: metal parts from gabions and manhole were stolen and release pipe opening/closing mechanism blocked with large stone, right) dam M1: damage to dam due to the use of material not adhering to the specifications (Picture taken by A. Steinel in 2011).

The study also documents for the first time problems with vandalism and conflicts of interests. Downstream farmers wanted to increase release rates to allow water harvesting in their own dams, while Bedouins blocked the pipes, so the water could longer be used for livestock watering. Furthermore, all removable metal parts were stolen over the first few years (see Fig. 14 left). To prevent any unauthorised change in release pipes condition (open or closed), large rocks were positioned around the release pipes. This, however, resulted in the complete closure of the only open release pipe (lowest) due to sedimentation[7]. In addition, damage to the dams occurred due to large floods and the use of unsuitable building material (Fig. 14 right) (de Laat and Nonner, 2011).

9.2.3 Wadi Butum

At Wadi Butum (catchment 155 km², avg. rainfall about 80 mm) construction of 3 consecutive dikes and 3 consecutive infiltration basins (recharge basins each having a volume of 155 000 m³ storage capacity; dikes: 8700 - 16600 m³) downstream of the dikes has been completed in 2011 to recharge the B4 aquifer. Using flood measurement from nearby Wadi Muwaqqar for regionalisation suggests about 0.084 MCM/a runoff in 1.8 events/a for the Wadi Butum catchment (Orient ECD, 2010), while the CN method calculates about 0.235 MCM/a (Chehata et al., 1997) highlighting the overestimation of runoff with the CN method and the very low runoff coefficient of <1 % (see section 10.2.1). Equipment to monitor the effectiveness of this scheme is not installed yet. The installation of one monitoring well is planned[8]. Infiltration tests gave an infiltration rate of 0.15 - 0.24 m/d (Abu-Taleb, 1999).

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[7] 2011, personal observation A. Steinel
[8] M. Al Atrash (MWI), 2012, personal communication

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9.3 Existing MAR potential maps

> **Recently developed MAR suitability maps only considered the hydrogeological feasibility, not the availability of runoff or any socio-economic factors.**

Recently, two investigations have evaluated the potential for MAR for the Lower Jordan Valley including most of AMZ (Rapp, 2008) and for the Azraq basin (Alraggad and Jasem, 2010) with GIS techniques. Both studies used as main selection criteria (a) outcropping hydrogeology (classified into aquifer, aquitard and enhanced aquifer due to alluvial cover of high permeability), (b) slope (classified into <5 % or >5 %), (c) urban areas (with 250 m buffer) and (d) distance to available water resources (buffer of 5 km downstream of dams and 250 m along wadis).
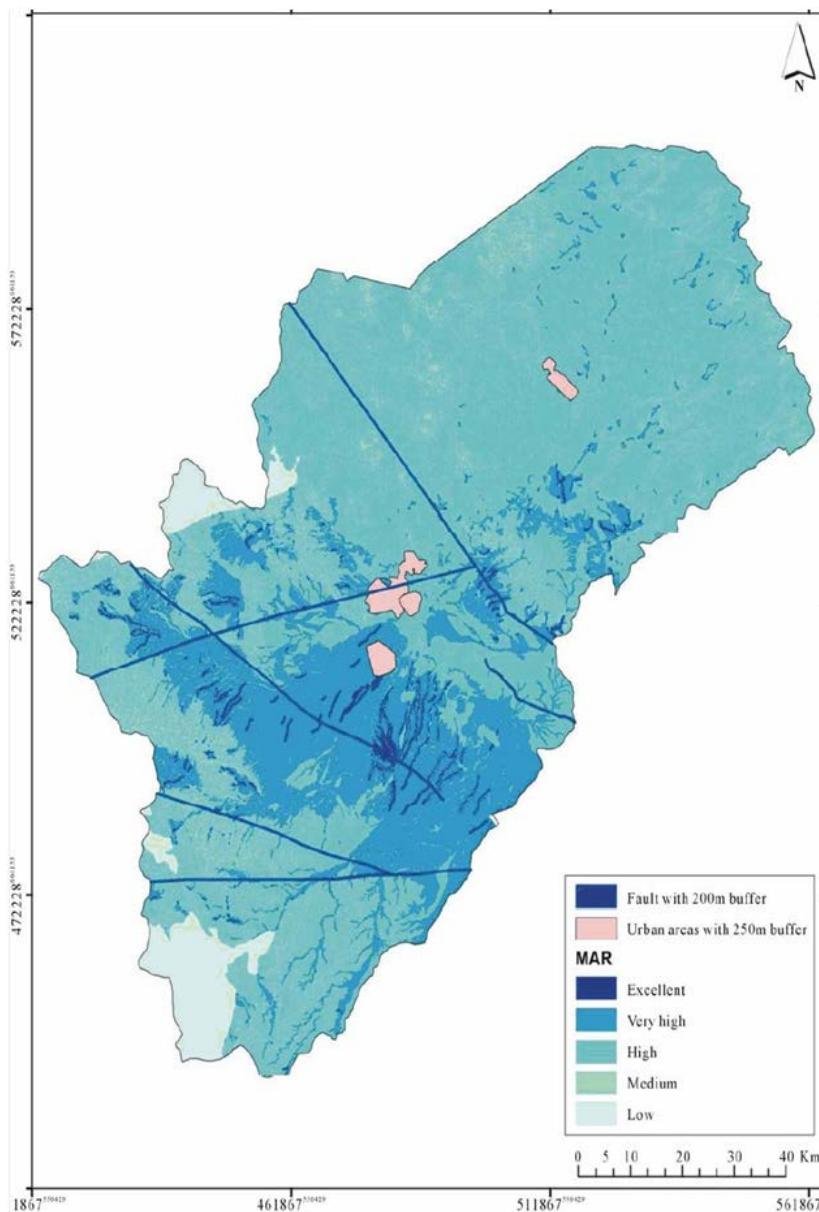
Fig. 15: Potential map for MAR through surface infiltration in the Azraq basin combined with urban areas and fault system (Alraggad and Jasem, 2010).

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![BGR Bundesanstalt für Geowissenschaften und Rohstoffe]

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Alraggad and Jasem (2010) also assessed existing fault lines (with 200 m buffer) as preferential criteria, where recharge would be enhanced. For Azraq basin 84.5 % was classified as high to very high potential (Fig. 15). For AMZ basin an estimated 60 % was classified as high to very high potential (Fig. 16). Both studies hence conclude that there are sufficient aquifers to provide large amounts of storage capacity. Both studies used only successive intersection of thematic maps without weighing and focussed on site selection, but have not assessed the potential for surface runoff and thus source water availability. Rapp (2008) addressed the proximity to existing dams and WWTPs, but not available non-committed volumes.
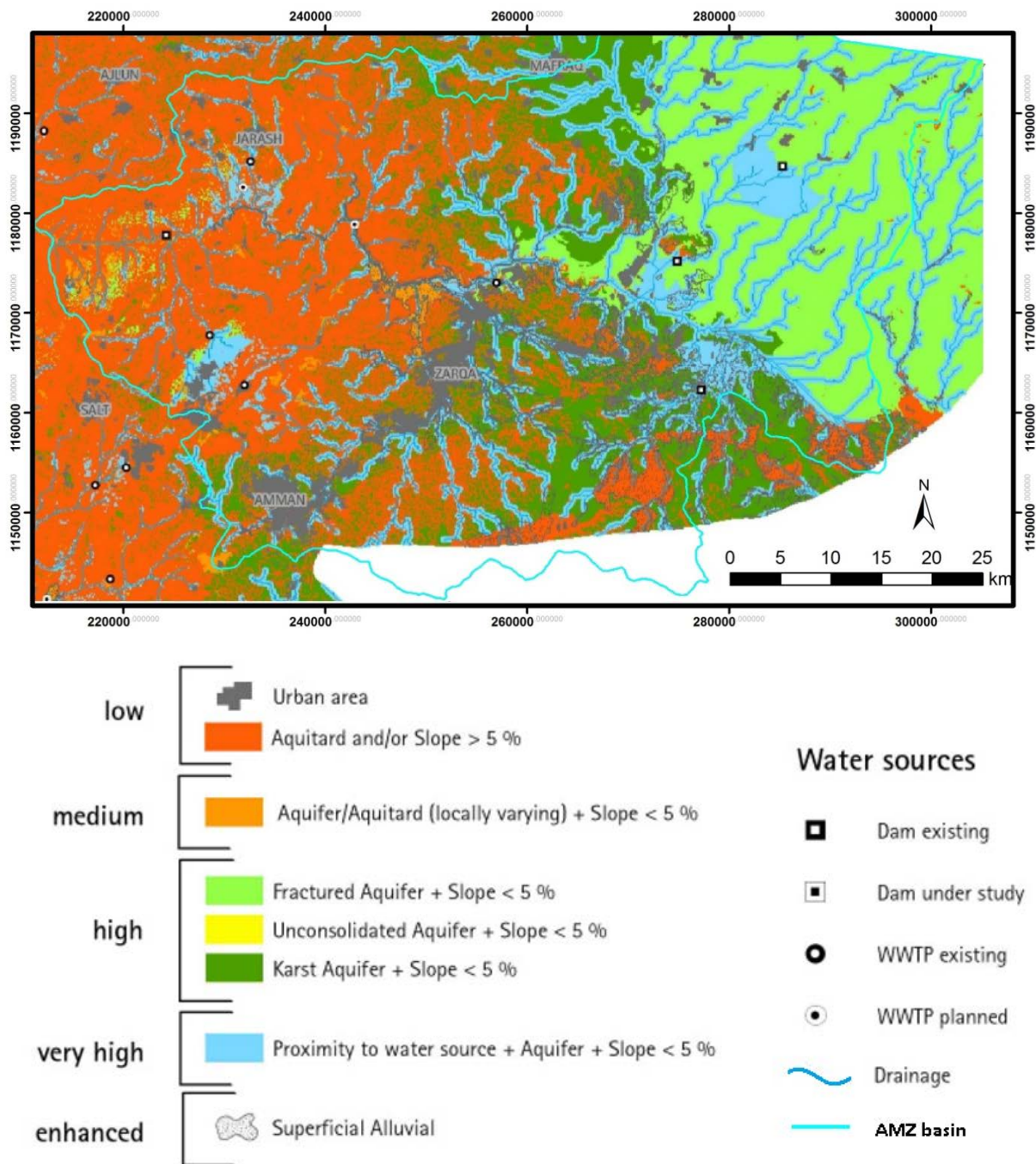
Fig. 16: Potential map for MAR via surface infiltration, extracted for AMZ basin (modified from Rapp, 2008).

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10 Data assessment

> **The three main questions to be answered for a technical feasibility study are: 1) Is there enough source water available for recharge; 2) Can the aquifer accept this water in terms of storage space and 3) can the water get to the groundwater rapidly enough?**

A range of parameters need to be assessed to evaluate the potential for MAR. The main criteria are the availability of a suitable aquifer with storage space at the surface (section 10.2), the availability of surface water resources (section 10.2), the possibility of infiltrating the harvested water to the aquifer (section 10.4) and general criteria like topography and land use (section 10.1). This short term study was based on and limited to the data supplied by the Jordanian partner institutions and published data. All maps are presented in Palestine Belt 1923[9] (PB) coordinate system, a Transverse Mercator projection based on the Clarke 1880 (Benoit) spheroid.

10.1 Basin description

Amman-Zarqa basin:	Azraq basin:
• steep slopes in the western part	• mostly flat
• highly populated, many factories, quarries and commercial farms	• sparsely populated
• reasonably good rainfall	• rainfall mostly <100 mm

This study is concerned with two very different basins: the AMZ basin (WIS code AL) is the most densely populated basin in Jordan containing the capital Amman (2.2 Mio inhabitants) as well as the second largest city Az-Zarqa (around 0.55 Mio inhabitants). A total of around 4.5 Mio people are living in AMZ basin, or about 65 - 70 % of Jordan's total population (Fig. 17) and about 80 - 90 % of all industries (Hammouri and El-Naqa, 2007a).

In contrast, Azraq basin (WIS code F) is very rural and has only about 29 000 inhabitants (Mesnil and Habjoka, 2012). The largest towns are Azraq and Umm Al Qettein with <6000 inhabitants each.

The AMZ watershed comprises a total area of 4010 km² of which 3673 km² are located within Jordan (remaining areas lie within Syria). The Azraq watershed is much larger with around 11880 km², of which 11313 km² lie within Jordan (Fig. 18). It encompasses another internal basin, the Qaa Khanna, with 825 km² (Fig. 18). The catchment areas were delineated using the USGS-DEM[10]. It was noticed that 81 km² (part of the Abu Suwwanah catchment) are assigned to the official Azraq basin, but actually belong to the AMZ basin. Flow from an area of about 326 km² (Wadi Salma, Wadi Al Maltat, Wadi Hashshad, Wadi Jarjir) in the northernmost part of Azraq is actually directed towards Syria and the area was hence subtracted for watershed calculations. Official (MWI) catchment sizes (Jordan only) are 3592 km² and 11720 km² for AMZ and Azraq, respectively.

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[9] Older data available in Palestine Grid can be converted into Palestine Belt by adding 1 000 000 to the Northing.

[10] The USGS HydroSHEDS is based on high-resolution elevation data obtained from NASA's Shuttle Radar Topography Mission (SRTM). http://hydrosheds.cr.usgs.gov/datasource.php

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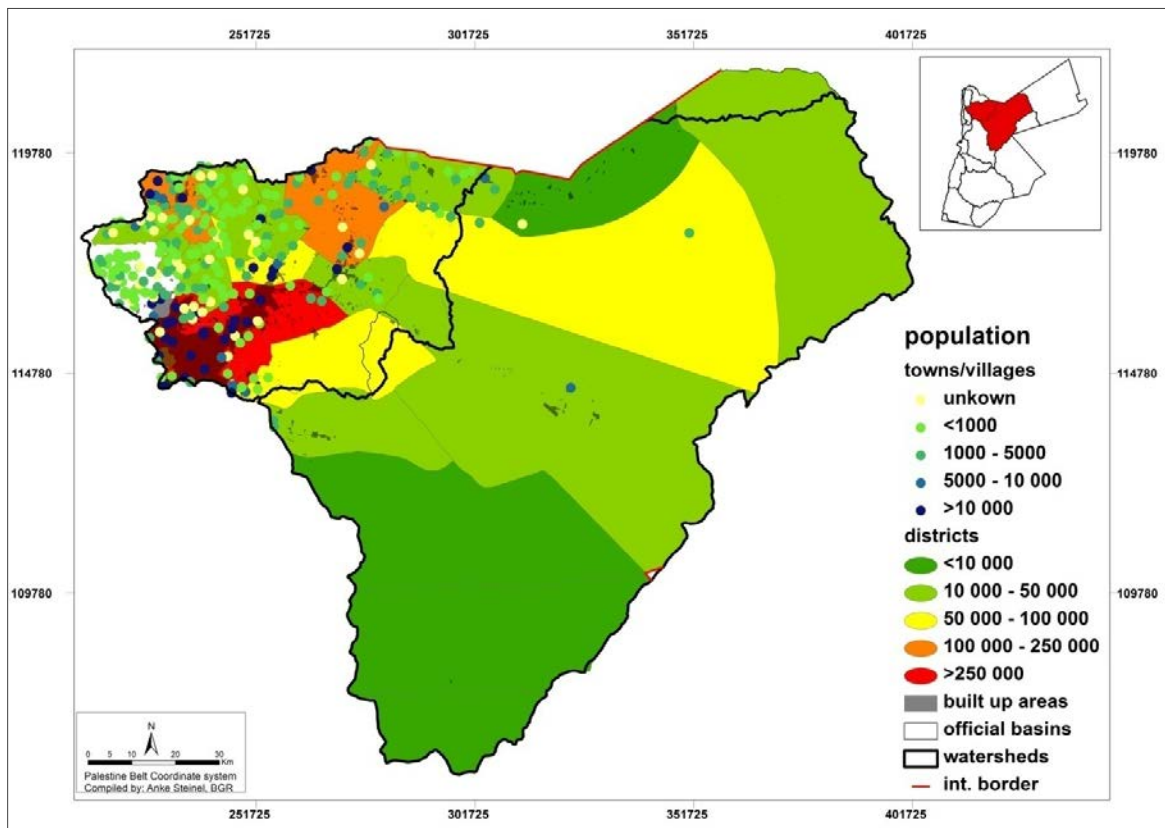
Fig. 17: Distribution of population in the AMZ (left) and Azraq (right) basins on district level and for individual towns and villages (arranged after DOS data, 2011).
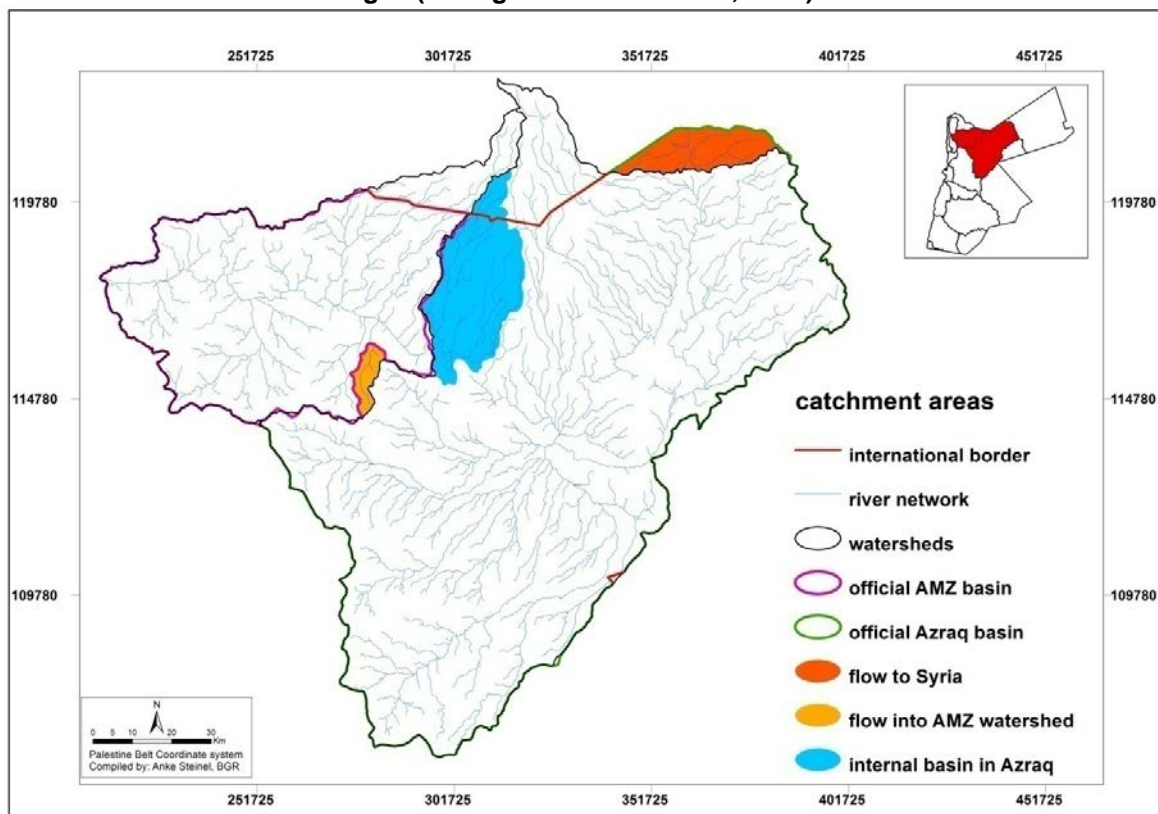
Fig. 18: Delineation of AMZ and Azraq watershed areas and differences to official basin outline; blue basin called Qaa Khanna (arranged after USGS-DEM).

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10.1.1   Topography

The topography (Fig. 19) 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 the Jebel el Druze/Jebel el Arab (1750 m) in Syria (highest point in Jordan is about 1150 m); (2) in the west, the Zarqa river and its tributaries have steeply incised valleys into the north-south trending highland mountains down to the lowest point in the catchments (-194 m); (3) in the middle of the Azraq basin, a very extensive flat depression without outflow (qaa) has developed at around 500 m. Accordingly, the morphology shows very steep slopes in the western part of AMZ. The rest of the study area is mostly below 10 % slope except for some volcanic/scoriaceous cones around the Jebel al Arab (Fig. 20).

In the basaltic area in the N and NE older lava flows show more rounded gently undulating hills and a well-developed drainage pattern. In contrast, more recent flows are characterised by more irregular topography and many silt filled depressions with poorly connected drainage network[11] (Al-Homoud et al., 1996). Different types of depressions can be distinguished: (a) *qaa:* flat area with no outflow, often saline, (b) *marab*: flat area fed and drained by wadis, seldom saline, and (c) mini-*qaas:* small depressions acting as sediment traps with no drainage (Allison et al., 1998). Qaas collect runoff and may be filled with water for a couple of months until all water is evaporated. Radial drainage is also possible in limestone areas of Azraq (Allison et al., 1998).
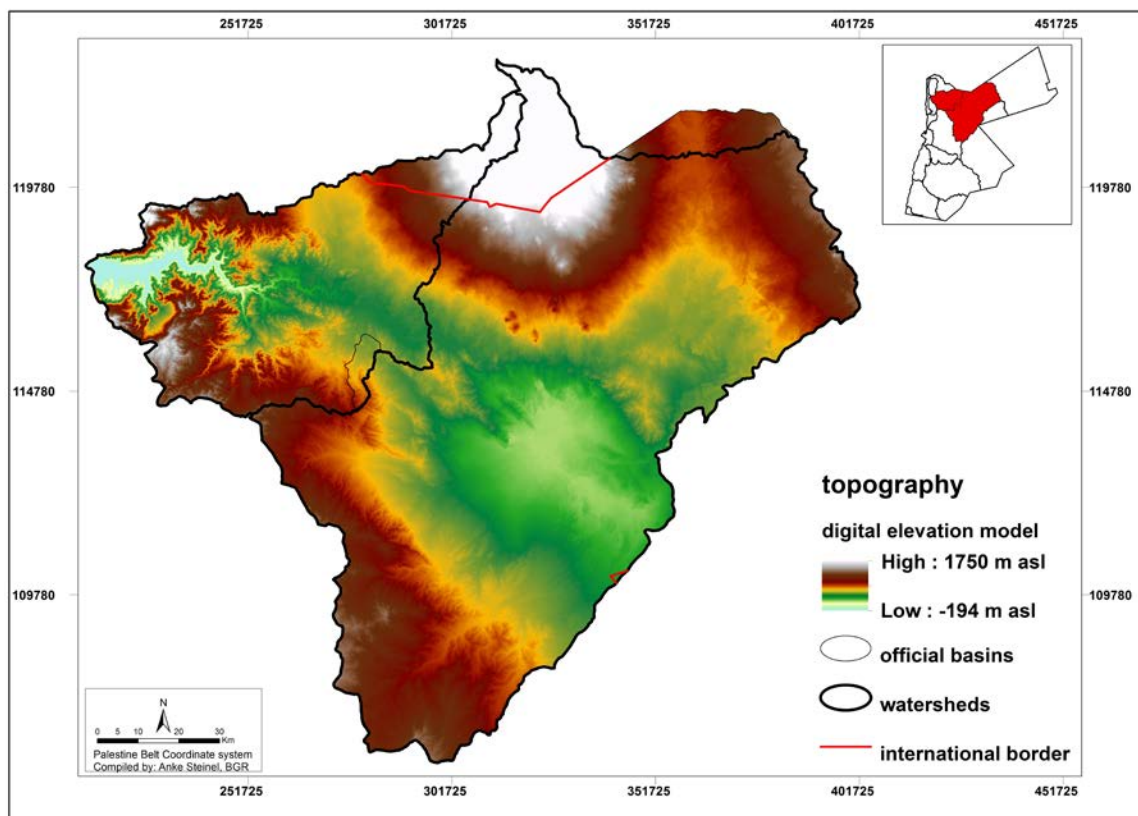
Fig. 19: Topography of the AMZ and Azraq basins (based on USGS-DEM).

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[11] The DEM is not detailed enough to recognise smaller depressions that might not be connected to the network and hence calculated catchment areas might too large.

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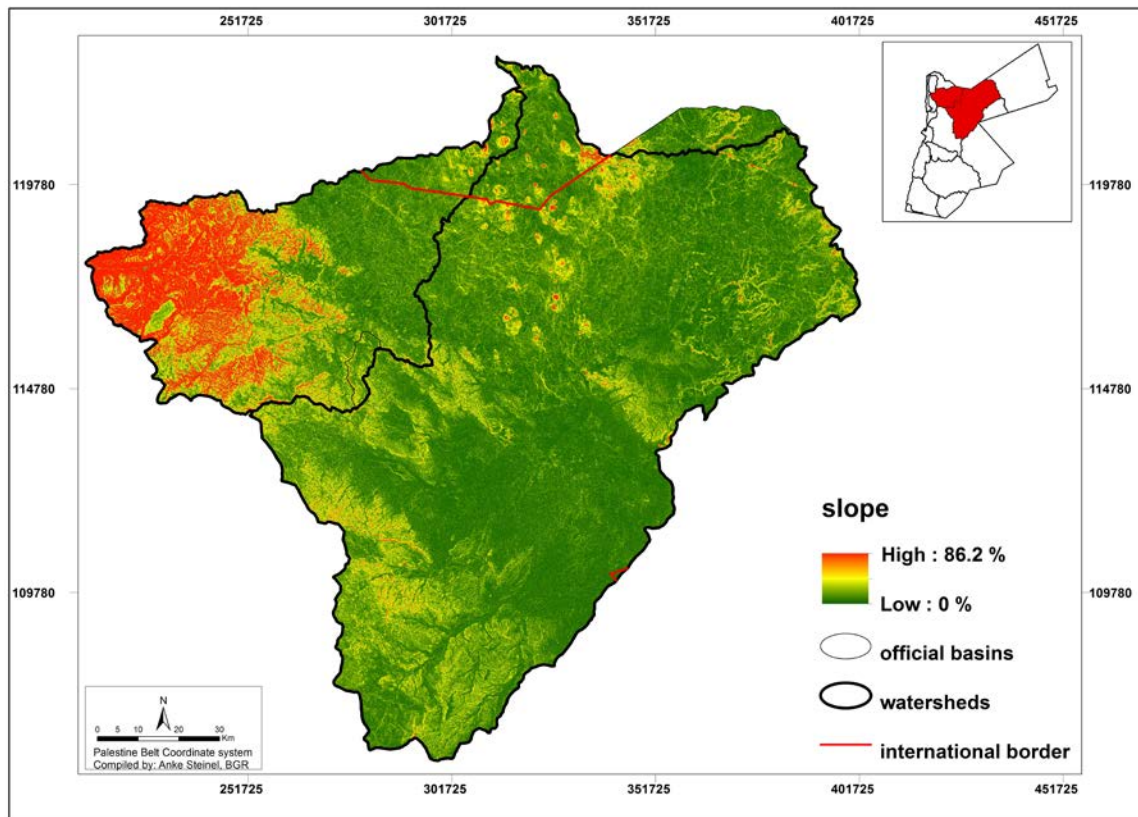
Fig. 20: Slope (%) of AMZ and Azraq basins (generated from USGS-DEM).

10.1.2   Land use

About 50 % of the AMZ basin is not used and mostly bare, 20 % is covered by fields with vegetables, grains and tree crops plus an additional 17 % with pastures. Since 2005 the urban areas have increased significantly from 6 to 16 % coverage (Table 8).

About 98 % of the Azraq basin is not used and is covered with bare basalt rocks, chert plains and alluvial deposits and is only very sparsely vegetated. Only around Azraq town and in the basaltic area in the NW are some field crops and olive trees grown (Fig. 21 and Table 8). Other sources estimate similar values of about 290 km² (~2.3 %) as agriculturally used (Huber, 2010).

With the increase in precipitation from south to north lichen/vegetation growth and the number of fields increases also (Al-Homoud et al., 1996). Generally, smaller farms (<5 ha) with olive trees are found near the former oasis, while new larger farms (>25 ha) with improved irrigation systems, often growing stone fruits, are mainly found in the North (Mesnil and Habjoka, 2012).

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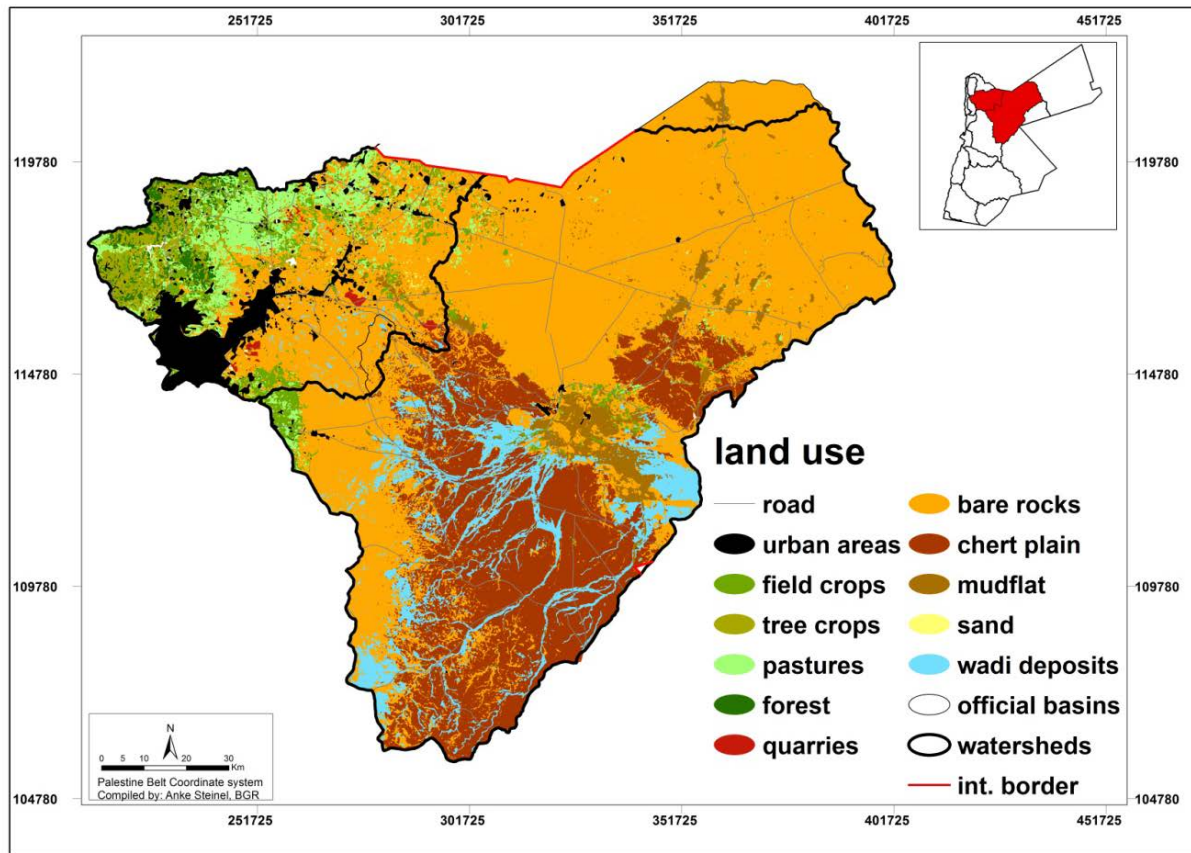
Fig. 21: Land use classification for AMZ and Azraq basin (modified from Land cover map (RJGC, 2011)).

Table 8: Land use classification (modified from land cover map (RJGC, 2011)) [12]**.**

land use	AMZ		Azraq		combined	
	km²	%	km²	%	km²	%
urban areas	221.6 (~576)* (~960)**	6.1 (~15.9)* (~26.5)**	3.9 (*105)**	0.03 (~0.8)**	225.5 (~580)* (~1065)**	1.5 (~3.8)* (~7.0)**
field crops	403.6	11.2	161.5	1.4	565.1	3.7
tree crops	329.1	9.1	3.5	0.0	332.6	2.2
pastures	616.7	17.1	81.8	0.7	698.5	4.6
forest	171.7	4.7	0.2	0.0	171.9	1.1
quarries	32.2	0.9	0.0	0.0	32.2	0.2
bare rocks/soil	1710.1	47.3	6768.4	57.8	8478.5	55.3
chert plain	20.6	0.6	3162.0	27.0	3182.6	20.8
mudflats	71.4	2.0	500.9	4.3	572.3	3.7
sand	6.5	0.2	0.8	0.0	7.2	0.0
wadi deposits	32.9	0.9	1025.6	8.8	1058.4	6.9

* urban areas digitized from GoogleEarth 2012[13]; ** buildup area map from MoMA (Ministry of Municipal Affairs, 2012)[14]

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[12] The RJGC land cover map is based on satellite images from 2005, verified by field inspections and released in 2011

[13] Urban areas including larger separate buildings, farms and factories were digitized in GoogleEarth to display the newest possible situation. Classification from Landsat images could not distinguish between natural rock formations and houses built out of the same rocks. Quickbird images could be purchased to allow pattern recognition at a high resolution.

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10.1.3   Climate

> **Jordan is characterised by cool winters with rainfall between October and April and a dry and hot summer between May and September. Rainfall often occurs in thunderstorms with irregular intensity, duration and high spatial variations. Potential evaporation is high, characterising the area as arid to hyper-arid.**

In the basins there are five active climate stations with daily data, two with monthly data and one closed climate station with three years of reading (AL0057, 2002/03 – 2005/06). There are two kinds of rainfall stations: daily[15] recorders and yearly totalisers that are read out on the 31st May[16] each year. There are 33 active daily rainfall stations, 24 closed daily stations and one closed totaliser with the code AL. Furthermore, there are 5 each active/closed daily stations and 5 each active/closed totalisers with the code F[17] (Fig. 22). At three rainfall stations in each basin rainfall intensity is measured in about 10 min. intervals[18]. In addition, three Syrian stations (code S; mean values from 1966 - 1990[19]) were added after Al-Kharabsheh (1995).

Rainfall

For the calculation of isohyets the weighted average (Thiessen polygons, (Chow, 1988)) yearly mean precipitation of all active stations with more than 20 years of record were used[20]. In correlation with the topography precipitation is highest (up to 450 mm/a[21]) in the western mountains and decreases quickly towards the south-eastern desert (<50 mm/a) (Fig. 22). Most of Azraq basin has less than 100 mm/a rainfall; only near the Syrian border rainfall is higher. Snow is not uncommon in the western highlands in winter. About 821 MCM/a and 914 MCM/a of total long-term average rainfall can be expected for AMZ and Azraq watersheds (including Syrian part) using the isohyets.

Annual variations are large (Fig. 24). For example some stations in Azraq basin record no rain[22] at all for some years and up to 150 mm in others. Standard deviations from the mean precipitation value are around ±45 %. The year 1991/92 was a particularly wet year, while the drought in 1998/99 cut rainfall by up to 70 %. Typically, there seems to be a dry period lasting between 3 to 5 years followed by a wet period lasting between 2 to 3 years (evaluated

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[14] The map includes some farmed areas and excludes some villages. It also excludes the metropolitan part of Amman, for which ~230 km² were added in the table above.

[15] There are often no readings on the weekend and also for other days. It is not clear whether there was no rain that day or no reading, so the next reading could be a cumulative value.

[16] If there is a very high daily reading for May 31, when there would be no rain expected. This is most likely a yearly value and these values have been deleted from the daily records.

[17] Notice that some stations are assigned a code not matching the basin they are lying in. It is unclear if the code is wrong or the coordinates.

[18] Intervals vary between 5 min and 1 hour and sometimes some hours are not recorded, but it is still counted as one event.

[19] Mean values were modulated for each year according to dry, normal or wet year conditions based on the variations of the three Jordanian stations closed to the border.

[20] Overall, records used start with 1937/38 and end with 2010/11.

[21] The long-term rainfall isohyets supplied by MWI show even higher rainfall in the western part. This is due to two reasons: (1) the isolines were mislabelled (i.e. missing the 300 mm isoline) which results in values that are 50 mm too high above 300 mm. (2) It was also found that yearly values calculated from available monthly rainfall data were reflecting calendar years (Jan - Dec) not water years (Oct - Sep)

[22] It could also be due to non-functioning of the equipment.

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for AMZ basin, Hammouri and El-Naqa, 2007a). The definition of a wet or dry year varies between ±30 % (Otova et al., 1989b), ±25 % (Alraggad, 2009) and ±10 % of mean precipitation. Using the MWI definition[23] 'normal' years occurred in about 29 %, wet years (>110 % of mean precipitation) in about 27 % and dry years (<90 % of mean precipitation) in about 44 % of the time. Over the last 45 years the 10 % percentile, median and 90 % percentile are 72 %, 94 % and 152 % of mean yearly rainfall, respectively, showing that the deviation from the mean is higher for wet years.

Long term trends (1937 - 2010 data) indicate a decrease in annual rainfall for many stations. However, some stations show no trend and some even show an increase in rainfall (Fig. 23). Global and regional climate models predict a significant decrease in rainfall for the Middle East (Kunstmann et al., 2007; Zereini and Hötzl, 2008) and also downscaled regional models forecast a decrease in rainfall due to a decrease in rainfall events through cyclones (Black et al., 2011) (see also Box 6). For Jordan, climate change might have a significant impact as in most areas groundwater recharge will be reduced by up to 30 % (Margane et al., 2008). For the Azraq basin a decrease in rainfall has been reported (Mesnil and Habjoka, 2012).
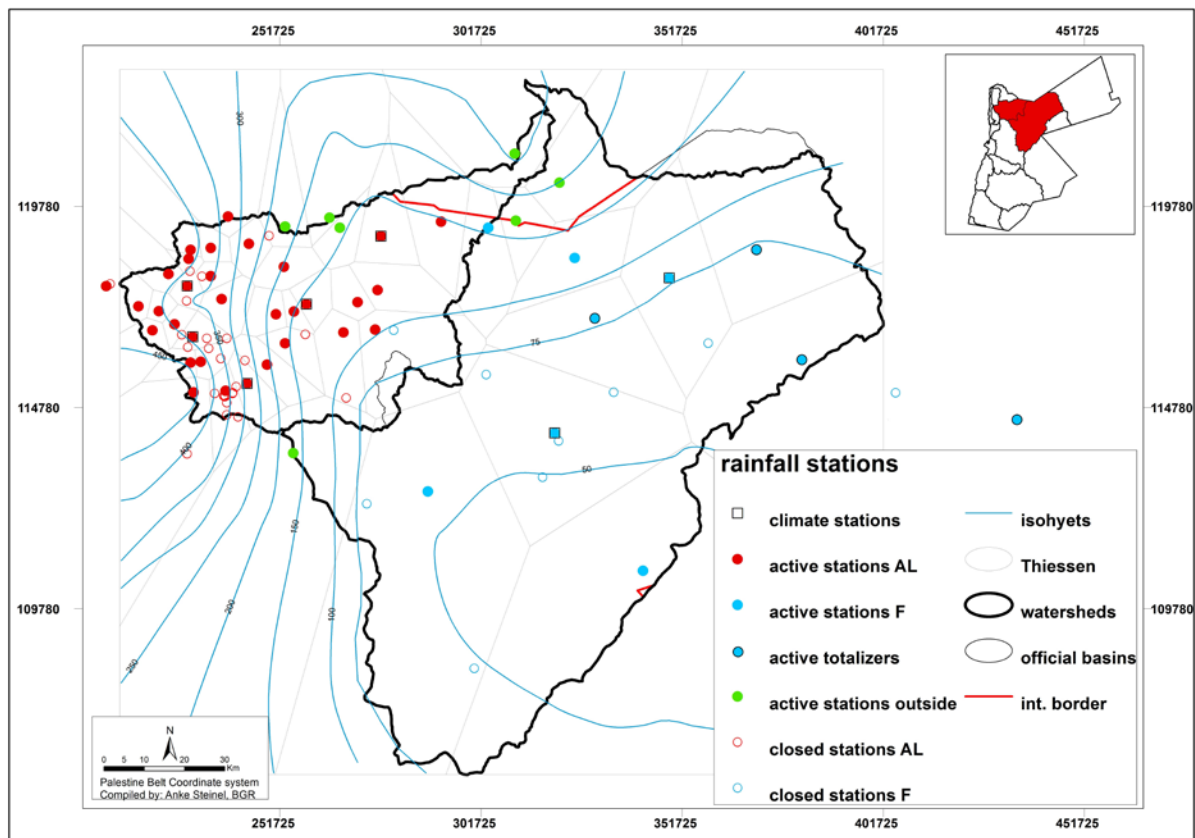
Fig. 22: Climate and rainfall stations in and around AMZ and Azraq basins. Isohyets in 50 mm increments plus a 75 mm contour line (arranged after corrected WIS data, MWI).

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[23] Z. Haj Ali (MWI), 2011, personal communication

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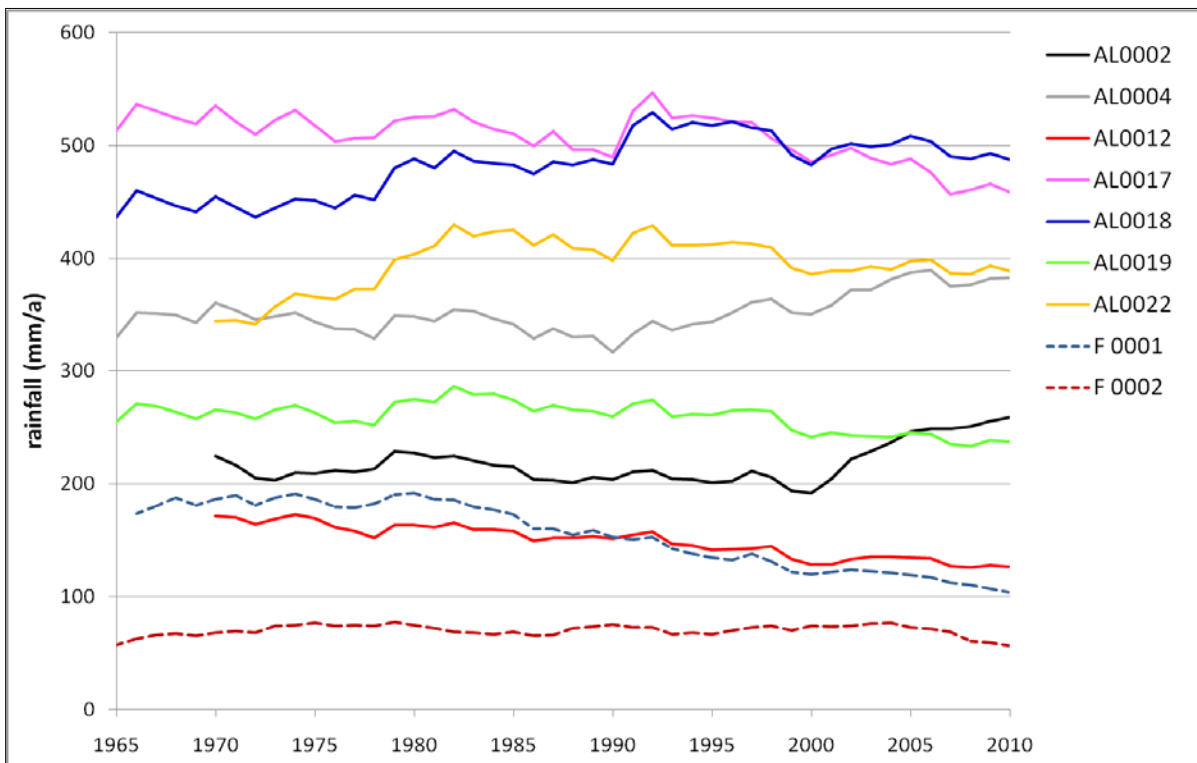
Fig. 23: 20 year moving average of selected rainfall stations with more than 50 years of record showing different long-term trends (arranged after corrected WIS data, MWI).
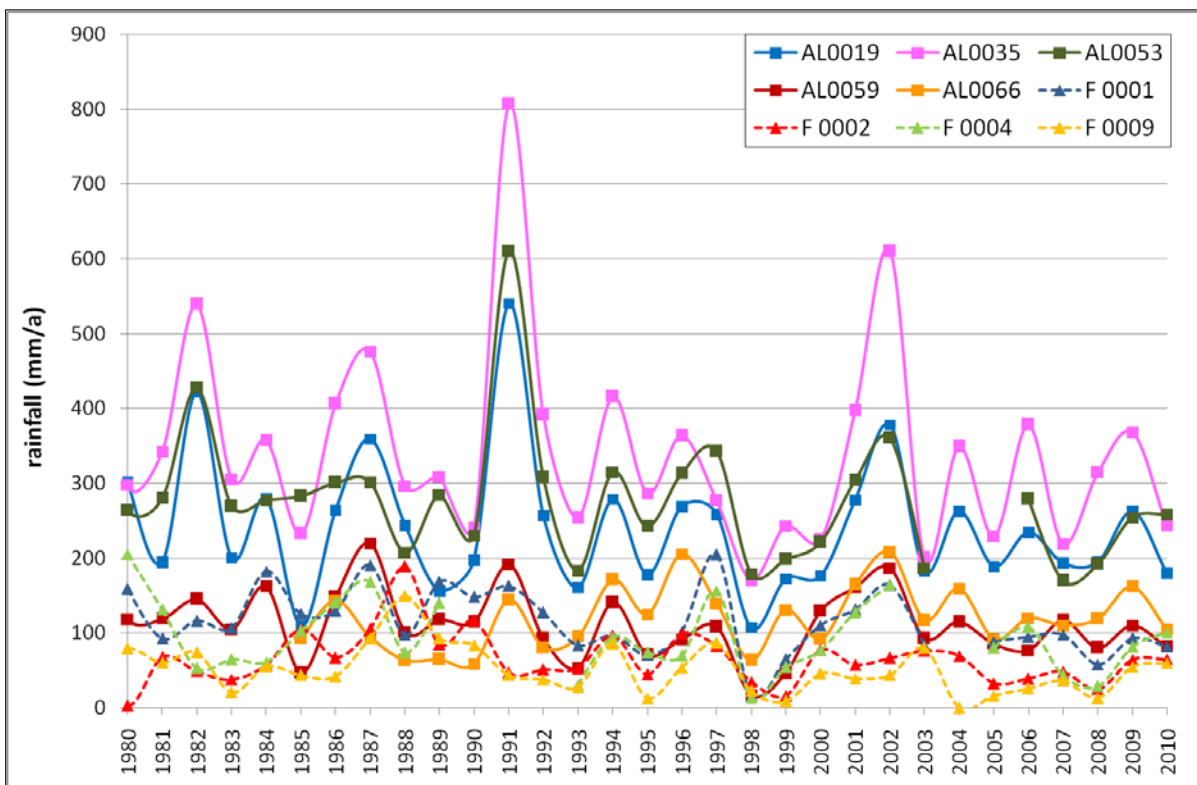
Fig. 24: Annual variations in precipitation for selected stations (arranged after corrected WIS data, MWI).

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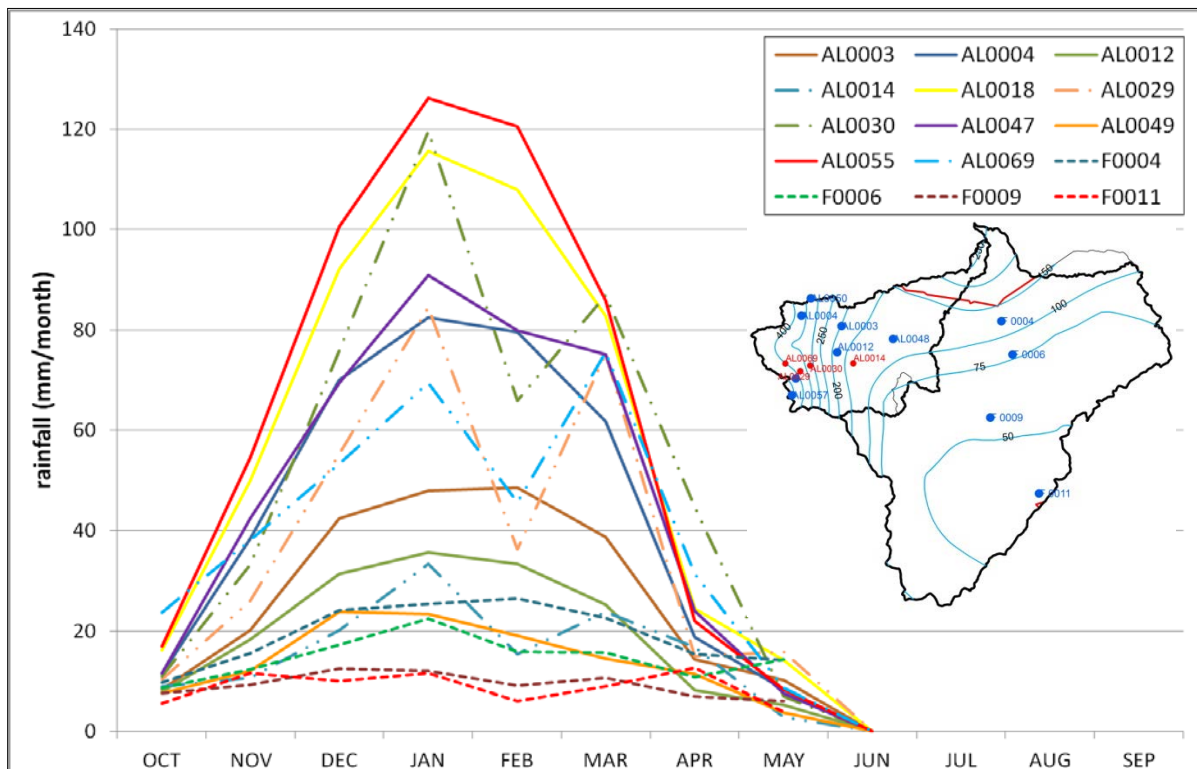
Fig. 25: Mean monthly rainfall of selected stations in AMZ and Azraq basin (variable time frames); insert: blue stations are active, red stations are closed (arranged after WIS data, MWI).

The distribution of precipitation over one year typically shows an increase in rainfall from Oct to Jan/Feb, then a decrease until May and no rain from June to Sep (Fig. 25), with 80 % of rainfall occurring between December and March. Interestingly, most closed stations showed lower values for February compared to March (Fig. 25), which seems to be a phenomenon occurring before the 1990s (i.e. two peaks were also reported by Otova et al., 1989b). **Monthly** precipitation values of 10 - 30 mm are common in Azraq, while in AMZ monthly rainfall can be up to 100 - 140 mm. Drought conditions are most likely in some months (e.g. December and October), while wet conditions are most likely in other months (e.g. November and January) (evaluated for AMZ basin, Hammouri and El-Naqa, 2007a).

The evaluation of all **daily** rainfall stations showed that it rained on average on about 26 days/per year (min. 2.5, max. 50 days per year) with an average reading value of 8.4 mm/d per station (min. 1.8, max. 16 mm/d). Values of more than 20 mm/d were recorded only in about 1 - 4 % of all rainy days at Azraq stations and in about 10 % of all rainy days at AMZ stations, where storm events might bring even about 40 - 60 mm/d. Maximum daily readings are around 85 mm/d.[24]. Commonly, rainfall events are reported in return periods, which are defined based on the probability of occurrence. For example, a 5 year return period is equal to the 80 % percentile[25].

The analysis of **intensity data** from 2000 - 2005 showed that the median total depth of rainfall events is around 1 mm and only about 2 - 10 % of all events reach more than 10 mm depth (Fig. 26). The mean duration was between 12 - 48 min and was longer than 10 hours

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[24] Maximum readings of 237 and 240 mm/d were recorded, but could also be an error and actually read 23.7 and 24.0 mm/d.

[25] 10, 20 , 50 and 100 year return periods are equal to the 90, 95, 98 and 99% percentile

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Table 9: Statistical analysis of single rainfall events from 2000 - 2005 for 6 stations[26] for the parameters total duration (h), avg. intensity (mm/h) and max. intensity (mm/h) (arranged after MWI data).

		Min.	25 %	50 %	75 %	90 %	95 %	Max.	no. of events
total duration (h)	AL0015	0.1	0.2	0.8	3.8	6.7	10.9	15.3	199
	AL0049	0.1	0.2	0.5	3.1	6.2	7.6	16.2	146
	AL0059	0.1	0.2	0.8	3.8	7.5	9.4	18.0	204
	F0001	0.1	0.1	0.2	1.5	3.5	4.8	11.1	80
	F0002	0.1	0.2	0.5	2.0	4.5	7.1	19.8	102
	F0009	0.1	0.2	0.7	2.0	4.1	5.2	13.5	84
avg. intensity (mm/h)	AL0015	0.1	0.9	1.6	2.1	3.2	4.8	29.2	199
	AL0049	0.1	0.9	1.6	2.8	5.3	9.7	49.7	146
	AL0059	0.2	0.9	1.5	2.6	4.3	6.1	44.2	204
	F0001	0.3	1.3	2.7	5.4	8.4	11.6	14.2	80
	F0002	0.1	0.9	1.4	2.2	3.1	4.6	20.1	102
	F0009	0.2	0.9	1.4	2.2	2.8	4.2	32.3	84
max. intensity (mm/h)	AL0015	0.9	1.8	2.7	3.8	7.2	10.4	132.0	199
	AL0049	0.9	1.9	2.9	5.3	12.2	25.8	63.4	146
	AL0059	0.9	1.9	2.9	4.6	8.6	12.6	40.1	204
	F0001	0.9	2.3	4.3	7.8	11.3	17.1	38.5	80
	F0002	0.9	1.4	1.9	3.0	5.0	7.5	27.7	102
	F0009	0.2	1.6	2.1	3.2	8.1	15.9	43.8	84
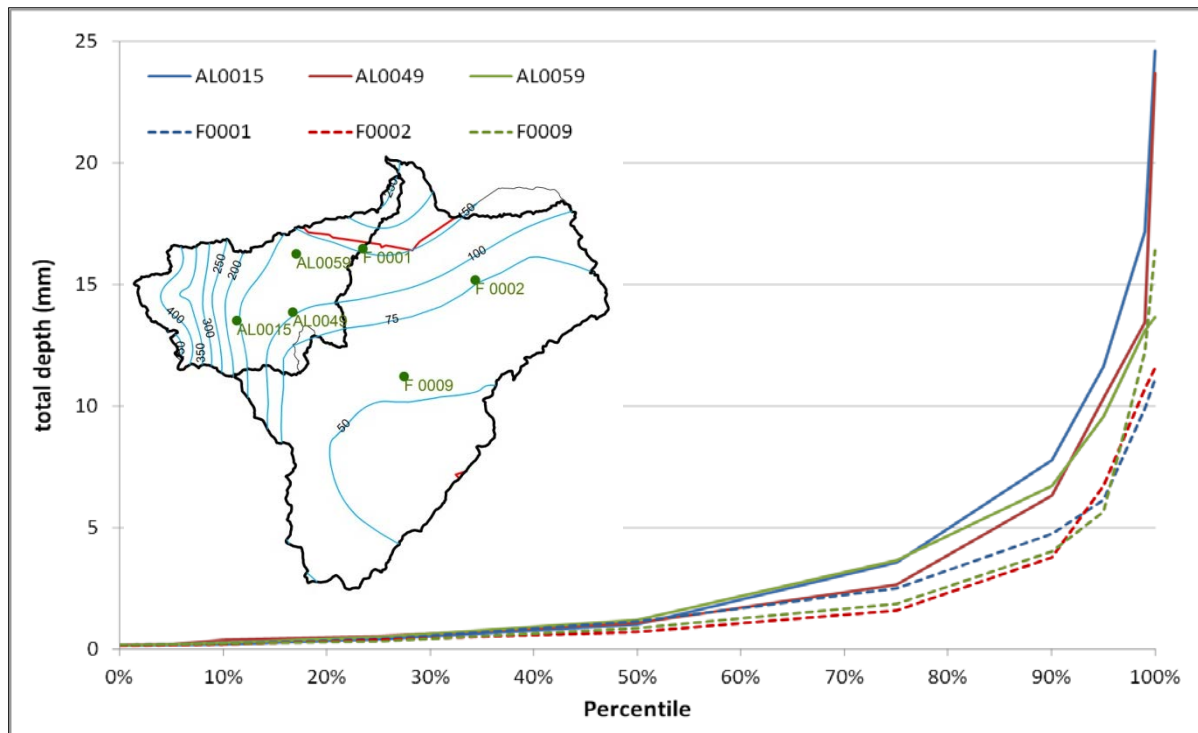
Fig. 26: Statistical analysis of single rainfall events from 2000 - 2005 for the parameter total depth (mm) per event for 6 stations (arranged after MWI data, 2011).

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[26] In the original data station F0009 was labelled Azraq station (F0005). As Station F0002 and F0005 are at the same location and station F0009 is usually called Azraq, the ID was changed to F0009.

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in 1 - 5 % of all events (Table 9). Average mean intensity per rainfall event lies around 1.5 mm/h and is >10 mm/h in about 5 % of events (Table 9). The average maximum intensity at the stations was around 2 - 3 mm/h with the recorded max. of 132 mm/h at AL0015 lasting for 6 min (Table 9). While total depth and total duration is generally higher for the stations in AMZ basin, intensities are highest for F0001.

Due to the high spatial variability (see Box 5) the limited number of rainfall stations in the Azraq basin (mean Thiessen area of 1230 km²) cannot reliably represent the actual rainfall over a selected catchment.

Box 5: Spatial variability of rainfall
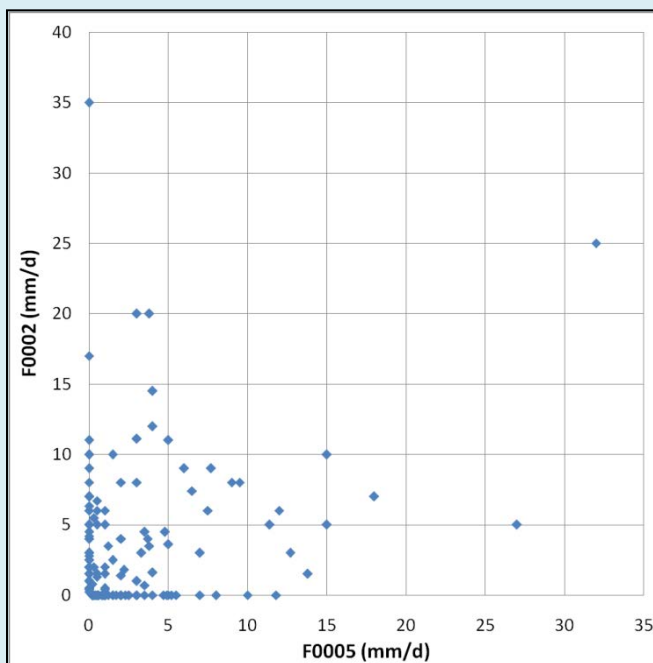
As the rainfall mostly occurs in short duration storm events that move over the region, lateral variations are very high. The stations F0002 and F0005 are located at the same coordinates (should not be more than a few meters apart) and ran in parallel for 5 years (around 100 rainy days). Nevertheless, a comparison of the data shows that daily variation of up to 35 mm occurred and only on about 50 % of the time was there a reading at both stations for the same day. No correlation could be established (Fig. 27).

Fig. 27: Comparison of daily rainfall for two stations at the same location from 1962/63 - 1967/68 (arranged after WIS data, MWI).

Temperature

Mean monthly temperature is around 27 °C in summer and 8 °C in winter (Fig. 28, Table 10). The daily temperature extremes range from over 40 °C in summer to -10 °C in winter. Temperature differences between summer and winter and over the course of one day are more extreme towards the eastern desert.

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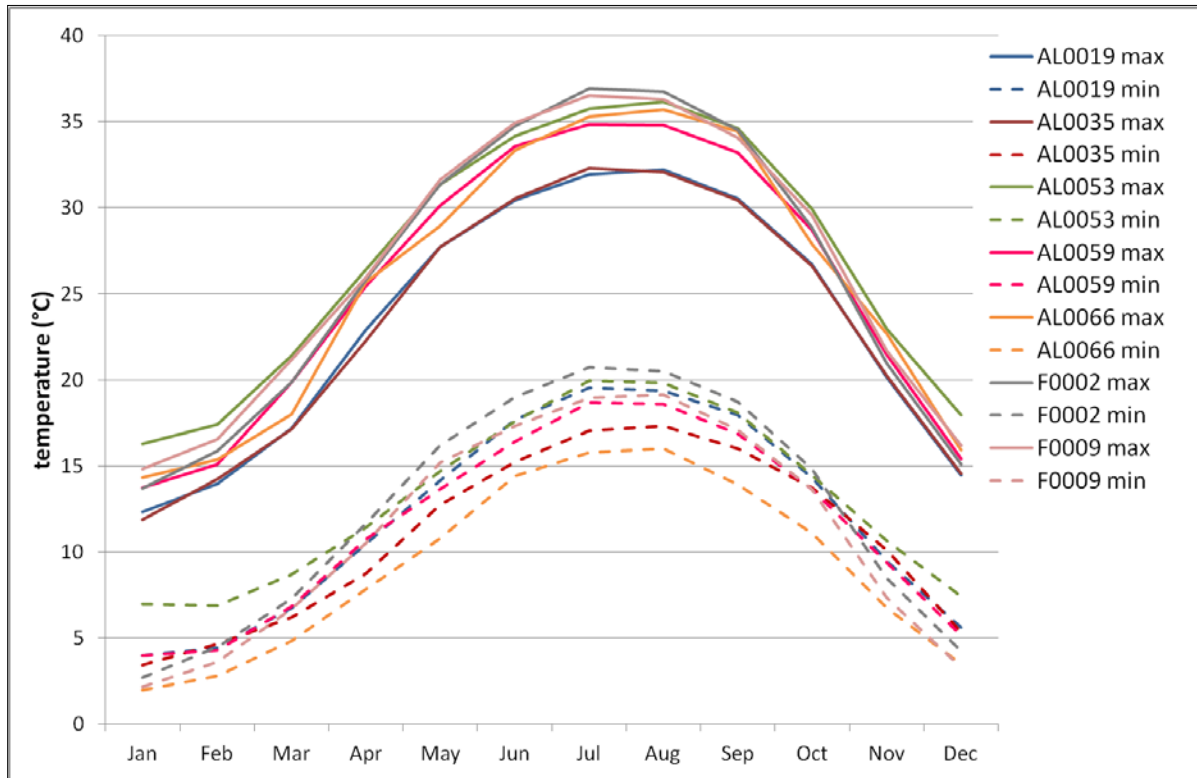
Fig. 28: Comparison of monthly minimum and maximum temperatures (°C) (arranged after corrected[27] WIS data, MWI).

Table 10: Statistical analysis of daily readings from 5 active climate stations for mean, min. and max. temperature (arranged after corrected[28] WIS data, MWI).

	Station	Min	25 %	50 %	75 %	90 %	Max	no. of readings
mean temp. (°C)	AL0019	0.3	11.15	18.55	24	26.7	35.5	11 705
	AL0035	0	11.5	18	23	26	36.25	15 103
	AL0059	-0.5	12.5	19.5	25	27.5	38	15 237
	F0002	-0.5	12	20.1	26.8	29.5	38.45	13 998
	F0009	-1	12	20	26	28.5	37	16 667
max. temp. (°C)	AL0019	0.6	16.3	25	30.6	33.5	43.5	11 676
	AL0035	1	16	25	31	34	46	15 106
	AL0059	0	18	27	33	36	45	15 193
	F0002	3	18	27.4	35	37.8	46.4	13 936
	F0009	3	19	28	34	37	46	16 669
min. temp. (°C)	AL0019	-7.5	6.4	12.2	17.5	20.4	29.8	11 676
	AL0035	-5	6	11	16	19	35.5	15 106
	AL0059	-8	7	12	17	19	35	15 193
	F0002	-6.2	6	13	19	21.7	32.2	13 936
	F0009	-10	5	12	17	20	31	16 669

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[27] Supplied monthly data were calculated by summing up daily readings, but did not account for missing daily values leading to unusually low monthly values. Therefore, for this report monthly values were divided by the number of days in a month (not accounting for leap years in February) and missing data were accounted for by assuming mean monthly values for these days. Errors in daily data were corrected in monthly data as well.

[28] If min. temperature was higher than max temperature the values were exchanged. Very large/low values outside the normal range of values were deleted or the decimal point corrected judging from values the week before and after.

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Evaporation

The climate stations commonly have a Class A Pan and a Piche atmometer to measure potential evaporation directly. They also measure radiation, temperature, dry/wet bulb temperature for humidity, wind speed/direction and sometimes sunshine duration so potential evaporation can be calculated with the Penman equation. Plant transpiration is of minor importance in the Azraq basin as there is hardly any vegetation cover, but it should be accounted for in vegetated areas in AMZ basin. To calculate evaporation for the water budget the Wundt equation and sometimes the Penman equation are used in Jordan[29].

In line with temperature, yearly potential evaporation increases from the western stations in AMZ with about 2500 mm/a (Class A pan) to around 3500 - 3700 mm/a (Class A pan) for the stations in the Azraq basin desert. Similarly monthly values increase from about 80 - 100 mm/month in winter to about 380 - 420 mm/month in summer (Fig. 29). Accordingly, daily evaporation, which averages around 10 mm/d over the year, is about 1 - 5 mm/d in winter and about 15 - 25 mm/d in summer. In the last decade, evapotranspiration was 86 - 91 % and 93 - 97 % of rainfall in AMZ and Azraq basin, respectively (see Fig. 35 and Fig. 37) Jordan's long-term average evaporation rate is 92.5 % of rainfall, ranging from 63 % in the highlands to around 99 % in the eastern desert (Hammouri and El-Naqa, 2007b).
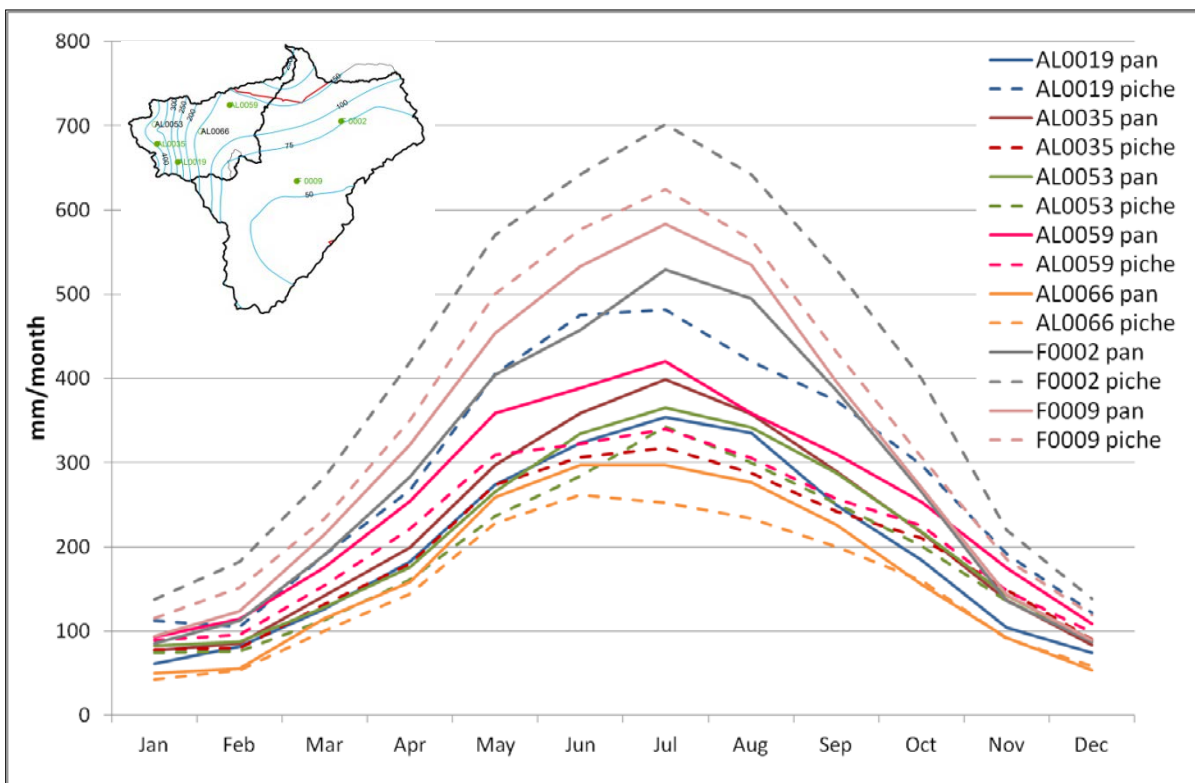
Fig. 29: Comparison of monthly evaporation values from Class A Pan and Piche atmometer (arranged after corrected[30] WIS data, MWI).

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[29] Z. Haj Ali (MWI), 2012, personal communication
[30] Supplied monthly data were calculated by summing up daily readings, but did not account for missing daily values leading to unusually low monthly values. Errors in daily values were corrected for in monthly data as well for this report.

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Different conversion factors can be used to convert Class A pan evaporation to potential evaporation (Haude, 1955; Kohler et al., 1955). For Muwaqqar area, it was found to be 1.25 - 1.3[31]. For the AMZ basin a factor of 1.5 - 1.8 has been used previously (Otova et al., 1989b)

The comparison of monthly potential evaporation from Class A Pan and Piche atmometer showed no explainable trend, with three stations having 15 - 20 % higher and four stations having 10 - 30 % lower Class A pan readings compared to Piche (Fig. 29, Table 11). Generally, errors associated with Class A pan readings in a desert environment are higher, due to accumulation of dirt in the pan, exposure to wind, birds drinking out the pan and the storage of heat in the pan water resulting in evaporation during the night as well. Elevated Piche values could occur, if the atmometer is not shaded properly or if there is a lot of wind (van Zyl et al., 1989; Messing, 1998). Higher Piche evaporation values compared to Class A Pan have been recorded for Jordan previously (AHT and BGR; 1977) and have been found at other arid locations, for example at Sidi Bouzid (Tunisia) (Messing, 1998) or Giza (Egypt) (Gangopadhyaya et al., 1966). Class A pan values seem to be more realistic though for estimating evaporation from reservoirs as they are subject to similar conditions.

Table 11: Statistical analysis of 5 active daily climate stations for Class A pan evaporation (mm/d), Piche atmometer evaporation (mm/d)*, radiation distillate and humidity (%) (arranged after corrected[32] WIS data, MWI).

	Station	Min	25 %	50 %	75 %	90 %	Max	no. of readings
evaporation, Class A pan (total mm/d)	AL0019	0.1	3	6	10	12	29	11 136
	AL0035	0.1	4	7	11	14	31	10 949
	AL0059	0	5	8	12	15	32	14 708
	F0002	0	4.1	9	14	18	33	12 358
	F0009	0	5	10	16	20	30	16 420
evaporation, Piche atmometer (total mm/d)*	AL0019	0.1	4.6	8.6	13.4	17.8	33.4	4 185
	AL0035	0	3.5	6.2	9	11.8	30	12 682
	AL0059	0	4	7.1	10	12.6	28	13 184
	F0002	0	6.5	13	19.7	24.1	39.6	9 862
	F0009	0	5.5	10.8	16.6	21	32	15 420
radiation (total distillate in cm³)	AL0019	0.2					26.8	only 24
	AL0035	0.3	9.9	16.5	20.4	22.4	29.5	4 954
	AL0059	0.4	8	15.6	20.6	22.9	34.3	6 442
	F0002	1	11	17.2	21.3	23.2	31.5	3 344
	F0009	0.5	15.6	22.3	28	32.5	38.8	14 962
humidity (%)	AL0019	0.5	40.1	62.5	82.2	93.4	100.0	11 626
	AL0035	0.4	51.1	64.3	75.9	86.1	100.0	15 131
	AL0059	2.1	55.3	68.4	78.6	87.3	100.0	15 185
	F0002	1.0	36.2	52.7	73.8	88.6	100.0	13 873
	F0009	6.1	52.9	67.4	79.0	87.1	100.0	16 630

* It is assumed that the unit should read mm/d not cm/d, otherwise Piche would be 10 times higher than Class A pan values.

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[31] E. Salameh (University of Jordan), 2012, personal communication

[32] Very large/low values outside the normal range of values were deleted or the decimal point corrected judging from values the week before and after. If dry bulb temperature was lower than wet bulb temperature the values were exchanged. If both read the same, the data were deleted for the summer months as it was assumed that there was water missing for the wet bulb measurement. Obvious misplaced values were moved to the right column, if many values seemed to be mixed up and could not be reconstructed, they were deleted.

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The aridity factor (AF) calculated from the ratio between annual precipitation and potential annual evapotranspiration (both in mm) shows arid conditions (AF = 0.05 - 0.2) for the three stations furthest west in AMZ and hyper-arid conditions (AF = <0.05) for Azraq basin and the eastern AMZ basin where precipitation is below 150 mm/a[33]. Only for some wet years with rainfall >500 mm/a, the station furthest west (AL0035) reaches semi-arid conditions (AF = 0.2 - 0.5).

10.2   Source water

The Zarqa River is the only perennial river draining the AMZ catchment to the west, flowing down the steep escarpment towards the Jordan River. It is fed by surface water runoff, groundwater discharge (many springs and effluent conditions in the lower catchment area west of As Samra WWTP), treated wastewater from the As Samra WWTP and other smaller WWTPs (about 76 MCM in 2005) as well as untreated sewage (Al-Omari et al., 2009). The river is intercepted by the King Talal dam and pumped mainly into the King Abdullah Canal for irrigational use.

The Azraq basin is only drained by ephemeral wadis. Most of these are flowing towards the Azraq Qaa, except for one separated internal basin (Qaa Khanna) of 825 km², where Wadi Al Ghurabi, Wadi Irayniba, Wadi Nimrat Arbaa, Wadi Quais etc. drain to[34]. There are also several smaller mini-qaas that cannot be distinguished with the resolution of the DEM.

As explained (see section 2.1.1) surface runoff occurs when the rainfall depth exceeds the infiltration capacity of the surface, which could be due to high intensity rainfall events, saturated soil conditions or impervious surface like desert pavement, bare rocks or clayey soils. An increase in slope leads to higher runoff generation. An increase in watershed size often results in less runoff generation as transmission losses, rainfall heterogeneity, evaporation and depression storage increases (Simanton et al., 1996; Abu-Awwad and Shatanawi, 1997). Transmission losses or infiltration in wadi beds after runoff generation can vary by magnitudes depending on soil characteristics and antecedent moisture conditions (Sorman and Abdulrazzak, 1997).

10.2.1   Quantity of floodwater

Due to the low rainfall, runoff is limited. Recorded runoff is even lower than calculated runoff and shows average runoff coefficients around 1 - 3 % and an estimated mean total flood flow of about 20 and 10 MCM/a for AMZ and Azraq basin, respectively.

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[33] Similar results are received with other climate classifications. The Jordanian Ministry of Agriculture uses four zones: <200 mm = arid zone, 200 - 350 mm = marginal zone, 350 - 500 mm = semi arid zone, >500 mm = subhumid zone (Ayed, 1986)

[34] During the calculation of the watershed areas with ArcGIS Spatial Analyst Tools, the program could not handle the existence of natural internal basin and filled these basins until the water would flow over at the edge (using ASTERGDEM from http://www.gdem.aster.ersdac.or.jp). For the Azraq Qaa the flow was directed towards the SE flowing into Saudi Arabia, the Qaa Khanna basin was directed towards the Zarqa river. Therefore, the USGS HYDROSHEDs files (void filled DEM, flow direction and flow accumulation) were used instead (http://gisdata.usgs.gov/website/HydroSHEDS).

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> **Apart from King Talal dam (design storage 75 MCM), water harvesting structures with a total design storage capacity of around 12 MCM are already in place, reducing excess runoff considerably.**
>
> ⇒ **The volume of excess runoff seems too low to consider additional MAR structures feasible.**

Runoff measurements

The first flood gauge was installed in 1963 on the Zarqa River on the Jerash Bridge (AL0060). In AMZ, six more gauging stations followed in the next decade (AL0040, 0061, 0062, 0063, 0064, 0065) and the latest one in 2002 (AL0070). In Azraq basin, four stations (F0022, 0023, 0024, 0025) were installed for the Azraq Oasis Conservation Project in 1995/96 (Fig. 30). One vandalised station (F0025) was reinstated in 2000 (vandalized again in 2011).
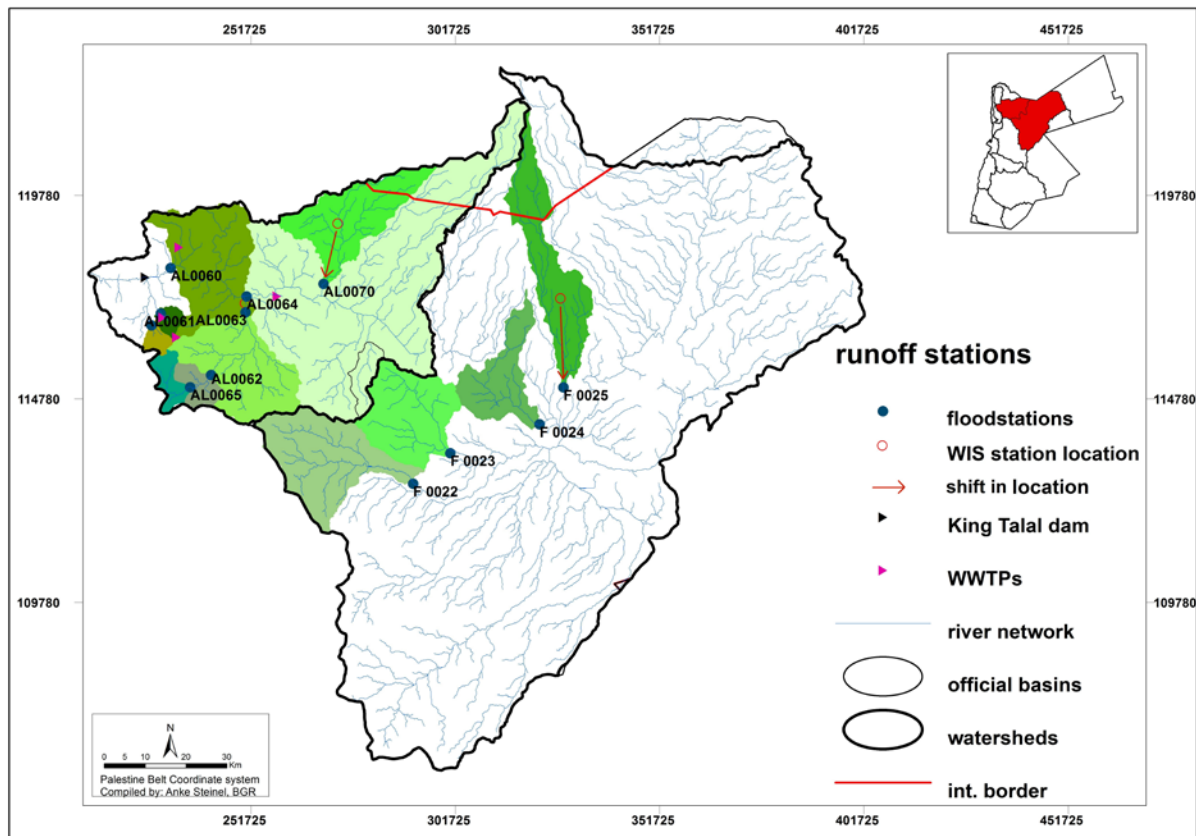
Fig. 30: Location and catchment areas (coloured areas) of existing flood stations, King Talal dam and four WWTPs (arranged after corrected[35] WIS data, MWI).

All these stations are equipped with a Stevens' type water level recorder and the chart logger papers are exchanged and evaluated monthly. Rating curves for the correlation of water level to flow area are established from manual measurements. At New Jerash Bridge station

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[35] Field inspection showed that F0025 was about 22 km and AL0070 about 15 km further downstream than the official coordinates in the WIS (arrows). AL0063 has been moved about 2.4 km upstream. AL0065 could not be inspected as it was closed in 2003.

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(AL0060), cableway or manual flow measurements are regularly undertaken and recently a water level radar has been installed. Flow velocity is not known for ephemeral stations. The separation of base and flood flow is done manually by an MWI expert[36]. Base flow is commonly wastewater and not spring discharge[37].

The flow measurements suffer from a number of potential problems (Fig. 31): (a) rubbish can clog the slotted steel pipe (Fig. 31 left), (b) if the location of the station is not in the main through flow of the wadi, low flow events will be missing from the record (Fig. 31 left), (c) cross sections are not well defined and can change after each flood event (Fig. 31 right), (d) in ephemeral wadis the floating device can get stuck in the mud and response can be delayed, (e) human errors when changing plotter paper.

Fig. 31: left) AL0063 Zarqa, Sukhne Station: rubbish accumulation around slotted steel pipe and station is not situated in the main flow channel; right) F0023 Wadi Butum Station: very uneven cross-section, likely to change with strong flow events. (Pictures taken by A. Steinel, 2012).

Yearly variations in flood flow volumes at each station are large with standard deviations of >200 % of the mean value (Fig. 32 and Fig. 33). All stations (except AL0060) show years with no flood flow[38]. There is only a very weak correlation across the stations for the same year or for the same event, which implies that rainfall is not uniform across the basin. Even though AL0062 is only about 7 km downstream of AL0065, there is only limited correlation between the yearly values of these stations. There are even years, when the flow decreased between the up- and the downstream station.

The analysis of **daily flood flow data** shows that peaks are commonly very short and runoff mostly lasts for only a day or two (except for AL0060, where flood flow can last a week) [39]. Accordingly daily runoff values are comparatively large, reaching >1 MCM/d for some stations. When normalizing daily runoff data to the size of the catchment, a median flood flow of around 70 m³/d/km² occurs (Fig. 34). The high values for AL0065 could be attributed to the fact that the catchment is mostly urbanized with a high percentage of sealed surfaces that

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[36] A. Obeidat (MWI), 2012, personal communication
[37] As the water budget does not use actual flood measurements, the inclusion of wastewater runoff does not impact the water budget, but should be subtracted if runoff data would be used for budget calculations.
[38] It could also be due to non-functioning of the equipment.
[39] It is to be suspected that some flood peaks resulted from irregular discharge of treated wastewater and should hence be subtracted from flood flow data.

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results in high runoff generation[40]. Stations F0022 shows the lowest runoff generation, which could be due to the high number of water harvesting structures in the catchment (see Fig. 43).

The analysis of flood **events** showed that between 0.7 and 8.1 (mean 3.2) runoff events per year occur across the basins and the expected general decline in events with decrease of mean total rainfall (Table 12). The fact that F0022 has a relatively higher number of events, but the lowest recorded average daily runoff reinforces the assumption that existing water harvesting structures might have an impact on flood records.

Table 12: Analysis of average number of events at each station (calculated[41] after corrected WIS data, MWI).

stations	station name	catchment (km²)	number of events	number of years	avg. events/ year
AL0040	Wadi Um al Dananeer	37.1	180	43	4.2
AL0060	Zarqa at New Jerash Bridge	3554.3	373	46	8.1
AL0061	Wadi Sleihi	38.0	228	46	5.0
AL0062	Ain Ghazal	155.7	67	16	4.2
AL0063	Wadi Zarqa at Sukhne	642.8	110	30	3.7
AL0064	Wadi Dhuleil at Sukhne	2375.0	40	17	2.4
AL0065	Wadi Abdoun	75.9	68	26	2.6
AL0070	Wadi Zatari	421.6	14	9	1.6
F0022	Wadi El Janab	551.6	49	15	3.3
F0023	Wadi Butum	441.7	24	15	1.6
F0024	Wadi Ratam	300.4	19	16	1.2
F0025	Wadi Hassan	484.95	5	7	0.7

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[40] The high values for station F0025 are due to the fact, that only 10 days recorded runoff.
[41] One event was defined as flood flow on consecutive days and events were separated by flow peaks.

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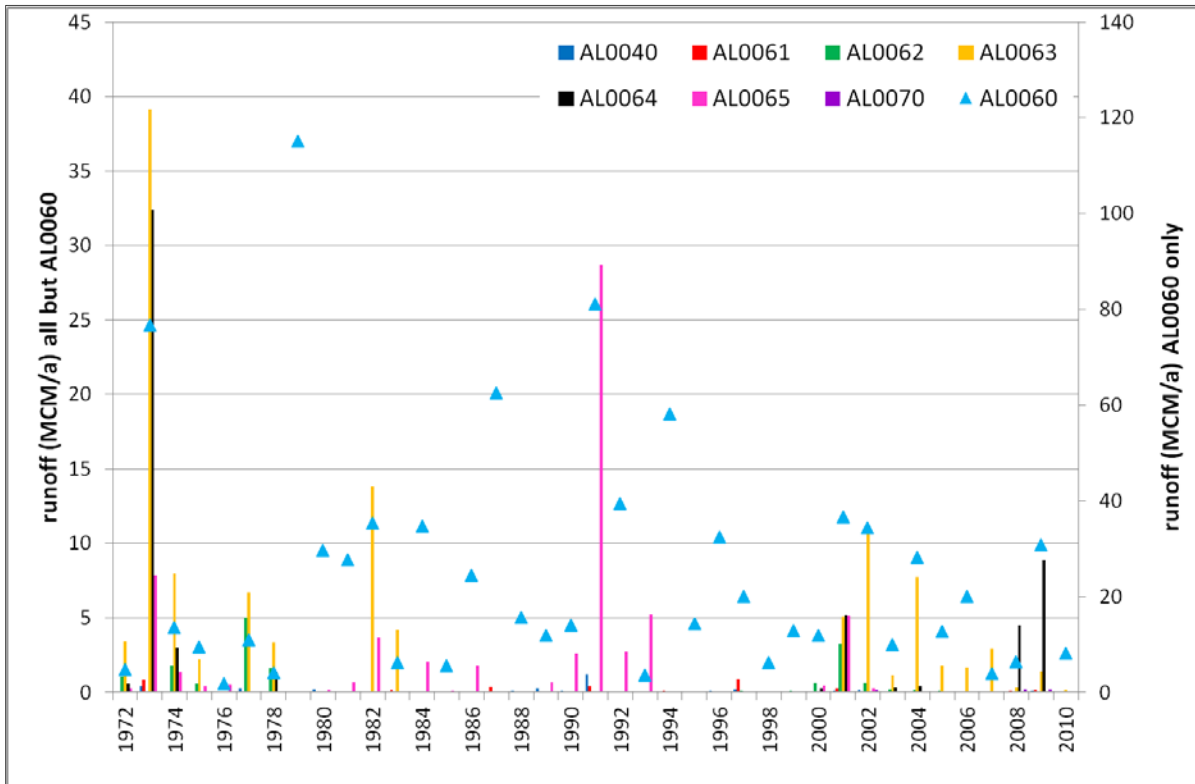
Fig. 32: Yearly flood runoff (MCM/a) for runoff stations in AMZ basin (AL0060 on secondary axis) (arranged after corrected WIS data, MWI).
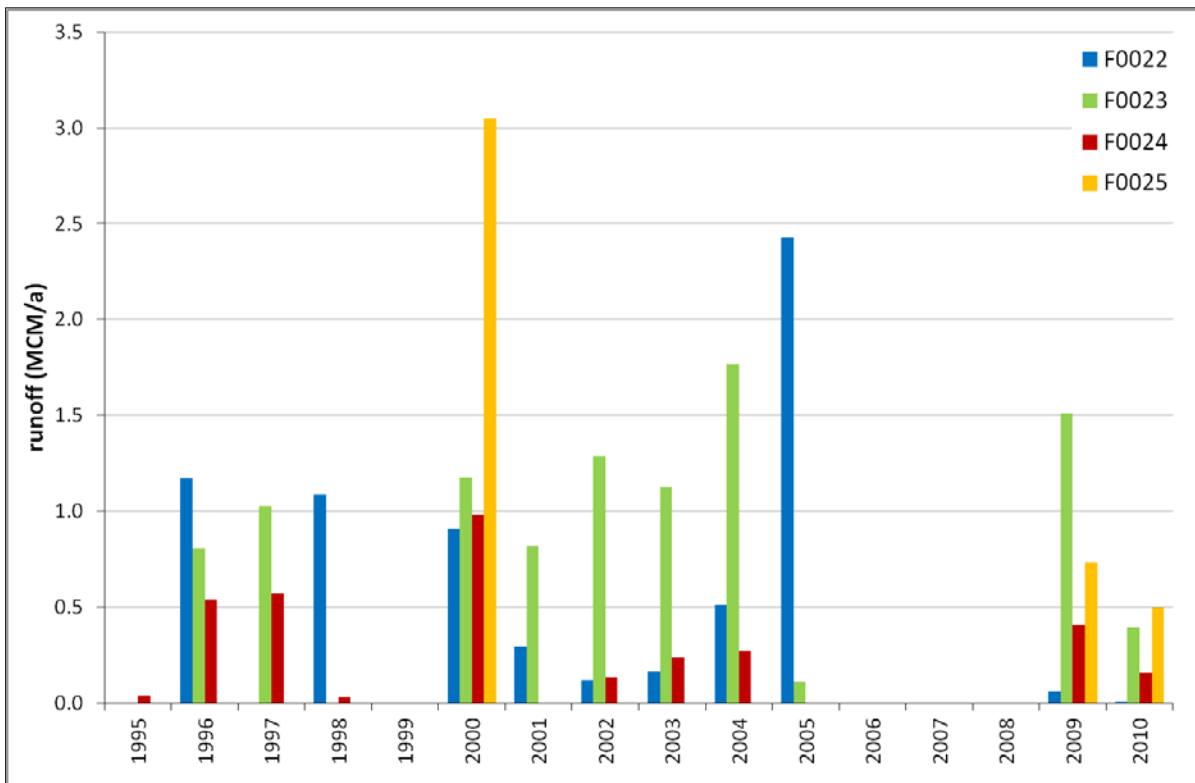
Fig. 33: Yearly flood runoff (MCM/a) for runoff stations in Azraq basin (arranged after WIS data, MWI).
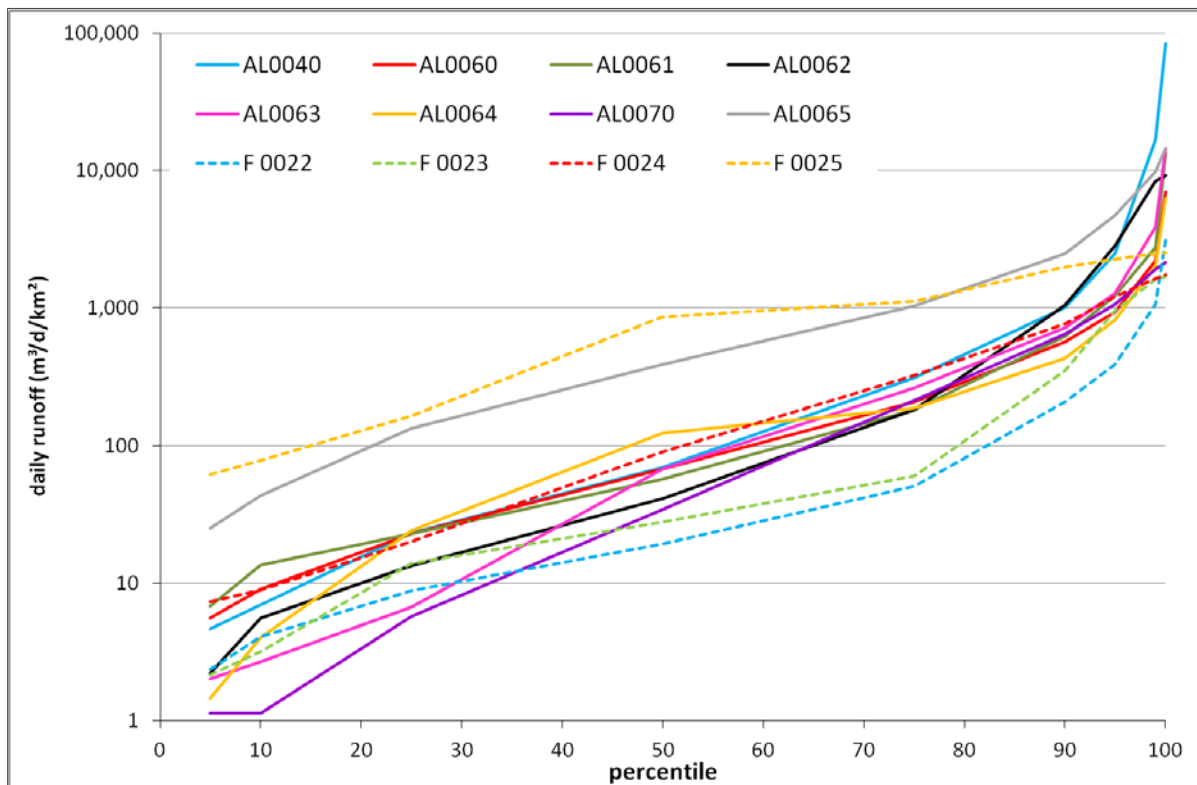
Fig. 34: Statistical evaluation of daily runoff values normalised to catchment size (log scale) (arranged after corrected[42] WIS data, MWI).

Water budget

The water budget calculations undertaken by MWI (Fig. 35 and Fig. 37) are based on the following methods: Total rainfall is calculated using the isohyetal method, evapotranspiration is calculated using the Wundt or Penman equation and runoff is calculated using the CN method. The CN used are 76 and 82 (normal year), 87 and 86 (dry year), 72 and 79 (wet year) for Amman-Zarqa and Azraq, respectively[43]. Actual runoff measurements are not used by the MWI for calibration.

Values for infiltration/recharge to groundwater result from the difference in the water budget. On the one hand, actual groundwater recharge could be lower than calculated, as not all infiltrated water will reach the groundwater and instead will evaporate from the soil profile (Al-Kharabsheh, 1995). On the other hand, actual groundwater recharge could be higher as calculated, as indirect recharge through transmission losses in the wadi channels are not accounted for (Margane et al., 2009b). Elevated groundwater recharge rates of up to 20 % are likely for the basalt areas (Borgstedt et al., 2007; Margane et al., 2009b).

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[42] On 19.Jan 2005 AL0060 recorded 865 m³/s and was corrected to 8.65 m³/s (otherwise there would have been a flood of 74.7 MCM in one day, which is more than the yearly runoff for 98 % of years.
[43] Z. Zudhi (MWI), 2012, personal communication

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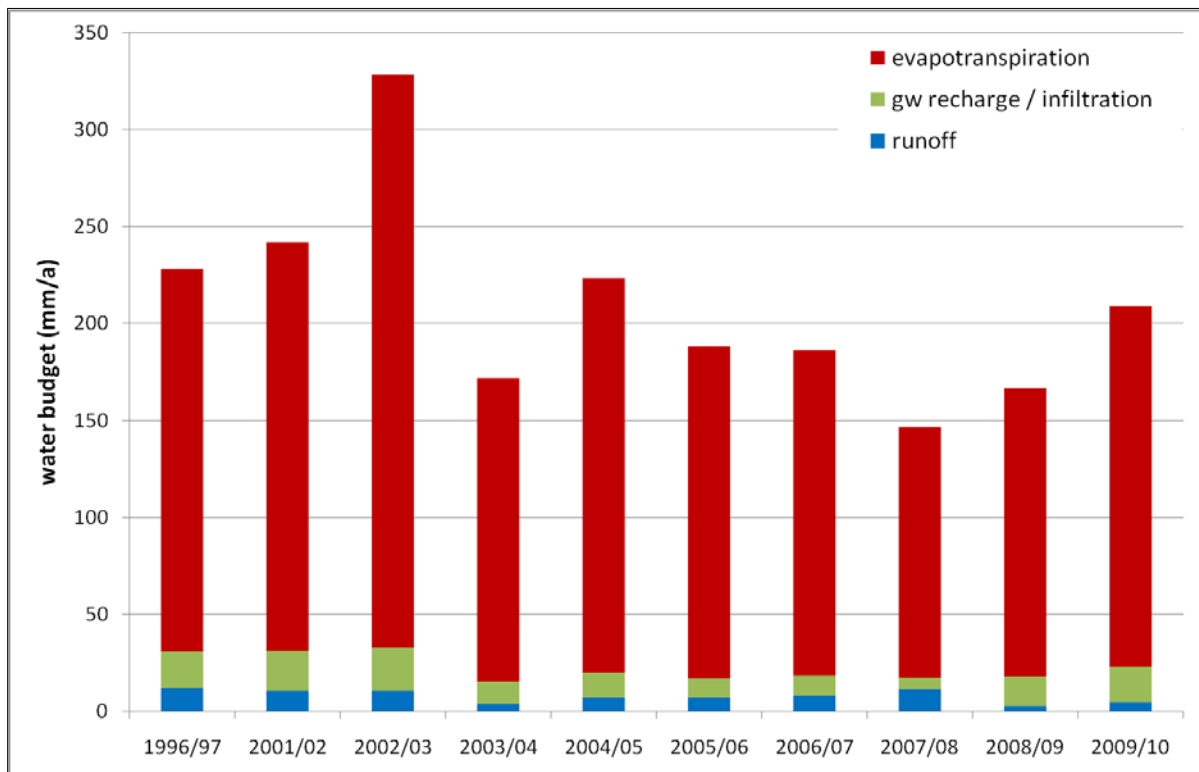
Fig. 35: Water budget for AMZ basin for evapotranspiration, runoff and infiltration (mm/a) based on CN method calculations (arranged after available MWI data[44]).
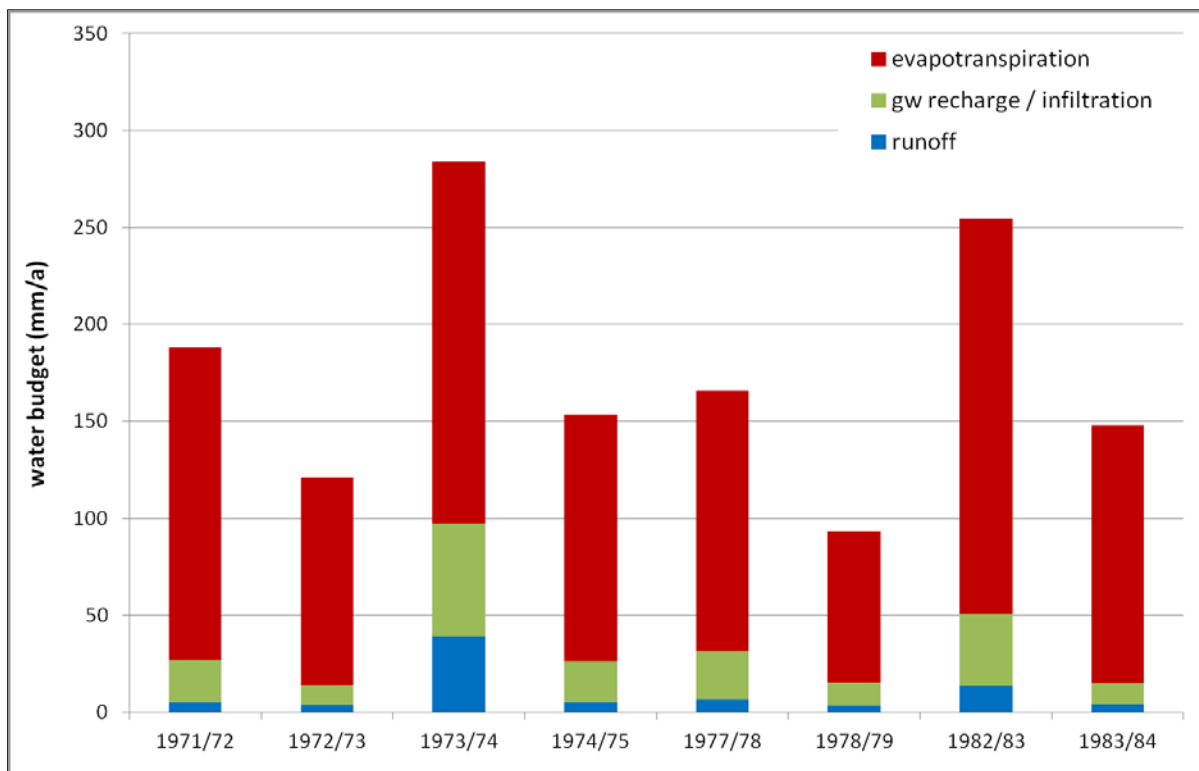
Fig. 36: Earlier water budgets for AMZ basin for evapotranspiration, runoff and infiltration (mm/a) based on CN method calculations (arranged after Otova et al., 1989b).

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[44] Water budget for earlier years were not supplied.

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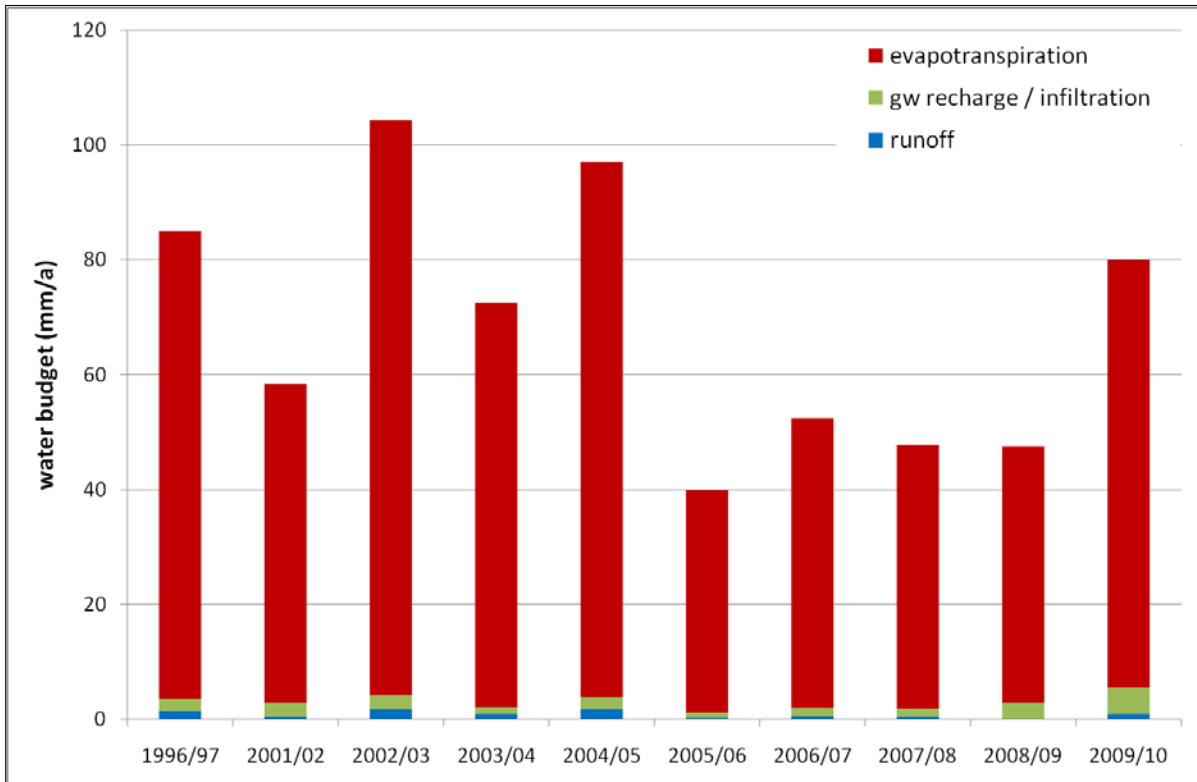
Fig. 37: Water budget for Azraq basin for evapotranspiration, runoff and infiltration (mm/a) based on CN method calculations (arranged after available MWI data).
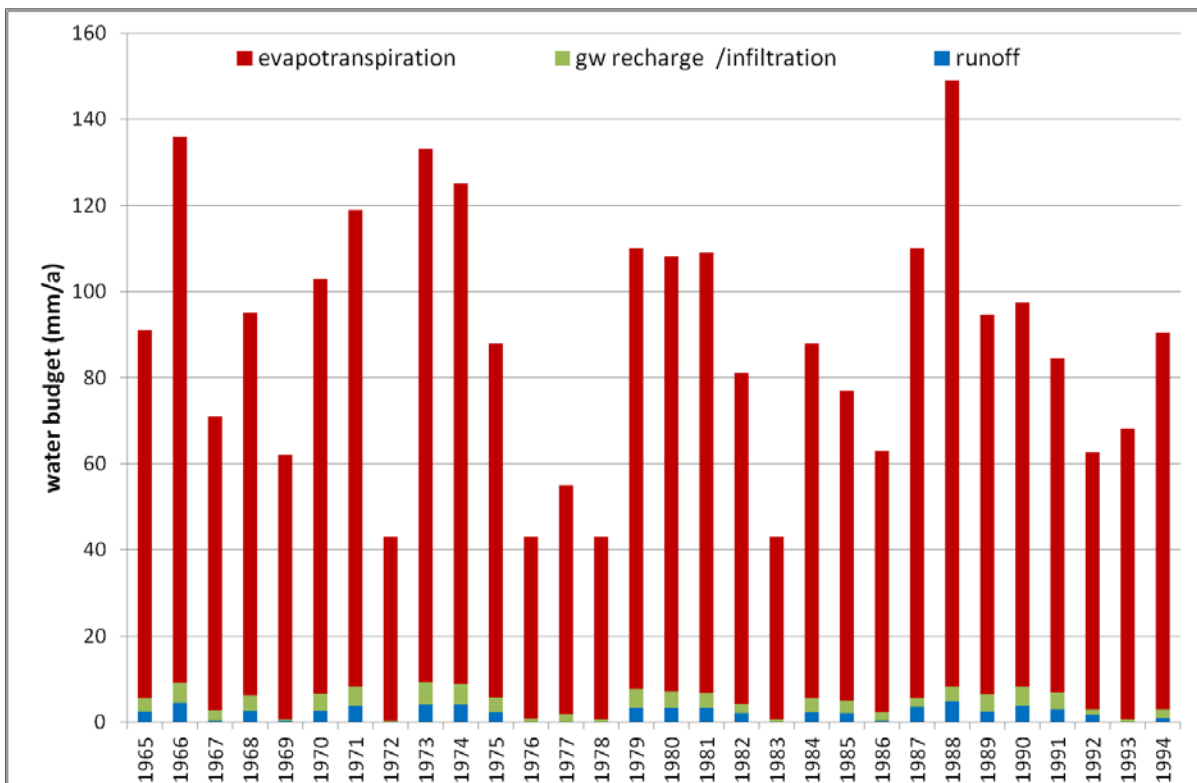
Fig. 38: Earlier water budgets for Azraq basin for evapotranspiration, runoff and infiltration (mm/a) based on CN method calculations (arranged after Al-Kharabsheh, 1996).

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The water budgets show that more than 90 % of all rainfall evaporates and only around 3.9 % (range 1.6 - 7.7 %) and 1.1 % (range 0.3 - 1.8 %) is turned into runoff in AMZ and Azraq basin, respectively. Previous water budgets for AMZ (Fig. 36) and Azraq basin (Fig. 38) based on the same calculations result in about 4.8 % (range 2.6 - 13.7 %) and 2.2 % (range 0.2 - 4.8 %) of generated runoff, respectively. Naturally, there is a general trend that groundwater recharge and runoff rates are higher in wet years (Fig. 36).

Keeping in mind that these calculations are based on the CN method and not on real measurements, it can be seen that the runoff coefficient increases with increasing rainfall volumes until about 100 mm/a of rain (Fig. 39). This is due to the fact that the initial losses are high in dry years and runoff generation is higher, when the soil is already wetted. For Azraq basin, the runoff coefficient stabilises at around 3.2 % for rainfall above 100 mm/a, while runoff is negligible below 50 mm/a of rainfall. Higher total rainfall is often correlated with higher rainfall intensity and, at least for Wadi Madoneh, an increase in rainfall intensity coincided with an increase in runoff coefficient (de Laat and Nonner, 2011).
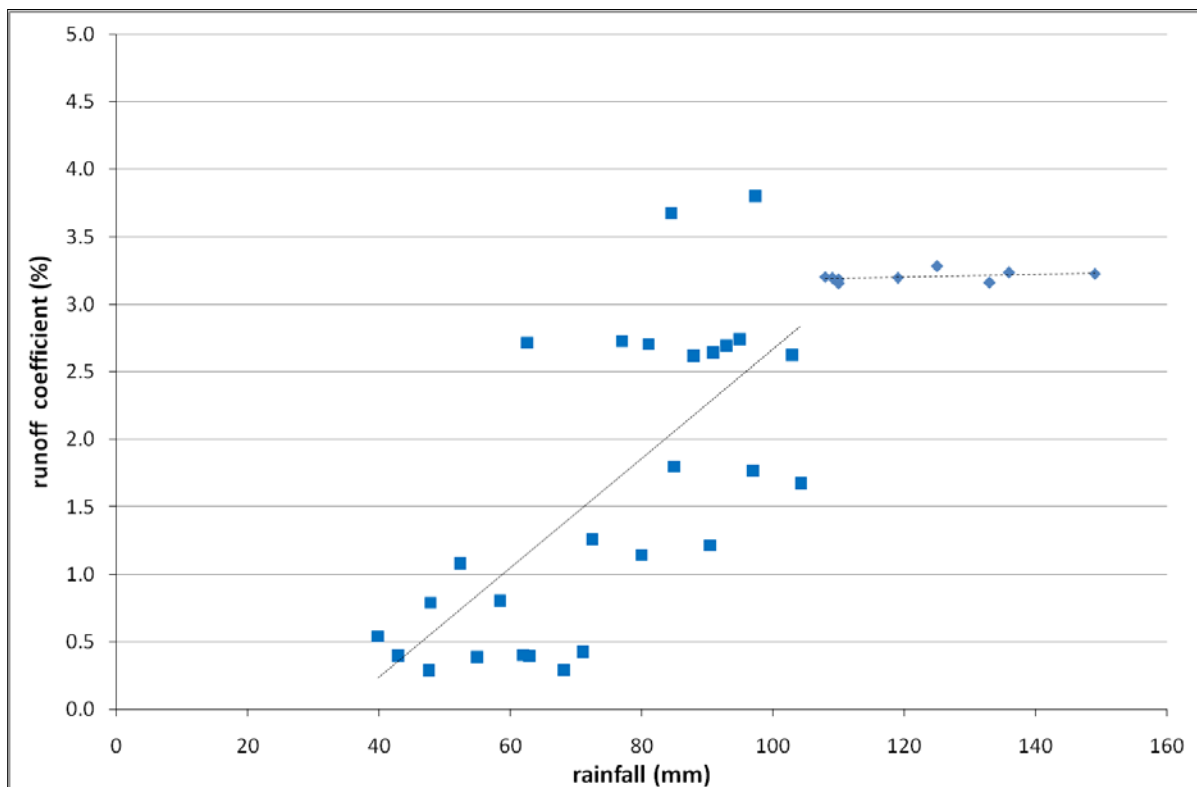
Fig. 39: Correlation between annual rainfall (mm) and CN derived runoff coefficient (%) for Azraq basin (arranged after data from Fig. 37 and Fig. 38).

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Runoff coefficient

As actual flood measurements are available, a further evaluation of the rainfall-runoff data for the existing flood stations was performed[45] to investigate any difference between the catchments. The overall highest runoff coefficient was recorded for the main Zarqa flood station AL0060 (New Jerash Bridge). Other stations produce nearly no runoff in 30 % of all years (Fig. 40). The small urban catchment of AL0065 shows very high runoff coefficients due to a high level of imperviousness. Wadi Zatari (AL0070) shows very low runoff coefficients for all events, which is due to the limited amount of years with reading (only 9 years of record, 4 years without recorded flow[46]). Statistical analysis for Wadi Hassan (F0025) is also skewed as only 7 years of records are available of which 4 years did not show any flow and one year recorded a huge flood. For the lower Zarqa catchment area, where slopes are steeper, there is a marked non-linear correlation between runoff coefficient and catchment size (Fig. 41), i.e. runoff coefficients increase with catchment size. It could be suspected that in areas with lower slope channel transmission losses are higher or that catchment sizes are actually smaller than delineated due to mini-qaas and *marabs* that interrupt runoff flow.

The calculated runoff coefficients are within the range of other studies (Table 13). Only very intense rainfall events have generated larger runoff. As noted above, in general, the runoff coefficient decreases with a decrease in rainfall, e.g. from 5.4 % in a wet year to 2 % in a dry year for the Mujib basin (Alraggad, 2009). Naturally, infiltration also decreases with a decrease in rainfall, e.g. from 7.9 % in a wet year to 2.8 % in a dry year for the Wala dam catchment (Ta'any and Al Atrash, 2009).

When applying average runoff coefficients[47] to a normal year[48], about 18 MCM/a (= 4.5 mm/a) and 9.6 MCM/a (=0.8 mm/a) of runoff would be generated in AMZ and Azraq basin, respectively. This is slightly less than the measured runoff of 26.2 MCM/a for AMZ basin (equivalent to 3.2 % runoff coefficient), which could be due to the involuntary inclusion of treated wastewater into the measured runoff or/and the influence of existing water harvesting structures in lowering the derived runoff coefficient.

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[45] Delineation of floodstation catchment areas from USGS-DEM were intersected with Thiessen polygons from active rainfall stations. Calculated rainfall for each year was compared with recorded runoff at each station in mm/km²/a.

[46]. It is unclear if zero readings actually reflect years with no flow or are merely due to non-functioning recorders.

[47] increase in runoff coefficient from 0.5 to 3.5 % from 50 mm/a to 450 mm/a rainfall

[48] mean total rainfall of 821 MCM/a and 914 MCM/a for AMZ and Azraq basin, respectively

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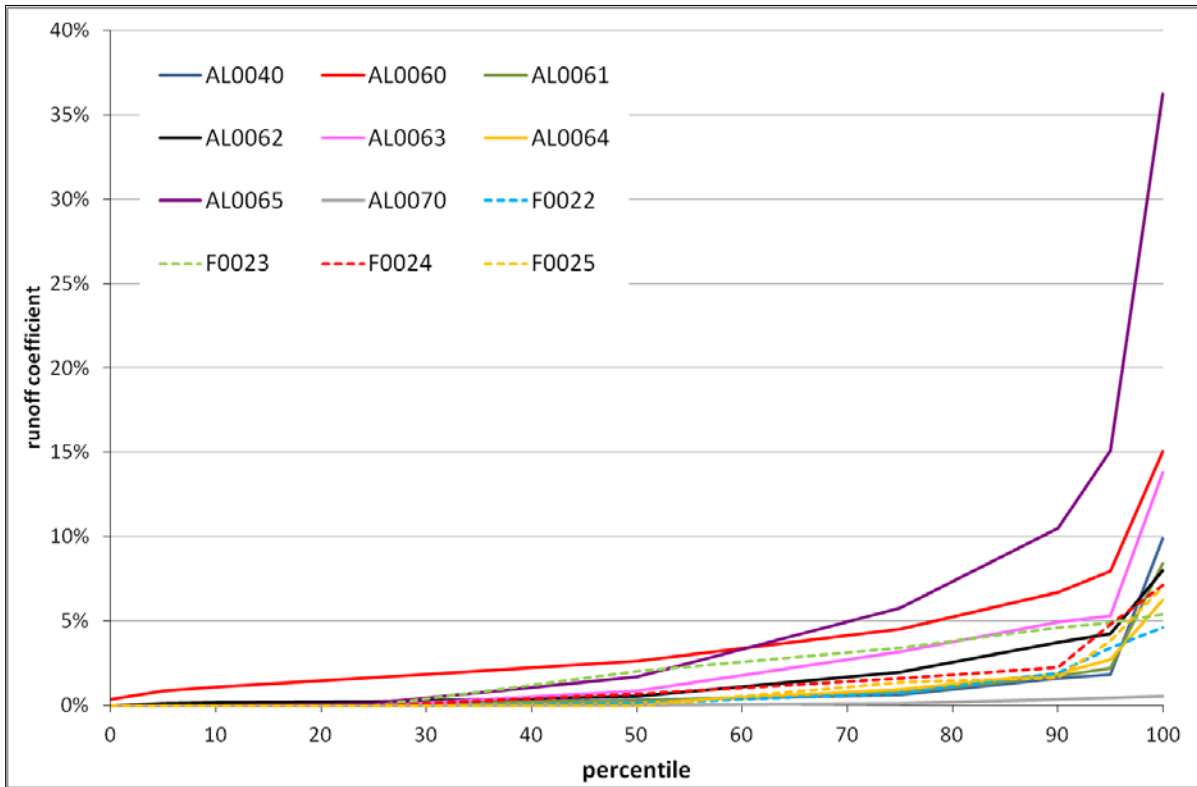
Fig. 40: Statistical evaluation of runoff coefficient distribution of existing flood stations for the years recorded (calculated from WIS data, MWI).
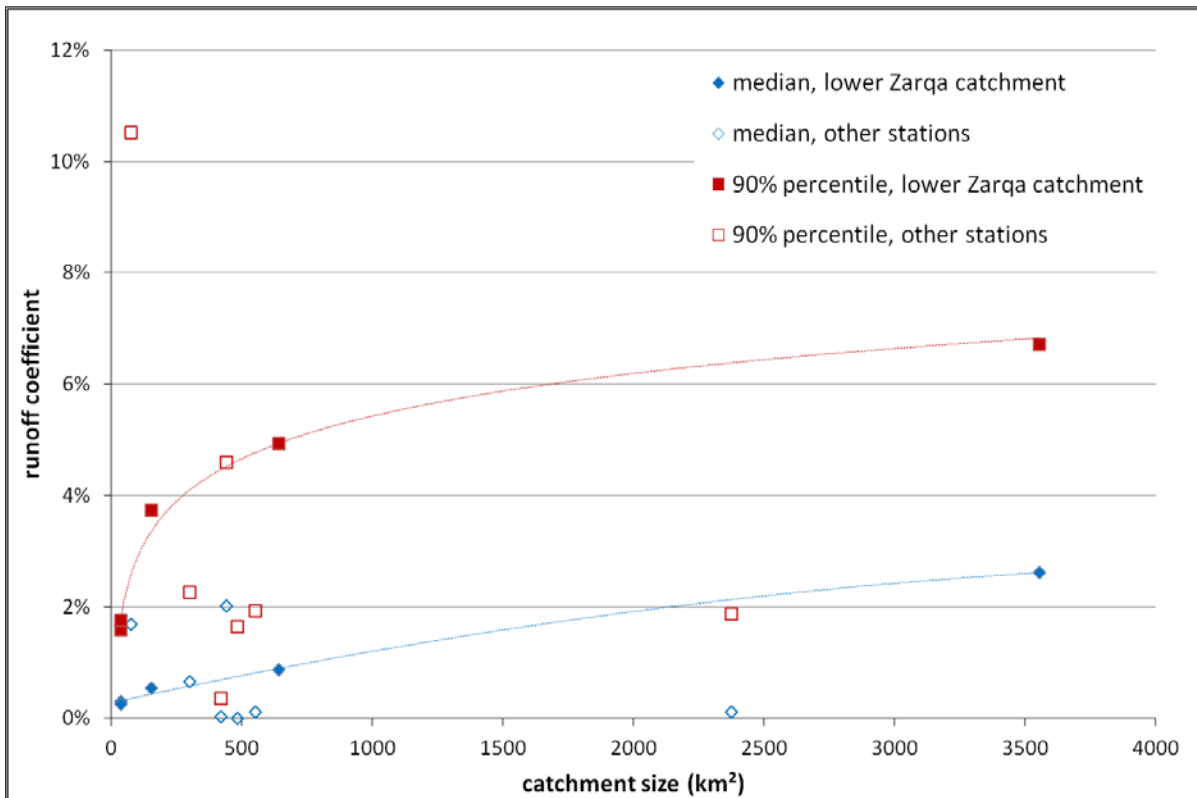
Fig. 41: Correlation between catchment size (km²) and median and 90 % runoff coefficient (%) for lower Zarqa catchment stations (AL0040, AL0060 - 0063) and other stations.

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Table 13: Compilation of runoff coefficients reported in the literature from actual measurements and from estimations based on the CN method.

from actual measurements			
reference	catchment	runoff coeff. (%)	remark
this study	Wadi Um al Dananeer	0 - 9.9 (median 0.29)	
	Zarqa (New Jerash Bridge)	0.36 - 15 (median 2.6)	
	Wadi Sleihi	0 - 8.4 (median 0.25)	
	Ain Ghazal	0 - 8 (median 0.54)	
	Wadi Zarqa (Sukhne)	0 - 13.8 (median 0.87)	
	Wadi Dhuleil (Sukhne)	0 - 6.3 (median 0.12)	
	Wadi Abdoun	0 - 36 (median 1.7)	
	Wadi Zatari	0 - 0.52 (median 0.02)	
	Wadi El Janab	0 - 4.6 (median 0.12)	
	Wadi Butum	0 - 5.4 (median 2.0)	
	Wadi Ratam	0 - 7.1 (median 0.66)	
	Wadi Hassan	0 - 7.3 (median 0.00)	
de Laat and Nonner, 2011	Madoneh (37 km²)	1 - 11 (mean 3.5)	only 6 rainfall events
AHT and BGR, 1977	Azraq basin	1.2	basin climate index, estimation
	Wadi Um ed Dananeer	1.8	only 2 years
	Zarqa - (old) Jerash Bridge	2.65	only 3 years
	Wadi Sleihi	1.4	
	Ain Ghazal	29	extreme flood event
	Wadi Dhuleil	3.4	extreme flood event
	Zarqa at Sukhne	15.9	extreme flood event
	Wadi Abdoun	10.1	extreme flood event
Alkhoury, 2011	Wadi Kafrein	3.3 - 5	3 years only
Abu-Awwad and Shatanawi, 1997	Muwaqqar watershed (6 km²)	12 - 83	6 high intensity rainfall events (>20 mm)
Parker, 1970	AMZ basin	2.3	method unclear

CN method				
reference	area	runoff coeff. (%)	CN used	remark
Ta'any, 1997	Wadi Er Ratam	1.1	not given	
	Wadi El Janab	3.6	not given	
	Wadi Butum	2.5	not given	
Al-Kharabsheh, 1996	Azraq basin	2.5	not given	
Otova et al., 1989a	Azraq basin	2.4		runoff coeff. 1 - 11.1 % for subcatchments
Otova, et al., 1989b	AMZ basin	5.7	59	runoff coeff. 2.6 - 13.7 % for 1971 - 1983
CES and Arabtech CE, 1994	Azraq basin	1.2	75 - 83	runoff coeff. 0.1 - 2.1 % for subcatchments
Al-Kharabsheh, 1995	Azraq basin	2.5	70 - 78	
Hammouri and El-Naqa, 2007b	Madoneh (19 km²)	18 - 25	78	43 mm and 59 mm events
	Madoneh (19 km²)	11 - 19	84.6	43 mm and 59 mm events
Taqieddin et al., 1995	Wadi Jilad/ Badia (111 km²)	22.9	78.5	47 mm event
	Badia	2.9	72.5 - 78.5	annual; runoff coeff. 0.8 - 7.3 % for 1966 - 1989
Chehata et al., 1997	Wadi Madoneh (57 km²)	4 (13, 30, 49)	82	annual and (for 2, 10, 25 year event)
	Wadi Butum (138 km²)	1.7 - 3.8 (13, 30, 37)	86	annual and (for 2, 10, 25 year event)

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Curve number

The CN method (see section 3.1) is commonly used for the calculation of runoff in ungauged catchments. Hence, the available rainfall-runoff data were used to calculate the yearly curve numbers (CN) with the following formula (Simanton et al., 1996):

$$S = 5 \left(P + 2Q - \sqrt[2]{4Q^2 + 5PQ} \right) \text{ and } \qquad CN = 25400 / (254 + S)$$

with S = potential maximum soil moisture retention after runoff begins (mm), P = precipitation depth (mm), Q = runoff depth (mm)

The statistical analysis reveals that CNs typically range between 13 and 60 (median 31) for the flood station catchments. Catchments in Azraq basin have the highest CNs and lowest CNs are found for the smallest catchments in AMZ basin. A high CN can result from sealed surfaces like urban areas, as well as desert pavements or bare rocks as they are frequently found in Azraq basin. Rainfall occurring mainly in heavy storms that quickly overcome the infiltration capacity of the soils could also result in a high CN. Low CNs are due to high soil moisture storage capacities and high rates of infiltration, which are enhanced by vegetation frequently found in the smaller catchments with low CNs.
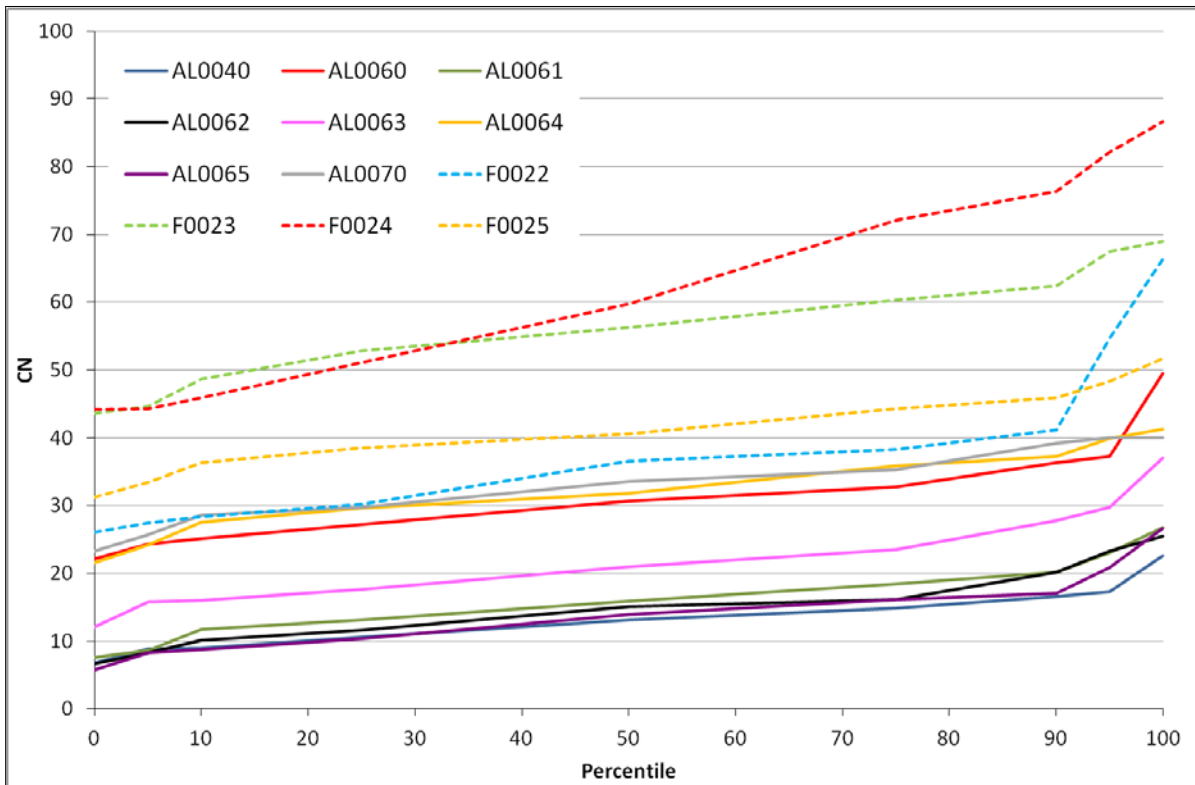
Fig. 42: Statistical evaluation of CN distribution of existing flood stations for the years recorded (calculated from WIS data, MWI).

Commonly used CN values lie between 70 - 85 (Table 13). However, in this study only Wadi Ratam has CN values >70 in 30 % of years, while none of the other catchments comes even close to 70 (Fig. 42). Accordingly, the use of CNs >70 systematically overestimates available runoff. This was also attested by a study for Wadi Madoneh (de Laat and Nonner, 2011). Other rainfall-runoff models found that runoff is commonly overestimated at the start and end of the rainy season, when the initial losses are large due to high loss by plant interception, high infiltration rates on dry soil and surface storage of water (Ismail, 1986). A comparison

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between the rational runoff coefficient method and the CN method showed that the CN method results in higher peak discharges especially for high rainfall events and for open spaces (McCuen and Bondelid, 1981). The very generalising CN method cannot adequately depict the small scale differences in soil, underlying geological formation, rainfall intensity and surface topography. Therefore, its applicability to large catchments (>250 km²) should be viewed with caution (Ponce and Hawkins, 1996).

Runoff and rainfall intensity

The frequency and intensity of rainfall events are one of the main controlling factors for runoff generation. A comparison of daily rainfall data with daily runoff data for catchments of the Azraq runoff stations often showed no obvious correlation between rainfall and runoff. However, the following trend was observed: days with more than 10 mm of rainfall were very likely to generate runoff, days with 5 - 10 mm of rainfall sometimes generated runoff and days with less than 5 mm of rainfall only very seldom resulted in measured runoff. The observed non-correlation between runoff and rainfall might be due to the fact that rainfall is often very local and does not affect the whole catchment.

Other studies found that runoff generation only occurs when rainfall events exceed around 10 - 15 mm/d (Noble, 1994; Chehata et al., 1997; Hammouri and El-Naqa, 2007b). The amount of precipitation required to generate runoff will also depend on other prevailing conditions such as antecedent soil moisture, the nature of surface materials and vegetation (Al-Homoud et al., 1996) as well as the formation of sealing crusts (Le Bissonnais and Singer, 1993)

If the mean daily rainfall depth over all stations are calculated for each basin, only 21 % and 4 % of all rainy days have rainfall >15 mm in AMZ and Azraq basin, respectively. Hence, a larger runoff event is to be expected only on 5.5 or 0.66 days per year in AMZ and Azraq basin, respectively (Table 14). These numbers agree quite well with the observed number of runoff events (Table 12).

Table 14: Number of days with rainfall depth >10, >15, >20 and >40 mm for the two basins in % of rainy days and absolute rainy days per year. [Average total rainy days 26 and 18 for AMZ and Azraq basin, respectively] (arranged after WIS daily rainfall data).

		>10 mm/d	>15 mm/d	>20 mm/d	>40 mm/d
AMZ basin	% of rainy days	33.5 %	21 %	16 %	3.5 %
	no of days per year	8.7	5.5	4.2	0.9
Azraq basin	% of rainy days	9 %	4 %	1.5 %	
	no of days per year	1.6	0.7	0.27	

Excess runoff

After looking at the runoff generated in the catchments, one has to evaluate how much of this runoff is actually excess runoff and not already harvested and used[49]. In general, virtually all runoff in AMZ is already harvested in the King Talal dam and used mainly for irrigational purposes (Mohsen, 2007; Aulong et al., 2009). The Jordan Valley Authority (JVA) also constructed a number of desert dams with a total design storage capacity of around 9 MCM over both basins (Table 15). In addition, there are 40 older lagoons and 27 ponds in both basins with a total design storage capacity of 0.14 and 3.92 MCM, respectively (Table 16). A further 10 small water harvesting dams are planned for this year in Azraq with a combined

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[49] Data on surface water usage was not available.

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design storage capacity of 0.95 MCM. On top of these official dams, there are more than 300 private water harvesting constructions (Fig. 43) like small earth dams, hafirs, diversions into ponds and cisterns. Estimations of private water harvesting capacity are about 0.6 MCM for private ponds and about 1 MCM for private earth dams[50]. These are not evenly distributed and could hence harvest large percentages of potential runoff in some catchments. It has also been reported that runoff from the Syrian part of the watersheds has decreased due to the construction of dams in Syria[51] and one larger dam could be seen in the Rajil watershed on GoogleEarth. When adding up these numbers it seems that >100 % of all runoff in Azraq and ~25 % (excluding King Talal dam) in AMZ basin could already be captured in a normal year[52] (Table 16).

Table 15: Existing governmental dams in AMZ and Azraq basin (see Fig. 43 for locations) Source: JVA data supplied 2011 and de Laat and Nonner, 2011

ID	Name	year	design capacity (MCM)	height (m)	catchment (km²)*
			AMZ basin		
AL0075	King Talal	1977 raised 1987	75	108	3214
AL0076	Al Khaldeya	1983	1.4	15.0	395
AL0077	Al Lahfi		2.3	8	85
AL0078	Abu Suwwanah	1962	0.25	4.0	88
AL0079	Wadi al Ish	2001	0.07	8.0	30
(A2)	Wadi Madoneh	2007	0.0019	2.8	1.2
(B0)	Wadi Madoneh	2007	0.0213	5.8	13
(M1)	Wadi Madoneh	2007	0.0664	3.3	18
(M2)	Wadi Madoneh	2007	0.0032	3.2	2
			Azraq basin		
F 0025	Wadi Rajil	1992	3.5	9.0	2777 (3243**)
F 0026	Jelat		0.1	6.0	134
F 0027	Deir El Kahf	1950	0.05	5.0	92
F 0028	Al-Muwaqqar	1960	0.1	10.0	5
	Wadi Harth	2011	1.0		250
	Wadi Butum	2011	0.038	2	168

* excluding catchment of upstream dams, calculated based on DEM, ** value given by JVA

Table 16: Capacity (MCM) of existing dams and water harvesting structures in AMZ and Azraq basin (Source: JVA data supplied 2011 and mapping in GoogleEarth).

	Amman-Zarqa	Azraq	total capacity (MCM)
JVA dams	4.11	5.13	9.24
lagoons	0.08	0.06	0.14
official ponds	0.66	3.26	3.92
MoA dam		1.00	1.00
planned hafirs		0.95	0.95
private earth dams	0.28	0.70	0.98
private ponds	0.04	0.54	0.58
Syrian catchment	0.05	0.15	0.20
total harvesting capacity	**5.22**	**11.79**	**17.01**
normal year runoff	20	10	30
total harvesting capacity in % of runoff	26 %	118 %	57 %

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[50] Ponds are assumed to be about 2 m deep, earth dams to hold around 1 m depth over a triangular area behind the dam.

[51] JVA, personal communication

[52] estimated 10 and 20 MCM/a flood runoff for Azraq and AMZ basin

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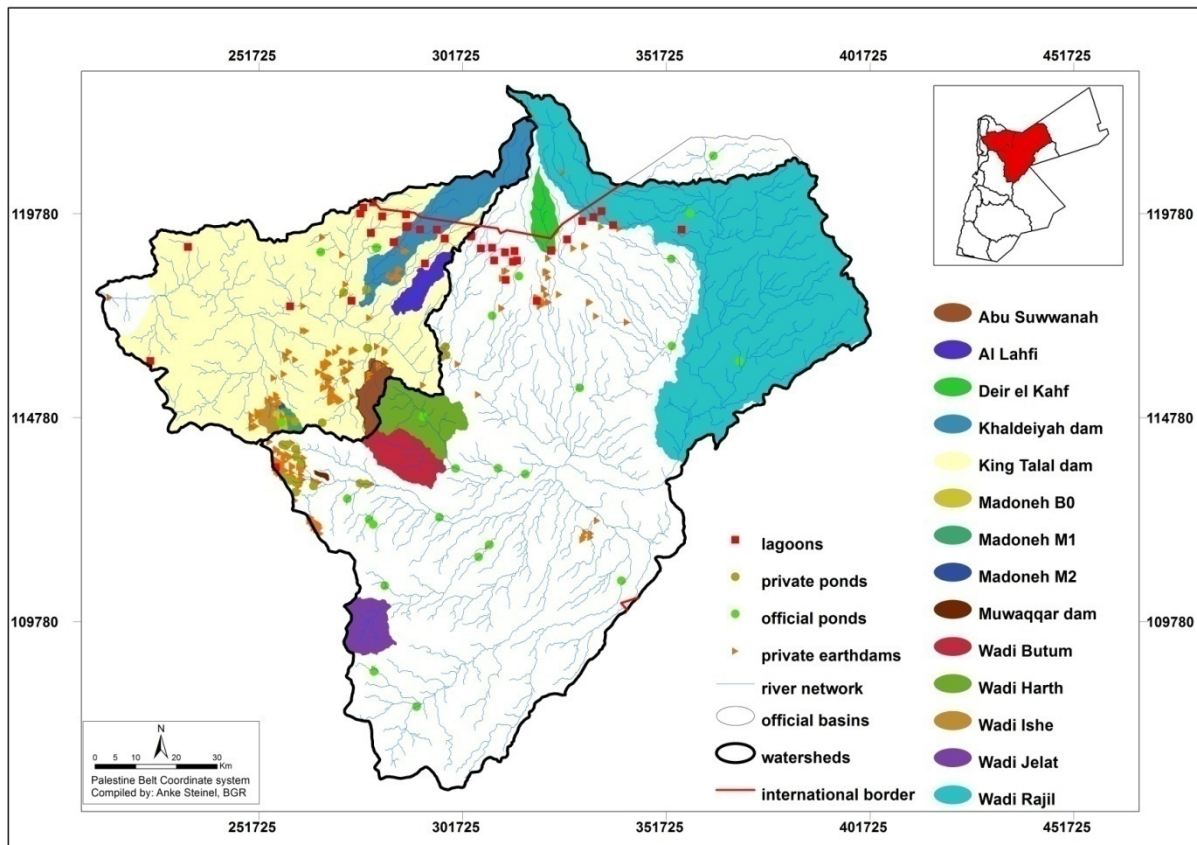
Fig. 43: Existing official and mapped private water harvesting structures; catchments[53] of the larger JVA dams are shown in colour (arranged after JVA data and GoogleEarth survey).

Apart from human use, runoff also fulfils other purposes, for example, the dilution of low quality water like treated and untreated wastewater. This is crucial for Zarqa river where water quality is already impaired. Another purpose is the maintenance of environmental flows that sustain flora and fauna along the wadis, in the marabs and qaas. Especially in Azraq basin these areas are the only vegetated areas sustaining biodiversity and providing pastures. A fully flooded Azraq Qaa attracts many water birds.

Once runoff is caught in a dam not all of the harvested water is available for infiltration due to technical constraints, trapping in vadose zone and evaporation (de Laat and Nonner, 2011; Racz et al., 2012). Monitoring at the Omdel site, Namibia, showed that only about 50 % of the harvested water infiltrated to the aquifer, while about 25 - 30 % evaporated and 10 - 20 % could be released from the dam due to technical constraints (Zeelie, 2002). Other estimations for sites in Iran showed that 45 - 65 % of harvested water was available for recharge and only 85 % of this could be recovered (Kalantari et al., 2010).

It is also to be considered that high floods in wet years will spill over the dam or even damage the dam, unless dams are constructed very large and sturdy. Hence, there are economical restrictions influencing the maximum flood volumes that are possible to be captured. Chehata et al. (1997) set the economically feasible dam size for Jordan at about 0.5 MCM per dam or a storage capacity to be able to capture a 20 - 40 mm precipitation

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[53] As the river network is generated from the DEM it does sometimes not replicate the real situation. For example, the location of Dheir el Kahf dam had to be shifted to the closest river that would replicate the actual catchment the best.

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event (depending on catchment size). If runoff events follow very quickly after each other the dam might still be filled with water from previous events and not be able to capture more water, also reducing possible volumes to be captured. Example calculations at the Omdel site, Namibia, showed that a 40 MCM dam would have captured about 50 % of all runoff over 48 years as 31 years where basically dry and 4 years had a flow of >40 MCM (DWA, 1994).

All of the above mentioned assessments are undertaken for 'normal' years, which in reality are occurring in only about 50 % of years and will be occurring even less often with the expected effects of climate change (Box 6). In dry years (30 % of years), hardly any runoff production takes place, while in wet years (20 % of years) only a limited percentage of the produced runoff could be captured and recharged. Overall, the water harvesting is hampered by the unpredictability, infrequency and short duration of flood volumes.

10.2.2   Quality of floodwater

Surface runoff contains high concentrations of fine suspended solids (about 500 mg/L) that silt up water harvesting structures and reduce infiltration capacity.

Surface water quality may be affected by hazards like agrochemicals, quarries and wastewater from animal farms or factories, but only limited records on floodwater samples are available.

No monitoring of flash floods in ephemeral wadis is taking place. Surface water samples are taken only at a number of sites along the Zarqa river (monthly to 3 times per year) and in the large dams (monthly), mainly to analyse the treated wastewater baseflow, but not for flood events.

The main quality problem of flash flood runoff is the high concentration of fine **sediments**, which is visible as sediment accumulation behind every dam (Fig. 44). Only five TSS analysis of flood runoff sample were found (all from one event in Dec 1987 from the upper Zarqa river catchment) with TSS concentrations ranging from 252 to 924 mg/L (Obeidat and Abu Muheisin, 1989). One non-quality controlled sample of a flash flood was taken on 9.2.2012 from southern Wadi Butum with 674 mg/L TSS. For comparison, one flood event in Namibia showed a variation in silt concentration from >5000 mg/L at peak flow to about 350 mg/L at flood end (Crerar et al., 1988). Values from Iran range from 50 to 5000 mg/L suspended solids in flood flows (Mousavi and Rezai, 1999; Kalantari et al., 2010). For Jordan's desert regions sediment volumes of 1.1 - 1.5 % of runoff volume were estimated (Hydrosult, 1988), which would be equivalent to about 30 000 – 40 000 mg/L. Similarly sediment loads in Yemen were estimated at 1 - 2 %, with measured loads of 11 400 – 55 700 mg/L at Wadi Tuban and 3 200 – 13 600 mg/L at Wadi Bana (Shahin, 2007). While the first value appears too high, the latter value seems realistic when comparing this to sedimentation rates observed in dams (see section 10.4.3). The higher value can be explained with the fact that about ⅔ of the load is transported as bed load and not in suspension and is hence not sampled. Assuming 1 % of sediments in floodwaters, each 50 000 m³ flood would bring about 500 m³ of sediments.

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A maximum TSS concentration of 50 mg/L is required for recharge to groundwater (JISM; 2006), but it should be even lower to limit clogging effects. A maximum concentration of <20 mg/L has been suggested for a sandy aquifer in Namibia (DWA, 1996), CGWB recommends 10 - 12 mg/L for fractured rocks in India and turbidity values of <10 NTU are recommended for basin recharge over alluvium in the USA (ASCE, 2001). If quarries are operational in the surface water catchment or close by, an increase in sediment load is to be expected.

Fig. 44: Sediment accumulation with mud cracks at Wadi Madoneh dam (M2) of about 40 cm at dam wall. (Pictures taken by A. Steinel, 2011).

Three samples of dried clogging layer from reservoirs were taken and analysed at BGR, Hannover, for grain size (X-ray granulometry, Sedigraph), cation exchange capacity (CEC) (Cu(II)-triethylentetramin method) and for mineralogy (X-ray diffraction, XRD). The results show that clay and fine silt are the dominant fractions (Table 17). As all samples show only minor differences in CEC and XRD, it is assumed that sample 1 contains aggregated clay minerals rather than silt.

Table 17: Results from grain size analysis (Sedigraph method) and cation exchange capacity (CEC) from three accumulated sediment samples in desert dams.

	clay	silt			sand	CEC
Samples	<2 µm	2 - 6.3 µm	6.3 - 20 µm	20 - 63 µm	>63 µm	meq/100 g
1	23.8	39.7	34.8	1.7	0	19
2	58.7	33.2	4.4	1.3	2.4	18
3	63.5	20.8	4.2	3.1	8.4	19

In accordance with the geology, the mineralogical analysis showed the non-clay minerals of quartz, feldspar, dolomite, and traces of hematite and goethite. The clay fraction contains large amounts of palygorskite and kaolinite as well as illite, chlorite and expandable smectitic clay minerals (e.g. montmorillonite). Analyses of clayey soil samples in the Wadi Al-Arab catchment have also confirmed the occurrence of montmorillonite.[54] The smectitic clay minerals are mainly responsible for the CEC. Montmorillonite and palygorskite are characterised by their high water retention capacity. Palygorskite is also stable against flocculation even at higher salinity levels (Neaman and Singer, 2004; Önal and Sarikaya, 2009). Accordingly, these particles have a low settling velocity and removal rates due to settling are limited.

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[54] S. Kraushaar (UFZ), 2012, personal communication

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Other analysis have shown that while the bulk of the sediments could consist of sand (Shatnawi, 2012), the clogging layer depositing at the top consists of clayey silt to silty clay with a median grain size of <4 μm (Zemann, 2008).

Larger 'particles', i.e. garbage that is either deliberately dumped in wadis or transported there by wind and water, is another problem (Fig. 45). Depending on the kind of trash this could decrease surface water quality considerably. Trash screens should be installed and periodically cleaned to prevent it from entering the infiltration facility.

Fig. 45: (left): garbage dumped in Wadi Al Mamriyya, (right) windblown garbage at Wadi Ratam. (Pictures taken by A. Steinel, 2012).

The **salinity** in the rainfall is very low (electrical conductivity (EC) <200 μS/cm, Salameh and Rimawi, 1987) and only increases slightly due to contact with the soil and further due to evaporation. For Azraq basin, salinity of flood waters has been cited as 195 - 350 μS/cm and chloride concentrations between 3 - 22 mg/L (Salameh et al., 1991 (cited in Orient ECD, 2010[55]); Al-Kharabsheh, 1995). Even after further evaporation in the dams these concentrations are well below the drinking water standards of 500 mg/L Cl or 1000 mg/L total dissolved solids (TDS)[56](JISM, 2008). Other major ions are not critical either. Only areas with salic soil horizons near the surface might have strongly elevated salinity concentrations in stormwater runoff. Salinity is also elevated if wastewater is contributing to runoff, but concentrations are still mostly below the limits for recharge of groundwater (JISM, 2006) (Table 18). Total dissolved solids (TDS) values in the dams show a cyclic pattern with the highest values at the end of summer after evaporation was highest and with the lowest values at the peak of the wet season, when dilution is greatest.

Other parameters of interest are nutrients and pathogens, which result mainly from wastewater disposal and excessive use of fertilisers. Floodwaters in Azraq have low nutrient concentrations, while the large dam lakes along the Jordan Valley and the Zarqa river can have maximum values exceeding the standards. The Zarqa river also commonly contains highly elevated concentrations of pathogens. TSS values vary greatly and show single peaks from extreme flood events, but no yearly pattern. The highest values were found for Shueib dam (up to 16 440 mg/L). As particles settle in the dam lakes and samples are likely taken from the surface, values <50 mg/L TSS are most common.

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[55] The original publication Salameh et al., 1991 could not be obtained.
[56] equivalent to about 1500 μS/cm depending on solution composition

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Table 18: Surface water samples from various sources compared to regulations and recommendations.

	parameter	pH	EC	TDS	CL	NO3	PO4	*E.coli*	TSS
reference	unit		µS/cm	mg/L	mg/L	mg/L	mg/L	MPN/ 100 mL	mg/L
JISM, 2008	Drinking water limits	6.5 - 8.5		1000	500	50 (70)		1.1	5 NTU
JISM, 2006	recharge to gw (JS 893)	6.0 - 9.0		1500	350	30	15	2.2	50
GTZ, 2006	irrigation water limits	6.0 - 9.0	3000			30		1000	
Orient ECD, 2010	Wadi Mugheir[57]	8	255		10.6	5.6			
Al-Kharabsheh, 1995	Azraq basin (5 samples)[58]	7.4	282		8.7	4.8	0.08		
Salameh and Al-Ansari, 1999	North Zatari (4 samples)		140 - 175		7 - 12	1.2 - 6.2	0.7 - 3.8		
	Middle Zatari (4 samples)		170 - 305		10 - 21	0.2 - 9.3	1.4 - 3.3		
	South Zatari (4 samples)		160 - 385		0 - 7	2.5 - 12.4	1.4 - 3.9		
	Khaldeya dam (4 samples)		180 - 195		7 - 10	6.2 - 12.4	1.3 - 4		
	Wadi Dhuleil (4 samples)		235 - 350		18 - 25	6.2 - 10.5	1.6 - 5.8		
	Al Ghaderr dam (5 samples)		240 - 320		7 - 11	8.0 - 19.8	0.2 - 2.3		
JVA data (2006 - 2011)	King Talal dam (70 samples)	7.7 - 9.6	1480 - 2690	821 - 1652	235 - 486	0.02 - 38	1.1 - 65	<1 - 7.9*10^5	<2 - 118
	Kafrein Dam (71 samples)	7.4 - 10.2	638 - 1360	338 - 782	64 - 245	0.01 - 15	<0.03 - 2.9	<1 - 2.4*10^4	<2 - 486
	Mujib dam (70 samples)	7.6 - 8.6	485 - 2030	214 - 1305	32 - 293	<0.01 - 44	<0.03 - 5.3	<1 - 2.4*10^4	<2 - 573
	Shueib dam (70 samples)	7.8 - 9.4	580 - 1300	332 - 938	58 - 197	0.01 - 15	<0.03 - 13.5	10 - 1.1*10^5	3 - 16440
	Wala dam (66 samples)	7.6 - 8.9	224 - 1085	126 - 668	7 - 114	0.05 - 4.4	<0.03 - 12	<1 - 2.4*10^4	<2 - 607
WAJ data (2010 - 2012, monthly), Zarqa stream	Ain Ghazal (3 samples)	7.8		640		27	6.9	1.2*10^5	32 - 69
	Ruseifa (4 samples)	8		557		46	1.8	9.9*10^4	3 - 47
	Al Zawahreh (5 samples)	7.9		912		29	4.8	6.4*10^5	5 - 83
	West of Zarqa (3 samples)	8.3		964		38	5.7	6.0*10^5	10 - 18
	Abu Al Zigan (3 samples)	7.8		614		39	3.4	3.7*10^5	5 - 20
	Jerash Bridge (26 samples)	8.4		1360		65	13	2.0*10^3	15 - 48

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[57] 170 samples over 3 years, cited from Salameh et al., 1991

[58] one in each catchment (Wadi Kleita, Wadi Butum, Wadi Erratam, Wadi Aritain, Wadi el Maghayer)

Due to the high pH in limestone areas, heavy metals are not soluble and measured values are well below drinking water limits (Salameh et al., 1991 (cited in Orient ECD, 2010); Al-Kharabsheh, 1995).

Apart from TSS it is expected that surface water quality would be sufficient to satisfy limits for groundwater recharge, unless there are highly contaminating facilities like industrial animal farms, factories, large settlements, WWTP, etc. in the surface water catchment.

Box 6 Climate change predictions and impacts on water resources

All global climate models (GCMs) predict an overall increase in temperature and most predict a reduction in rainfall for the Middle East (IPCC, 2007). Regional climate models, that simulate cyclones that bring most of the precipitation to Jordan and are commonly not well resolved in GCMs, also predict a significant decrease in rainfall due to a reduction in cyclones for Jordan (Black et al., 2011). For the wider region of the Jordan Valley annual mean precipitation is expected to decrease by 11.5 % and 20 % for the period 2031 - 2060 and 2070 - 2099 compared to 1961 - 1991, respectively (Smiatek et al., 2011). Especially the mountainous part could experience a decrease of up to 25 % in precipitation and 23 % in runoff for the 2070 - 2099 period (Kunstmann et al., 2007). Furthermore, the projected increase in temperature would lead to an increase in evapotranspiration, which alone could lead to a decrease in runoff and groundwater recharge by between 1.2 % and 3.6 % per degree temperature increase (Abdulla et al., 2009).

However, these changes in runoff and recharge are insignificant compared to the results of changes in precipitation. Runoff varies in the same extent with changes in rainfall, but recharge is projected to decrease by a much larger percentage as a certain threshold in soil moisture has to be reached before recharge occurs. Hence, groundwater recharge could potentially decrease by 52 % from a 20 % decrease in rainfall (Abdulla et al., 2009; Jassim and Alraggad, 2009). Accordingly, reduced precipitation could trigger exponentially larger drops in groundwater tables (AFD, 2011) (Table 19).

The simulations also show an increased coefficient of variation in annual precipitation, indicating that larger interannual precipitation variability can be expected in the future with lower numbers of rainy days (Smiatek et al., 2011; Lelieveld et al., 2012). This means that during drought years, there might be no surface water available for infiltration at MAR structures and during years with intense rainfall, floods might be too high to be captured effectively making optimal dam dimensioning complex (Nassopoulos et al., 2012). In addition, intense rains would carry significantly higher concentrations of sediments as well as fertilizer, pesticides and solid wastes into water harvesting structures (AFD, 2011). In conclusion, expected impacts from climate change would not be conducive to MAR via infiltration of surface runoff.

Table 19: Projected change in annual surface runoff and groundwater recharge in Jordan for various scenarios of precipitation and temperature change (after AFD, 2011).

precipitation change (%)	change in annual surface runoff in Jordan (%)		change in annual groundwater recharge in Jordan (%)	
	+1°C	+3.5 °C	+1°C	+3.5 °C
-20%	-32.5 to -21.6	-60 to -24	-54.1	-57.5 to 51.9
-10%	-40 to -13.2	-50 to -15.5	-34.1	-33.7 to -38.9
0%	-10 to -1.2	-35 to -4.2	-3.5	-10.5 to -8.6
10%	+15 to +33	-30 to +11.1	37.3	+24 to +26.9

![BGR logo]

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10.3   Hydrogeology

> **There are a number of suitable outcropping aquifers in the study area to consider MAR feasible: the basalt aquifer, the B4/5 and the A7/B2 limestone aquifer.**
>
> **Water levels are sufficiently deep to provide ample storage space.**
>
> **Hydraulic gradients are flat and horizontal travel times could be as low as 10 m/a.**

The assessment whether an aquifer is suitable for MAR mainly involves the evaluation of hydraulic properties, storage capacity, depth to groundwater table, flow gradient/direction and groundwater quality (see chapter 2.4). Ideal areas for MAR by infiltration would be thick permeable aquifers without impermeable layers in the unsaturated zone and groundwater close to drinking water quality.

10.3.1   Aquifer systems and characteristics

The general geology (e.g. Masri, 1963; Bender, 1974; Andrews, 1992a, b) and hydrogeology (e.g. Parker, 1970; Howard Humphreys Consulting Engineers, 1983; Powell, 1989; Gibbs, 1993; CES and Arabtech CE, 1994; UN-ESCWA-BGR, 1996; Margane et al., 2002a; Wagner, 2011) of Jordan has been well described previously and hence will be presented briefly here.

The **lithostratigraphic** table (Table 20) shows a sequence of consolidated sedimentary rocks overlain by young basalts and unconsolidated alluvium. They are tilted to the east and vertically displaced along some major faults (Fig. 48) resulting in a more or less consecutive outcropping of younger formations from west to east (Fig. 46).

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): 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)). 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. 21, Fig. 47 left). The B2 formation encompasses also the Al-Hisa phosphorites.

The Neogene and Quaternary basalts (Fig. 51) belong to the Harrat Ash Shaam basaltic province stretching from Syria to Saudi Arabia (Ibrahim, 1993). They are mainly composed of alkali-olivine basalt lava flows and pyroclastic sediments and encompass five groups: Wisad, Safawi, Asfar (Neogene), Rimah and Bishriyya (Quaternary) (Ibrahim, 1993). The topmost vesicular basalt flows are termed *fahda*, show variable weathering, fracturing and contain many qaas (Allison et al., 1998) (Fig. 47). Between the six phases of major eruptions layers of tuff and up to 5m thick fossil clay soils can be found (Margane et al., 2002a).

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.

There are a number of structural **faults**, the most dominant one being the Sirhan depressional fault zone in the SE of Azraq basin with very thick sediment sequences and a

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vertical displacement of more than 3 km. Major NW-SE striking faults are the Fuluq Fault (eastern boundary of Sirhan Graben, clearly visible vertical displacement (see Fig. 52)), Amman-Hallabat fault zone (dextral shear zone), and Berein Fault. Major dyke systems in the basalt also trend NW-SE, e.g. Kharrouba fault (serving as hydraulic barrier) (Al-Homoud et al., 1996). W-E striking fault zones are commonly displaced laterally to the right and a smaller fault system trends ENE to WSW (e.g. Zarqa Ma'in -Azraq Fault) (Fig. 49) (Margane et al., 2002a).
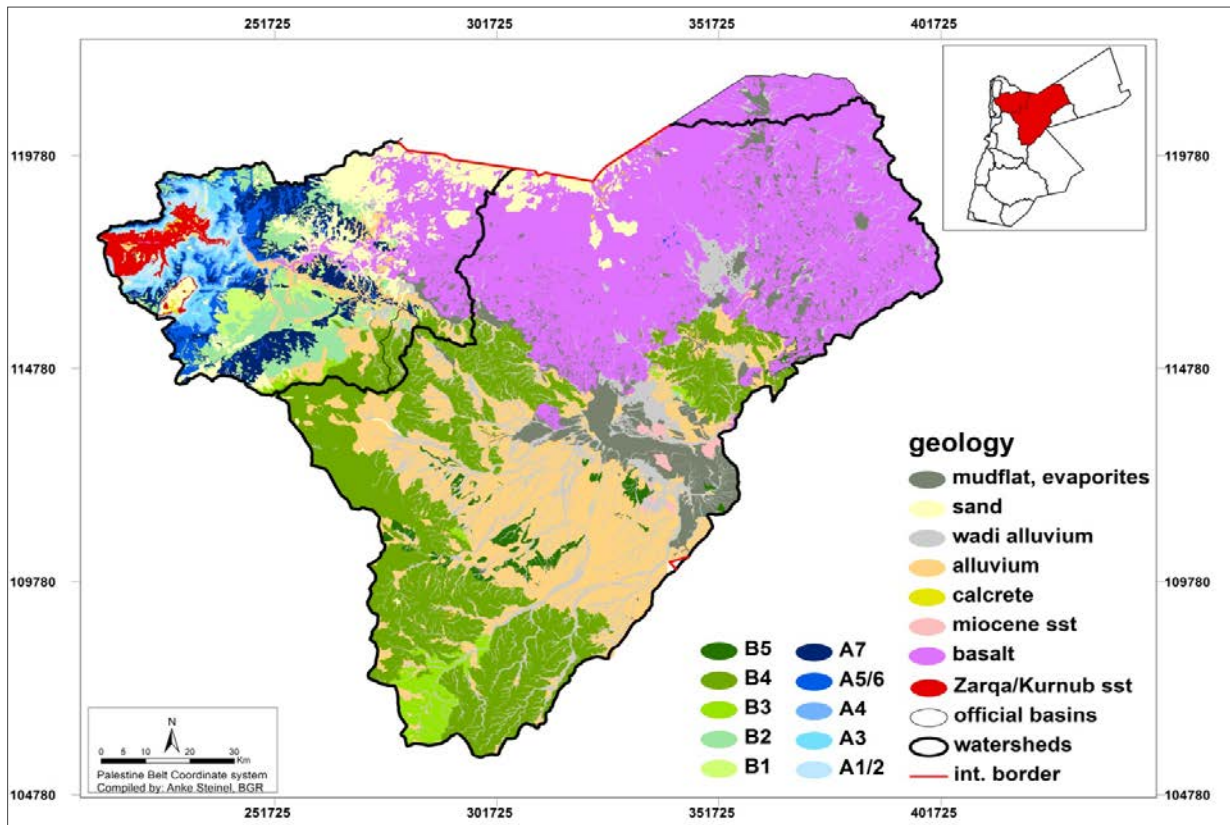
Fig. 46: Near-surface geology (arranged after NRA data, 1:50 000 and 1:100 000 sheets); sst = sandstone.

Fig. 47: left) desert pavement with cherts; right) surface strewn with basalt boulders (clasts). (Pictures taken by A. Steinel, 2011).

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Table 20: Lithostratigraphy and hydrogeological classification of rock units outcropping in AMZ and Azraq basin (after Margane et al., 2002a).

ERA	SYSTEM	EPOCH	GROUP	FORMATION	SYMBOL	LITHOLOGY	THICKNESS [m]	AQUIFER UNIT
CENOZOIC	QUATERNARY	Holocene	JORDAN VALLEY (JV)	Alluvium	Qal	clay, silt, sand, gravel		ALLUVIUM (AQUIFER) / BASALT (AQUIFER)
		Pleistocene		Lisan	JV3	marl, clay, evaporites	> 300	
	TERTIARY (Neogene)	Pliocene		Samra	basalt	conglomerates	100 - 350	
		Miocene			JV1-2			
		Oligocene		Neogene		sand, gravel		
	TERTIARY (Paleogene)	Eocene	BELQA (B)	Wadi Shallala	B5	chalky and marly limestone with glauconite	0 - 550	B4/5 (AQUIFER)
		Paleocene		Umm Rijam	B4	limestone, ckalk, chert	0 - 310	
MESOZOIC	CRETACEOUS (Upper)	Maastrichtian		Muwaqqar	B3	chalky marl, marl, limestone chert	80 - 320	B3 (AQUITARD)
		Campanian		Amman-Al Hisa	B2	limestone, chert, chalk, phosphorite	20 - 140	A7/B2 (AQUIFER)
		Santonian		W.Umm Ghudran	B1	dolomitic marly limestome, marl, chert, chalk	20 - 90	
		Coniacian	AJLUN (A)	Wadi as Sir	A7	dolomitic limestone, limestone, chert, marl	60 - 340	
		Turonian		Shueib	A5/6	marl, limestone	40 - 120	A5/6 (AQUITARD)
				Hummar	A4	limestone, dolomite	30 - 100	A4 (AQUIFER)
		Cenomanian		Fuheis	A3	marl, limestone	30 - 90	A3 (AQUITARD)
				Naur	A1/2	limestone, dolomite, marl	90 - 220	A1/2 (AQUIFER)
	CRETACEOUS (Lower)	Albian	KURNUB (K)	Subeihi	K2	sandstone, shale	120 - 350	KURNUB (AQUIFER)
		Aptian						
		Barremian						
		Hauterivian		Aarda	K1	sandstone, shale		
		Valanginian						
		Berriasian						
	JURASSIC		ZARQA (Z)	Azab		siltstone,sandstone, limestone	0 - >600	ZARQA (AQUIFER)
	TRIASSIC			Ramtha		siltstone,sandstone, shale limestone, anhydrite, halite	0 - >1250	
	PERMIAN			Hudayb		siltstone,sandstone, limestone	0 - >300	
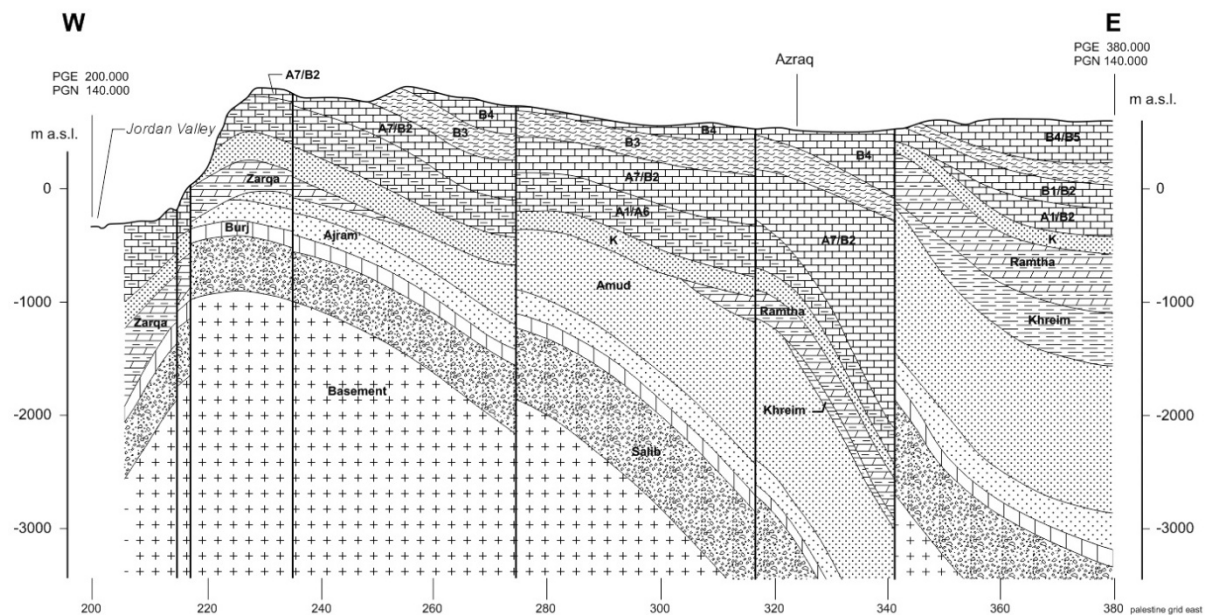
Fig. 48: Geological cross-section from the Jordan Valley in the west across Azraq Qaa towards the Hamad desert in the east (after Margane et al., 2002a).

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With respect to **mineralogy** limestone is obviously dominated by calcite and dolomite and can contain layers with an increased level of halites, sulphates or phosphates. Marly layers contain clay minerals like kaolinite, illite or smectite. Chert nodules with high SiO_2 content are also common in some layers (Al-Homoud et al., 1996; Ibrahim, 1996). The basalt contains mainly plagioclase, potassium-feldspar, pyroxene, amphiboles, biotite, olivine and magnetite. Minor minerals are commonly quartz, zeolite, calcite, epidote, chlorite, apatite, goethite and sulphides like pyrites (UN-ESCWA-BGR, 1996; Ibrahim, 1996). Weathering would lead to an oxidation of iron rich minerals, the formation of clay minerals like goethite, halloysite and smectite as well as the release of cations like Ca and Mg that precipitate as carbonates after addition of atmospheric CO_2. Heavy metals (e.g. As, Ni) associated with pyrites can be mobilised if oxygenated water reaches previously anoxic aquifers (Mirecki, 2004; Maliva and Missimer, 2010).

From a **hydrogeological** point of view there are two main aquifer systems of interest in the study area: (1) the upper aquifer system: the basalt aquifer which is hydraulically connected to the underlying B4/5 aquifer (e.g. Al-Homoud et al, 1996; El-Naqa et al., 2007; Alraggad and Jasem, 2010) and separated by the B3 aquitard from (2) the middle aquifer system: the A7/B2 limestone aquifer (even though the B1 formation is an aquitard and can in areas hinder water movement between A7 and B2 (Lenz, 1999)) (Fig. 49). In the NE of AMZ basin the A7/B2 is hydraulically connected with the overlying basalt.

The lower Ajlun formations (lower aquifer system: often combined into the A1/6 system, which consists of intercalated aquifers (A2 and A4) and aquitards (A1, A3 and A5/6)) and the sandstone aquifers (deep aquifer system: Kurnub and Zarqa) are only outcropping in the lower Zarqa valley. The latter two systems are therefore of limited interest to this study as the area is outside of the highlands and characterised by very steep slopes unsuitable for infiltration. The shallow alluvial aquifer is generally hydraulically connected to any underlying top-most aquifer and only limited data are available.

Data on **aquifer characteristics** rely on drilling logs, pump tests and borehole testing (gamma log, permeability test etc.). The WIS does not contain all the information for all wells[59] and there is only a very limited number of monitoring wells with current readings for water level (Table 21).

The only hydraulic property recorded in the WIS is **transmissivity** (recorded for only 5 - 6 % of all wells). No meaningful interpolation could be undertaken with the available data and the heterogeneity of data (Table 22). For the shallow aquifer system (Basalt + B4/5) two clusters of high transmissivity values are found, one just north of Azraq town and the other in the NE of AMZ basin (Fig. 50). Similar values were published by Al-Kharabsheh (1995). For the middle aquifer system (A7/B2), high values and low values are found very close to each other, showing the high heterogeneity of the karstified aquifer system (Fig. 50).

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[59] Water level and salinity values were mostly measured directly after drilling and hence are not up to date values. The bore logs only name the formation (average thickness of recorded layers ~110 m). Information on filter depth is not included, so wells cannot be reliably related to individual aquifers and parameters might represent composite values from more than one aquifer.

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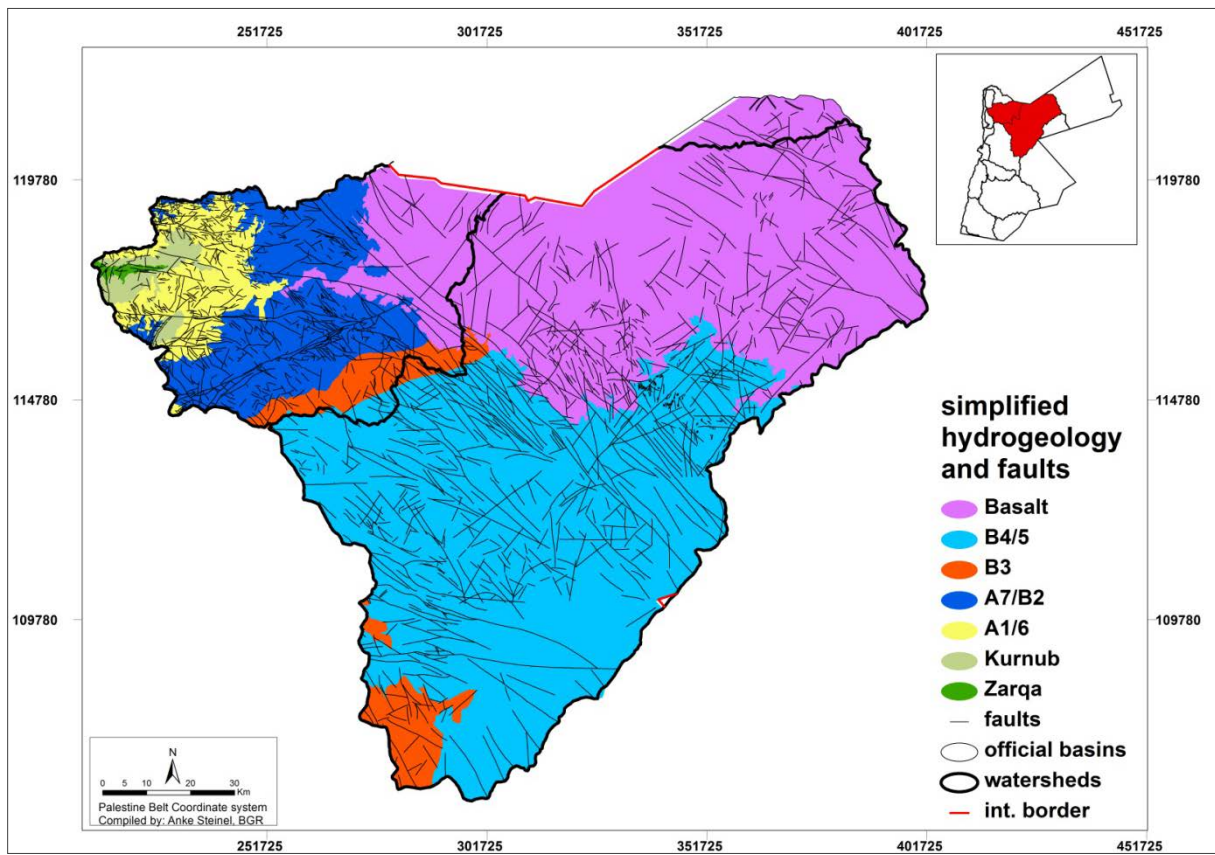
Fig. 49: Simplified outcropping hydrogeology and fault lines (arranged after Hobler et al., 2001 and data from NRA).

Table 21: Available well data for AMZ and Azraq basin from WIS (MWI).

		AMZ (AL code)		Azraq (F code)	
		total = 2060	% of total wells	total = 1422	% of total wells
status	used	1528	74 %	893	63 %
	capped	168	8 %	152	11 %
	dry/abandoned/backfilled	200	10 %	302	21 %
	unknown	164	8 %	75	5 %
aquifer tapped	alluvium	49	2 %	8	1 %
	basalt	272	13 %	126	9 %
	B4/5	4	0 %	116	8 %
	A7/B2	655	32 %	68	5 %
	A1/6	168	8 %	1	0 %
	K/Z	186	9 %	2	0 %
	unknown	725	35 %	1100	77 %
total depth values		1788	87 %	657	46 %
transmissivity values		117	6 %	67	5 %
salinity values		1046	51 %	449	32 %
static water level values		1405	68 %	382	27 %
formation logs		904	44 %	241	17 %
monitoring wells		total = 63	% of total m. wells	total = 21	% of total m. wells
Dec 2010* reading	basalt + B4/5	4	6 %	14	67 %
	A7/B2	27	43 %	2	10 %
	A1/6	12	19 %	0	0 %

*The other monitoring wells did not have a reading for Dec 2010.

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Table 22: Transmissivity values (m²/d)[60] for AMZ and Azraq basin (arranged after WIS data, MWI).

aquifer	transmissivity range (m²/d)	transmissivity median (m²/d)	number of values
basalt	3 - 60 650	3 200	42
B4/5	2 - 6 400	132	22
A7/B2	<1 - 31 000	183	60
A1/6	1 - 1 500	48	27
K	<1 - 30 000	83	30
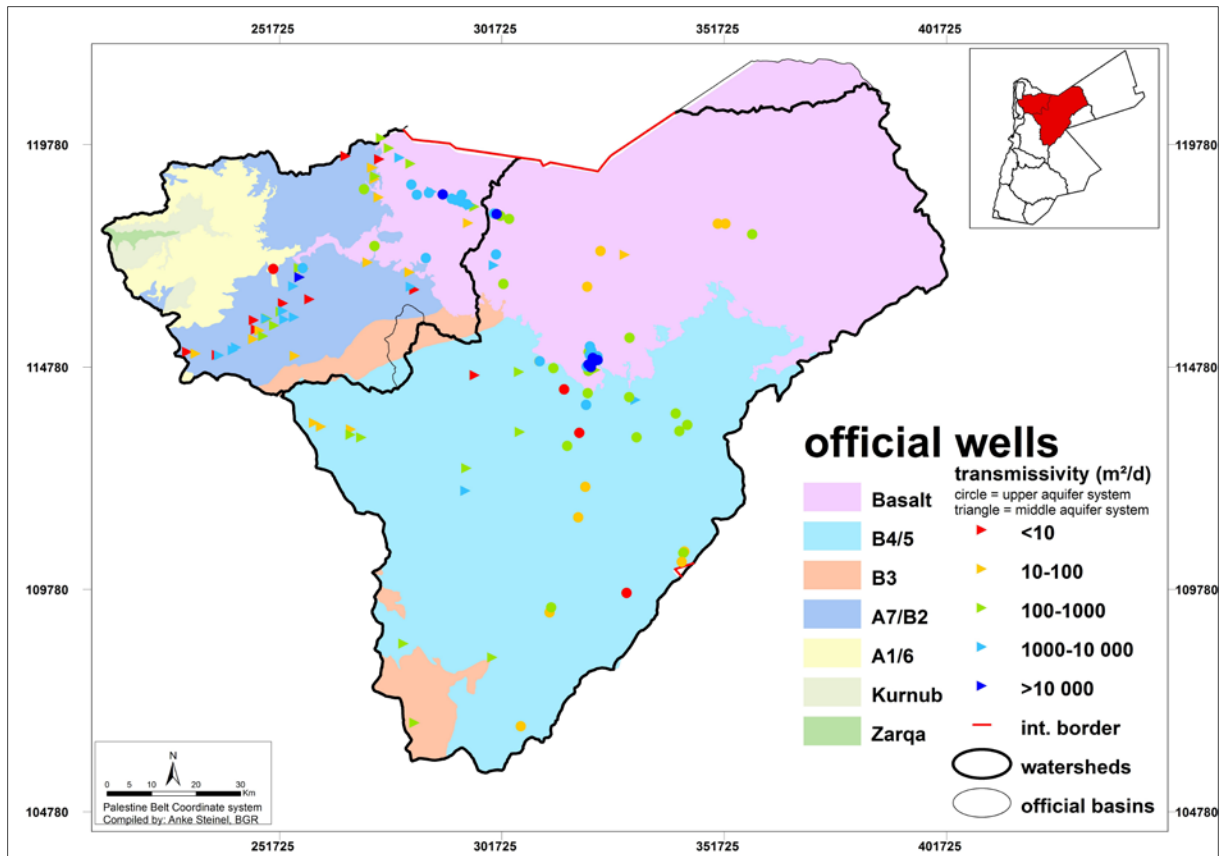
Fig. 50: Transmissivity values for the upper aquifer system (basalt + B4/5 (circles)) and the middle aquifer system (A7/B2 (triangles)) (arranged after WIS data, MWI).

The **basalt** exhibits the characteristic features of a fractured aquifer with potentially high but extremely variable transmissivity, high hydraulic anisotropy and discontinuous heterogeneity (Howard Humphreys Consulting Engineers, 1983). Permeability is enhanced along the fault lines and preferential flowpaths have developed horizontally along the flow boundary layers, especially scoria containing zones, and vertically along cooling joints (UN-ESCWA-BGR, 1996; Margane et al., 2002a). Perched groundwater bodies can form on top of clayey paleo-soils. Neogene basalt flows show a lower permeability than Quaternary flows due to the influence of weathering (Fig. 51; UN-ESCWA-BGR, 1996). In the AMZ basin the basalt lies on top of the A7/B2 aquifer and is hydraulically connected to it, while in the northern parts of the Azraq basin it is separated from the A7/B2 through up to 100 m of B3. In the eastern parts of Azraq basin, the basalt is connected to the B4/5 aquifer (Fig. 52). It was noticed that

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[60] The unit is inferred as it is not recorded in the WIS.

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groundwater decline increased once the basalt was dewatered, as the underlying A7/B2 had a lower hydraulic conductivity (Borgstedt et al., 2007).

The hydraulic properties of the **B4/5** aquifer vary with the degree of karstification and fractures. The B5 formation contains marly clayey layers and can act as aquitard in the northern area below the basalt, while it is more sandy and classified as aquifer in the south (Otova et al., 1989b).

The **A7 and B2** formations are characterised by a variable degree of karstification and are locally separated by a thin marly layer of the B1 formation. The formation is confined in the Azraq basin where it is overlain by the B3 aquitard.

The **A1/6** aquifer has a high variability in vertical permeability due to the presence of clay and marl layers (Al-Kharabsheh, 1995).

In the study area, mean thickness of 225 m (up to 690 m) for the basalt, 225 m (up to 850 m) for B4/5 and 407 m (up to 3145 m) for A7/B2 were estimated.

A range of hydraulic conductivities (permeability) for vertical leakage and horizontal flow is given in Table 23. For example, with a vertical permeability of 8.6 m/d as it is estimated for the basalt, it would take less than 2 weeks to reach a groundwater table at 100 m below the surface.
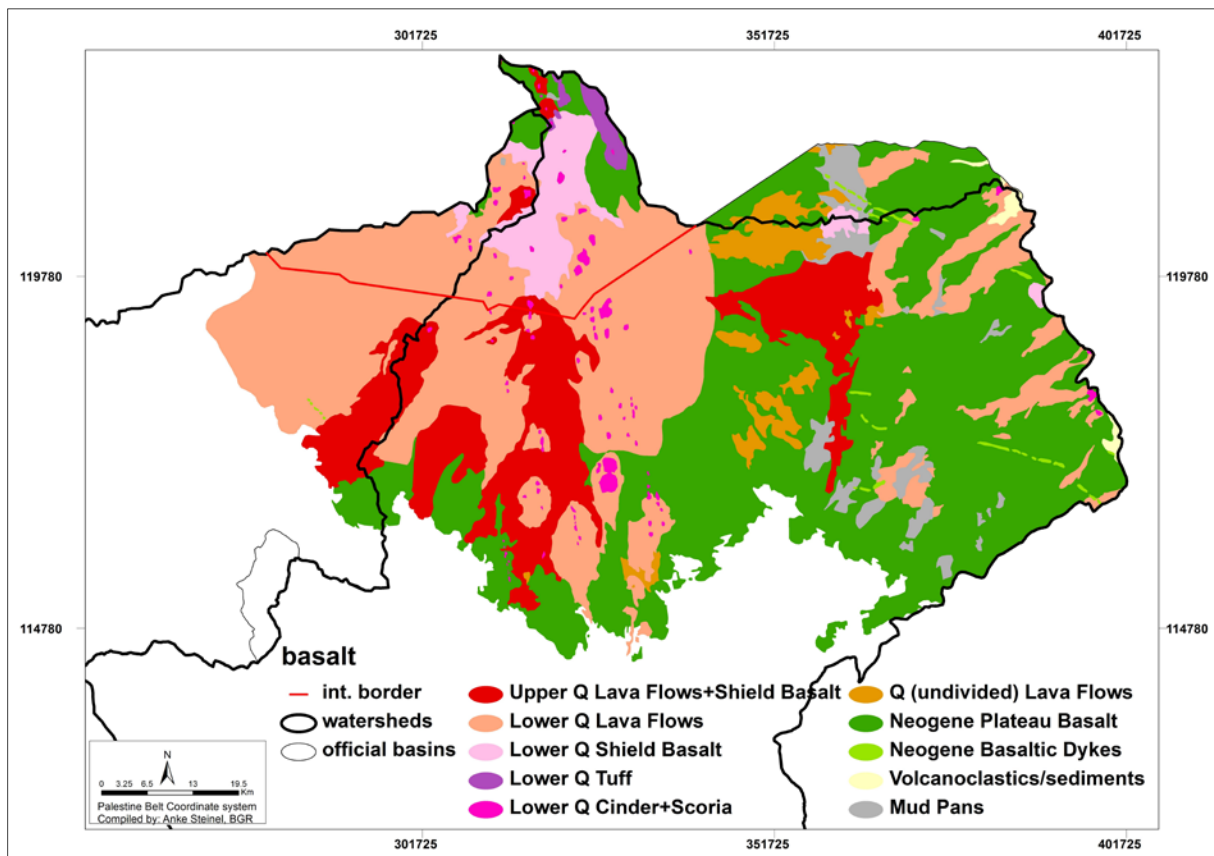
Fig. 51: Differentiation of basalt flows in study area (Q: Quaternary) (after UN-ESCWA-BGR, 1996).

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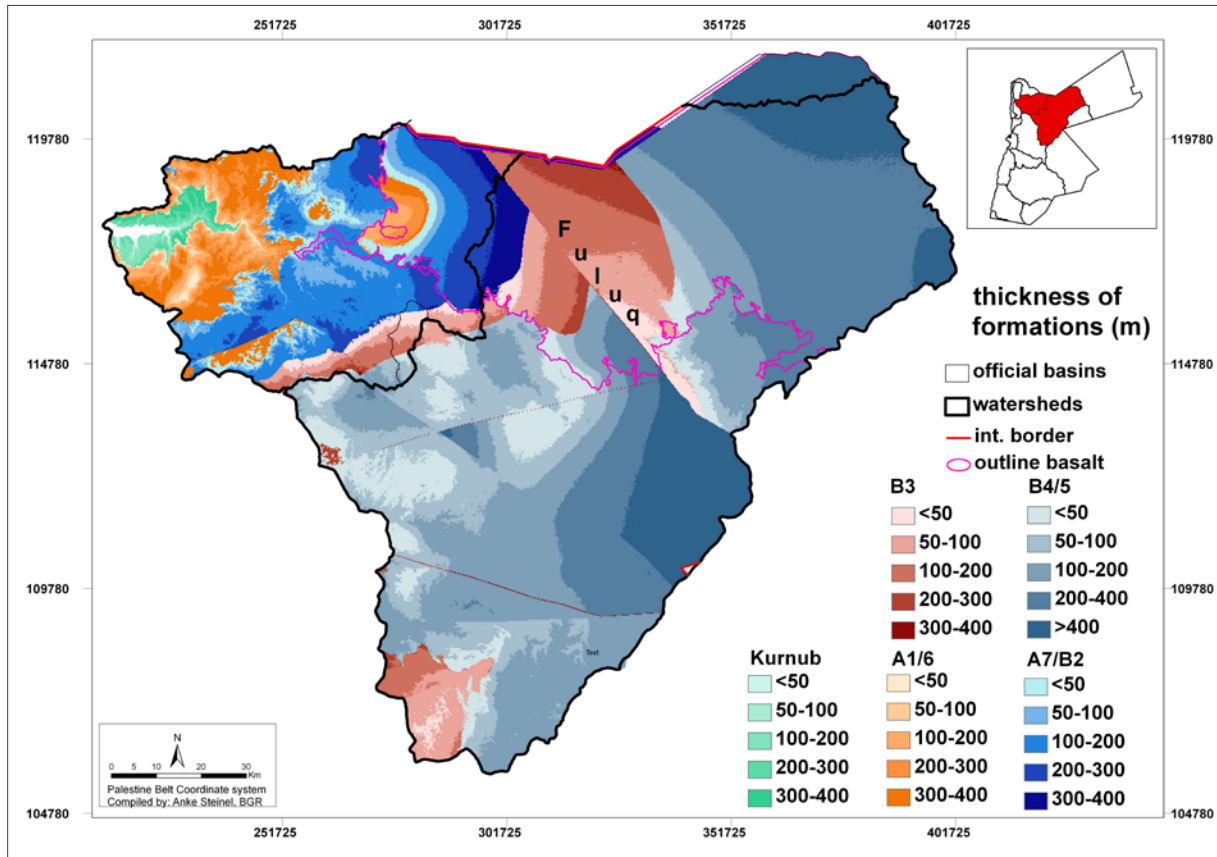
Fig. 52: Thickness (m) of geological formations from Kurnub to B4/5 and the outline of the basalt. The Fuluq fault is clearly visible. (Calculated after data from A. Margane, BGR).

Table 23: Hydraulic conductivity[61] of aquifer systems partially from well measurements, partially from modelling results (arranged after 1: Hobler et al., 2001; 2: Margane et al., 2002b, 3: Margane et al., 2002a).

aquifer	hydraulic conductivity (m/d) = permeability			
	horizontal[1]	vertical[1]	vertical[2]	overall[3]
basalt	17	1.7	8.6	34
B4/5	0.3 - 8.6	0.03 - 0.86	0.05 - 5	4.3
B3	$0.03 - 3*10^{-5}$	$1.7*10^{-6} - 1.7*10^{-4}$		$8.6*10^{-5}$
A7/B2	11 - 605	0.17 - 8.6		1.7
A1/6	0.004	$4*10 - 6$	0.8 - 65	$8.6*10^{-5} - 1.7$
Kurnub	0.0026	0.002 - 0.1	0.6 - 45	2.6

10.3.2   Groundwater quantity and flow systems

Flow direction

Groundwater flow is generally directed from the recharge areas towards the discharge areas or structural lows (e.g. Sirhan Graben) unless some paleo-groundwater mounds from historic pluvial times are superimposed on the current flow pattern (Fröhlich et al., 1987).

Natural discharge occurred in two springs at the Azraq Oasis until 1991 and occurs in the lower Zarqa valley at some springs and as baseflow into the Zarqa river and side wadis (Schulz, 2011). Recharge occurs in the high rainfall areas mainly along the highland ridge in

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[61] A compilation of hydraulic conductivities can also be found in Rapp (2008)

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the west of the study area and on the basalt in Syria (Jebel al Arab). Accordingly, for the shallow aquifer system (basalt + B4/5), flow is directed towards the topographic low in the centre of the Azraq basin (Alraggad and Jasem, 2010; Hobler et al., 2001) and towards the Sirhan Graben in the SE (Fig. 53). For the middle aquifer system (A7/B2), groundwater flow is divided: (1) below the western recharge area, flow is directed westwards discharging at a number of springs and wadis along the escarpment; (2) in the confined part further east groundwater is flowing eastwards down the slope of the formation towards the Sirhan Graben, (3) in the NW groundwater flow is towards the Yarmouk basin (Fig. 54). Where the basalt directly overlays and feeds the A7/B2 (Fig. 52), flow is also directed westwards. Hence the groundwater divide extends further NE than the surface water divide (Borgstedt et al., 2007; Margane et al., 2009b).

For the lower aquifer system (A1/6) and the deep aquifer system (Kurnub/Zarqa) the regional flow is directed towards the Jordan Valley and the side wadis. Flow directions can be locally disturbed due to faults, topographic lows and abstraction cones. For example the large abstractions at Corridor wellfield have created a groundwater divide (Borgstedt et al., 2007).
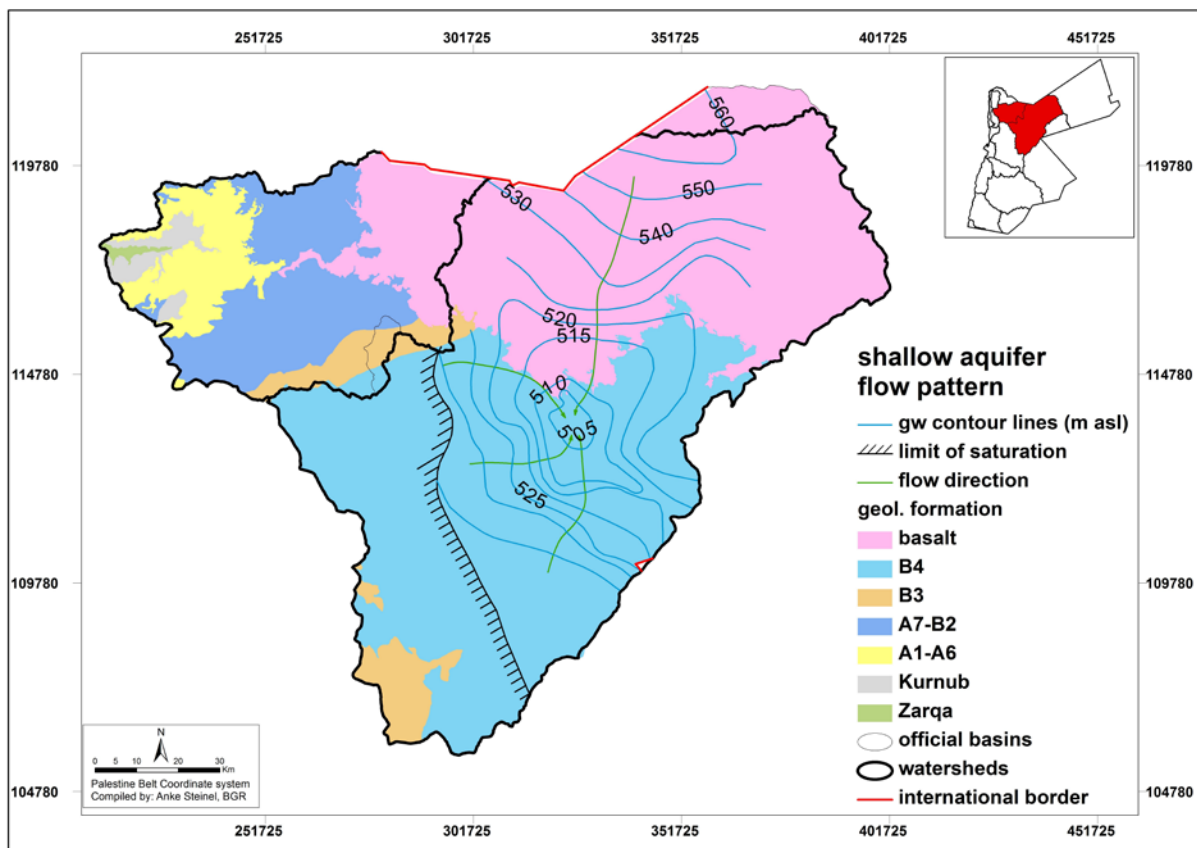
Fig. 53: Groundwater flow pattern of the shallow aquifer (alluvium, basalt, B4/5) in the Azraq area (arranged after Hobler et al., 2001).

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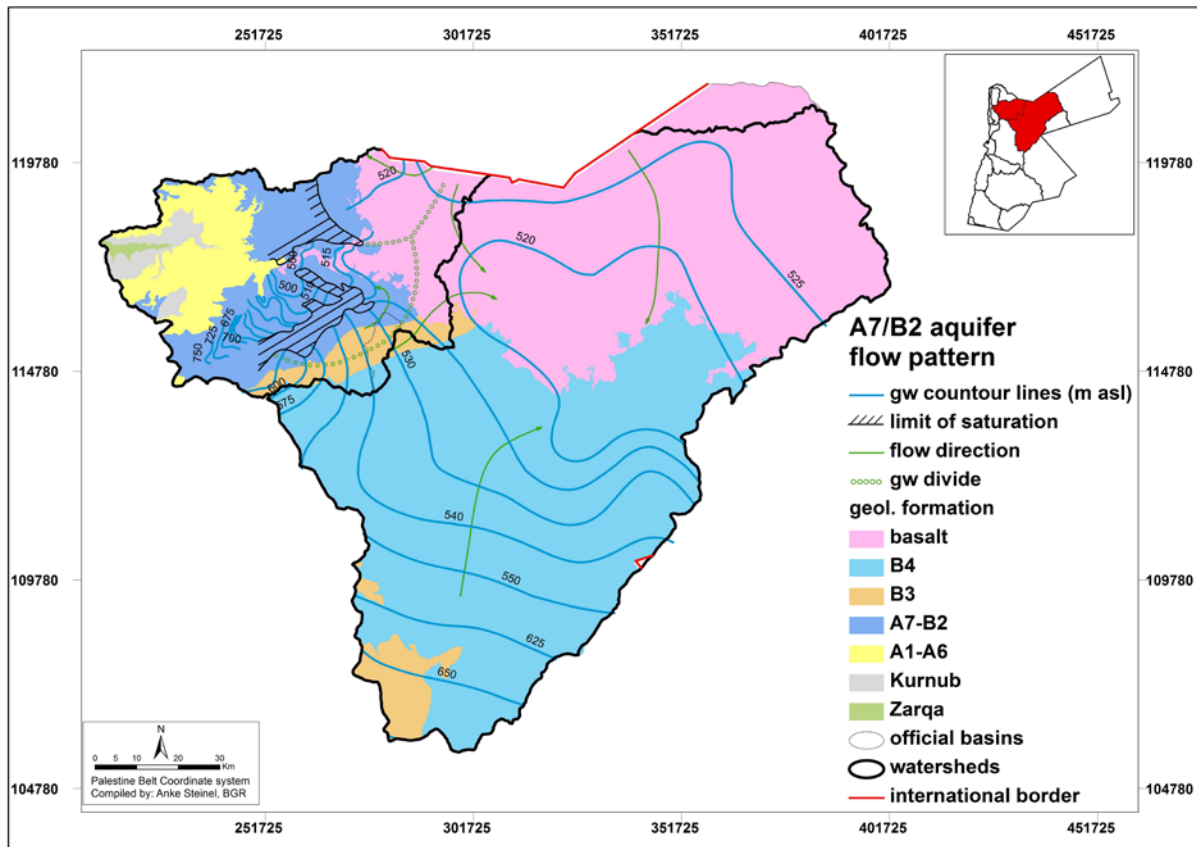
Fig. 54: Groundwater flow pattern of the A7/B2 aquifer (modified after Hobler et al., 2001).

The hydraulic gradient is reasonably steep for A7/B2 near the groundwater divide and towards the west (average 3.9 % (Lenz, 1999)) and flattens out towards the east. The gradient for the shallow aquifer system is overall rather low making it hard to estimate flow velocities. Around the Hallabat and Corridor wellfields gradients around 0.26 - 0.4 % have been found (Borgstedt et al., 2007; Margane et al., 2009b). Near the Azraq Qaa the gradient is 0.1 - 0.2 % (El Naqa et al., 2007). In areas with heavy abstractions the gradient is increased upstream and decreased downstream (Margane et al., 2009b).

Depth to groundwater

Due to the limited number of monitoring wells for each aquifer with current readings no reliable interpolation was possible. Available current data showed (Fig. 55) that depth to groundwater decreases with the flow direction from the edges of Azraq basin towards the centre (from >250 m in the North to around 12 m below Azraq Qaa) (Fig. 56) and generally decrease in AMZ basin from east to west with flow direction and decreasing thickness of the aquifer system (from >300 m to <10 m) (Hobler et al., 2001). It was also noticed that some abstraction cones can be found around the main wellfields in AMZ. Overall depth to groundwater is steadily increasing due to overabstraction (see below), so depicted groundwater levels are likely to have declined since 1995.

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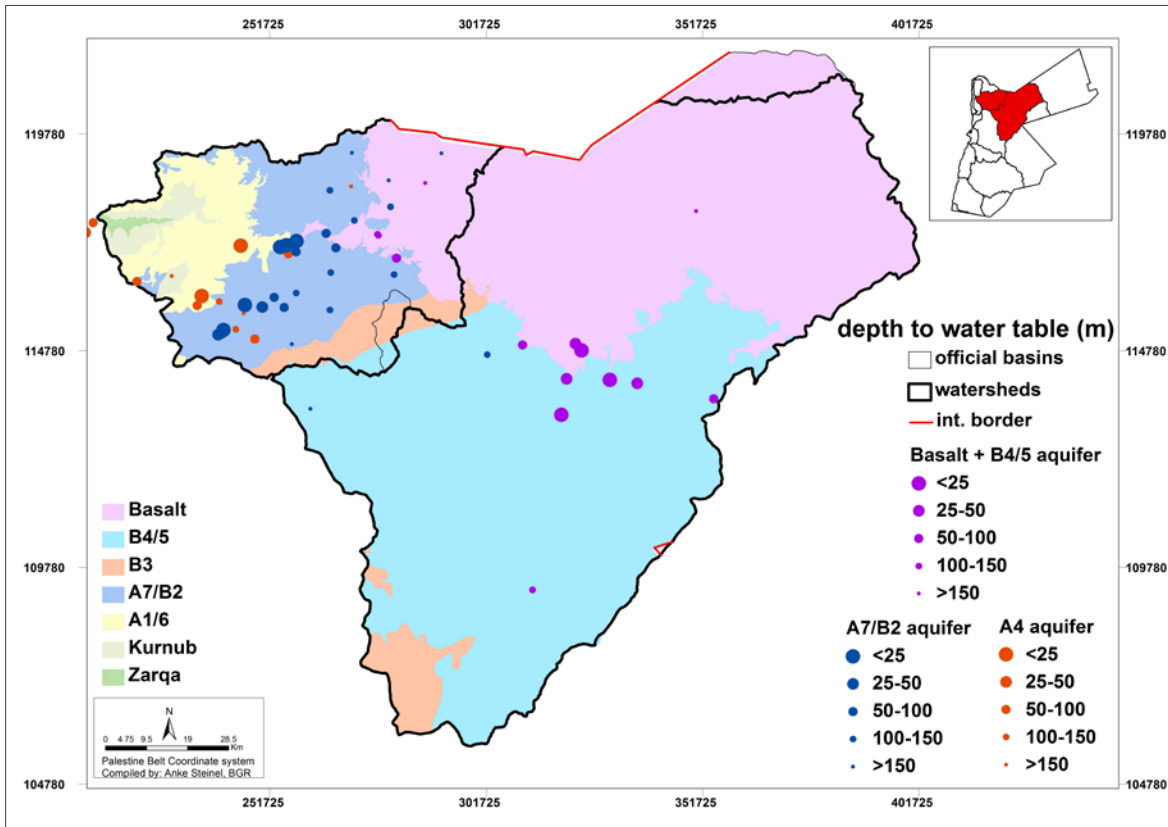
Fig. 55: Depth to water (m) for available monitoring wells in Dec 2010 (arranged after WIS data, MWI).
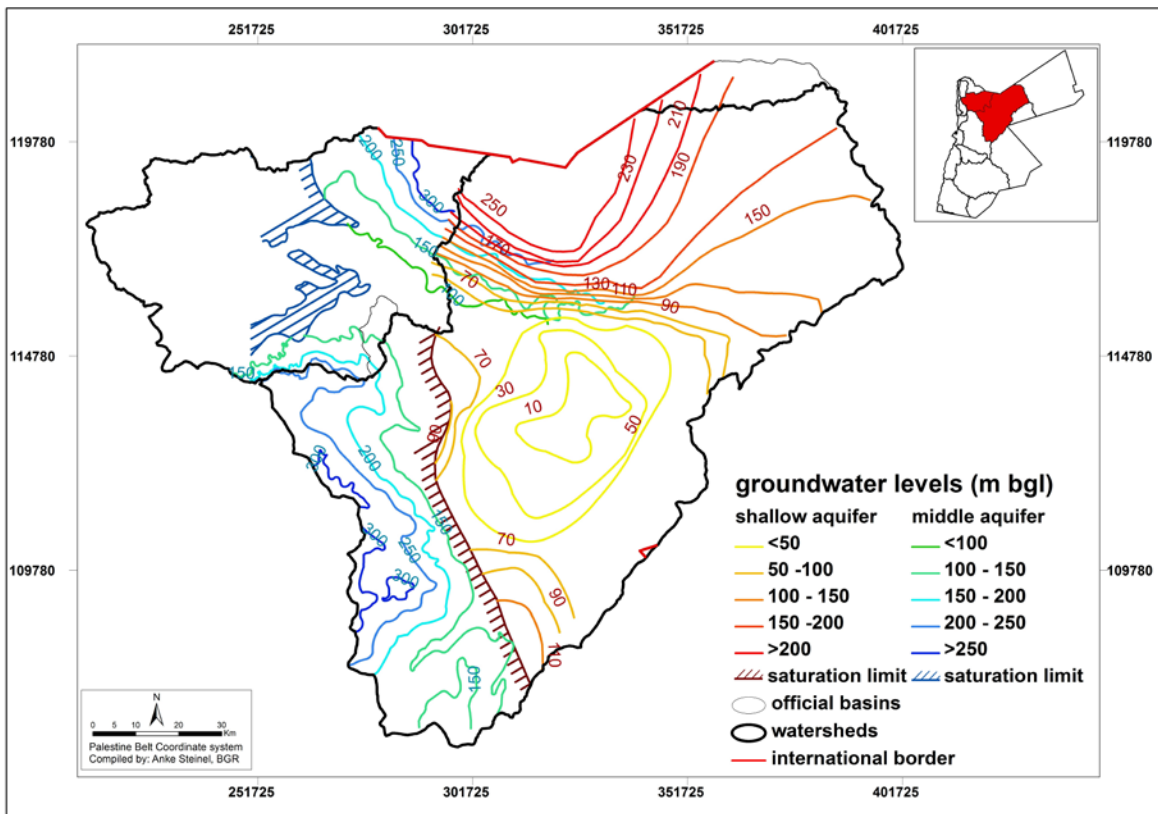
Fig. 56: Depth to water (m bgl) for the shallow and middle aquifer complex before 1995 (arranged from Al-Kharabsheh, 1995; Hobler et al., 2001).

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Recharge

Recharge occurs directly via infiltration of precipitation or indirectly through infiltration of runoff in wadis. Apart from the intensity and depth of rainfall it depends on the permeability of the soil and underlying formation, slope, vegetation and antecedent soil moisture conditions. Direct measurements are not possible, but estimations on recharge could be based on water level fluctuations age of groundwater, chloride mass balance, infiltration rates, water budget, surface conditions or modelling (Scanlon et al., 2002). Further complication may result from changes in water level due to abstractions, up/downward leakage, lateral subsurface flow and irrigation return flows. Accordingly estimations vary widely for the study area. For Azraq and AMZ basin 0.8 - 3.3 mm/a or 0.9 - 3.7 % and 5.6 - 31.6 mm/a or 2 - 11 % of annual precipitation were calculated, respectively (Table 24). For the Azraq basin, this amount can be mostly attributed to indirect recharge in wadi beds. WEAP (Water Evaluation and Planning System) simulations for Azraq basin estimate that about 50 % of the runoff infiltrates (Huber, 2010). However, recharge from flash floods in wadi channels can be inefficient as ponding time is short, entrapped air has to be displaced and sediment loads reduce infiltration rates (Missimer et al., 2012). Both basins also experience transboundary flow from Syria, which is estimated to be around 18 MCM for the Azraq basin (Mesnil and Habjoka, 2012).

Groundwater recharge is very sensitive to precipitation. The frequency and quantity of storms with rainfall are the most important factors for groundwater recharge. In regions with precipitation < 200 mm direct recharge is negligible (Lloyd, 1986). Recharge of 3 - 5 % of total rainfall is possible when rainfall is >250 mm/a (Lloyd and Bradford, 1992). Modelling results on a storm by storm basis for station F0001 show basically no recharge below 125 mm of precipitation (not even indirect recharge), but recharge of up to 15 % of rainfall (mean 3.6 % of rainfall or 8.5 mm/a) for higher precipitation depths (Fig. 57) (Noble, 1994). In AMZ basin, simulated groundwater recharge is approximately proportional to the square of precipitation and hence increases from east (<10 mm/a) to west (>150 mm/a) with an average of 24 mm/a (11 % of rainfall) (Schulz, 2011).

Indirect recharge has been observed in wells below wadis with recharge spikes 2 - 10 days after rain event (UNDP, 1966). Stable isotope measurements indicate that the basalt recharges mainly in area >850 m asl (Drury, 1993) and that recharge can be as high as 20 % of rainfall (15 - 23 mm/a) (Margane et al., 2009b). The B4/5 aquifer is recharged mainly in the northern Azraq basin (3 % of rainfall) and the basalt/A7/B2 aquifer receives <10% to >30 % of rainfall as recharge depending on rainfall distribution, topography, soil cover and karstification (Margane et al., 2002a).

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Table 24: Compilation of natural groundwater recharge estimates for both basins.

reference	MCM/a	mm/a	% of mean rainfall	method
Azraq basin				
Lloyd et al., 1966	10	*0.8*	*0.9*	Penman evaporation
El-Naqa et al., 2007	15	*1.3*	*1.4*	spring discharge
Gibbs, 1993	16	*1.4*	*1.6*	spring discharge
Parker, 1970	18.1	*1.5*	*1.7*	flow net
Al-Kharabsheh, 1995	20	*1.7*	*2.0*	water budget (SCS-CN)
UNDP, 1966	21	*1.8*	*1.9*	spring discharge
Baker and Harza, 1956 (cited in Noble, 1994)	*24.8*	*2.1*	2.3	spring discharge
MWI (2001 - 2009 data)	26.4	*2.2*	*3.3*	water budget (SCS-CN)
Hüser et al., 1987	28.4	*2.3*	*2.6*	water balance
AHT and BGR, 1977	28.4	*2.5*	*2.7*	water balance
Mudallal, 1967	30	*2.5*	*2.8*	flow net analysis
Barber and Carr, 1973 (cited in Noble,1994)	30	*2.5*	*2.8*	flow net analysis
Almomani and Seiler, 1995	*32.4*	2.7	*3.0*	chloride mass balance
Howard Humphreys Consulting Engineers, 1983	33.1	*2.8*	*3.1*	flow net analysis
El-Naqa et al., 2007	34	*2.8*	*3.1*	infiltration in basalt
Drury, 1993	21	*2.9*	*3.2*	isotopes
Al-Kharabsheh, 1996	35.4	*2.9*	*3.2*	water budget (SCS-CN)
Arsalan, 1976 (cited in Noble 1994)	35	*2.9*	*3.2*	water balance
Noble, 1994	37	*3.3*	*3.7*	modelling
AMZ basin (or subcatchments)				
Al Mahamid, 2005	22	*5.6*	*1.9*	modelling
Shahin, 2007	25	*6.6*	*2.2*	not given
MWI (2001 - 2009 data)	54.2	14.6	6.9	water budget (SCS-CN)
AHT and BGR, 1977	65.2	*16.1*	*5.4*	water balance
IUCN, 2008	87.5	*23.0*	*7.7*	not given
Talozi, 2007	88	*23.2*	*7.7*	water budget (SCS-CN)?
Schulz, 2011	106	24.0	11.0	modelling
Al-Abed and Al-Sharif, 2008	120	*31.6*	*10.5*	modelling
Margane et al., 2009b		13.3	9.0	water level and modelling
Borgstedt et al., 2007		24.1	17.8	water level and modelling

Italic numbers are calculated values. If no other values were given in the reference a catchment size of 12 000 km² for Azraq and 3800 km² for AMZ basin and a mean rainfall of 90 and 300 mm/a, respectively, was used. Basin sizes vary between the references if the Syrian parts are included or not.

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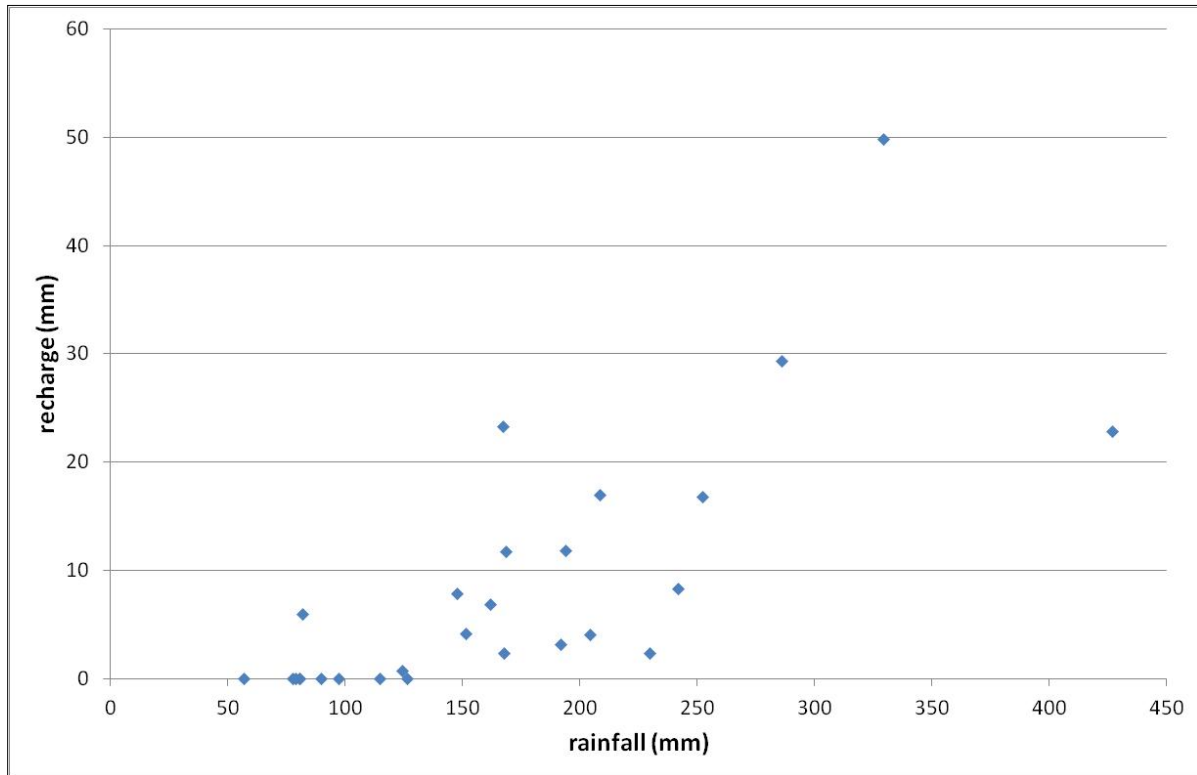
Fig. 57: Relation of groundwater recharge and rainfall events for station F0001 (Um el Qettein) in Northern Azraq basin (670 km²) based on modelling (arranged after Noble, 1994).

Age

In contrast to the high hydraulic conductivity and fast response to recharge observed, carbon dating gave groundwater ages of 5000 - 25 000 years (Table 25). Age increases along the flowpath from the Jebel al Arab to Azraq oasis from about 5000 years to up to 20 000 years (Table 25). Tritium, which would indicate recharge after the 1960s, has not been detected in the wells (Mesnil and Habjoka, 2012). It was suggested that spring discharge at Azraq oasis resulted from a prehistoric groundwater mount (Fröhlich et al., 1987). The dating also suggest a travel time of about 10 m/a, which is at about 10 times slower than the lowest given horizontal permeability of 0.3 m/d (see Table 23). This may be explained by the very flat hydraulic gradient and would mean that water recharged at dams in Azraq basin could take more than 100 years to reach abstraction wells some kilometres downstream.

Table 25: Compilation of groundwater ages based on carbon dating.

reference	location	age of groundwater (years)
Dottridge and Abu Jaber, 1999	Badia	5000
Almomani and Subah, 2005	Khaldiya (AL1926)	6500
Holden, 1998	Umm el Qettein	7400
	AWSA wellfield	13 000
Fröhlich et al., 1987	Druze springs (basalt aquifer)	12 000
	Soda springs (B4 aquifer)	15 000
El-Naqa et al., 2007	Jebel al Arab to Azraq oasis	4000 - 20 000
Rimawi, 1985	Azraq basin	5000 - 20 000
Noble, 1994	Azraq basin	12 000 - 25 000

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Storage capacity

Possible storage capacity was estimated based on the effective porosity and the mean unsaturated thickness of the aquifer units in the study area. For the different aquifers effective porosity (specific yield) values range between 1 - 10 % for the basalt, 1 - 5 % for B4/5 and 1 - 5 % for A7/B2 (Table 26) (Noble, 1994; Abu Ajamieh, 1998; Taqieddin et al., 1995; Hobler et al., 2001; Margane et al., 2002b). This very rough estimation suggests a potential water storage capacity of 8.6 - 86 BCM for the basalt, 3.2 - 16 BCM for the B4/5 and another 1.6 - 8 BCM for the A7/B2 aquifer. So there would be ample storage space (min. 13.4 BCM), even when considering that not all storage space could be filled evenly. Currently, more storage space is created every year with the lowering of the water table due to overabstraction (see below).

Table 26: Estimation of storage capacity based on effective porosity (specific yield) and mean unsaturated thickness below outcropping area.

aquifer	basalt	B4/5	A7/B2
outcropping area (km²)	5707	6344	1590
mean depth to groundwater level = mean unsaturated thickness (m)	150	50	100
storage volume (km³)	856	317	159
mean storage capacity (BCM) at 1 % effective porosity	8.6	3.2	1.6
mean storage capacity (BCM) at 5 % effective porosity	42.8	15.9	8.0
mean storage capacity (BCM) at 10 % effective porosity	85.6		

Abstractions

The WIS contains data on yearly abstraction from private and governmental owners. It obviously does not contain illegal wells and records are in general 15 - 18 % lower than abstraction values provided by WAJ[62]. Estimations for Azraq suggest that illegal abstractions have overtaken licensed private abstractions and account for about 13 MCM/a (Mesnil and Habjoka, 2012). Hence, presented values should be viewed as minimum abstraction values.

The evaluation of the available data shows that abstractions in AMZ basin are overall higher and have reached a total of 2753 MCM over the last 22 years of record (184.7 MCM in 2010) compared to 1057 MCM (56.4 MCM in 2010) for Azraq basin. About 60 % and 90 % of all wells are used for irrigation, 28 % and 9 % are used for domestic supply and 12 % and 1 % are used for industrial purposes in AMZ and Azraq basin, respectively. In Azraq, all farming is dependent on groundwater for irrigation, which is heavily subsidized, e.g. free for the first 100 000 m³ per well[63], even though agricultural revenues are low (Mesnil and Habjoka, 2012). Accordingly, agricultural abstraction by private wells increased and is about 55 % of all abstracted water in Azraq basin (Mesnil and Habjoka, 2012).

Current abstractions at a single well have been up to 3.3 MCM/a in AMZ and 1.95 MCM/a in Azraq, while median abstractions are 0.12 MCM/a and 0.047 MCM/a, respectively (Fig. 58). In both basins, current abstraction (2010) is slightly lower than median abstractions indicating that yields have been decreasing. Abstractions in Azraq basin are mainly taking place at the AWSA wellfield and private irrigation wells near Azraq town from the shallow aquifer system. In AMZ basin a number of active wellfields can be found abstracting mainly from the basalt and A7/B2 aquifer system near Amman-Zarqa urban areas and along the road between Mafraq and Safawi (Km wells) (Fig. 59). When comparing these abstraction values to the

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[62] A. Mesnil (Highland water forum), personal communication
[63] in other basins free limits are 150 000 m³

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estimated recharge (see Table 24), it is clear that both basins are largely overdrafting their renewable groundwater resources with an overabstraction of 181 % and 222 % in 2010 for AMZ and Azraq basin, respectively (Mesnil and Habjoka, 2012).

Azraq Oasis is a famous example of the impact of overabstraction on spring discharge and groundwater dependent ecosystems. A number of springs (Shishan and Druze spring complex) used to discharge groundwater at Azraq oasis. Since abstractions at the nearby AWSA wellfield started in 1982, the continuous lowering of the groundwater table (currently about 12 m bgl at the former oasis) resulted, accordingly, in the cessation of spring discharge in 1991/92 (Al-Kharabsheh, 1995; Dottridge and Abu Jaber, 1999). A decrease in spring discharge and base flow as well as drying of wells and decrease in borehole yields has also been observed in many other areas (Margane et al., 1995b; MWI-GTZ, 2005).

Published declines in groundwater table vary from wellfield to wellfield and mean values range around 0.5 to 2 m/a (Table 27). Over the last three years, water levels have declined the most in the A7/B2 aquifer (up to 5.8 m/a), while the shallow aquifer system shows generally lower decline rates (up to 1.8 m/a). Average drawdown rates from 2008 to 2010 vary between 0.6 to 1.1 m/a depending on the aquifer system (Fig. 60).
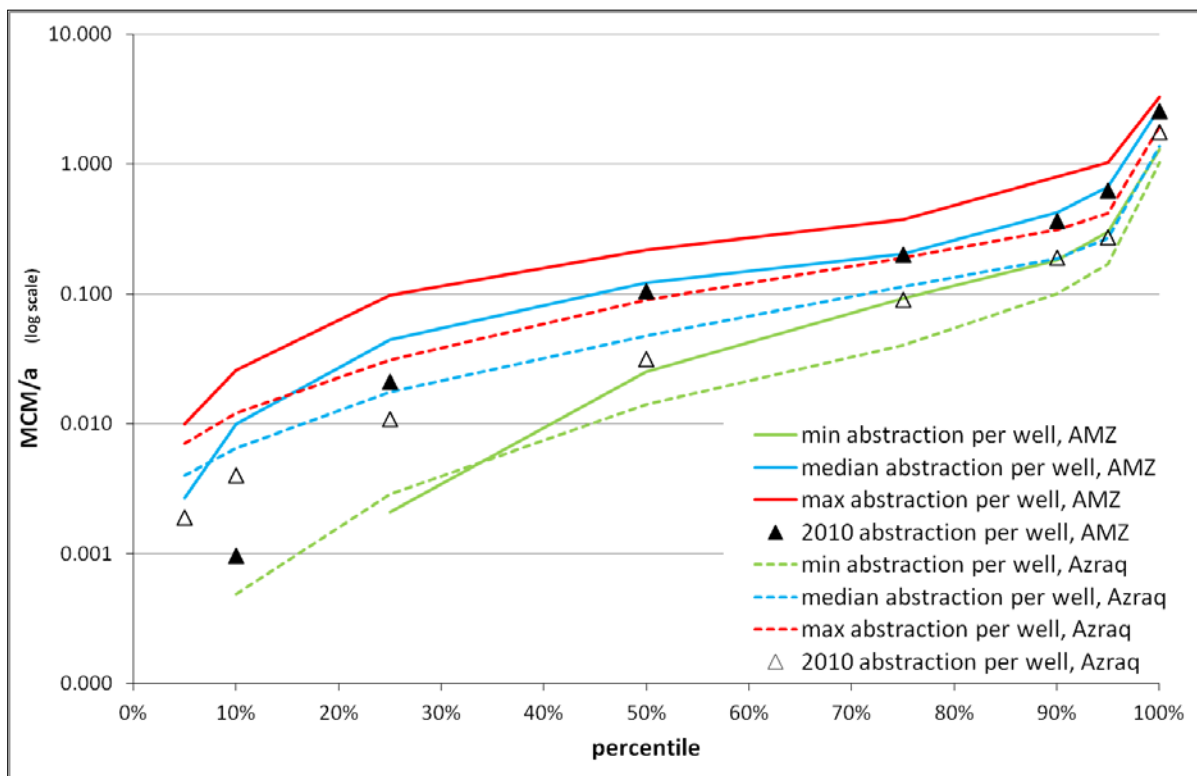
Fig. 58: Statistical analysis of available data for abstraction from active wells (997 in AMZ and 613 wells in Azraq basin) (calculated[64] after WIS data, MWI).

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[64] Different uses of abstraction were combined for each year at each well. Average calculations were undertaken for all years recorded. Total abstraction was calculated using mean abstraction values for years without record.

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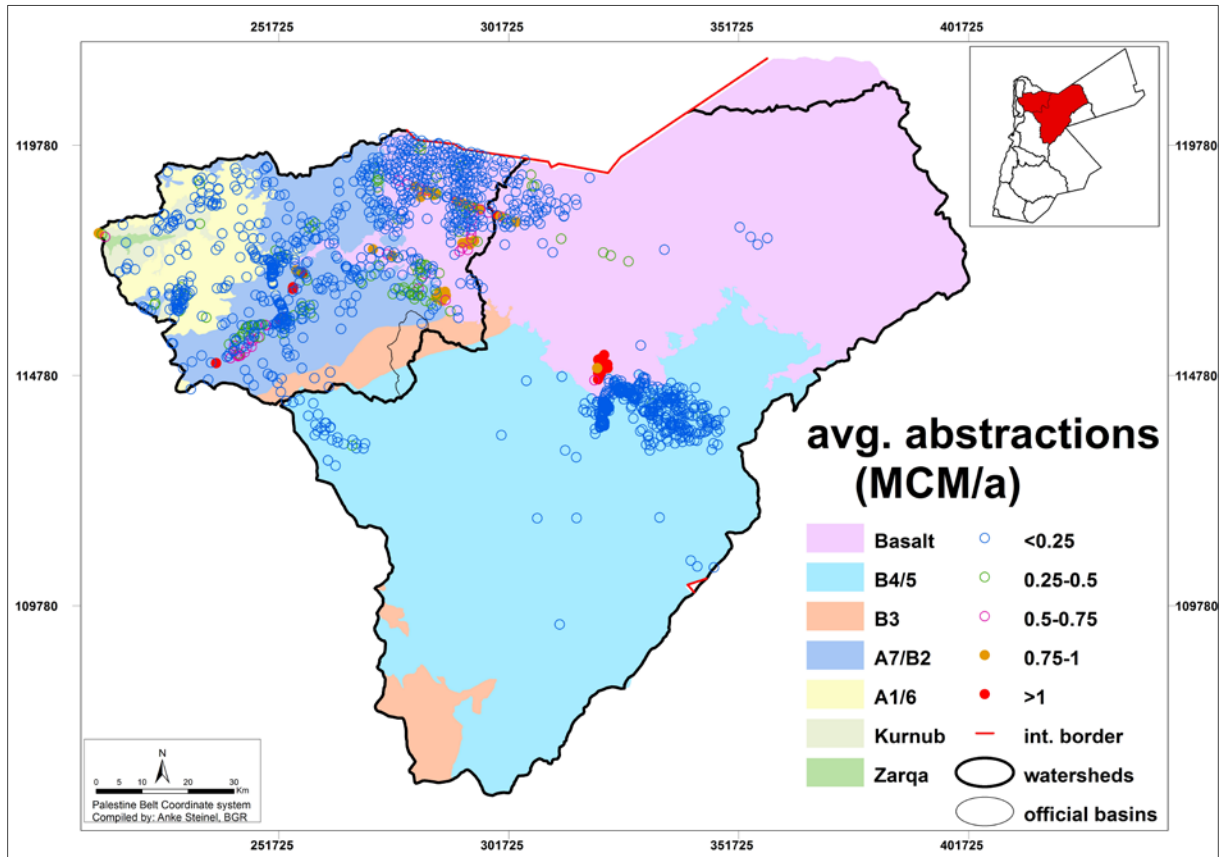
Fig. 59: Average abstractions (MCM/a) of active wells in AMZ and Azraq basin (arranged after available WIS data, MWI).

Table 27: Compilation of groundwater level declines (m/a) for different areas.

reference	area (time span)	decline in groundwater table (m/a)
Alraggad and Jasem, 2010	Azraq basin	0.7
Borgstedt et al., 2007	Corridor wellfield (2001 - 2005)	1.5
El-Naqa et al., 2007	AWSA wellfield	0.3 - 0.8
Dottridge and Abu Jaber, 1999	AWSA wellfield	0.35 - 0.6
MWI-GTZ, 2005	AL1043, A7/B2 (1968 - 2003)	0.5
Margane et al., 2009b	Hallabat wellfield (1989 - 2008)	0.7 - 1.6
Margane et al., 2002a	A7/B2 at groundwater divide	2
WIS data, MWI	Azraq and AMZ basin	0.6 - 1.1

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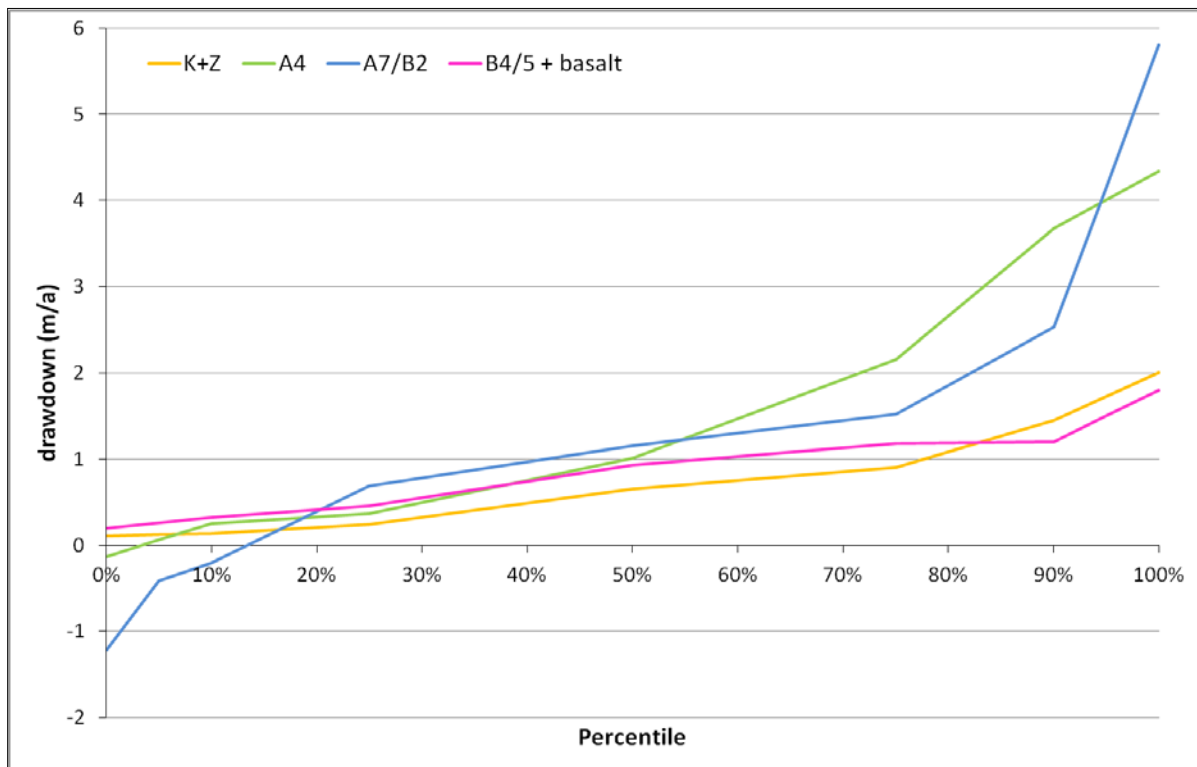
Fig. 60: Statistical analysis of groundwater table decline in monitoring wells in AMZ and Azraq basin from Jan 2008 to Dec 2010 separated by aquifer. K/Z aquifer (7 wells), A4 aquifer (11 wells), A7/B2 aquifer (29 wells), basalt+B4/5 aquifer (11 wells) (calculated after WIS data, MWI).

10.3.3   Groundwater quality

WAJ laboratories provided available analyses from governmental production wells from 222 wells in AMZ and 39 wells in Azraq for the years 2003 - 2010[65] with a variable number of parameters.

Limestone aquifers commonly produce groundwater of the Ca-HCO$_3$ type. The basalt aquifer usually has Na-(Ca-Mg)-Cl type groundwater (Margane et al., 2002a). Around Azraq (B4/5 aquifer) and the Dhuleil/Hallabat area (A7/B2 aquifer) elevated concentrations of sodium and sulphate have been found (Margane et al., 2002a). Geochemical reactions like precipitation of Fe/Mn-oxyhydroxides during recharge with surface water (Maliva and Missimer, 2010) should be limited, as iron and manganese values in the groundwater are low. Dissolution of calcite, dolomite or anhydrite minerals is possible, but should not be significantly more than under normal conditions (Al-Kharabsheh, 1995).

Salinity

In general, groundwater salinity increases with the residence time in the aquifer, i.e. increases along the flowpath (Fig. 62) and with age of the formation (El-Naqa et al., 2007). The shallow aquifer in Azraq basins contains fresh groundwater in the recharge areas in the

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[65] Average values were calculated from the latest three analyses or over the values from the last three years. EC values and TDS values were converted with the formula TDS (mg/L) = EC (µS/cm)/1.562. The tapped aquifers were added from WIS data or judged by location and well depth.

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North, but shows a strong increase around the AWSA wellfield and Azraq Qaa (Fig. 61) likely due to return flow from the saline qaa or upward leakage (Mesnil and Habjoka, 2012).

Nevertheless, the majority of wells sampled (about 80 %) are below the drinking water standard (JISM, 2008) of 1000 mg/L TDS (Fig. 63). Highly mineralised waters can be found in the deep sandstone aquifers but also in the shallower aquifers due to upward leakage of the deep saline waters fostered by lowering of the water table in the upper aquifer (El-Naqa et al., 2007; Almomani and Seiler, 1995). Alluvial aquifers and shallow aquifers can experience an increase in salinity also due to irrigation return flows or the dissolution of salts from salic or gypsic soil horizons (HTS and SSLRC, 1993). The B4 and B3 formations contain halites and gypsum that can locally increase salinity levels (El-Naqa et al., 2007). Regions with low recharge and high evaporation will also show elevated levels in groundwater salinity (Margane et al., 2002a).

Short term trends from 2003 - 2010 data showed a significant increase in salinity for some wells, while other wells showed a decrease in salinity. Other studies found a built up of salinity of 30 µS/cm per year in AMZ basin (Al Kuisi et al., 2009) and a general increase in groundwater salinity for a number of other basins, especially when assessing long-term developments (Salameh, 2008).
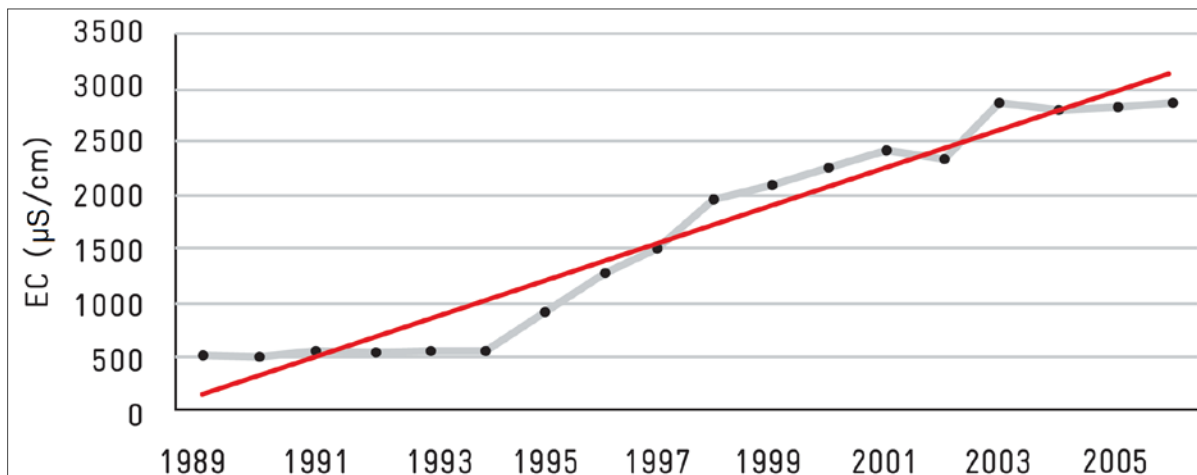
Fig. 61: Salinity increase in a well[66] close to the depression in Azraq basin (MWI-WIS data) (Mesnil and Habjoka, 2012).

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[66] detailed location or ID not given in reference

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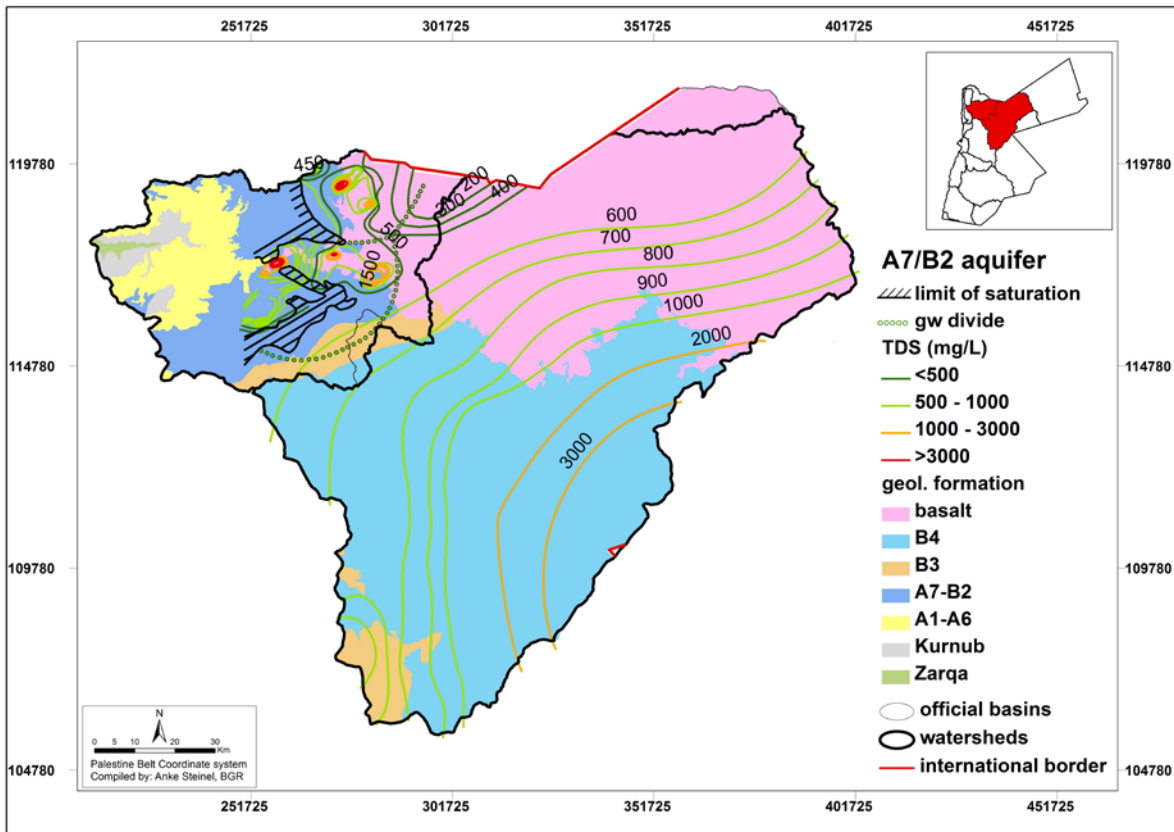
Fig. 62: Groundwater salinity of the A7/B2 aquifer (modified after Hobler et al., 2001).
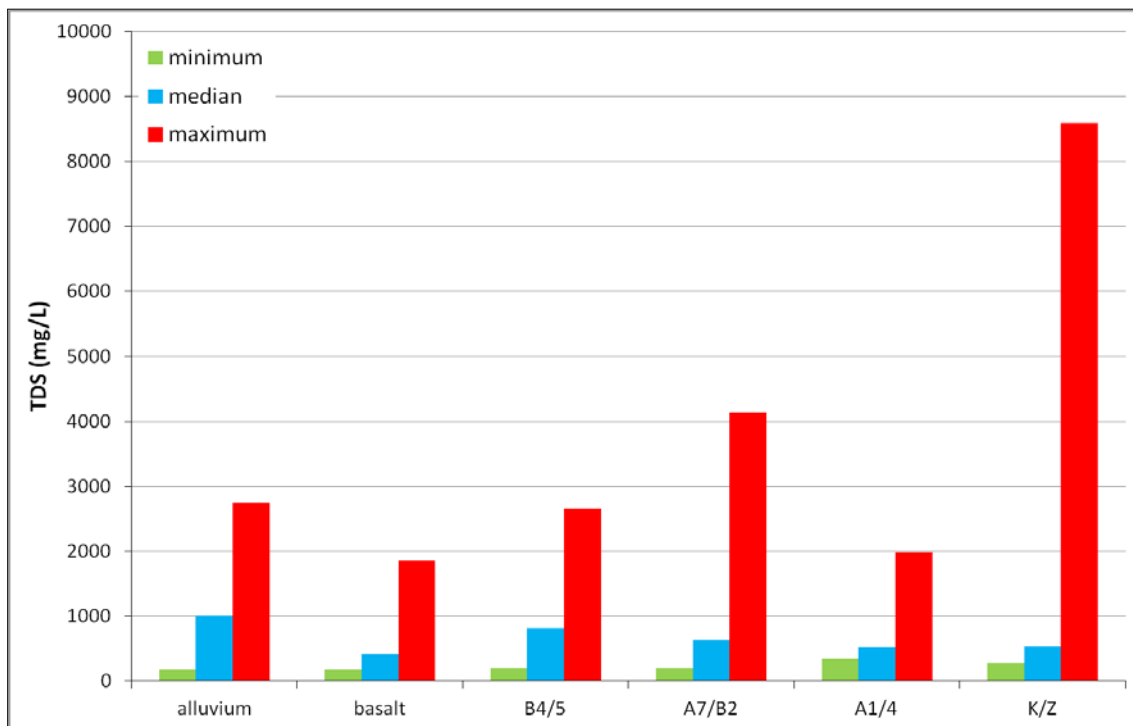
Fig. 63: Analysis of latest available[67] salinity data (TDS (mg/L)) (arranged after WAJ data).

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[67] Number of wells with analysis for TDS or EC in 2009 - 2011: 6 alluvium, 23 basalt, 19 B4/5, 97 A7/B2, 31 A1/4, 28 K/Z

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Nitrate

Elevated concentrations of nitrate are an indication for pollution from fertilizers and wastewater (Al Kuisi et al., 2009). In areas with a high risk of contamination and where the aquifer is vulnerable, elevated nitrate concentrations have been found (Al Kuisi et al., 2009; Al-Adamat et al., 2003).

In 122 wells in AMZ and 2 wells in Azraq basin, nitrate was measured from 2003 - 2010. The results show that in more than 75 % of these wells nitrate is above the drinking water limit of 50 mg/L and in more than 20 % is even >100 mg/L (Fig. 64). However, these results might be biased as more wells with known contamination problems are monitored regularly. The elevated concentrations are clustered around the urban regions and areas with intensive agriculture (Fig. 65). A built up of nitrate concentration of around 22 mg/L per year in AMZ has been reported (Al Kuisi et al., 2009).

Water treatment plants need to have efficient means of elimination of NO_3. If groundwater is used for agricultural purposes only, elevated nitrate concentrations could actually be a valuable additional source of fertilization. Farmers could reduce other fertilizer amounts accordingly. Nevertheless, high nitrate levels are often associated with elevated concentrations of other contaminants, which could be problematic for agricultural uses.
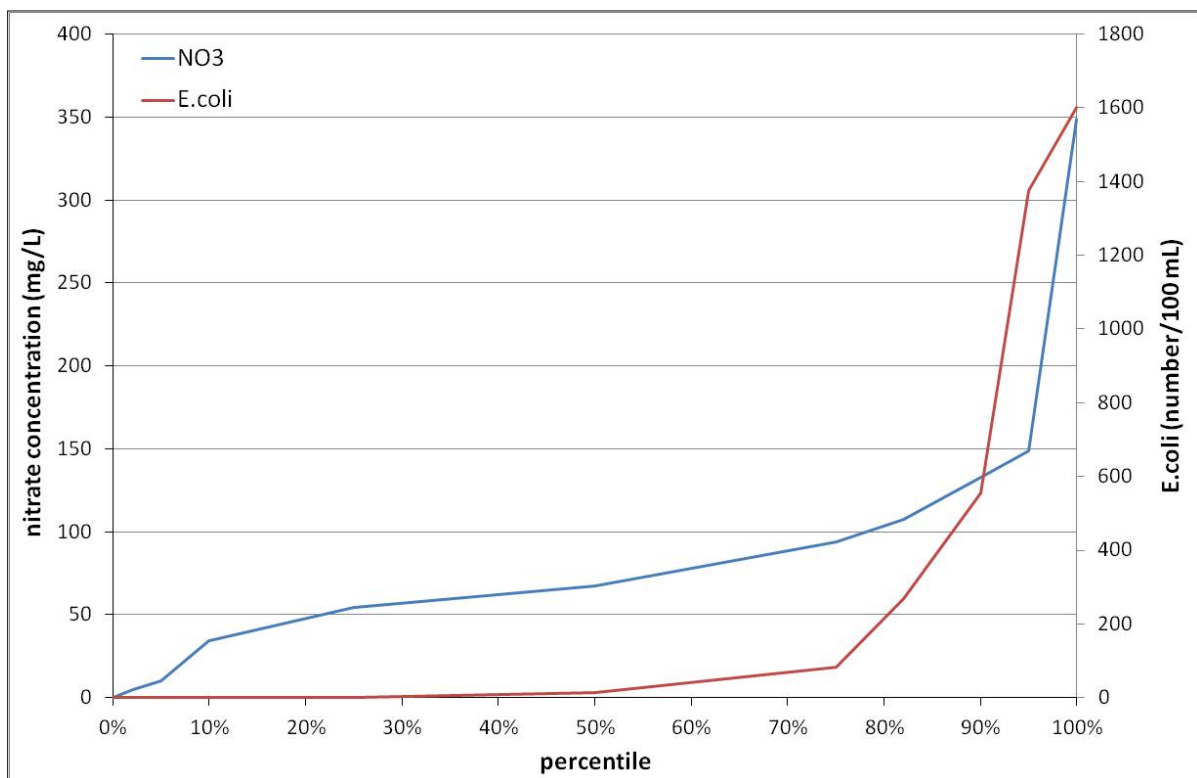
Fig. 64: Statistical analysis of nitrate and *E.coli* values (124 wells for nitrate, 63 wells for *E. Coli*) (calculated[68] after WAJ data).

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[68] Mean values of all available nitrate and E. coli records for each well were taken to eliminate temporal variability.

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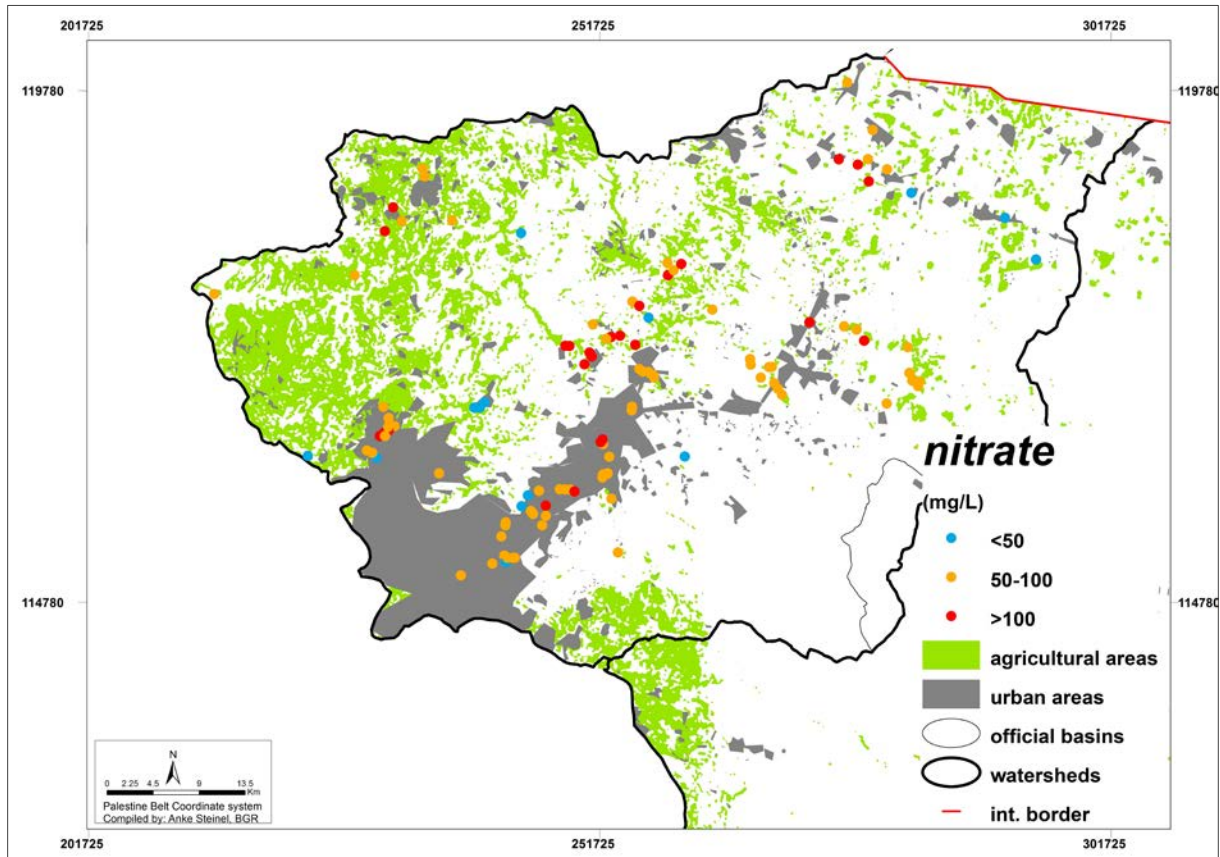
Fig. 65: Distribution of nitrate concentrations (mg/L) in AMZ basin (arranged after WAJ data).

E.coli

Bacteriological contaminations are an indication of pollution with domestic or agricultural wastewater or leakage from manure dumps and have, for example, been found at Hallabat wellfield (Margane et al., 2009b). *E.coli* has been measured in 62 wells in AMZ and 1 well in Azraq from 2003 - 2010. The results show that about 50 % of wells show values below or near the detection limit, but about 8 % of wells show *E.coli* contaminations of >1000 MPN/100 mL (Fig. 64). Most elevated values are again found near urban areas in the same wells that also show high nitrate levels. Analyses from springs in Jordan found 70 % contained faecal contamination, suggesting wide-spread diffuse pollution (Mohsen, 2007).

Water treatment plants would need proper disinfection mechanisms to prevent health problems.

Hazards

The main hazards for groundwater (and surface water) quality deterioration are agrochemicals (fertilizer, pesticides, fungicides), inappropriate disposal of solid wastes and of municipal, agricultural and industrial wastewater (Fig. 66a) (World Bank, 2009). It has been reported that domestic wastewater from septic tanks has been disposed of into monitoring wells as this is cheaper than delivering it to the WWTPs[69]. Manure dumps and carcasses of farm animals can be found lying on the ground without any precautions against leaching to the groundwater (Fig. 66b). The number of chicken and cow farms is high in some areas of

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[69] H. Kirsch (GIZ), 2012, personal communication

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AMZ basin (Margane et al., 2009b). In Azraq basin, about 250 000 sheep/goats and about 600 cows on 10 dairy farms are existing (Mesnil and Habjoka, 2012). Many houses are not connected to a wastewater treatment system. Other hazards are leakage or spills from oil and fuel at petrol stations and various pollutants from factories. Quarries are also potential contamination sources, as the aquifer is directly exposed to heavy machinery and potential oil/fuel spills. They also produce many fines that can be washed into ground- and surface water (Margane et al., 2009b).

Measured contamination from production wells could also result from direct contamination at the well site, as protection measures are not always followed, e.g. well covers are not always complete (Fig. 66c). In addition, Bedouins often live next to production wells because of the easy access to water and electricity and animals can enter into groundwater protection zone 1 to drink (Fig. 66d). A new water resources protection guideline has been implemented recently to address these problems (MWI-BGR, 2011).

When no detectable deterioration in water quality has been seen, this could partly be due to a lack of monitoring as commonly only governmental production wells and pump stations are monitored regularly.

Fig. 66: a) wastewater disposal, b) cow manure dump, c) open borehole allowing direct contamination, d) open/broken fence around groundwater wells with Bedouin camps next to it. (Picture taken around Hallabat wellfield by H. Kirsch, 2012, and A. Steinel, 2011).

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Vulnerability

Groundwater vulnerability is dependent on intrinsic properties of the unsaturated and saturated zone like porosity, thickness of soil cover and depth to water table. The attenuation capacity of the soil is influenced by properties like pH, oxidation-reduction potential, cation exchange capacity as well as organic matter, clay and metal oxide content (Margane, 2003). Limestone aquifers are especially vulnerable due to fast flow in the karst network and hence low natural attenuation (e.g. Ford and Williams, 1989).

A number of smaller scale vulnerability maps exist for the Halllabat wellfield (Margane et al., 2009b), the Corridor wellfield (Borgstedt et al., 2007) and parts of Badia (Al-Adamat et al., 2003). A good vulnerability map in fractured and karstic aquifers requires good knowledge of existing karst features and fault lines as well as detailed information on the soil cover und unsaturated zone (thickness, effective field capacity), which are not available for Jordan. Hence, vulnerability maps should not be taken at face value. Areas with high infiltration rates/recharge zones are generally vulnerable areas. Overall, areas where the A7/B2 aquifer crops out are of high vulnerability, while areas covered by basalt are of lower vulnerability (Margane et al., 2009b). High risk activities like landfills (El-Naqa, 2004), industrial factories and animal farms should not be located in high vulnerability areas to protect groundwater quality.

10.4 Infiltration

> **The infiltration capacity of a soil depends on the effective porosity which is governed by grain size distribution and packing density. Infiltration rates are dominated by the top surface layer and decrease significantly even with only a thin clogging layer.**

Once the water is harvested it needs to infiltrate into the underlying aquifer. The first barrier is the soil, the second barrier the unsaturated zone of the aquifer. Water stored in the unsaturated zone might evaporate later. Yearly evapotranspiration rates from the aquifer were estimated at about 1 MCM/a (Al-Khatib, 1999).

10.4.1 Soils

The soils of Jordan have been investigated in the 1990s by the Ministry of Agriculture in three levels of detail. The reconnaissance soil survey (level 1) resulted in a country wide map of soil map units. Different soil subgroups for each soil map unit are given depending on the morphological position and representative profiles with analysis on grain size and chemical parameters are appended (HTS and SSLRC, 1993). In a semi detailed study five selected areas mostly of agricultural potential were investigated in more detail and profiles were tested for average water holding capacity (AWC). Two of these areas (North Western Area (Irbid, Mafraq, Salt) and North Eastern Area (Wadi Rajil)) are located within the study area (HTS and SSLRC, 1994). Soil properties like field capacity and permeability could not derived from given maps.

The physiographic position along the slope, the moisture regime and the type and age of parent material are the main features leading to different soil development (Ziadat et al., 2010). In the aridic zone plateaus often show exposed bedrock and sediment thickness increases along the slope towards the valley. Due to the difference in stone and boulder

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cover on the basalt slopes will exhibit a varied hydrological response as the spacing, size and shape of stones influence surface roughness, overland flow paths and speed (Allison and Higgitt, 1998; Tansey et al., 1999). On older basalt flows Xerochrepts with gypsic and calcic horizons have developed while on more recent flows only weakly developed Xerothents are found (Allison et al., 1998).

The study area comprises 57 soil map units spread over 6 physiographic regions (8: north highland dissected limestone plateau, 11: Jordan highlands plateau, 13: east Jordan limestone plateau, 15: north Jordan basalt plateau, 16: north-east Jordan basalt plateau and 18: Ajlun highlands dissected limestone plateau) (Fig. 67). The most dominant or most representative[70] soil subgroups were selected for each soil map unit series. In the westernmost regions (8 + 18) with xeric moisture regime (>250 mm) typic deep calcixerollic Xerochrepts and entic Chromoxerert are most common. In the xeric-aridic moisture regime (150 - 250 mm) the regions 11 and 15 are dominated by moderately deep to deep xerochreptic Camborthid and Calciorthid, respectively. The aridic (<150 mm) limestone region 13 contains a mix of typic Calciorthid, typic Camborthid, typic Torrifluvent, lithic Torriorthent and shallow lithic Gypsiorthid. The aridic basalt region 16 is dominated by very shallow typic and lithic Torriorthent on the plateau and deep typic Camborthid in the mudflats (Fig. 67). Salinity of soils increases with the decrease in precipitation.

As the wadis are the most interesting part for MAR, they were assessed separately and the most dominant soil type for wadi fills and depressions was selected for each soil map unit and applied with a 200 m buffer around the river network. Most of the soils are 50 to >80 cm thick, with clayey to loamy texture and often contain a high percentage of gravels, stones and boulders. Thickness and clay content depend largely on the erodibility, slope steepness and curvature of the upslope parent material (Ziadat et al., 2010). Qaa deposits can be up to 5 m thick (Borgstedt et al., 2007). Salinity of wadi soils is generally weaker than on the plateaus and slopes. Xerochreptic and typic Camborthids, typic and calcixerollic Xerochrepts and xeric and typic Torrifluvents are the main soil types (Fig. 67).

The physical and chemical properties of a soil are crucial to its moisture retention and infiltration capacities. In the study area clay content decreases from north to south and from west to east in accordance with to the decrease in rainfall and the extent of weathering. It also increases with depth potentially impeding drainage to underlying bedrock (HTS and SSLRC, 1993). Jordanian soils have a low content of organic matter (0.2 - 1 % in region 13 + 16; 1 - 2 % in region 11+15, 0.5 - 2.5 % in region 8). Sealing and crust formation dynamics are faster on dry soils than on wet soils and enhanced in soils with low organic matter content and high aluminium and iron content as found in Jordan (Le Bissonnais and Singer, 1993). As the soils vary significantly with physiographic position, permeability also varies with it (Ziadat et al., 2010). It was highest for the foot-slope position (alluvium), second highest for the upslope position and lowest for the mid-slope position (colluvium) and was higher for xeric soils (max. 9.5 m/d) than aridic soils (min. 0.64 m/d) (Schulz, 2011).

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[70] For example around the Azraq Qaa soils of the map unit 'RAJ' the most dominant soil type was a shallow petrogypsic Gypsiorthid (30 %) with sandy texture, but as the other 70 % of soils are deep, saline and clayey, the typic Calciorthid + Camborthid with 25 % dominance was selected as most representative soil subgroup for the further assessment.

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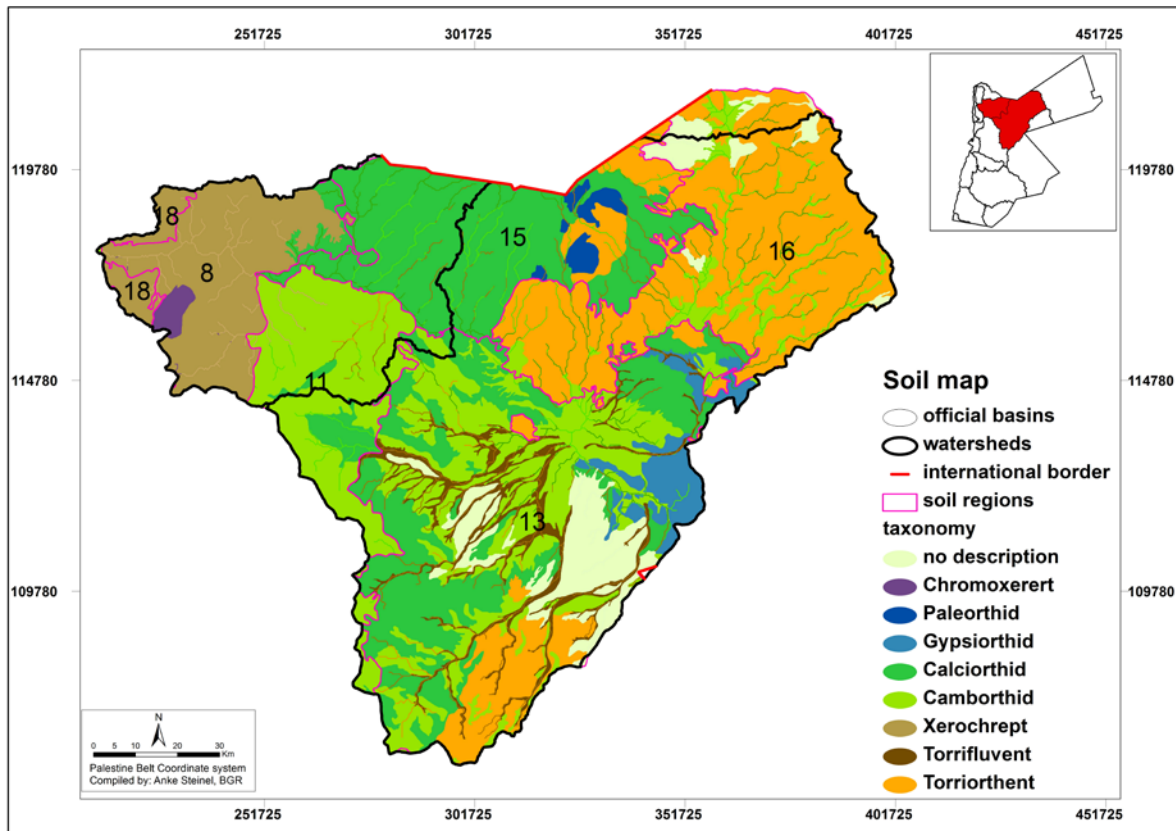
Fig. 67: Soil map for AMZ and Azraq basin based on most dominant soil subgroup in each soil map unit and in wadi fills including outline of regions (arranged after HTS and SSLRC, 1993).

There are many different pedo-transfer functions to estimate the saturated hydraulic conductivity (Kf) of soils based on grain size distribution, bulk density, organic matter content etc. Most estimation methods perform best for loamy sand, while increasing clay content and possible additional effects (e.g. macropore or shrinking and swelling) deteriorate the prediction (Tietje and Hennings, 1996). The effect of crusts and coatings can also not be simulated with pedo-transfer functions (Abu-Awwad and Shatanawi, 1997). Nevertheless two pedo-transfer functions were used to find the least permeable horizon for representative profiles:

1) The function of Cosby et al. (1984) is very simple and uses only clay (<2 μm) and sand (0.05 - 2 mm) content, but it performs well for estimation of mean saturated hydraulic conductivity (Tietje and Hennings, 1996):

$$Kf\ (cm/d) = 60.96 * 10^{(-0.6+0.0126*sand(\%) - 0.0064*clay(\%))}$$

2) The function of Saxton et al. (1986) also uses only clay (<2 μm) and sand (0.05 - 2 mm) content but is more complicated. The range of predicted values is comparable to the values from Cosby et al. (1984):

$$Kf\ (cm/d) = 24\exp\left\{12.012 - 0.0755 * sand \right.$$
$$\left. + \frac{-3.895 + 0.03671 * sand - 0.1103 * clay + 0.00087546 * clay^2}{0.332 - 0.0007251 * sand + 0.1276 * \log_{10}(clay)}\right\}$$

Other functions (e.g. Vereecken et al., 1990) using dry bulk density and the content of organic matter could not be used satisfactorily as no values for dry bulk density were

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available in the soil survey and most samples also did not have values for OM. As sensitivity to slight variations in these values was high the estimation of these values was not reasonable.

As not for all representative profiles grain size analysis was undertaken, only a very fragmented Kf map could be generated. The range of predicted hydraulic conductivities (Kf) ranged from 5 - 265 cm/d for the Cosby et al. (1984) function and 3.5 - 400 cm/d for the Saxton et al. (1986) function over 305 horizons evaluated. For the least permeable horizon of 85 profiles the range went only up to 110 cm/d for both functions and the median was around 11 - 16 cm/d (~$1.5*10^{-6}$ m/s).

When applying the average water holding capacity given for common soil subgroups in the level 2 study (HTS and SSLRC, 1994) to the representative wadi soils and their respective soil depth a range of 21 - 184 mm (median 111 mm) was obtained. As these are mostly clayey soils the retained water is to about 2/3 immobile water or adsorbed water trapped in the fine pores that will not percolate down (Scheffer and Schachtschabel, 2010). This water will not generate recharge but reduce the volume of runoff.

10.4.2   Infiltration rate

Infiltration is a complex process depending on pore size distribution and connectivity of pores as well as soil moisture content and could be hindered by entrapped air (see section 2.3.1) (Philip, 1957a,b; Grismer et al., 1994; Ma et al., 2011). One has to differentiate between the unsaturated and the saturated hydraulic conductivity. The former depends on capillary forces, fillable porosity, moisture content, while the latter depend on permeability and gravitational forces. Capillary forces modify the flow and there is a hysteresis effects with the increase or decrease of saturation (Seiler and Gat, 2007). During the saturation phase infiltration rates are higher due to the initial saturation than reducing to a constant saturated hydraulic conductivity. The wetting front moves depending on small scale heterogeneities (Sorman and Abdulrazzak, 1997; Warburton, 1998), which is not reflected by grain size distribution analysis, but requires infiltration tests. Hence, infiltration can be very heterogeneous in spatial and temporal respect even under seemingly homogeneous conditions (Sharma et al., 1980; Warburton, 1998; Racz et al., 2012). Generally coarse soil textures allow higher infiltration rates (Table 28).

Table 28: Representative values of saturated hydraulic conductivity for different soil textures (after Clapp and Hornberger, 1978).

texture	m/d	texture	m/d	texture	m/d
sand	15.21	loam	0.60	sandy clay	0.19
loamy sand	13.51	sandy clay loam	0.55	silty clay	0.09
sandy loam	2.99	silty clay loam	0.15	clay	0.11
silty loam	0.62	clay loam	0.21		

Infiltration rates in an infiltration basin will change due to sediment accumulation, sediment penetration, or biofouling. Silt carried by flood waters can effectively seal the alluvial surface of the wadi floor even during the flood event at unexpectedly high flow velocities (0.36 m/s) making it the main factor for recharge (Crerar et al., 1988). For (semi-)arid regions high sediment loads and consequent sealing is common due to soils with low aggregate stability (El-Swaify et al., 1984; Arshad and Mermut, 1988; Abu-Awwad, 1997; Akasheh and Abu-

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Awwad, 1997) Due to the accumulation of silt, permeability reduces to reach a minimum infiltration rate controlled by the permeability and thickness of the clogging layer (Bouwer, 1988). For Muwaqqar area this was found to be about 0.01 - 0.06 m/d and was reached after about 20 days of infiltration (Salameh et al., 1991 (cited in Al-Kharabsheh, 1995)). The initially higher infiltration rate can result from preferential flow along mud cracks (Novák et al., 2000; Jarvis, 2007) that will later close due to swelling and the filling of stagnant pores, which would not contribute to recharge. Even a very thin layer of 1 mm significantly reduces the infiltration rate (McIntyre, 1958; Le Bissoinnais and Singer, 1993). Tests with low turbidity water (~60 mg/L) (compared to Jordanian values) in sandy basins showed a decrease in permeability by two to three orders of magnitude and that clay particles are able to penetrate the uppermost surface layers (Schuh, 1988; Schuh, 1990). During the settlement of sediments in the reservoir larger particles will settle quicker than fine particles and a graded layer will exhibit. In a normal wadi, this clogging layer will be broken up with the next big flood (Schälchli, 1992), while in the reservoir another graded layer will settle on top, giving more seepage control than compacted liner (<1 cm/d) (Bouwer et al., 2001). Additional clogging can occur due to biological processes like microorganism growth in the soil forming a biofilm (Bouwer, 1988) or the precipitation of carbonates or iron oxyhydroxides due to changes in pH due to algal photosynthesis (Schuh, 1990). Underlying fault lines would not make significant difference, unless silt removal is undertaken regularly.

Infiltration rates from reservoirs are commonly calculated based on the water budget. Due to errors in evaporation values and water level rating curves the chloride methods gives more reliable results if inflows and outflows are recorded (Sukhija et al., 1997).

A number of infiltration tests have been conducted in Jordan and worldwide (Table 29). It is assumed that the upper alluvial layers are the limiting factor to infiltration and not the highly fractured underlying rock formations (Abu-Taleb, 1999). This assumption cannot be tested with infiltration tests though. Infiltrated water could also be ponding at the base of a gravel layer after initial infiltration (Noble, 1994). A conservative infiltration value of 0.04 m/d has been suggested for recharge basins (Al-Amoush et al., 2012). The infiltration rate in mudflats is extremely low as there is still water standing even months after the rainfall event, so the main process would be evaporation (Noble, 1994; Al-Kharabsheh, 1995). The Azraq Qaa soil was found to be dry at 30 cm depth indicating that there is no deep infiltration apart from initial preferential flow along mudcracks (Noble, 1994).

If there is no clogging layer, there is a slight correlation between an increase in infiltration rate with increase in ponding level especially during the initial saturation phase. If a thin clogging layer has developed, shallow basins are more effective as the high water pressure would compact the clogging layer even more (Bouwer, 1988). If a thick clogging layer has developed deep basins are more effective as lateral infiltration can occur and horizontal hydraulic conductivity is generally higher than vertical conductivity (DWA, 1994; Zemann, 2008).

Investigations into transmission losses show a great spatial variability due to differences in antecedent soil moisture, small scale texture differences and the amount and duration of runoff (Sorman and Abdulrazzak, 1997; Dahan et al., 2008). Transmission losses found in Wadi Kafrein can range from 18 - 44 % of the generated runoff (Alkhoury, 2011). The WEAP model for Azraq basin assumes about 50 % of transmission losses (Huber, 2010).

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Table 29: Compilation of infiltration tests results (Kf: saturated hydraulic conductivity) from Jordan and international cases.

reference	Wadi or country	texture	Kf (m/d)	method
Salameh et al., 1991 (cited in Al-Kharabsheh, 1995)	Muwaqqar	with silt accumulation	0.01	basins
Noble, 1994	Azraq Druze	palm soil	4.22	infiltrometer (40 cm)
	Wadi Mukeifta		0.22 - 0.86	infiltrometer (40 cm)
Al-Kharabsheh, 1995	el Maghayer	gravelly sand	8.47	not given
	Butum	gravelly loamy sand	7.14	
	Kleita	gravelly loamy sand	1.05	
	Erratam + Aritain	gravelly loamy sand	0.14	
Agnew et al., 1995	Ruwashed	wadi alluvium	0.580	infiltrometer (15 cm)
		playas (silty clay)	0.036	infiltrometer (15 cm)
Chehata et al., 1997; Abu Taleb, 1999	Madoneh	gravel with sand, silt	0.41 - 0.47	basin (24+50 m²)
	Butum	gravel with sand, silt	0.16 - 0.24	basins (0.56 - 100 m²)
Zemann, 2008	Kafrein	sandy gravel + clogging layer	0.1 - 0.2	basin (35 m²)
Schulz, 2011	Amman-Zarqa basin	silty clay - silty clay loam	0.06 - 2.49	infiltrometer (20 cm)
Salameh et al., 2011 (cited in Gabi, 2012)	Deir Allah	natural ponds	0.02 - 0.06	infiltrometer
Sawarieh (unpublished) (cited in Rapp, 2008)	Ed Dadur	Pleistocene sediments	1.73	infiltrometer
Crerar et al., 1988	Namibia, Swakop river	alluvium	0.1 - 0.4	channel observation
Hida and Ohizumi, 2005	Japan	alluvial gravel	2.9 - 3.8	2 basins (>1000 m²)
Ting et al., 2005	Taiwan	sandy gravel	5.25	basin (400 m²)
Lai and Ren, 2006	China	silt loam	0.22 - 0.57	infiltrometer (120 cm)
Ghavoumian et al., 2007	Iran	sand to sandy loam	1.0 - 1.8	infiltrometer
		silty loam - clay loam	0.14 - 0.26	infiltrometer
Racz et al., 2012	California	silty sand	<0.1 - >1	basin (3 ha)

10.4.3   Sedimentation rate

As outlined above sedimentation is a major problem to recharge dams and sediment loads are high, but only very limited data exist for sedimentation rate measurements (Table 30). Estimated sedimentation rates vary between 4 - 4056 m³/a/km² depending on runoff volumes, land use and rainfall intensity and duration. For King Talal existing data on inflow volumes and accumulated volumes suggest a sediment load of 0.1 - 1.4 % (average 0.7 %), despite the fact that large portions of inflow are treated wastewater with comparatively lower TSS values. In the Wadi Madoneh dams 10 - 30 cm/a has accumulated over the first two years (de Laat and Nonner, 2011). Investigations at the Alghadeer dam showed that large portions of the accumulated sediments was sand (Shatnawi., 2012) transported by bed loads rather than in suspension.

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Table 30: Compilation of sedimentation rates (m³/a/km²) from literature and JVA data.

reference	dam	estimated sedimentation rate m³/a/km²	total MCM in 2010
JICA, 1987 (cited in Hydrosult, 1988)	Qatrana	4	2
	Sultani	36	1.1
Otova and Ayed, 1989a	Bowayda	170	
CES and JCE, 1992 in Zemann 2008	W. Kafrein	638	
Shahin, 2007	W. Kafrein	664 - 1590	3.36 (1994)
Al-Ansari and Shatnawi (2006); Shatnawi, 2012	Alghadeer	320	0.67
	W. Ziglab	433	1.62
	W. Arab	1674	6.26
JVA data	W. Mujib	45	1.3
	King Talal	118	14.5
	W. Wala	122	1.5
	W. Arab	267	1.7
	Karameh	806	0.65
	W. Ziglab	4056	20.2

Sediment loads could also be estimated from erosion rates in the catchment. Current investigations in the Wadi Al Arab catchment showed a yearly eroded volume of around 100 t/ha/a from olive tree plantations (measurement based on relief changes) and sediment relocation rates of about 80 t/ha/a from overgrazed natural slopes (measured with erosion pin fields).[71]

Sediment inflow to recharge dams could be reduced by installing stilling basins or pre-dams upstream which in turn would need to be emptied but less regularly (van Steenbergen and Tuinhof, 2009). Sedimentation load can also be reduced through limitation of erosion in the catchment by vegetation, terraces etc, which is not practical for large desert catchments.

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[71] S. Kraushaar (UFZ), 2012, personal communication, preliminary results

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11 Pre-feasibility study for MAR potential

After the available data are presented (see chapter 10) they had to be evaluated in the light of MAR criteria and turned into thematic maps (see chapter 3). One has to distinguish between the suitability of the catchment for generating runoff to be harvested for MAR (section 11.1) and the suitability of a site to built a dam and to allow transfer of the harvested water into a suitable aquifer (section11.2). For both aspects the same criteria might be evaluated differently and are compiled in Table 33 and Table 34. Previous MAR potential maps have focussed mainly on the second aspect.

With the overlay of these thematic maps (section 11.3) the different criteria can be weighted, which will again be assessed for the catchment and for the site selection. Some criteria are 'knock out' criteria resulting in a constraint map. And there are aspects that are 'nice-to-have' adding extra bonus to the potential site.

11.1 Thematic map development for the MAR catchment to generate runoff in suitable quantity and quality

> **The main criteria for the generation of suitable runoff in the catchment are the amount of rainfall, the slope, the absence of existing dams and the absence of built up areas to prevent pollution.**

11.1.1 Topography classification

The slope influences runoff generation and runoff velocity. For the catchment moderate slopes are preferable. If the slopes are too high, the potential for erosion and increase in sediment load are a limiting factor (Table 33). If the slope is too low, water will stagnate in small depressions rather than generated runoff (Fig. 68). This means that large parts of Azraq basin are unsuitable for runoff generation.

11.1.2 Land use classification

Land use is a main factor for surface water quality. Urban areas and quarries should be excluded from the catchment as far as possible. A buffer of 500 m is applied to account for further spreading of built up areas. The input of sediments, fertiliser and pesticides will be enhanced in agricultural areas and are hence less preferable. Forest areas are 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 are most suitable (Table 33). A catchment covered with surface crusts like chert plain is especially suitable as runoff generation will be high. Mudflats are unsuitable due to the slope, the fine sediments and the often increased salinity of the soil (Fig. 69).

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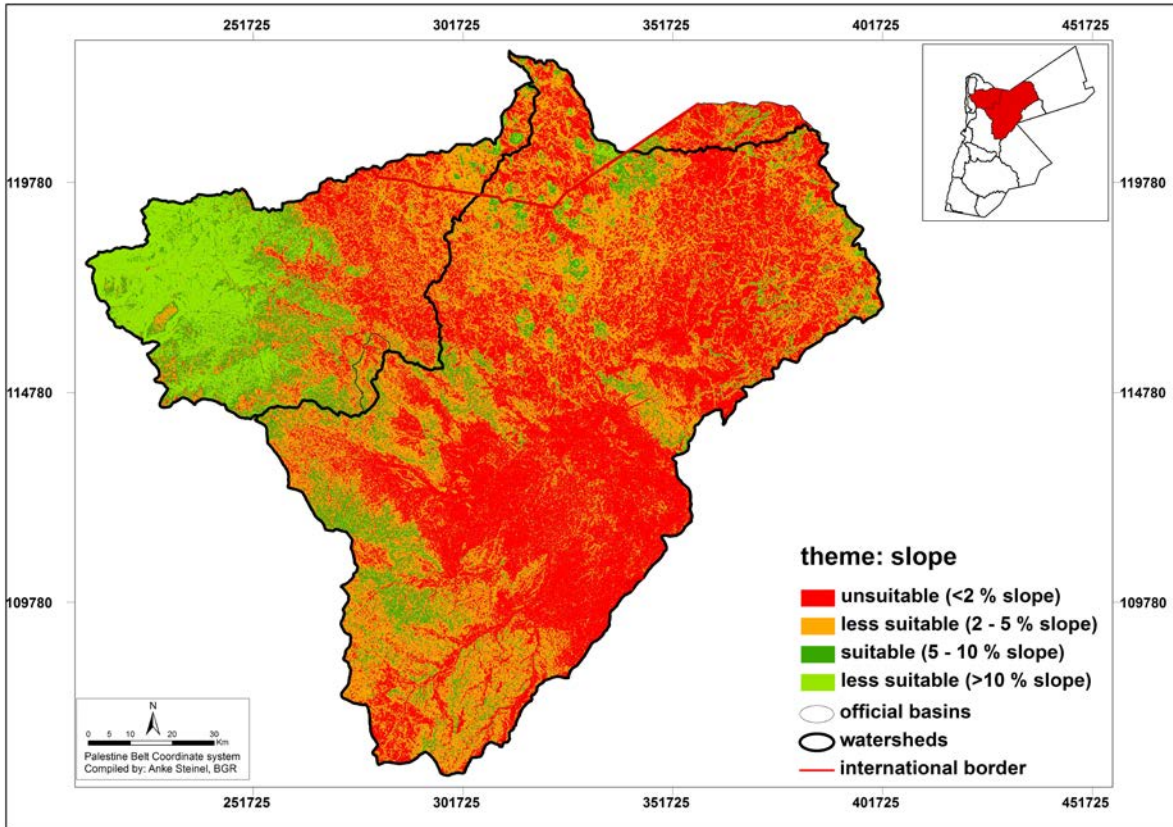
Fig. 68: Classification of slope regarding the suitability for runoff generation in the catchment.
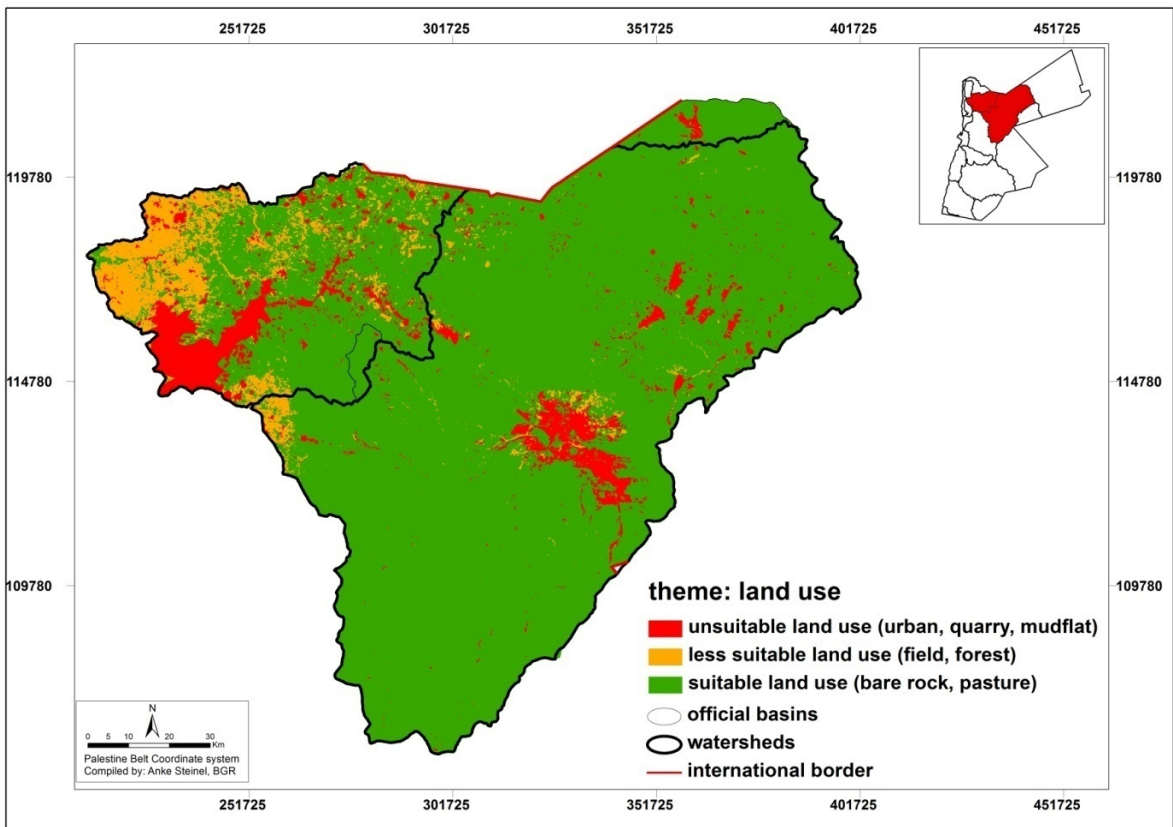
Fig. 69: Classification of land use regarding the suitability for runoff generation of suitable quality.

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11.1.3   Rainfall and runoff

The MAR catchment should generate sufficient runoff, which depends mainly on catchment size and rainfall volume. Catchments in regions with rainfall <50 mm can be neglected (Al-Kharabsheh, 1995). Regions with <100 mm rainfall are not economically feasible either (Sharda et al., 2006) unless the catchment is very large and slopes are sufficiently high to actually allow the water to reach the MAR site from all of the catchment. This situation is not found in Azraq basin. Commonly, MAR schemes start at rainfall of about 200 mm/a (see Table 3) (Fig. 70).
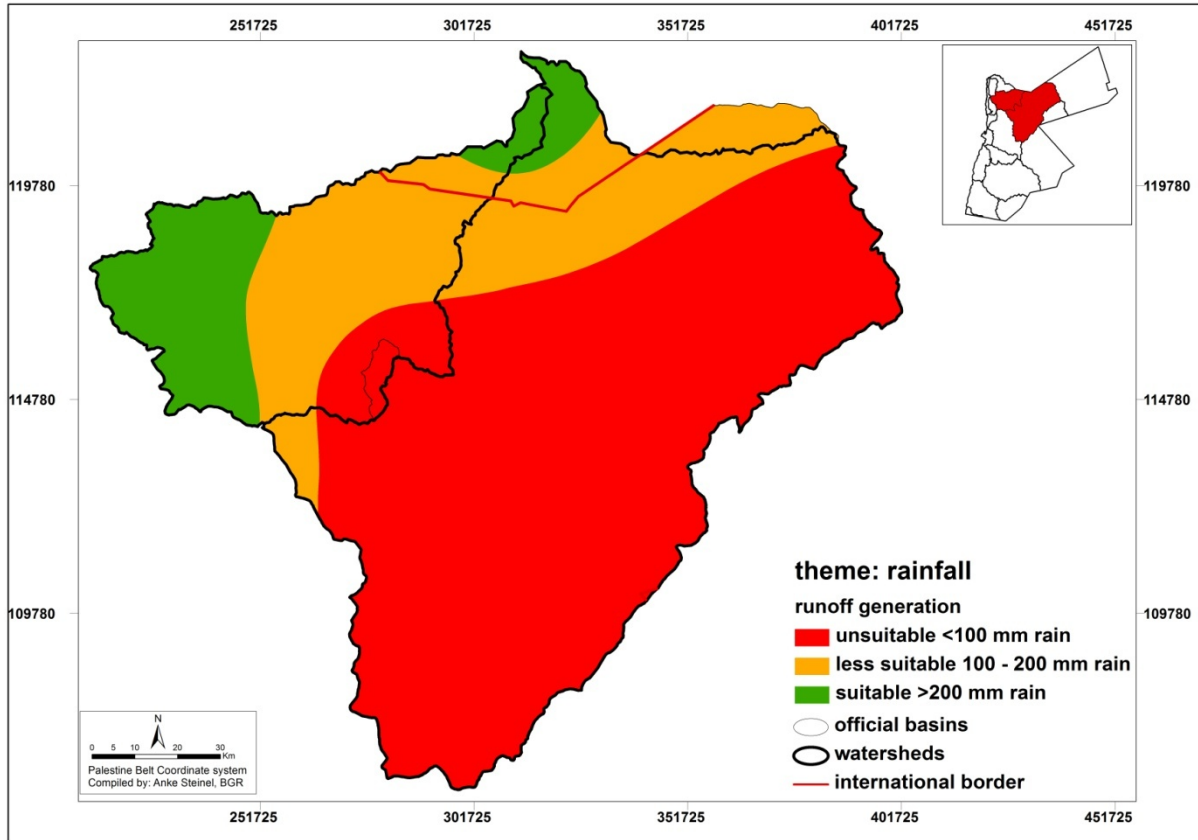
Fig. 70: Classification of rainfall amounts regarding the suitability for runoff generation in the catchment.

11.1.4   Hydrogeological classification

The situation below the surface is primarily important for the site selection, while the hydrogeological conditions in the catchment area of lower importance. A high permeability of the underlying formation or superficial deposits in the catchment is actually less preferable for runoff generation, while aquitards will allow more runoff generation and are favoured for the catchment (Table 33). Similarly, less permeable superficial deposits would be preferred for the catchment, but they provide potential for high sediment loads and should be avoided (Fig. 71).

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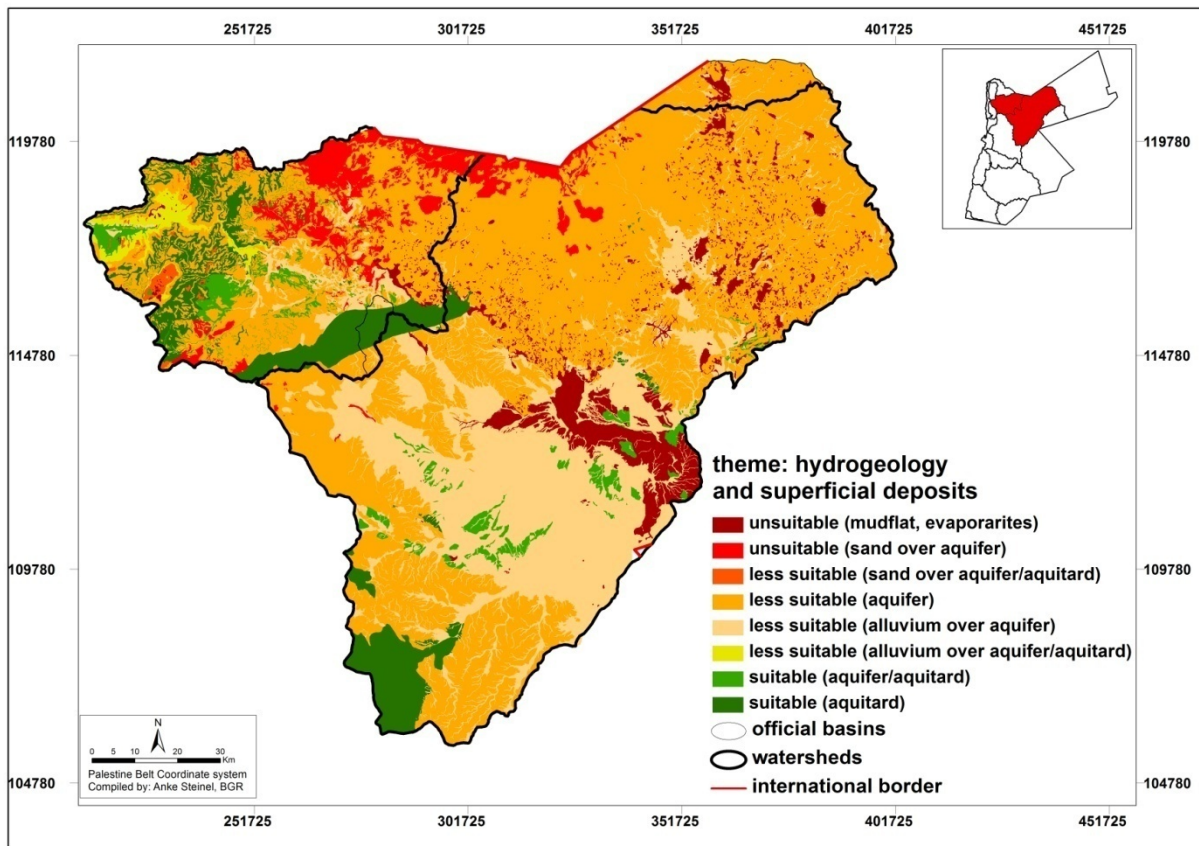
Fig. 71: Classification of hydrogeological formation and superficial deposits regarding the suitability for runoff generation in the catchment.

11.1.5 Soil

For the catchment assessment it is preferable to have thin soils and soils with limited fine content, so sediment loads are small. Saline soils should be avoided in the catchment as this might impact on the runoff water quality (Fig. 72, Fig. 73, Fig. 74). Soils with high moisture holding capacity are also less preferable as this will reduce runoff generation (Table 31).

The three aspects of the soil have been combined to one soil classification values with a weight of 60 % on texture, 20 % on thickness and 20 % on salinity (Fig. 75). Suitable are ratings >1.33, less suitable are ratings from 0.67 - 1.33, unsuitable are ratings <0.67. This leaves only about 840 km² as suitable. For the overlay with other thematic maps the actual soils scores ranging from 0 to 1.7 have been kept (Table 33).

Table 31: Classification, rating and weight of soil criteria for a total soil score.

criteria	weight	classification	suitability	rating
soil thickness	**60 %**	very shallow to shallow (<50 cm)	suitable	2
		moderately deep (50 - 80 cm)	less suitable	1
		deep to very deep (>80 cm)	unsuitable	0
soil texture	**20 %**	silt + clay	unsuitable	0
		loam	less suitable	1
		sand	suitable	2
		gravelly and stony	increases suitability	+0.5
soil salinity	**20 %**	non to weak	suitable	2
		moderate	less suitable	1
		strong to very high	unsuitable	0

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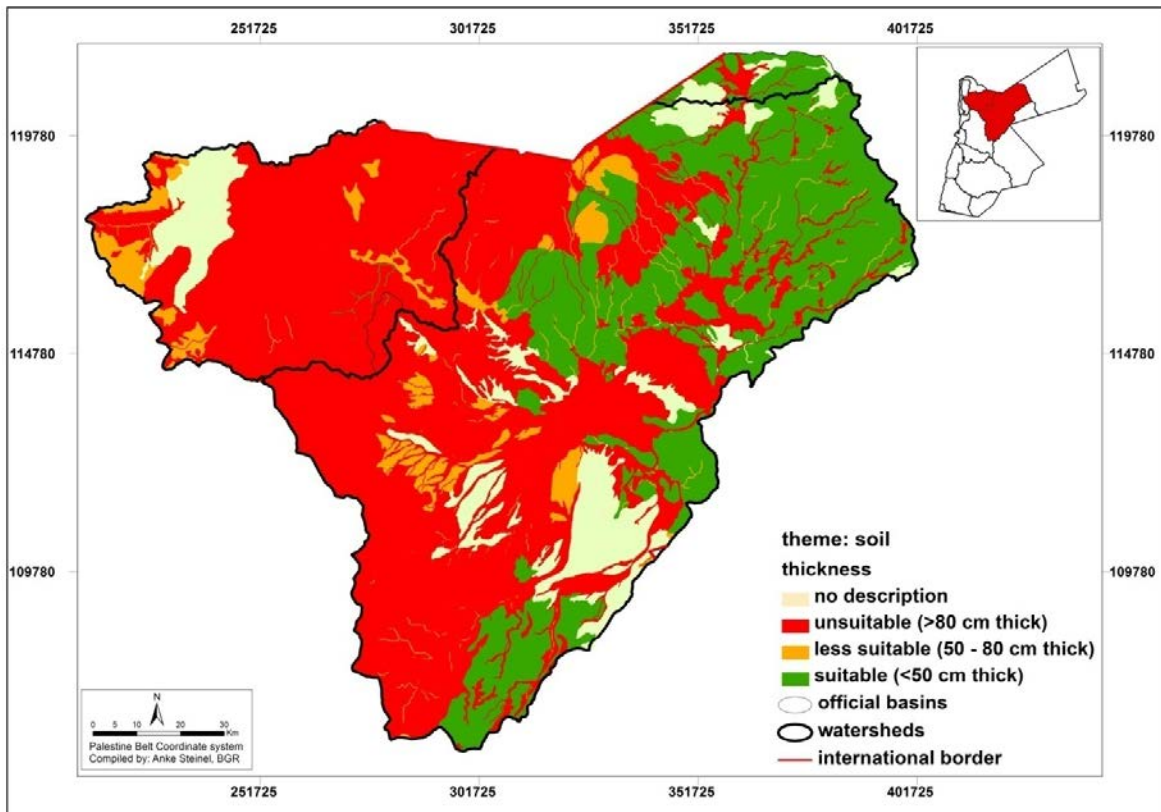
Fig. 72: Classification of soil thickness regarding the suitability for runoff generation and sediment loads.
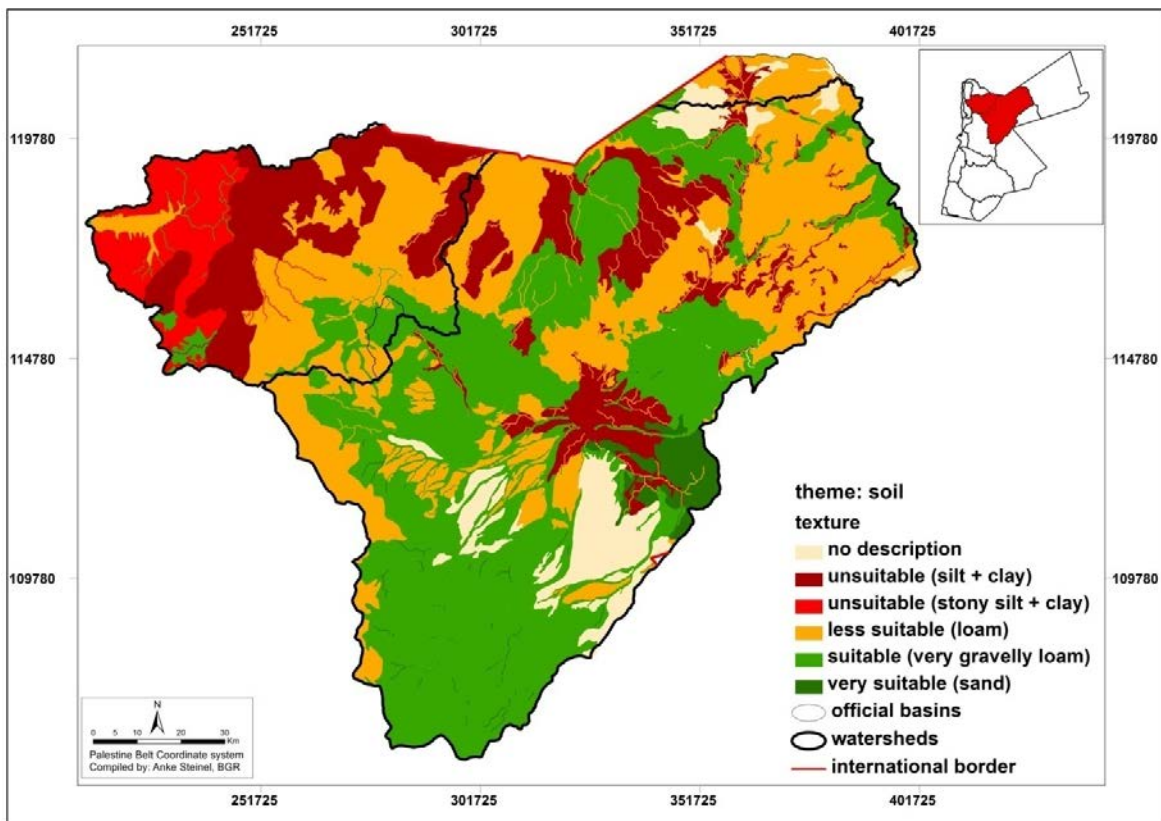
Fig. 73: Classification of soil texture regarding the suitability for runoff generation and sediment loads.

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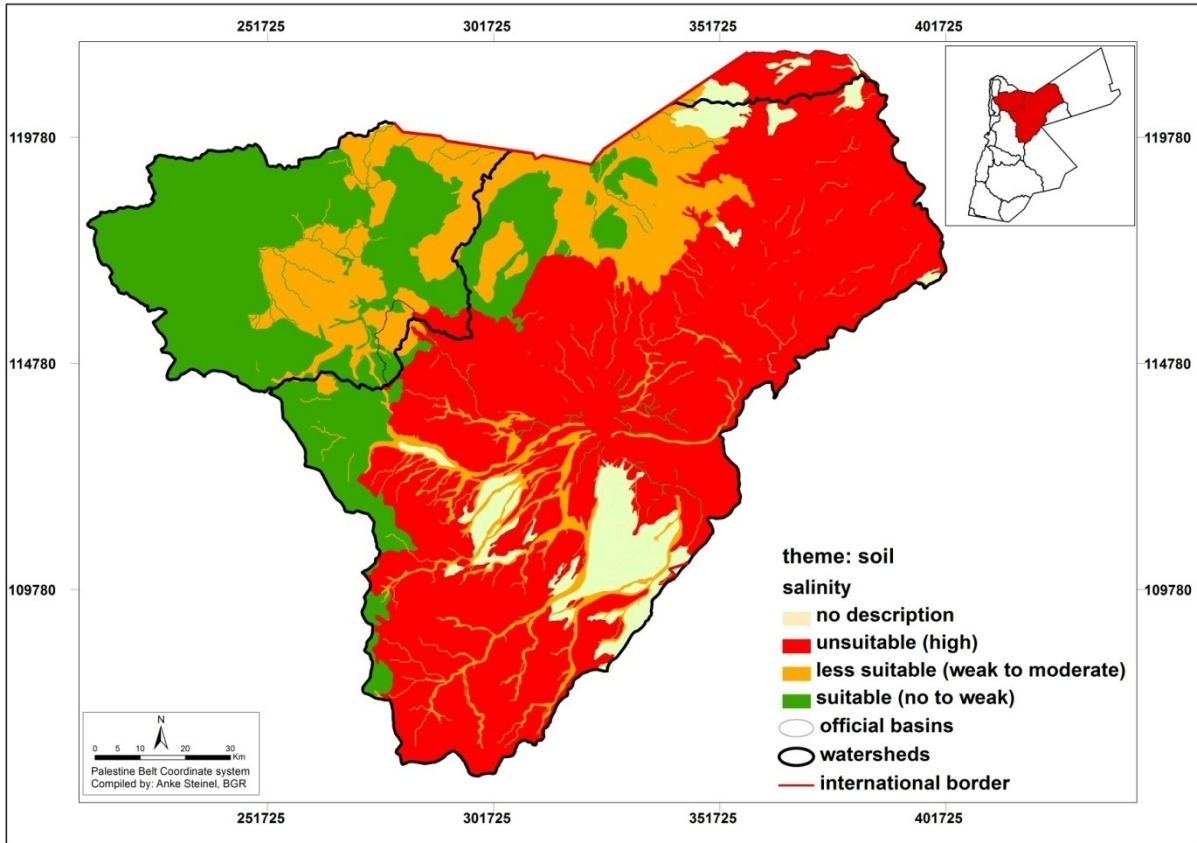
Fig. 74: Classification of soil salinity regarding the suitability for surface water quality.
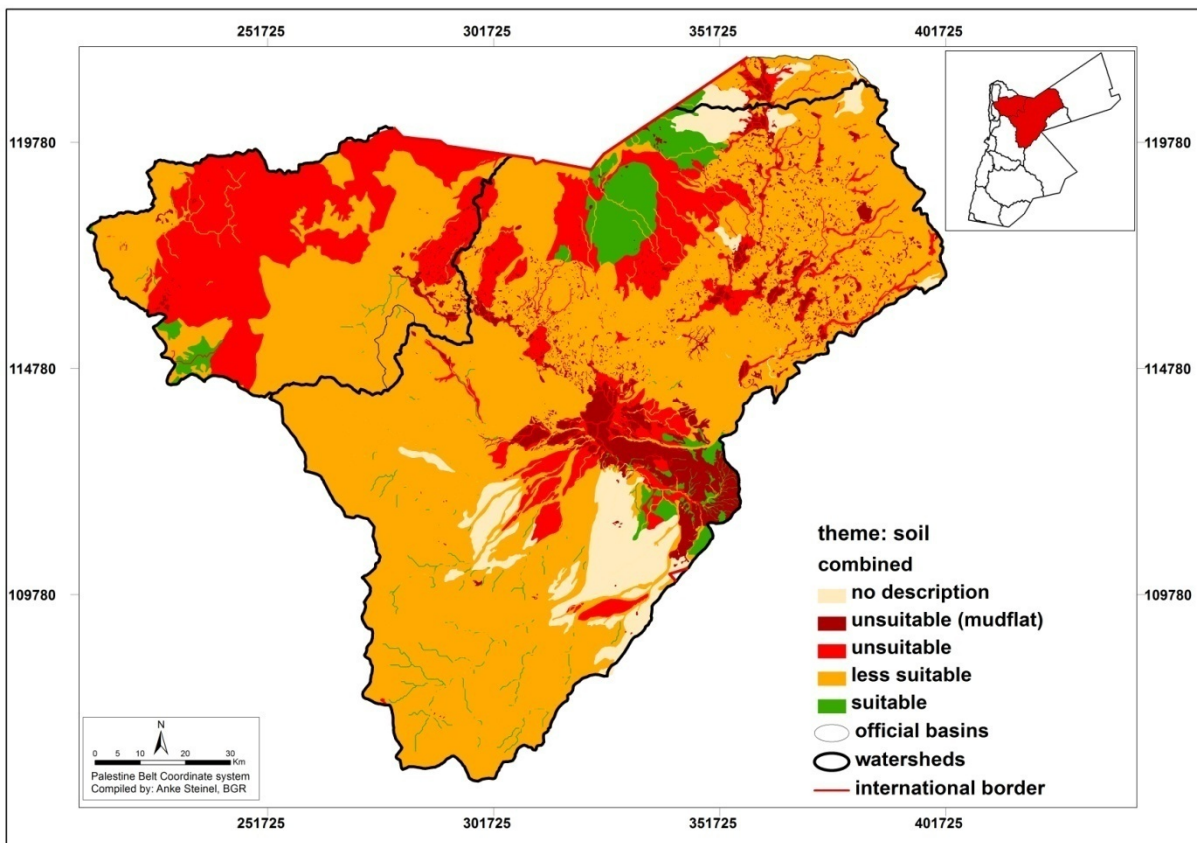
Fig. 75: Classification of soil based on texture, thickness and salinity combined.

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11.1.6   Existing dams

Obviously catchments where the runoff is already collected by official or private water harvesting structures (see Fig. 43) are not suitable. As the main aim is to keep the water in the highland, King Talal dam catchment is considered suitable in the upstream part. The upstream end of Wadi Rajil dam is also considered suitable, as it is doubtful that the water will really flow all the way to the dam due to the many marabs. Other dam catchments are classified unsuitable. For smaller water harvesting structures, structures with more than 10 000 m³ storage capacity are taken into account with a 5 km distance up and downstream (Fig. 76). Smaller structures will not have a large impact, unless there are many of them (Table 33). The size, current status and number of harvesting structures would need to be assessed by site-specific surveys though.
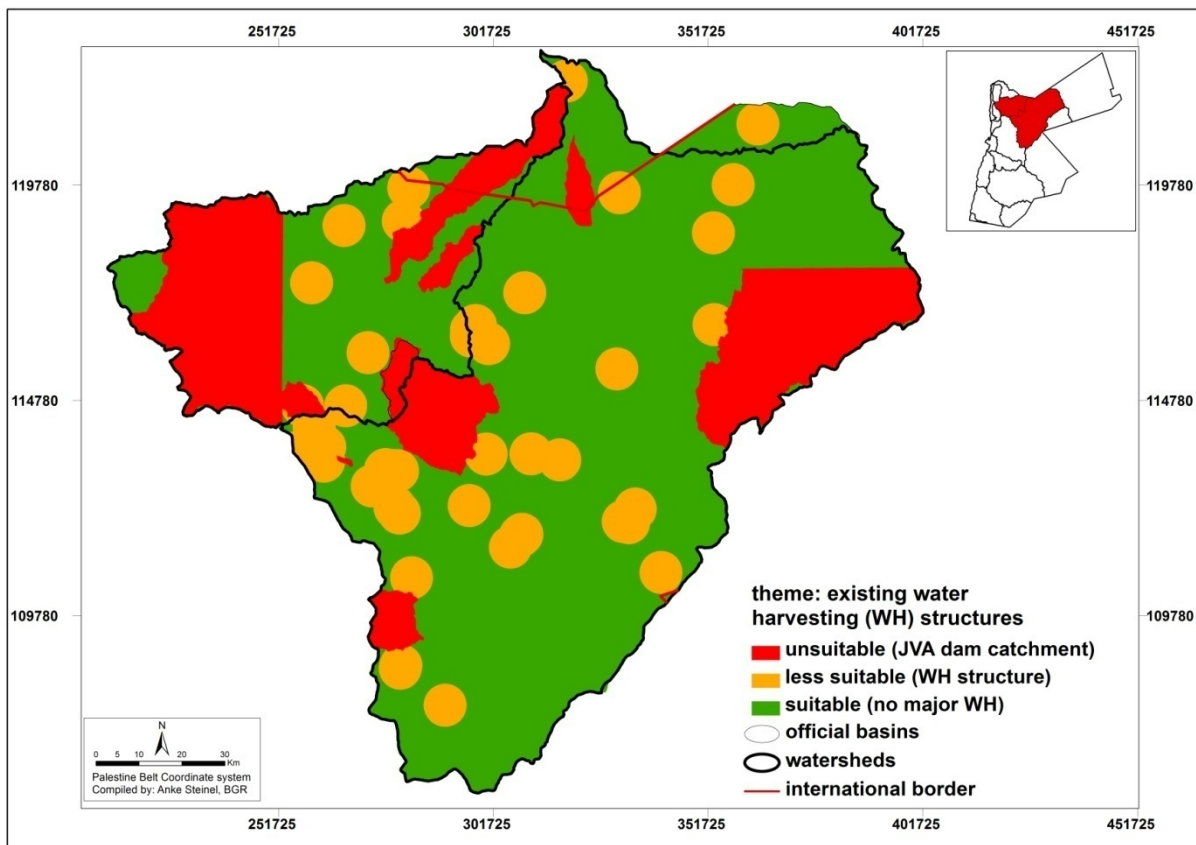
Fig. 76: Assessment of existing water harvesting (WH) structures for site selection.

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11.2   Thematic map development for the MAR site selection

The main restricting criteria for the position of a MAR infiltration site are the presence of a suitable aquifer, the slope, the current land use and the soil as indicator for infiltration capacity.

Due to the scale and the resolution of input data, all maps are based on simplification. A detailed site specific assessment for all the criteria will have to be made.

Dams can obviously only be built in a wadi channel. It would be possible to transfer available water from a dam site to a nearby infiltration site. The basin site should be downhill from the dam site, so water can flow there by gravity, but this consideration has not been implemented graphically as the DEM resolution is not high enough. A distance of 5 km downhill from dams has been suggested as economically feasible for larger dams (Rapp, 2008; Alraggad and Jasem, 2010). This distance was considered to be too long to be economically feasible for small scale dam sites with less water volume and a buffer of 2 km for a potential infiltration basin site was chosen in the following assessment (Table 34).

11.2.1   Topography classification

For the actual infiltration site gentle slopes are needed to prolong the residence time of the water to allow infiltration in the wadi or basin (Fig. 77). It should be taken into account that it is possible to modify the slope and possible to construct a suitable infiltration basin nearby. Slopes vary also on a smaller scale than the available resolution of the DEM, so site conditions need to be assessed in the field.

If recharge dams without release would be used, steeper slopes would actually be preferred as this allows for horizontal infiltration. The area with slopes >5 % is primarily located in the western part of the AMZ basin (Fig. 77), which is of low MAR potential, as here the King Talal dam collects surface runoff already and urban areas as well as areas with aquitards are present. Accordingly, in the highlands, where most areas have slopes <5 %, recharge release dams are more suitable and this criteria has been used in previous MAR investigations (see section 9.3).

11.2.2   Land use classification

Similar to the evaluation for runoff generation, land use is a main factor for land availability and potential for vandalism. Urban areas and quarries should be excluded for both reasons from the site selection. A buffer of 500 m is applied to account for further spreading. Agricultural areas commonly create a conflict of interest with MAR as farmers often have their own water harvesting structures and prefer to store the water above ground (see section 10.2.1). Uninhabited areas with bare surface or pastures are most suitable (Fig. 78). Obviously crusts would need to be removed at the infiltration site and are also less common in the wadi channels themselves. A site assessment will need to assess the actual situation and the land ownership.

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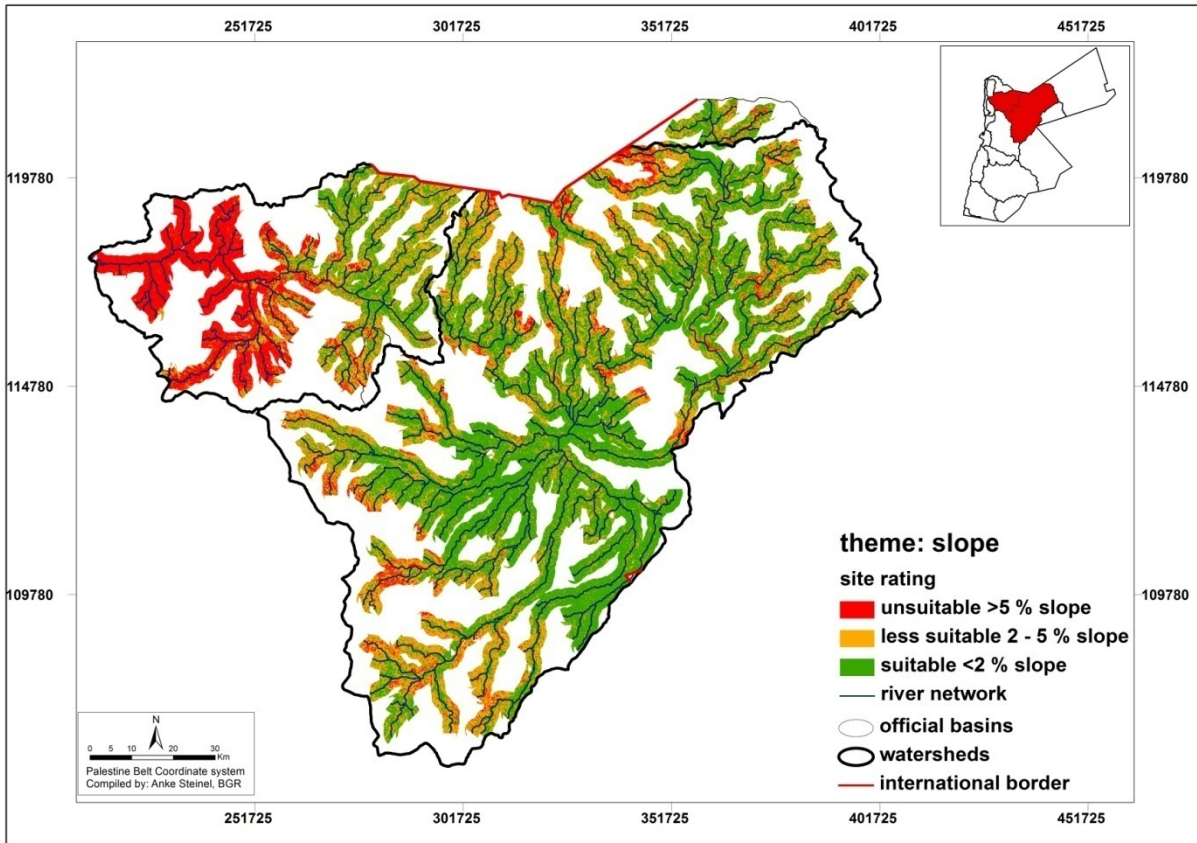
**Fig. 77: Classification of slope regarding the suitability for MAR infiltration sites.**

Fig. 78: Classification of land use regarding the suitability for MAR infiltration site.

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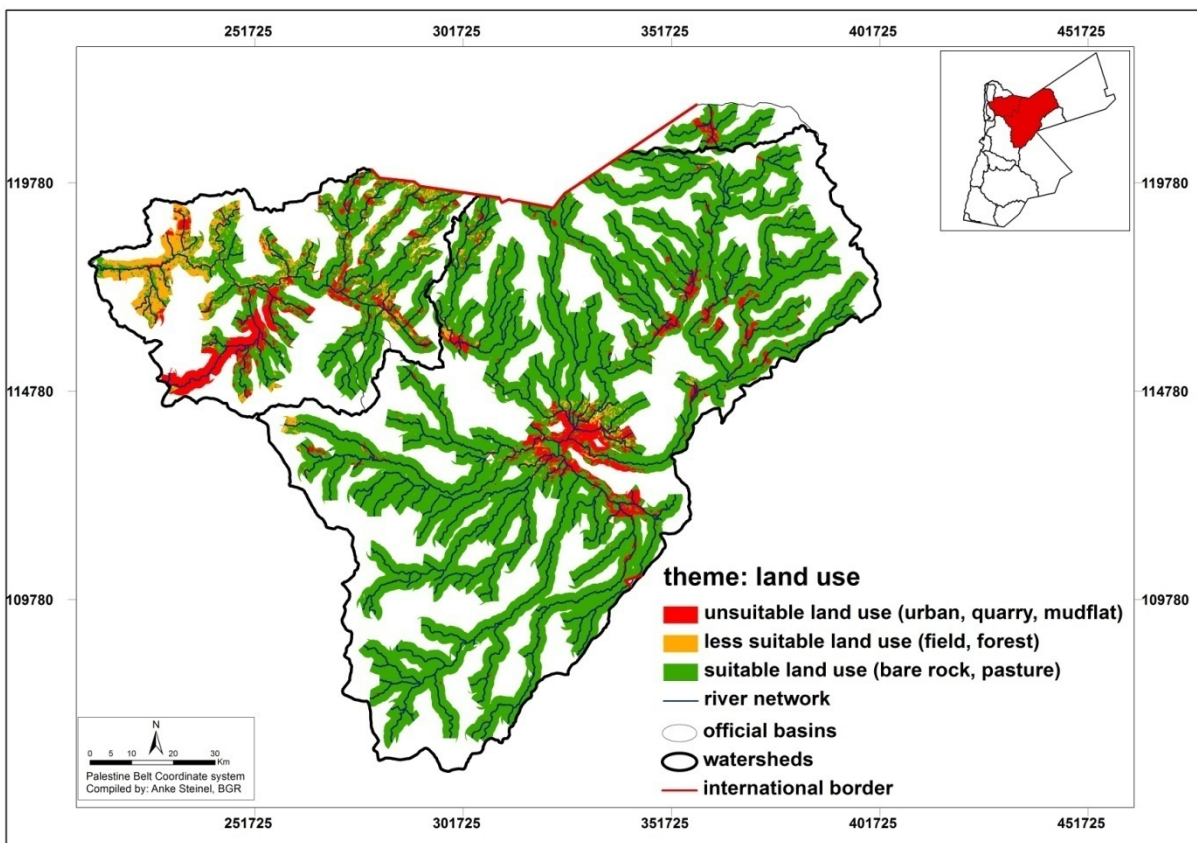
11.2.3   Rainfall and runoff

The MAR site should be situated in a wadi with sufficient runoff depending on rainfall and catchment size. The actual rainfall at the infiltration site is not so important, if the overall catchment receives higher rainfall (see section 11.1.3). The 75 mm rainfall line was chosen as limit. As the runoff coefficient increase with rainfall the minimum catchment size increases non-linear with rainfall range from about 25 km² in low rainfall regions to about 4 km² in high rainfall regions (Table 32). As most of the potential area is located in the low rainfall range (100 - 250 mm) a mean value of 18 km² minimum catchment size was chosen for a mean annual runoff of 50 000 m³. This is equivalent to a flow accumulation >2500 pixels of the DEM and is depicted by the extent of the river network (Fig. 79).

Table 32: Calculation of minimum catchment size depending on rainfall and runoff coefficient for 50 000 m³ runoff in a normal year.

rainfall range	100 - 150 mm	150 - 200 mm	200 - 250 mm	250 - 300 mm	300 - 350 mm	350 - 400 mm	400 - 450 mm
minimum runoff coefficient (% of total rainfall)	1.5	1.75	2	2.25	2.5	2.75	3
minimum catchment size (km²) for 50 000 m³ annual runoff	26.7	16.3	11.1	8.1	6.2	4.8	3.9
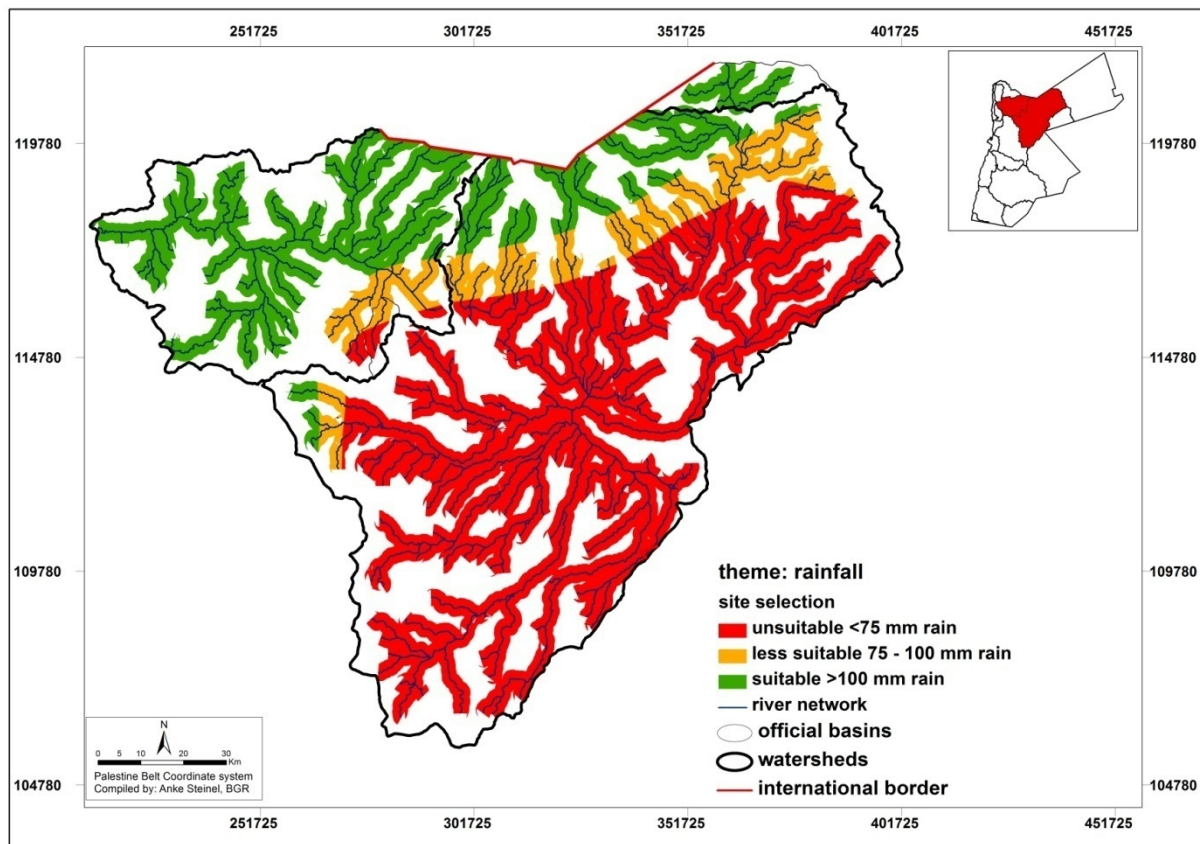
Fig. 79: Classification of distance to wadi and catchment size for site selection.

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11.2.4   Hydrogeological classification

The suitability of the aquifer and the contained groundwater depends on a number of criteria and is primarily important for the selected site and the flowpath to a recovery site.

Spatially detailed data on aquifer **permeability** are not available, so simplified assumptions have to be made. There are a number of suitable outcropping aquifers in the area (see section 10.3.1). Most suitable are areas above the basalt, B4, B2, A7, A4 and A1/2, while B3, A5/6, A3 are aquitards and hence not suitable and will be a constraint for further assessment. The formations B5 and B1 are commonly group together into the B4/5 and the A7/B2 aquifer and only limited information is available for these formations by themselves. B5 varies in characteristics from north to south with higher permeability in the south. Both are classified as less suitable (Fig. 80). Due to local heterogeneities in aquifer characteristics, site specific assessment will need to confirm the actual suitability of the aquifer at a chosen site.

Additionally the **superficial cover** is important to allow infiltration into the underlying aquifer. Areas with sandy deposits will enhance infiltration, while mudflats are not suitable for infiltration. The alluvial encompasses a range of deposits from gravel to clay and hence their potential is variable and needs size specific assessment. In some areas alluvial deposits might be thick enough to allow for local storage in alluvial aquifers, but information on this is too limited for a systematic assessment.
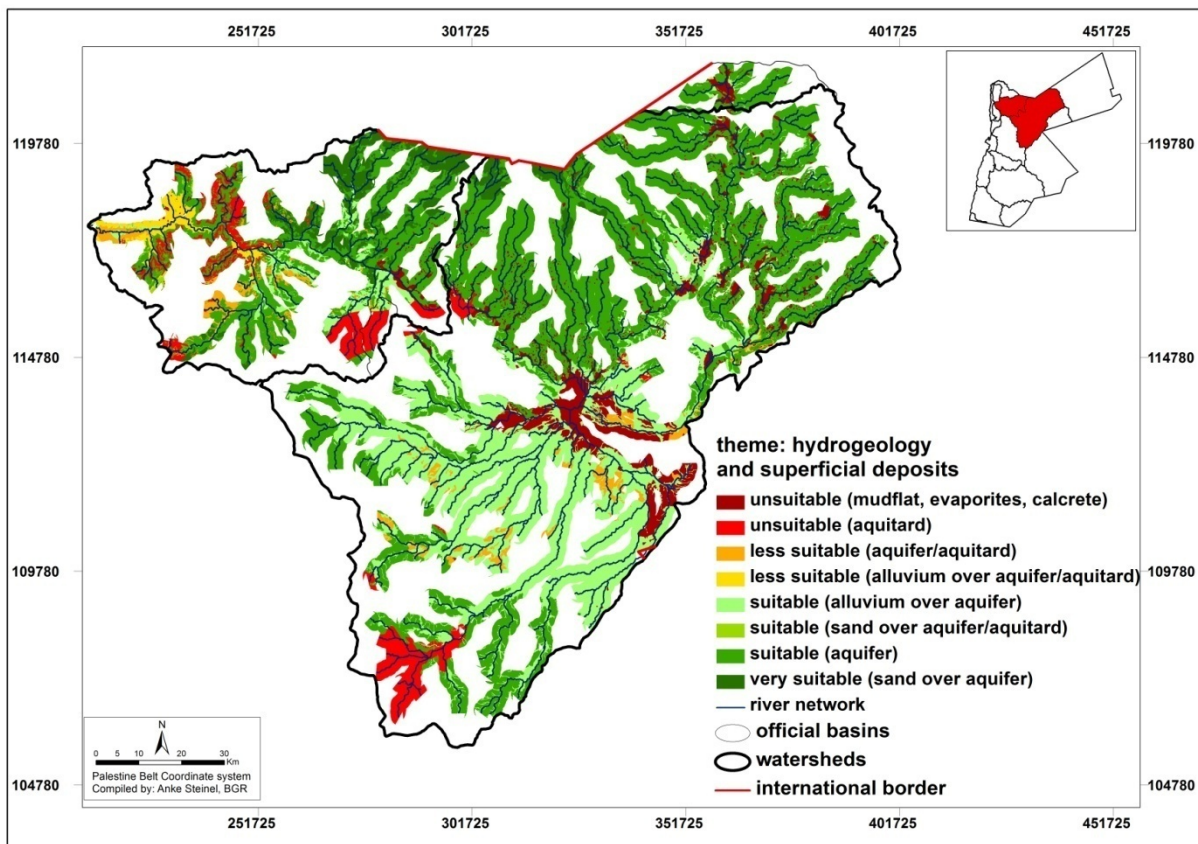
Fig. 80: Classification of the geological formation and superficial deposits for MAR potential site selection.

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There are only small areas where the **water table** is too shallow and discharge of the recharged water to the surface or interference with the foundations of buildings is feared. Shallow water tables limit the available storage capacity. Areas with very deep groundwater table are less preferred as infiltrated water might not reach the groundwater due to impermeable layers. It is also a cost factor for recovery purposes if the pumping lift is high (Fig. 81). Unfortunately the density of data available for this report is limited and the assessment can only be performed for limited regional extent on the available older maps (see section 10.3.2). Depth to water levels will have changed over the years and need to be assessed site specifically. Areas outside the limit of saturation of the aquifer are not suitable as recovery from the unsaturated zone will not be possible.

The **thickness** of the aquifer unit restricts the available storage capacity and thin aquifer units are hence not suitable for MAR. As no detailed thickness maps for the A1/2 and A4 aquifer are available, only the middle and shallow aquifer complex have been assessed. Commonly aquifer units are thick enough, but are obviously thinning out towards the edges (see section 10.3.1). Overall there are only a few areas where the aquifer thickness might be a limiting factor (Fig. 82).

The groundwater **flow gradient** is of interest for the recovery of the water. A high flow gradient limits the recovery efficiency as the recharged water will be dispersed over a large area and might mix with groundwater of unsuitable quality. The available groundwater table contour lines (see section 10.3.2) have been used to calculate the flow gradient. As with all interpolations, values might not be correct along the edges of the interpolation, and edges of aquifer outcrops also pose a problem for the interpolation (Fig. 83). Flow gradients are also likely to have increased around large abstraction areas.

Groundwater quality is important for the recovery of the recharged water and suitability depends on the intended use. Groundwater salinity below 1000 mg/L is suitable for all uses, while salinity up to 3000 mg/L could be acceptable for irrigational use and livestock watering. Salinity maps for the A//B2 aquifer show suitable conditions in the outcropping areas and less suitable conditions in the confined regions that cannot be used by MAR via infiltration anyway (Fig. 84). For the shallow aquifer no detailed maps are available and available data is not covering the region equally to generate reliable maps. The overall groundwater quality is acceptable for the shallow and middle aquifer system (see section 10.3.3).

Areas with known **groundwater contamination** should be avoided as the recovered water should be suitable for domestic use. Areas with groundwater contamination also indicated that there are a number of hazards in the catchment that would also have a negative impact on surface water quality. These areas are commonly related to point contamination related to hazard sites for which no regional map exists or are related to the land 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 (Fig. 85). This factor would be most important downstream of the MAR site, but has not been implemented graphically. 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.

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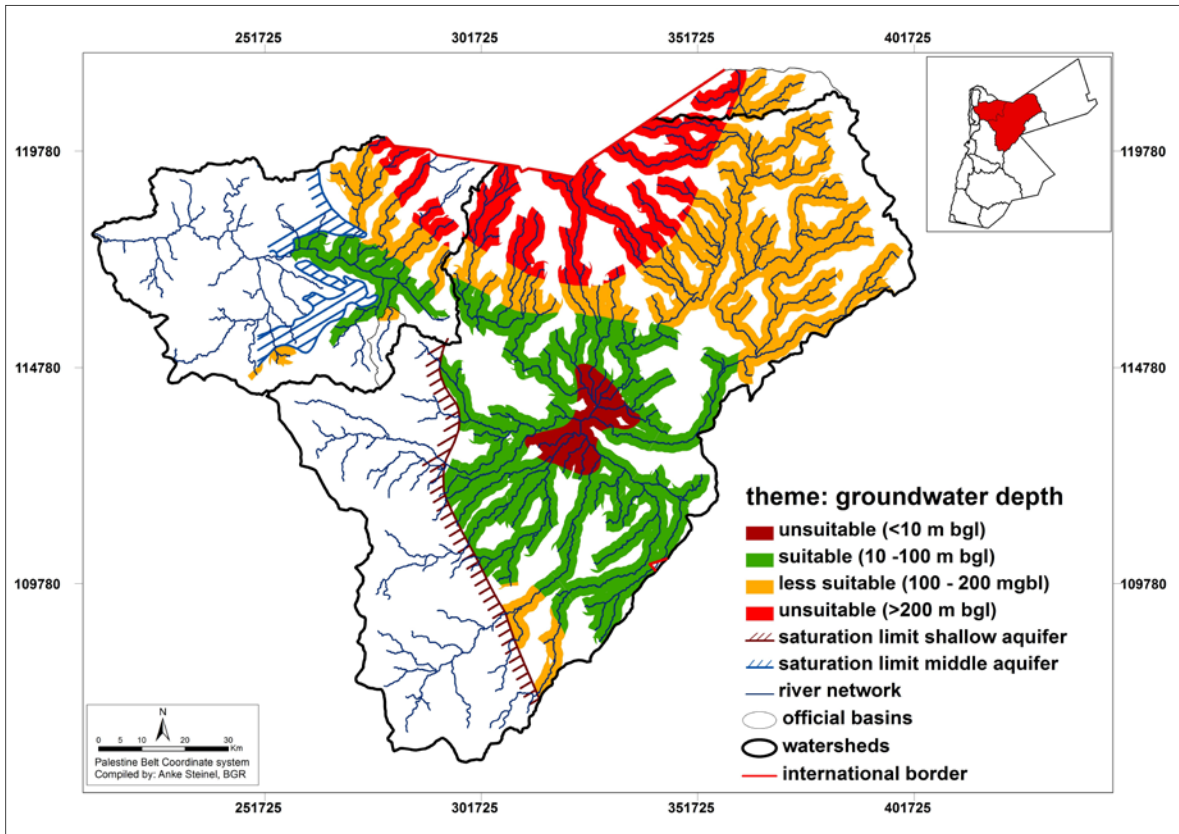
Fig. 81: Classification of depth to water table for the shallow and the middle aquifer system (arranged after Al-Kharabsheh, 1995 and Hobler et al., 2001)
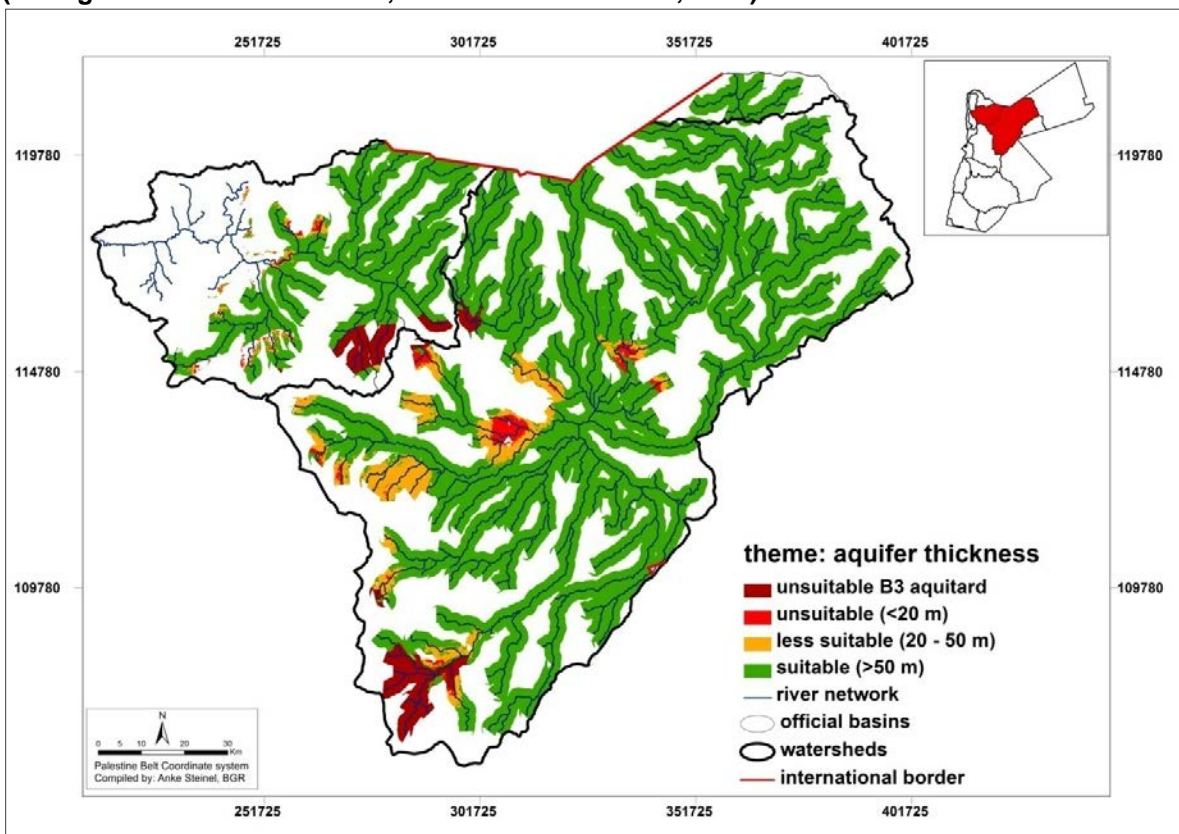
Fig. 82: Classification of thickness of aquifer units for MAR potential site selection.

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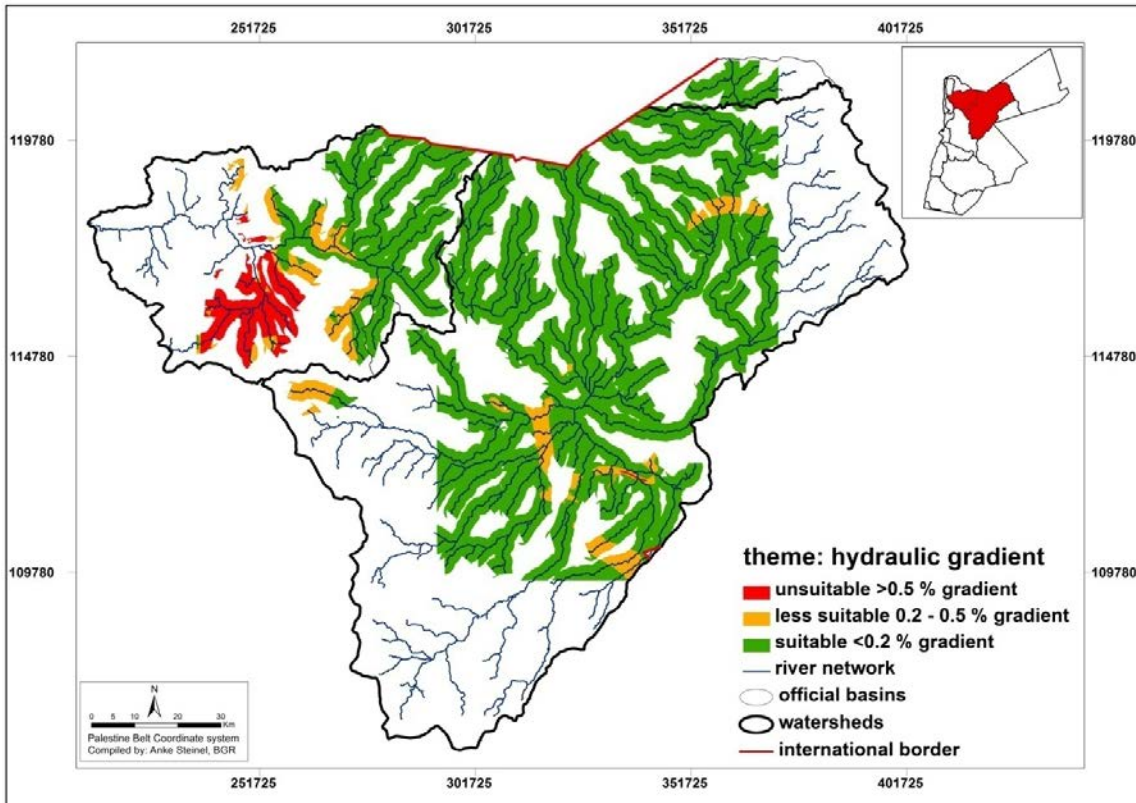
Fig. 83: Classification of flow gradient for shallow (Basalt + B4/5) aquifer and A7/B2 aquifer for MAR potential site selection (arranged after groundwater table contour maps from Hobler et al., 2001).
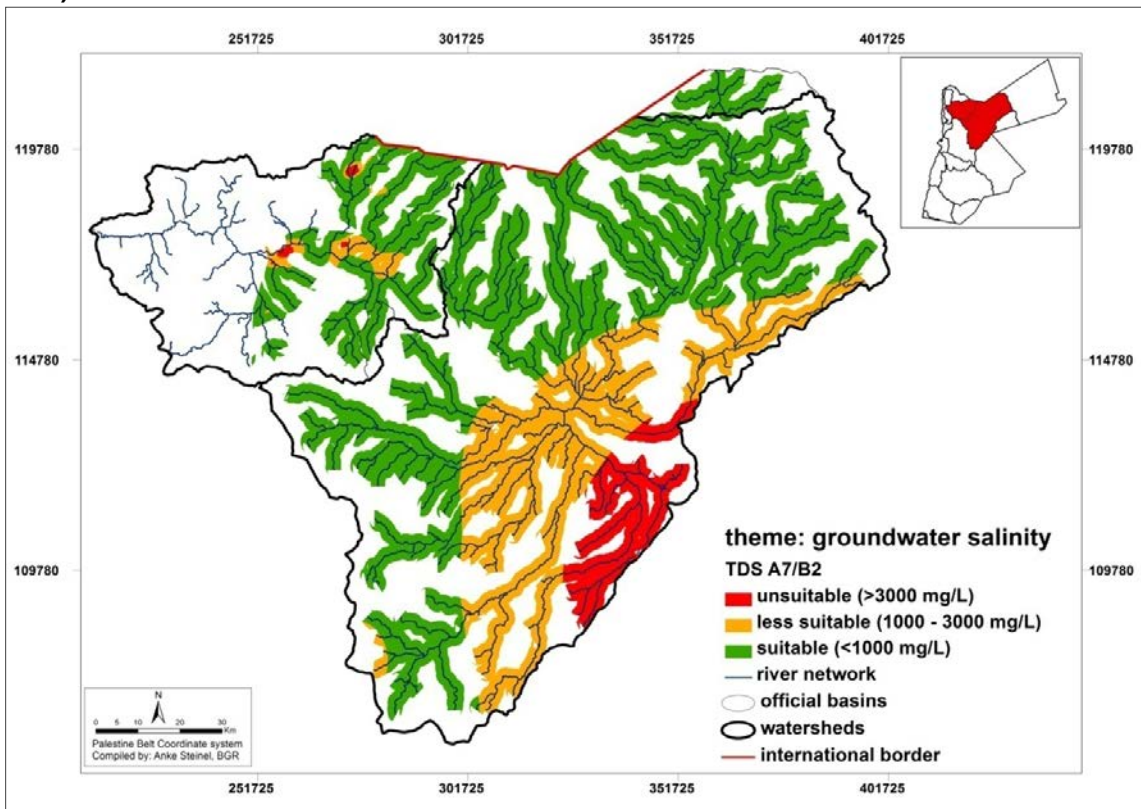
Fig. 84: Classification of groundwater salinity in the A7/B2 aquifer for MAR potential site selection (arranged after Hobler et al., 2001).

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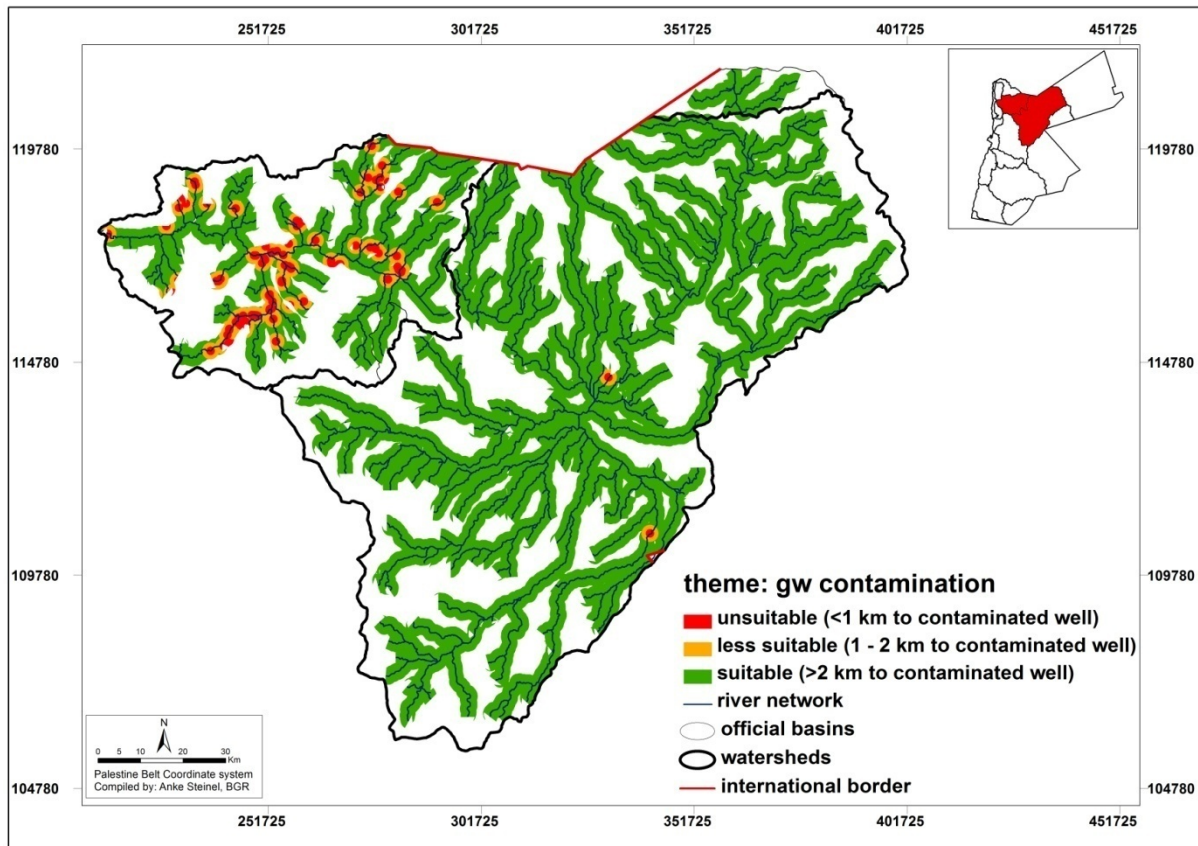
Fig. 85: Assessment of distance to contaminated wells for site selection.

11.2.5   Soil

Unfortunately the soil maps do not contain regionalised information on infiltration capacity. Only generalised estimations of soil thickness, texture and salt content could be generated using the most representative subsoil group for each soil map unit overall and in the wadis (see section 10.4.1). The evaluation of the criteria for infiltration sites is the same as for the catchment (see section 11.1.5), i.e. coarse textured, thin soils with low salinity are the most suitable to allow fast infiltration. As described (see section 10.4.1) soils in the wadi often differ from the main soil type and have been assessed separately (Fig. 86). It can be seen that the suitability of the wadi soils does not always match with the suitability of the most representative soil in the map unit.

11.2.6   Existing dams

Obviously the site selection for a new dam should not interfere with existing official dams and should also limit the conflict with existing private water harvesting structures (Fig. 87). The same assessment as for the catchment has been used (see section 11.1.6). This leaves about 60 % of the wadi length as suitable.

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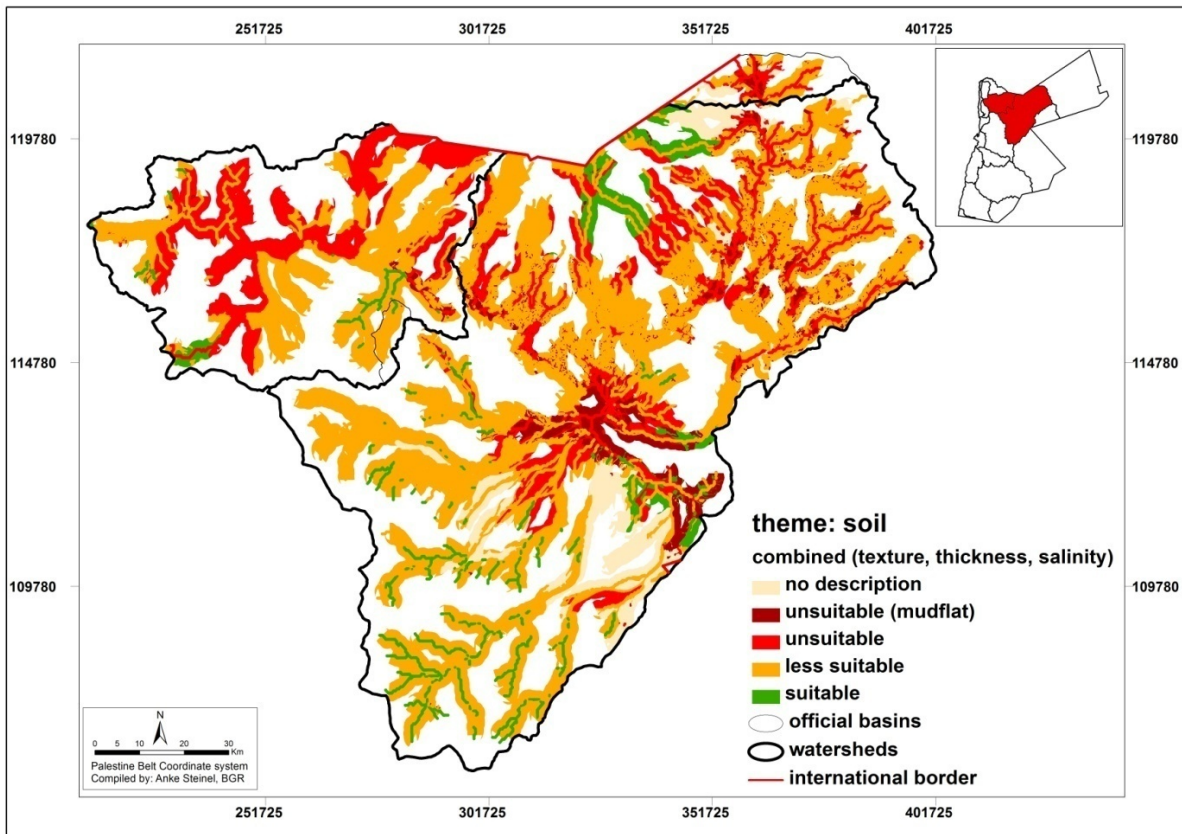
Fig. 86: Classification of soil regarding MAR infiltration sites based on texture, thickness and salinity combined.
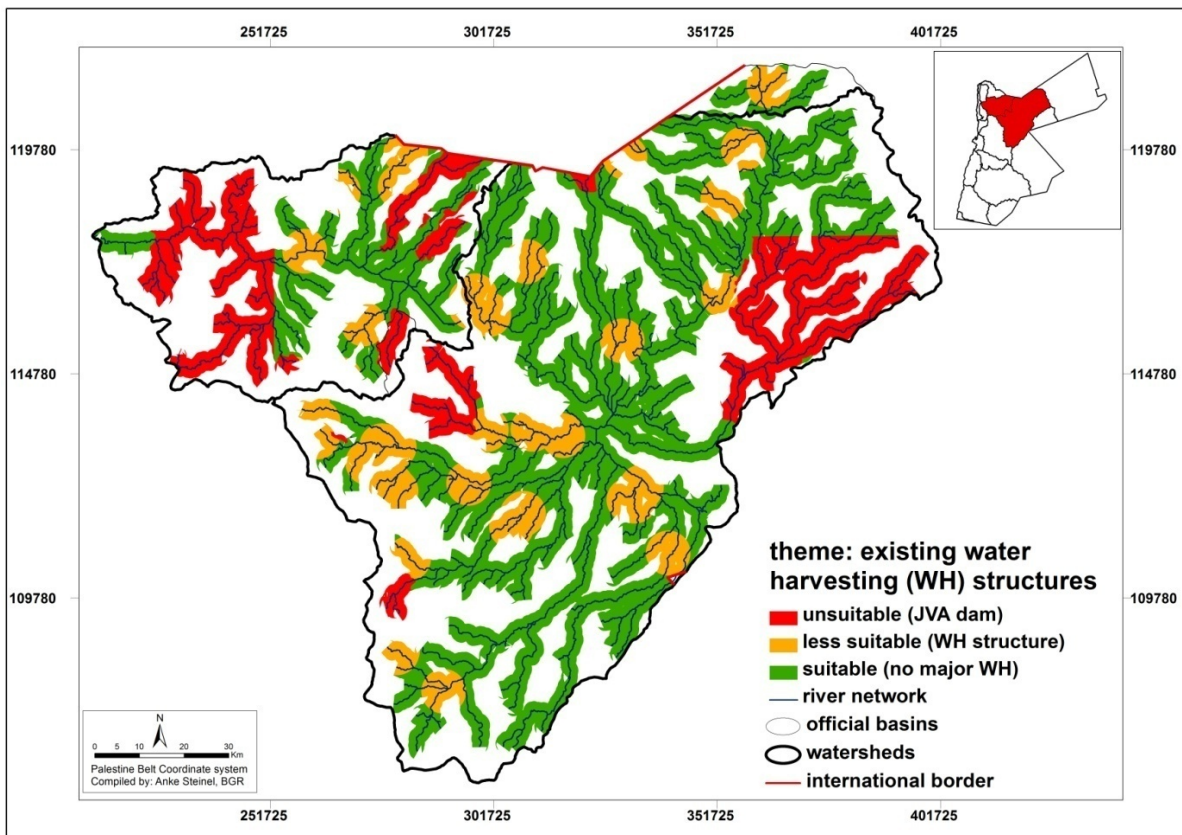
Fig. 87: Assessment of existing water harvesting (WH) structures for site selection.

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11.2.7   Other criteria

Apart from the above main criteria there are also a number of criteria that are favourable or are restricting the actual site selection.

Fault lines could potentially be preferable for enhancing the vertical hydraulic conductivity and hence the infiltration potential as higher transmissivity values have been found associated with fault zones (Al-Khatib, 1999; Alraggad, 2009). They are 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 is used as acceptable distance of influence and when intersected with the 2 km buffer around the wadi system around 2108 km² for visible faults and 1665 km² for inferred faults would give additional benefit (Fig. 88).

Site access to the dam site should be reasonably easy for the construction and maintenance of the MAR site, but should not be too easily visible from the main road or settlements to not attract vandalism. The available road map was separated into main roads/roads in settlements, secondary roads and gravel roads. A distance of 1 km along main roads is not suitable, 1 km along secondary roads is less suitable, while a distance of <2 km from gravel roads is preferable (Fig. 89).

The **distance to the international borders** should be a minimum of 2 km for security reasons[72], which is around 1.3 % of the total area (Fig. 89).
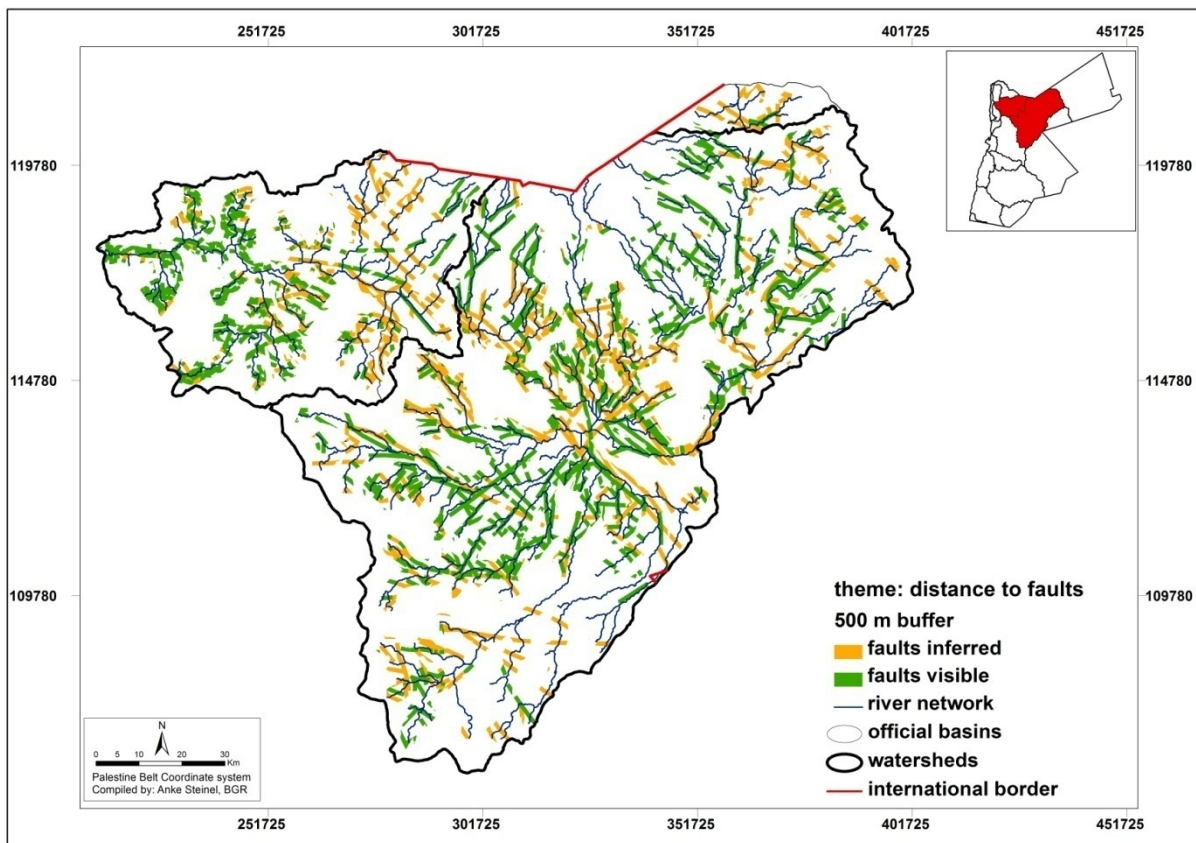
Fig. 88: Assessment of distance to visible and inferred faults.

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[72] Al-Adamat et al. (2010) suggested 1 km security distance. Due to the current conflict in Syria a larger distance has been selected.

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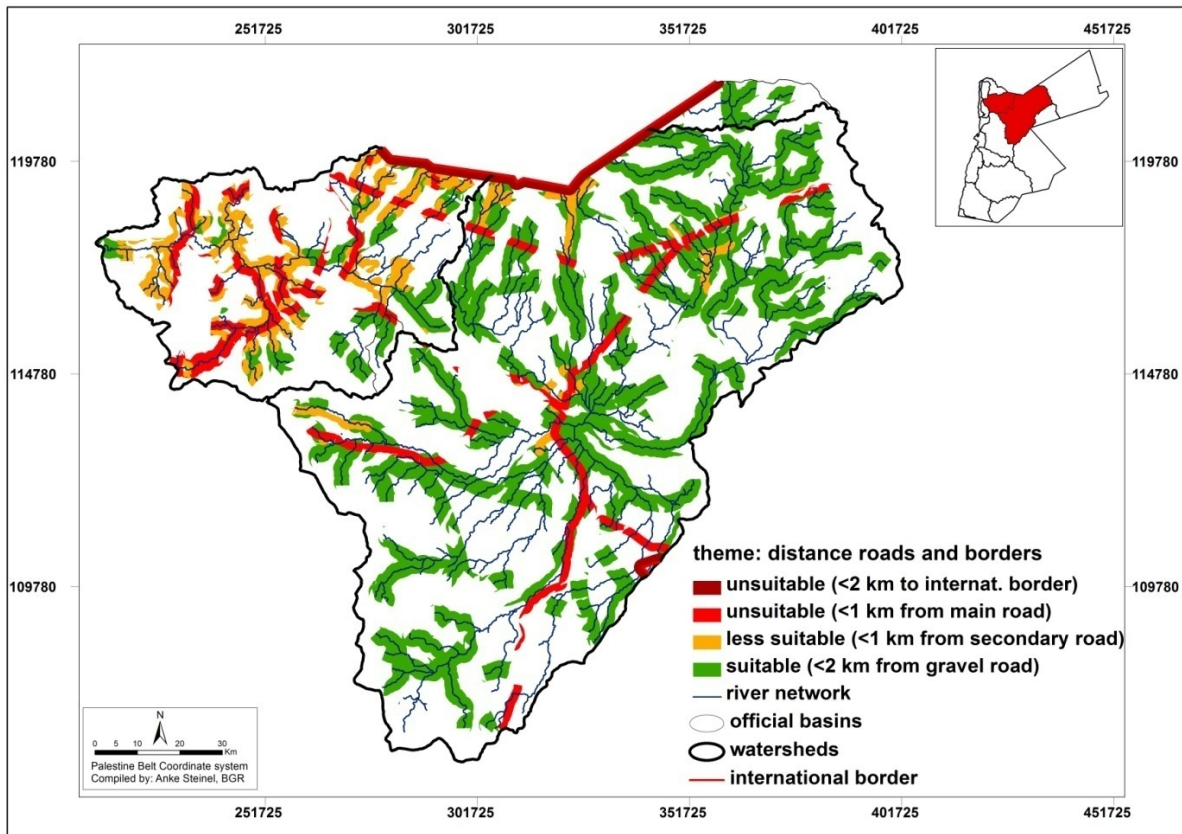
Fig. 89: Assessment for site selection regarding distance to roads as negative factor in relation to potential vandalism and as positive factor in relation to site access.
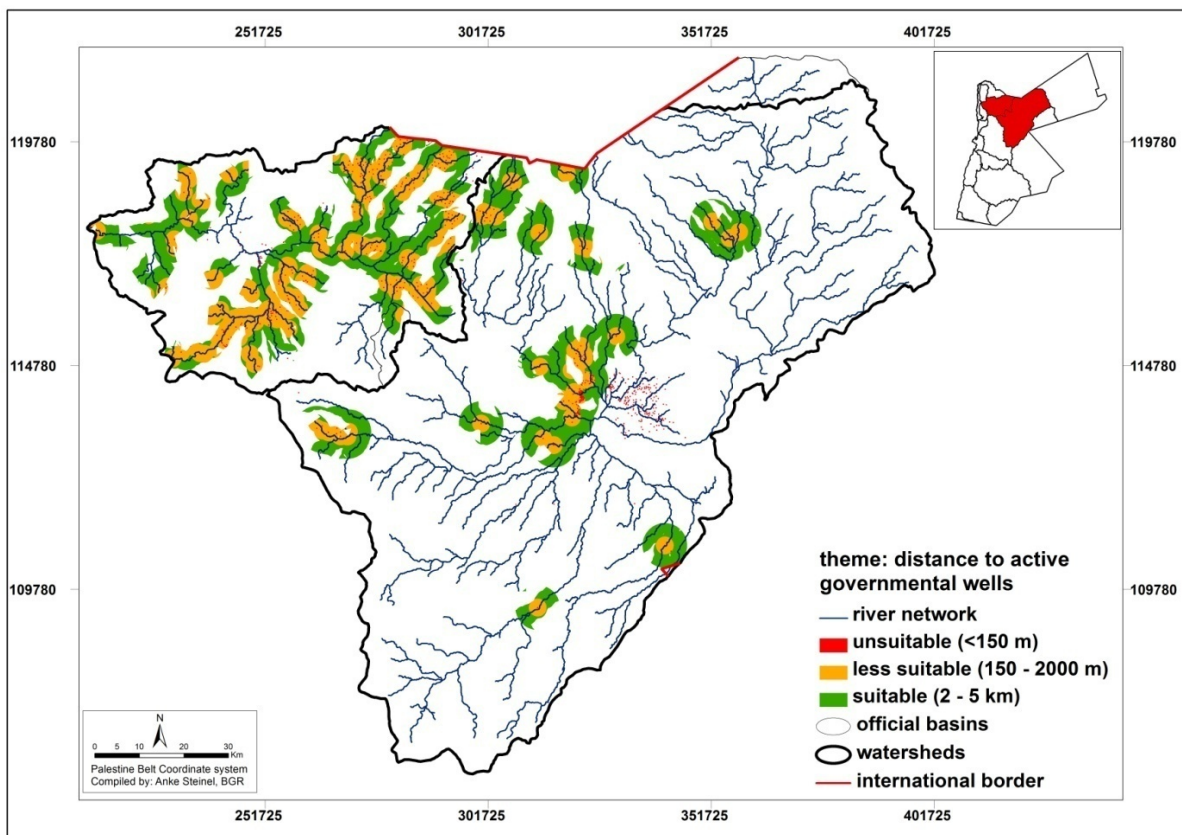
Fig. 90: Assessment of distance to active wells for site selection.

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Existing wells are another criteria. It is an economic incentive if active production wells are downstream of the MAR site that would benefit from the recharged water. Preferably these are governmental wells and not private ones. Of the 1566 active wells with data only 310 are governmentally owned. Commonly groundwater protection zone 2 is delineated with a minimum of 150 m and a maximum of 2 km from the well to prevent any potential bacteriological contamination reaching the wells. As flow velocities are unknown and seem to vary considerably along preferential flow paths, a limit of 2 km between the infiltration site and the well is preferable and a general buffer of 150 m around all existing wells is classified unsuitable for well protection. If the distance between infiltration site and well becomes too large the recharged water might take too long to be of short term benefit. So the optimal distance would lie between 2 - 5 km upstream from a production well (Fig. 90). The applied buffer includes up- and downstream areas, so the groundwater flow direction and if the well is pumping from the uppermost aquifer system has to be assessed site specifically. If the well is further away, the flow velocity should be estimated based on the flow gradient.

11.3 Thematic map overlay

There are two basic overlay techniques. The Boolean logic allows only a rating as suitable or unsuitable (0 and 1 value) and is commonly used for creating constraint maps. It means that an area will be regarded as suitable if it fulfils the minimum value for all the criteria, while the area will be rated unsuitable if only one criterion value is below the minimum threshold. Completely unfeasible areas will be screened out in this process.

The weighted linear combination allows the combination of classification inside each criterion with different weights across all criteria and is used to create suitability maps. It means that areas that are unsuitable for one criterion can still get a high class if all other criteria are valued suitable.

11.3.1 Constraint map for MAR catchment assessment

As described above the selection of a suitable catchment generating enough runoff in a suitable quality is based mainly on three criteria. Areas fulfilling any of the below criteria are rated unsuitable:

(a) rainfall <75 mm
(b) inside the catchment of existing dams (all small catchments and the lower part of the large catchments)
(c) land cover is built up, quarry or mudflat

About 70 % of the Jordanian part of the catchment area does not fulfil these minimum criteria and are hence excluded from further assessment for the catchment (Fig. 91). The catchment constraint map serves as a mask for the catchment suitability map.

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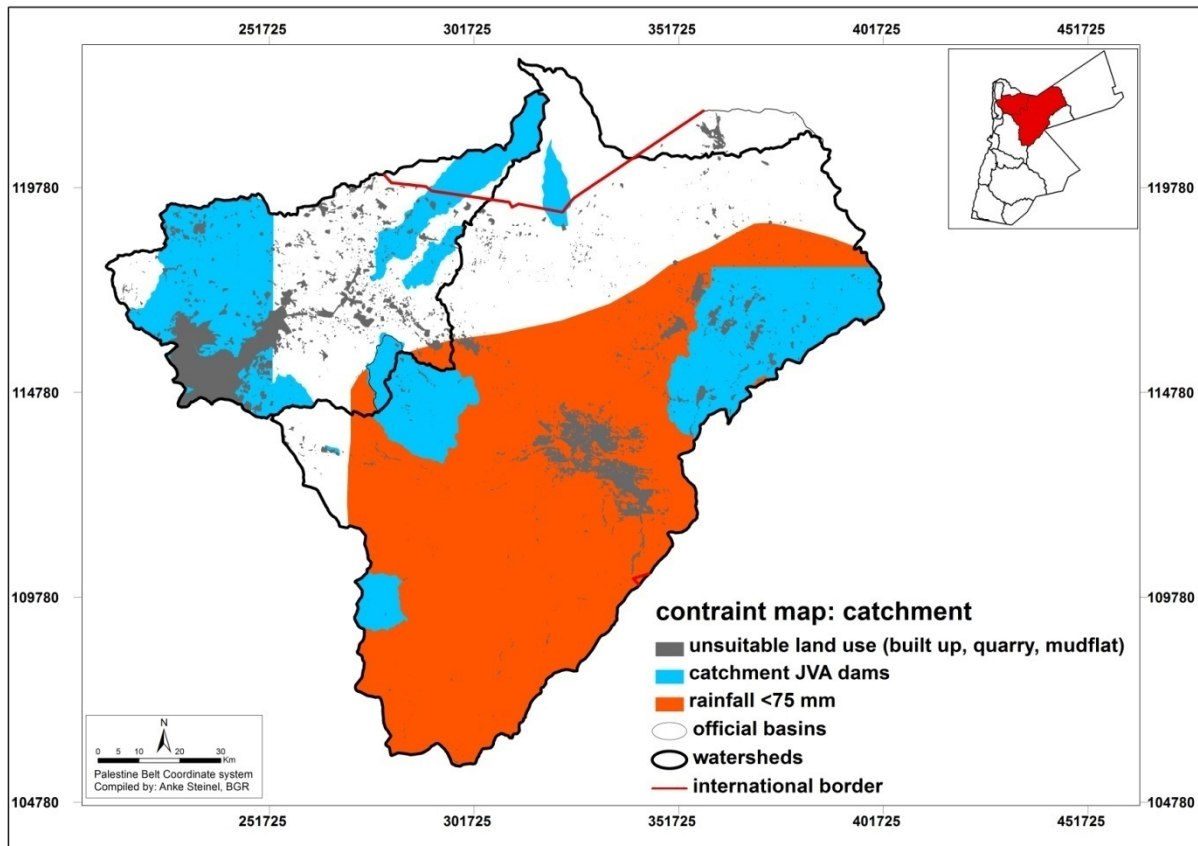
Fig. 91: Constraint map for MAR catchment based on land use, existing dams and rainfall.

11.3.2   Suitability map for MAR catchment assessment

The thematic maps presented under section 11.1 were now combined into one catchment suitability map using weighted linear combination. The weights and ratings used are compiled in Table 33. The final score[73] was based on the following formula[74]:

catchment suitability score = (5*score rain + 4*score slope + 3*score WH structures + 2*score soil + score hydrogeology + score land use) / 16

The total catchment area[75] outside the constraint area was assessed as 11.1 % suitable, 80 % less suitable and 8.9 % unsuitable (Fig. 92). The most suitable areas are downstream of the King Talal dam outside the highland area. Smaller suitable areas can be found inside Syria due to higher rainfall, along the border to Syria and southwest of Zarqa. Most unsuitable areas are concentrated in the region between 75 - 100 mm/a of rainfall.

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[73] The suitability map can be created as a union of shape files (the slope raster was reclassified and converted to shape file) calculating the final score with the field calculator or all shape files can be converted to raster and processes with the raster calculator.

[74] Other weighing factors could easily be implemented to assess sensibility.

[75] For the Syrian part no information on soils was available and the area was set to 1 for the soil rating. The hydrogeology is also set to 1 (less suitable) in accordance with the basalt area in Jordan, but no information on superficial deposits is available. Hence the suitability rating for the Syrian part should be viewed as preliminary.

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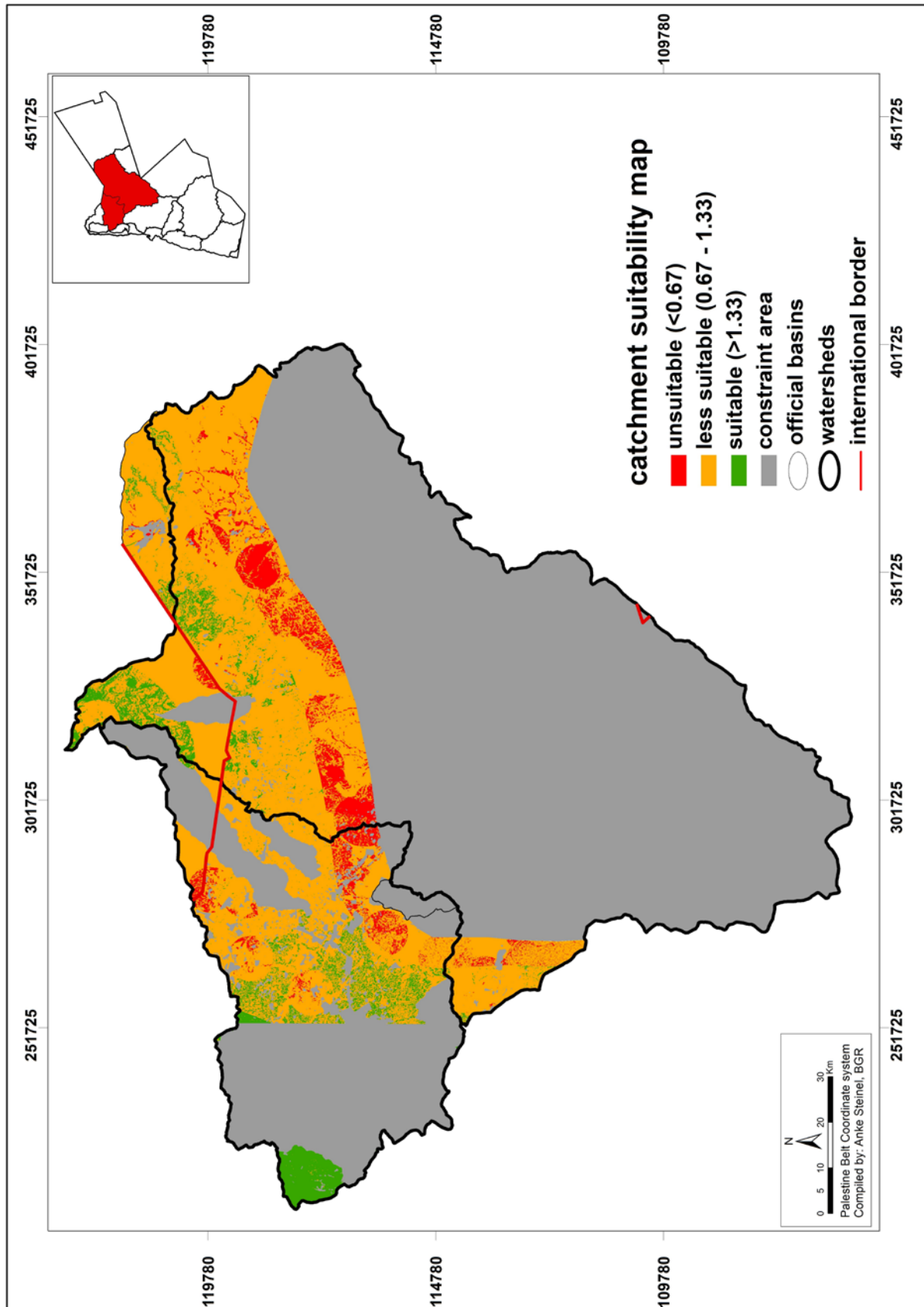
Fig. 92: Assessment of catchment area for MAR suitability (max. possible score of 2).

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Table 33: Criteria, weights and rating for MAR catchment constraint and suitability assessment.

criteria	weight	classification	rating*	area in Jordan	area incl. Syria
rainfall	5	<75 mm	constraint	56 %	53 %
		75 - 100 mm	0	12 %	11 %
		100 - 200 mm	1	23 %	24 %
		>200 mm	2	9 %	11 %
slope	4	0 - 2 %	0	45 %	45 %
		2 - 5 %	1	37 %	38 %
		5 - 10 %	2	10 %	10 %
		>10 %	1	8 %	8 %
existing dams	3	other area	2	61 %	60 %
		within 5 km of existing WH structure	1	22 %	23 %
		catchment JVA dam	constraint	17 %	17 %
soil score** (60 % texture, 20 % thickness, 20 % salinity)	2	score >67 %	2	4 %	
		score 33 - 67 %	1	64 %	
		score <33 %	0	26 %	
		no description	1	6 %	
land use	1	urban, quarries, mudflats	constraint	8 %	
		field and tree crops, forest	1	6 %	
		bare rock, chert plains, sand, wadi deposits, pastures	2	86 %	
hydrogeology and superficial deposits	1	aquitard (B3, A5/6, A3)	2	7 %	
		mudflats, evaporites, calcrete	0	6 %	
		aquifer/aquitard (B5, B1, K/Z)	2	3 %	
		alluvium over aquifer/aquitard	1	1 %	
		sand over aquifer/aquitard	1	0 %	
		alluvium over aquifer/aquitard	1	23 %	
		aquifer (basalt, B4, B2, A7, A4, A1/2)	1	55 %	
		sand over aquifer	0	5 %	
overall suitability		**constraint**	**0**	**69 %**	**67 %**
		score <33 %	**<0.67**	**3 %**	**3 %**
		score 33 - 67 %	**0.67 - 1.33**	**25 %**	**26 %**
		score >67 %	**>1.33**	**3 %**	**4 %**

*0 = unsuitable, 1 = less suitable, 2 = suitable, ** actual score (range 0 - 1.7) from combining the three soil aspects was used for overlay

11.3.3   Constraint map for MAR site selection assessment

As described above the selection of a suitable dam and infiltration site is based on more criteria. Areas fulfilling any of the below criteria are rated unsuitable:

  (a) rainfall <75 mm
  (b) land use: urban, quarry or mudflat
  (c) catchment of existing JVA dam
  (d) slope >5 %
  (e) areas over aquitards
  (f) aquifer thickness <20 m
  (g) areas over unsaturated aquifer
  (h) distance to contaminated well <1 km
  (i) distance to international border <2 km
  (j) distance to wadi >2 km
  (k) catchment size <18 km²

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About 88 % of the Jordanian part of the catchment area does not fulfil these minimum criteria and are hence excluded from further assessment for the site selection (Fig. 93). The site constraint map serves as a mask for the site suitability map.
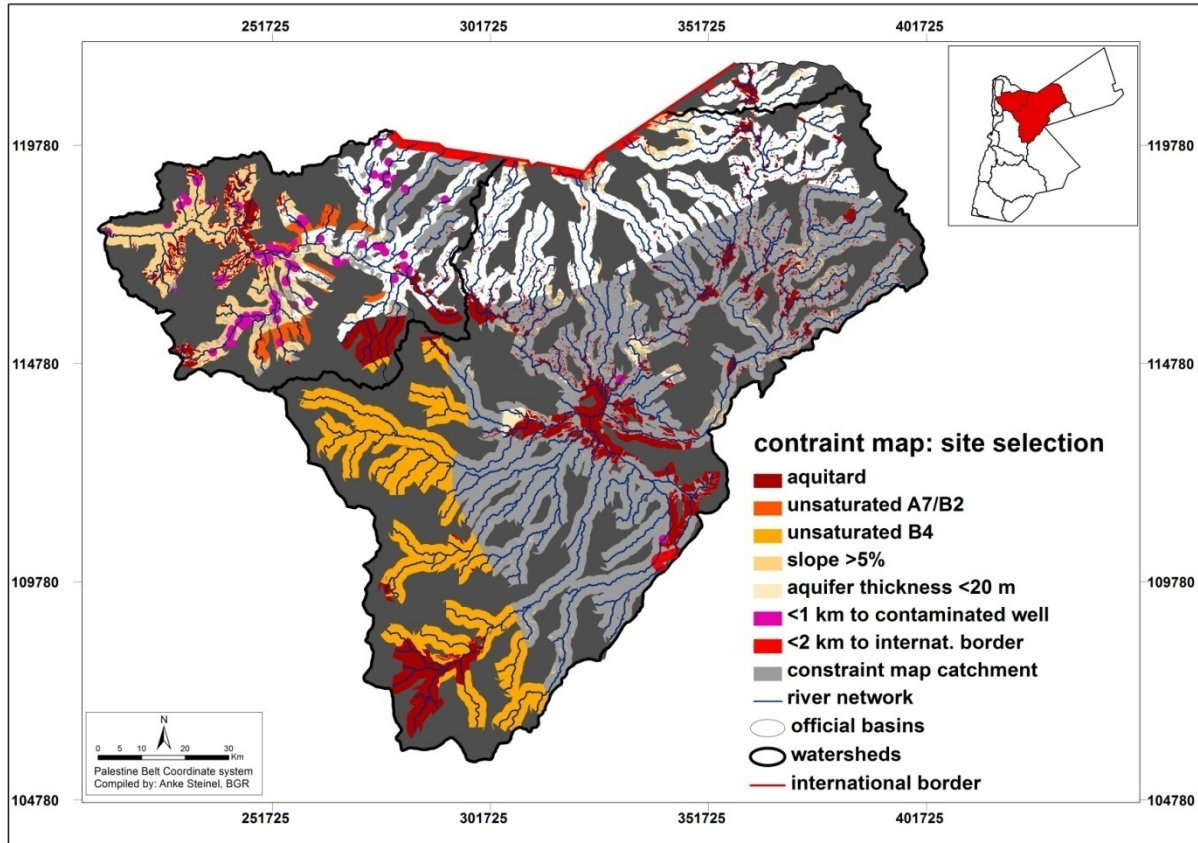
Fig. 93: Constraint map for MAR site selection.

11.3.4   Suitability map for MAR site selection assessment

The thematic maps presented under section 11.2 were now combined into one site suitability map using weighted linear combination The weights and ratings used are compiled in Table 34. The final score was based on the following formula[76]:

site suitability score = (1*score rain + 4*score slope + 5*score WH structures + 4*score soil + 4*score hydrogeology + 3*score land use + 2* score aquifer thickness + 5*score depth to water table + 1*score hydraulic gradient + 3*score gw salinity + 4*score faults + 4*score distance to roads + 4*score distance to wells + 3*score distance to contaminated wells) / 47

The total area[77] outside the constraint area was assessed as 72 % suitable, 28 % less suitable and 0 % unsuitable, as the most unsuitable area has been excluded through the constraint map already (Fig. 94). The most suitable areas (3.1 %) are scattered around the Dhuleil-Hallabat area, where many hazards to water quality are occurring.

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[76] Other weighing factors could easily be implemented

[77] For the Syrian part no information on soils was available and the area was set to 1 for the soil rating. The hydrogeology is also set to 1 (less suitable) in accordance with the basalt area in Jordan, but no information on superficial deposits is available. Hence the suitability rating for the Syrian part should be viewed as preliminary.

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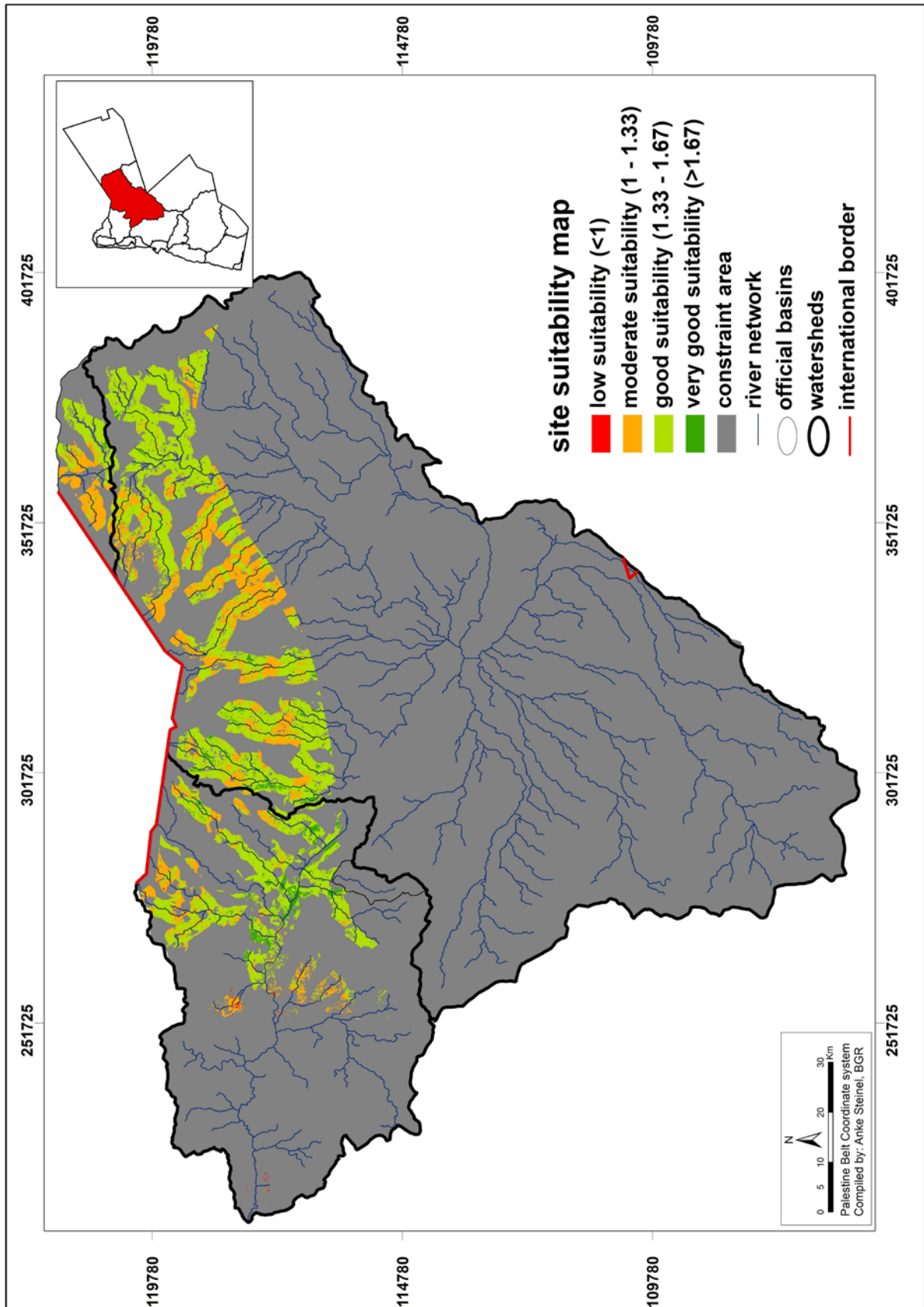
Fig. 94: Suitability map for MAR site selection (max. possible score of 2).

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Table 34: Criteria, weights and rating for MAR site selection constraint and suitability assessment.

	criteria	weight	classification	rating	area (km²)	area (%)
	distance to int. borders		<2 km	constraint		
	distance to wadis		>2 km	constraint		
	catchment size		<18 km²	constraint		
surface criteria	rainfall (mm)	1	<75 mm	constraint	5186	58 %
			75 - 100 mm	1	1070	12 %
			>100 mm	2	2612	29 %
	land use	3	urban, quarries, mudflats	constraint	753	8 %
			field and tree crops, forest	1	474	5 %
			bare rock, chert plains, sand, wadi deposits, pastures	2	7646	86 %
	slope	4	0 - 2 %	2	4667	53 %
			2 - 5 %	1	3036	34 %
			>5 %	constraint	1181	13 %
	soil score** (60 % texture, 20 % thickness, 20 % salinity)	4	score >67 %	2	388	4 %
			score 33 - 67 %	1	5418	61 %
			score <33 %	0	2502	28 %
			no description	1	616	7 %
subsurface criteria	hydrogeology and superficial deposits	4	aquitard (B3, A5/6, A3)	constraint	489	6 %
			mudflats, evaporites, calcrete	constraint	640	7 %
			aquifer/aquitard (B5, B1, K/Z)	1	252	3 %
			alluvium over aquifer/aquitard	1.25	109	1 %
			sand over aquifer/aquitard	1.5	16	0 %
			alluvium over aquifer/aquitard	1.75	2495	28 %
			aquifer (basalt, B4, B2, A7, A4, A1/2)	2	4377	49 %
			sand over aquifer	2.5	487	5 %
	thickness of aquifer	2	0 - 20 m	constraint	124	2 %
			20 - 50 m	1	505	6 %
			>50 m	2	7469	92 %
	depth to water table	5	10 - 100 m	2	2570	40 %
			100 - 200 m	1	2459	38 %
			>200 or <10 m	0	1370	21 %
	flow gradient	1	<0.2 %	2	8648	84 %
			0.2 - 0.5 %	1	931	9 %
			>0.5 %	0	660	6 %
gw quality	gw salinity (TDS)	3	<1000 mg/L	2	5356	66 %
			1000 - 3000 mg/L	1	2108	26 %
			>3000 mg/L	0	593	7 %
	gw contamination (NO₃ >50 mg/L or *E.coli* >10 MPN/100 mL)	3	<1 km from well	constraint	188	2 %
			1 - 2 km from well	1	346	4 %
			>2 km from well	2	8333	94 %
other criteria	existing dams	5	other area	2	1780	58 %
			within 5 km of existing WH structure	1	677	22 %
			catchment JVA dam	constraint	614	20 %
	distance to faults	4	<0.5 km (visible fault)	2	2108	24 %
			<0.5 km (inferred fault)	1	1665	19 %
			other area	0	5095	57 %

*0 = unsuitable, 1 = less suitable, 2 = suitable; ** actual score (range 0 - 1.7) from combining the three soil aspects was used for overlay

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Table 34 (cont.): Criteria, weights and rating for MAR site selection constraint and suitability assessment.

	criteria	weight	classification	rating	area (km²)	area (%)
other criteria	**distance to roads**	4	<1km from main road	0	905	10 %
			<1km from secondary road	1	844	10 %
			<2km from gravel road	2	4308	49 %
			other area	1	2811	32 %
	distance to active governmental wells	4	<0.5 km	0	73	1 %
			0.5 - 2 km	1	1055	12 %
			2 - 5 km	2	1603	18 %
			> 5 km	1	6137	69 %
overall suitability for site selection			constraint	0	13446	87.6 %
			score <50 %	<1	2	0.0 %
			score 50 - 67 %	1 - 1.33	533	3.5 %
			score 67 - 83 %	1.33 - 1.67	1316	8.6 %
			score >83 %	>1.67	60	0.4 %

*0 = unsuitable, 1 = less suitable, 2 = suitable; ** actual score (range 0 - 1.7) from combining the three soil aspects was used for overlay

11.3.5   Assessment of suitable catchment and suitable site

Based on the suitability maps created, for final assessment of finding a suitable site at the outlet of a suitable catchment both suitability maps were graphically overlaid with 30 % transparency for the site suitability map. Each potential wadi needs to be assessed individually.

In the **AMZ basin** suitable catchments would be Wadi Al Hajar, Wadi Saida and Wadi Al Qahwyana southeast of Zarqa (Fig. 95). Here suitable sites are rare, the flow gradient is high and the aquifer might be unsaturated and downstream groundwater salinity could be impaired. In addition, urban areas are close by, which results in downstream wells to be contaminated and the risk for vandalism is probably high. Small recharge schemes might be possible furthest upstream.

Large parts of the catchment of Wadi Al Mamriyya upstream of the As Samra WWTP seems to be suitable, but the catchment also contains a number of built up areas, quarries and chicken farms and downstream wells are contaminated. Site suitability is therefore also limited. Small recharge schemes might be possible in the most upstream part.

Wadi Al Qahwaji contains suitable parts of catchment, but sites are only available downstream of a large chicken farm, quarries and cement factory, which limits the suitability.

Large parts of the Wadi Zatari catchment are rated less suitable. The catchment encompasses also many settlements like Mafraq, Al Thughra, Az Zatari and Umm al Jemal.

The catchments of Wadi Dhuleil, Wadi Al Khurayriba, Wadi ad Dafyana, Wadi Rukban and the wadi (name unknown) east of Wadi Al Lahfi are all rated less suitable to unsuitable, so the availability of suitable sites is of minor relevance.

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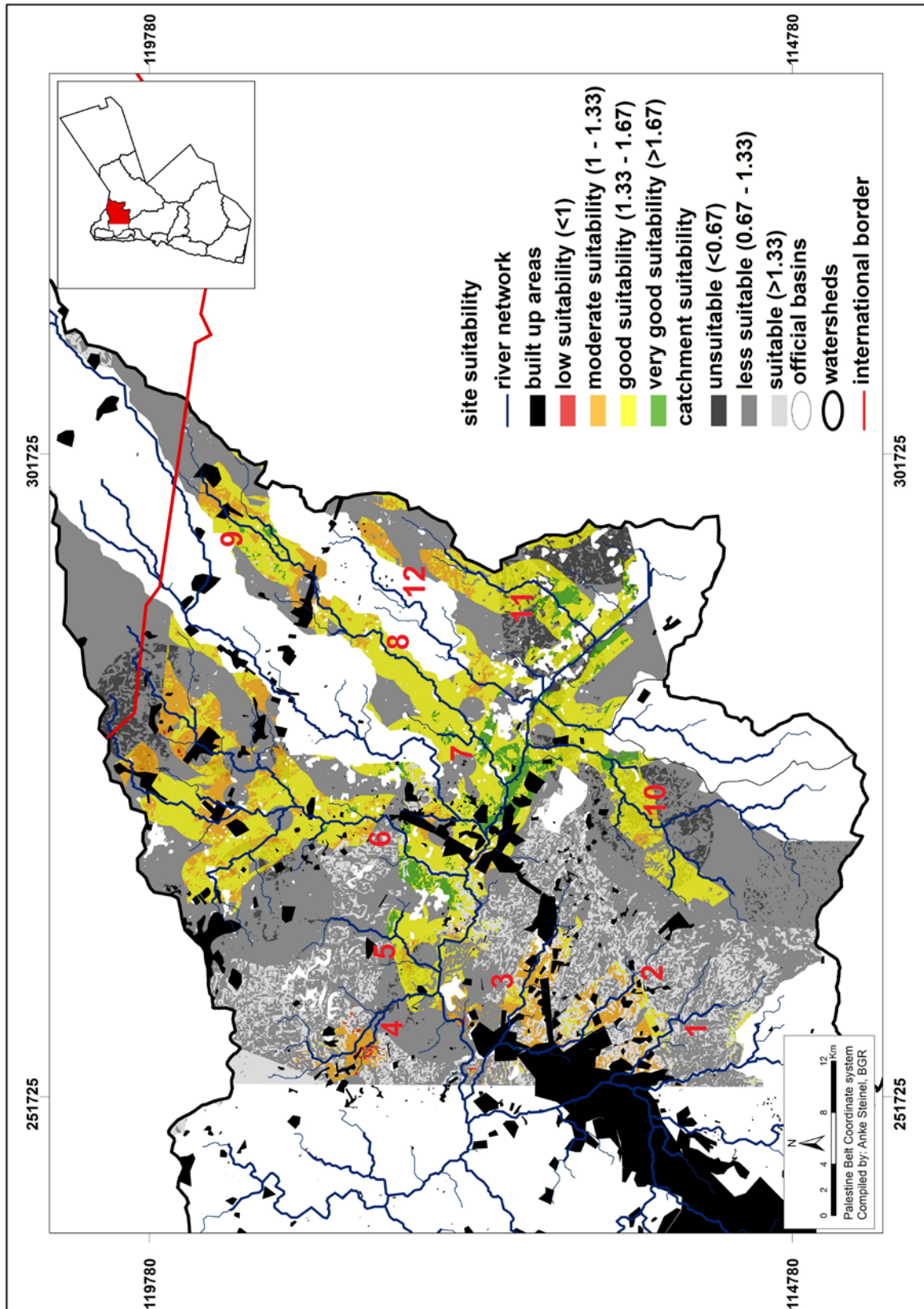
Fig. 95: Overlay of catchment gend site suitability for AMZ basin outside of constraint area. 1: Wadi Al Hajar, 2: Wadi Saida, 3: Wadi Al Qahwyana, 4: Wadi Al Mamriyya, 5: Wadi Al Qahwaji, 6: Wadi Zatari, 7: Wadi Dhuleil, 8: Wadi Al Khurayriba, 9: Wadi ad Dafyana, 10: Wadi Rukban, 11: wadi (name unknown), 12: Wadi Al Lahfi.

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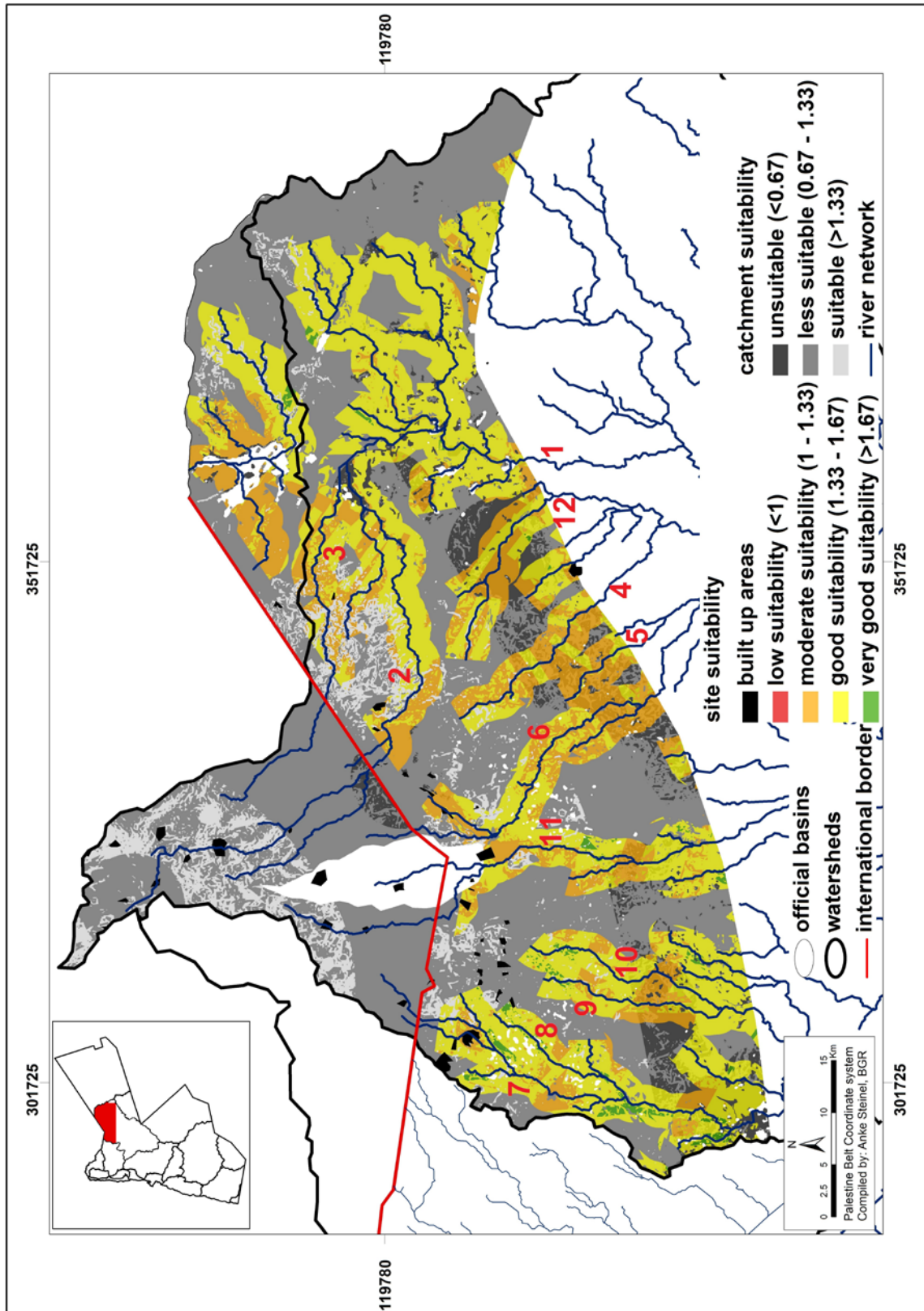
Fig. 96: Overlay of catchment and site suitability for Azraq basin outside of constraint area 1: Wadi Rajil, 2: Wadi Mira, 3: Wadi Al Buraqiyya, 4: Wadi As Safawi, 5: Wadi Ali, 6: Wadi Shua, 7: Wadi Quais, 8: Wadi Al Ghurabi, 9: Wadi As Salayta, 10: Wadi Nimrat Arbaa, 11: Wadi Jallad, 12: Wadi Al Lahfi.

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In the **Azraq basin** only the northernmost areas encompass suitable catchments (Fig. 96). Due to the gentle slope catchment sizes might be smaller than calculated and would need to be assessed with a topographic survey. The main drawback to this region is the depth to water table, which ranges between 200 - 250 m bgl for almost all the sites.

The upper reaches of Wadi Rajil before the first large marab (Wadi Mira, Wadi Al Buraqiyya) could be suitable sites, but there are no recovery wells close by. Similarly, Wadi As Safawi, Wadi Al Lahfi, Wadi Ali and Wadi Shua lack suitable recovery wells. In contrast, wadis draining into the Qaa Khanna (Wadi Quais, Wadi Al Ghurabi, Wadi As Salayta and Wadi Nimrat Arbaa) and Wadi Jallad have potential recovery wells close by. Some smaller settlements (Umm Al Quettein, Al Mkefteh, Nayifa) with around 10 000 people are located here though. These catchments might be the most promising. It would be important to assess potential hazards and potential conflicts with up- and downstream water harvesting structures. Suitable sites with high infiltration capacity and good cross-section for dam construction might be rare.

> **In conclusion, there are no promising catchments and associated sites that fulfil most criteria and can be recommended for further investigation. However, the demonstrated method for MAR potential mapping could be applied to other basins in Jordan.**
>
> **It is highly recommended to incorporate knowledge on MAR potential for individual catchments into future land use planning. Catchments with MAR potential could be set aside (even before a MAR scheme is implemented) and potentially delineated as groundwater protection zones. This could allow for a higher ground- and runoff water quality for a future MAR scheme.**

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12 Further investigations undertaken for site selection

The above undertaken prefeasibility assessment is part of the hydrological and hydrogeological assessment and based on lumped classifications, limited resolution and simplifications. It can therefore not be excluded to find suitable areas inside previously unsuitable rated areas. However, the generated maps can give an indication and can be used for preselecting areas for further investigation that are potentially suitable.

Infiltration capacity is one of the main criteria where the most simplifications have been used, but which is very important to assure project success. It was hence decided to undertake a number of infiltration tests during this study. Unfortunately not all data were available or assessed at this stage, so not all selected sites are within the site constraint map. However, they represent the different hydrogeological settings and fulfil some of the selection criteria. Further in-depth investigations at the most suitable sites were not within the scope of this study.

> **The selected infiltration test sites are not necessarily appropriate for practical implementation of MAR. None of the sites fulfilled all criteria. However, they represent the different hydrogeological settings present in the study area.**
>
> **Soil sample analysis showed loose packed sandy soils with variable gravel content and low salinity at all selected wadis. However, measured infiltration rates and high water content at field capacity suggest that more fine material is present than measured during grain size analysis. Infiltration rates during MAR operation with turbid water are estimated to be around 0.3 - 3 cm/d maximum.**

12.1 Field inspections

The pre-selection of sites was mainly based on land use, slope, rainfall, the exclusion of aquitards and existing dams. Sites should further be at least 2 km from the Syrian border, encompass a catchment of >18 km² and preferably be in the upstream part of a production well with good groundwater quality. Field inspections at about 50 locations in both basins were undertaken to assess the topography for runoff generation and a potential dam construction site, width and depth of wadi channels, depth and texture of wadi soils, existing private water harvesting structures and potential hazards within the catchment. In addition, access to the site for the infiltration tests was taken into consideration. None of the visited sites fulfilled all wanted criteria, so a compromise had to be struck (Fig. 97).

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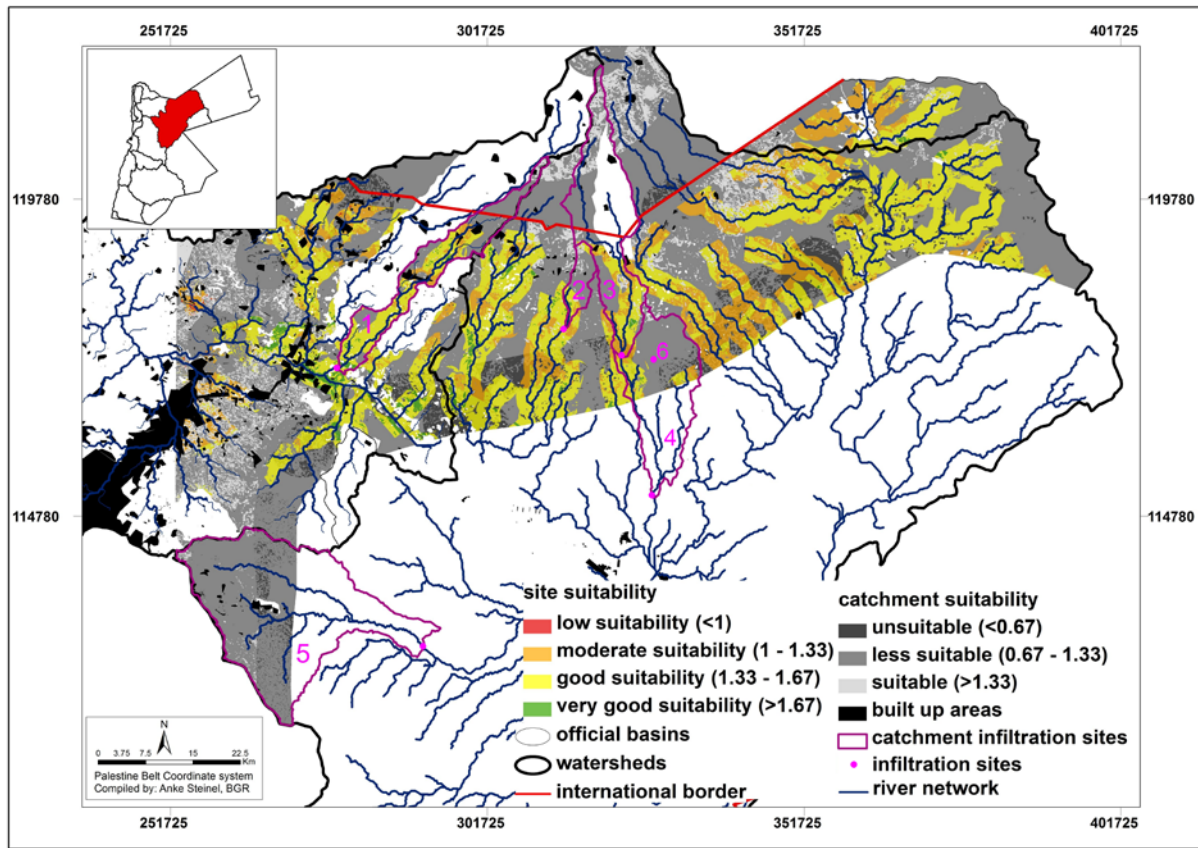
Fig. 97: Catchments of selected infiltration sites (infiltration sites at most downstream point) in comparison to catchment and site suitability. 1: Wadi Dhuleil catchment, 2: Wadi Nimrat Arbaa catchment, 3: Wadi Jallat catchment, 4: Wadi Hassan catchment, 5: Wadi Janab catchment, 6: Wadi Aritain site.

12.1.1 Wadi Dhuleil site

This site (PBN: 1171220, PBE: 277937) is situated in the Wadi Dhuleil about 4 km north of the road between Dhuleil and Hallabat and above about 200 m of A7/B2 aquifer. The watershed is about 167 km² and the estimated depth to the water level is around 100 m. A number of productions wells are situated in this area. The actual site therefore scores a high suitability (83 %). The cross section was modified already by heightening the sidewalls of the wadi.

The drawback is the catchment. It has an overall gentle slope, which will limit runoff generation and contains urban and agricultural areas in the upper catchment. Accordingly, the groundwater quality in the closest wells is high in nitrate (>100 mg/L) and elevated in TDS (1170 mg/L) Also a number of private harvesting structures are within the catchment. It would be highly recommended to measure actual runoff for a number of years before the construction of a dam and to conduct a groundwater quality assessment.

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This is the only selected site in the AMZ basin, as most other visited locations contained too many hazards (chicken farms, manure dumps, settlements, garbage dumps, factories, quarries) in the catchment to be considered.

12.1.2   Wadi Nimrat Arbaa site[78]

This site (PBN: 1177675, PBE: 314028) in the Wadi Nimrat Arbaa is situated above about 350 m of basalt aquifer with a catchment of about 37 km². The site suitability score is still good (68 %). The cross section seems suitable for a small dam construction. The catchment contains only few small settlements and no animal farms, but again the slope is mostly gentle. The main drawback is the depth to water with >200 m and the production well is too close by, so a site further upstream would be preferable.

12.1.3   Wadi Jallat site / Wadi Aritain[79]

The selected site (PBN: 1177627, PBE: 323384) in the Wadi Jallat is situated upstream of the Wadi Hassan site and is quite similar to the Wadi Nimrat Arbaa site (above 350 m of basalt, depth to groundwater >200 m bgl) but has a larger catchment (256 km²), of which 92 km² drain into the existing Deir el Kahf dam. It has the highest rainfall over the catchment of all sites (about 170 mm/a), if the catchment actually drains all the way from Syria to this site.

The actual catchment size would need to be assessed in more detail as internal basins and marabs could potentially interrupt the flow. However, the cross section is not suitable for a dam construction. The production wells are slightly upstream from the site, so a location further upstream would be needed. Unfortunately, no soil samples were taken and no infiltration tests done.

However, soil samples and infiltration tests were actually undertaken at Wadi Aritain (PBN: 1172645, PBE: 327734) draining only a very small catchment (<8 km²) from a volcanic cone. The rock is highly weathered and crumbly. The available runoff would be too small and would be further reduced by losses in the scoriaceous soil, therefore the site is not regarded as suitable.

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[78] labelled Maf-Saf West in original report (see appendix)
[79] labelled Maf-Saf East in original report (see appendix)

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12.1.4   Wadi Hassan site

This site (PBN: 1150907, PBE: 328122) in the Wadi Hassan lies above about 20 m of basalt over 250 m B4/5 aquifer. It is inside the constraint map as rainfall is <75 mm/a at the site, but the complete watershed is about 485 km² , but might be much smaller due to internal sinks and marabs. The main advantage of this site is the low depth to groundwater (about 35 m) and the many wells about 4 - 5 km downstream. The cross section is also suitable for a dam construction.

The site is close to the Wadi Hassan flood station which indicates that on average 0.7 runoff events per year with about 1 MCM per event could be occurring. It is also clear from the data that the runoff variability is very high, with some years with no flow and a few years with very high runoff, which lowers the effectiveness of a potential infiltration scheme.

12.1.5   Wadi Janab site

This site (PBN: 1126920, PBE: 291675) in the Wadi Janab lies above 70 m of B4 aquifer with a catchment of 552 km². Rainfall over the whole watershed is about 120 mm/a, but the site is outside of the site suitability map as the aquifer is likely to be unsaturated in this area. Accordingly, the production wells in the region are tapping the middle aquifer, which is separated from the B4 aquifer by about 100 m of B3 aquitard.

The site was chosen as it represents the B4 aquifer system and MAR with weirs and infiltration ponds have been studied here before by the University of Jordan. More drawbacks are the existing water harvesting structures in the catchment and the settlement and animal farms in the upper part of the catchment. The site is located close to the Wadi Janab flood station which indicates that about 0.48 MCM/a occur in 3.3 events/a. This is hence a reasonably good catchment. It might be investigated to use infiltration wells to transfer harvested water to the A7/B2 aquifer or if it is possible to create a saturated lens under the infiltration site over a number of years. However, the recovery efficiency is likely to be low.

12.1.6   Sites selected by MAR team during training

During a training course for the MAR team three sites were selected by the team based on the same criteria available as for the selection of the infiltration sites (but without field visits) (see above). All three sites are located in Azraq basin on top of the basalt aquifer (Fig. 98).

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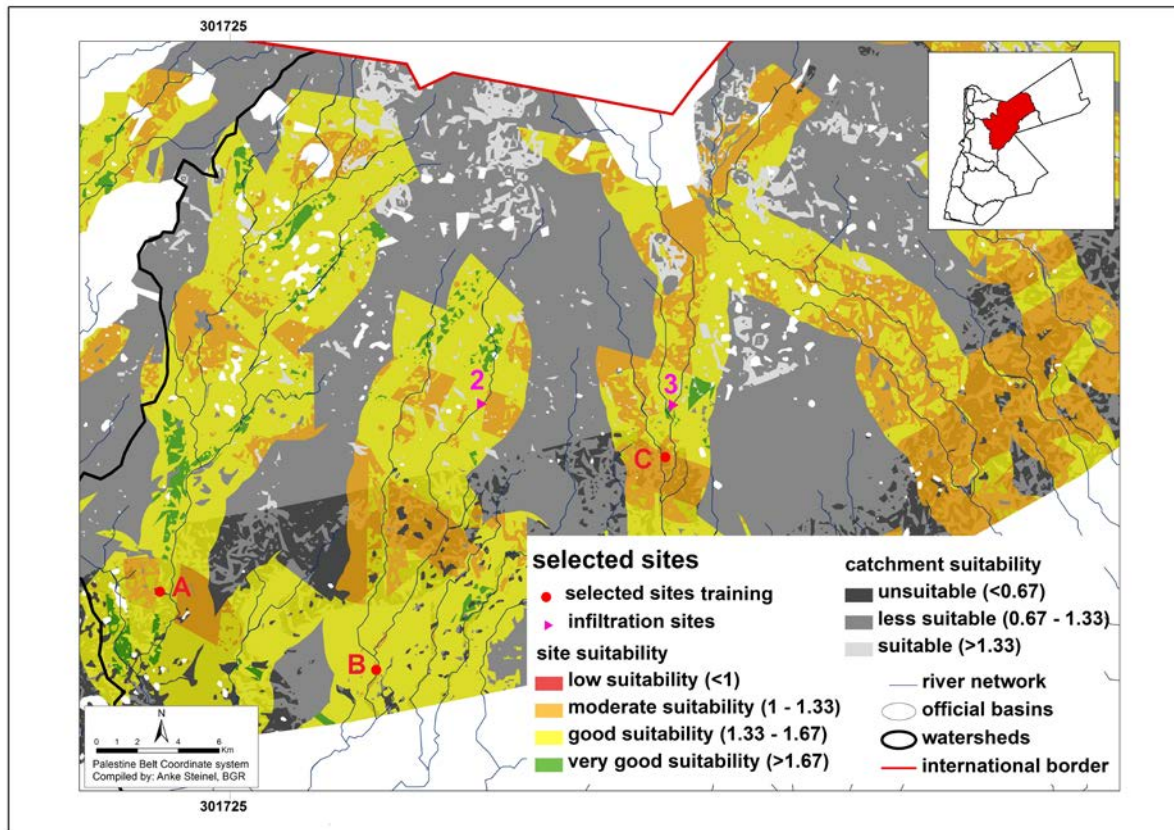
Fig. 98: Sites selected for further investigation by the MAR team. A: Wadi Al Ghurabi, B: Wadi Nimrat Arbaa and As Salayta, C: Wadi Sahawi, 2: Wadi Nimrat Arbaa field site, 3: Wadi Jallat site.

Site A is on Wadi Al Ghurabi (PBN: 1168532, PBE: 298306) draining into Qaa Khanna. The catchment of ~300 km² receives about 150 mm/a of rainfall. At the site, about 110 m of basalt overlie the A7/B2 aquifer. The groundwater level in the basalt is unknown; the groundwater level in the A7/B2 aquifer stands around 175 m bgl. A private abstraction well is situated about 3 km SW, the next governmental abstraction well is ~25 km downstream. About 4 - 5 km downstream are a number of private water harvesting structures built across the wadi. Soil suitability might be impaired by texture or thickness.

Site B is at the confluence of Wadi Nimrat Arbaa and Wadi As Salayta (PBN: 1164715, PBE: 308862) about 13 km downstream of Wadi Nimrat Arbaa infiltration site (site 2) also draining into Qaa Khanna. The catchment of ~160 km² receives about 110 mm/a of rainfall. At the site, about 120 m of basalt lie above ~90 m of B3 aquitard. The groundwater level in the basalt is unknown; the groundwater level in the A7/B2 aquifer stands around 160 m bgl. Similar to site A no abstraction well is close by and one private water harvesting structure is about 8 km upstream on Wadi As Salayta.

Site C is in Wadi Jallad (PBN: 1175085, PBE: 322982) about 2.3 km downstream of the (previously selected but not tested) Wadi Jallad site and closer to the main road and settlement. The catchment covers about 260 km² (of which 92 km² drain into the Deir el Kahf dam) and receives about 170 mm/a of rainfall. Due to marabs the flow might not reach all the way from Syria. The basalt is >300 m thick and lies above ~120 m of B3 aquitard. The groundwater level in the basalt is unknown; the groundwater level in the A7/B2 aquifer

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stands at >250 m bgl. Soils might not be suitable in thickness and texture, but two production wells are located downstream (1 - 2 km).

12.2 Field investigations

The field investigations were carried out by Prof. E. Salameh and Dr. M. Alraggad from the University of Jordan. Chemical analyses were performed after DIN or ASTM standards undertaken in a certified Jordanian laboratory (NCARE - National Center for Agricultural Research and Extension). For details refer to the final reports attached in the appendix.

12.2.1 Soil analysis

Six shallow (up to 30 cm) disturbed and wherever possible also undisturbed (diameter about 10 cm, height about 15 cm) soil samples were taken at the each infiltration site.

All soil samples have low **EC** values ranging from 110 - 490 µS/cm with the exception of the Wadi Hassan sample with 840 µS/cm. **pH** values are slightly alkaline (7.6 - 8.1), even though **inorganic carbon** concentrations were only 0.44 % on average (Table 35). The latter value seems to be too low given the fact that the soils are derived from basalt and influenced by carbonate dust. Other basalt soils show values of around 15 - 35 % for $CaCO_3$ (HTS and SSLRC, 1993). **Total organic carbon** content was less than 0.5 % for all samples, which is common for arid regions with limited plant cover. Overall, the chemical composition of the soil is favourable for MAR infiltration and would not pose a risk of salinisation or adverse reactions with the infiltrated water.

Dry bulk density and porosity were analysed for the undisturbed samples used thereafter for the soil retention curve analysis. Porosity is high (around 53 %) and dry bulk density is accordingly low (around 1.24 g/cm³) (Table 35). The soils are hence only loosely packed. Grains are mainly unrounded allowing for high porosity.

Grain size analyses were undertaken by sieving and hydrometer. The latter showed a very long settling time indicating that some very fine particles were present. The percentage of grain sizes <0.002 mm could not be measured and was assumed to be negligible (<0.2 %) or zero[80]. The results show a large variation in grain size distribution (GSD) for the five sites and even within one site (Fig. 99) (Table 35). The coarsest soil samples were found in Wadi Janab and Wadi Aritain, while Wadi Dhuleil had the finest soils. The median grain sizes (D_{50}) vary from fine to coarse sand giving all soils the FAO texture classification of weakly to very strongly gravelly sand (except for the finest soil sample from Wadi Dhuleil being a medium gravelly loamy sand). The effective grain size (D_{10}) varies between fine silt to medium sand. Permeability values estimated after the Hazen method (suitable for sandy soils) are ranging from $7.4*10^{-5}$ to $2.2*10^{-4}$ m/s (6.4 - 19 m/d) for most samples and 10^{-7} to 10^{-6} m/s (0.009 - 0.09 m/d) for the three finest samples from Wadi Dhuleil.

The results are in contrast to published grain size distributions (HTS and SSLRC, 1993), where soils developed on basalt are commonly have silty clay loam textures with 20 - 40 % of clay and 30 - 60 % of silt. In addition, the results of infiltration tests (see below) do not match the infiltration rates expected from grain size distributions and are generally much lower, especially for Wadi Janab. Only Wadi Dhuleil showed higher infiltration rates than

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[80] Prof. E. Salameh, 2012, personal communication

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![BGR Bundesanstalt für Geowissenschaften und Rohstoffe]

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expected from the high silt content. Grain size distributions should hence not be used without infiltration tests for site assessment and are generally prone to overestimate infiltration rates. Special care needs to be taken that no loss of the smallest size fractions occurs during sampling and analysis.

Table 35: Summary of soil analyses results (for details see report in appendix).

	unit	Median	Std.dev	Min	Max
elect. conductivity	µS/cm	262	145	110	845
pH		7.9	0.1	7.4	8.1
inorganic carbon	%	0.43	0.32	0.00	1.52
total organic carbon	%	0.04	0.14	0.02	0.47
porosity (undisturbed)		0.53	0.03	0.47	0.57
dry bulk density (undisturbed)	g/cm³	1.24	0.09	1.13	1.41
clay (<2 µm)	%	0.2	0.9	0.0	3.1
silt (2 - 63 µm)	%	1.3	5.4	0.0	26.9
fine sand (63 - 200 µm)	%	13.1	13.9	0.6	52.9
medium sand (0.2 - 0.63 mm)	%	18.7	17.8	2.3	68.6
coarse sand (0.63 - 2 mm)	%	14.0	8.6	2.1	34.2
fine + medium gravel (2 - 20 mm)	%	34.5	22.5	5.6	84.2
coarse gravel (>20 mm)	%	13.7	13.6	3.9	40.8
pF2.5 (field capacity)	water content (%)	25.1	7.4	16.2	42.5
pF 4.2 (wilting point)	water content (%)	14.4	4.4	8.4	26.1
effective field capacity	water content (%)	11.0	3.7	6.1	18.7
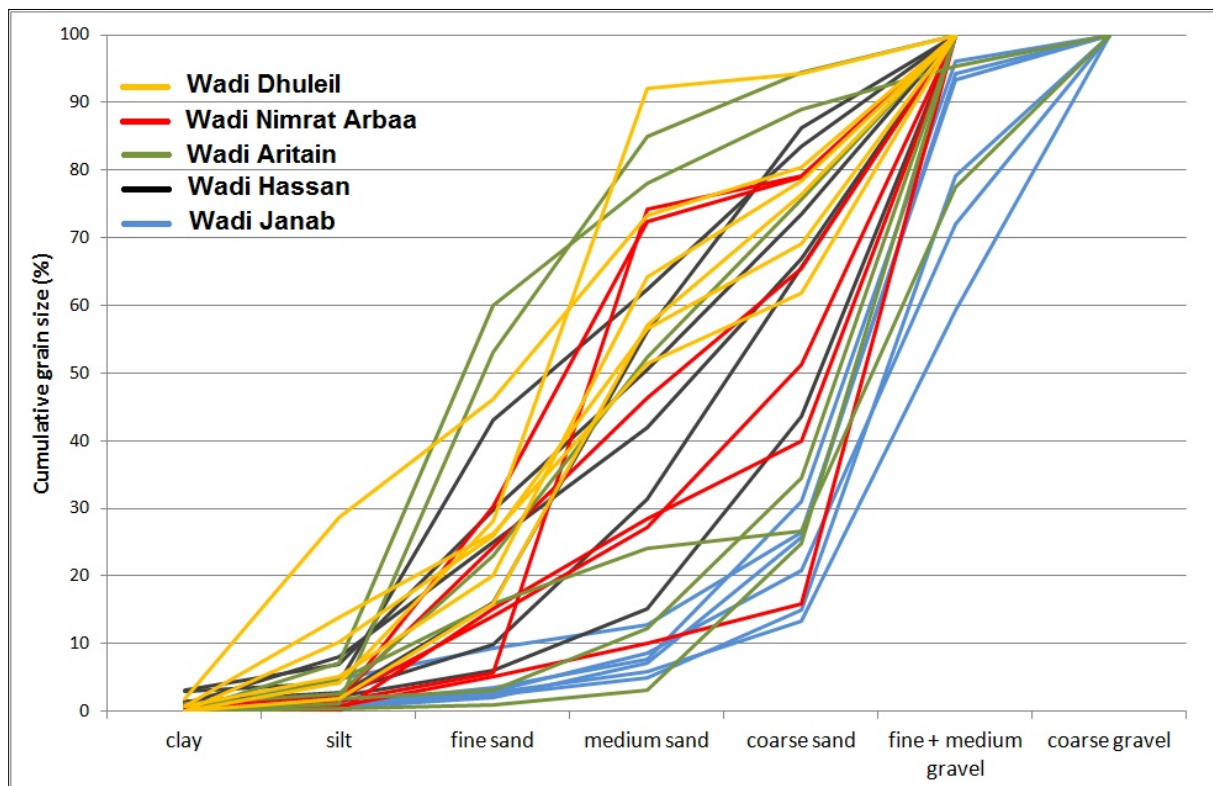
Fig. 99: Cumulative grain size distribution of all soil samples.

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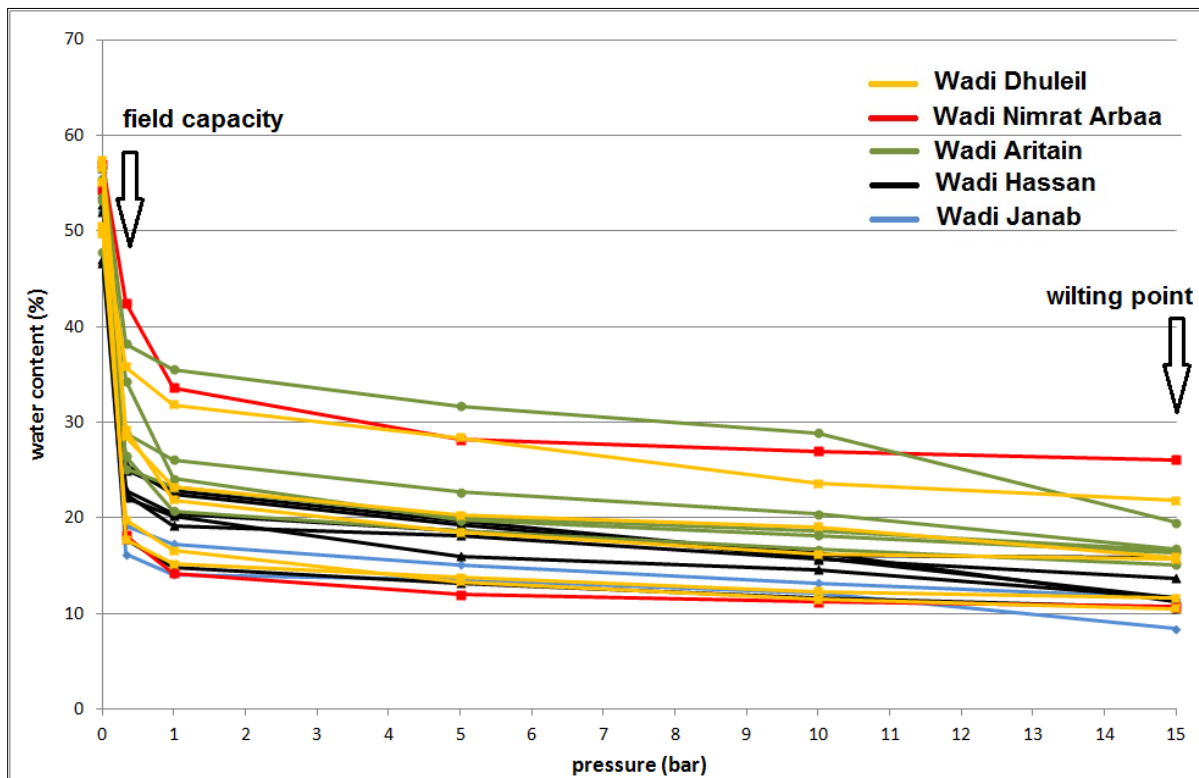
Fig. 100: Summary of results from soil retention testing (pF curve).

The **soil retention curves** were performed only under dewatering conditions and showed a water content between 16.2 - 42.5 (median 25.1) % at field capacity (pF 2.5, 0.33 bar) and 8.4 - 26 (mean 14.4) % at wilting point (pF 4.2, 15 bar) (Table 35). Reasonably high variation is observed between and within sites (Fig. 100). The results reflect the conditions of the finer soils, as the very coarse soils could not be sampled undisturbed. Common estimations of loose packed sandy soils are around 15.5 % for field capacity and 6.5% at wilting point (Finnern et al., 1994) and increase with an increase in fine material. Hence, the results from the soil retention measurements support the suspicion, that fine materials are underrepresented in the grain size analyses.

Saturation above field capacity is needed before percolation would begin (average 25 %). The difference between field capacity and wilting point, i.e. the effective field capacity (average 11 %), is the percentage available for plants and evapotranspiration. Accordingly, for a theoretical 1 m³ of dry soil at wilting point with 50 % porosity and 11 % effective field capacity a minimum of 55 mm of rain would be needed before percolation would start not accounting for evaporation. This rough calculation emphasises the fact that direct groundwater recharge may only happen very seldom and infiltration occurs mainly through preferential flow paths and after runoff accumulation. More accurate information about deep percolation and groundwater recharge could be obtained using the soil and climate data in different models (Wagenet et al., 1991). For example, the simple pedo-transfer function model CROPWAT (Clarke et al. 1998) requires annual sums of precipitation and potential evapotranspiration and one soil parameter. The mechanistic model SWAP (Kroes and van Dam, 2003) needs daily climate data and soil parameters for every soil horizon. The functional model MABIA (Allen et al. 1998), which is also based on daily climate data, needs only two soil parameters (water capacity of the root zone and subsoil hydraulic conductivity)

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and seems to be a good compromise between complexity and usability and has been used successfully for Syria (Schlote et al., 2012b).

12.2.2   Infiltration tests

A number of basins and ring infiltration tests have been undertaken at the sites to investigate the infiltration capacity into the soil. Basin infiltration tests with 6 m² area and when possible double ring infiltrometer tests with 30 cm inner and 60 cm outer diameter were performed with clean water. Within about two hours infiltration rates reached a more or less constant values (Fig. 101). Declining water level was applied for the basin and constant water level for the ring infiltrometer tests. At Wadi Nimrat Arbaa and Wadi Janab gravel content was too high to perform ring infiltrometer tests and two basin tests were performed instead.

Results vary from no infiltration after two hours at Wadi Janab to 0.58 m/d at Wadi Nimrat Arbaa (Table 36). Ring infiltrometer tests show a consistently higher infiltration rate of around 0.55 m/d, which is due to the higher relative lateral losses in relation to the smaller infiltration area (see section 4.3 and section 13.2.2). The high heterogeneity of the wadi soils is reflected by the high variation in infiltration rates for the triplicate ring tests and the double basin test at Wadi Nimrat Arbaa.

Due to the high stone and gravel content at some sites, the heterogeneity is high and sealing along the edges of the test basins was problematic. Lateral spreading of infiltrated water was visible at many tests. This would have increased observed infiltration rates compared to realistic rates during MAR operation. In addition, while clean water was used during the tests, suspended solids in the recharge water would decrease infiltration rates by one or two magnitudes. Consequently, infiltration rates during MAR operation are estimated to be around 0.3 - 3 cm/d for Wadi Dhuleil, Wadi Nimrat Arbaa and Wadi Aritain, around 0.1 - 1 cm/d for Wadi Hassan and negligible for Wadi Janab. As evaporation is on average around 1 cm/d, the investigated Wadi Hassan and Wadi Janab site do not seem feasible under these conditions. For the other three sites between 25 - 75 % of the water might evaporate during recharge. MAR recharge is hence only feasible if infiltration rates are kept high with regular maintenance.

Table 36: Final infiltration rate (m/d) of basin and ring infiltration tests.

(m/d)	basin 1	basin 2	ring 1	ring 2	ring 3	ring (mean)
Wadi Dhuleil	0.29		0.72	0.79	0.07	**0.53**
Wadi Nimrat Arbaa	0.58	0.14				
Wadi Aritain	0.29		0.07	1.44	0.14	**0.55**
Wadi Hassan	0.14		0.72	0.86	0.29	**0.62**
Wadi Janab	0.00	0.00				

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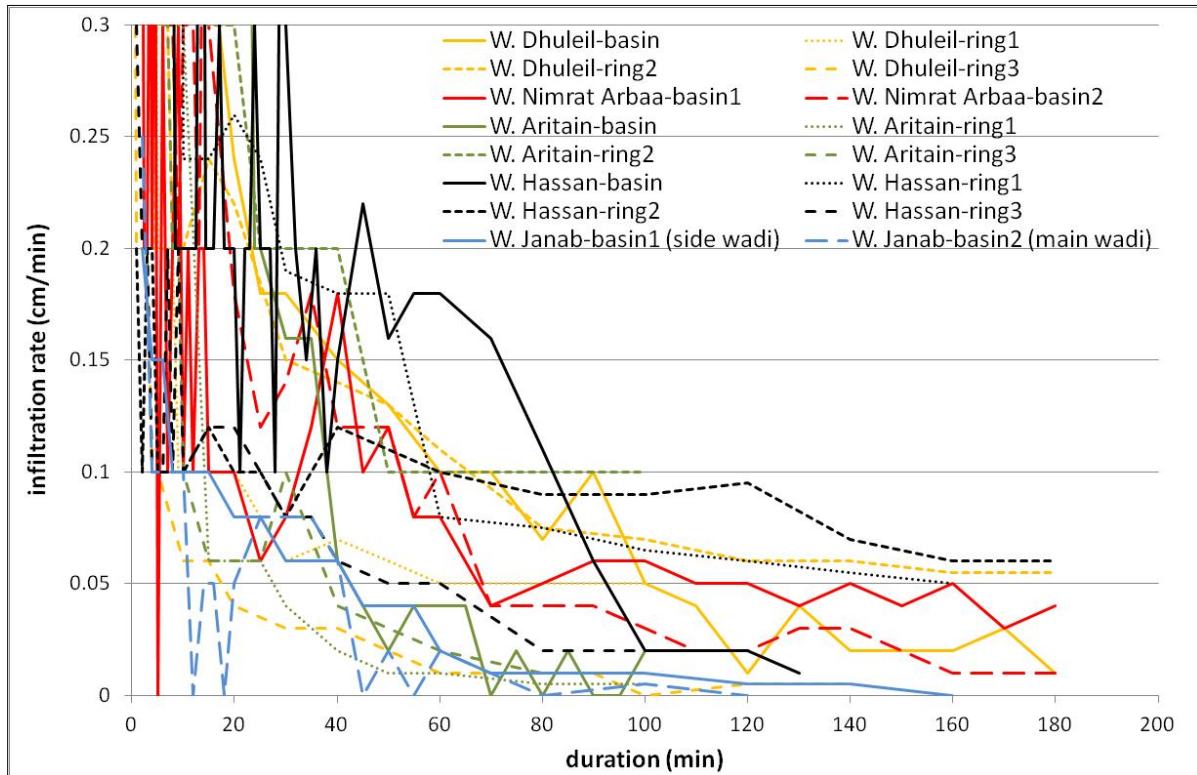
Fig. 101: Development of infiltration rate (cm/min) during the test duration (min).

13 Feasibility study before implementation

> **In addition to missing maintenance, a major hindrance to a beneficial MAR project often is insufficient planning, pre-assessment and monitoring.**
>
> **The feasibility study for pre-selected sites encompasses the assessment of the source water (quantity and quality), the local aquifer characteristics, the groundwater water characteristics through field investigations.**
>
> **In addition, an impact and risk assessment as well as a cost-benefit analysis should be undertaken to allow the comparison with other potential alternatives. MAR will not work everywhere as schemes may neither be socially acceptable nor economically feasible.**

As described in chapter 4 there are a number of investigations to be undertaken, before a successful MAR project can be implemented. A good example of tasks to be undertaken is already documented in MWI (1996).

13.1   Catchment modelling

> **The availability of non-committed surplus water is paramount to a successful MAR implementation. A meteorological and hydrological study can be assisted by rainfall-runoff modelling to arrive at a refined site water balance. The most urgent data gap to be filled is runoff quantity and quality.**

If recharged water is to be harvested from surface runoff, available data on rainfall quantity, intensity and distribution, climate and runoff need to be assessed in a detailed hydrological study. WEAP models for all surface water basins in Jordan have been developed, but due to lack of data are also not able to calculate wadi runoff for smaller subcatchments (Huber, 2012). WEAP cannot account for evaporation from soil and is not event based, but rather works with monthly or yearly averages.

For the estimation of potential runoff of selected catchments it is recommended to use more sophisticated rainfall-runoff models than the CN number method, which is currently applied by the MWI using a single CN for each basin. For example, the J2000 model (Krause, 2001; Schulz, 2011; Krause, 2012) and the TRAIN-ZIN model (Alkhoury, 2011) have been successfully applied in Jordan.

Rainfall-runoff models commonly require data about rainfall, topography, soil characteristics, land use and runoff data for calibration. The use of remote sensing data in hydrology can aid with input data and model parameter estimations (Kite and Pietroniro, 1996; Schultz, 1996).

There is a great uncertainty related to rainfall gauge data as storms are often very local and this spatial variability is not properly covered with the existing monitoring network. Especially in (semi-)arid regions variability in rainfall intensity can lead to high runoff estimation errors (Wilson et al., 1979; Troutman, 1983; Blöschl and Sivapalan, 1995; Faurès et al., 1995; Dong et al., 2005; Vischel and Lebel, 2007). It is possible to estimate rainfall from cloud cover measurements and these TRMM (Tropical rainfall measuring mission) satellite data

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(resolution 0.25 degrees) are freely available (http://trmm.gsfc.nasa.gov) (Kummerow et al., 2000). BGR has developed a tool (written in Visual Basic) to extract point and areal TRMM data into csv files including monthly sums (Blümel, 2012). Comparison of TRMM rainfall data to measured data for the Aleppo Basin, Syria, showed a high correlation (Schlote et al., 2012a). Other studies in the Middle East have also successfully integrated satellite precipitation data (Morin and Gabella, 2007; Abushandi and Merkel, 2011; Khalaf and Donoghue, 2012).

The resolution of the current DEM is not sufficient (90 * 90 m) to detect small internal sinks and predict the flow through marabs. It would be advisable to obtain high resolution Cartosat-1 (5 * 5 m) or Quickbird satellite images for selected catchments to investigate the flow generation in more detail and could replace a detailed topographic survey of the catchment. It would also allow assessing current land use in more detail.

Evapotranspiration and interception could also be modelled from satellite images using leaf area index (LAI) or normalised difference vegetation index (NDVI) (Schultz, 1996).

The main problem is the lack of data to feed these models. One main restriction in Jordan for finding suitable catchments is the limited amount of runoff stations and hence the high uncertainty for estimating actual runoff or calibration of models. It is therefore highly recommended (and has been recommended for more than 20 years (e.g. Hydrosult, 1988)) to install more flood gauges in pre-selected wadis and measure runoff over a number of years to allow a cost-effective MAR scheme design. The Madoneh investigation and the analysis of existing data (see section 10.2.1) showed that runoff estimations with the CN method are overestimating the actual runoff (de Laat and Nonner, 2011). A number of suitable flood gauging locations with a defined cross section, where wadis are channelled underneath roads, have been noticed during the field trips.

Soil data input is also problematic as soil heterogeneity is high depending on grain size distribution, morphological position, slope, rainfall, upslope soil sequence etc. (Ziadat et al., 2010). Even though remote sensing data can also aid in soil characterisation, they require detailed investigations for calibration (Pedretti et al., 2012a). Infiltration, especially transmission losses in wadi channels, will hence always be the most uncertain parameter (Hughes, 2008). To get a better large scale idea about infiltration properties, a number of MAR feasibility studies have investigated the drainage density (Anbazhagan et al., 2005; Das, 2007; Jasrotia et al., 2007; Chenini and Ben Mammou, 2010; Chowdhury et al., 2010). The lower the drainage density the higher is the infiltration under similar rainfall conditions and could be assessed with high-resolution satellite images or GoogleEarth.

13.2   Site investigations in the field

Field investigations consist of the evaluation of surface and subsurface characteristics of the soil and aquifer as well as groundwater flow direction and quality of ground- and surface water.

13.2.1   Topographic survey, hydrogeological mapping and soil sampling

Once a suitable catchment has been selected, finding the right site for dam construction and infiltration requires a topographic survey for cross-sectional and longitudinal profiles of the

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wadi. The dam site should allow for the required storage capacity with limited construction costs (Hydrosult, 1988; Chehata et al., 1997; Abu-Taleb, 2003, Kalantari et al., 2010). Hence, an incised narrower cross-section of the wadi is most suitable. The survey also needs to assess the ponding area and related water surface. Small water surface areas are preferable to limit evaporation. The flooded area should also not encompass any existing infrastructure or housing (CGWB, 2000).

The topographic survey also needs to define the hydrologic boundaries of the catchment especially if sinks and depressions are present and keep record of potential hazards in the catchment.

The field survey should also include a detailed (hydro-)geological mapping of the area to see if the regional data hold true at the specific site. It is also necessary to see if the foundation conditions are suitable for dam construction (Hydrosult, 1988; Chehata et al., 1997).

A number of soil samples need to be taken mainly for grain size analysis and analysis of geotechnical properties (e.g. Atterberg limits) to investigate the suitability of the material for dam construction and allow estimation of hydraulic conductivity (Abu-Taleb, 2003).

13.2.2   Infiltration tests

Infiltration capacity shows a high spatial variability and estimations from soil characteristics often do not depict actual conditions (Chapuis, 2012; Racz et al., 2012). Testing the infiltration capacity over the anticipated wetted area is highly recommended. Basin infiltration tests are more suitable to overcome spatial variability and lateral spreading effects and are hence superior to ring infiltrometer tests (Youngs, 1991; Lai and Ren, 2006). The most realistic testing for in-channel infiltration capacity would be a controlled release of larger quantities of water monitoring the wetted area, ponding depth and time for infiltration (DWA, 1994). Even though infiltration tests will not allow the assessment of percolation to the groundwater, they are a useful tool as surface conditions have a significant effect on infiltration processes.

13.2.3   Shallow drilling and geophysical survey

As infiltration tests only allow the assessment of the uppermost soil, investigations into the subsoil are needed. Shallow drillings allow the detection of impermeable layers. In addition to subsoil sampling, double packer pump-in pressure permeability tests allow the investigation of subsoil permeability (Hydrosult, 1988). A number of shallow drillings, auger tests and test pits should be undertaken to assess the spatial heterogeneity of soil material at the site (Hydrosult, 1988; Chehata et al., 1997). While permeable conditions are favourable for infiltration, dam construction would be better above impermeable layers (Orient ECD, 2010).

Shallow geophysical investigations (e.g. high resolution seismic reflection and refraction and electromagnetic surveys) are recommended for any MAR scheme to assess the resistivity of the underground allowing the detection of clay layers, vertical discontinuities (fault zones) (Chehata et al., 1997; CGWB, 2000; Orient ECD, 2010). This data helps to narrow down the target zone.

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13.2.4   Deep drilling

To investigate if the recharged water would be able to reach the groundwater through the commonly thick unsaturated zone, deep drillings down to the water table are needed. Less permeable layers that might lead to perched water tables can be detected with borehole geophysical logs like natural gamma log, neutron log and electromagnetic (EM) log (Segesmann, 1980; Serra, 1984; Timur and Toksöz, 1985).

These wells could later be used for monitoring groundwater level and quality. The installation of tensiometer and heat dissipation probes would allow the detection of saturated conditions above impermeable layers and the measurement of the vertical infiltration velocity of the recharge front through the unsaturated zone (Reece, 1996; Hubbell and Sisson, 1998; Izbicki et al., 2008).

13.2.5   Groundwater investigations

The observation of groundwater levels over the region will allow the assessment of groundwater flow direction and hence the selection of a suitable recovery well site (Hydrosult, 1988). Flow velocity from the recharge site to the recovery well could be tested with natural or artificial tracers (e.g. Käss, 1998; Kalbus et al., 2006; Luhmann et al., 2012).

Conducting pump tests along the downstream path would give local information on hydraulic conductivity of the aquifer and together with the depth to water level allows for a more concrete estimation of storage potential.

If the water is supposed to be recovered for domestic water supply, it is necessary to select a location, where groundwater quality meets the drinking water standards as closely as possible. Groundwater sampling allows the detection of groundwater contamination and areas to be avoided for recharge.

13.2.6   Surface water quality investigations

Another knowledge gap is the quality of flash floods. For the assessment of sediment loads and a number of flash floods should be analysed for TSS before the implementation of MAR schemes. Sediment loads can vary considerably between flash flood events and during one event (Crerar et al., 1988; Mousavi and Rezai, 1999) necessitating a high frequency of sampling during one event and over the season (e.g. Neal et al., 2012; Skarbøvik et al., 2012). Sediment concentration >10 - 20 mg/L TSS are not considered suitable for recharge (DWA, 1996; CGWB, 2000). Results from flash flood sampling and sediment traps will allow for the correct design of the MAR scheme and establishment of a suitable operation and maintenance (O&M) plan, and hence for a better estimation of operational and construction costs.

In addition, flash floods can bring contaminations in the form of salts, nutrients, bacteria/virus, heavy metals and organic pollutants with them depending on the land use (Pitt et al., 1999). Catchments containing any potential hazards like settlements, agricultural farms and fields, factories, petrol stations etc. should be sampled and analysed. If concentrations do not meet the required standards for the desired use, the need for pre-treatment might arise. The cleaning effect of the unsaturated zone and sufficient retention times might also help in preventing groundwater contamination (Dillon and Toze, 2005; Schmidt et al., 2011). More sophisticated MAR schemes only allow water to be recharged if it meets the set

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requirements (Dillon and Molloy, 2006). It should also be taken into consideration that source water quality can change during the storage in the dam due to algae growth or contamination from livestock being watered out of the dam.

13.3 Impact assessment

> **A complete feasibility study for implementation of MAR schemes should also encompass the environmental and socio-economic consequences that might occur.**

In general downstream areas will be affected more than upstream areas, unless the ponding area is very large. The harvesting of surface runoff leads to reduced surface water flows downstream. Wadis, marabs and qaa are basically the only areas sustaining some vegetation for most parts of the Azraq basin, as soil moisture is increased in these areas. The reduction of stream flow could therefore lead to the decline of habitats as well as decline of pasture for Bedouin livestock. Similarly, the retention of fine sediments in the dam will decrease loads of fertile sediments to the downstream area, reducing soil fertility and plant habitat. On the other hand a new small fertile land with high soil moisture would be generated in the dam reservoir.

Local inhabitants would probably appreciate the new water source, while downstream farmers, who practice water harvesting themselves, will not favour the new dams. Conflicts due to changes in water usage might arise. After the experiences from Madoneh dam, it is also questionable if release dams are going to be accepted by the population, as they commonly prefer to store water on the surface.

During the construction time disruption for local inhabitants will arise due to noise, dust etc. It might also be necessary to change land ownership at the dam site. The land availability in terms of ownership is rather complicated especially in Azraq basin where tribal rules are governing land distribution (Mesnil and Habjoka, 2012).

If recharged water contains bacteriological contamination, the groundwater quality could deteriorate and groundwater user downstream might incur health problems. On the other hand, groundwater quality might increase with respect to salinity due to dilution with fresher surface water.

Modelling the groundwater system downstream of the recharge site could also be used to assess the potential environmental and health impacts (e.g. groundwater level change, groundwater quality changes). For example, if groundwater with higher salinity is present in the aquifer, the recharged water might push this saline water towards existing wells, lowering the acceptance (Rahman, 2011). As the source water is also infiltrating naturally to the aquifer and volumes are comparatively small, it is not expected to have any major problems with interactions of source water and native groundwater that would deteriorate the current groundwater quality.

On the positive side groundwater levels will rise (even though only locally) reducing energy consumption from pumping lift. It is not expected to be able to recharge sufficient amounts to restore the groundwater discharge at the Azraq springs, which would be a huge environmental benefit.

In order to assess acceptance of MAR schemes, site visits need to determine affected stakeholders and conduct interviews and workshops with them. This needs to be

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accomplished before implementation. If there is no acceptance in the local community, the recharge scheme will not be successful.

13.4   Costs and benefits

> **Apart from technical considerations one main question to be addressed is the question if the project is going to be effective. There is only limited information for an economic benefit assessment and costs are often limited to construction costs only. Costs related to (pre-)feasibility studies, O&M and monitoring need to be included though. MAR schemes will only be cost-effective, if regular maintenance is taking place as this increases the life time of the scheme significantly.**

> **If recharged water is used for irrigation, recharge dams are economically unfavourable.**

> **To prove the effectiveness of MAR schemes new projects should monitor and quantify accrued costs and benefits before, during and after implementation. The current data do not allow for a detailed analysis. The main missing information is the volume of water reaching the groundwater.**

This study will only highlight some aspects but will not be able to undertake a full scale cost-benefit analysis (see other sources ADB, 1998; Interwies et al., 2004; TECHNEAU, 2008; US EPA, 2010). Comparison with other countries is difficult as labour and material costs vary widely. A site specific cost-benefit analysis will have to be made for each recharge project (Dillon et al., 2009).

13.4.1   Costs

> **The costs comprise capital costs, operational costs as well as social and environmental costs before, during and after the implementation of a MAR scheme.**

The most obvious costs are the **construction** costs and these are often considered solely in a cost-effectiveness analysis. From available Jordanian data (Fig. 102) it is obvious that there is a nearly linear increase in costs with the increase in storage capacity of the dam, but that there is an initial construction costs of about 30 000 JD for the first 1 m³. Accordingly, dam construction costs per m³ decrease from about 13 JD/m³ for 2000 m³ to <1 JD/m³ for 250 000 m³ storage capacity (Fig. 102). It is hence more economical to build larger dams than many small dams. For check dams in Yemen about 1.26 US$/m³ storage volume was calculated (van Steenbergen et al., 2011). The economics of scale show that costs decrease with increase in size for about the first 0.1 MCM (Dillon et al., 2009), but the construction of oversized dams is not cheaper, when they are not filled. It is therefore not economically feasible to construct enough storage space to collect the infrequent large runoff events (maybe every ten years) that lead to a flooded Azraq Qaa.

If recharge release dams are not suitable, additionally infiltration basins might need to be built. Here costs range about 1 JD/m³ capacity, which would double the costs for construction. Costs for construction would also increase with increasing distance to the next

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urban centre and if local materials are not suitable for dam construction, but have to be transported there. For previous dam constructions local materials have been suggested to be used, but could also result in dam failure[81].

More costs could be involved when stilling basins, pre-dams, sand filter or other pre-treatment options were to be constructed to decrease the silt accumulation in the main dam.

As has been described above there are a number of investments required **before the construction** of a dam can begin. The existing data have to be evaluated, site investigations have to be undertaken, environmental impact assessment as well as cost-benefit analysis has to be done (Tuinhof et al., 2011), which are commonly undertaken by local consultants rather than by MWI employees. Pre-feasibility monitoring costs could also involve the drilling of new wells and the installation of water level recorder and rain gauges. Similarly to the construction cost, there is an initial cost, regardless of the size of the dam. These costs (Table 37) easily add to >150 000 JD. In addition, land for construction might have to be acquired or potentially affected downstream users might have to be compensated. It has not been investigated what costs this might involve, as this would be very site-specific, but land acquisition has been the single largest cost in other projects (Nightingale et al., 1983; OCWP, 2010).
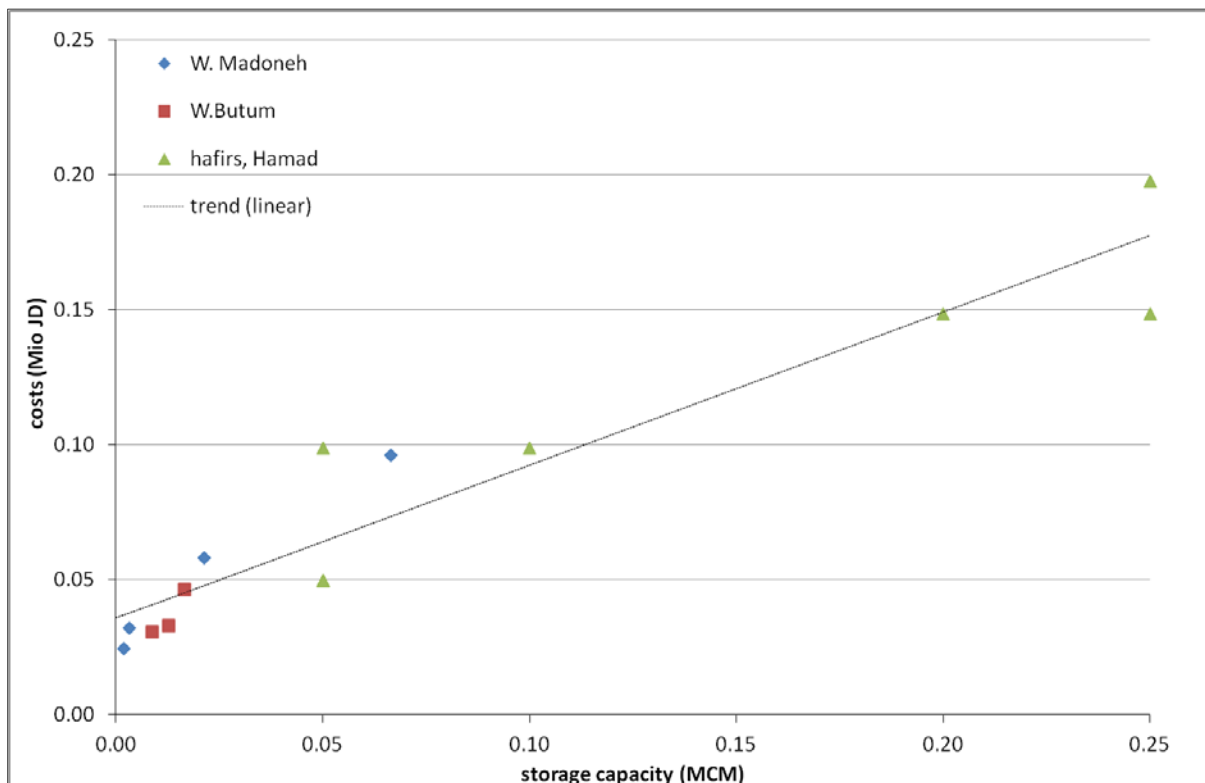
Fig. 102: Compilation of actual construction costs for Wadi Madoneh and estimated costs for Wadi Butum and hafirs planned in Hamad area. Trendline: costs (JD) = 0.57*capacity (m³) + 36 000 JD (arranged after de Laat and Nonner (2011), Orient ECD (2010) and WAJ data, 2011).

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[81]Inspection at the Madoneh M1 dam showed hole in dam wall and larger missing part next to spillway and was attributed to incorrect construction material (P. de Laat (UNESCO-IHE), 2011, personal communication).

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Table 37: Compilation of estimated costs for a feasibility study[82].

Item	estimated cost (JD) per unit
consultant analyzing existing data (per week)	1 500
topographic survey for dam site selection (per ha)	700
hydrogeological mapping (per ha)	2 000
soil sampling	40
soil analysis for Atterberg limits	30
soil analysis for grain size distribution	30
infiltration test with ring infiltrometer	300
infiltration test with basin	400
shallow drilling (10 m)	350
shallow geophysical investigations (per profile)	300
bore log geophysics (per well)	1 – 10 000
monitoring well (200 m deep well)	15 - 60 000
pumptest	5 - 20 000
groundwater level logger (water level, EC, temp.)	2 000
multiparameter probe (EC, temp., turbidity, pH, NO3)	8 000
maintenance and control of monitoring equipment (per year)	~3 000
flood or rain gauge installation	2 500
reporting (per year)	1 000
international consultant (per month)	~15 000

After implementation, O&M costs as well as **monitoring costs** are accrued. As a rule of thumb together these are about 10 % of the construction costs (Tuinhof et al., 2011). They can vary between 2 % (Chehata et al., 1997); 5 % plus community labour (Kalantari et al., 2010), 8 % (Nightingale et al., 1983) to between 2 - 18 % depending on the scheme (Fleskens et al., 2007). For recharge of treated wastewater O&M costs were even estimated at 80 % of construction costs (not including WWTP construction) (Rahman, 2011). These costs should cover, for example, the removal of sediments, the replacement of wear and tear parts, the repair of damages to the dam[83] or infiltration basins, the replacement of stolen parts[84], the personnel to inspect the site regularly, the sampling and analysis of groundwater and surface water, the monitoring of groundwater levels and flood gauges and the personnel to asses collected monitoring data. An example for monitoring and operational costs for recharge through infiltration wells at Wala is supplied in Table 38 and sum up to >150 000 JD/a. Current undertaken routine maintenance at desert dams costs around 2000 JD/a. JVA estimates the costs for sediment removal to be about 1 JD/m³ sediment. With the assumption of 1 % of sediment load this would results in about 500 JD sediment removal costs for a 50 000 m³ flood. Without these measures the recharge scheme will be effective only for about 2 - 3 years, after which the damage and sediment accumulation will basically hold infiltration.

For the **recovery**, energy costs (pumping) are about 0.06 and 0.15 JD/m³ in Azraq and Mafraq, respectively, and are related to the depth of the water table (Mesnil and Habjoka, 2012).

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[82] most values supplied by A. Tmaizeh (GeoTech Consultants, Jordan), 2012, personal communication
[83] The repair of the Madoneh M1 dam was assessed to be around 12 500 Euro (J. Nonner (UNESCO-IHE), 2011, personal communication)
[84] experienced to be a problem for any metal parts (de Laat and Nonner, 2011)

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Table 38: Example of some operational and monitoring costs for recharge via infiltration wells at Wala dam. Not all experts are needed for 12 months a year. (Source: JVA[85]).

Wala Dam monitoring and investigation	JD
resident engineer (per month)	2 300
mechanical engineer (per month)	2 600
expert during recharge injection (per month)	2 000
engineer during recharge injection (per month)	14 250
accountant (per month)	1 200
geologist (per month)	1 400
surveyor (per month)	920
controller (per month)	960
surface water analysis (full analysis: major ions, nutrients, heavy metal, pathogens, organic contaminants) (monthly sample)	450
groundwater sample analysis (physical, nutrients, major ions)	1 940

A rough example calculation (Table 39) clearly shows that larger dams are more cost effective than smaller dams and that **O&M measures increase efficiency significantly, especially for the small scale dams**. MAR schemes will hence only be cost-effective, if regular maintenance is taking place (Lindsey et al., 1992). Obviously, these values are only calculated against storage capacity, which is not equal to recharged volume. A dam might be able to collect more than one flood event in a year, thereby increasing cost-effectiveness, or there may be no runoff lowering the cost-effectiveness. Also, only about 50 % of the harvested water will actually reach the groundwater and be of benefit due to losses through evaporation and the saturation of the unsaturated zone (Kalantari et al., 2010).

It should not be forgotten, that there could be contingency cost, e.g. if polluted water was recharged, dam failure occurred resulting in damage downstream or legal challenges arise. Contingency costs of 10 – 15 % of the project costs are typical (ASCE; 2001).

Table 39: Rough cost-effectiveness example calculation for a small and medium scale recharge dam with and without maintenance costs based on storage capacity (not equal to recharged water).

	unit	small sized dam	medium sized dam	large sized dam
storage capacity	m³	10 000	100 000	1 000 000
costs feasibility study	JD	100 000	150 000	250 000
costs construction	JD	45 000	125 000	900 000
lifetime without O&M	years	3	3	3
costs without O&M	**JD/year/m³**	**4.83**	**0.92**	**0.38**
costs O&M	JD	4 500	12 500	90 000
lifetime with O&M	years	20	20	20
costs with O&M	**JD/year/m³**	**1.18**	**0.26**	**0.15**

There are also **indirect costs**, that should be included for example the costs of potential groundwater contamination with unsuitable source water (Rahman. 2011), the environmental impact for downstream users (Gale et al., 2006; Perrin et al., 2012), impacts on biodiversity (Seely et al., 2003). If the source water is actually used downstream for dilution of low quality water (i.e. the Zarqa river needs dilution of the discharged wastewater), then the harvesting of this water will create costs further downstream. The dam also prevents natural recharge in the downstream wadi and this volume needs to be abstracted from intentionally recharged water (DWA, 1994). In wadis with high transmission losses, MAR schemes are therefore not

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[85] personal communication N. Seder (JVA) in 2011

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viable. Environmental costs are also the carbon emissions generated during the scheme (e.g. for construction), subtracted from the carbon emissions that are saved because of an increase in groundwater level. The costs of biodiversity loss due to reduced wadi runoff could be estimated using the ecological services approach (TEEB, 2010).

> *"Hence the costs of reduced downstream consumptive allocations and environmental flows, accentuated in times of historically low inflows, may outweigh the benefits of reduced evaporation losses and additional storage attributable to MAR." (Dillon et al., 2009)*

A number of studies have tried to do an economic analysis. Unfortunately none have included indirect costs or assessed the actual volumes reaching the groundwater (Table 40). It is also often not clear if recovery costs and community work are included. Chehata et al. (1997) estimated, if 100 MAR sites with a total runoff harvesting of 30 MCM/a were to be constructed, the recharged water would cost about 0.48 JD/m³[86] including annual running costs, but excluding groundwater abstraction and transport costs. MAR schemes seem to be cheaper in other countries, but this might be due to lower labour and material costs as well as the utilisation of community work.

Table 40: Compilation of costs per m³ water recharged reported in the literature without the inclusion of pre-investigation costs or the monitoring of volumes recharged.

reference	location	maintenance costs included	volume recharged (MCM/a)	life time	costs
Kalantari et al., 2010	Iran	yes (5 % of construction costs)	2.2	20	~0.05 US$/m³ + community work
van Steenbergen et al., 2011	Yemen	yes (10 % of construction)	not given	20	0.1 US$/m³
de Laat and Nonner, 2011	Jordan, Madoneh	no	0.2	10	0.15 US$/m³
Rahman, 2011	North Gaza	yes (0.25 US$/m³)	13*	>30	0.26 US$/m³
Chehata et al., 1997	all of Jordan	yes (2 % of construction costs)	30	10	0.48 JD/m³[87]
MWI, 2001	Jordan Valley	yes	0.365*		1 JD/m³[88]

* = treated wastewater not surface runoff

13.4.2   Benefits

Benefits of MAR schemes can vary depending on the specified objectives of the scheme and the actual set up. As the objectives of the current MAR study are not well defined, it is difficult to evaluate the benefits. The monetary assessment of benefits is not straight forward and requires surveys among the stakeholders to assess their willingness-to-pay for the water and their perceived increase in living conditions due to intangible benefits (TECHNEAU, 2008). First of all this would require a diagnose of the likely beneficiaries and loss-makers.

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[86] After applying the inflation rate (around 3.5 % between 1990 - 2004 and 8 % until 2012 (SeBa World, 2012)) to the stated amount of 0.2 JD/m³ to get a minimum value for today.

[87] value 0.2 JD/m³ in 1997 estimated to current prices as outlined in above footnote

[88] value 0.5 JD/m³ in 2001 estimated to current prices as outlined in above footnote

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To account for the benefit of **recharged water** the rate of infiltration in relation to evaporation and losses in the vadose zone needs to be established. It depends not only on the runoff and design, but also on the decline in infiltration rate due to clogging (Sukhija et al., 1997; Neumann et al., 2004). If decline rates in reservoir water level have decreased to a few mm/d this is equivalent to evaporation and means that the recharge structure is completely inefficient. 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. Estimations on water infiltrated to water harvested range from 20 % (Gale et al., 2006) to 30 - 35 % (Sukhija et al., 1997) to 50 % (Zeelie, 2002; Kalantari et al., 2010) and up to 75 % (Haimerl, 2004). High values might be due to errors in the water balance though (Sukhija et al., 1997). In addition, the amount of infiltrated water is not equivalent to recharged water, as a significant amount will be lost in the vadose zone and hence will not be recoverable (Kalantari et al., 2010). It was estimated that it would take around one year of infiltration only to saturate the unsaturated zone (65 m thickness) underneath the recharge facility and in the second year recharge to the groundwater could occur (Al-Kharabsheh, 1995). Measurements have shown that it might take about 3 years for the wetted front to reach the groundwater level at 120 m depth for the first time (Izbicki et al., 2008). This means that benefits will most certainly show a lag time, which will depend on the infiltrated volume, depth to groundwater and degree of saturation. 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.

The benefits of recharged waters have to be assessed over the whole catchment, if the source water was actually used downstream either for environmental flows, dilution of low-quality water, natural recharge or irrigation water, the MAR project would only be a relocation of water availability, but not be an additional benefit (Gale et al., 2006). Accordingly, all prevented downstream benefits have to be subtracted from the MAR benefits. As the natural recharge rates are only vaguely known there is a high degree of uncertainty, how much water is actually added to the groundwater, but transmission losses of around 50 % are possible (Huber, 2010). Direct monitoring could be done with FTDR probes (flexible time domain reflectometry) (Dahan et al., 2008)

> **Overall, there is very limited documentation on actual recharge efficiency from arid regions leading to high uncertainty in benefit analysis.**

The main benefit would be the recharged water that is available for **abstraction** and would be paid for (in the best case). In Jordan, the water prices vary depending on the use, the location, the quantity abstracted, the salinity and the licensing conditions. For agricultural well prices are between 0 - 0.07 JD/m³, potash industry pays between 0.25 - 1.8 JD/m³ (Mesnil and Habjoka, 2012) and other industry pays about 0.53 JD/m³ (Qudah, 2011). Chehata et al. (1997) assumed the economical return to be <1 JD/m³ for agricultural use, 1.5 JD/m³ for domestic use and 5 JD/m³ for industrial/touristic use (all values for 1997) for Wadi Madoneh and Wadi Butum (Table 41). They further considered that the recharged water would primarily benefit nearby private wells (industry, farm). If private well owners are mainly profiting from the recharge benefits, it should be considered that they also participate in the costs. For example they could be made responsible for the maintenance and operation costs.

Many recharge schemes have been evaluated with the main benefits of an increased **agricultural** production (Kalantari et al., 2010; van Steenbergen et al., 2011). For Jordan, agricultural returns are stated at around 0.3 JD for each m³ water used, while tourism and industry could generate a benefit of about 25 and 40 JD/m³, respectively (Mesnil and Habjoka, 2012). For the Karak dam feasibility study, it was estimated that it was economically viable, if the revenues of agriculture are >250 JD/du/a (Qudah, 2011). For Azraq basin, small scale farms generate about 9 JD/du/a and even professional farms generate only about 130 JD/du/a (Mesnil and Habjoka, 2012). Comparing the agricultural returns and abstraction revenues to the recharge costs, it is obvious that **recharge for agricultural purpose is not economically viable**. In general, irrigation of olive trees in Azraq basin has a negative cost-benefit balance even with the highly subsidized water supply and no recharge costs and should not be supported with additional water supply through MAR schemes close to private irrigation wells. Instead farming of water demanding crops might need to be curtailed (Salameh, 2008). It would most likely be cheaper to compensate small farmers for their income loss when not performing agriculture than to subsidize the groundwater and pay for the impacts of the groundwater level decline.

Through the anticipated **increase in groundwater level** a decrease in pumping costs is also envisaged. The height of the groundwater mound underneath the MAR facility depends on the amount of recharged water and the porosity of the aquifer, while the shape is determined by the permeability. While the increase in groundwater level might be up to a few meters below the recharge facility, the recharge mound dissipates quickly <1m at 100 m distance, to a couple of cm after 350 m and is virtually indistinguishable 6 months after the end of recharge (Kaledhonkar et al., 2003; Gale et al., 2006). The increase is negligible at >2 km, where recovery wells could be located to guarantee a certain residence time. Close to the recharge facility an increase in 1 m of groundwater level would only compensate the groundwater level drawdown for 1 - 2 years (see section 10.3.2). The impact on the regional groundwater level is even smaller. Spreading an assumed recharge volume of 50 000 m³ over an assumed 50 km² catchment area, results in an overall water addition of 1 mm or about 4 mm increase in groundwater level assuming 25 % porosity. This matches with estimations that of 100 mm/a rainfall about 1 mm of recharge could be generated (Sharda et al., 2006). For all of Jordan a water harvesting capacity around 30 - 50 MCM/a has been estimated (Salameh and Bannayan, 1993 (cited in Mohsen, 2007)), over the area of nearly 90 000 km² this would also be around 5 mm. Hence, the benefits due to decreased groundwater lifting costs seem to be low. Decreasing pumping rates would be much more beneficial in improving groundwater level recovery.

> *"Recharge may contribute to the volume of water stored in a large aquifer but, because the mound associated with a given structure dissipates quickly, would not have any noticeable impact on water levels [...]." (Gale et al., 2006)*

There is also the potential for **double accounting** potential benefits in agricultural revenue AND groundwater level increase. Generally, the provision of more water to agriculture encourages more abstraction and might even result in a further decline of groundwater levels, as it is the main contributor to groundwater level declines in the first place.

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> *"Indeed the dilemma [...] is that recharge interventions may encourage investment in unsustainable farming systems [...]." (Gale et al., 2006)*

One potential benefit is the **dilution** of more saline groundwater with fresh surface water and hence raising the potential beneficial use, and potentially increase revenues from water prices, e.g. the improvement from >1500 to slightly below 1500 ppm TDS increases the water price by 0.005 JD/m³ (Mesnil and Habjoka, 2012). Increasing groundwater levels might also help with limiting upward leakage from more saline underlying aquifers.

Another benefit, which is one of the main objectives of the MAR schemes in the Jordanian highlands, is the decrease in **transport costs** of water. Most available water resources in Jordan are located in lower topographic regions than the main demand site (Amman) and high pumping costs are involved when transporting water from the large storage dams, from the Disi aquifer or from a desalination plant at the coast to the capital. If local demand can be covered with local supply, this would reduce operational costs compared to other supply.

Another benefit that has been completely ignored in any cost-benefit analysis for Jordan so far is the use of the collected **sediments** for construction or soil fertilisation, which is common practice in other countries (Sendil et al., 1990; van Steenbergen et al., 2011). Even if sediments were made available for free, it would save on maintenance costs and improve recharge efficiency. It could also be beneficial in terms of job creation. Palygorskite present in the clogging layer is a sought-after resource used in drilling suspensions under saline conditions, which might be possible to mine.

> **From an economical point of view MAR in (semi-)arid regions of Jordan seems not worthwhile, but political and/or strategic considerations might also play a role.**

13.4.3   Sensitivity analysis and risk assessment

A comprehensive cost-benefit analysis should vary the estimated costs and estimated benefits to depict worst-case and best-case scenarios. An assessment of uncertainty and viability of different alternatives should be included (e.g. Al-Sheriadeh et al., 1999; TECHNEAU, 2008; Pedretti et al., 2012b).

For example costs could increase if the first site investigations show that the pre-selected site is unsuitable and site investigations have to be repeated at a different site. Cost for recovery can increase if the fuel prices increase (which are also highly subsidized in Jordan), but could decrease if farmers get access to the electric network (Mesnil and Habjoka, 2012). Cost could increase if the source water is not fit for recharge and pre-treatment has to be implemented or worse, rehabilitation for a contaminated aquifer has to be undertaken.

As described above, a great limitation to the benefit estimation is the high degree of uncertainty of actual infiltration rate. Current data are not sufficient to underpin the actual volumes recharged. For future estimations of benefits, the high variability of rainfall and runoff has also to be considered. The reliance on highly undependable surface water flows is associated with high risks. Years with low flow would hence reduce possible benefits even further. **The Al Wehdah and Wadi Rajil dams exemplify that the construction of a dam does not generate runoff and high storage capacities do not warrant the harvesting of these volumes.**

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Considering that volumes harvested have been largely overestimated (about 50 %) (de Laat and Nonner, 2011) and do not represent the recoverable volumes (about 50 %), the cost-benefit analysis would be much lower than estimated and could even turn negative, especially if industrial usage was lower. An example calculation with more realistic recharge volumes (about 75 - 80 % lower), accounting for proper maintenance and monitoring costs and usage reflecting current use of abstracted groundwater in each basin shows that Wadi Butum would not be profitable (Table 41).

Table 41: Cost-benefit analysis for the feasibility study of Wadi Madoneh and Wadi Butum in 1997 values (arranged after Chehata et al., 1997 and own estimations).

	unit	Chehata et al., 1997		other scenario	
		Wadi Madoneh	Wadi Butum	Wadi Madoneh	Wadi Butum
volumes harvested	m³/a	380 000	235 000	100 000	50 000
construction cost	JD	375 000	550 000	375 000	550 000
lifetime	years	20	20	20	20
reconstruction cost after 10 years	JD	190 000	275 000	included in O&M	
annual cost O&M	JD	5 000	10 000	37 500	55 000
total recharge costs	JD/m³	0.088	0.218	0.563	1.650
recovery cost (pumping)	JD/m³	0.3	0.2	0.3	0.2
total annual costs*	**JD/m³**	**0.388**	**0.418**	**0.863**	**1.850**
agricultural use[1]	%	40	50	50	60
domestic use[2]	%	20	20	40	39
industrial/touristic use[3]	%	40	30	10	1
total annual benefit **	**JD/m³**	**2.66**	**2.25**	**1.550**	**1.175**
overall value	**JD/m³**	**2.273**	**1.832**	**0.688**	**-0.675**

* no inflation or discount rate used **values calculated from the assumed use percentages and their estimated economic return value, 1: economic return <1 JD/m³; 2: economic return 1.5 JD/m³; 3: economic return 5 JD/m³

13.4.4   Comparison to other alternatives

> *"In terms of sustainability, findings do not suggest that recharge interventions alone will halt or reverse longer-term problems of groundwater overdraft [...]." (Gale et al., 2006)*

Comparing the potentially recharge for small scale surface runoff recharge schemes to the **water demand**, the overall significance for Jordan is low. MAR schemes could only be significant in the water balance for small communities with low pumping rates (Neumann et al., 2004).

Previous water sector analysis (JICA, 2001; Mohsen, 2007; Salameh, 2008; AFD, 2011) showed that most benefit could be gained from investing in network improvement, water saving devices, water pollution control and reallocation of water resources away from ineffective agriculture, than in supply increase through large-scale project with high capital costs. Small-scale runoff harvesting has not been included in most of the analysis though. The current MWI water strategy foresees a decrease in supply through artificial recharge (which is defined as leakage from pipes and irrigation return flow) from 55 MCM in 2007 to 25 MCM in 2022 due to an increase in network efficiency (MWI, 2009). Managed aquifer recharge with treated wastewater is envisaged, while recharge from surface water is summarized under the term 'rainwater harvesting' or 'developed surface water', and is

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supposed to increase from 295 MCM in 2007 to 365 MCM in 2022 (MWI, 2009). Rainwater harvesting is to be encouraged for irrigational use and is expected to also allow for leakage to the groundwater.

Chehata et al. (1997) found in their comparison that MAR schemes had a favourable cost-effectiveness (Table 41) compared to large scale projects like large dams (Al Wehda, Mujib), the Disi conveyor or Red Sea-Dead Sea project. Nevertheless, most of these options are completed (Al Wehda and Mujib dam), under construction (Disi conveyor) or under close investigation (Red Sea-Dead Sea project), implying that either the cost-effectiveness was incorrect or other factors need to be considered. It seems, that foreign donors and the government are favouring large-scale supply project as they can be advertised and marketed much better than demand reduction measures (Bonn, 2011). Change in perception is needed from political decision makers, financial supporters and the general public.

One alternative to the construction of new recharge dams is the conversion of existing recharge dams to recharge release dams with proper monitoring and yearly maintenance. This has been estimated to cost about the same amount as the construction of a new dam (Chehata et al., 1997). Overall, it would be cheaper as it does not involve any pre-construction costs,increases infiltration rates and reduces additional environmental impacts, and has therefore been highly recommended previously (Chehata et al., 1997). Existing water harvesting structures like ponds could also brought back to use by silt removal (Allison et al., 1998). The lack of implementation might to be due to political considerations.

Another option is the harvesting of rainwater in urban areas of Amman-Zarqa, where rainfall quantities are higher, demand is highest and surfaces are sealed, i.e. runoff generation is at its maximum. The current stormwater drainage system in Amman is rudimentary and stormwater from street runoff is of highly variable quality (e.g. Cole et al., 1984; Makepeace et al., 1995; Pitt et al., 1999; Wong, 2006), so MAR would not be feasible without proper pre-treatment. In contrast, roof runoff is generally of high quality and would complement the supply of potable water with supply for non-potable uses like toilet flushing or garden watering without costly transport (Abdulla and Al-Shareef, 2006; Evans et al., 2007). It should be investigated, if roof runoff harvesting could be made mandatory for new constructions where roof design could be adjusted accordingly.

13.5   Regulatory issues and financing

Apart from the technical and economical feasibility, MAR schemes are often hindered by the administrative feasibility. After a site has been selected, it has to be examined what regulatory hurdles have to be taken, if there are any water rights of existing users to be considered or if the ownership of the dam site and catchment prohibits construction. The legislation might require prove that public health would not be impaired and would not impact on the beneficial use of the groundwater. A management and monitoring plan should be prepared and potential contingency plans need to be in place. Models can help in finding the best management plan (Pedretti et al., 2012b).

Finally, the funding for construction and more importantly for operation and maintenance has to be secured. While construction costs are often covered by foreign donors, further O&M costs are commonly not included, jeopardizing the success of the schemes.

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13.6   Public awareness and community participation

> **A successful MAR project will involve the local stakeholders in planning, site selection, design as well as operation and maintenance to achieve a broad consensus, a sense of ownership and increases the chances for sustainability**

Community awareness and participation is a vital step to assure the success of a MAR scheme. It has been experienced in many technical cooperation projects that it is not enough to do a proper investigation and a good design, if the local community is not informed, involved and in favour of the project (Gale et al., 2006). Similarly, if projects are managed by foreign organisations and consultants for the ministry, the feeling of ownership and responsibility will hinder a proper maintenance and operation, once the project has been handed over[89] (World Bank, 1998).

Therefore, the participatory approach is a core principle of a sustainable integrated water resources management concept (World Bank, 1996; Warren, 1998; Cap-Net, 2005). After the identification of stakeholders it is highly recommended to start a dialogue between them as early as possible in the planning process (ODA; 1995; Rietbergen-McCracken and Narayan, 1998). To be able to decide, whether MAR is an option for their area, first of all stakeholder (e.g. tribal leaders, farmers, residents, nomad Bedouins, regional water authority personnel, NGO representatives) need to understand the concept of MAR as well as costs and benefits. Unless a broad consensus has been achieved about the MAR proposal, it is unlikely to be viable.

If stakeholders agree on the objectives and priorities and have assessed the impacts, the best design and O&M measures have to be chosen. Technical decisions have to be supported by sufficient technical expertise (Khwaja, 2004). Rules need to be transparent and accepted by the stakeholders and a process for reviewing and adjusting rules has to be defined. It is extremely important to clarify obligations, responsibilities and rights for each step of the process (Gale, 2005). Stakeholders with the highest benefit should be identified and involved in the financing or contribute their share through labour. This strengthens the feeling of ownership and increases the sustainability.

Failure of community based projects could happen in Jordan as there is a legacy of government driven programmes such that people expect the government to take responsibility and the incentives for involvement are small or unclear. However, in the AMZ basin a participatory approach for sustainable groundwater management has been tried previously (Chebaane et al., 2004) and the Highland Water Forum has started a process of participatory management of water resource in the Azraq basin (Mesnil and Habjoka, 2012). Both have not dealt with MAR, but this could be the right forum to address MAR issues in the future.

> **The Highland Water Forum could be a platform to discuss MAR with local stakeholders.**

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[89] The Madoneh dams are a classical example, where UNESCO-IHE conducted a good project, but the MWI/JVA has neither the funds nor the capacity to follow it up.

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13.7 Example for pre-feasibility assessment based on Australian guidelines for the infiltration test site Wadi Jallat

As an example an entry level assessment for the infiltration site in Wadi Jallat is undertaken according to the Australian guidelines (NRMMC-EPHC-NHMRC, 2009b; Page et al., 2010). Stage 1 assesses the viability (Table 42) and the degree of difficulty (Table 43) and identifies knowledge gaps or further required action.

Table 42: Entry level risk assessment - part 1 viability.

question	answer	
1. intended water use		
Is there an ongoing local demand or clearly defined environmental benefit for recovered water that is compatible with local water management plans	Yes, two active governmental production wells are between 3 - 4 km downstream. End use would most likely be for drinking and irrigation water supply.	👍
2. source water availability and right of access		
Is adequate source water available, and is harvesting this volume compatible with catchment water management plans?	Unknown, as there are no runoff data and the catchment size could be smaller than estimated; existing WH structures in Syria are not known.	?
3. hydrogeological assessment		
Is there at least one aquifer at the proposed managed aquifer recharge site capable of storing additional water?	YES, the basalt aquifer has a thickness of around 350 m and >200 m of unsaturated zone.	👍
Is the project compatible with groundwater management plans?	The latest National Water Master Plan needs to be consulted, but due to scale differences it might not be possible to answer the question comprehensively.	?
4. space for water capture and treatment		
Is there sufficient land available for capture and treatment of the water?	The area is sparsely populated and enough area would be available, if this is privately owned or governmental land is not known.	👍
5. capability to design, construct and operate		
Is there a capability to design, construct and operate a managed aquifer recharge project?	An operator/manager of the scheme has not been identified yet.	👎

> The viability assessment shows that a number of factors would need clarification; the main activity required would be the installation of runoff stations. Regulatory requirements would need clarification as well. In addition, a management plan would need to find skilled personnel to operate and manage a future facility properly.

Table 43: Entry level risk assessment - part 2 degree of difficulty.

question	answer	action required
1 Source water quality with respect to groundwater environmental values		
Does source water quality meet the requirements for the environmental values of ambient groundwater?	Unknown, but highly likely as this is water that would naturally recharge as well	analysis of source water for nutrients, pathogens, inorganic and organic chemicals
2 Source water quality with respect to recovered water end use environmental values		
Does source water quality meet the requirements for the environmental values of intended end uses of water on recovery?	Unknown.	evaluation of attenuation processes during passage through unsaturated zone

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Table 43 (cont.): Entry level risk assessment - part 2 degree of difficulty.

question	answer	action required
3 Source water quality with respect to clogging		
Is source water of low quality, for example: total suspended solids, total organic carbon and total nitrogen each >10 mg/L, And is soil or aquifer free of macropores?	YES, source water will contain around 30 - 40 g/L of sediments with about 500 mg/L as fine suspended sediments.	strategy for sediment removal needed
4 Groundwater quality with respect to recovered water end use environmental values		
Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	Unknown as no groundwater quality results were available to this study, but highly likely to be suitable.	groundwater quality evaluation against environmental regulations (if existing)
5 Groundwater and drinking water quality		
Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	YES, drinking water is recovered from this aquifer	groundwater quality evaluation against drinking water regulations
6 Groundwater salinity and recovery efficiency		
Does the salinity of native groundwater exceed: (a) 10 000 mg/L, or (b) the salinity criterion for uses of recovered water	NO, groundwater salinity is suitable for drinking water supply	none
7 Reactions between source water and aquifer		
Is redox status, pH, temperature, nutrient status and ionic strength of source water and groundwater similar?	Unknown, but likely to be similar by the time the recharged water reaches the groundwater as this is the naturally recharged water	none
8 Proximity of nearest existing groundwater users, connected ecosystems and property boundaries		
Are there other groundwater users, groundwater-connected ecosystems or a property boundary near (within 100 - 1000 m) the MAR site?	No active private wells are registered, but illegal wells cannot be excluded; There are no connected ecosystems as groundwater levels are too low. Property boundaries are not known.	investigate land ownership and property boundaries as well as private wells
9 Aquifer capacity and groundwater levels		
Is the aquifer confined and not artesian? Or is it unconfined, with a watertable deeper than 4 m in rural areas or 8 m in urban areas?	YES, water tables are >200 m	none
10 Protection of water quality in unconfined aquifers		
Is the aquifer unconfined, with an intended use of recovered water being drinking water supplies?	YES	develop monitoring and contingency plans to prevent pollution from source water
11 Fractured rock, karstic or reactive aquifers		
Is the aquifer composed of fractured rock or karstic media, or known to contain reactive minerals?	YES, fractured rock aquifer; geochemical analysis of basalt not known	geochemical analysis of basalt aquifer ; tracer test to assess recovery efficiency and travel times

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Table 43 (cont.): Entry level risk assessment - part 2 degree of difficulty.

question	answer	action required
12 Similarity to successful projects		
Has another project in the same aquifer with similar source water been operating successfully for at least 12 months?	NO	requires stage 2 investigations
13 Management capability		
Does the proponent have experience with operating MAR sites with the same or higher degree of difficulty, or with water treatment or water supply operations involving a structured approach to water quality risk management?	As the operator is not clear WAJ is familiar with groundwater monitoring and water supply operations; but no institution is familiar with maintenance.	identify manager with competencies and provide training to local operators
14 Planning and related requirements		
Does the project require development approval? And is it in a built up area; on public, flood-prone or steep land; close to a property boundary; contain open water storages or engineering structures; likely to cause public health, safety or nuisance issues, or adverse environmental impacts?	Property situation unknown, small desert dams have to be approved of by Ministry of Planning. No adverse impacts are expected as area is only sparsely populated.	Check permit requirements. It might also be advisable to delineate surface/groundwater protection zones for new dams

If defined environmental values for groundwater are lacking in the jurisdiction, it should be assumed that all environmental values that are met by the native groundwater quality need to be protected during the entry-level assessment purposes (NRMMC-EPHC-NHMRC, 2009b).

The assessment of difficulty shows that the quality of source water and groundwater would need to be analysed as well as geochemical analysis of the host rock to assess potentially unwanted interactions. Land ownership and permit requirements would need clarification. The biggest challenges would be to design a management plan with a suitable solution to the clogging problematic and skilled operators and funding to maintain the facility.

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14 Implementation

If all the above investigations show a positive result and MAR is found to be technically, economically, environmentally and socially feasible, the next step is to find a suitable design before starting construction (see also chapter 2).

14.1 Design

> **For MAR schemes using stormwater runoff, interception and transfer provisions are required. The most recommend designs are recharge release dams followed by dams with release to infiltration basins. Recharge dams are only viable if horizontal infiltration is dominant.**
>
> **Design should be as simple as possible and as complex as needed to reduce the risk of failure. The design needs to account for the expected source water quality and allow for proper monitoring.**

As outlined in chapter 2, there is a variety of different MAR methods, but no standard design. Site-specific design criteria are the peak runoff, wadi topography, required storage capacity, sediment load and availability of materials etc. It is important to size the system correctly to have maximum benefit with minimum costs. It is outside the scope of this study to provide detailed design specifications, but instructions can be found in a number of publications (Huisman and Olsthoorn, 1983; Asano, 1985; SAIC, 1997; Barr Engineering Company, 2001; Stephens, 2010). A design storage capacity that is able to contain 10 year return period floods has been recommended previously (Hydrosult, 1988).

For the **interception** dikes, hafirs, (permeable) check dams, earth dams and concrete dams are possible. All of these retention structures have been implemented in Jordan already, experience in construction exists and a number of design reports are available at the Water Document Centre of WAJ. However, there is a lack of experience with transfer techniques. Apart from Wadi Madoneh, all MAR schemes are based on recharges dams (also called percolation ponds), i.e. the infiltration should happen in the dam reservoir.

The main methods for **infiltration** outside of the reservoir are the use of the downstream wadi channel (in-channel) or the construction of specific infiltration structures (off-channel) like infiltration basins, infiltration trenches, infiltration galleries, infiltration wells. The former is the cheapest option as it does not require any further constructions, while the latter can be more effective, as the area with the most permeable conditions can be chosen. In-channel infiltration can be enhanced by slowing down the water through small dikes in the channel (Abu-Taleb, 2003). The transport from the dam to the off-channel infiltration structure should be constructed so that gravity flow is possible and allow for overflow back into the wadi (Chehata et al., 1997). As lateral permeability has been found to be considerable (example Wala dam), deep basins and high water level in the basins seem to be the best option for turbid waters. As soil clay concentrations have been found to increase with depth (Ziadat et al., 2010), infiltration basins should be excavated deeper than the layer with the lowest permeability, which would have been determined during field investigations.

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A **release** mechanism is required to allow the water to flow out of the retention structure. The simplest design is the installation of one or more release pipes or culverts through the lower part of the retention structure without any valves or further mechanisms that simply decrease throughflow via the diameter of the pipe (example Madoneh dams) (see Fig. 5). Recharge release dams in Oman are also equipped with culverts at the bottom of the dam leading into stilling basins before final release downstream through gabion mattresses (see Fig. 4).

A more sophisticated but still mechanistic approach is a floating intake device presented by Chehata et al. (1997). Electronically controlled options are the control of outflow through valves or gates that open based on water level, sediment concentration in the water or other defined threshold limits (e.g. DWA, 1994). Weirs with movable gates and overflowing closures can be flap gates, double flap gates, drum gates (see Fig. 6), crest gates etc. where the locks are moved hydraulically (active or passive) or via a rack and pinion gears. Due to the remoteness of the area and the unpredictable nature of events, it is unlikely that personnel is available to actually open and close any valves or gates at the required time, so passively controlled mechanisms are preferable. If possible, mechanisms should not be accessible without authorisation to prevent vandalism.

The most energy intensive approach is the use of pumps preferably combined with a floating device/pontoon. The more mechanic and electronic parts are required, the higher will be the possibility for failure due to the harsh environmental conditions in arid regions as well as vandalism, and the higher O&M costs would arise.

Due to the high **sediment** loads in Jordan, protection of recharge structures from sediment accumulation is of major importance (Almomani and Subah, 2005) and design should take this fact into consideration. There are a number of methods to decrease sediment concentration in the recharged water. It is recommendable to build a cascade of retention structures to decrease suspended sediment concentration in the last and biggest retention structure (Al-Kharabsheh, 1995; van Steenbergen et al., 2011). Silt fences, inflatable weirs and leaky gabion dams could be used in small tributaries, while silt traps, desilting basins etc can be installed before the inflow to the infiltration structure. While sedimentation dams are common practice in many countries, Jordan has not practiced it and officials seem doubtful about the effectiveness for retaining silt and clay[90]. As the highest volumetric content is commonly fine sand (Shatnawi, 2012) even the settlement of fine sand only should greatly reduce sediment loads. It would be highly recommendable to study the decrease in sediment accumulation of existing recharge dams after implementation of sediment trapping check dams.

As sediments settle at the bottom, cleaner water can be found at the top of the reservoir. Gates that allow the water to pass over the retention structure are hence favoured over under-dam release structure, and floating or raised intake devices are better than intake pipes at the bottom of the dam, even if this prevents the complete drainage of the reservoir. Flushing of sediments from the reservoir (e.g. through sluice gates) is unlikely to clean the reservoir bed sufficiently to increase infiltration rates in the reservoir substantially, but could be used to increase storage capacity. However, if downstream in-channel infiltration is practiced, it could lead to clogging downstream.

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[90] F. Ejelat (JVA), 2011, personal communication

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It would also be of advantage to start the release of water only after about 5 days of settling per m of water level to allow settling of clay particles. The water level reader would need to communicate with the valve/gate opening mechanism. Another option is the spreading of flood waters over a number of large basins using level-silled channels or conveyance spreader channels. The accumulation of fines in the first basins is used to build up fertile soils for agriculture (van Steenbergen et al., 2011).

More expensive and maintenance intensive options are the construction of sand filters (rapid, slow, surface sand filters). The sediment concentration suitable for recharge will be lower the smaller and less accessible the area for infiltration is, i.e. infiltration basins can handle more turbid water than infiltration trenches or infiltration wells (Bouwer, 1996). At Wala dam six sand filter units (80 µm) have been installed to increase water quality of the already settled surface water (<5 NTU) before recharge through infiltration wells. All filters will require regular cleaning either through backflushing or complete exchange of filter medium adding to maintenance costs. The selected sediment removal design should be based on the raw water quality, a cost-benefit analysis and with consideration of possible restriction due to the remoteness.

To control garbage (either dumped deliberately into wadis or transported there via wind and water) trash screen or permeable gabions should be installed across the wadi before the dam reservoir and in front of the culvert or pipe. Regular cleaning of all screens is required to allow proper functioning.

The design should also incorporate monitoring equipment like continuous stage recorder, staff gauges, and discharge measurements, which need to be accessible for maintenance but protected from vandalism. Vandalism could be kept low by transfer of responsibility to and bearing of maintenance costs by the stakeholders, so they have a vested interest in keeping the structure running.

14.2   Construction

Once a suitable site has been selected, regulatory issues and land ownership has been clarified, the construction of retention, release and infiltration structures can begin. The construction also encompasses the installation of monitoring wells and monitoring equipment for flood volumes, recharge rates etc. It is commonly undertaken by a local contractor. The terms of reference for contractors should be quite precise to avoid the use of substandard materials that could impair the functionality.

Depending on the decisions from the stakeholder forum or the institutional set up of the MAR scheme, construction can be aided by community work, especially if the scheme comprises a number of small scale structures rather than one large scale structure. A number of successful examples worldwide have been reported (van Steenbergen, 2006).

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![BGR logo](Bundesanstalt für Geowissenschaften und Rohstoffe)

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15 Activities after implementation

> *"The success of a project relies heavily on proper monitoring and O&M activities. Indeed, a project does not end once construction is completed, it merely begins." (SAIC, 1997)*

It is highly recommended to implement proper O&M and monitoring, and prove the effectiveness at existing and future sites. Further MAR schemes should assure that maintenance and monitoring as well as stakeholder participation is guaranteed.

15.1 Operation and maintenance

As has been outlined (see section 13.4.1 and chapter 5) that proper O&M is an important factor for the economic feasibility of a project and even though new costs are accrued, the costs will be outweighed by the benefits. It is therefore a waste of money to construct a MAR scheme without the funds or resources for O&M. It cannot be the aim to increase the number of silted up dams, as every failed project reduces the acceptance in the community and will result in negative impacts and indirect costs.

The main O&M measures are:

- regular inspection of the facility before and during the wet season to judge if there are any problems that need rectification,
- annual maintenance of all equipment (pipes, valves, logger, gates, etc.),
- annual cleaning of the infiltration structure from accumulated sediments during the dry season
- annual cleaning of screens and release structures
- repair to the facility and monitoring equipment caused by natural forces and vandalism before the next runoff event can be expected.

The complete removal of accumulated sediments is preferable over scratching or ploughing of the surface, as the impact of the latter is only short-term, allows the distribution of fine material into deeper layers (Bouwer, 1996) and is not expected to be much cheaper. It is even recommended to scrape more than the accumulated sediments as the finest particles can penetrate up to 40 cm into the surface material (Schuh, 1988; Mousavi and Rezai, 1999). Removal frequencies should be at least annually during the dry season. Depending on the recharge technique, number of recharge events and water quality, cleaning even between events in one wet season might be required, as the fining up sequences of settled sediments decrease the infiltration rate more effective than a homogenous layer (Bouwer et al., 2001). Most continuous recharge facilities require drying and cleaning after about two weeks, when infiltration rates have decreased to the minimum (Al-Kharabsheh, 1995; Zeelie, 2002).

Beneficiaries might bear the main responsibility for the O&M measures, which would limit costs considerably (Gale, 2005). In any case, they should be informed how they can report

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any problems with the facility to the local responsible authorities. If it is possible to have a local guard present continuously this could prevent vandalism.

> *Unfortunately, in the "MWI, there is no explicitly assigned office or directorate that is responsible for MAR operations. Such an institution should be established, staffed and funded to carry out the duties and responsibilities necessary for the efficient and successful operations." (SAIC, 1997)*

It requires clearly defined responsibilities and assignment of skilled personnel to oversee O&M activities. Since more than 15 years, when it was first recommended, no specific department/directorate or working unit for MAR activities has been established. Currently, JVA is responsible for the management of dams including construction and maintenance. Some desert dams have been constructed by the Ministry of Agriculture in cooperation with JVA. The MWI has been involved in the implementation of dams in Wadi Madoneh and Wadi Butum as project related activities, but they will be handed over to JVA who is responsible for dams. The Ministry of Environment is also to be involved in the construction of water harvesting structures[91]. As responsibilities are not clearly defined and JVA is mostly involved with the large storage dams along the Jordan Valley, there has not been any proper O&M for the existing desert dams. If community participation should be involved duties and obligations have to be spelled out even more clearly. But, if there is no capability to operate a MAR project neither in the community nor in the institutions, implementation should not go ahead (Dillon et al., 2009).

15.2   Monitoring

> **Monitoring is undertaken to prevent any groundwater contamination, to generate detailed data for a better cost-benefit analysis, for optimising the system operation and (if existing) to fulfil regulatory requirements.**

Monitoring needs depend on the recharge system and design. The minimum monitoring requirements should guarantee that no groundwater contamination occurs or at least can be detected early. Minimum parameters should be TSS, TDS, nitrate and *E.coli*. Depending on the hazards present in the catchment further parameters like organic contaminants (pesticides, oil, MTBE, etc) should be added.

Monitoring needs have been prescribed previously (e.g. SAIC; 1997; Orient ECD, 2010), but were hardly implemented. However, it is vital to increase the data base to allow a better cost-benefit analysis. This would require the detailed recording of inflow and outflow volumes of the facility, as well as the recording of wetted area and evaporation. The evaluation of stored and infiltrated volumes requires a water level rating curve. A different method to separate evaporation from infiltration would be the regular analysis of chloride concentrations in the reservoir water (Sukhija et al., 1997). More sophisticated systems would allow the monitoring of the actual recharge front in the unsaturated zone until it reaches the groundwater with

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[91] N. Seder (JVA), 2011, personal communication: Construction of small water harvesting dams (50 000 – 200 000 m³) for increase in biodiversity and livestock watering funded by the Iraqi War Compensation Fund in 2011 and 2012.

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tensiometers and temperature sensors (Izbicki et al., 2008). This could be sponsored by research institutions.

To optimise the design and operation of the facility, sediment loads associated with the recharge volumes should be recorded via measuring of sediment thickness at representative points, collection in sediment traps etc. Sediment samples should be analysed for grain size distribution including hydrometer. Sampling of flash floods for TSS requires a high sampling frequency due to the high variability (e.g. Neal et al., 2012; Skarbøvik et al., 2012), so measuring the inflow volumes of water, the accumulated sediments and the turbidity in release water would be a cheaper approach.

As the groundwater mound dissipates quickly a number of observation wells in increasing distance downstream and one or two upstream are needed to distinguish intentional recharge impact from natural recharge.

The main parameters for monitoring are:

- daily rainfall and evaporation records and continuous runoff records
- continuous monitoring of groundwater levels in monitoring wells
- continuous records about inflow and outflow of retention and infiltration structures (water level measurements, spillway discharge, release volumes etc.)
- assessment of wetted area to be able to calculate infiltration rate
- sampling of ground- and surface water for quality analysis (TSS, TDS/EC, NO_3, *E.coli* etc.) about 3 - 4 times a year
- sampling of reservoir water for Cl (about every week) to estimate recharged volumes
- assessment of sediment loads with sediment traps, measurements of sediment thickness at representative points
- evaluation of stored and infiltrated volumes (requires water level rating curves)
- evaluation of collected data

Organic micropollutants are easier to monitor with passive samplers over a longer period than with grab samples. Some of these monitoring activities (rainfall, runoff, groundwater levels, surface water and groundwater quality) should start a few years before implementation during the feasibility assessment phase. Once established like at Wadi Madoneh, it is paramount to continue collecting and interpreting data for at least a decade (Gale et al., 2006), to assess the long-term impact.

Obtaining representative groundwater samples requires properly constructed wells, an appropriate pumping mechanism, proper flushing of the well and correct sample preparation, storage and preservation and should hence only be undertaken from skilled personnel. There are a number of guidelines outlining proper groundwater sampling techniques (Schuller et al., 1981; Barcelona et al., 1985; Johnston, 2007; Sundaram et al., 2009). WAJ laboratories are equipped for analysing all required parameters.

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16 Conclusions and recommendations for Jordan

A summary of all aspects of the previous assessment and further insights into the situation and problems in Jordan is given below.

16.1 Technical and socio-economic feasibility

The pre-feasibility assessment undertaken has evaluated the fundamental questions as follows:

1) Is there enough source water?

For most of the investigated area, rainfall is too sparse to guarantee sufficient regular runoff that would be possible to harvest. However, currently available runoff data are too sparse to evaluate the question fully. Existing water harvesting structures further reduce the availability of runoff. For the AMZ basin there is no non-committed water. For Azraq basin the potential impact of reduction in environmental flows to qaa and marab ecosystems would need further investigation.

2) Is there enough storage space in the aquifer?

Due to the low groundwater levels there is ample storage space in the basalt and limestone aquifers. Groundwater quality is mainly suitable for potable uses allowing for high recovery efficiency.

3) How can the source water be transferred to the aquifer?

As large areas have unconfined aquifers that are outcropping, surface infiltration would be the most suitable and economically feasible solution. Detailed bore logs would be useful to assess if the water would reach the groundwater from the selected site. Recharge release dams are the most appropriate technique for regions with high sediment loads.

4) Is a potential intervention going to be effective?

MAR can only be successful, if proper sediment management plans and funding are in place and implemented, as the high suspended solid load in the source water would otherwise clog infiltration facilities and obstruct effective transfer to the aquifer. It would also have to be investigated whether the negative downstream effects do not outweigh the potentially positive recharge effects.

> *"In times of budget shortfall it is doubtful that adequate funds will be available for inspectors and for maintenance needed [...]." (Lindsey et al., 1992)*

While MAR recovered for municipal and industrial purposes might be economically sustainable, it will not be for recovered agricultural uses. Problems with vandalism and limited incorporation of local stakeholders would need to be addressed.

16.2 Data and knowledge management

> **Reliable long-term data are the fundament for any water management. Recommendations are to increase quality control, make more use of existing data and collect more data especially for runoff volumes and surface water quality.**

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The **Water Information System** (WIS) is the central database of the MWI. WAJ has their own databases and official letters have to be written to get access to their data. No central data management at JVA was visible. Problems have been experienced when extracting large datasets out of the WIS oracle database into excel spreadsheets. A revision of the current database would be advisable also to incorporate the large amount of data that are generated by the newly installed telemetric stations. Problems with the quality of the data have also been noticed (see also Huber, 2012). The most common errors are missing units[92], mix up between calendar and water year; mix up of daily and yearly data; mix up of parameter across the columns, wrong decimal points etc. Another major deficit is the unreliability of coordinates of wells and stations, e.g. it is impossible to draw a groundwater contour map, if the altitude of wells is not correct. In addition, some data are only available based on governorates boundaries that do not necessarily coincide with watershed boundaries.

The MWI is aware of these shortcomings of the data in the WIS, but has not found a suitable solution. This limits the usability of the data especially for short term consultants or technical cooperation personnel as time-consuming plausibility validation and pre-processing of data is required each time. To improve the data quality, it is highly recommended to increase the usage and presentation of available data by the MWI not only for yearly budgets but also for a more detailed interpretation as part of a regular reporting system. For example, the water budget calculations could be greatly improved using actual runoff data and subtracting known quantities of treated wastewater runoff. CN values could be calculated for individual sub-catchment to improve water budget estimations.

The climate data seem to contain the most errors and their usage is the lowest. It is therefore recommended to transfer existing MWI climate stations to the Department of Meteorology (DoM) and in return negotiate the access to quality controlled data from all climate stations[93] on request.

As described previously a range of parameters needs to be assessed to evaluate the technical feasibility of MAR. Even though a range of data is already available, some data are missing completely or are very sparse. The main improvement for a proper MAR potential assessment would be more data on:

- **runoff**: Especially in Azraq only a few stations with a limited number of years are available. Runoff data are needed to assess available source water and to design retention structures cost-effectively. Runoff stations should be installed properly to be able to measure all throughflow.
- **rainfall**: While rainfall station density is acceptable in AMZ, it is not sufficient in Azraq basin due to high spatial variability.
- **surface water quality**: Flash flood sampling is needed. Auto-sampler could be installed to allow for a timely and repeated sampling of flood waters in ephemeral streams. Analysis for TSS would enable a better cost estimation for maintenance and choice of recharge method, and potential contamination of surface waters could also be detected.

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[92] It could be that these are just not correctly extracted.
[93] The DoM supports their own climate stations, but these data are not used by the MWI.

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- **detailed bore logs**: Neither detailed descriptive nor geophysical logs are available rendering it impossible to assess if the recharged water would reach the groundwater level or be perched.
- **depth of filter units**: Due to missing information on the depth of the filter units in the wells, analysed groundwater samples can often not be assigned to the right aquifer system.
- **hydraulic conductivity**: Only about 5 - 6 % of all bores have transmissivity data and no local hydraulic conductivity data are given to allow for the assessment of residence time.
- **water level**: The current network of monitoring wells is not sufficient to draw a reliable groundwater level contour map to provide estimations on flow direction and flow velocity.
- **surface water usage**: No information on private or public surface water usage is available to assess the non-committed fraction of surface runoff.
- **transmission losses**: Natural recharge estimates could be more reliable with a finer network of runoff stations permitting the estimation of benefits through additional recharge. In addition, highly permeable sections of a wadi could be identified to facilitate site selection for retention structures.

Another knowledge management system is the **Water Document Centre** (WDC) at WAJ. Here many reports and books are collected. The access and search through the database could be improved and the number of available reports could also be increased. Newer reports should be available in electronic copy as well. This study is not the first evaluation regarding MAR potential in Jordan. However, the transfer of existing knowledge and the implementation of previous recommendations is commonly lacking.

16.3   Operation and maintenance

> **The costs for operation and maintenance can evidently not be covered by the JVA budget. International donors need to ensure that O&M funding is set aside and the participation of beneficiaries should be followed up.**

Recharge dams face a number of problems: destruction due to natural forces, vandalism, general wear and above all clogging. Accordingly, basically every report about MAR in Jordan has recommended to undertake regular (about once a year) sediment removal from recharge dams (e.g. Hydrosult, 1988; Al-Kharabsheh, 1995; Chehata et al., 1997; Almomani and Subah, 2005), which would be reasonably easy in desert dams, as these are dry in summer. Nevertheless, sediment removal has not been practiced at any dam site, even though all dams face serious siltation problems. Costs were named as the main hindrance. Instead it has been recommended to heighten dam walls or construct new dams, which does not address the problem.

> *"Costs of cleaning 1 m³ sediments from the reservoir is approximately 10 fils (WAJ, 1990). Because of the low costs, no sedimentation remediation problems are anticipated."* (Al-Kharabsheh, 1995)

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Current estimated costs for sediment removal are about 1 JD/m³[94]. With the assumption of 1 % of sediment load this would results in about 500 JD sediment removal costs for a 50 000 m³ flood, which is far less than any new construction.

The expenses for dam construction are commonly covered by international donors, while the maintenance has to be summoned up by the JVA budget. Hence, it seems cheaper to build a new dam instead of maintaining existing ones. This seems to be a flaw in the system. International donors should therefore ensure that part of the budget is set aside for long-term maintenance during finance negotiations. It should also be investigated if participatory approaches where maintenance has to be undertaken by the beneficiaries of MAR schemes could be an option.

> *"As main recommendation, protection of artificial recharge dams from silts and sediments is required. Accumulation of silt should be a major factor to be considered in the evaluation and design of artificial recharge systems in Jordan." (Almomani and Subah, 2005)*

Other forms of reducing sediment accumulation could be the installation of pre-sedimentation dams or gabions upstream or the use of desilting basins that would considerably reduce bed load. These structures would obviously also require maintenance, but at lower frequency.

Another problem is the vandalism experienced at wells and other water infrastructure[95]. This problem can be tackled by using simple (theft proof) technology requiring as little as possible metal or electronic parts and by involving the local community into the MAR process. Site selection should take into consideration if a resident nearby could function as guard to the facility.

16.4   Monitoring and documentation

> **The effectiveness of recharge structures has to be monitored and documented to justify further replication. A comparison between the 'before' and 'after' situation should be achieved. Detailed research could be supported by local and international research institutes.**

While a number of recharge dams have been built, the documentation of success or failure is very limited. An actual measurement of recharged volumes or of increase in groundwater table is not carried out. Also, the siltation of dams and related decrease in infiltration rates has not been monitored or investigated. Recharge wells are in use at Wala dam since 2011. Documentation on recharge volumes, water quality, clogging problems, and resulting increase in groundwater table is not available. At least, JVA is estimating infiltrated volumes based on the water budget method at Wala dam. At Khaldeya dam, recharge wells were installed but their use or the reason why they were not used, seems not documented or known. While a number of studies might have been undertaken, their existence is not known to the author and the MAR team from MWI, JVA and WAJ, or access might be restricted.

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[94] A. Al-Sous (JVA), 2012, personal communication

[95] Jordan times, 29th May 2012: 'Water network violations on the rise' Infringements lead to disruptions in distribution programme.

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Research into the effectiveness of recharge structures is apparently not seen as valuable and the construction of new dams is promoted without this knowledge. This might be due to the less tangible nature of research in general, and, in particular, to the tangibility of structures that provide visible evidence of 'successful' actions by the government.

However, the effectiveness of recharge structures should be investigated if further construction is considered. Monitoring of all components of the water budget of the recharge structure and the impact on the groundwater level over some distance downstream is needed. An elegant and cheap method to quantify infiltrated volumes is via the chloride balance (Sukhija et al., 1997), while isotope monitoring is more expensive and would need to be supported by research through universities or donor organisations. Monitoring of temperature changes could also be investigated (DWA, 1994; Izbicki et al., 2008).

The effectiveness of recharge structures also has to consider downstream impacts. This would involve monitoring of the 'before' situation and the 'after' situation to allow comparison. If the intervention merely relocates the availability of water from a downstream to an upstream user, the effectiveness is low. Downstream 'use' also encompasses the natural recharge through stream beds, the maintenance of ecological flows and the dilution of low quality water (Gale et al., 2006).

16.5   Legal implementation

> *"It is therefore essential to develop a national strategy and an action plan for implementation of artificial recharge country-wide." (Chehata et al., 1997)*

The national water strategy does not particularly mention MAR with flash floods and foresees a decrease in artificial recharge[96] (MWI, 2009). Only MAR with treated wastewater has been highlighted. Accordingly, there are no policies, no standards and no institutional framework to plan, implement and operate recharge facilities (Chehata et al., 1997). First of all, it would therefore be necessary to develop a strategic plan with defined MAR objectives. Responsibilities, institutional arrangements and funding have to be predefined. Questions about ownership of recharged water, water rights and permits as well as liabilities for any caused problems have to be clarified (Asano, 1985).

In the absence of direct legislation for MAR with stormwater, practice must at least not contravene existing regulations (Hochstrat et al., 2010). The main standard of interest is the specification for reuse of reclaimed water (JS 893/2006):

> "*4.2.1: Reuse for the purpose of artificial groundwater recharging:*
>
> *4.2.1.1: Treated wastewater may be used for the purpose of artificial groundwater recharging whenever its quality is in agreement with the standards shown in table 2 [reproduced in Table 44].*
>
> *4.2.1.2: This water should not be used for recharging groundwater which is utilized for drinking water purposes.*

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[96] It is unclear if the definition of ‚artificial'recharge in this document also includes unintentional artificial recharge like leakage from sewage lines. The figure on p.1 - 7 cites 55 MCM for artificial recharge in 2007 and 25 MCM in 2022.

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4.2.1.3: Appropriate Technical studies should be carried out before using this water for recharging groundwater specified for irrigation so as to show that this water will not affect ground water basins specified for drinking purposes."

Table 44: Allowable limits of water quality which may be used for artificial groundwater recharging purposes (JISM, 2006).

Standards	mg/L*	Standards	mg/L	Standards	mg/L	Standards	mg/L
BOD_5	15	FOG	8	Al	2	Fe	5
COD	50	Phenol	<0.002	As	0.05	Hg	0.001
DO	>2	MBAS	25	B	1	Li	2.5
TSS	50	TDS	1500	Be	0.1	Mn	0.2
pH	6 - 9	Total PO_4	15	Cd	0.01	Mo	0.01
Turbidity (NTU)	2	Cl	350	CN	0.1	Ni	0.2
NO_3	30	SO_4	300	Co	0.05	Pb	0.2
NH_4	5	HCO_3	400	Cr	0.05	Se	0.05
T-N	45	Na	200	Cu	1.5	V	0.1
E.coli (MPN or CFU/100 mL)	<2.2	Mg	60	F	2	Zn	5
		Ca	200				
Intestinal Helminth eggs (eggs/L)	≤1	SAR	6				

* allowable amount in mg/L if no other unit stated

This standard basically prohibits intentional recharge with reclaimed wastewater, as virtually all aquifers are also used for drinking water purposes and the costs for a technical study to prove otherwise would be too expensive to carry out. As unintentional recharge of treated and untreated wastewater is taken place already through irrigational return flows and leaking sewage pipes, the standard is currently under review[97]. The new standard is likely to loosen the restrictions to allow recharge of tertiary treated wastewater with near drinking water quality to all aquifers.

Foremost, MAR regulations should guarantee the protection of groundwater quality. Current guideline No 5106 for groundwater protection could be applicable here as well (MWI-BGR, 2011). Stormwater is usually treated like freshwater, even though it most certainly will not fulfil drinking water standards (JS 286:2008) for turbidity (5 NTU) and potentially not for *E.coli* (< 1.1 MPN/100 mL). However, one has to account for the treatment through the infiltration into the ground and residence time, which will decrease TSS and pathogens (Dillon and Toze, 2005). The Hazard analysis and critical control point (HACCP) approach should be investigated (Page et al., 2010) and less stringent criteria might then apply to areas where the groundwater is already contaminated. Obviously, no water quality checks are currently required for MAR schemes.

It has been shown that bottom-up participatory approaches perform better than top-down technocratic approaches, if enough technical information has been provided to the stakeholders (Gale et al., 2006). Hence, MAR regulations should also consider including the participatory approach and defining rights and responsibilities under this programme. The procedure for required permits as well as the compensation for land owners and downstream user has to be elucidated.

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[97] A. Uleimat (JVA), 2012, personal communication

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It is outside the scope of this study to spell out comprehensive policies or regulations for MAR, but these should certainly include mandatory O&M and monitoring requirements and assess the environmental and economic impact. International examples could be used for guidance (e.g. CGWB, 2000; Murray et al., 2007; NRMMC-EPHC-NHMRC, 2009a, b). National MAR directives should be developed in dialogue with national stakeholders.

> **If MAR is to be pursued in Jordan, national MAR regulations should be developed in a dialogue with national stakeholders. It is recommended that they include regulations for impact assessment before implementation as well as mandatory O&M and monitoring after implementation. A certain budget needs to be set aside for these measures.**

16.6 Capacity building

> *"In MWI, there is no explicitly assigned office or directorate that is responsible for MAR operations. Such an institution should be established, staffed and funded to carry out the duties and responsibilities necessary for the efficient and successful operations."* (SAIC, 1997)

There is no specific MAR unit within the MWI. The human resources at the MWI are limited as the number of staff is already not sufficient to perform all needed tasks (e.g. data evaluation, quality control) let alone to fulfil new tasks related to MAR. A brain drain of young dynamic staff into jobs in industry or overseas has been experienced. A handful of permanent employees are assigned to work with technical cooperation projects in addition to their normal duties. As this means additional work with only limited benefits, the motivation is generally low. If MAR activities are to be pursued, it is highly recommended to extent the existing JVA Dam Directorate with competent staff to be able to perform the additional work load. It is recommended that strategic planning and the development of a regulatory framework as well as the oversight of MAR activities should be undertaken by the MWI. Any future technical cooperation on MAR should clearly define responsibilities and objectives of both partners and allow sufficient time for a successful cooperation.

Previous technical cooperation projects have conducted numerous workshops and trainings for capacity building at the MWI. However, it is not visible that the newly acquired knowledge has been transferred to the daily work. There is no documentation on work processes. Commonly, only one person is responsible for one task and knowledge leaves the ministry with the leaving person. The overall workflow and responsibilities are difficult to follow up and there is room for improvement to enhance institutional structure inside and across the Ministries.

If MAR was to be pursued further, more skilled staff would be required with clearly defined assignments and responsibilities. A consensus with stakeholders should be achieved on the best use of wadi flash floods. This dialogue cannot be solved with technical knowledge alone, but it is clear that stakeholders need to be educated about the advantages/ disadvantages and technical feasibility as well as the costs and benefits of MAR facilities. It is highly valuable to transfer knowledge on underground processes to the community also

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with respect to groundwater protection. Another path to pursue is the exchange of knowledge about MAR with other (semi-)arid countries. For example Oman has successfully implemented a number of recharge dams[98], so has Saudi Arabia (Sendil et al., 1990; Al-Muttair et al., 1994; Alrehaili and Hussein, 2011) and Tunisia has experience with gabion dams and gravel filled infiltration wells in wadis (Ouessar et al., 2004; Bouri and Dhia, 2010) and recharge releases (Zammouri and Feki, 2005; Ketata et al., 2011).

16.7 Final conclusions

> *"[...] MAR is not a substitute for demand management in resolving groundwater over-abstraction." (Gale et al., 2006)*

This study was commissioned by the MWI with the task to find more suitable sites for MAR via infiltration of flash floods in the highlands of AMZ and Azraq basin with the aim to replicate existing MAR schemes. However, objectives for the recovery were not well defined and the objective of some existing structures is also unclear. Without a clear definition of objectives, the selection of suitable sites is hindered.

Interest in augmenting water supply is understandable with the severe decline in groundwater levels due to overabstraction. However, a replication of currently failed MAR schemes in the highlands cannot be the aim and MAR will not be the magic bullet to stop declining groundwater tables, as the available volumes of non-committed surface water are not sufficient in this region.

The more worthwhile option of agricultural demand reduction has been attempted with limited success and is obviously a much less popular action, even though it is outlined in the national strategy (MWI, 2009). It would require cooperation with the Ministry of Agriculture, the political elite and tribal leaders (Bonn, 2011; Mesnil and Habjoka, 2012). The other very worthwhile option of reduction of unaccounted for water would require more effort in regular maintenance as well as a shift in communal perception that water is not a free commodity, but that issued bills should be paid.

It was found that the knowledge to undertake this kind of study already existed in Jordan and is documented (e.g. Hydrosult, 1988; Chehata et al., 1997). It is also clear that the main reason for failure (i.e. siltation of reservoirs) has been described and the remedy (i.e. regular maintenance) has also been prescribed before. Hence, there is not a lack of knowledge but a lack of implementation and enforcement. It requires more political will and cooperation between all affected Ministries, tribal leaders and the wider community to prioritise monitoring and maintenance and direct the technical and financial cooperation towards these objectives to make MAR with flash floods a viable option in Jordan.

> **The MAR maps produced during this study only look at the technical feasibility of MAR. They cannot depict the socio-economic feasibility of MAR and do not fully reflect water availability.**

The assessment of available data showed that there is ample storage space and large areas where suitable unconfined aquifers are outcropping. In contrast, available non-committed

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[98] R. Klingbeil (UN-ESCWA), 2012, personal communication

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surface water resources are limited. This might seem paradoxical, when the Azraq Qaa is flooded every few years[99] with large volumes of water, but it would not be possible to capture these extreme events economically. Instead, these extreme events are hindering water harvesting as their destructive force can damages harvesting structures. Estimations show that even if large volumes of surface runoff could be captured and recharged, this could not solve the regional groundwater level decline, as the scale of overabstraction far outweighs the contribution that MAR could make. MAR will not be able to replace demand reduction measures, but has been fostered as decision making is generally reflecting the availability of funds rather than feasibility and effectiveness. Even for existing MAR schemes in the highlands it is sometimes unclear what the specific objective was[100] and mistakes are repeated[101].

If MAR is to be beneficial, its effectiveness has to be proven by monitoring. Building dams by itself will not generate runoff and interception of runoff will not lead necessarily to infiltration and increase of groundwater supply, but could only be a redistribution of already used resources. If facilities are not maintained correctly, MAR could also turn into the exact opposite of what it was trying to achieve, i.e. increase loss of resources through evaporation.

> **As it does not seem possible to maintain the existing dams, it is highly recommended to have guaranteed maintenance, monitoring and stakeholder involvement for any new MAR scheme. It is recommended to retrofit existing recharge dams into recharge release dams and start proper maintenance and monitoring of effectiveness.**

One key recommendation is (again) the need for greater investment in monitoring before and after any MAR project, as there is a lack of baseline data on the current situation and a need for prove on the effectiveness of MAR, particularly in relation to cost and benefits (Gale et al., 2006). This does also involve the assessment of current natural recharge that will be hindered downstream of water harvesting structures.

Creating beneficial MAR schemes requires a political process. Funds should only be made available if maintenance of the envisaged MAR scheme forms an integral part of future projects. It is hoped that this report sparks further discussion and is used as a starting point for the development of a national strategy and associated regulations.

> *"Until we admit that program implementation does not stop with the construction of facilities and are willing to deal with the financial implications of this reality, these programs are guaranteed to fail." (Lindsey et al., 1992).*

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[99] No record on flood frequency could be found, but personal reports were given and one Landsat picture showed a flooded Qaa in Jan 1989
[100] i.e. Rajil dam is not close to any abstraction well
[101] i.e. there is no monitoring of recharge volumes, water levels or water quality or maintenance plans for the new Wadi Butum infiltration basins constructed last year

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