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Groundwater Drought Vulnerability in the Amman-Zarqa catchment in Jordan

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THE SWIM AND H2020 SUPPORT MECHANISM PROJECT (2016-2019)

The SWIM-H2020 SM is a Regional Technical Support Program that includes the following Partner Countries (PCs): Algeria, Egypt, Israel, Jordan, Lebanon, Libya, Morocco, Palestine, [Syria] and Tunisia. However, in order to ensure the coherence and effectiveness of Union financing or to foster regional co-operation, eligibility of specific actions will be extended to the Western Balkan countries (Albania, Bosnia Herzegovina and Montenegro), Turkey and Mauritania. The Program is funded by the European Neighborhood Instrument (ENI) South/Environment. It ensures the continuation of EU's regional support to ENP South countries in the fields of water management, marine pollution prevention and adds value to other important EU-funded regional programs in related fields, in particular the SWITCH-Med program, and the Clima South program, as well as to projects under the EU bilateral programming, where environment and water are identified as priority sectors for the EU co-operation. It complements and provides operational partnerships and links with the projects labelled by the Union for the Mediterranean, project preparation facilities in particular MESHIP phase II and with the next phase of the ENPI-SEIS project on environmental information systems, whereas its work plan will be coherent with, and supportive of, the Barcelona Convention and its Mediterranean Action Plan.

The overall objective of the Program is to contribute to reduced marine pollution and a more sustainable use of scarce water resources. The Technical Assistance services are grouped in 6 work packages: WP1. Expert facility,WP2. Peer-to-peer experience sharing and dialogue, WP3. Training activities, WP4. Communication and visibility, WP5. Capitalizing the lessons learnt, good practices and success stories and WP6. Support activities.

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ABBREVIATIONS

AZ	Amman-Zarqa
CIS	Common Implementation Strategy
DVI	Drought Vulnerability Index
GDVI	Groundwater Drought Vulnerability Index
EEA	European Environment Agency
EG	Expert Group
EPA	Environment Protection Agency
EWP	European Water Partnership
LTAA	long term annual average
MCM	Million Cubic Meters
MWI	Ministry of Water and Irrigation
OECD	Organization for Economic Co-operation and Development
RB	River Basin
RBD	River Basin District
WFD	Water Framework Directive
WSD	Water Scarcity and Drought

1 INTRODUCTION

The current report presents an analysis and quantification of groundwater vulnerability to drought in the Amman-Zarqa River Basin in Jordan, based on the estimated over-abstraction (i.e. abstraction above the safe yield limits) in the domestic, agricultural and industrial sectors in the area. The Amman-Zarqa basin is located in the Northeast part of Jordan, has a total area of 4,120km^2 (around 95% of the area falls within Jordan and the remaining in Syria), and is one of the largest developed areas in Jordan. Groundwater is the main source of water supply in the basin, yet heavily overexploited due to over-abstraction beyond the safe yield levels. The water scarcity problem in the basin is multi-vector, as it is the combined result of the wide fluctuations in annual rainfall, the growth in population, the competing water uses and growing water needs, and the water quality deterioration. The average annual unmet demand in the basin is about 46.6 million cubic meters which represents about 36% of the total water demand.

Vulnerability to drought cuts across different temporal and spatial scales, and different sectors: agriculture, livestock, domestic, tourism, etc. Hence, its definition requires detailed assessment of the prevailing socio-economic conditions, and at times it inevitably requires the prioritization of the most important components and pressing factors which shape a region's potential risk. In the context of water stressed areas this pressing (or limiting) factor is usually the balance between water availability and demand, for the various economic sectors (including the environment), and at the relevant spatiotemporal resolution. Unmet demand, which is associated with different drivers (be it physical or anthropogenic), and water supply reliability, are commonly the limiting factors and main pressures leading to increased vulnerability conditions of the surface and groundwater systems in periods of drought. In the current analysis, a Groundwater Drought Vulnerability Index (GDVI) is calculated on the basis of these parameters for the Amman-Zarqa River Basin in Jordan. It is nevertheless often that such data on unmet demand and water supply reliability are not available at an adequate disaggregation level (spatial, temporal, or sector-specific), and thus estimates and proxies must be used. In this context, the development of adequate modelling frameworks which can capture and represent the salient features of the hydrological cycle on one side, and water users' needs on the other side (especially in data scarce cases) is a valuable tool in identifying and mapping these vulnerability components. The Water Evaluation and Planning System (WEAP21) has been used in the case of the Amman-Zarqa River Basin to simulate the basin's water resources and deliver estimates of the groundwater over-abstraction and water supply reliability in relation to the actual groundwater abstractions.

2 THEORETICAL BACKGROUND

2.1 WATER SCARCITY INDICATORS

In the past 20 years many indices have been developed to quantitatively evaluate water scarcity or water stress. The difficulty of characterizing water stress is that there are many equally important facets to water use, supply and scarcity. Selecting the relevant criteria to assess water scarcity can be as much a policy decision as a scientific decision (Brown and Matlock, 2011). Some simplistic approaches use indicators that express water scarcity in terms of the per capita water availability, based on the logic that having identified how much water is needed to meet human demands, the water that is available to each person can then serve as a measure of scarcity (Rijsberman 2006). An overview of the most commonly used water scarcity indices in decision making is presented in Table 2-1 below. It is apparent that similar indicators providing some representation of water scarcity and stress, bearing different names and definitions are developed globally. It is evident that no single common approach is adopted when it comes to characterising water stress conditions. Some of the indicators only provide some awareness-level relevant information being highly aggregated in terms of temporal and spatial resolution, while others attempt to identify hotspot areas adopting a smaller spatial scale of analysis. It is nevertheless apparent that no systematic assessment or framework is available.

Table 2-1: Overview of water scarcity and stress related indicators

Indicator / Index	Reference	Spatial Scale	Required Data
Water Exploitation Index (WEI)	EEA, 2008	country, some River Basins (RBs)	annual freshwater abstractions long term annual average freshwater availability (LTAA) *It can also be disaggregated for groundwater and surface water (i.e. Groundwater Exploitation Index = Annual groundwater abstractions over LTAA groundwater availability*
Water Exploitation Index= (WEI+) *It can also be disaggregated for groundwater (GWEI+) and surface water (SWEI+)*	WFD CIS EG WSD, in Faergemann, 2012	RBD, RB	annual (or monthly) freshwater abstraction and returned water, annual (or monthly) renewable water resources (i.e. precipitation, external inflow, actual evapotranspiration, change in storage, natural outflow)
Intensity of use of water resources	OECD, 2001	country, region	annual freshwater abstractions total renewable water resources
Index of Watershed Indicators (IWI)	EPA, 2002	watershed	15 condition and vulnerability indicators
Exploitation index of renewable resources	Plan Bleu	country	Mediterranean
Water Stress Index (WSI) per source	EWP Water Stewardship Programme	site specific	water abstraction/ consumption as percentage of available water per source (%) with the water abstraction volume per source in [m3/month or season] and average [m3/year]

Indicator / Index	Reference	Spatial Scale	Required Data
Water discharge index (WDI)	EWP Water Stewardship Programme	site specific	total amount of water discharge [m3/time period] in relation to total amount of available water body [m^3/time period
Indicator of water scarcity	Heap et al., 1998	country, region	annual freshwater abstractions desalinated water resources internal renewable water resources external renewable water resources (ERWR) percentage of the ERWR that can be used
Water availability index WAI	Meigh et al., 1999	region	time-series of surface runoff (monthly) time-series of groundwater resources (monthly) water demands of domestic, agricultural and industrial sector
Vulnerability of Water Systems	Gleick, 1990	watershed	storage volume (of dams) total renewable water resources consumptive use proportion of hydroelectricity to total electricity groundwater withdrawals groundwater resources time-series of surface runoff
Water Resources Vulnerability Index (WRVI)	Raskin et al., 1997	country	annual water withdrawals total renewable water resources GDP per capita national reservoir storage volume time-series of precipitation percentage of external water resources
Water Stress Indicator (WSI)	Smakhtin, et al., 2005	River basin	Annual water withdrawals environmental water requirements (as % of the long-term mean annual river runoff hat should be reserved for environmental purposes) mean annual runoff
Water Poverty Index (WPI)	Sullivan, 2002	country, region	internal renewable water resources external renewable water resources access to safe water, access to sanitation irrigated land, total arable land, total area GDP per capita under-5 mortality rate UNDP education index Gini coefficient[1] domestic water use per capita GDP per sector Water quality variables, use of pesticides Environmental data (ESI)

[1] measuring inequality in the distribution of income

2.2 DROUGHT AND WATER SCARCITY VULNERABILITY FRAMEWORKS

According to the UN International Strategy for Disaster Reduction Report (UNISDR, 2004) there are two essential elements in the formulation of risk: the potential event (hazard), and the degree of susceptibility of the elements exposed to that source (vulnerability). Their interaction can be described by the following mathematical formula: *Risk = Hazard x Vulnerability*. Therefore, a conceptual approach to drought risk assessment can be broken down into a combination of the hazard and vulnerability, i.e. the combination of the physical nature of drought (frequency, severity, extent) and the degree to which a system is vulnerable to the effects of drought. (Shahid and Behrawan, 2008).

Within the drought risk management framework, vulnerability pertains to consequence analysis. The concepts and definitions of vulnerability have been analyzed by many authors. The most common concept of vulnerability is that it describes the degree to which a socio-economic system or physical assets are either susceptible or resilient to the impact of natural hazards (Wilhelmi and Wilhite, 2002). It is determined by a combination of several factors (physical, social, economic, environmental) which are interacting in space and time. These include the conditions of human settlements, the infrastructure, the public policy and administration, the organizational abilities, the social inequalities, the economic patterns, etc. Vulnerability is thus inversely related to the capacity to cope and recover or adapt (Finan et al. 2002). Multiple methods have also been proposed to systematize vulnerability. They can be generally grouped under two perspectives, associated also with the evolution of the concept of vulnerability: (a) the technical or engineering sciences perspective, and (b) the social sciences perspective. The former focuses mostly on the physical aspects of the system and on the assessment of hazards and their impacts, while the role of human systems in mediating the impacts is downplayed (Blaikie et al., 1994; UNDRO, 1980). The social vulnerability perspective focuses on human system and on determining the capacity of the society to cope, respond and recover from the impact of a natural hazard (Blaikie et al., 1994), taking into account various factors that influence vulnerability (physical, economic, social, environmental, institutional) (UNISDR, 2004). Relevant socio-demographic characteristics include age, socio-economic status, experiences, gender, race, and wealth.

During the last decades, various conceptual models and frameworks have been proposed to quantify and measure vulnerability, with their own advantages and drawbacks, such as the “double structure of vulnerability” (Bohle, 2001), the “vulnerability within the context of hazard and risk (Davidson, 1997)”, the “vulnerability in the context of global environmental change community” (Turner et al., 2003), the “holistic approach to risk and vulnerability assessment” (Kappes et al., 2012), and the “Pressure and Release Model (PAR model)” (Wisner et al., 2004). The PAR model focuses on the drivers of vulnerability and their interaction and categorizes them as: (a) “root causes” (e.g. limited access to structures or resources, political and economic settings), (b) “dynamic pressures” (e.g. demographic and social changes, urbanization), and (c) “unsafe conditions” posed by the physical or socio-economic environment. This framework goes beyond the identification of vulnerability into the driving forces rooted in the human-environment system. Additional models include the “Sustainable Livelihood Framework” (Chambers and Conway, 1992), the “UNISDR framework for disaster risk reduction” (UNISDR 2004), the “onion framework” and the “BBC conceptual framework” developed by UNU-EHS (UN University, Institute for Environment and Human Security), the “DROP model (Cutter et al., 2008), and the most recent “MOVE model” (Birkmann et al. 2013). These conceptual models and frameworks incorporate, in general, parameters which reflect the physical, economic, social, environmental, political and institutional dimensions. With regard to the diversity and lack of convergence among all the frameworks and models, Adger (2006) argues that is a strength and sign of vitality, not a weakness of vulnerability research.

While our ability to understand vulnerability is enhanced by these conceptual models, only some of them result in paradigms of quantitative or qualitative drought vulnerability assessments. A vulnerability assessment is the process of identifying, quantifying, and scoring the vulnerabilities in a system (CWCB, 2010), with an ultimate target to identify risk and define priorities, select alternative strategies or formulate new response strategies. Defining quantification criteria and methods is still a challenge (Babel et al., 2011; Downing et al., 2001). The most common assessment methods of vulnerability are vulnerability curves (intensity-damage functions), fragility curves, damage matrices, vulnerability profiles and vulnerability indicators or indices (Kappes et al., 2012). Indicator-based assessments are the most common and widely used, expressing drought vulnerability through a number of proxy indicators or through composite indices (Stathatou et al., 2014). The use of a composite index to assess the vulnerability could result into loss of information or over-simplification, as compared to the use of numerous indicators which allow for a more comprehensive analysis (Hamouda et al., 2009; Komnenic et al., 2009]. On the other hand, the condensed information provided by composite indices allows for a broad variety of issues to be addressed through a single value, and an easy communication to stakeholders and to decision makers, and they have thus been adopted in a number of water-related studies (Raskin, et al., 1997; Huang and Cai, 2009; Alessa et al., 2008). All these assessments have several common aspects, regardless of the framework or school they are based on, as well as limitations which impede their comparability and reproducibility under different areas since they tend to be specific or context-dependent.

As a conclusion it is identified that the various methods and approaches for assessing drought vulnerability (and the resulting risk) are exemplifying the complexity around the issue. This complexity is attributed to the fact that drought vulnerability is (Vogel and O’Brien):

(a) multi-dimensional and differential (it varies for different dimensions of a single element or group of elements and from a physical context to another, with a wide variety of impacts strongly correlated to regional characteristics),

(b) scale dependent (with regard to the unit of analysis e.g. individual, local, regional, national etc.)

(c) dynamic (the characteristics that influence vulnerability are continuously changing in time and space)

This complexity is also further exacerbated by the existing conflicting views on the concept of vulnerability and its constitutive elements and key drivers (Urquijo et al., 2014). Consequently, there are still no universal frameworks, while consensus around the criteria, parameters and thresholds used has not been reached. For example, in developing countries, drought vulnerability constitutes a threat to livelihoods, the ability to maintain productive systems, and economies. In developed economies, drought poses significant economic risks and costs for individuals, public enterprises, commercial organizations, and governments (Downing and Bakker, 2000). Therefore, the selection of vulnerability components is linked to the local study context (UNDP, 2004). The most important goal when developing tools or methods for assessing and quantifying drought vulnerability is their use in supporting risk reduction strategies, and their operational application in the decision-making processes. In this context, it is necessary to know the main objectives of the assessment, the target groups, the end-users of the results and their interpretation of the later (Ciurean, R.L. et al.).

3 METHODOLOGICAL APPROACH

The fact that water scarcity and drought (a) operate on many scales (spatial and temporal) and levels (moderate to severe), (b) are a complex result of both natural and anthropogenic factors, (c) have a wide variety of impacts affecting many economic sectors, and (d) mitigation is highly dependent on the prevailing socio-economic conditions and adaptive capacity of a system, makes it inherently difficult to frame a single pathway into assessing the nature and degree of vulnerability and subsequent risk (Kossida et. al., 2012). Nevertheless, as in all risks associated with climate change, key parameters which hold a central role do exist, and they need to be coherently and scientifically integrated (i.e. exposure, sensitivity, impacts etc.) into a framework which can support accurate communication and consistent analysis, eliminating ambiguous interpretation.

On the basis of this concept the current study followed a stepwise methodology for developing and mapping the Groundwater Drought Vulnerability Profile of the Amman-Zarqa River Basin. **This methodology involves the development of a drought vulnerability profile using a Drought Vulnerability Index (DVI) (Kossida, 2015) focusing on the reliability, sensitivity and resilience of the system.** The Groundwater Drought Vulnerability Map of the Amman-Zarqa River Basin reflects the spatial variability of the proposed Groundwater Drought Vulnerability Index (GDVI) and has been compiled following four methodological steps:

1. Analysis of the components of physical and socio-economic groundwater vulnerability at a disaggregated spatial scale in the basin. In this step, the development of a detailed water resources management/water balance model, which can adequately represent the salient features of the hydrological cycle and the cause-effect relations between the physical (e.g. precipitation, inflows) and socio-economic parameters (e.g. water demand), is deemed necessary.
2. Selection of sub-indicators which can capture the reliability and sensitivity of the investigated system (within the constraints imposed by data availability). The suggested sub-indicators relate to the groundwater over-abstraction and water supply reliability, and can be derived as an output of a detailed water balance model.
3. Calculation and classification of the sub-indicators, and assignment of relevant scores for each calculation unit.
4. Blending of the sub-indicators in GIS, using relevant weights, into a Groundwater Drought Vulnerability Index (GDVI) for each assessment unit.

Groundwater vulnerability to drought and water scarcity in the Amman-Zarqa River Basin cuts across sectoral spheres (i.e. agriculture, domestic, industrial) and is constantly evolving and changing over time and geographic areas. In such a context, where groundwater vulnerability is attributed to numerous factors, the identification of the most pressing factors and the prioritization of corresponding risk management measures are necessary. Thus, in the Amman-Zarqa basin, the total **groundwater over-abstraction** (i.e. abstraction above the groundwater safe yield levels) has been identified as the main pressing factor and impact to mitigate. The volume of groundwater over-abstraction reflects a portion of “unmet water demand” since it has been used to cover part of the water users’ demand which cannot be covered by the sustainable groundwater exploitation levels. Should the groundwater safe yield levels be respected, an unmet demand would have occurred for each economic sector the area of analysis (i.e. agriculture, domestic, industry) equal to the amount that was over-abstracted. This over-abstraction reflects thus the pressure caused on the society by the irregularity of the natural process, and incorporates different vulnerability components which are commonly discussed in literature, such as population, land use, irrigated areas, etc. since these are in fact the main drivers of the water demand (**Error! Reference source not found.**).It also incorporates, indirectly, the current practices in the area of a nalysis, since it is on the basis of these practices that water demand occurs. Should a change in practices (e.g. adoption of water saving measures) be implemented, this would normally be reflected as a decrease in the water demand (rebound effects may of course be applicable here which can hinder the problem) and thus in the level of over-abstraction

Table 3-1: Vulnerability components as captured by the “unmet demand” which lead to over-abstraction

Drivers	Pressures	State
▪ Population ▪ Daily water use per capita ▪ Rate of losses	▪ Domestic Water Demand ▪ Water supply delivered (as a function of availability and priority)	**Unmet demand in the Urban sector, leading to over-abstraction**
▪ Number of nights spent in touristic lodges (hotel, motel, etc.) ▪ Daily water use rate per lodge type (hotel, motel, etc.) ▪ Rate of losses	▪ Touristic Water Demand ▪ Water supply delivered (as a function of availability and priority)	
▪ Animals’ population (per type) ▪ Typical daily water use rates (per animal type) ▪ Rate of losses	▪ Livestock Water Demand ▪ Water supply delivered (as a function of availability and priority)	**Unmet demand in the Agricultural sector, leading to over-abstraction**
▪ Crop types ▪ Irrigated area (per crop type) ▪ Irrigation needs (per crops type) ▪ Combined irrigation efficiency (conveyance, application)	▪ Irrigation Water Demand ▪ Water supply delivered (as a function of availability and priority)	
▪ Number of industrial units/facilities (per type) ▪ Daily water use rate per unit (per industry type) ▪ Return water from industry (inflow minus consumption)	▪ Industrial Water Demand ▪ Water supply delivered (as a function of availability and priority)	**Unmet demand in the Industrial sector, leading to over-abstraction**

On the basis of the groundwater over-abstraction (i.e. the difference between the actual groundwater abstraction and the safe yield), three sub-indicators have been blended into a groundwater vulnerability index, which reflect metrics of reliability, distance to target (to meet demand) and resilience to extreme conditions, as presented below:

REL: percent (%) of years with groundwater over-abstraction within the period of analysis (i.e. 2001-2015). This sub-indicator is used as metrics of "**water supply reliability**".

DIS: Average groundwater over-abstraction within the period of analysis as percentage (%) of the respective total groundwater abstraction. This sub-indicator is used as metrics of "**distance to target**".

EXT: Maximum annual groundwater over-abstraction within the period of analysis as percentage (%) of the respective total groundwater abstraction of that same year. This sub-indicator is used as metrics of "**resilience to extreme conditions**".

To calculate these three sub-indicators, model output data of groundwater over-abstraction for 15 years have been used and applied across all sectors (agriculture, domestic, industry). A water resources management model of the Amman-Zarqa River Basin has been developed in WEAP21 for the period 2001-2015 for that purpose, and the output of the model was used to feed the necessary data for the calculation of the above sub-indicators. These sub-indicators have been applied across all sectors, but can also be applied per sector, if desired, thus flagging out the most vulnerable sectors. Table 3-2 to Table 3-4 present the suggested classification of the above sub-indicators.

Table 3-2: Classification of the REL sub-indicator

% of years with groundwater over-abstraction	Score / Class
0-19%	1 - low
20-39%	2 – moderate
40-59%	3 – high
>60%	4 – very high

Table 3-3: Classification of the DIS sub-indicator

Average groundwater over-abstraction as % of Total abstraction	Score / Class
0-9%	1 – low
10-19%	2 - moderate
20-29%	3 - high
>30%	4 - very high

Table 3-4: Classification of the EXT sub-indicator

Maximum annual groundwater over-abstraction as % the total abstraction of the corresponding year	Score / Class

0-19%	1 – low
20-39%	2 – moderate
40-59%	3 – high
>60%	4 – very high

Upon calculation and classification of the above 3 sub-indicators, these are then blended into a Groundwater Drought Vulnerability Index (GDVI) using equal weights, using the following equation:

$$GDVI = \frac{score_{REL} + score_{DIS} + score_{EXT}}{3} \quad (1)$$

In case different weights (i.e. not equal) need to be used, then the score of each sub-indicators should be multiplied by a relevant weight θ_i. In the current analysis equal weights have been preferred over variable weights since a calibration process against observed impacts is not been feasible at the current stage.

The GDVI values are expected to range from 1-4 (less to more vulnerable to the drought hazard) since all the sub-indicators scores are 1-4 and their relevant weights are all equal. The following classification is proposed for the GDVI values (Table 3-5).

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Table 3-5: Classification of the Groundwater Drought Vulnerability Index (GDVI)

GDVI value	Vulnerability class
1.00 – 1.49	1 – low
1.50 – 2.49	2 – moderate
2.50– 3.49	3 – high
3.49 – 4.00	4 – very high

The GDVI can be obtained at different spatial and temporal scales depending on the level of the desired analysis. On the basis of the GDVI, vulnerability maps for the area of interest can be derived (River Basin District, River basin, sub-catchments) to allow for any easy visualization and comparisons.

4 GROUNDWATER DROUGHT VULNERABILITY ANALYSIS IN THE AMMAN-ZARQA CATCHMENT

4.1 Land uses contributing to drought vulnerability

The Amman-Zarqa is considered one of the most important basins and aquifer systems in terms of water supply. Five Governorates fall within the basin's boundaries, namely the Amman, Zarqa, Jerash, Balqa, Mafraq Governorates (Figure 4-1). The basin hosts about 60% of Jordan's population (Al-Omari et al., 2009), including two main cities (Amman and Zarqa), and more than 85% of the industries in Jordan (about 60 industrial units). The main industrial activities in the basin include the al-Hussein thermal power plant, oil refinery, textile industries, paper processing, leather production, food Industries, distilleries, drugs and chemical industries, intermediate petrochemicals, engineering industries, paper and carton products and mining industries (Al-Qaisi, 2010), while their majority is located within the Zarqa Governorate. Irrigation is also practiced in this basin with a growing trend since the early 1980s (Al-Bakri et al., 2013), located in two main zones. The first zone is to the east of Mafraq City (Mafraq Governorate) and includes farms of olives, fruit trees and vegetables (Al-Bakri, 2015). The second zone is located between As-Samra WWTP and the King Talal Dam (Jarash, Zarqa and Mafraq Governorates) and includes irrigated farms of forage, olives, and fruit trees and nurseries plantations. Natural forests occurring in the mountainous part are composed of oak, pine, juniper, wild olive and cypress (Al-Qaisi, 2010). The different land use covers in the Amman-Zarqa basin, both total statistics in the basin and per Governorate, are depicted in Tables 4-1 to 4-3. Land use in Amman-Zarqa basin has undergone considerable changes (Al-Qaisi, 2015). The expansion of Amman and surrounding towns has been extensive: large areas of grazing land and more fertile agricultural lands between Amman and other towns have now developed into a sprawling urban conglomerate (Shammout et al., 2018). Considering the abovementioned facts, the basin is the most important area in Jordan where competition on ground and surface water resources is taking place among the different sectors (Al-Bakri, 2015) and a mix of water demands must be covered.

Figure 4-1: Governorates within the Amman-Zarqa catchment boundaries

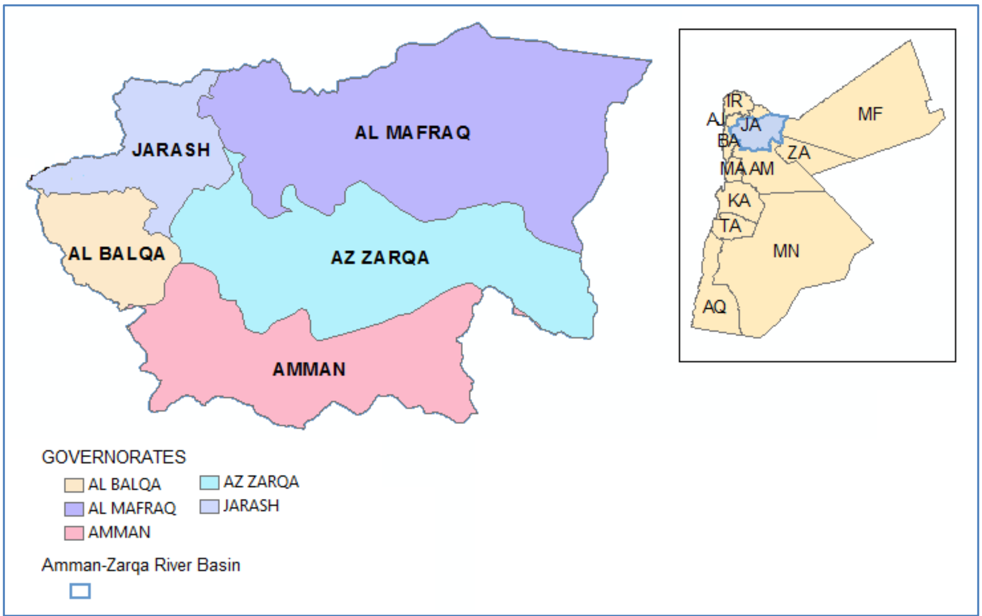


Table 4-1: Land uses in the Amman-Zarqa basin

Land Uses	Area covered (km^2)	Area covered (%)
Urban areas	360.36	10.02 %
Irrigated areas	181.28	5.04 %
Forests	84.59	2.35 %
Other land uses	2,969.59	82.58 %
Industrial units (number of)	61	
Total area (km^2) of the AZ basin	**3,595.82**	**100 %**

Source: based on data provided by the MWI

Table 4-2: Main irrigated crops in the Amman-Zarqa basin

Irrigated crops	Area covered (km^2)	Area covered (%)
Vegetables	77.37	42.68%
Fruit trees	41.18	22.72%
Olives (medium cover)	26.81	14.79%
Olives (high cover)	19.66	10.85%
Olives (low cover)	3.39	1.87%
Forage	6.38	3.52%
Mixed crops	4.39	2.42%
Plastic houses	1.49	0.82%
Nursery, plantation	0.61	0.34%
Total irrigated (km^2)	**181.28**	**100 %**

Source: based on data provided by the MWI

Table 4-3: Land use per Governorate within the Amman-Zarqa basin

Land Uses per Governorate within the AZ Basin	Amman	Zarqa	Mafraq	Jarash	Balqa
Urban areas (km²)	190.59	82.26	51.16	16.67	16.09
Irrigated areas (km²)	0.95	43.77	124.59	4.88	6.76
Forests (km²)	4.03	4.61	4.53	45.48	25.94
Industrial units (number of)	6	38	10	1	5
Total area (km²) of the Governorate within the AZ basin	**735.29**	**947.79**	**1327.49**	**320.14**	**254.71**

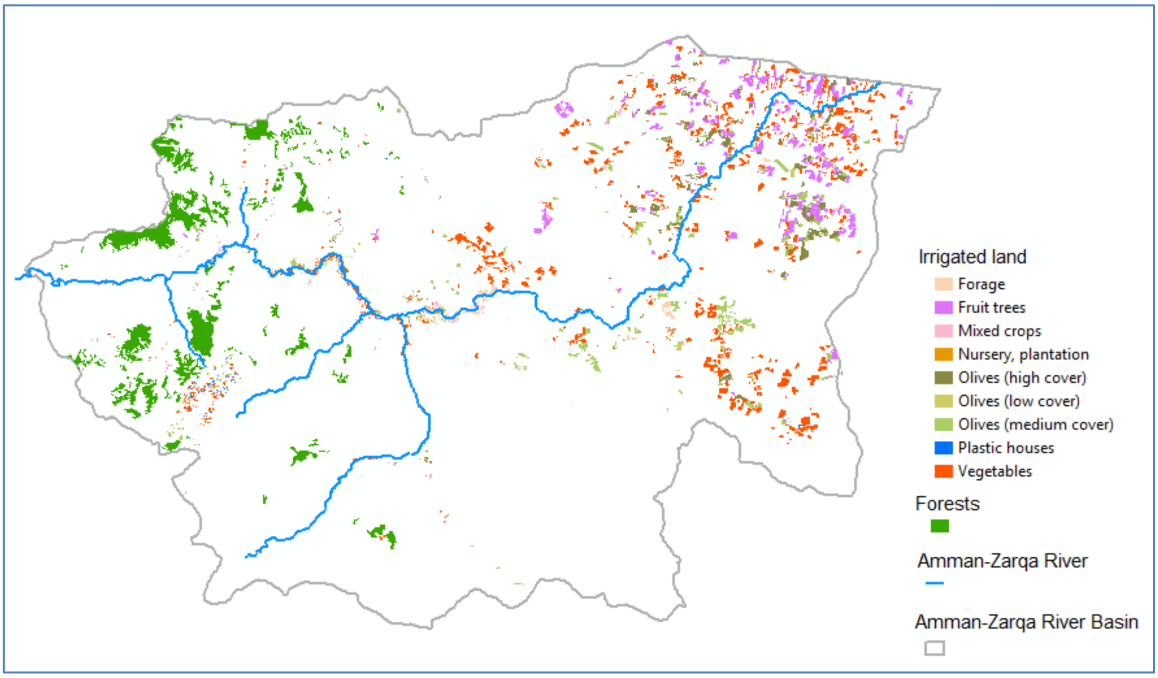
Source: based on data provided by the MWI and GIS analysis

Groundwater is the main supply used to cover the water demand of the different sectors (domestic, agriculture, irrigation) in the basin. About 137.74 million cubic meters (MCM) are annually abstracted on average and supplied to the users, while the groundwater safe yield is 88 MCM. It is thus apparent that an average over-abstraction of about 50 MCM/year is occurring, on average, annually. Other sources of irrigation water in this basin are the treated wastewater and the water harvested in earth dams in Hallabat area. The amounts of treated wastewater in year 2013 were 91 MCM from As-Samra wastewater treatment plant (WWTP), 4.9 MCM from Baq'a, 1 MCM from Abu Nusier and 1.3 from Al-Mira'd WWTP, summing up to a total of 98 MCM. According to MWI, the agreements with farmers include the use of about 15 MCM of this amount for irrigating forage, olives and nursery plantations (Al-Bakri, 2015).

To gain a better insight of the water demand and supply in the basin, and further investigate the prevailing groundwater over-abstraction, a water resources management model has been developed for the Amman-Zarqa catchment using the WEAP21[2] software from the SWIM-H2020 project experts. The model was set-up around 15 water demand and supply sites (nodes), representing the three main sectors (domestic, agriculture, industry) and the 5 Governorates which fall within the catchment boundaries (Amman, Zarqa, Jerash, Balqa, Mafraq) (Figure 4.1). The distribution of the relevant land uses (as previously described), related to these nodes, are depicted in Figure 4-2 and Figure 4-3.

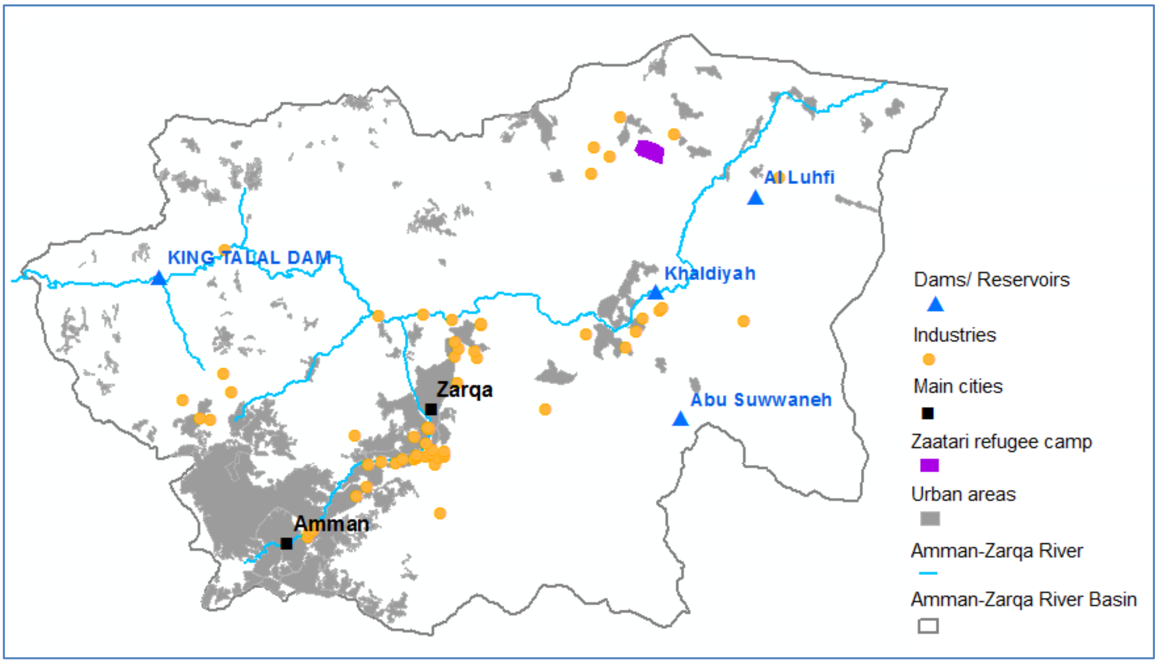
[2] "Water Evaluation And Planning" system (WEAP), Stockholm Environment Institute (SEI) - U.S. Center, www.weap21.org

Figure 4-2: Land use (irrigation and forestry) in the Amman-Zarqa catchment



Source: based on data provided by the MWI

Figure 4-3: Land use (urban areas and industries) in the Amman-Zarqa catchment



Source: based on data provided by the MWI

According to the Amman-Zarqa WEAP model results, the groundwater abstracted and supplied to the users for the years 2001-2015 is presented in Table 4-4 below. An average of 137.7 MCM/year are abstracted from groundwater and supplied to all users, ranging from 127.3 (year 2006) to 147.5 (year 2010). Regarding the monthly variation, less water is on average supplied during February, and the months of April, June, September, while more water is supplied during the remaining months. The deviation is about 0.38-1.12 MCM (or 3-11%) (Figure 4-5). With regard to the water supplied at each Governorate, most groundwater is supplied to the Mafraq Governorate (66.60 MCM/year on average for the period 2001-2015), followed by the Zarqa Governorate (45.37 MCM/year on average for the period 2001-2015), and the Amman Governorate (16.11 MCM/year on average for the period 2001-2015). The groundwater supplied to the Balqa and Jerash Governorates are 6.43 and 3.23 MCM/year respectively (Figure 4-4). The monthly variation is depicted in Figure 4-6. Finally, with regard to the highest and lowest water consuming sectors, most groundwater is supplied for domestic/ urban use (70.33 MCM/year on average for the period 2001-2015), closely followed by the agricultural use (60.92 MCM/year on average for the period 2001-2015) (Figure 4-4). Less water, about 6.48 MCM/year is supplied for industrial water use. The monthly variation is depicted in Figure 4-7.

Figure 4-4: Average annual groundwater abstraction in the Amman-Zarqa catchment for the period 2001-2015 per Governorate (left) and sector (right) (units in million cubic meters MCM/year)

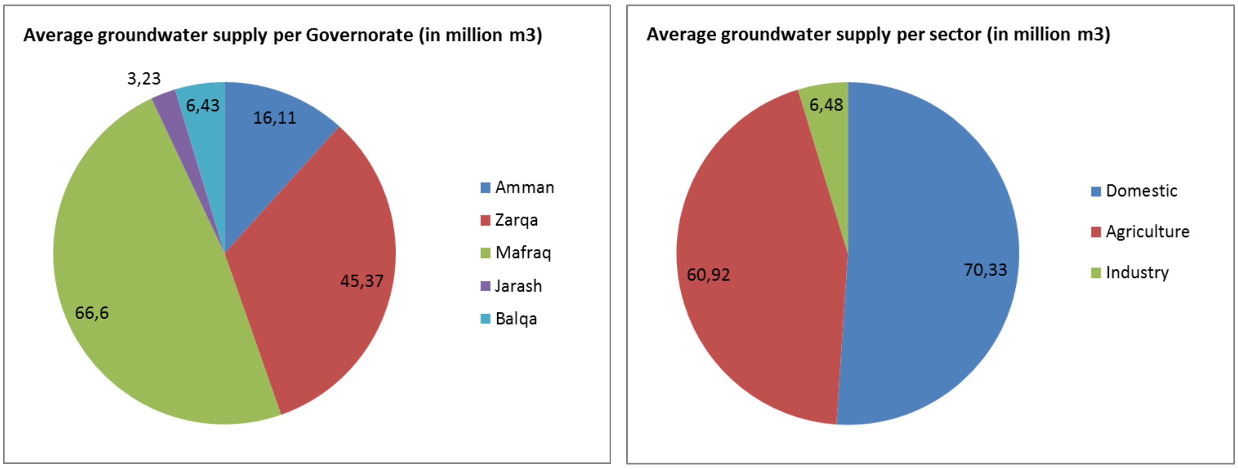
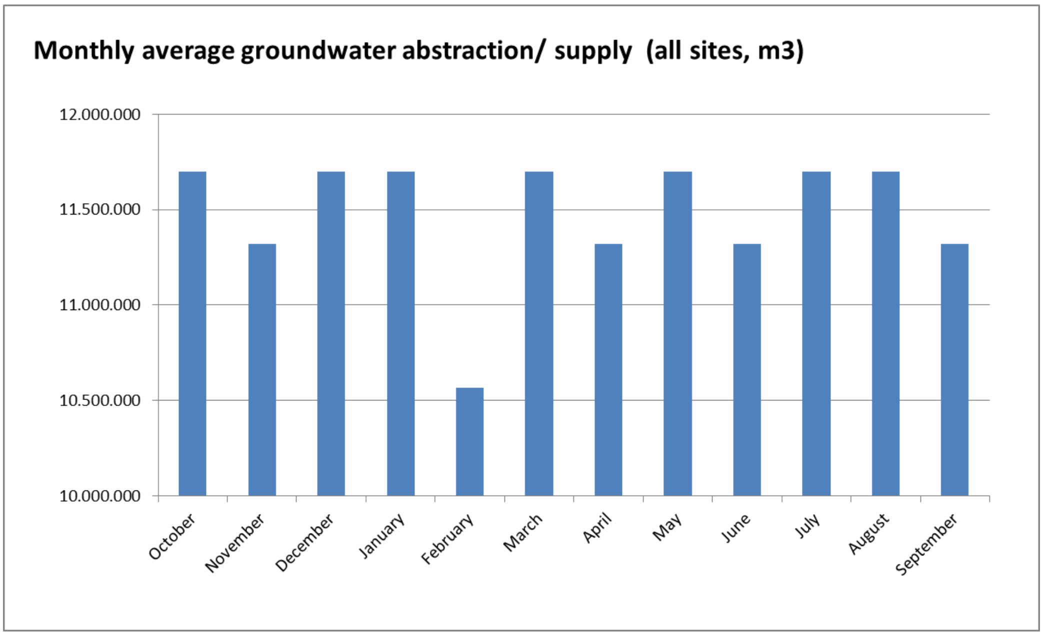


Table 4-4: Groundwater abstracted and supplied for use to the Amman-Zarqa basin (per year and per demand site; units in million cubic meters MCM/year)

DEMAND SITES/ NODES	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2012	2014	2015	SUM	AVERAGE
Amman Agricultural	0,54	0,55	0,68	0,87	0,75	0,78	0,82	1,07	1,30	1,26	1,08	1,05	1,01	0,61	1,50	13,86	0,92
Amman Domestic	15,59	18,03	18,73	15,19	15,94	10,28	14,39	17,35	16,51	15,66	14,10	14,83	14,70	10,37	13,54	225,19	15,01
Amman Industrial	0,03	0,14	0,12	0,14	0,19	0,12	0,12	0,11	0,19	0,27	0,25	0,33	0,23	0,16	0,20	2,60	0,17
Balqa Agricultural	3,28	2,99	2,55	2,77	2,87	2,66	2,64	2,68	2,43	2,18	2,27	2,13	2,28	2,15	1,81	37,68	2,51
Balqa Domestic	5,50	4,48	3,53	3,56	2,80	4,20	3,73	3,27	3,27	3,24	3,53	3,99	3,73	3,12	2,76	54,71	3,65
Balqa Industrial	0,29	0,27	0,21	0,24	0,18	0,15	0,17	0,23	0,30	0,39	0,42	0,34	0,33	0,26	0,28	4,06	0,27
Jerash Agricultural	1,99	1,75	1,40	1,34	1,62	1,63	1,51	1,59	1,77	1,60	1,80	2,12	2,19	2,60	1,99	26,89	1,79
Jerash Domestic	1,48	1,04	0,86	1,54	1,26	1,30	1,43	1,33	1,32	2,07	1,61	1,62	1,36	1,51	1,67	21,42	1,43
Jerash Industrial	0,00	0,00	0,02	0,00	0,02	0,00	0,01	0,00	0,00	0,01	0,01	0,01	0,01	0,02	0,01	0,12	0,01
Mafraq Agricultural	22,90	28,94	30,57	36,00	37,34	36,34	40,17	39,14	44,94	44,70	45,91	45,53	43,53	53,38	51,81	601,20	40,08
Mafraq Domestic	29,71	31,66	31,44	29,30	27,20	26,11	23,11	22,90	20,94	25,07	24,19	24,05	22,44	23,79	23,03	384,94	25,66
Mafraq Industrial	0,51	0,28	0,21	1,36	0,83	0,60	1,17	0,60	0,88	1,08	1,45	1,14	1,92	0,45	0,36	12,85	0,86
Zarqa Agricultural	20,41	19,28	18,87	18,11	17,10	15,39	15,13	14,11	14,19	13,63	13,24	15,03	14,22	14,22	11,31	234,23	15,62
Zarqa Domestic	22,26	21,35	21,65	21,48	21,52	22,51	28,03	28,37	27,94	29,95	30,50	29,63	21,56	19,42	22,56	368,74	24,58
Zarqa Industrial	4,89	4,92	5,00	4,89	5,63	5,19	5,18	5,72	5,55	6,38	5,51	5,02	4,87	4,67	4,21	77,61	5,17
TOTAL	**129,4**	**135,7**	**135,8**	**136,8**	**135,3**	**127,3**	**137,6**	**138,5**	**141,5**	**147,5**	**145,9**	**146,8**	**134,4**	**136,7**	**137,0**	**2066,1**	**137,7**

Figure 4-5: Monthly average groundwater abstraction in the Amman-Zarqa catchment for the period 2001-2015



Source: based on data provided by the MWI

Figure 4-6: Monthly average groundwater supply per Governorate in the Amman-Zarqa catchment for the period 2001-2015

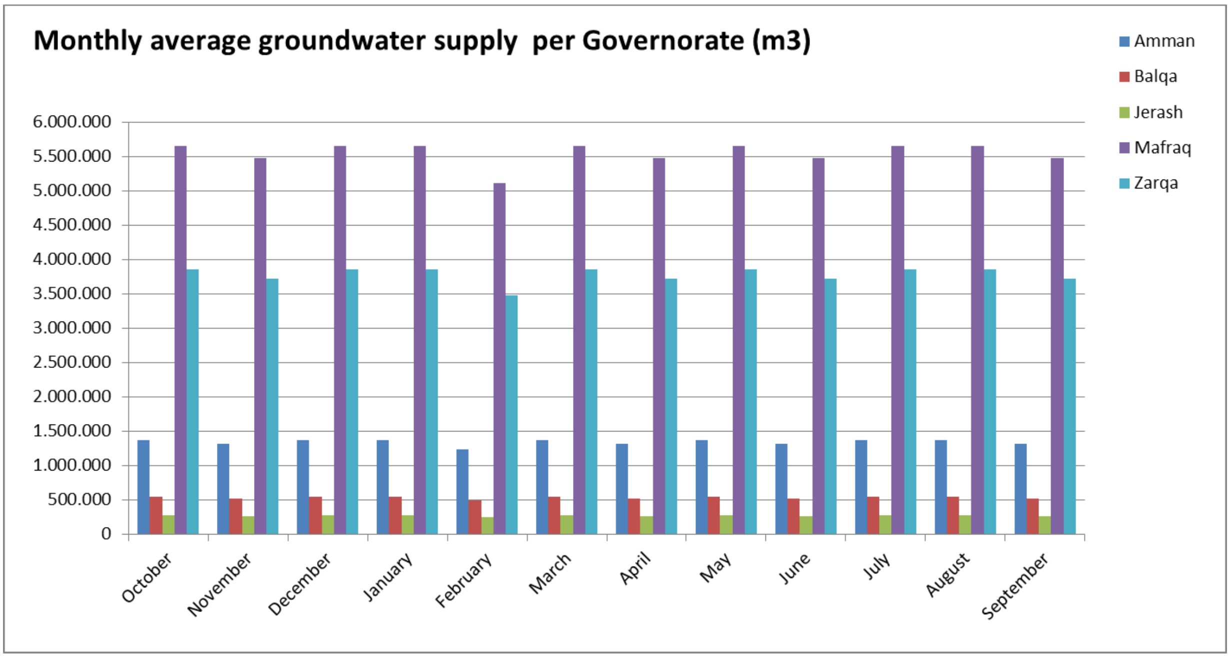
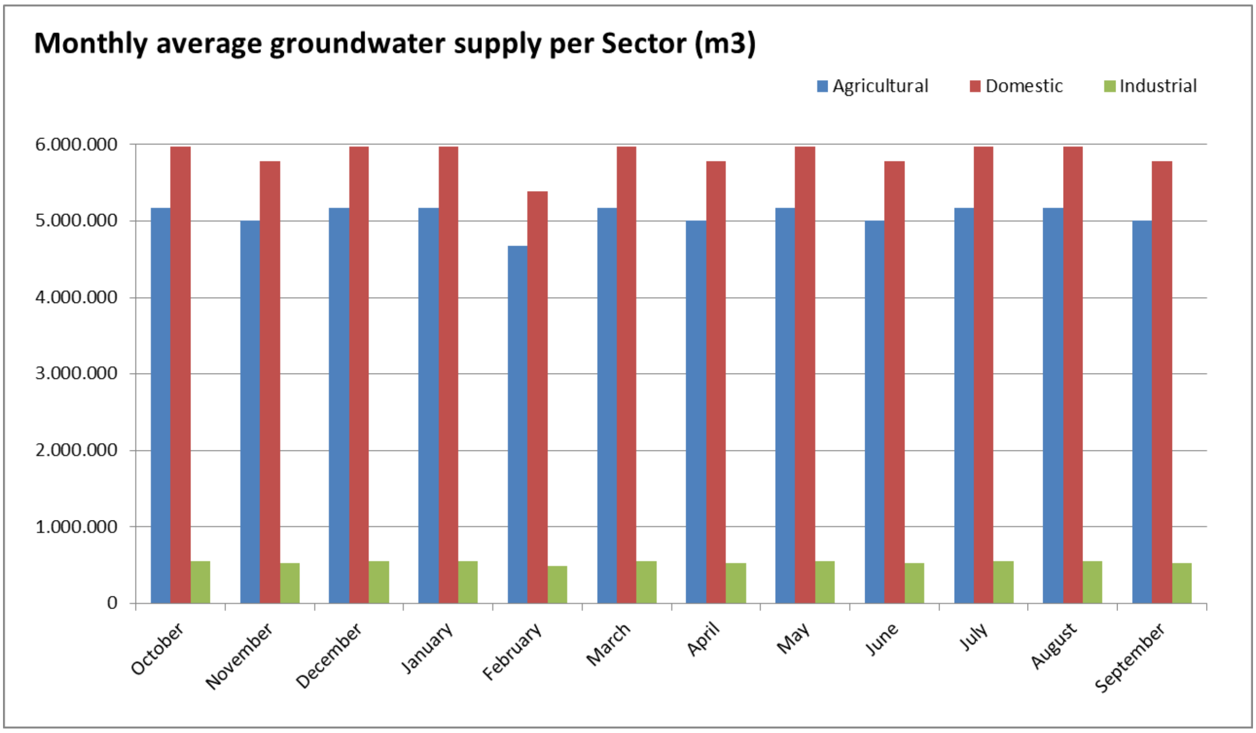


Figure 4-7: Monthly average groundwater supply per Sector in the Amman-Zarqa catchment for the period 2001-2015



4.2 Results of the application of the GDVI

The Groundwater Drought Vulnerability Index (GDVI) described in the previous Chapter has been applied in the Amman-Zarqa catchment for the period 2001-2015. For obtaining the necessary groundwater over-abstraction data, the water resources management model developed by the SWIM-H2020 SM project experts for the Amman-Zarqa catchment (in WEAP21 software) has been used. This model was set-up around 15 water demand sites (nodes), representing three sectors (domestic, agriculture, industry) and 5 Governorates which fall within the catchment boundaries (Amman, Zarqa, Jerash, Balqa, Mafraq) (Figure 4-1). The relevant land uses related to these demands (urban, industrial, agricultural) have been presented in the previous section 4.1. The water demands in the 15 demand sites were not modelled using activity level functions (i.e. related to the per capita water requirements or the irrigated crop water requirements); instead the model considered the supply delivered at each site. Thus, the demand in each site (node) was set to be equal to the groundwater supply delivered at each site respectively. The idea behind this modelling approach is that this amount of actual groundwater abstraction (which is used to cover the demand) will be compared in WEAP with the natural groundwater recharge values originated in Amman-Zarqa basin. The WEAP model then behaves like a comparative model analysis between the two amounts of groundwater recharge and groundwater abstraction. The difference between these two volumes indicates where over-abstraction is occurring. If the actual abstraction (i.e. groundwater supplied to cover demand) is higher that the natural recharge (i.e. the safe yield) then over-abstraction is evident in the basin. In this case the amount of over-abstraction is considered as "unmet demand" since it should not have been used for water supply in the first place. If the actual abstraction isn less than the safe yield, then there is no groundwater over-abstraction during the period investigated. It is evident that this modelling approach may underestimate the actual unmet demand, which might be higher than the difference between groundwater abstractions and safe yield. Given the fact that no disaggregated data on water demands per sector and per site were available in the Amman-Zarqa catchment, this approach has been deemed adequate as a first trial into estimating the GDVI.

The groundwater over-abstraction for each demand site (node) and year for the period 2001-2015 is presented in Table 4-6 below. The average over-abstraction in the whole basin is 49.6 MCM, ranging from 39.8 in 2005 to 60.0 in 2010 (about +/- 22%), and a standard deviation of 6.5 MCM (Table 4-5). This volume represents about 36% of the total groundwater abstracted and supplied to the users. Most over-abstraction occurs in the Mafraq_Agriculture (14.5 MCM/year on average) and the Mafraq_Domestic (9.2 MCM/year on average) nodes, followed by the Zarqa_Domestic (8.9 MCM/year), Zarqa_Agricultural (5.6 MCM/year) and Amman_Domestic (5.4 MCM/year). All industrial nodes present 0-0.35 MCM/year groundwater over-abstraction, with the exception of Zarqa_Industrial (1.9 MCM/year).

Table 4-5: Summary statistics of groundwater over-abstraction in the Amman-Zarqa basin for the period 2001-2015

Annual groundwater over-abstraction	MCM / year
Mean	49.57
Median	49.29
Standard error	1.69
Maximum	59.99 (year 2010)
Minimum	38.32 (year 2005)
Range	21.67
Standard deviation	6.54
Variance	42.71
Sum of the period 2001-2015 (15 years)	743.60 MCM

Table 4-6: Groundwater over-abstraction in the Amman-Zarqa basin (per year and per demand site; units in million cubic meters MCM/year)

DEMAND SITES/ NODES	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2012	2014	2015	SUM	AVERAGE
Amman Agricultural	0,17	0,19	0,19	0,31	0,26	0,24	0,30	0,39	0,49	0,51	0,43	0,42	0,35	0,22	0,54	5,04	0,34
Amman Domestic	5,05	6,40	5,29	5,47	5,63	3,21	5,24	6,39	6,31	6,37	5,64	5,99	5,13	3,73	4,90	80,75	5,38
Amman Industrial	0,01	0,05	0,03	0,05	0,07	0,04	0,04	0,04	0,07	0,11	0,10	0,13	0,08	0,06	0,07	0,95	0,06
Balqa Agricultural	1,06	1,06	0,72	1,00	1,01	0,83	0,96	0,99	0,92	0,88	0,90	0,86	0,79	0,77	0,65	13,41	0,89
Balqa Domestic	1,78	1,59	0,99	1,28	0,99	1,31	1,36	1,20	1,25	1,32	1,41	1,61	1,30	1,12	1,00	19,50	1,30
Balqa Industrial	0,09	0,10	0,06	0,09	0,06	0,05	0,06	0,08	0,11	0,16	0,17	0,14	0,12	0,09	0,10	1,47	0,10
Jerash Agricultural	0,64	0,62	0,39	0,48	0,57	0,51	0,55	0,58	0,67	0,65	0,72	0,86	0,76	0,94	0,72	9,66	0,64
Jerash Domestic	0,48	0,37	0,24	0,55	0,44	0,40	0,52	0,49	0,50	0,84	0,64	0,65	0,47	0,54	0,60	7,76	0,52
Jerash Industrial	0,00	0,00	0,00	0,00	0,01	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,04	0,00
Mafraq Agricultural	7,42	10,28	8,63	12,98	13,19	11,36	14,63	14,41	17,16	18,18	18,38	18,40	15,18	19,22	18,73	218,15	14,54
Mafraq Domestic	9,62	11,25	8,87	10,56	9,61	8,16	8,41	8,43	8,00	10,20	9,68	9,72	7,83	8,57	8,33	137,23	9,15
Mafraq Industrial	0,16	0,10	0,06	0,49	0,29	0,19	0,43	0,22	0,33	0,44	0,58	0,46	0,67	0,16	0,13	4,71	0,31
Zarqa Agricultural	6,61	6,85	5,32	6,53	6,04	4,81	5,51	5,20	5,42	5,55	5,30	6,07	4,96	5,12	4,09	83,37	5,56
Zarqa Domestic	7,21	7,58	6,11	7,74	7,60	7,04	10,21	10,45	10,67	12,18	12,21	11,97	7,52	6,99	8,16	133,64	8,91
Zarqa Industrial	1,58	1,74	1,41	1,76	1,98	1,62	1,88	2,10	2,11	2,59	2,20	2,03	1,70	1,68	1,52	27,90	1,86
TOTAL	41,87	48,18	38,32	49,29	47,76	39,77	50,10	50,97	54,03	59,99	58,38	59,33	46,85	49,22	49,55	743,60	49,57

The monthly variation of the groundwater over-abstraction is depicted in Figure 4-8, where it is observed that over-abstraction occurs from June to November, with the highest picks in the months of August, September and October, and a monthly average variation from 0 (in February) to 9.1 (in August) m^3 /month. With regard to the abstraction for each Governorate, most over-abstraction occurs in the Mafraq Governorate (24 MCM/year on average for the period 2001-2015), followed by the Zarqa Governorate (16.37 MCM/year on average for the period 2001-2015), and the Amman Governorate (5.8 MCM/year on average for the period 2001-2015). The groundwater over-abstraction for the Balqa and Jerash Governorates are 3.3 and 1.2 MCM/year respectively. The annual variability is presented in Figure 4-9, while the monthly variation is depicted in Figure 4-10. Finally, with regard to the water using sectors, most groundwater over-abstraction occurs for domestic/ urban use (25.26 MCM/year on average for the period 2001-2015), closely followed by the agricultural use (21.98 MCM/year on average for the period 2001-2015). Less water, about 2.34 MCM/year is over-abstracted for industrial water use. The annual variability is presented in Figure 4-11, while monthly variation is depicted in Figure 4-12.

Figure 4-8: Monthly average groundwater over-abstraction in the Amman-Zarqa catchment for the period 2001-2015

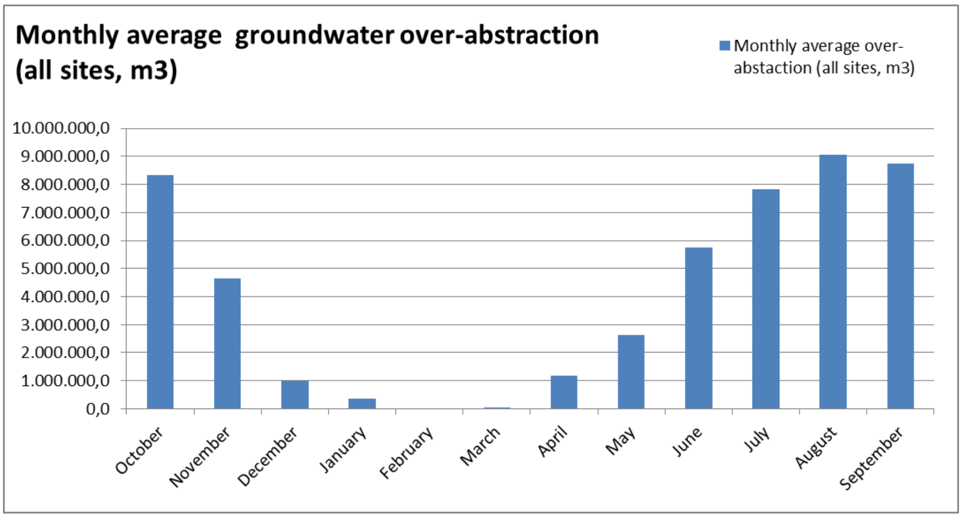


Figure 4-9: Annual groundwater over-abstraction per Governorate in the Amman-Zarqa catchment for the period 2001-2015

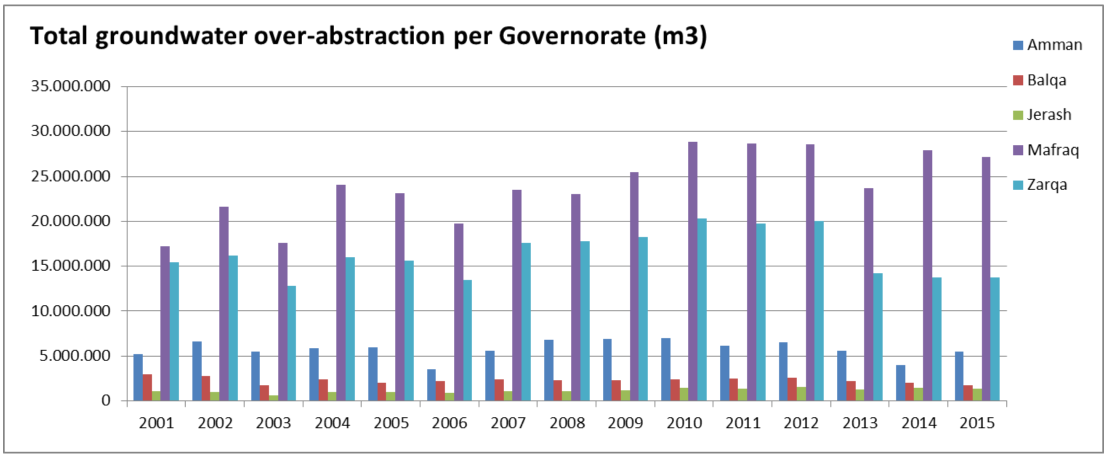


Figure 4-10: Monthly average groundwater over-abstraction per Governorate in the Amman-Zarqa catchment for the period 2001-2015

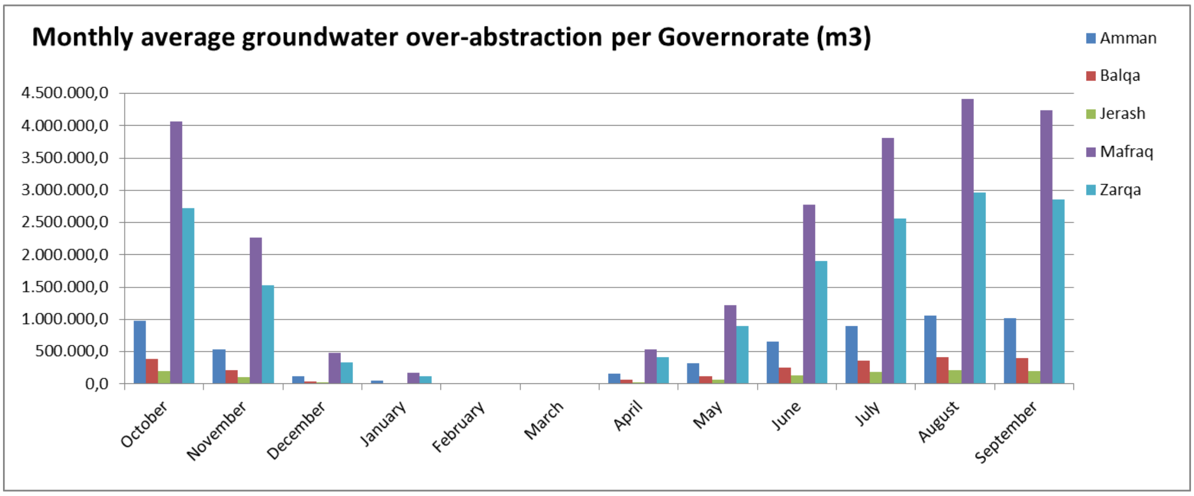


Figure 4-11: Annual groundwater over-abstraction per Sector in the Amman-Zarqa catchment for the period 2001-2015

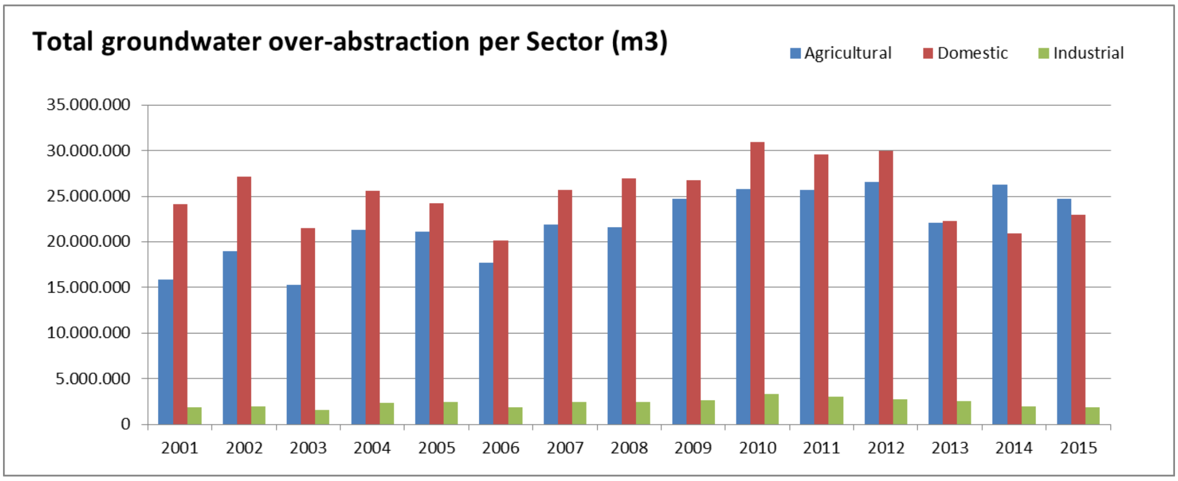
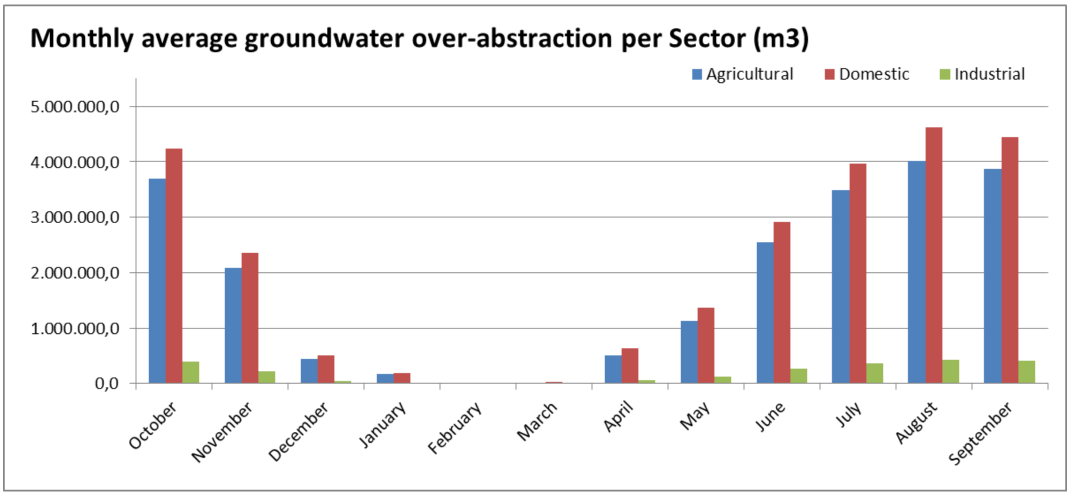


Figure 4-12: Monthly average groundwater over-abstraction per Sector in the Amman-Zarqa catchment for the period 2001-2015



The Reliability of the system in supplying the requested demand differs among the uses. Reliability is defined as the percent of the time steps in which a demand site (node) was fully satisfied. For example, if a demand site has over-abstractions in 9 months out of a 15-year scenario, the reliability would be ((15 * 12) - 9) / (15 * 12) = 95%. The reliability (i.e. the percent of the requirements met without over-abstraction) in the Amman-Zarqa catchment varies from month to month, with higher reliability rates (above 90%) observed in December through March, medium vulnerabilities observed in November, April and May (59-89%), and low reliabilities in June through October (50-23%) (Figure 4-13). The months with the lowest reliability are August (22.7%) and September, while the highest reliability is observed in February (100%) and March (99.7%) (Table 4-7). All the demand sites demonstrate the same reliability per month, with the exception of the Jerash industrial demand which has higher reliability rates.

Figure 4-13: Monthly reliability (%) of each demand site in the Amman-Zarqa catchment for the period 2001-2015

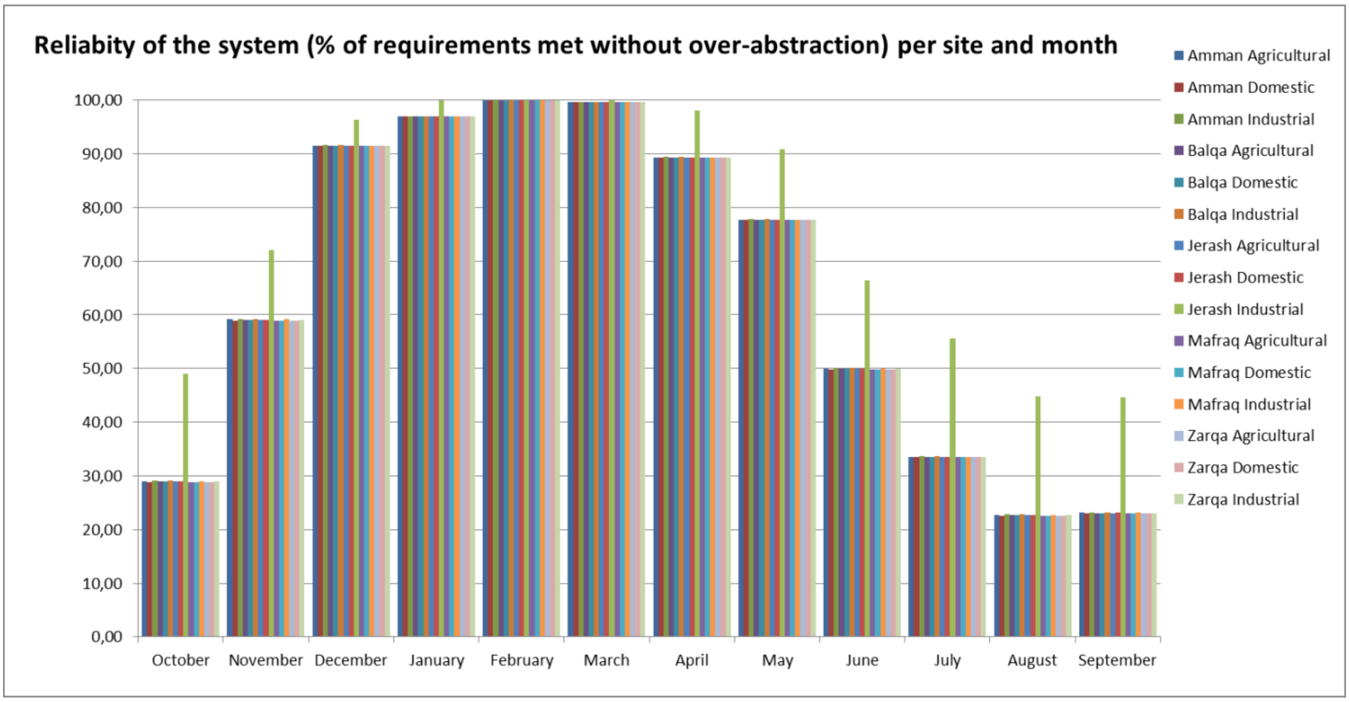


Table 4-7: Percent (%) of months that fall under the 4 reliability classes (very low, low, medium, high, very high) for the 15-year period 1995-2010 in the Amman-Zarqa basin

Reliability class	% of Months	Respective months
Very High (>95%)	25.0% (3 months)	January, February, March
High (85-95%)	16.7% (2 months)	April, December
Medium (70-85%)	8.3% (1 month)	May
Low (50-70%)	8.3% (1 month)	November
Very Low (<50%)	33.3% (4 months)	July, August, September, October

As mentioned previously, the Amman-Zarqa model output data of over-abstraction have been used to feed the calculation of the three GDVI sub-indicators applied across all sectors (domestic, agriculture, livestock, industry) as follows:

REL: percent (%) of years with groundwater over-abstraction within the period of analysis. This sub-indicator is used as metrics of “water supply reliability”.

DIS: Average groundwater over-abstraction within the period of analysis as percentage (%) of the respective total groundwater abstraction. This sub-indicator is used as metrics of “distance to target”.

EXT: Maximum annual groundwater over-abstraction within the period of analysis as percentage (%) of the respective total groundwater abstraction of that same year. This sub-indicator is used as metrics of “resilience to extreme conditions”.

On the basis of the results, each of the 15 demand sites (nodes) has been classified into a class (1 being a low, to 4 being a very high vulnerability class) for each sub-indicator, following the classification proposed in Chapter 3 (Table 3-2 to Table 3-4). The values and score for each sub-indicator are provided per catchment in the Table 4-8 below.

Table 4-8: Results and classes for the REL, DIS and EXT sub-indicator for each demand site

Demand sites (nodes)	REL sub-indicator			DIS sub-indicator		EXT sub-indicator			
	Number of years with groundwater over-abstraction	% of years with groundwater over-abstraction	REL sub-indicator Class	Annual average groundwater over-abstraction as % of the Total groundwater Abstraction	DIS sub-indicator Class	Maximum groundwater over-abstraction (m^3)	Year of maximum groundwater over-abstraction	Max groundwater over-abstraction as % of the Total groundwater Abstraction of that year	EXT sub-indicator Class
Amman Agricultural	15	100%	4	36.4%	3	542,223	2015	36.1%	3
Amman Domestic	15	100%	4	35.9%	3	6,402,272	2002	35.5%	3
Amman Industrial	15	100%	4	36.7%	3	133,398	2012	40.3%	4
Balqa Agricultural	15	100%	4	35.6%	3	1,060,904	2002	35.4%	3
Balqa Domestic	15	100%	4	35.6%	3	1,776,013	2001	32.3%	3
Balqa Industrial	15	100%	4	36.3%	3	166,412	2011	39.8%	3
Jerash Agricultural	15	100%	4	35.9%	3	935,683	2014	36.0%	3
Jerash Domestic	15	100%	4	36.2%	3	843,085	2010	40.6%	4
Jerash Industrial	10	67%	4	35.2%	3	6,940	2014	35.8%	3
Mafraq Agricultural	15	100%	4	36.3%	3	19,220,202	2014	36.0%	3
Mafraq Domestic	15	100%	4	35.7%	3	11,245,921	2002	35.5%	3
Mafraq Industrial	15	100%	4	36.7%	3	667,647	2013	34.8%	3
Zarqa Agricultural	15	100%	4	35.6%	3	6,847,283	2001	33.6%	3
Zarqa Domestic	15	100%	4	36.2%	3	12,209,471	2011	40.0%	4
Zarqa Industrial	15	100%	4	35.9%	3	2,594,289	2010	40.6%	4

The above 3 sub-indicators calculated for each demand site, have been blended into a Groundwater Drought Vulnerability Index (GDVI) using equal weights, using the following equation:

$$DVI = \frac{score_{REL} + score_{DIS} + score_{EXT}}{3} \qquad \text{[Eq. 1]}$$

The resulting GDVI values range from 1-4 (less to more vulnerable to the drought hazard) since all the sub-indicators scores are 1-4 and their relevant weights are all equal. The classification proposed for the GDVI values in Chapter 3 (Table 3-5) has been applied, and the resulting GDVI values per demand site are provided in the Table below (Table 4-9).

Table 4-9: Results and classes for the Groundwater Drought Vulnerability Index (GDVI) for each demand site for the period 2001-2015 in the Amman-Zarqa catchment

Demand sites (nodes)	Drought Vulnerability Index (DVI) value	Vulnerability Class
Amman Agricultural	3.33	3
Amman Domestic	3.33	3
Amman Industrial	3.67	4
Balqa Agricultural	3.33	3
Balqa Domestic	3.33	3
Balqa Industrial	3.33	3
Jerash Agricultural	3.33	3
Jerash Domestic	3.33	3
Jerash Industrial	3.67	3
Mafraq Agricultural	3.33	3
Mafraq Domestic	3.33	3
Mafraq Industrial	3.67	3
Zarqa Agricultural	3.33	3
Zarqa Domestic	3.33	4
Zarqa Industrial	3.33	4

Out of the 15 demand sites (nodes), 3 are classified in class 4 (very high vulnerability), while the reaming 12 are in class 3 (high vulnerability) when analyzing the entire period 2001-2015. In terms of percentages, a 26.7% of the sites are within the very high vulnerability class and 73.3% within the high vulnerability class. The sites with very high groundwater vulnerability to drought are the Amman_Industrial, the Jerash_Domestic, the Zarqa_Domestic and the Zarqa_Industrial nodes. This differentiation is attributed to the EXT sub-indicator with depicts the maximum annual groundwater over-abstraction within the period of analysis as percentage (%) of the respective total groundwater abstraction of that same year and aims to represent metrics of “resilience to extreme conditions”. With regard to the other two sub-indicators (REL, DIS) their scores are homogeneous across the sites.

The same analysis has been performed at the Governorate level, by summing-up all the over-abstraction occurring from all 3 demand sites within each Governorate. The results of the analysis are presented in Table 4-10, while the resulting GDVI values and classes are presented in Table 4-11 below.

Table 4-10: Results and classes for the REL, DIS and EXT sub-indicator for each Governorate

Governorates	REL sub-indicator	DIS sub-indicator	EXT sub-indicator

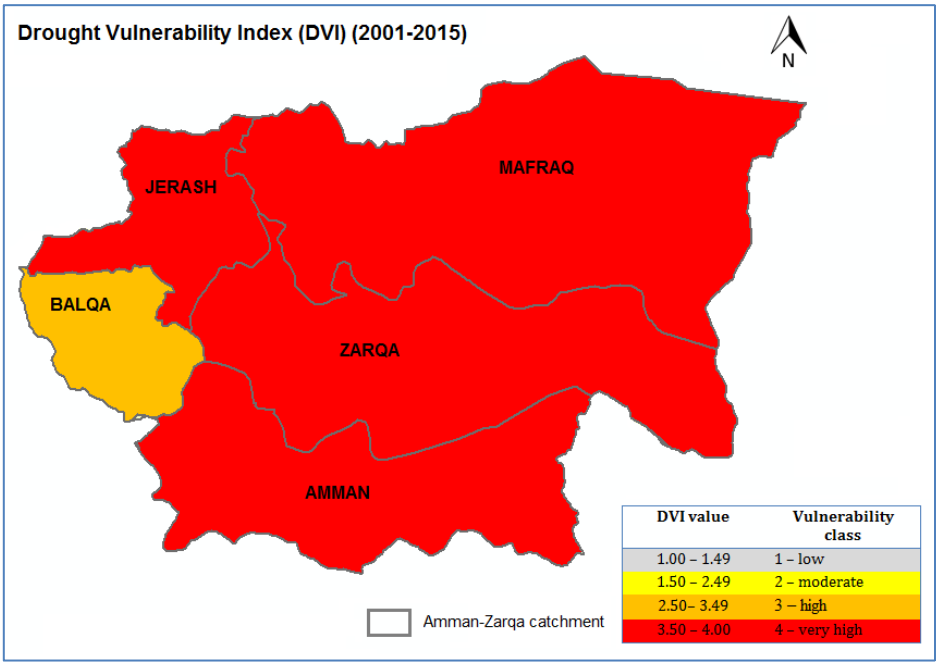
	Number of years with groundwater over-abstraction	% of years with groundwater over-abstraction	REL sub-indicator Class	Annual average groundwater over-abstraction as % of the Total groundwater Abstraction	DIS sub-indicator Class	Maximum groundwater over-abstraction (m^3)	Year of maximum groundwater over-abstraction	Max groundwater over-abstraction as % of the Total groundwater Abstraction of that year	EXT sub-indicator Class
Amman	15	100%	4	35.9%	3	6,988,564	2010	40.7%	4
Balqa	15	100%	4	35.6%	3	2,928,855	2001	32.3%	3
Jerash	15	100%	4	36.1%	3	1,514,341	2012	40.4%	4
Mafraq	15	100%	4	36.0%	3	28,820,192	2010	43.2%	4
Zarqa	15	100%	4	36.0%	3	20,322,037	2010	40.7%	4

Table 4-11: Results and classes for the Groundwater Drought Vulnerability Index (GDVI) for each demand site for the period 2001-2015 in the Amman-Zarqa catchment

Governorates	Drought Vulnerability Index (DVI) value	Vulnerability Class
Amman	3.67	4
Balqa	3.33	3
Jerash	3.67	4
Mafraq	3.67	4
Zarqa	3.67	4

Out of the 5 Governorates, 4 are overall classified in class 4 (very high vulnerability), namely Amman, Jerash, Mafraq and Zarqa. The Balqa Governorate is under the high vulnerability class (class 3). A map of the resulting GDVI for the entire 2001-2015 period, is provided below (Figure 4-14) at the Governorate level. It is clear of course, as predicted from the analysis of the results at the node level, that variability in terms of drought vulnerability classes within each Governorate and across its different water users does exist. It also has to be noticed that the GDVI reflects the groundwater vulnerability to drought as a result of the prevailing over-abstractions. The overall vulnerability of the hydro-system to drought, if analysed on the basis of the total actual unmet demand (for which data are not currently available) might give a different picture, since in some areas, the use of surface water from dams and treated wastewater alleviates the problem of unmet demand in agriculture (e.g. Hallabat area, As-Samra area, etc.).

Figure 4-14: The GDVI in the Amman-Zarqa catchment at the Governorate level for the period 2001-2015



5 CONCLUSIONS

The Amman-Zarqa is considered one of the most important basins and aquifer systems in terms of water supply. Five Governorates fall within the basin's boundaries, namely the Amman, Zarqa, Jerash, Balqa, Mafraq Governorates. The basin hosts about 60% of Jordan's population (Al-Omari et al., 2009), including two main cities (Amman and Zarqa), and more than 85% of the industries in Jordan (about 60 industrial units). The expansion of Amman and surrounding towns has been extensive: large areas of grazing land and more fertile agricultural lands between Amman and other towns have now developed into a sprawling urban conglomerate (Shammout et al., 2018). Considering the abovementioned facts the basin is the most important area in Jordan where competition on ground and surface water resources is taking place among the different sectors (Al-Bakri, 2015) and a mix of water demands must be covered.

To assess the balance between groundwater availability and supply, and the resulting groundwater drought vulnerability, a distributed physical-based model of the Amman-Zarqa basin has been developed using WEAP21 software, containing 15 water demand sites (nodes), representing three sectors (domestic, agriculture, industry) and the 5 Governorates (Amman, Zarqa, Jerash, Balqa, Mafraq) which fall within the catchment boundaries for the period 2001-2015. The water demand in each site (node) was set to be equal to the groundwater supply delivered at each site respectively. The idea behind this modelling approach is that this amount of actual groundwater abstraction (which is used to cover the demand) will be compared in WEAP with the natural groundwater recharge values originated in Amman-Zarqa basin. The difference between these two volumes indicates where over-abstraction is occurring. If the actual abstraction (i.e. groundwater supplied to cover demand) is higher than the natural recharge (i.e. the safe yield) then over-abstraction is evident in the basin. If the actual abstraction in less than the safe yield, then there is no groundwater over-abstraction during the period investigated. It is evident that this modelling approach presents some limitation as it may underestimate the actual unmet demand, which might be higher than the difference between groundwater abstractions and safe yield. Given the fact that no disaggregated data on water demands per sector and per site were available in the Amman-Zarqa catchment, this approach has been deemed adequate as a first trial into estimating the groundwater vulnerability to drought.

According to the model results for the simulation period 2001-2015, 137.7 MCM/year are abstracted on average from groundwater and supplied to all users, ranging from 127.3 (year 2006) to 147.5 (year 2010). Most groundwater is supplied to the Mafraq Governorate (66.60 MCM/year on average for the period 2001-2015), followed by the Zarqa Governorate (45.37 MCM/year on average), and the Amman Governorate (16.11 MCM/year on average). The groundwater supplied to the Balqa and Jerash and Jerash Governorates are 6.43 and 3.23 MCM/year respectively. With regard to the highest and lowest water consuming sectors, most groundwater is supplied for domestic/ urban use (70.33 MCM/year on average), closely followed by the agricultural use (60.92 MCM/year on average). Less water, about 6.48 MCM/year is supplied for industrial water use.

The average over-abstraction in the whole basin is 49.6 MCM, ranging from 39.8 in 2005 to 60.0 in 2010 (about +/- 22%), and a standard deviation of 6.5 MCM. This volume represents about 36% of the total groundwater abstracted and supplied to the users. Most over-abstraction occurs in the

Mafraq_Agriculture (14.5 MCM/year on average) and the Mafraq_Domestic (9.2 MCM/year on average) nodes, followed by the Zarqa_Domestic (8.9 MCM/year), Zarqa_Agricultural (5.6 MCM/year) and Amman_Domestic (5.4 MCM/year). All industrial nodes present 0-0.35 MCM/year groundwater over-abstraction, with the exception of Zarqa_Industrial (1.9 MCM/year). Groundwater over-abstraction occurs from June to November, with the highest picks in the months of August, September and October, and a monthly average variation from 0 (in February) to 9.1 (in August) m3 /month. With regard to the abstraction for each Governorate, most over-abstraction occurs in the Mafraq Governorate (24 MCM/year on average for the period 2001-2015), followed by the Zarqa Governorate (16.37 MCM/year on average for the period 2001-2015), and the Amman Governorate (5.8 MCM/year on average for the period 2001-2015). The groundwater over-abstraction for the Balqa and Jerash Governorates are 3.3 and 1.2 MCM/year respectively. With regard to the water using sectors, most groundwater over-abstraction occurs for domestic/ urban use (25.26 MCM/year on average for the period 2001-2015), closely followed by the agricultural use (21.98 MCM/year on average). Less water, about 2.34 MCM/year is over-abstracted for industrial water use. The reliability (i.e. the percent of the requirements met without over-abstraction) in the Amman-Zarqa catchment varies from month to month, with higher reliability rates (above 90%) observed in December through March, medium vulnerabilities observed in November, April and May (59-89%), and low reliabilities in June through October (50-23%). The months with the lowest reliability are August (22.7%) and September, while the highest reliability is observed in February (100%) and March (99.7%). All the demand sites demonstrate the same reliability per month, with the exception of the Jerash industrial demand which has higher reliability rates.

The Amman-Zarqa model output data of over-abstraction have been used to feed the calculation of three groundwater drought vulnerability sub-indicators applied across all sectors (domestic, agriculture, livestock, industry), which have been blended into a Groundwater Drought Vulnerability Index (GDVI) using scores and equal weights. The three sub-indicators represent metrics of “water supply reliability”, “distance to target” and “resilience to extreme conditions”. The GDVI has been classified in 4 vulnerability classes, from low to very high, across all demand nodes. Out of the 15 demand sites (nodes), 3 nodes (i.e. 26.7% of the demand sites) are classified in class 4 (very high vulnerability), while the reaming 12 nodes (i.e. 73.3% of the demand sites) are in class 3 (high vulnerability) when analyzing the entire period 2001-2015.The sites with very high groundwater vulnerability to drought are the Amman_Industrial, the Jerash_Domestic, the Zarqa_Domestic and the Zarqa_Industrial nodes. At the Governorate level, 4 out of the 5 Governorates (i.e. 80%) are overall classified in class 4 (very high vulnerability), namely Amman, Jerash, Mafraq and Zarqa. The Balqa Governorate is under the high vulnerability class (class 3). It is clear of course, as predicted from the analysis of the results at the node level, that variability in terms of drought vulnerability classes within each Governorate and across its different water users does exist.

The vulnerability of the groundwater to drought conditions is assessed based on the current groundwater abstraction practices. Should demand increase, or should availability declines, groundwater over-abstraction might be even more significant in order to cover the needs. On the other hand, should more surface water or treated wastewater is used for agricultural purposes, the over-abstraction might be reduced and thus the resulting groundwater drought vulnerability. It has to be noticed that the GDVI reflects the groundwater vulnerability to drought as a result of the prevailing over-abstractions. The overall vulnerability of the hydrosystem to drought, if analysed on the basis of the total actual unmet demand (for which data are not currently available) might give a different picture, since in some areas the use of surface water from dams and treated wastewater alleviates the problem of unmet demand in agriculture (e.g. Hallabat area, As-Samra area, etc.). The finding of the current study are depicting that the groundwater resources in the Amman-Zarqa are highly vulnerable to drought due to the hidh level of over-abstraction above the groundwater safe yield. The study presents limitations in the fact that the actual water demands per sector have not been fully assessed due to data limitation issues. The current study and modelling approach should be extended to simulate the actual total water demands in the basin (on the basis of data or proxies) and assess the total resulting unmet demand in order to have a better understanding of the possible future development and trends in groundwater over-abstraction, as well as an estimation of the entire system vulnerability to drought (i.e. not just groundwater) using an all-inclusive Drought Vulnerability Indicator (DVI). In this direction the following extensions of the work are suggested:

- Integration of the actual water demands per sector with the current model
- Disaggregation on the modelled areas in 5 sub-catchments
- Investigate the interactions with other neighbouring basins in terms of water supply
- Simulate and assess the cost-effectiveness of different measures and interventions to manage demand across the key water-consuming sectors and reduce groundwater over-abstraction\
- Simulate future climatic and socio-economic projection and assess the impact on the water resources of the basins under the Business as Usual (BaU) scenario and alternative policy scenarios whch include the implementation of a mix of demand management measures and interventions
- Build a Link with the MODFLOW/SWAT models at National-Wide Scale to have better data on the surface and groundwater mass balances
- Gather data on observed/ experienced impacts to calibrate the future Drought Vulnerability Indicator (DVI).

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