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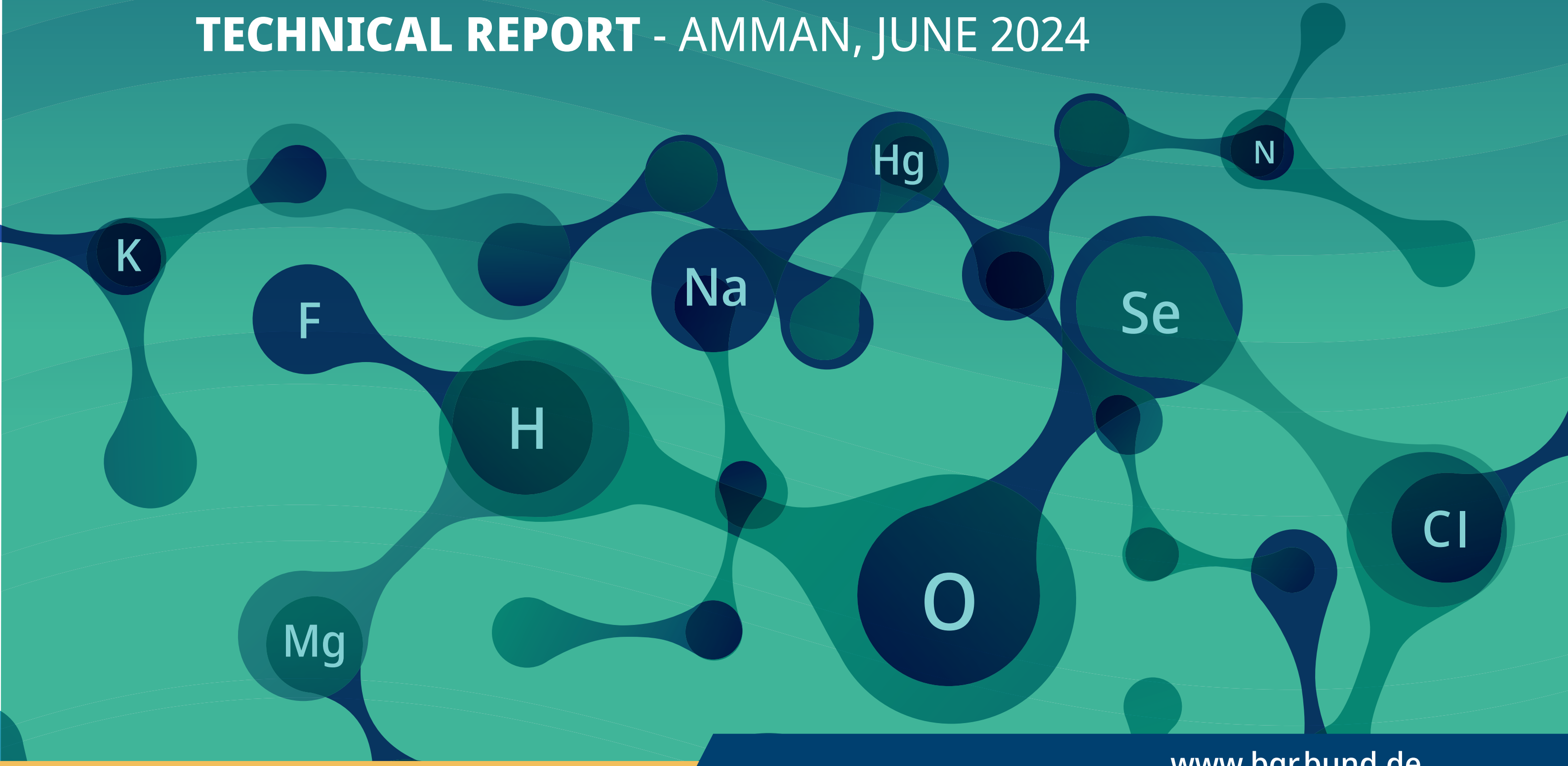
WATER AUTHORITY

GROUNDWATER RESOURCES MANAGEMENT IN JORDAN

Nationwide Groundwater Quality Baseline 2020-23

Inorganic Hydrochemistry Results of the Annual Groundwater Sampling 2022 and the Nationwide Well Sampling 2020-2023

TECHNICAL REPORT - AMMAN, JUNE 2024



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GROUNDWATER RESOURCES MANAGEMENT IN JORDAN

Nationwide Groundwater Quality Baseline

Inorganic Hydrochemistry Results of the Annual Groundwater Sampling 2022 and the Nationwide Well Sampling 2020-2023

TECHNICAL REPORT - AMMAN, JUNE 2024

In the framework of the German-Jordanian technical cooperation financed by the Federal Ministry for Economic Cooperation and Development (BMZ), the Ministry of Water and Irrigation (MWI) and the Federal Institute for Geosciences and Natural Resources (BGR) implement the project "Groundwater Resources Management, Jordan".

Jordan is one of the most water-scarce countries in the world, and groundwater is the main source to meet domestic, industrial and agricultural water demands. Significant groundwater abstractions have resulted in declining groundwater levels in nearly all aquifers and triggered a deterioration of the water quality, which could lead to further drinking water treatment.

In order to assess the current groundwater quality situation in Jordan, BGR together with the Laboratory of the Water Authority of Jordan (WAJlab), conducted a nationwide baseline study between 2020 to 2023. The focus of this study was to survey the current general hydrochemistry, electrical conductivity and nitrate distribution and to identify areas with trace element contaminations.

The last nationwide study including groundwater quality was conducted in the 1990s by the BGR (Hobler et al., 1991, Hobler et al., 2001). Since then, several local to regional studies focusing on specific topics have been performed (e.g. Al Kuisi et al., 2009, Al Kuisi et al., 2010, Al Kuisi et al., 2015, El-Naqa, 2010, Dorsch et al., 2020, GIZ, 2020). Amongst those, an assessment of the declining water resources in Northern Jordan (GIZ, 2020) identified the need for a wide-spread systematic mapping of trace elements and parameters of concern for water quality.

In this study, the BGR together with the WAJlab conducted a nationwide field campaign to collect samples for the analysis of an extensive hydrochemical parameter suite and the comparison against Jordanian Drinking Water Specifications for inorganic parameters. This study did not address microbiology, radioactivity or organic pollutants and was limited to the monitoring locations available for the survey.

The details of the fieldwork as well as the results of the analysed samples are presented in this report. These results are only representative for the groundwater quality encountered at the monitoring locations and may not show the actual drinking water quality of a specific area.

Acknowledgments

This study was accomplished in close cooperation with the staff from the laboratory of the Water Authority of the Hashemite Kingdom of Jordan. We greatly acknowledge the significant contributions by the laboratory staff to the field campaigns and analyses, whose direct involvement in the project was a pre-requisite for success. Furthermore, we highly appreciate the cooperation and support from Yarmouk Water Company and Miyahuna Water and thank both for kindly supplying historical water quality data. Finally, the authors wish to thank everyone else who contributed to the success of this study.

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Abbreviations

Abbreviation	Meaning
AGS	Annual Groundwater Sampling
bgl	Below ground level
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (German Federal Institute for Geosciences and Natural Resources)
BGRlab	Water laboratory of BGR
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (German Federal Ministry for Economic Cooperation and Development)
A7/B2	Hydrogeological Unit of Wadi As Sir and Amman Formation
B3	Hydrogeological Unit Muwaqqar Formation
B4/B5	Hydrogeological Unit of Umm Rijam and Wadi Shallala Formations
EC	Electric conductivity
GW	Groundwater
JDWS	Jordanian Drinking Water Specification (JSMO 286/2015)
LoD	Limit of Detection
LoQ	Limit of Quantification
Ministry ID	Unique code for a single spring or production well usually consisting of a combination of letter and numbers (e.g., AL3484 for the Znayya 4 production well)
MWI	Ministry of Water and Irrigation of the Hashemite Kingdom of Jordan
NWS	Nationwide Well Sampling
PBE	Palestine Belt East (coordinates)
PBN	Palestine Belt North (coordinates)
TE	Trace Elements
TDS	Total Dissolved Solids
TH	Total Hardness
WAJ	Water Authority of Jordan
WAJlab	Water Authority of Jordan Laboratories
WWTP	Wastewater Treatment Plant

1.

Introduction

Jordan is one of the most water-scarce countries in the world. Groundwater is the main water supply source and is used for domestic, industrial, and agricultural purposes. Low groundwater recharge, combined with high abstraction rates due to agricultural and industrial activities and a continuously increasing population has led to the “mining” of groundwater. The abstraction of the “old” groundwater (>5000 years old in many places) leads to a subsequent decline in water level (>1 m/year in some areas) (MWI & BGR, 2019, Brückner et al., 2021; Gropius et al., 2022).

The subsequent drawdown may induce the intrusion of more saline waters, and the mobilization of trace elements from the aquifer rocks

Due to this, the Jordanian water supply is increasingly at risk in regard to water quantity as indicated by various studies (MWI & BGR, 2019). Less known are the risks with regard to water quality: The subsequent drawdown may induce the intrusion of more saline waters, and the mobilization of trace elements from the aquifer rocks. Furthermore, agricultural and industrial activities may serve as a direct source for anthropogenic contamination. In many areas, the groundwater water quality has decreased to a state, where additional water treatment is necessary before further usage. Increasing salinity, nitrate and trace element concentrations are of big concern, as associated treatments severely increase the costs for water production, which are already extremely high in international comparison.

As part of the Jordanian-German technical cooperation and funded by the German Federal Ministry for Economic Cooperation and Development (BMZ), BGR and MWI have been working together since many years on different topics in the field of groundwater resources in the Hashemite Kingdom of Jordan. After predominantly working on the monitoring and development of groundwater quantity (e.g. MWI & BGR, 2019), this study focuses on the state of the groundwater quality.

In the past, groundwater quality monitoring campaigns in Jordan took place mostly on a case triggered base connected to a specific event, as for example the inauguration of a new production well or the monitoring of a local groundwater quality contamination. Regular water resource monitoring mostly consisted of raw (drinking) water monitoring at locations that combine groundwater from several different monitoring location, for example pumping stations or pipelines. This form of monitoring is useful to test the product to be delivered to the consumer for the compliance of the raw water quality with drinking water standards. However, it is ill-suited for improving the understanding of hydrogeological and hydrochemical processes in groundwater.

When various undesirable changes in the raw water quality continued to challenge the water suppliers, BGR supported WAJ in initiating an Annual Groundwater Sampling program (AGS) of approximately 80 monitoring sites across Jordan. This monitoring program aims at (i) surveying the state of groundwater quality in Jordan, (ii) gaining a more thorough understanding of the overall groundwater quality trends and (iii) identifying the drivers behind the groundwater quality changes. The first round of the AGS took place in 2021/22 and comprised 79 groundwater samples from springs and production wells.

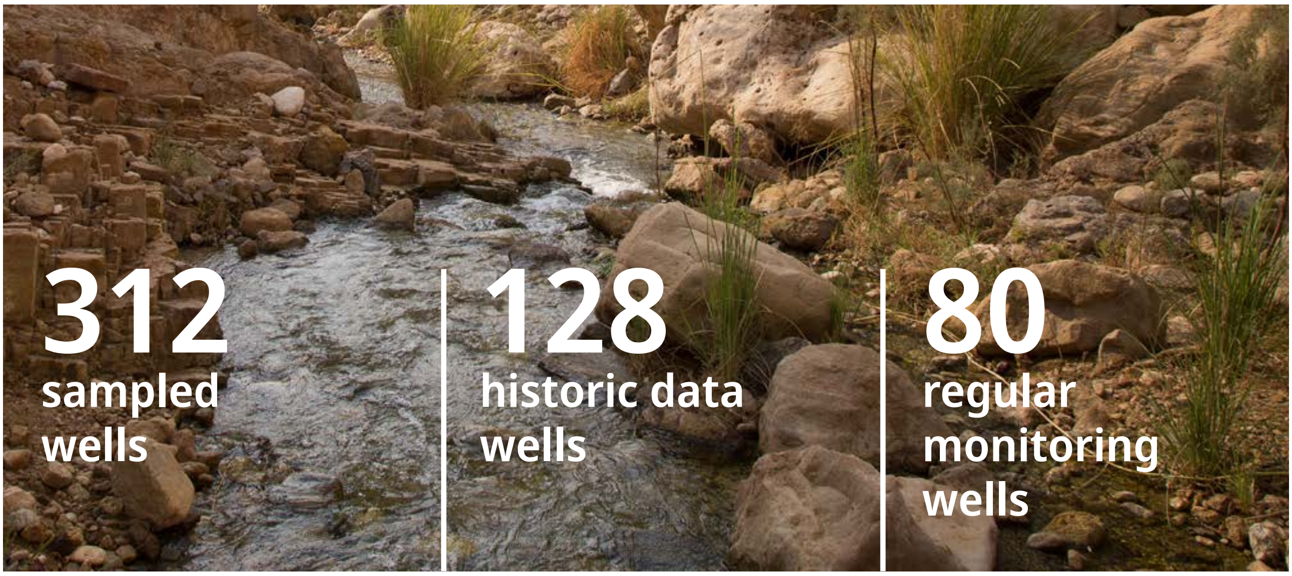
In addition to this regular monitoring program, BGR conducted a comprehensive Nationwide Well Sampling (NWS) in order to contextualize the results of the AGS and to survey the current state of groundwater quality in greater detail. Between the years 2020 and 2023, over 300 groundwater samples were collected from production wells across Jordan and analysed for a wide set of parameters.

This study presents the results from the NWS and from the first round of the AGS and aims at creating a nationwide hydrochemical baseline on the basis of these samples. It is complemented by recent groundwater quality analyses (2020-2023) from local groundwater quality surveys, conducted by WAJlab, Yarmouk Water Company and Miyahuna. In total, 520 sampling locations across Jordan were included in this study. Furthermore, historical data was included for selected monitoring points to analyze trends in water quality.

The study focuses on salinity (TDS), various nitrogen species (nitrate, nitrite, ammonia), fluoride, and a set of trace elements, of which nickel and oxyanions such as Mo, Se, and V are considered the most relevant for the Jordanian context. The study did not include an assessment of organic or (micro) biological parameters, nor an assessment of radioactivity. Nevertheless, these topics are considered important and should be investigated in future studies.

> Focus on salinity, nitrogen species, fluoride and trace elements

Due to the missing documentation of well design and completion, the majority of the water samples could not be uniquely assigned to a specific aquifer and may constitute mixed groundwater from all aquifers intersected by the screens. For simplicity, these water samples were still termed groundwater samples, but they are subject to constraints regarding generalisation. Similar constraints also apply for water samples from locations where local effects are suspected. Even though substantial effort was invested in 520 locations, the data set is still insufficient for a meaningful spatial interpolation, as local effects prevail at many locations, constraining geostatistical approaches. Consequently, all monitoring locations are displayed as point data on a map to report the observed parameter variability. Some generalization was achieved by grouping the parameters into large concentration categories based on the Jordanian Drinking Water Specifications (JSMO 286/2015). Furthermore, it was not possible to sample all wells of relevance in the Jordanian groundwater context due to time and access constraints.



312 sampled wells

128 historic data wells

80 regular monitoring wells

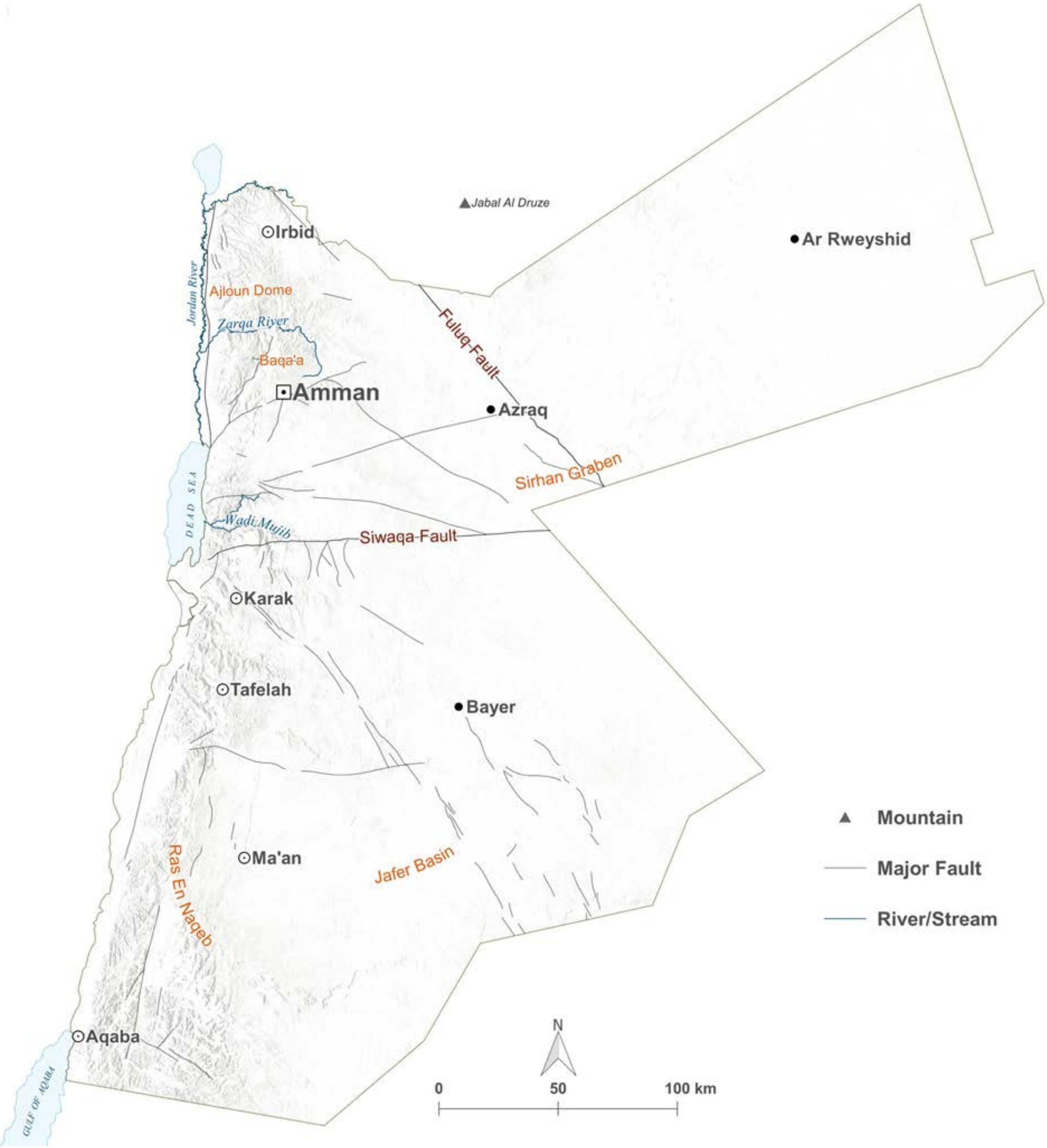


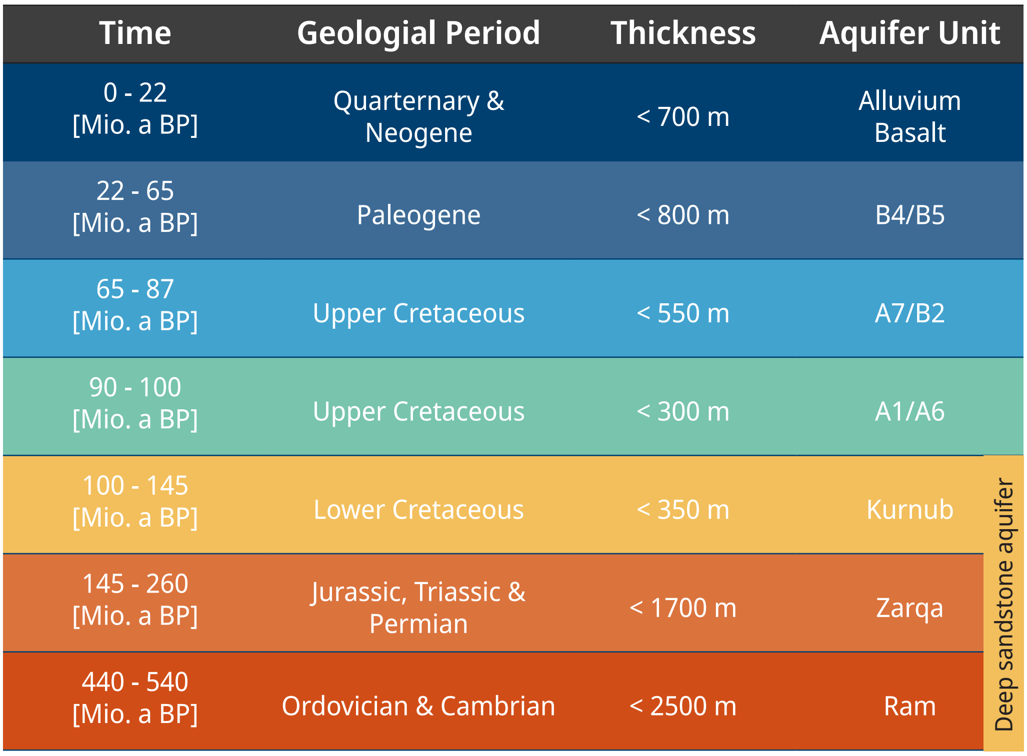
Figure 1: The Hashemite Kingdom of Jordan with major tectonic faults and geographical features.

2. Hydrogeological Setting

The hydrogeology of Jordan has been described in detail in many previous studies. This section is based on “Groundwater Resources of Northern Jordan – Contributions to the Hydrogeology of Northern Jordan” (Hobler et al., 2001), Geology of Jordan (Bender, 1974) and the Contributions to the Hydrogeology of Northern and Central Jordan (Margane et al., 2002).

The hydrogeology of Jordan consists of different aquifers (permeable) and aquitards (impermeable). They form an alternating succession of sedimentary layers, which has been investigated since the 1970s (Bender, 1974). While aquitards act as confining units between the different aquifers, aquifers convey water to wells. Therefore, the focus in this study lies on the relevant aquifers in Jordan, presented in Figure 2.

Aquitards are important factors for groundwater protection and quality, but will not be examined closely here, as they are rarely the targets for groundwater abstraction. The same applies to the magmatic/metamorphic basement rocks, which are mostly considered impermeable.



Time	Geologial Period	Thickness	Aquifer Unit	
0 - 22 [Mio. a BP]	Quarternary & Neogene	< 700 m	Alluvium Basalt	
22 - 65 [Mio. a BP]	Paleogene	< 800 m	B4/B5	
65 - 87 [Mio. a BP]	Upper Cretaceous	< 550 m	A7/B2	
90 - 100 [Mio. a BP]	Upper Cretaceous	< 300 m	A1/A6	
100 - 145 [Mio. a BP]	Lower Cretaceous	< 350 m	Kurnub	Deep sandstone aquifer
145 - 260 [Mio. a BP]	Jurassic, Triassic & Permian	< 1700 m	Zarqa	
440 - 540 [Mio. a BP]	Ordovician & Cambrian	< 2500 m	Ram	

Figure 2: The most important aquifer units in Jordan, geological era/period of their formation and their approximate thickness (after MWI and BGR, 2019).

The series of sedimentary rocks can reach more than 3000 m of thickness. It can be subdivided into three major hydraulic complexes, which are distinguishable within almost the entire region:

- The shallow (upper) aquifer system, consisting of Paleogenic/Neogenic and Quaternary sedimentary and igneous rocks (alluvium, basalt, B4-B5)
- The intermediate Upper Cretaceous A7/B2 limestone aquifer (the most important aquifer in Jordan) and the A1-A6 limestone-marl aquifer-aquitard group
- The deep Kurnub-Zarqa-Ram/Disi Sandstone aquifer system (composed of the Paleozoic Ram Group, including the Disi Formation and the Lower Cretaceous Kurnub Sandstone with intercalated thin layers of sand and sandy limestone of the Jurassic Zarqa Group)

The outcrops of these aquifers (and the intercalated aquitards) are shown on a simplified map in Figure 3. The map was originally created by the MWI and combines the geological formations with their respective hydrogeological characteristics.

This aquifer classification is only a general description, is actually much more complex than presented here and can vary locally. In some areas, the A7/B2 aquifer is directly connected to the overlying basalt aquifer. In other areas – where the A7/B2 aquifer is already unsaturated – the deeper A4 or A1/A2 aquifer can be locally important. Furthermore, the three members of the "Deep sandstone aquifer" are hydraulically connected in some parts of Jordan, while in others (especially in the north and east) they are separated by aquitards.

The classification of aquifers and their (dis)connection from each other is an assumption, taken by hydrogeologists relying on the data, they have for a specific region at a specific point in time. The more we explore the underground, the more detailed our picture of it becomes and it is common that the permeability of an aquifer is much lower in one part of the country than elsewhere and that it might not even be classified as an aquifer anymore.

Finally, it is important to understand that most wells in Jordan are improperly designed, penetrating and screening several different aquifers, thus creating a hydraulic short-cut between them. This makes it often impossible to assign a sample from a well to a specific aquifer, as it consists of a mixture with unknown shares from the different aquifer waters, that are touched by the well. Furthermore, the constant drilling of improperly designed wells and their inadequate deconstruction after abandonment creates new hydraulic shortcuts between the different aquifers, leading to increasing mixing of these waters underground.

Most wells in Jordan are improperly designed

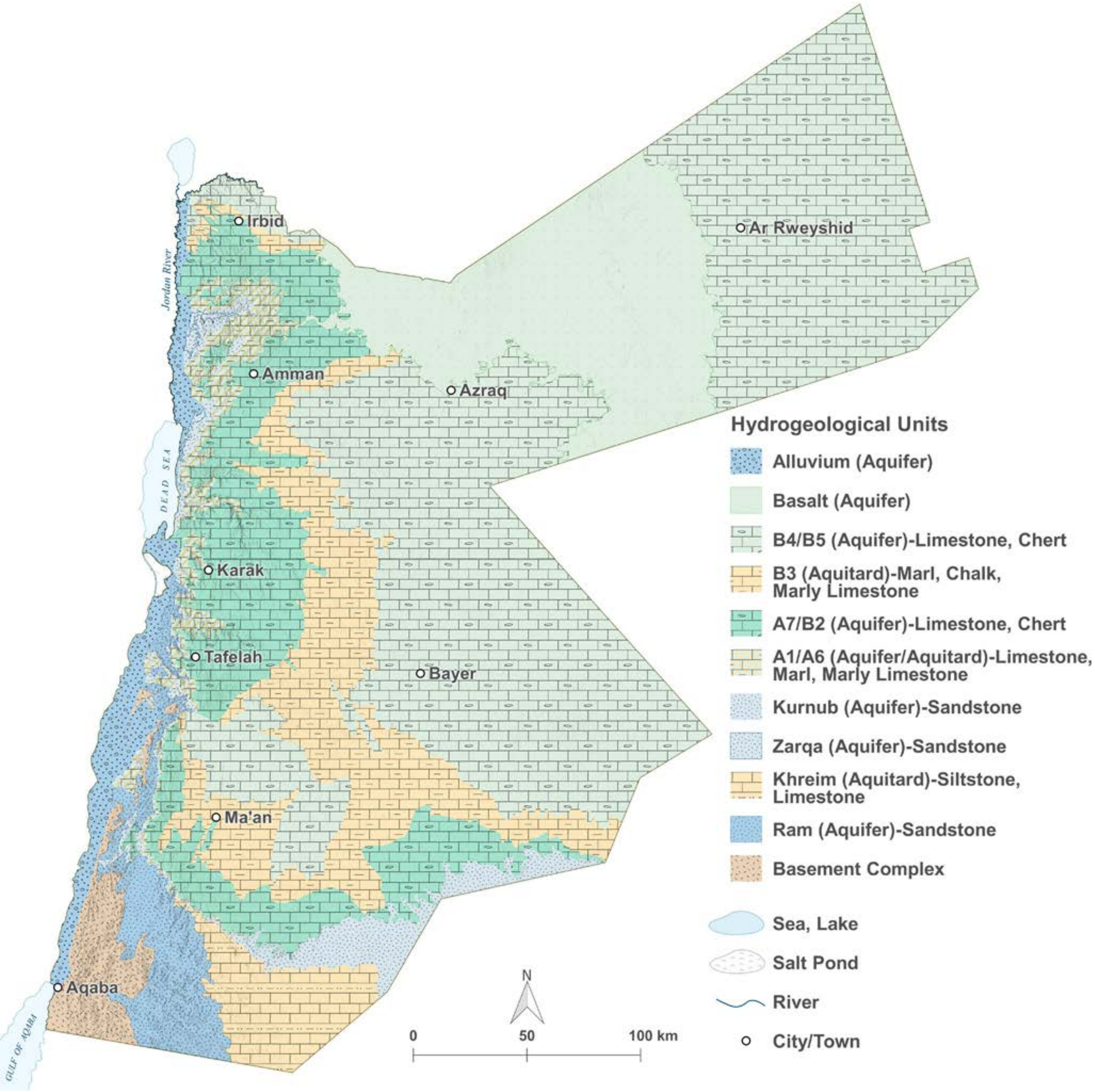


Figure 3: Simplified map of the outcropping hydrogeological units in Jordan.

3.

Groundwater Monitoring Programs

The nationwide hydrochemistry baseline considers data from (i) the first round of the Jordanian Annual Groundwater Sampling (AGS), (ii) the Nationwide Well Sampling study conducted in the context of the National Well Census 2022/23 and (iii) additional recent and historical groundwater quality analyses from other sampling campaigns that were provided by the water suppliers.

3.1 Monitoring Locations

Due to the lack of a dedicated groundwater monitoring network in Jordan, the monitoring locations employed for this study consist of captured springs and active production wells. In most cases, the completion of these production wells is unknown, but it is assumed that in general long screens and missing or corrupted annular sealing are common. This results in depth-integrated water samples from all water bearing formations intersected by these wells.

Consequently, the sampled water cannot be attributed to a specific aquifer at locations where the screen spans across several aquifers. As the mixing ratio, as well as the original groundwater compositions contributing to the mixed sample remain unknown. They allow for water quality compliance and trend analyses at this specific well, but cannot be used for hydrogeochemical modelling or spatial interpolation. At locations where the screen covers a single aquifer, the sampled water can be attributed more or less precisely and represents groundwater from this aquifer. Analysis results from these locations are (in theory) suitable for more elaborated analyses, provided local effects can be excluded.

The allocation of an aquifer to a specific monitoring location was based predominantly on local knowledge (WAJ, BGR, GIZ). For locations with missing or contradicting information, the deepest intersected aquifer (minimum 30 m intersection) was chosen, based on a comparison between well depth and the formation structure contour lines in GIS. As the A7/B2 aquifer represents the most important aquifer for water supply across wide areas in Jordan, it also makes up the largest share of possible locations for water sampling. In total, 53% of the total samples represent A7/B2 monitoring locations (sometimes in unclear distinction to overlying aquifers).

3.2 Annual Groundwater Sampling Program (AGS)

79 groundwater samples from springs and production wells

In order to identify the main drivers behind groundwater water quality changes and to gain a more thorough understanding of the trends in groundwater quality, WAJ (together with BGR) initiated an annual sampling program at 88 selected monitoring sites across Jordan.

The first round of this Annual Groundwater Sampling (AGS) took place in 2021/22 and comprised 79 groundwater samples from springs and production wells, represented as red stars in Figure 4 (nine locations could not be sampled). The monitoring locations were chosen to represent the different aquifers across Jordan. However, an emphasis was laid on the A7/B2 aquifer as it constitutes the most intensely used aquifer in the country. The determined parameters comprise field parameters, inorganic chemistry (major anions/cations) and an extensive trace element analysis done in the laboratory of the WAJ (WAJ-lab).

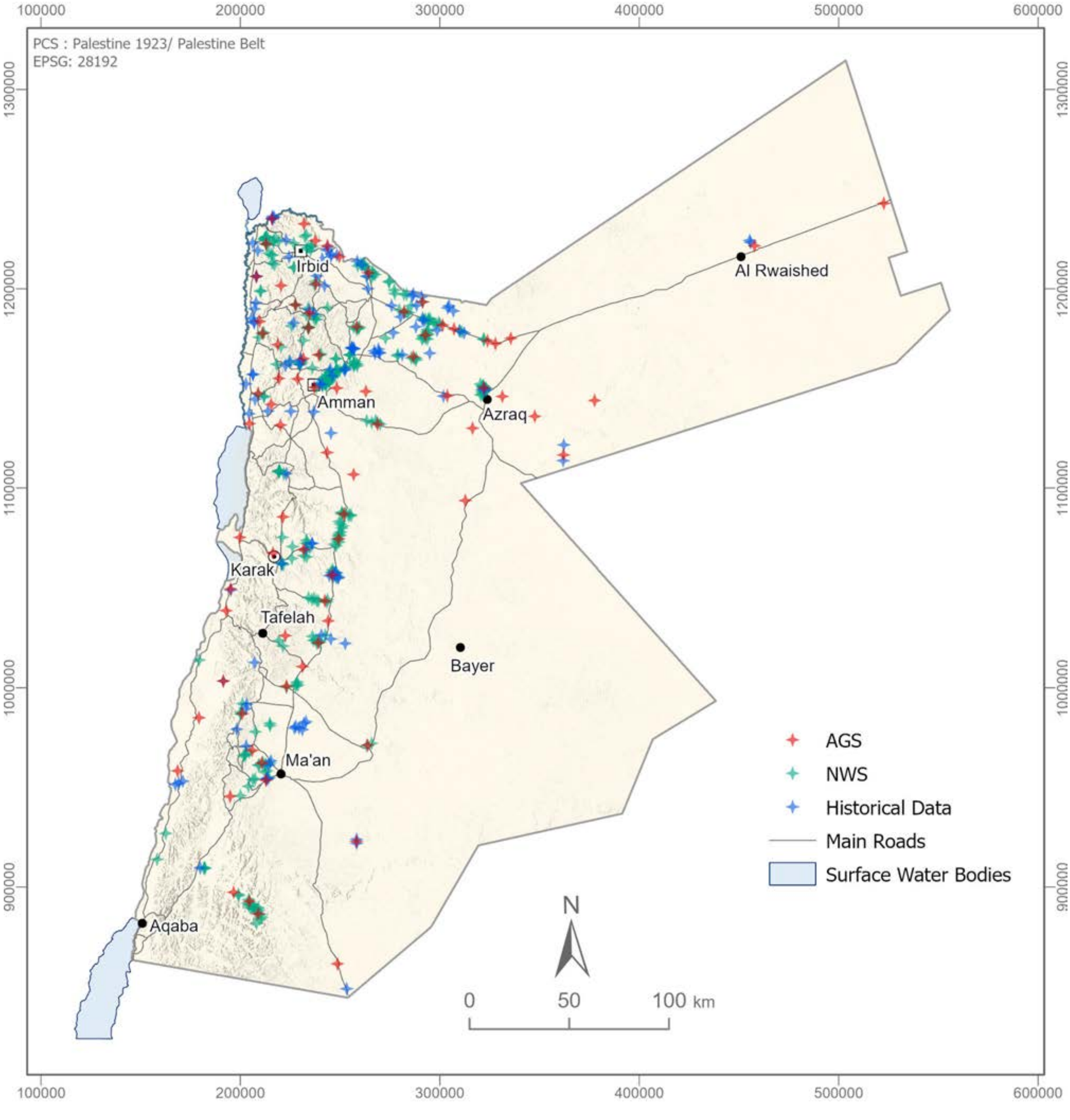


Figure 4: Wells assessed in the scope of the Baseline Study: The monitoring locations of the AGS (88) were selected to represent the different aquifers in different regions of the Kingdom, the NWS-wells (313) and the wells with historical data (128) tend to concentrate in areas with high groundwater abstraction activities.

3.3 Nationwide Well Sampling (NWS)

In addition to the AGS program, the BGR, together with WAJlab, conducted a comprehensive nationwide hydrochemical sampling campaign of production wells, in order to contextualize the results of the annual monitoring and to survey the current state of groundwater quality in more detail.

Between the years 2020 and 2023, a nationwide assessment on well functionality was conducted for production wells across Jordan by BGR in cooperation with MWI/WAJ and the local water suppliers (BGR, 2022; BGR, 2023a; BGR, 2023b; BGR, 2023c; BGR, 2023d; BGR, 2023e). In the scope of this survey, 313 groundwater samples were collected and analysed, they are presented as green stars in Figure 4. The analysis included major inorganic chemistry and a comprehensive suite of trace elements at BGR laboratories (238 samples) as well as WAJlab (75 samples).

Due to this production well assessment, the monitoring locations are concentrated in densely populated areas with many drinking water wells and show a clustering at well fields. These samples represent the water quality state at exclusively drinking wells and are particularly suited to highlight wellfield water quality variability that might be missed by a coarser distribution of monitoring points, but is of high relevance for the current water supply situation.

3.4 Historical Groundwater Analyses

In order to identify groundwater quality trends and to extend the monitoring locations of the Baseline study, groundwater analyses from other groundwater quality surveys in Jordan were provided from WAJlab, Miyahuna and Yarmouk Water Company (YWC) as well as BGR.

The WAJlab LIMS database, as well as the databases of Miyahuna and Yarmouk Water Company, were searched for historical groundwater quality data related to the monitoring locations included in the AGS program and adjacent wells. The BGR LIMS database was searched for all hydrochemical data available from previous projects and reports in Jordan.

In summary, 128 groundwater analyses younger than 01.01.2020 supplement the AGS and NWS samples in the Baseline study and are presented as blue stars in Figure 4. Furthermore, where available, an analysis of historical groundwater quality analyses was implemented into the study.

4.

Groundwater Sampling and Laboratory Analysis

This section describes the methodical approach followed for the AGS and NWS monitoring programs as well as the practical aspects of fieldwork and data acquisition. The same methods and field equipment were applied for all sampling events. As the historical groundwater samples originate from different groundwater quality surveys, no detailed information for their field or laboratory analysis can be provided.

4.1 Field sampling

All AGS and NWS samples were taken from active production wells or running springs, which had a functional sampling outlet. As no inactive production wells were sampled, no prior pumping of the standing water in the well was necessary, as it is the case for regular monitoring wells. Due to uncertainties regarding the coordinates of some locations, the coordinates for all AGS and NWS monitoring locations were identified by hand-held GPS prior to sampling. For both sampling campaigns, only new sampling containers from reliable suppliers were employed. The field parameter devices were calibrated on the day of sampling and cross-checked or re-calibrated during the field work when deemed necessary.

For the Annual Groundwater Sampling campaign, the groundwater samples were collected following the Jordanian field sampling procedures. Parameters determined in the field included electrical conductivity (EC), temperature (T) and pH. Each sampling was conducted by filling two 1L PE sample bottles (one of them prepared with 1 mL ultrapure 65% HNO3). All sampling bottles were cooled directly after sampling until delivery to the WAJlab. Upon arrival in the WAJlab, the water samples were treated according to the laboratory guidelines.

For the Nationwide Well Sampling, the groundwater samples were collected following BGR field sampling procedures. All new sample containers were additionally pre-cleaned in the laboratory. Upon arrival at the field site, the sampling outlet was flushed and cleaned of all visible dirt and debris. If possible, a flow cell was attached to the sampling outlet. If not, a beaker with 10 L was used for the field probes. In any case, the parameters determined in the field included EC, T, pH and redox potential. For each location a pre-cleaned 500 mL PE sample bottle was filled from a beaker and water from the same beaker was filtered through a 0.45 um syringe filter into a pre-cleaned 100 mL PE sample bottle. This 100 mL bottle, was prepared with 1 mL of ultrapure 65% HNO_3 in the laboratory. All sample bottles were cooled immediately after sampling. If analysed at the the WAJlab, they were delivered there and treated equally to the AGS samples. If analysed at the BGR laboratory, they were sent there and treated according to the BGR laboratory guidelines.

4.2 Laboratory analysis

The methods applied for the different hydrochemical parameters are given in Table 1. Of the 520 baseline samples, 238 (46 %) were analysed in the water laboratory of BGR in Hannover. Major anions were measured with ion chromatography (IC), major cations were measured by inductively coupled plasma optical emission spectroscopy (ICP-OES). The trace elements were measured in the soil laboratory of BGR (Section 2.4) in Hannover, applying inductively coupled plasma mass spectroscopy (ICP-MS).

Further 154 samples (30 %) were analysed by WAJlab, either in the scope of the “Nationwide Well Sampling” (NWS) or the “Annual Groundwater Sampling” (AGS) in 2022. In both cases, ion chromatography with different protocols was used for the analysis of major cations as well as major anions. Trace elements were measured by ICP-OES.

The remaining 128 samples (24%) were historic data, analysed in the laboratories of WAJlab, YWC, BGR and Miyahuna after 2020. Even though most analysis methods here were equivalent to the 154 WAJlab samples from the NWS/AGS, the device for measuring trace element was switched in August 2021 from inductively coupled plasma atomic adsorption spectroscopy (ICP-AAS) to ICP-OES.

The charge balance error is below 5 % for all samples analysed in the scope of the baseline study (the median is even below 1%). Hence, the methodology applied by WAJlab in this context is considered sufficiently accurate for future tasks in the context of the AGS.

The laboratory methods used for the different target compounds in the WAJlab as well as in the BGRlab for AGS and NWA are listed in Table 1.

Table 1: Laboratory methods applied in groundwater analysis.

Target	BGR-Method	BGR: LOD [mg/l]	WAJ-Method	WAJ: LOD [mg/l]
F-	Ion Chromatography (ADAPTED): DIN EN ISO 10304-1 (2009)	0.003	Ion chromatography: User manual of Dionex	0.01
Cl-		0.003	Ion chromatography: Standard Methods 23rd edition4110B	0.7378
NO_2-		0.003		0.04
SO_4^{2-}		0.003		0.268
NO_3-		0.003		0.172
Br-		0.003		0.057
Na	ICP-OES (ADAPTED): DIN EN ISO 11885 (2009)	0.1	Ion chromatography: User manual of Dionex	0.28
K		0.1		0.7
Mg		0.001		0.4
Ca		0.01		0.21
PO_4		0.03		0.3
SiO_2		0.1	Heteropoly Blue Method	0.084
BO_2		0.01		0.1
Fe	ICP-MS (Agilent 7900)	3.0E-5	ICP-OES: Standard Methods 23rd edition 3120B	0.012
Mn		1.4E-5		0.003
Al		2E-6		0.004
As		2.6E-3		0.011
Ba		4.2E-6		0.003
Be		6.1E-7		0.005
Cd		3.2E-7		0.007
Co		1.0E-6		0.005
Cr		3.5E-6		0.009
Cu		1.9E-5		0.03
Li		1.5E-5		0.006
Ni		3.9E-5		0.003
Pb		1.9E-6		0.01
Sr		2.1E-6		0.004
Ti		1.6E-5		
V		3.3E-6		0.02
Zn		1.5E-5		0.01
Mo		5.2E-6		0.006
Se		3.7E-6		0.0049

4.3 Plausibility Checks

The electrical charge balance error between the sums of anions and cations indicates the accuracy and reliability of a chemical groundwater analysis and serves as indicator whether an important solute contributing to the electrical charge balance is missing from the analysis. In this study, the electrical charge balance error (CBE) was calculated with the following formula:

$$\mathrm{CBE} = \frac{Sum_{Cat} - Sum_{An}}{(Sum_{Cat} + Sum_{An}) * 0.5} * 100 \quad [\%]$$

where Sum_{Cat} represents the sum of the molar equivalent concentrations of the cations (Na, K, Ca, Mg) and Sum_{An} represents the sum of the molar equivalent concentrations of the anions (Cl, HCO_3-, NO_3-, SO_4^{2-}) in meq/L. Where available, the minor ions (NH_4+, Ba, Fe (filt), Mn (filt), Br, F, PO4) were included, if it improved the mean and median of the charge balance analyses. The acceptable charge balance error was assumed with ±5 % and only analyses satisfying this condition remained in the data set. The BGR laboratory uses a ±2% threshold.

Aluminum concentrations above the guideline limit (0.1 mg/L) are unusual in groundwater with near neutral pH, as dissolved aluminum is controlled by the solubility of aluminum hydroxides and concentrations of few µg/L are expected (Appelo and Postma, 2005). Therefore, elevated aluminum concentrations from filtered groundwater samples need to be checked for plausibility. An exceedance of the solubility controlled equilibrium concentration for aluminum in near neutral groundwater might indicate a compromised filtration leading to an inclusion of suspended clay particles in the acidified sample due to a rupture of the filter membrane or clay particles and/or colloids smaller than the filter size.

4.4 Parameter Correlation

Parameter correlation was assessed using the Spearman monotonic correlation method, with a level of significance set at α = 0.05. Spearman was chosen over Pearson as this method is more robust against outliers and non-normally distributed data. All values below the detection level (LOD) were assigned with 0.5*LOD. The correlation results are discussed in the later chapters. For trace elements, only ICP-MS measurements were used in the correlation in order to avoid distortion by strongly variable LODs. However, the focus on ICP-MS measurements introduces spatial bias into the correlations as water samples from the governorates of Ma'an and Irbid were exclusively measured by ICP-OES.

5.

Results

The 2023 nationwide hydrochemistry baseline was established using the analysis results from 520 locations: The AGS (79 locations), the NWS (313 locations) and recent historic data (128 locations). Every monitoring location has one unique entry in the baseline study and all entries are younger than 01.01.2020. In the scope of the AGS and the NWS the samples for cations, iron and trace elements were filtered on site, for all other samples no documentation was available. For this reason, concentrations for aluminum and iron from recent historic samples were discarded. Other elements prone to colloidal iron oxides or clay (As, Cd, Cr, Cu, Pb) stayed well below half of their guideline level, thus these measurements were kept. Historic molybdenum, nickel and selenium concentrations were also included, as they stayed well within the range observed at other wells in the baseline study.

5.1 Estimation of Total Dissolved Solids (TDS) by EC

Electrical Conductivity (EC) and Total Dissolved Solids (TDS) are closely related parameters. TDS refers to the total concentration of dissolved substances (typically salts) in groundwater, while EC measures the groundwater's electrical conductivity, which is mainly affected by dissolved salts. Due to their close relation, each parameter can be roughly estimated from the other. For example, Hölting (2013) gives an empirical approximation factor of TDS [mg/L] ≅ 0.725*EC [μS/cm], while other sources may suggest slightly different values. As every dissolved ion has its specific conductivity in water, these empirical factors depend on the relative solute composition of the groundwater.

Due to its easy application in the scope of a field measurement, EC is frequently used for the estimation of TDS in Jordan and a threshold of 1500 μS/cm representing a TDS of approximately 1000 mg/L has been established (e.g., Hobler et al., 2001). For a more detailed analysis of this rule of thumb, Figure 5 a and b show the scatterplots for (a) all 517 EC and TDS analyses from the baseline study and (b) a close up view of the drinking water relevant TDS range between 100 and 1500 mg/L. The horizontal spread of the curve represents the observed variability for salinity (TDS). For the rule of thumb threshold value of EC= 1500 μS/cm a TDS-range between 830 and 1200 mg/L, indicated by the red line in the lower graph (Figure 5 b), was identified. This means that EC can be used to roughly assess the groundwater salinity threshold if this range of possible TDS concentrations is acceptable. The grey lines in Figure 5 a and b indicate the linear regression lines through the origin for both data sets and result in empirical relationships of TDS [mg/L] ≅ 0.674*EC [μS/cm] for all baseline samples and TDS [mg/L] ≅ 0.696*EC [μS/cm] for samples with TDS < 1500 mg/L, both relationships show a coefficient of determination of R2 = 0.99. However, for higher certainty in decisions regarding the drinking water limit of 1000 mg/L, a full analysis of major cations/anions is recommended, especially if EC surpasses 1250 μS/cm, the lower EC limit for baseline samples with a TDS of 1000 mg/L, indicated by the blue dotted lines in the Figure 5b.

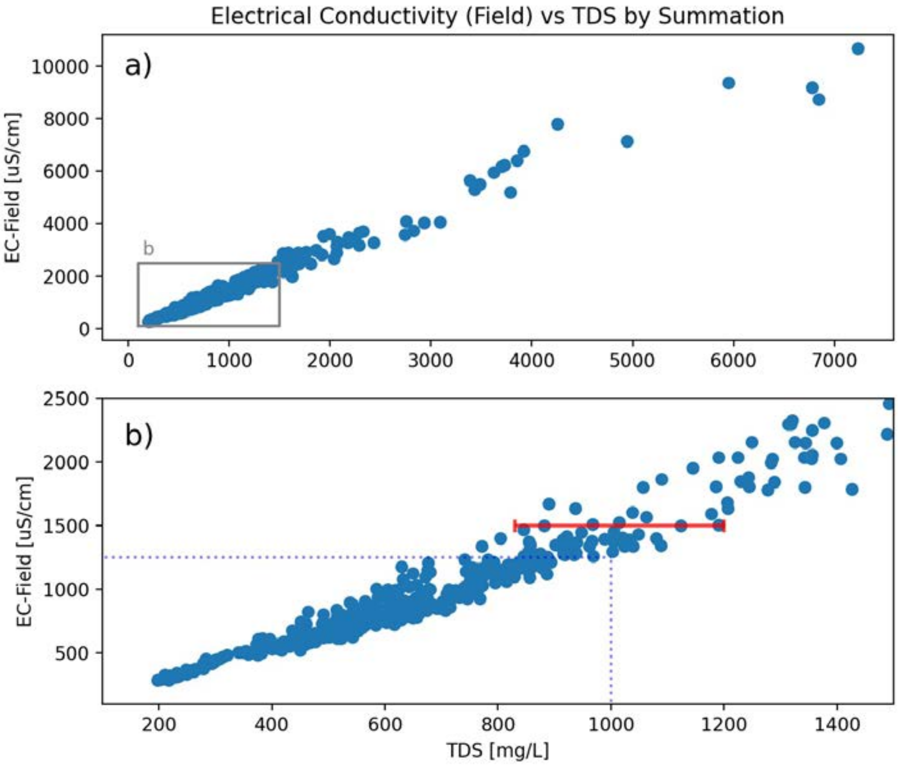


*Figure 5: Scatterplots of Electrical Conductivity (EC) vs Total Dissolved Solids (TDS), as determined in the baseline study (plot a: n=518, plot b: n=455). The peak value with TDS 15008 mg/L and 21900 μS/cm was omitted for better readability. The red line in plot b indicates a TDS range between 830 and 1200 mg/L for an electric conductivity of 1500 μS/cm. The blue lines mark the location for the lowest EC measured for a TDS of 1000 mg/L. The grey lines show the linear regression lines through the origin with a) y=1.483*x and b) y=1.436*x.*

5.2 Major Groundwater Chemistry

In order to reflect the observed concentration ranges, no sample fulfilling the plausibility requirements was discarded even if local anthropogenic influences are suspected. Hence, the baseline study might not reflect the initial geogenic groundwater quality, but it is highly representative for the observed water quality variation in an area.

The analysed major chemistry of the Baseline study samples was very variable in regards to total and relative concentrations (Table 2, Figures 6 and 7). For dissolved species, most total concentration ranges span several orders of magnitude. Nitrate was the most variable major parameter, which probably reflects the variation in landuse across Jordan, especially regarding agricultural and pastoral practices. The measurements for TDS as indicator of the total ion content range from fresh (~200 mg/L) to brackish water (~15000 mg/L).

In the Piper diagram (Figure 6) the analyses occupy a wide transition zone between calcium carbonate dominated and mixed water composition, to sodium and calcium chloride dominated compositions. Most water samples are of the CaCO3 type or mixed waters while pure NaCl and CaCl-type waters are less prevalent. SO_4^{2-} played a minor role in most wells. This distribution is in agreement with the majority of the productions wells tapping at least partially into carbonate aquifers, especially the highly productive A7/B2 aquifer.

In the Durov diagram (Figure 7) it becomes visible that almost all samples, which exceed the national drinking water limit for TDS (1000 mg/L) are dominated by sodium, rather than calcium. Furthermore, the majority of samples (456) remain below a TDS of 1500 mg/L.

The average yearly temperature in Jordan varies between 17°C (Ajloun region) and 26°C (Dead Sea). Recharging groundwater is expected to be in the same temperature range. However, due to the depth of many aquifers and the proximity to a rift zone, the geothermal component plays a significant role. Furthermore, Jordan is known for thermal springs. For the baseline study, the temperature ranges from 18 °C in the northern A1/A2 recharge zones to 61°C for very deep RAM wells (> 1800 mbgl). In general, shallow wells tend to show lower geothermal influence. However, groundwater temperature appears to be affected by the tectonic structure. One example here is the Muwaqqar well field, close to the Zarqa-Ma'in fault, which shows generally elevated temperatures of >35°C.

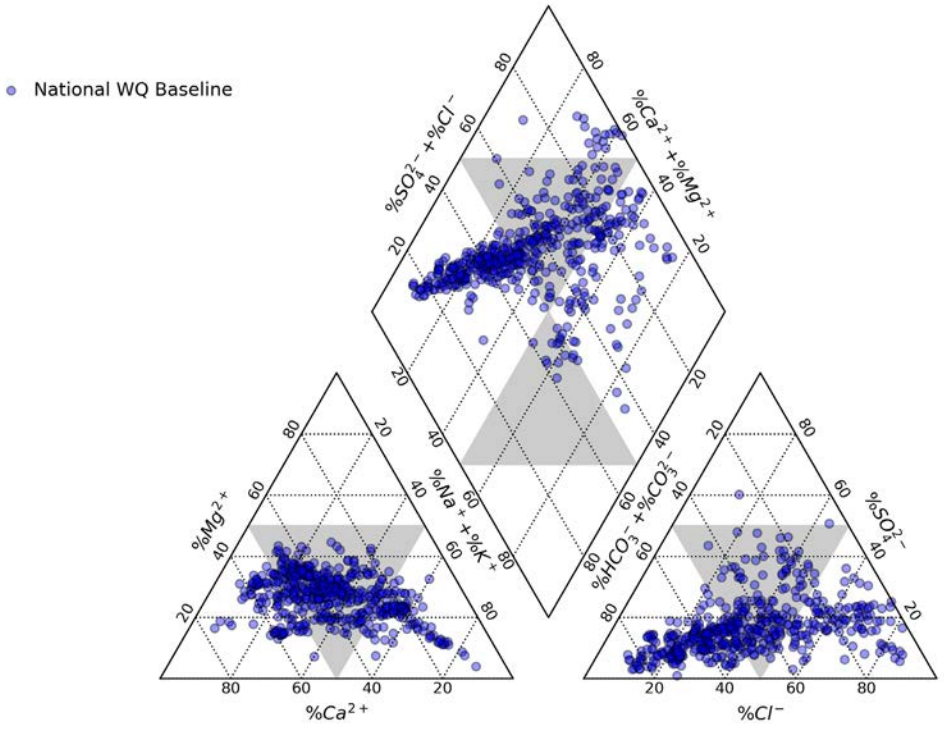


Figure 6: Piper diagram of the relative water composition observed in the samples from the baseline study. For the transparent sampling points darker areas indicate higher density of samples.

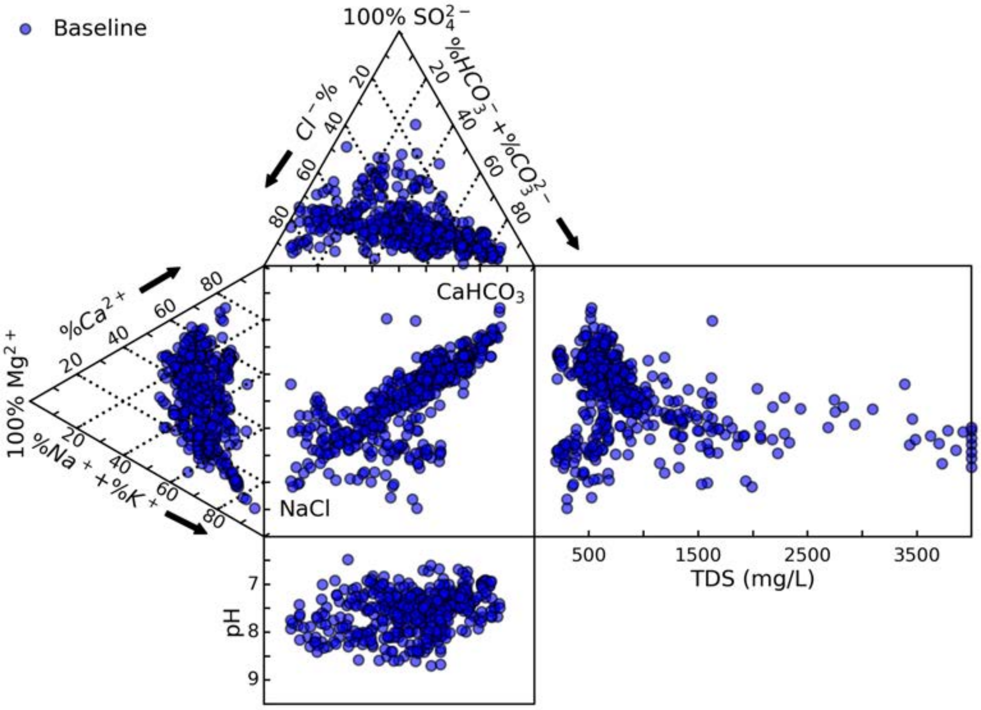


Figure 7: Durov plot of the major hydrochemistry data observed in the baseline study. TDS values greater than 4000 mg/L were reduced to 4000 mg/L to enhance readability. For the transparent sampling points darker areas indicate higher density of samples.

Table 2: Concentration ranges and number of analyses for major ions and field parameters observed in the baseline study.

	EC	TDS	pH	T	Na	K	Ca	Mg	Cl	HCO_3-	NO_3-	SO_4^{2-}
unit	[µS/cm]	[mg/L]	[-]	[°C]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]	[mg/L]
samples	518	520	437	406	520	520	520	520	520	520	520	520
mean	1345	933	7,6	27	124	8	94	44	230	273	19	132
std	1546	1032	0,4	5	197	16	82	66	440	125	31	238
min	286	198	6,5	18	11	0,5	7	2	21	52	< 0.5	4
25%	705	517	7,3	23	37	2	58	25	62	191	0.4	37
50%	937	673	7,5	27	72	4	81	33	116	287	9	63
75%	1340	916	7,9	29	117	7	103	45	210	337	25	122
max	21900	15008	8,7	61	2476	129	1055	1191	6871	1183	311	3143

Groundwater temperature appears to be affected by the tectonic structure

41% of the monitoring locations surpassed its threshold value of the JDWS

5.3 Jordanian Drinking Water Specifications

All analysed water samples from the national baseline locations were compared to the inorganic parameter thresholds of the Jordanian Drinking Water Specifications (JDWS) (JSMO 286/2015). Even though the **samples represent untreated water** and not necessarily the water, which is finally delivered to the households, the JDWS was considered the best indicator to evaluate its suitability for domestic supply. Recent information about the water usage was not available for all wells, but a minimum of 430 or 83% of the 520 monitoring locations are confirmed as drinking water wells. For the remaining wells, the comparison to drinking water standards was adhered to, even if the actual usage of the monitoring location was for different purposes (2.3%) or unknown (14.7%). Table 3 summarizes the 28 applied guideline values for inorganic parameters and – if applicable – their exemption threshold values.

Although it is not part of the drinking water regulation in Jordan, vanadium was included in the survey, due to the very high concentrations observed in the baseline study (up to 0.5 mg/L). It was assessed considering the Italian drinking water guideline value of 0.140 mg/L (Arena et al., 2015). Similarly, uranium was included in the analysis to account for an observed violation of its WHO (2022) chemical toxicity threshold and due to a significant weak to moderate correlation with other trace elements (As, Mo, Ni, Se, V, see chapter 5.5).

As a result, at 215 wells or 41% of the monitoring locations at least one parameter surpassed its threshold value of the JDWS inorganic water quality criteria (Figure 8, Table 4). These locations either require more thorough examination (NH_4+), parameter specific treatment or blending with water of better quality to ensure an acceptable drinking water quality. Alternatively, if no water source of better quality is available, the Jordanian Ministry of Health can also grant permission to assign a higher maximum threshold value for selected parameters, as indicated by the exemption values in Table 3. Overall, the total number of locations with a compromised water quality might be an underestimation as not all guideline parameters were analysed for every sample.

Spatially, the compromised locations are distributed across the whole of Jordan, but concentrate in density as well as in number of violations in Northern Jordan, around Amman, in the greater Karak region and along the depressions of the Jordan Valley and Wadi Arabah (Figure 8). In total, 530 guideline violations were registered and over half of the compromised monitoring locations show at least two, if not multiple JDWS violations. Table 4 sorts the inorganic parameters depending on the frequency of their guideline violations to present an overview about the most important groundwater quality issues encountered in the baseline study. When judging the parameter importance by the severity of the violations instead (indicated by the columns for the peak value), the parameters would arrange in a different order showing molybdenum as the most pressing water quality issue due to a peak value of 1828% or 18 times the guideline threshold.

Table 3: Jordanian Drinking Water Specifications for inorganic parameters.

Parameter	Symbol	JDWS-Limit	Unit	Exemption*
Total dissolved solids	TDS	1000	mg/L	1300
TH	TH	500	mg/l	600
Sodium	Na	200	mg/l	300
Chloride	Cl	500	mg/l	
Sulphate	SO_4^{2-}	500	mg/l	
Nitrate	NO_3-	50	mg/L	70
Nitrite	NO_2-	3.0	mg/L	
Ammonium	NH_4+	0.2	mg/L	Contamination indicator
Silver	Ag	0.1	mg/L	
Aluminum	Al	0.1	mg/L	0.2
Arsenic	As	0.01	mg/L	
Boron	B	2.4	mg/L	
Barium	Ba	1.0	mg/L	
Cadmium	Cd	0.003	mg/L	
Total Chromium	Cr	0.05	mg/L	
Copper	Cu	2.0	mg/L	
Fluoride	F	1.5	mg/L	2.0
Iron	Fe	1.0	mg/L	
Mercury	Hg	0.002	mg/L	
Manganese	Mn	0.4	mg/L	
Molybdenum	Mo	0.09	mg/L	0.27
Nickel	Ni	0.07	mg/L	
Lead	Pb	0.01	mg/L	
Antimony	Sb	0.02	mg/L	
Selenium	Se	0.04	mg/L	0.05
(Uranium)**	(U)	(0.03)	(mg/L)	
(Vanadium)**	(V)	(0.140)	(mg/L)	
Zinc	Zn	4.0	mg/L	

* If no other water source of better quality is available, the Ministry of Health can approve a higher maximum threshold value.
** Uranium and Vanadium are not part of the Jordanian Drinking Water Guideline parameter suite but were included due to high concentrations. The threshold value for uranium derives from the WHO (WHO, 2022) and considers solely its chemical toxicity. For vanadium the Italian Drinking Water Guideline value was applied (e.g. Arena et al. 2015).

Table 4: Numbers and peak values for parameter specific violations of their JDWS thresholds observed in the baseline study.

Parameter	Symbol	Number of JDWS Violations	Peak Value	
			Concentration [mg/L]	% of JDWS Value
Total Dissolved Solids	TDS	113	15008	1501 %
Sodium	Na	75	2476	1238 %
Nitrate	NO_3-	61	311	622 %
Chloride	Cl	59	6871	1374 %
Total Hardness	TH	50	3160	632 %
Fluoride	F	35	4.25	283 %
Selenium	Se	33	0.348	870 %
Ammonia*	NH_4+	23	2.25	1125 %
Sulphate	SO_4^{2-}	22	3143	629 %
Molybdenum	Mo	20	1.645	1828 %
Iron*	Fe	12	5.7	570 %
Nickel	Ni	9	0.215	307 %
Arsenic	As	6	0.03	300 %
Aluminium*	Al	5	0.68	680 %
(Vanadium)	(V)	(5)	(0.54)	(386 %)
Boron	B	2	2.8	117 %
Barium	Ba	2	3.82	382 %
Chromium	Cr	1	0.075	150 %
Nitrite	NO_2-	1	19.7	657 %
(Uranium)	(U)	(1)	(0.034)	(113 %)

* Ammonium functions as an indicator for contamination and poses no direct health risk. For the count of iron and aluminium violations, only filtered water samples were considered.

For the parameters silver, cadmium, copper, mercury, manganese, lead, antimony and zinc, all analyses of the baseline study showed values below their JDWS-thresholds.

The following sections summarize parameter specific observations in the baseline study for parameters that show at least one violation of the quality criteria. Where possible, historical and land use data were integrated in the parameter analysis and potential origins of elevated concentrations are discussed. The maps for the trace elements display all available parameter measurements and thus unify data from different laboratories and measurement techniques (ICP-OES, ICP-MS).

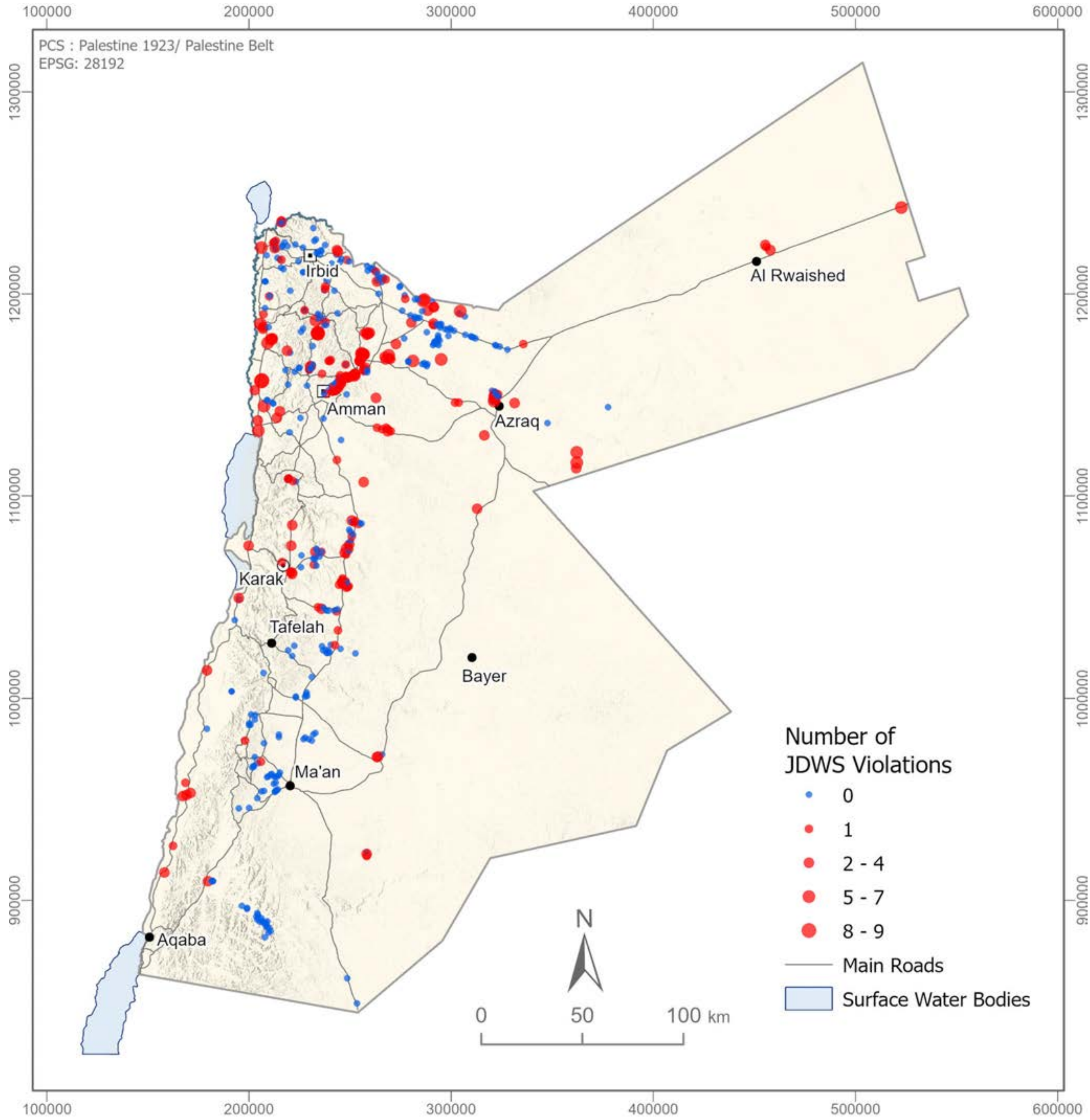


Figure 8: Number of violations of the Jordanian Drinking Water Specifications (JDWS) per monitoring location in the baseline study.

5.4 Salinity

Salinity or TDS represents the sum of the total solute content in mg/L. Therefore, this parameter correlates strongly with most major ions and other major ion sum parameters (Table 5), some of which have their own guideline levels in the Jordanian Drinking water specification guideline (Table 3).

TDS together with the salinity related parameters Total Hardness (TH), Na, Cl and SO_4^{2-} accounted for over half of the total number of guideline violations. However, all salinity related parameters violations occurred in addition to a TDS violation, indicating that TDS has the most sensitive guideline limit. The observed concentration range and distribution of TDS and salinity related parameters considered in the JDWS, are displayed together with their guideline limits (red lines) as boxplot distributions in Figure 9.

In a boxplot distribution, the box represents the parameters concentration range from the 25th to the 75th percentile and therefore 50% of the data. The median (50th percentile) is indicated as line within the box. The lines or whiskers extruding from the box extend to the lowest or highest observation within 1.5 times the interquartile range between Q1 and Q3 (=distance between the 25th to the 75th percentile). By standard practice, they indicate the area assumed to belong to the main distribution, while observations above or below the whiskers are defined as outliers.

TDS together with the salinity related parameters accounted for over half of the total number of guideline violations

Table 5: Spearman correlation coefficients for baseline analyses (n= 520) of major ions with significance p< 0.05.

	Depth	**Temp**	**pH**	**TDS**	**TH**	**Na**	**K**	**Ca**	**Mg**	**Cl**	**HCO_3-**	**SO_4^{2-}**	**SiO2**
Depth	1,00												
Temp	0,54	1,00											
pH	0,17	0,28	1,00										
TDS	-0,22		-0,38	1,00									
TH	-0,16		-0,30	0,94	1,00								
Na	-0,18	0,20		0,81	0,65	1,00							
K		0,20		0,60	0,55	0,69	1,00						
Ca	-0,25	-0,22	-0,60	0,86	0,94	0,49	0,40	1,00					
Mg	-0,17		-0,36	0,87	0,87	0,65	0,45	0,72	1,00				
Cl	-0,24			0,86	0,70	0,95	0,65	0,58	0,73	1,00			
HCO_3-	-0,15	-0,24	-0,72	0,51	0,55	0,10	0,09	0,69	0,44	0,13	1,00		
SO_4^{2-}	-0,10	0,25	-0,11	0,82	0,75	0,83	0,57	0,57	0,81	0,83	0,20	1,00	
SiO2	0,14	0,37	0,48		0,47	0,22	0,50			0,18	-0,25		1,00

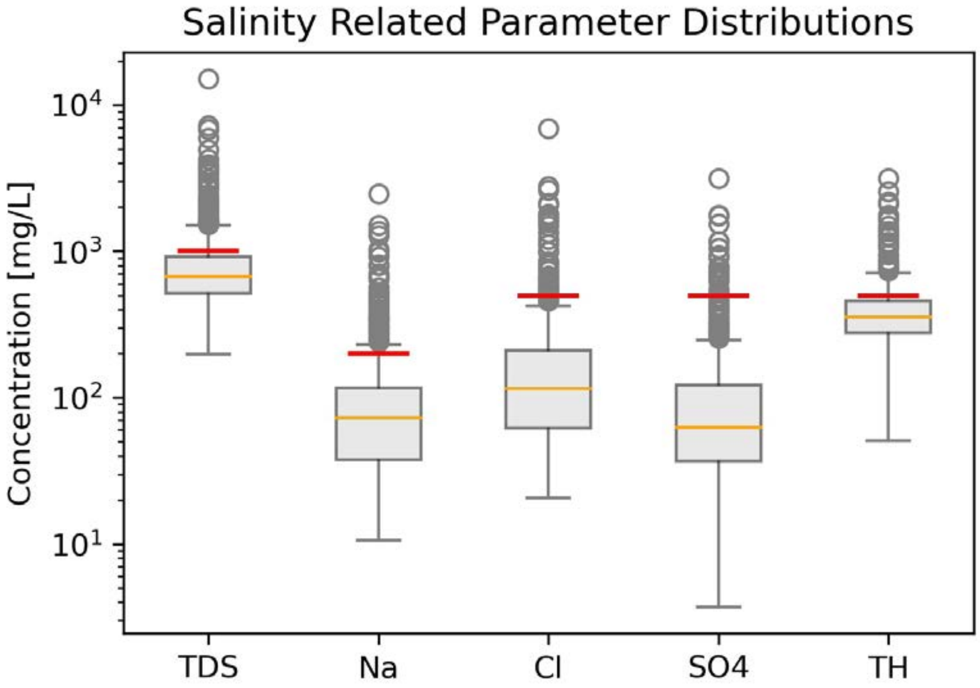


Figure 9 Boxplot distribution for baseline concentrations of the salinity related JDWS parameters. Red Lines display the JDWS guideline thresholds. Orange lines indicate median concentrations. Values displayed as circles are considered to represent outliers.

5.4.1 Total dissolved Solids (TDS)

With 113 guideline violations, the TDS criterion represents the most frequent cause for guideline violations in the baseline study and its peak value surpassed the JDWS-limit by more than one order of magnitude. For 23 monitoring locations, TDS was the only parameter impairing the drinking water quality. In the boxplot distribution in Figure 9, it becomes evident that TDS concentrations above drinking water levels are within the range of the plots upper whisker. This indicates that they do not represent outliers of the observed distribution and violations of the JDWS TDS criterion account for approximately the upper 20 percent of all TDS values.

For the visualization in Figure 10, the TDS concentrations were sorted into four categories:

Concentrations **below 850 mg/L** (=150 mg/L below Jordanian Drinking Water Limit) are seen as **unproblematic**. All concentrations above 850 mg/L were considered elevated and of these, concentrations, ranging **between 850 mg/L and 1000 mg/L** are considered **noticeable**, even though they don’t exceed the threshold value. Concentrations **between 1000 -1300 mg/L** are considered **critical.** Their use for drinking water purposes can be approved by the Ministry of Health, if no better water source is available, but they exceed the recommendations of WHO (WHO, 2022). Finally, concentrations **above 1300 mg/L** are considered **alarming** and require blending with lower salinity water or desalination.

For visual comparison, the A7/B2 high salinity area is included to highlight the region where TDS concentrations over 1000 mg/L are reported for the confined area of the A7/B2 aquifer (Hobler et al., 2001). Additionally, high salinity hotspots (TDS > 1000 mg/L) as identified by the same study are included.

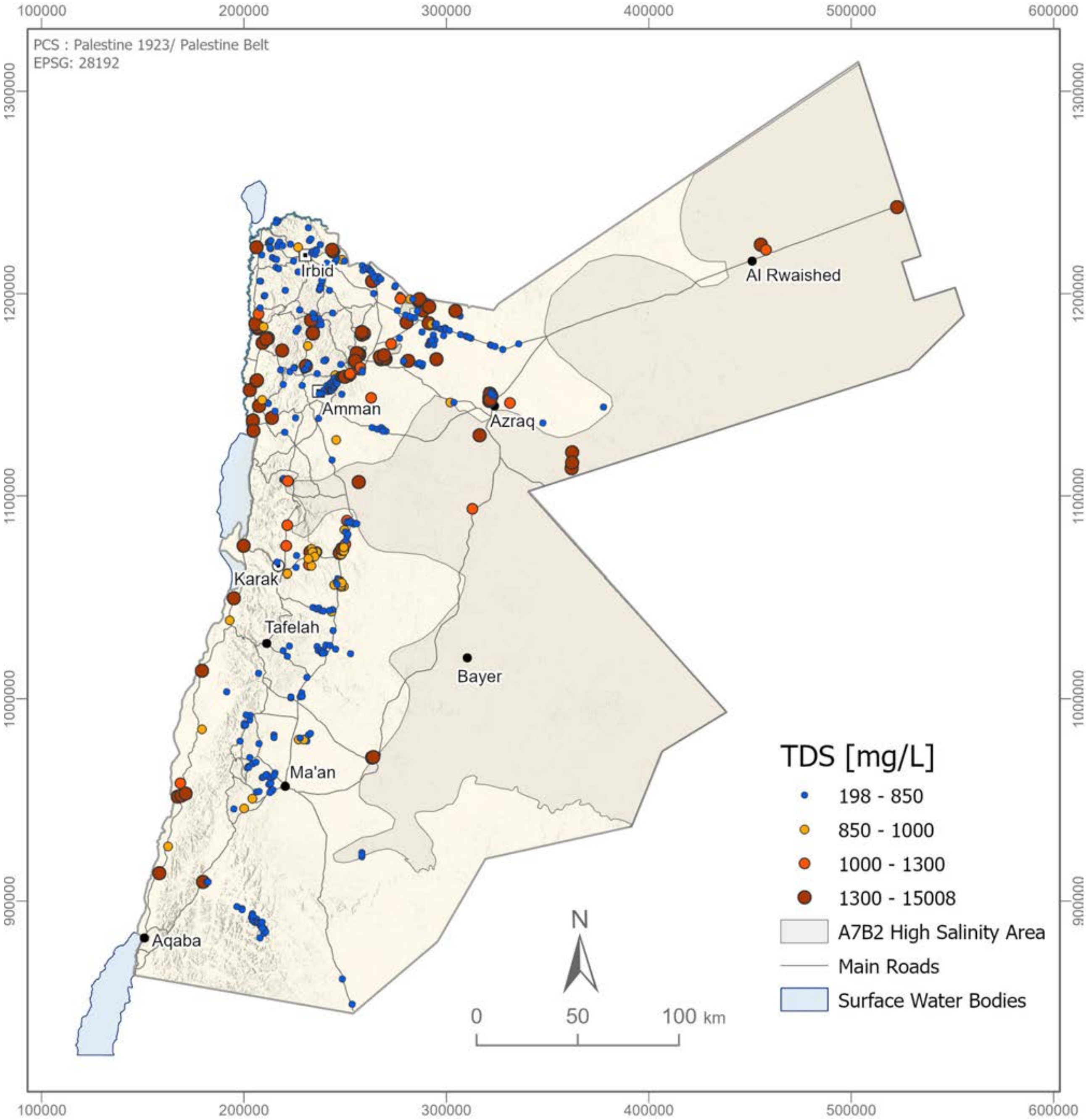


Figure 10: Total Dissolved Solids concentrations observed in the baseline study.

When analysing the spatial distribution of elevated TDS concentrations, the peak concentrations predominantly cluster in Northern Jordan, where locations with critical and alarming salinity concentrations agglomerate along the Jordan Valley and in an approximate triangle between the cities of Amman, Mafraq and Irbid, sometimes forming local high salinity patches. To the east, most of the wells along Baghdad road are uncritical, but high TDS concentrations are found around Azraq and at locations where the B4/B5 aquifer overlies the A7/B2 high salinity area. In Karak, elevated TDS concentrations were found in approximately half of the wells with one third of them showing critical concentrations. TDS violations in southern Jordan mostly follow the Wadi Arabah depression and cluster at Jafer.

Critical and alarming TDS concentrations were found in all aquifers

Critical and alarming TDS concentrations were found in all aquifers and affected between 6 to 69% of the total wells associated with a specific aquifer in the baseline study. Table 6 summarizes the total number of wells and observed TDS guideline violations per aquifer. For some of the aquifers, there were only very few wells (e.g. Zarqa), while for other wells the aquifer association might be incorrect. Therefore, this overview can only indicate a tendency which aquifers were most prone for showing TDS concentrations above the JDWS limit in the baseline study. Amongst the aquifers that are the most affected by high TDS concentrations were the Alluvium, the Zarqa, the Kurnub and the B4/B5 aquifer (median values > 1000 mg/L). The carbonate aquifers showed median values between TDS = 615 to 773 mg/L, with the A4 aquifer responsible for the highest median TDS value and highest percentage of wells with TDS violations. The basalt aquifer had the second lowest median TDS value and when overlying the B4/B5 or A7/B2, it also lowered the salinities of the underlying aquifers. The Ram aquifer showed the lowest median salinities and lowest percentage of affected wells.

Table 6: TDS violations per aquifer. For comparison, the mean TDS for all samples from the affected aquifers are shown. The remaining baseline locations had either no (11 wells) or a very broad (2 wells) aquifer association.

Aquifer	Total Locations	TDS Analyses	TDS Violations	Affected Locations	TDS Median	
Alluvium	26	26	18	69%	1609	[mg/L]
Basalt	10	10	2	20%	475	[mg/L]
BA, B4/B5	21	21	7	33%	585	[mg/L]
BA, A7/B2	15	15	3	20%	464	[mg/L]
B4; B4/B5	13 (B4/B5), 2 (B4)	13 (B4/B5), 2 (B4)	10	67%	1229 (B4/B5)	[mg/L]
A7/B2	263	263	30	11%	654	[mg/L]
A4	53	53	18	34%	773	[mg/L]
A1/A2; A1/A6	42 (A1/A2), 2 (A1/A6)	42 (A1/A2), 2 (A1/A6)	6	14%	615 (A1/A2)	[mg/L]
Zarqa	3	3	2	67%	1626	[mg/L]
Kurnub	26	26	15	58%	1381	[mg/L]
RAM	33	33	2	6%	262	[mg/L]

Previous studies identified the presence of brackish groundwater and brine in the alluvium of the Jordan valley (e.g., Salameh, 2001, Faber et al., 2004), Wadi Arabah (e.g. El-Naqa and Abu Al Adas 2023, Möller et al. 2006) and in the sandstone aquifers (Kurnub and Zarqa) along the Jordan valley (e.g., Salameh, 2001). Most of the high groundwater salinities in these formations were explained by the leaching of evaporites, predominantly halite and gypsum, from the sediment matrix (e.g., Hobler et al. 2001, Salameh, 2001, Faber et al. 2004). For both alluvium aquifers (Jordan Valley and Wadi Arabah) a strong temporal and spatial variability in salinity was identified (Faber et al. 2004, El-Naqa and Abu Al Adas 2023), which also was reflected in the baseline and historical data. Apart from geogenic salinity sources (e.g. evaporates and brines), irrigation return flow and the infiltration of desalination brines (especially in Wadi Arabah) and wastewater (especially in the Jordan valley) may additionally influence groundwater salinity.

The distribution of TDS violations north-east of Amman (Figure 11) overall confirmed the presence of the smaller high salinity hotspots that were previously identified by Hobler et al. (2001) in this area. The hotspots mostly represent areas that are strongly influenced by industrial, agricultural and mining activities. For the Hashimiya and Dhuleil area, Al Kuisi et al. (2009) show increasing salinity trends since the 1970s. A comparison with the baseline study data suggests that some of the high salinity areas may have expanded over the last decades, for example, the high salinity area east of Ruseifa appears to have extended further to the west. A more detailed survey of the extent of the brackish groundwater is recommended. Most of the current wells in the salinity hotspots areas are exploiting the A7/B2 or A4 aquifer.

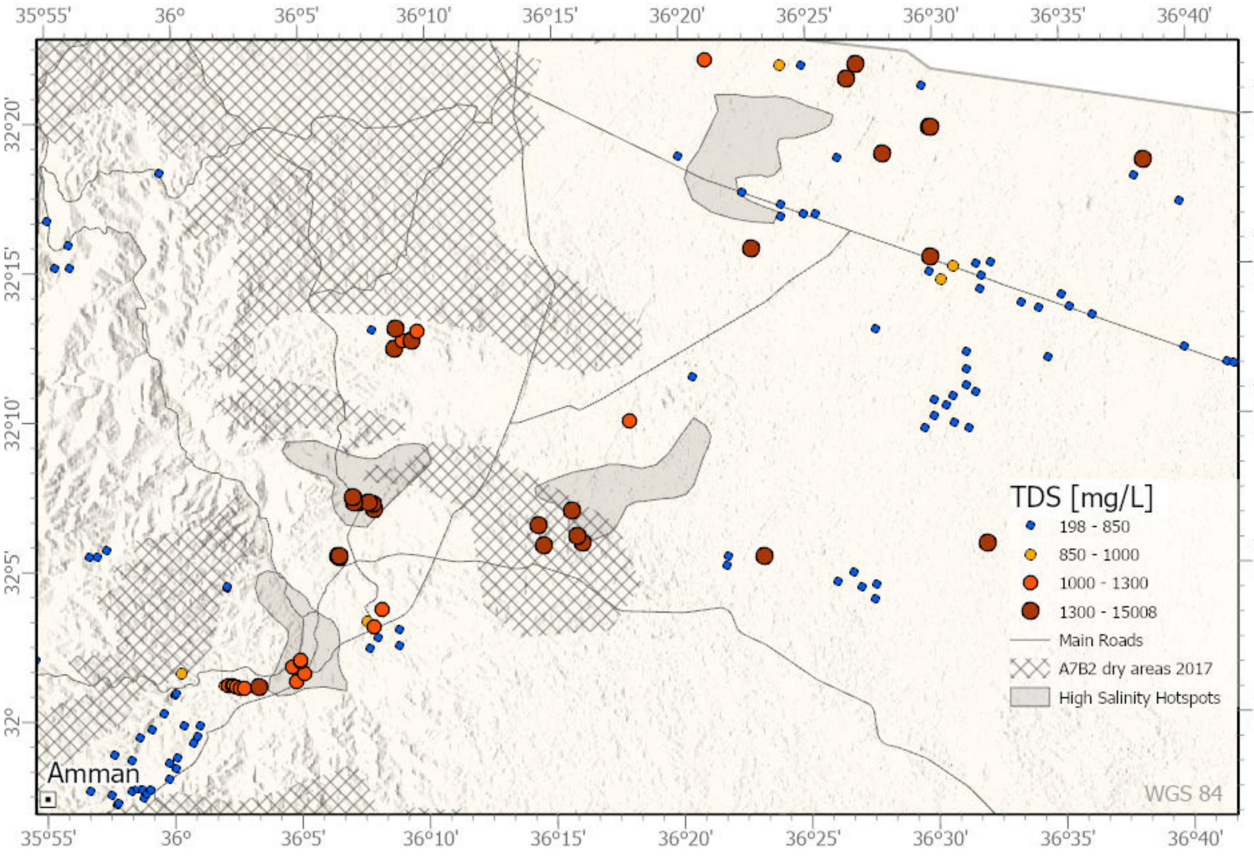


Figure 11: TDS concentrations around Amman in relation to areas with increased TDS >1000 mg/L defined in Hobler et al. (2001). The 2017 dry areas for the A7/B2 dry areas are adopted from MWI and BGR (2019).

In addition to the salinity hotspot areas defined in Hobler et al. (2001), clusters of high TDS concentration were found at the Mashtal Faisal (Kurnub) and Znaya (carbonate aquifers) wellfield. In addition, some wells at Baqa wellfield (Kurnub) indicate critical to alarming salinity and a rising trend (chapter 5.3.2). All of these locations also showed either high nitrate or ammonium concentrations. For Znaya and Baqa wellfield, a close TDS-NO_3- relationship was identified (chapter 5.3.2 and 5.4), possibly indicating a pollution by irrigation return flow, desalination brines or wastewater (e.g., from the Abu Nusair WWTP). The Mashtal Faisal wellfield shows high ammonium and fluoride as well as elevated boron concentrations that may indicate the influence of the Jerash WWTPs and/or the use of organic and phosphate fertilizer in local agriculture. Additionally, the prince Faisal Gardens Desalination plant is located directly at the wellfield.

Outside the salinity cluster and hotspot areas, elevated TDS concentrations occurred scattered in the area between Amman, Mafraq and Irbid. Sometimes large differences in TDS concentrations were identified for neighboring wells, even when they are situated in a similar depth range within the same aquifer complex. This results in a highly heterogeneous distribution of the TDS values that show no clear spatial trend. For example, the two locations showing the peak salinity concentrations in the baseline, AL2564 (TDS = 7230 mg/L) and F4203 (TDS = 15008mg/L), are surrounded by low salinity wells (TDS = 264 – 672 mg/L). Most wells are recorded to tap into the A7/B2 aquifer with the exception of one, which exploits the A4. For F4203, the targeted aquifers are indicated as the Basalt and the A7/B2, but no depth is recorded. If human error can be excluded, these concentrations most likely indicate a local contamination.

Along the Bagdad road, most locations did not show elevated salinity levels but salinity was found to correlate well with nitrate (chapter 5.4.1). This highlights the vulnerability to pollution in this area.

Further east, at the AWSA wellfield, the observed high TDS concentrations in parts of the wellfield agree well with the high salinity values reported by El-Naqa (2010). This study identified the intrusion of saline groundwater from shallow parts of the aquifer system as driver behind the observed salinization of the wells. Alternatively, the salinization could also derive from the intrusion of more saline groundwater from deeper parts of the aquifer. In any case, an analysis of the historic data for the AWSA wellfield (chapter 5.3.2) shows that the salinization process is still ongoing and further research into this issue is recommended.

Monitoring locations showing critical and alarming salinity concentrations east and south of Azraq (within the A7/B2 high salinity area) are almost exclusively exploiting the B4 or B4/B5 aquifer. For this area, Möller et al. (2006) identified intense evaporation and percolation of surface water and local uprising of CaCl2 brines as possible reason for high salinities. However, local effects, for example from the desalination plant at Rwaished may also play a role.

In Karak, the wells are mostly situated in the A7/B2 and the deeper carbonate aquifers. Four of nine locations with critical and alarming TDS concentrations exploit the deeper carbonate aquifers (A1/A2, A4). Further south, alarming TDS concentrations were observed at Jafer (G3020, G4186) in the B4/B5 aquifer and at the Saleh Mahmmoud Dreaat Well (ED1597) in the otherwise low salinity Ram aquifer.

In conclusion, there are several areas with critical and alarming TDS concentrations. Most of the salinity hotspots and clusters outside of the Alluvium or Zarqa Aquifer are situated in northern Jordan, particularly in the A4, A7/B2 and Kurnub aquifers. TDS concentrations above 1500 mg/L should be monitored more closely. This is especially true for locations outside of the already identified high salinity areas and hotspots or evaporate-bearing formations (e.g. Zarqa formation, Lisan formation and B4/B5). Furthermore, for the highest 5-percentile of the TDS distribution (26 wells with TDS greater than 2250 mg/L), 10 out of 14 ammonia analyses show values above 0.2 mg/L and thus indicate a possible anthropogenic contamination.

5.4.2 TDS and Electrical Conductivity Trends

Data indicated increasing salinity trends at multiple locations

This section compares recent TDS and EC values observed in the baseline study to historical data extracted from the water supplier databases and previous reports (especially Hobler et al. 1991, Hobler et al. 2001). For wellfields that could not be compared directly due to a change in active production wells, median TDS values were compared to establish overall trends. Where possible, specific baseline study locations were directly compared to their historical records. For many locations, mostly electrical conductivity (EC) data were available for comparison. Due to a strong correlation between both parameters (Table 5, chapter 4.3), EC measurements can be used as proxy for TDS concentrations. It is important to note however, that this overview only considers a small fraction of the total locations in Jordan and therefore is not representative.

The available data indicated increasing salinity trends at multiple locations displayed as red dots in Figure 12. One example for a strongly affected wellfield is the AWSA wellfield, where EC values increased at several locations over the last 20 years (Figure 13). However, also other monitoring locations record increasing trends in single or multiple wells (Figure 12), e.g. Jafer, Znayya, Slechat, Jraya, Baqa, Ruseifa, Awajan, or the springs between Salt and Fuhais. At some locations, this increase may act as a pre-warning in otherwise low TDS groundwater, for example, at the Hazzir, Fuheis, Shoreia and Baqouriyyeh spring (Figure 14). In other areas, the EC increase falls into a larger high salinity hotspot and may indicate that the process responsible of the salinization has not finished yet for example at the monitoring locations AL3656, AL5072, Al 5073 between Ruseifa and Awajan.

In contrast, decreasing salinities were observed at seven locations (blue dots). However, as declines in groundwater levels are measured in most areas of Jordan (MWI & BGR, 2019, Goode et al., 2013), they were not seen as indicators for larger scale freshening of the aquifer. Instead, they were interpreted as a change in local groundwater flow dynamics or anthropogenic influences. The section of alternating EC trends along the Bagdad road in the Aqeb wellfield (Ba, A7/B2), for example could indicate a change in local groundwater flow pattern (Figure 12). The EC decreases at the monitoring points Rwaished7 (H3074, B4) and Abu Elzeeghan Desalination 10 (AL3687, Kurnub) on the other hand could indicate fluctuations in the geogenic or anthropogenic salinity sources (both are located near desalination plants). For a thorough interpretation, however, a site specific study is required.

For the Karak region, a long term comparison between the average TDS concentrations of the Lajjoun, Siwaqa and Quatrana wellfield for TDS values published in Hobler et al. (1991, Annex 10) and the current study (A7/B2 wells only) resulted in a salinity increase between 21% at Qatrana and 35% at Siwaqa wellfield. These values can be seen as rough estimations only, as most of the wells presented in Hobler et al. (1991) were either not identifiable or could not be sampled in the scope of the current study. However, for Siwaqa 10 (CD1123) and Siwaqa 9 (CD1122) an increase of 65% and 24% could be determined, as shown for Siwaqa 10 in Figure 15. When comparing the difference in the water levels for 1995 and 2017, MWI & BGR (2019) reported a strong groundwater level drawdown for the Karak region. The lowering in groundwater level could result in cross-aquifer flow from lower, higher mineralized parts of the carbonate aquifer complex. Alternatively, the observed increase may be linked to a local reversal of the groundwater flow direction in response to overexploitation, leading to an attraction of higher mineralized water from the confined areas of the A7/B2 as predicted by Margane et al. (2002). For closer analysis, a detailed study is recommended.

For the Q'a wellfield in the Ram aquifer only a slight increase in average salinities from 253 to 274 mg/L was identified. However, at most location that allowed for a direct comparison, stronger increases were registered, especially at ED1003/ ED1004 which showed an increase from TDS = 198 / 211 mg/L (Hobler et al.,1991) to TDS = 459 / 622 mg/L (this study).

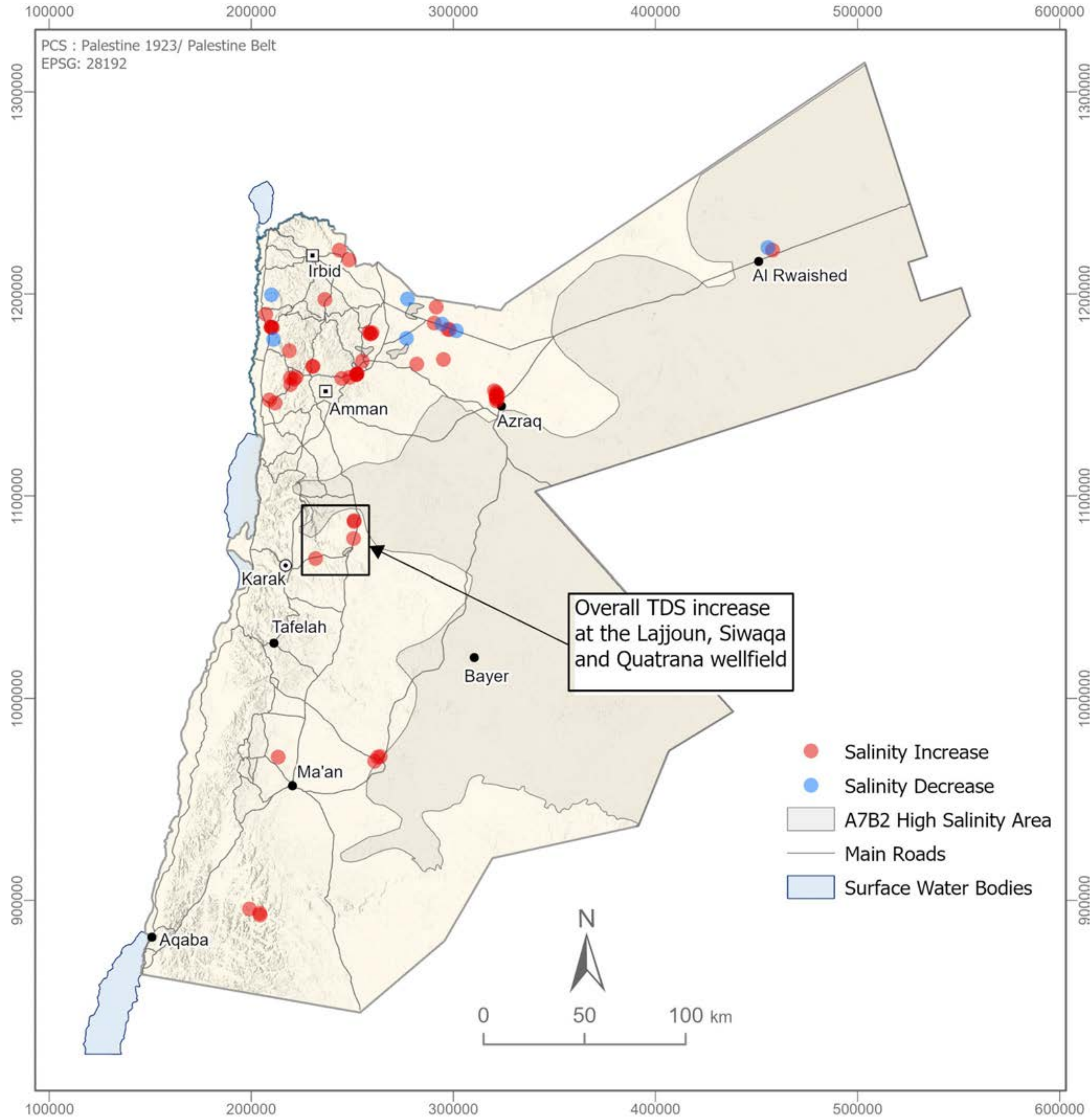


Figure 12: Salinity trends (EC and TDS) for selected locations.

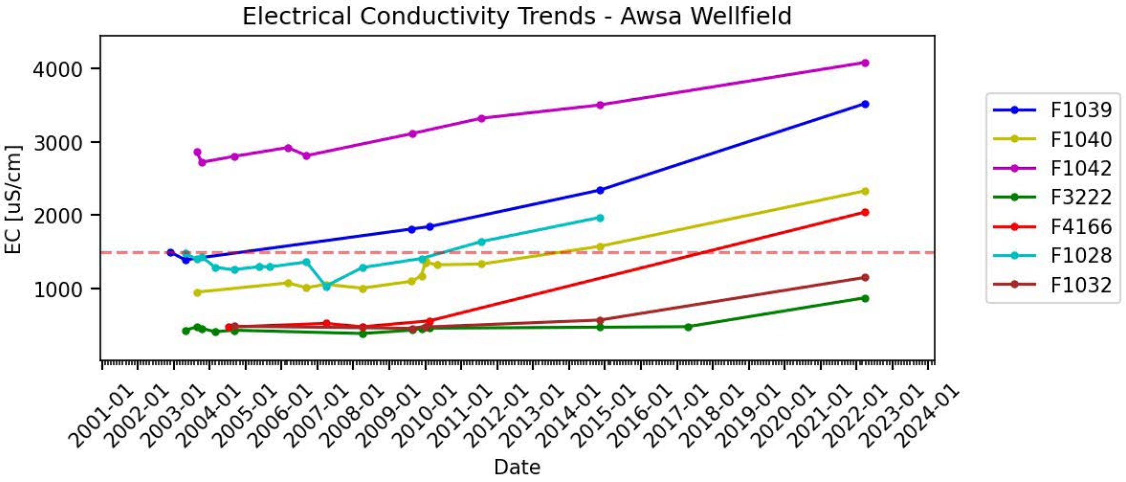


Figure 13 Increasing groundwater EC values at AWSA wellfield

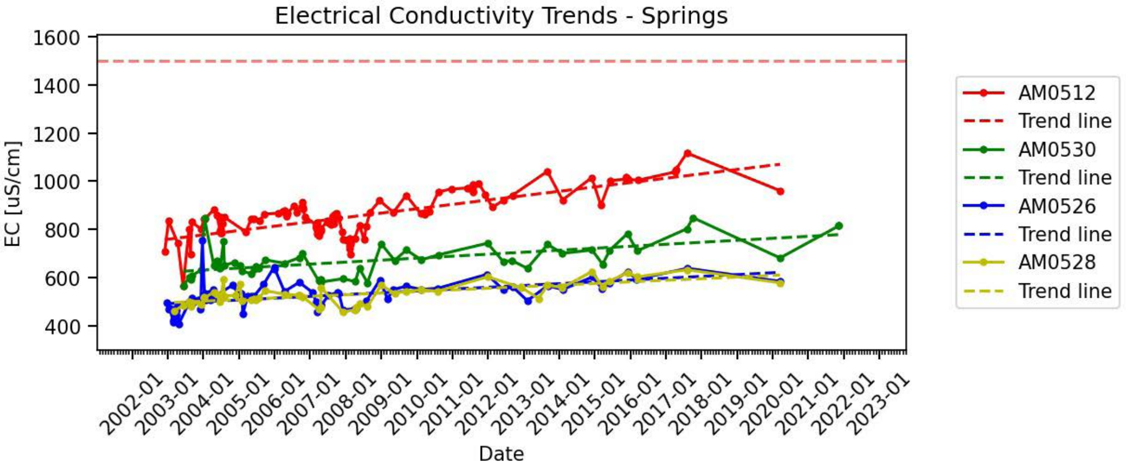


Figure 14: Increasing groundwater EC values at springs close to Wadi Fuheis.

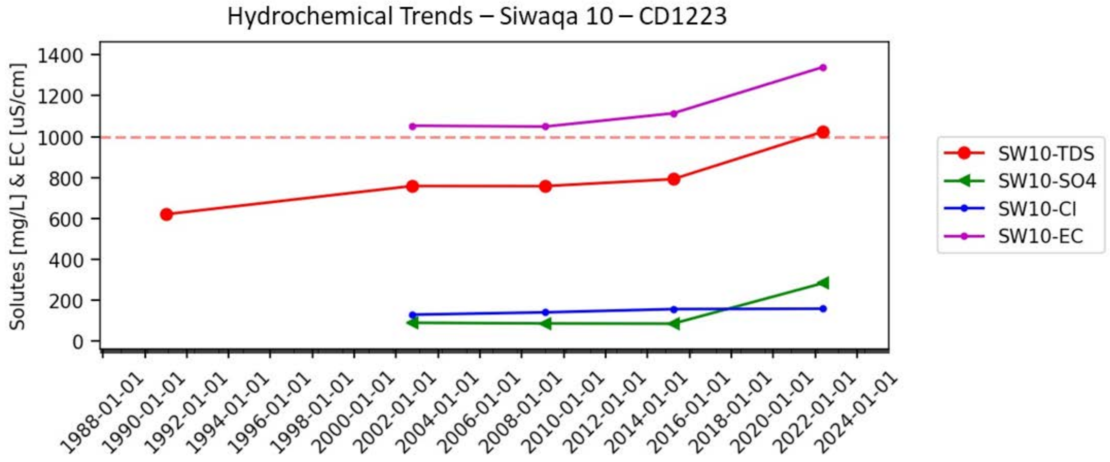


Figure 15: EC and selected major chemistry parameter at Siwaqa 10 (CD1223).

The distribution of the historic TDS and EC trends indicates a wide-spread tendency for groundwater salinity increase across Jordan. However, it is not representative, and only shows a limited extract of the overall trends as for most locations no time series were available. Frequently, increasing salinities only affected a few wells within a wellfield, while others remained stable or even showed a decrease in salinity. A previous study by Goode et al. (2013) also indicated highly variable trends for EC in Jordan. The increase of single wells within a wellfield may be attributed to a change in local groundwater flow pattern, land use, recharge rate, local contamination and/or the exploitation of a section of the aquifer. As long as the site-specific drivers of the groundwater salinization remain unknown, the identified trends are only valid in retrospective. In order to forecast future evolution of groundwater quality, the processes responsible for the salinity increase need to be determined in order to assess the scale and duration of the process.

The identification of the processes responsible for the observed high or increasing TDS concentrations requires a detailed site specific investigation that considers long-term hydrochemical trends, recent and historic groundwater flow, aquifer composition and land allocations. Unfortunately, these data were not available and beyond the scope of this study.

However, the following general observations were retained:

Wide-spread tendency for groundwater salinity increase across Jordan

In the baseline study, 29% or 33 of the 113 JDWS violations for TDS coincided with a violation for nitrate indicating a close relation of both parameters. A previous study by Al Kuisi et al. (2009) already reported a strong connection between nitrate and TDS and rising trends for monitoring location in of the Amman Zarqa Basin. In the baseline study, multiple locations show a simultaneous increase of nitrate and TDS in the groundwater indicating an (unintended) infiltration of agricultural irrigation water or municipal or industrial sewage (e.g. desalination brines). Evaporation processes in the field, pollution or higher initial TDS concentration may be responsible for the high TDS of the infiltrating water. Examples for affected areas include the Znayya and Baqa wellfields (Figures 16 and 17). Here, the identical behavior of TDS (blue line) and NO_3- (red line) indicates that the inflow of water containing a high nitrate concentration simultaneously raises the salinity of the water. Also, for the Ba-A7/B2 wells along the Bagdad road TDS shows a strong linear correlation (chapter 5.4.1) with NO3- concentrations possibly indicating agriculture return flows controlling the NO_3- and TDS concentrations.

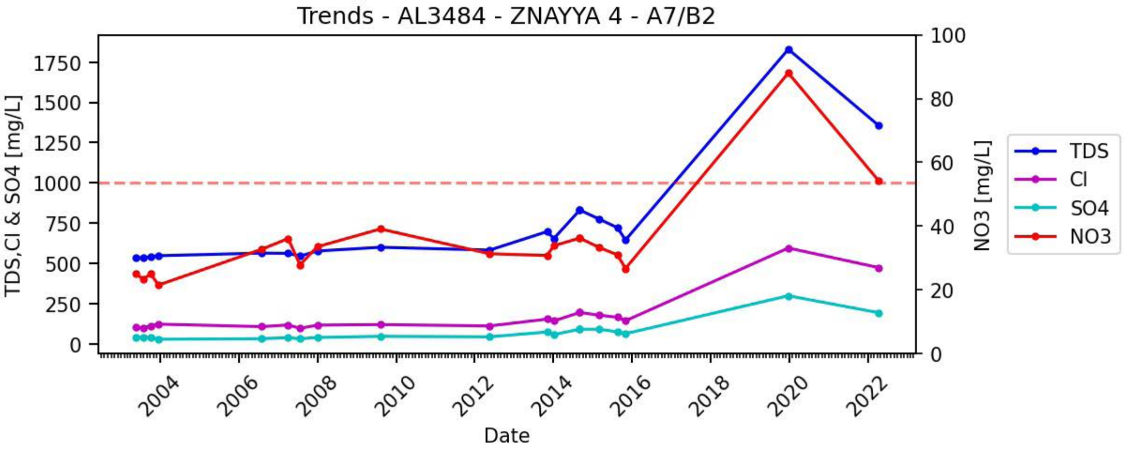


Figure 16: Hydrochemical time series of nitrate and salinity parameters at Znaya wellfield visualised for well Znaya 4. The dashed line indicates the TDS threshold value.

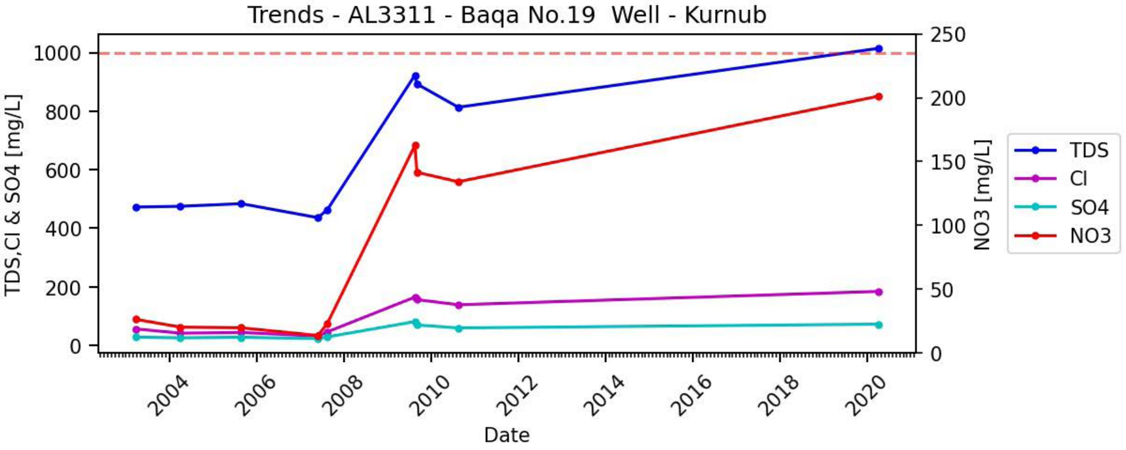


Figure 17: Hydrochemical behaviour of nitrate and salinity parameters at Baqa wellfield visualised at Baqa 19. The dashed line indicates the TDS threshold value.

Several locations exhibit a very rapid increase in salinity. Such an increase was captured in detail by the EC curve for the Abu Albassal 2 well (AD3121, Figure 18), where EC increased from the baseline study analysis of 1163 µS/cm in 2020 (red dot, TDS = 651 mg/L,) to over 2500 µS/cm within a year.

Similarly, at Abdelmuhsen Alwan Al Jam'an (F4203), the electric conductivity quadrupled over the course of one year. While in July 2020 the F4203 EC value was at 5203 µS/cm, it increased to 21900 µS/cm by July 2021 (baseline study value). The corresponding TDS concentration of 15008 mg/L or ~15 g/L in the approaches almost half-seawater concentration (TDS seawater: 33 – 37 g/L). If human error can be excluded, such rapid increase strongly points to a local contamination.

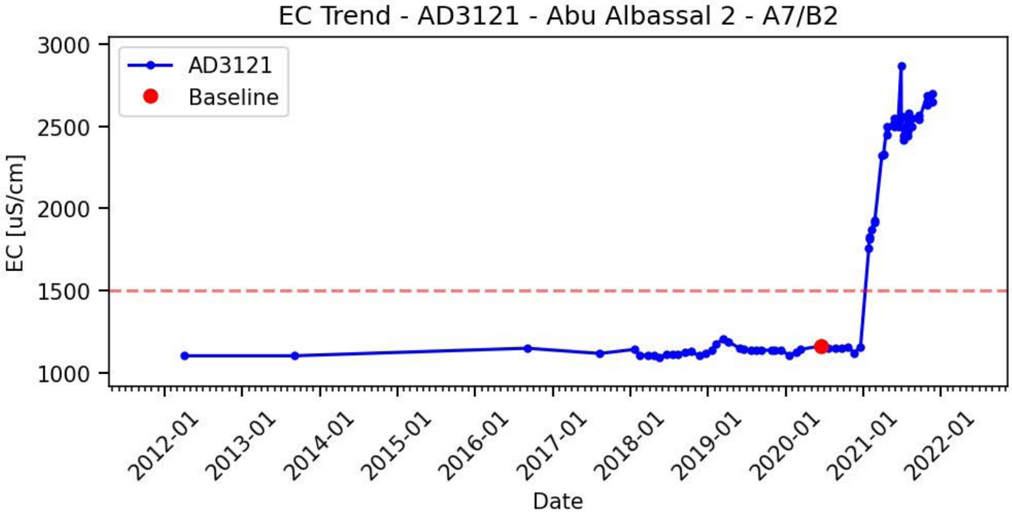


Figure 18: EC trend for Abu Albassal 2 well showing a sudden increase at the end of 2020. The red dot represents the baseline sampling.

Some locations show a long-term steady increase in TDS without an obvious connection to an external influence, for example a simultaneous rise in nutrient concentrations. Examples for this behaviour can be found at the AWSA wellfield (Figure 13), at Siwaqa 10 (Figure 15) or at the carbonate aquifers springs between Salt and Fuheis (Figure 14). The missing connection to external influences and the similar pattern for the salinity increases across the affected monitoring locations point to a more wide spread, geogenic source for salinity, e.g. an upconing from below.

5.4.3 Salinity Related Parameters – Na, Cl, SO_4^{2-} and TH

As the salinity related guideline parameters strongly correlate with TDS, their distribution follows the TDS distribution. Detailed maps for the single parameters are included in Annex A. However, they show a lower number of violations than displayed for TDS, as no violation occurred without a simultaneous TDS violation. The boxplot distribution for the parameters TH and Na in Figure 9 shows that guideline violations form a part of their observed main distribution as indicated by the whiskers above the red line for the threshold value. For chloride and sulphate, guideline violations occur only in outliers, as their individual limits are high when compared to other salinity parameters. For example, a chloride or sulphate violation above 500 mg/L already accounts for over half of the TDS threshold value of 1000 mg/L.

5.4.4 Boron

Boron was responsible for two JDWS-violations, while all other samples stayed well below the guideline level of 2.4 mg/L (Annex B). The violations with concentrations of 2.7 and 2.8 mg/L occurred at the shoulder of the Jordan valley in neighbouring wells (one tapping into the alluvial and one tapping into the Kurnub aquifer). Both monitoring locations had brackish water (TDS: 6781-6846 mg/L) and high ammonium concentrations above 2 mg/L. Boron can originate from various sources, including geological formations, geothermal activities or enclosed seawater. However, the co-occurrence of high boron concentrations with nutrients and a rather shallow well depth (45-158 m) at these locations could also indicate an origin from agricultural runoff (boron used in fertilizers and/or pesticides) or municipal wastewater (boron used in soaps and/or cleaning agents). As recycled wastewater is also used for irrigation in this area, a combination of both may also be the case. In the baseline study, all concentrations of boron that are greater than 1 mg/L were observed for locations with high TDS (1914-6846 mg/L) and either high ammonia (1.8- 2.2 mg/L) or high nitrate (76 - 83 mg/L) concentrations.

5.5 Nitrogen Species

The three relevant nitrogen species ammonium (NH_4+), nitrite (NO_2-) and nitrate (NO_3-) are commonly considered markers for anthropogenic contamination and are interconnected via the nitrogen cycle. For the local groundwater setting, this cycle starts when NH_4+ is formed by ammonification of organic material (e.g. human feces or manure) and dissolved in water infiltrating the subsoil. When reaction time and oxygen supply are sufficient during this infiltration, NH_4+ is oxidized via NO_2- to NO_3-. In the absence of oxygen, NO_3- then can act as an oxidizing agent. For example, with sediment organic matter or reduced sulfur species, nitrate is reduced to nitrogen gas (N2), which degasses into the atmosphere.

High nitrate is associated with blue baby syndrome and carcinogenic nitrosamines

In (semi-)arid areas, nitrogen fixation below the current ground surface or in paleosoils is not uncommon. Furthermore, phosphate-rich layers can accumulate nitrate, which is consequently leached during mining activities (Rosenthal et al. 1987). Ronen et al. (1983) showed that the agricultural development of formerly uncultivated land and the subsequent decrease in soil organic carbon resulted in significant increases in groundwater nitrate concentrations at the nearby Mediterranean coast. Furthermore, significant amounts of nitrogen has been found in aeolian deposits – e.g. in the Negev-desert (Offer, 1992) – offering another geogenic source for nitrogen into groundwater, if groundwater recharge at these sites is increased (e.g. by irrigation return flows). For Jordan, similar observations were made in the northeastern Badia-area, where elevated nitrate contents (>2000 mg/kg) were found at soil depths of 20 cm and lower (Al-Taani and Al-Qudah, 2013).

In the JDWS Guideline, the nitrogen species are considered as follows: The limit for NH_4+ is set to 0.2 mg/l and violations are treated as an indicator for recent faecal or industrial contamination, raising especially microbiological water quality concerns. The limit for NO_3- is set to 50 mg/l) and is caused by direct health considerations, as high nitrate concentrations are associated with the blue baby syndrome and the formation of carcinogenic nitrosamines. The limit for NO_2- is set to 3.0 mg/l for the same concerns as nitrate.

At most locations in Jordan, nitrate was the dominant dissolved nitrogen species in groundwater. This can also be seen in Figure 19, showing the concentration range and distribution of the N-species analysed in this study and displayed together with their guideline limits (red lines) as boxplot distributions. The figure shows an abundance of nitrate contaminations in Jordan, but also a relevant number of NH_4+-related violations. Nitrite is rarely detected in significant concentrations. The only observed high nitrite concentration at monitoring location Ghuwar 3 (CD1143) was interpreted as intermediate state of either nitrification or denitrification.

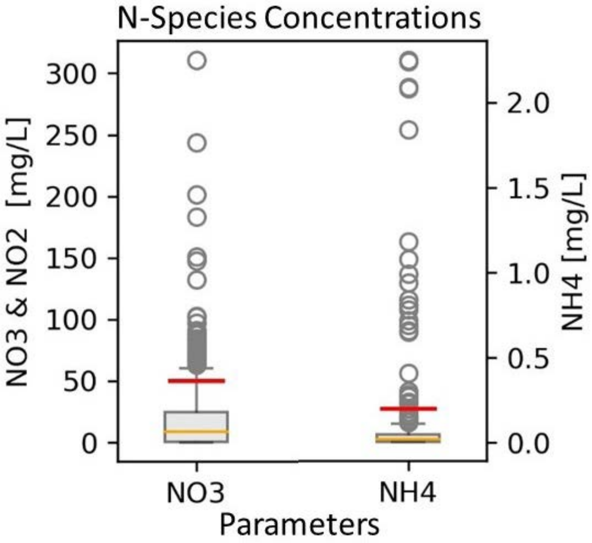


Figure 19: Boxplot for nitrogen species distribution observed in the baseline study. NO2- is not included in the plot, as only 30 values (out of 349 analysed samples) exceeded the LoD, of which only one single sample surpassed the JDWS-limit.

5.5.1 Nitrate

With a total of 61 monitoring locations (11.7%) above the guideline threshold of 50 mg/L, nitrate is responsible for the second most frequent guideline violations after the salinity parameters. At 27 of those locations, nitrate was the sole inorganic parameter responsible for exceeding the drinking water quality standards. The remaining nitrate violations coincide with salinity related exceedances (33), except for one location where concentrations of selenium and molybdenum are in excess.

Statistically, few significant correlations are observed. For TDS, despite the co-occurrence of salinity with nitrate violations, significant correlation was only identified on a local level. This is most probably due to the many different hydrogeological environments, where wells are affected by nitrate. Furthermore, anthropogenic nitrogen input occurs in very different forms, e.g. from agriculture, from industry or from (un-)treated sewage and the sources of groundwater salinity differ as well (desalination brine, dissolution of evaporates, inflow of brines from other aquifers, etc.). The same is true for most other major ions (always $r < 0.3$), except fluoride, which shows a negative correlation (-0.54). The weak negative correlation with fluoride could be due to the abundance of fluorine-rich waters in central Jordan, east of Karak and inside the Wadi Arabah (see Fig.27), where population density, agricultural activities and natural groundwater recharge (driving superficially applied nitrogen into the underground) are rather low. A weak positive correlation between NO_3- and several trace elements (Co, Cr, Se) can be observed. For oxyanions (such as Se), this could be due to their preferential presence / mobility under oxidizing groundwater conditions.

The spatial distribution of nitrate concentrations in the baseline study is presented in Figure 20. The four concentration categories represent the expected impacts regarding drinking water quality: Concentrations **below 25 mg/L** (= half of the Jordanian Drinking Water Limit) are considered **unproblematic**, while concentrations above 25 mg/L were considered elevated. Even though concentrations **between 25 mg/L and 50 mg/L** do not exceed the threshold value (yet), they are considered **noticeable** and should be monitored closely in the future. Concentrations **between 50 -70 mg/L** are considered **critical**, as they can have limited health effects but can be approved by the Ministry of Health if no better water source is available. Finally, concentrations **above 70 mg/L** are considered **alarming**, as they are not suitable for drinking purposes and require costly and laborious treatment or blending with low-nitrate water.

Nitrate is the second most frequent guideline violations after the salinity parameters

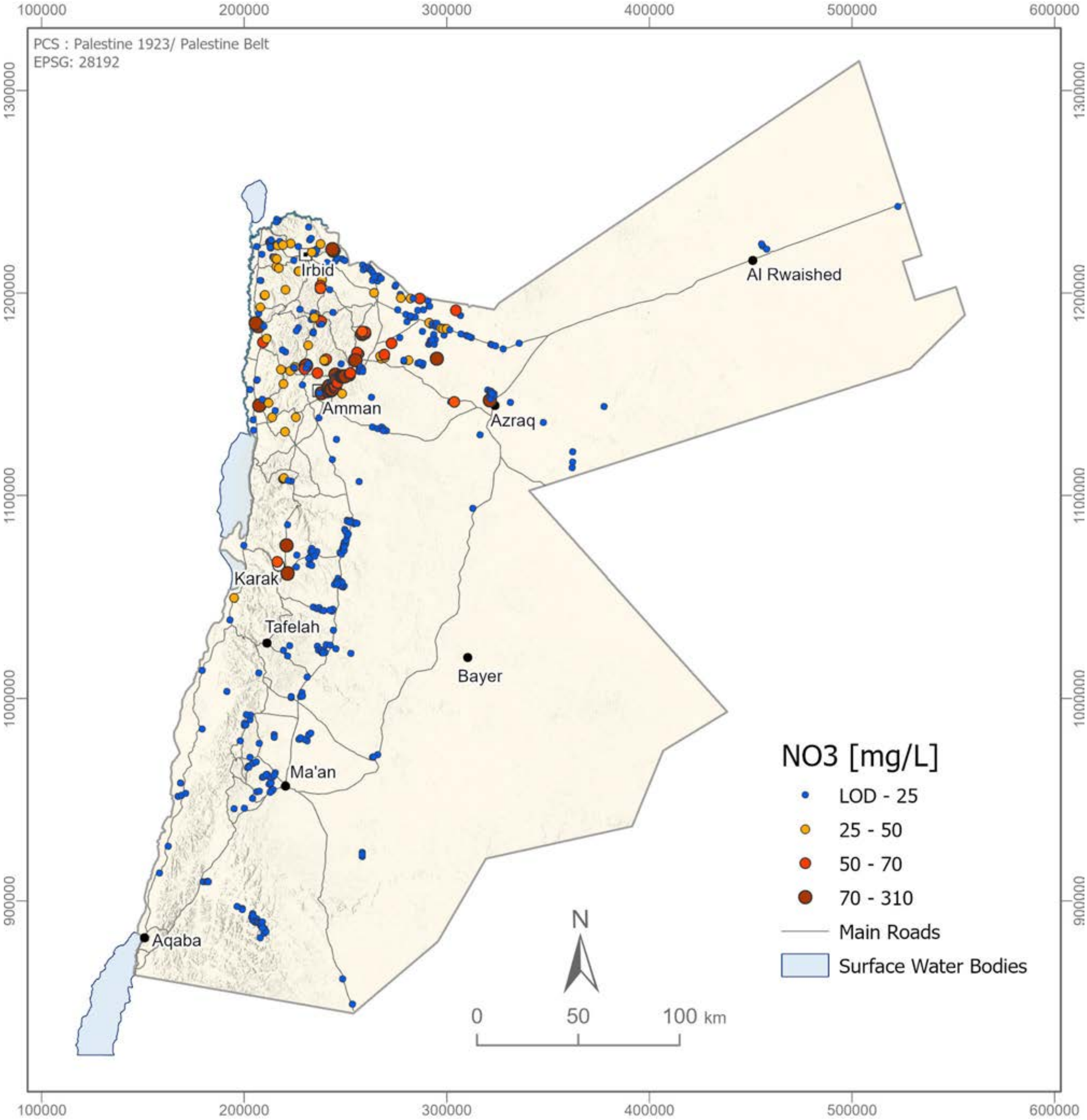


Figure 20: Nitrate concentrations observed in the baseline study.

Elevated nitrate concentrations are mainly observed in the northwest of the country around Amman, Mafraq, Irbid, inside the Jordan valley and around Madaba and Karak. These are the areas in Jordan with the highest population density and agricultural activity, which is mainly rain-fed in the northwestern part around Irbid. Around Irbid, no significant correlation was found between salinity-related parameters and NO_3-. Obeidat et al. (2021) made similar observations with no relation between NO_3- and any other salinity-related parameter than K (which is commonly used in fertilizers). N-isotope analyses in the same study concluded that nitrate contaminations were mainly connected to fertilizers and partly to urban sewage. (r<0.2).

This looks different further towards the east, where areas have only recently been developed for irrigated agriculture: For wells targeting the Basalt-aquifer there is a significant correlation between NO_3- and TDS (r>0.7). Without the AWSA-wellfield north of Azraq, where no agriculture at all is taking place, this correlation is even more pronounced (r>0.8). This can partly be explained by leaching of salts (including NO_3-) from irrigated areas. The source of the nitrogen itself, however, is unclear and could either derive from fertilizers or from the elevated geogenic nitrate content in the subsoil (as found by Al-Taani and Al-Qudah (2013) in this area). A more detailed study including N-isotopes could provide answers here.

The highest density of critical and alarming NO_3^--values was found in Amman along the Zarqa river, downstream of Ras al-Ain. In this densely populated area, agricultural activities are minor. Hence, N-input is most probably due to leakages from sewers. Downstream the Zarqa river, in the area of Russeifa and Zarqa, elevated NO_3^--concentrations correlate with elevated TDS-concentrations. Al-Kuisi et al. (2009) similarly observed this, connecting the salinity issues in the area around Russeifa and downstream to industrial activities (oil refinement, steel, paper, cement factories), while agricultural practices only play a role downstream the Zarqa-river in north and north-west of Amman.

Table 7: NO_3- violations per aquifer. The percentage of affected locations are calculated for the number of violations per number of analyses. For comparison, the mean NO_3- for all samples from the affected aquifers are shown. The remaining baseline locations had either no (11 wells) or a very broad (2 wells) aquifer association.

Aquifer	Total Locations	NO_3- Analyses	NO_3- Violations	Affected Locations	NO_3- Median	
Alluvium	26	26	3	12%	9	[mg/L]
Basalt	10	10	1	10%	16	[mg/L]
BA, B4/B5	21	21	1	5%	4	[mg/L]
BA, A7/B2	15	15	1	7%	12	[mg/L]
B4; B4/B5	13 (B4/B5), 2 (B4)	13 (B4/B5), 2 (B4)	1	7%	1 (B4/B5)	[mg/L]
A7/B2	263	263	32	12%	7	[mg/L]
A4	53	53	14	26%	32	[mg/L]
A1/A2; A1/A6	42 (A1/A2), 2 (A1/A6)	42 (A1/A2), 2 (A1/A6)	4	1%	15 (A1/A2)	[mg/L]
Zarqa	3	3	1	33%	16	[mg/L]
Kurnub	26	26	3	12%	1	[mg/L]

Correlations over time can be found between TDS and NO_3- at some wells in industrial areas or areas with irrigated agri- and horticulture (e.g. in Ruseifa, Znayya or Baq'a see Fig.21), while springs and wells in rain-fed agricultural areas show variations in nitrate completely unrelated to TDS (e.g. Hazzir or Azraq Fuheis spring). This matches the observation that parts of the nitrate contamination are probably introduced into the groundwater by significant amounts of waters rich in TDS (e.g. industrial waste water), while other parts are either associated to rather low saline water (e.g. domestic waste water) or with natural recharge (e.g. outwash from N-fertilized agricultural areas).

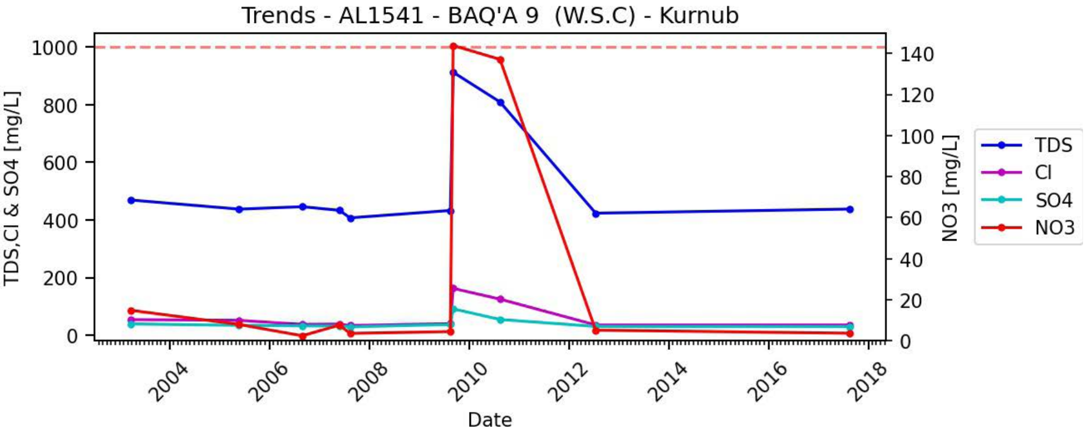


Figure 21: Time series of TDS, chloride, sulphate and nitrate in well Baq'a 9. A close relationship of the sources for increased TDS and increased NO3- is very likely in this case. The dashed line indicates the JDWS-limit for TDS.

In order to tackle the nitrate issues, more efforts are needed to improve the understanding in the different environments. In the northwestern areas, most nitrogen is apparently introduced by fertilizers, nitrogen balances in these regions need to be evaluated and fertilizer application has to be reduced. In other areas, the situation is more complicated, as any form of enforced percolation could increase the leaching of fixated nitrate. Hence, any form of agriculture requires monitoring and especially the development of new agricultural areas needs to be heavily restricted. Furthermore, any kind of artificial groundwater recharge in these areas (e.g. by MAR) would have to be monitored closely.

These conclusions, however, are rather straightforward, as the data situation does not allow a closer determination of causes for nitrate increases. Therefore, it is highly recommended to conduct a study on the origins of these increased nitrate contaminations at specific sites. Possible candidates in that regard would be the Znayya and the Baq'a well fields. Without appropriate measures, NO_3^--levels are expected to continue increasing in the future.

Another source for nitrate in groundwater is the percolation of wastewater, either from leaky sewers in completely untreated form or as outflow from wastewater treatment plants. It is obvious that it is a challenge for a country like Jordan, whose population doubled in the last 15 years, to constantly amplify its wastewater facilities (sewers and treatment plants). However, especially in the area of Amman, sewer networks should be expanded to serve as may inhabitants as possible and the (currently under dimensioned) wastewater treatment plants require upgrades to secure the drinking quality of groundwater.

5.5.2 NH_4+ and NO_2-

As mentioned before, NH_4+ is unstable under aerobic conditions and tends to sorb to negatively charged surfaces in soils. Only when oxidized to NO_3-, the nitrogen is mobile enough to be transported with normal groundwater recharge rates. Hence, it is rather not associated with extensive use of fertilizers over large areas, seeping slowly into the groundwater. Instead, it is seen as an indicator for recent anthropogenic contamination associated with point sources and preferential flow paths into the underground (e.g. infiltration basins, abandoned wells, sinkholes, leakage from sewers).

NO2-, can be an indicator for incomplete nitrification or denitrification, as it is an intermediate species in both processes. Therefore, it can also be associated with similar point sources as NH_4+. As NO_3- and NH_4+ are stable under different redox potentials, negative correlation is expected for these two species. This correlation, however, is rather weak (r = -0.27), which could be due to a mixing of waters with differing redox conditions or the slow kinetics and lack of oxygen, leading to an incomplete nitrification of ammonium. However, the coexistence of significant amounts of NH_4+ (>0.2 mg/L) and nitrate (>1 mg/L) is an exception (seven cases in 383 samples, analysed for both parameters). One of these exceptions is Ras al-Ain in the center of Amman, where 20 mg/l NO_3- (not elevated, but notable) coexist with 0.18 mg/l NH_4+ and 0.46 mg/l NO_2-, which is a clear sign for incomplete nitrification.

More correlations were found for ammonium with Mn – possibly connected to its mobility under reducing conditions – and various trace elements (r>0.5 for Ag, As, Be, Cd, Cu, Pb & Sb). The trace element connection could be derived from insufficiently treated domestic and/or industrial wastewater. Similar observations were made for NO_2-, but only for a very small set of samples. Annex C shows the areas with values exceeding JDWS thresholds for ammonium. Critical values are scattered all over Northern Jordan, mostly in proximity to NO_3^--contaminated sites, which indicates a close relationship between these two nitrogen species. The only isolated ammonium-cases are the two very remote cases of Rwaished (possibly due to livestock activities nearby) and the Shidiyya Ram deep wells. The spatial distribution of NO_2- measurements in Annex C mainly report the absence of elevated NO_2- concentrations, with all but one sample below less than half of the guideline value (< 0.5 mg/L) .However, one severe violation (19.7 mg/L) occurred in the Karak region at Ghuwair 3 / CD1143.

5.6 Oxyanions and Nickel

The oxyanion-forming elements arsenic, molybdenum, selenium, vanadium and uranium as well as the transition metal nickel were collectively studied due to their frequently simultaneous occurrence and weak to moderate positive correlations, which are listed in Table 8. Their concentration range and distribution observed in the baseline study is displayed in Figure 22.

Selenium (Se), molybdenum (Mo) and vanadium (V) are essential trace elements that play important roles in various biochemical processes, also for humans. However, while these elements are necessary for human health in low concentrations, their presence in higher concentrations can have adverse health effects. The metalloid arsenic (As), is classified as a toxic element and is considered harmful even at very low concentrations. Similarly, the heavy metal uranium (U) is not known for beneficial effects on the human body. In addition to its chemotoxicity, which is discussed here, long-term exposure can also induce harm due to its radioactive properties, which is not considered in this report. The WHO guideline level only addresses its chemical not its radiological aspects (WHO, 2022).

In addition to the trace elements included in Table 8, cadmium concentrations showed a weak to moderate positive correlation to trace elements in this suite, namely As (0.36), Mo (0.45), Ni (0.66), Se (0.50), U (0.50) and V (0.34).

Table 8: Spearman correlation coefficients (p= 0.05) for trace element analyses by MS (n=232). No data available for the governorates of Ma'an and Irbid.

	As	**Mo**	**Ni**	**Se**	**V**	**U**
Depth	-0.24	-0.20	-0.40	-0.29	-0.24	
Temp	-0.14		-0.34	-0.23		-0.25
pH		-0.13	-0.53	-0.13	0.20	-0.14
TDS	0.18	0.23	0.48	0.20		
As	1.00					
Mo	0.51	1.00				
Ni	0.43	0.55	1.00			
Se	0.36	0.55	0.51	1.00		
V	0.52	0.46	0.33	0.69	1.00	
U	0.20	0.32	0.38	0.53	0.36	1.00

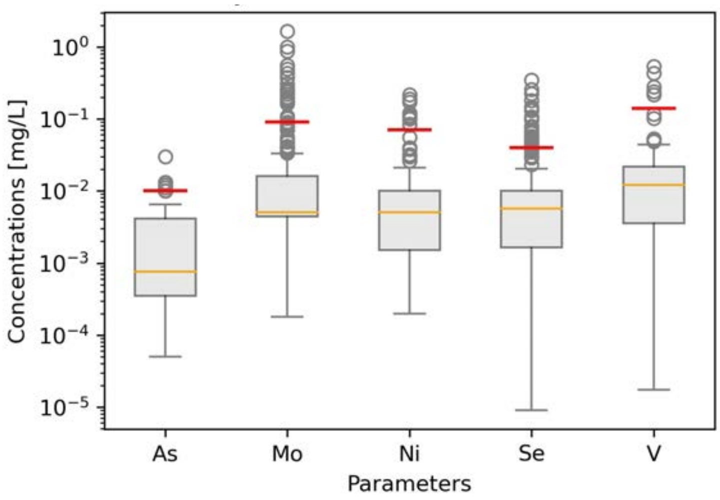


Figure 22: Boxplot distribution for trace element concentrations of As, Mo, Ni, Se, V and U as encountered in the baseline study. The red line indicates the trace elements JDWS guideline level (Table 3). Vanadium and uranium are not included in the JDWS guideline and therefore put in brackets. Vanadium displays the Italian drinking water threshold (140 µg/L, Arena et al. 2015), and uranium, displays the WHO chemical threshold (WHO, 2022).

5.6.1 Selenium and Molybdenum

Selenium (Se) and molybdenum (Mo) concentrations exceed the drinking water standards at 33 out of 411 (Se) and 20 out of 410 (Mo) monitoring locations. At over half of these locations, Se or Mo were the only parameter causing a JDWS-violation. As there is no treatment procedure for Mo and Se available in Jordan, this water needs to be blended with water from another source. The number of violations are likely to present an underestimation, given that only one sampling location in the Wadi Al Arab wellfield was analysed for Mo and Se. Dorsch et al. (2020) found 8 out of 17 wells to show alarming concentrations of >0.27 mg/l. In this sample and in four others from the Karak area, a joint guideline violation occurred for selenium and molybdenum. A visual analysis of the boxplots for the analysed selenium and molybdenum concentrations in Figure 22 reveals that all violations constitute outliers from the main distribution as indicated by the grey circles above the red lines marking the individual guideline limits.

For the visualization of the spatial distribution (Figures 23 and 24), selenium and molybdenum concentrations were sorted into four categories. Category 1 contains **unproblematic** concentrations **below half of the guideline threshold** represented as blue dots (Se < 0.02 mg/L, Mo < 0.045mg/L), while categories 2-4 represent elevated concentrations defined as above half of their guideline level and higher. Category 2 shows **noticeable** values **approaching the threshold** concentration (orange) (Se between 0.02 and 0.04 mg/L, Mo between 0.045 and 0.09mg/L). Category 3 represents **critical** values **surpassing the threshold** concentration (red) (Se between 0.04 and 0.05 mg/L, Mo between 0.045 and 0.09mg/L), and category 4 shows **alarming** values **surpassing the exemption** concentration (brown) (Se > 0.05 mg/L, Mo > 0.27 mg/L). All categories for elevated selenium and molybdenum concentrations (noticeable – alarming) can be considered above the main distribution for the Jordanian context, as they all fall into the outlier area in the boxplot distributions (Figure 22).

Monitoring locations affected by high selenium concentrations are predominantly situated in the Karak region, but single violations also occur in the greater Amman, Ma’an, and Zarqa area, with the highest recorded baseline concentration of Se = 0.348 mg/L (seven times the JDWS-limit) at the Deep 4 (AL3324, A1/A2) well between Amman and Ruseifa. In northern Jordan, selenium violations occur at Wadi Al Arab, Manda and Mukeiba wellfield. Elevated selenium concentrations (0.02 – 0.348 mg/L) were found at 47 wells and in all carbonate aquifers, but all locations were intersecting the A7/B2 aquifer. Approximately, 68% of the wells exploited only the A7/B2, and around 32% of the

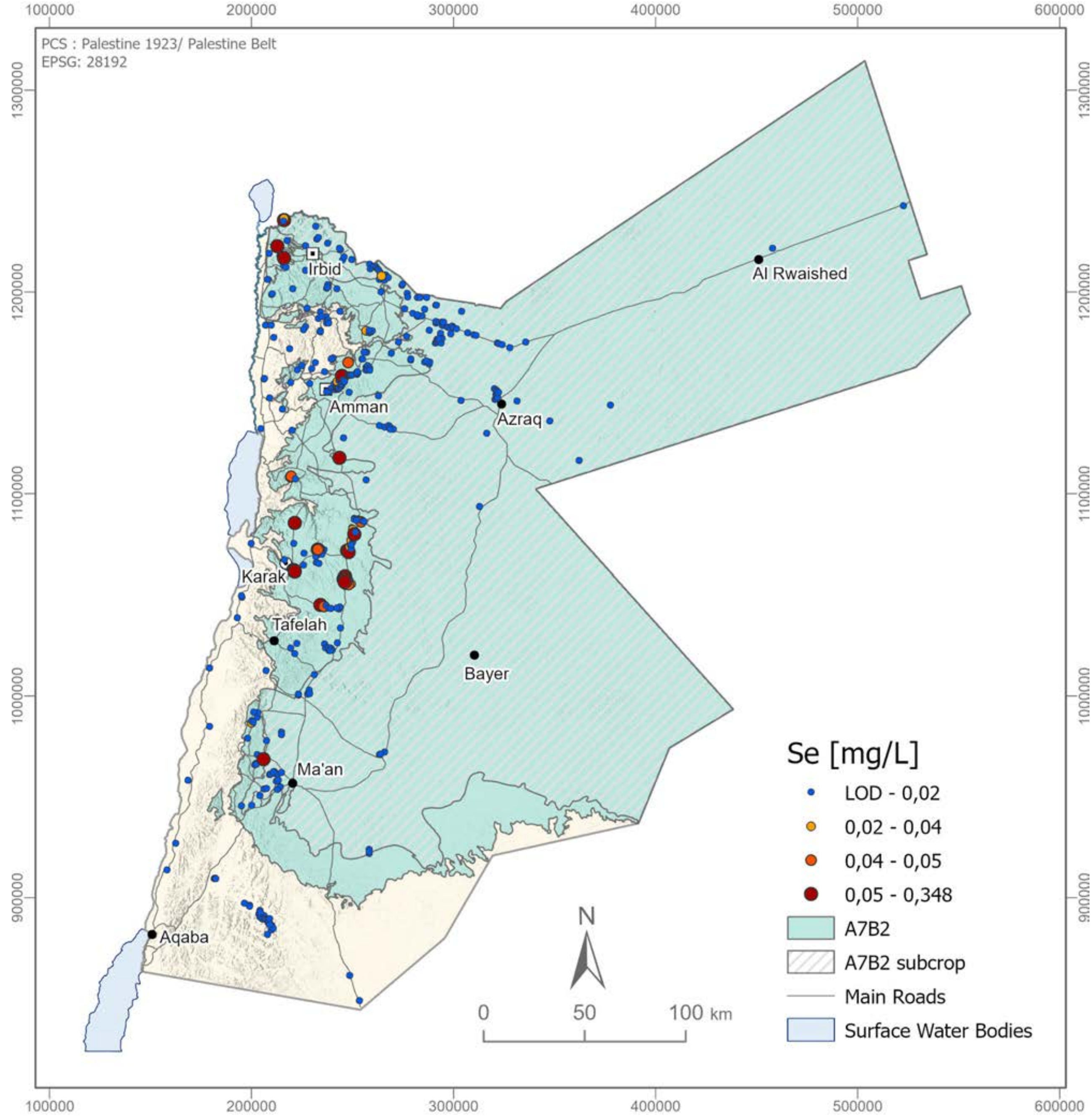


Figure 23: Selenium concentration observed in the baseline study.

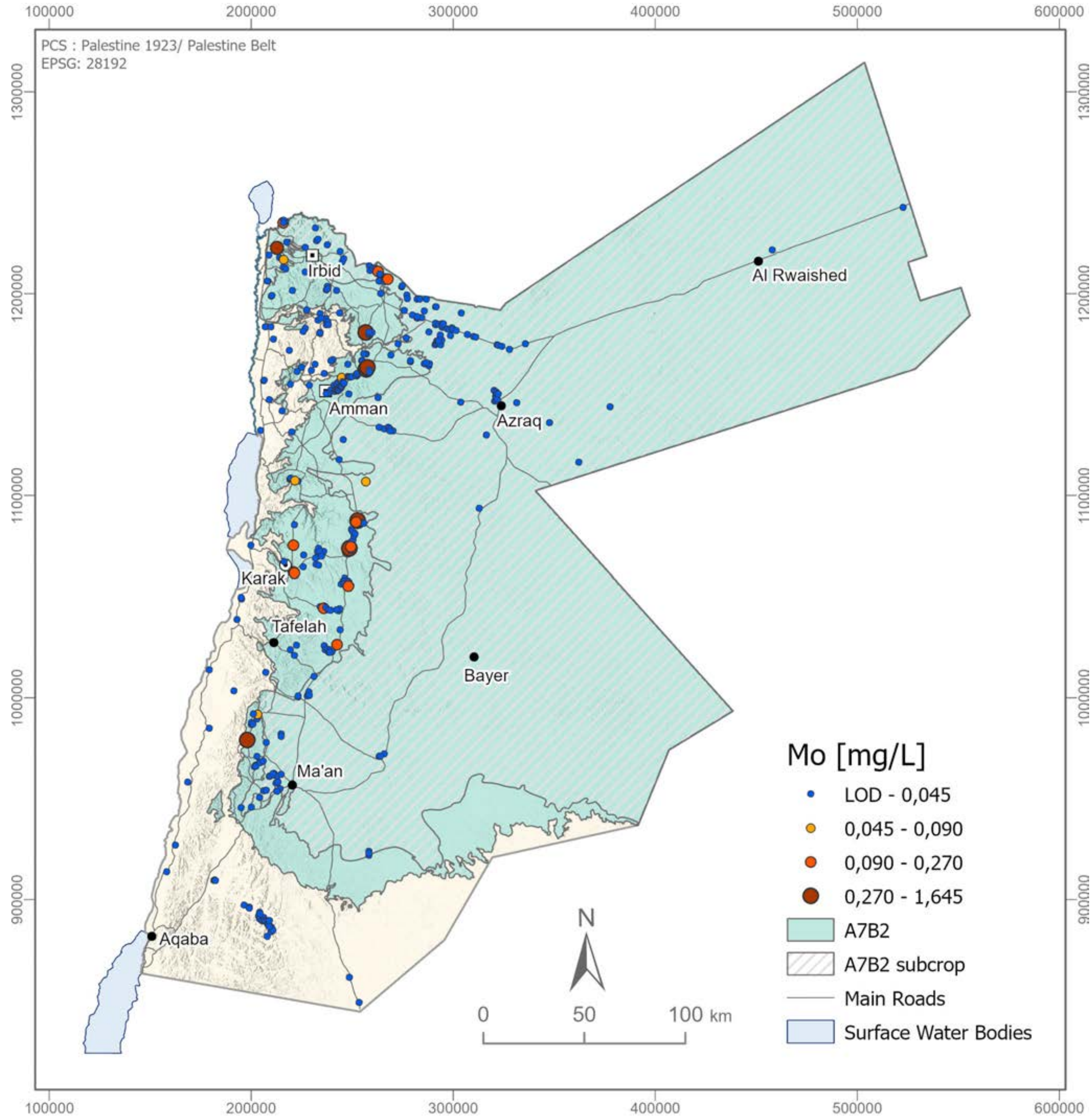


Figure 24: Molybdenum concentrations observed in the baseline study.

wells completely penetrated the A7/B2 aquifer and ended in a deeper carbonate aquifer (A1/A2, A4). Similarly, selenium violations occurred in all carbonate aquifers (Table 9), however, deeper carbonate aquifers were always overlain by the A7/B2 aquifer (see Figure 23).

There were only few historic analyses for selenium available and most of them were below the LOD or reached maximum concentrations of 5 µg/L. However, a study by Al Kuisi et al. (2010) reports selenium concentrations of up to 0.742 mg/L for a monitoring location in the A4 aquifer at the Amman Zarqa Basin and Kilani (1997, cited in Al-Kuisi et al., 2010) reports concentrations of up to 0.441 mg/L for the same aquifer. At the Siwaqa wellfield, a BGR sampling campaign in 2015 recorded guideline violations between 0.048 and 0.105 mg/L at four A7/B2 monitoring locations as detailed in Table 11.

Table 9: Number of Se violations per aquifer. The percentage of affected locations are calculated for the number of violations per number of analyses. For comparison, the median Se for all samples from the affected aquifers are shown.

Aquifer	Total Locations	Se Analyses	Se Violations	Affected Locations	Se Median	
A7/B2	263	217	25	12%	0.001	[mg/L]
A4	53	44	3	7%	0.004	[mg/L]
A1/A2; A1/A6	42 (A1/A2), 2 (A1/A6)	35 (A1/A2), 1 (A1/A6)	5 (A1/A2)	14%	0.001 (A1/A2)	[mg/L]

Molybdenum concentrations overall showed a distribution similar to selenium, with a cluster of violations in the Karak region and a single violation in the Ma'an area. In the Zarqa region, the Znaya and especially the Tamoween wellfield are affected and, as for selenium, this region is featuring the highest recorded value of Mo = 1.645 mg/L (18 times the JDWS-limit) at Tamoween No 6 (AL3646, A7/B2). In northern Jordan the Sirhan, Mukeiba and Wadi Al Arab wellfield record variable molybdenum violations. However, based on previous surveys, groundwater in the Wadi Al Arab wellfield is likely to contain very high molybdenum concentrations. Elevated molybdenum concentrations (0.045 – 1.645 mg/L) were found at 28 wells and all locations were intersecting the A7/B2 aquifer (Figure 24). Approximately, 57% of the wells exploited only the A7/B2 aquifer, and around 43% of the wells completely penetrated the A7/B2 aquifer and ended in a deeper carbonate aquifer (A1/A2, A4). Similarly, molybdenum violations (20) occurred in all carbonate aquifers (Table 10), however, deeper carbonate aquifers were always overlain the A7/B2 aquifer (see Figure 24).

Table 10: Mo violations per aquifer. The percentage of affected locations are calculated for the number of violations per number of analyses. For comparison, the mean Mo concentrations for all samples from the affected aquifers are shown.

Aquifer	Total Locations	Mo Analyses	Mo Violations	Affected Locations	Mo Median	
A7/B2	263	215	13	6%	0.007	[mg/L]
A4	53	44	4	9%	0.010	[mg/L]
A1/A2; A1/A6	42 (A1/A2), 2 (A1/A6)	36 (A1/A2), 1 (A1/A6)	3 (A1/A2)	8%	0.001 (A1/A2)	[mg/L]

In the past, molybdenum concentration have caused serious water quality problems at multiple wells across Jordan, especially in the Wadi Al Arab wellfield area (e.g., Al Kuisi et al. 2015, Dorsch et al., 2020, GIZ 2020, Hiasat et al. 2020, Brückner et al. 2021). Molybdenum concentrations of up to several milligrams per liter were detected at several production wells and have been linked to a geogenic origin, possibly reinforced by anthropogenic effects for the peak values (Dorsch et al., 2020, Table 11). Average trace element concentrations between 2014 and 2017 identified 14 of 20 production wells with severe guideline violations for molybdenum, six of them surpassing the extended limit (Dorsch et al., 2020), and high Mo concentrations have led to the shutdown of several wells at the Wadi Al Arab wellfield. However, despite displaying the highest concentrations for molybdenum in the historic data (Table 10), the Wadi Al Arab wellfield is not the only wellfield were molybdenum surpassed the drinking water guideline. Measurements of molybdenum concentrations higher than 0.09 mg/L (=JDWS-limit), frequently even surpassing 0.2 mg/L, were also reported for samples from the Abu Albassal, Hallabat, Jabir, Jafer, Kufr Asad, Mandah, Rwaished, Siwaqa, Wadi Al Abyad, Yazidiyya and Za'atari wellfields between the years 2009 to 2018 (Table 10). These wellfields predominantly target the A7/B2 and underlying carbonate aquifers with the exception of the Rwaished and Jafer wellfields, which exploit the B4/B5 aquifer. In the Awajan-Ruseifa-Zarqa wellfields, elevated molybdenum concentrations up to 0.06 - 0.07 mg/L were detected, but none of the samples exceeded the JDWS-limit. For example, the Deep 4 well (AL3324, A1/A2) in Ruseifa recorded elevated molybdenum concentrations in 2009 (Mo= 0.07 mg/L). and showed alarming selenium (0.348 mg/L) and elevated molybdenum (0.056 mg/L) concentrations in the baseline study.

Table 11: Monitoring locations with selenium and molybdenum violations at various locations outside of the Wadi Al Arab wellfield between the years 2009 to 2018.

Location	Ministry ID	Date	Mo [mg/L]	Se [mg/L]	Ni [mg/L]
Abu Albassal 4	AD3135	13.05.2013	0.14	<0.002	<0.01
Hallabat 23	-	13.04.2011	0.150	-	0.02
Jabir 8	AD3076	24.03.2009	0.26	-	<0.02
Jafer 32	-	14.11.2017	0.29	-	0.03
Kufr Asad 4	AE3011	13.03.2018	0.222	-	0.133
Mandah 2	AB4285	17.01. - 13.03.2018	0.09 - 0.109	-	0.033 - 0.035
Rwaished 1	H2015	22.01.2009	0.090	-	0.06
Rwaished 1a	-	14.04.2016	0.180	-	-
Rwaished 2	H1012	22.01.2009	0.100	-	<0.02
Rwaished 4	H3060	22.01.2009 & 22.08.2015	0.140 – 0.220	-	0.07
Siwaqa 1A	CD3222	23.03.2015	0.188	0.097	0.031
Siwaqa 5	CD1118	24.03.2015	0.023	0.105	0.008
Siwaqa 9	CD1119	24.03.2015	0.094	0.0002	0.056
Siwaqa 20	CD3224	31.03.2015	0.01	0.048	0.008
Siwaqa 27	CD3282	13.02.2011	0.140	-	-
Siwaqa 28	CD3220	13.02.2011	0.550	-	-
Siwaqa Army	CD3308	23.03.2015	0.020	0,050	0.013
Wadi Al Abyad	CD1180	24.08.2010 - 07.03.2012	0.380 - 0.700	-	0.09 – 0.12
Yazidiyya 1A	-	20.01. - 01.02.2011	0.090 - 0.100	-	< 0.01
Yazidiyya 8	AL3527	31.05.2009	0.24	-	< 0.02
Zatari 3	AL2710	27.05.2014	0.21	-	-

When analysing the spatial distribution of the **selenium and molybdenum**, it appears that the **elevated concentrations** for both parameters **follow the outcrop area of the A7/B2 aquifer** with few exceptions, as displayed in the Figures 23 and 24. A visual inspection of the detailed geological map, however, indicated predominantly the presence of lower Belqua Group sediments, especially the B2 formation, close to monitoring locations with elevated Se and Mo concentrations (Annex D). This apparent spatial relationship was also confirmed for historic Se and Mo violations, with the exception of Mo violations at the Rwaished and Jafer wellfield, which both tap the B4/B5 aquifer.

Previous scientific studies and reports have identified the Muwaqqar Chalk Mark Formation (B3) as the most likely source for dissolved molybdenum in the Wadi Al Arab wellfield region (e.g. Al Kuisi e al. 2015, Dorsch et al., 2020). Additionally, the B2 phosphorites were considered a potential source, as high molybdenum concentrations have been identified for both lithologies (Dorsch et al., 2020, Al–Hwaiti, 2013, Al Kuisi, 2015). Fleurance et al. (2013) reported the enrichment of trace elements, for example arsenic, cadmium, chromium, nickel, molybdenum, uranium, vanadium, zinc and sulfur, for several members of the Belqa Group, including the Al Hisa Phosphorites (B2), Muwaqqar Chalk Marl (B3) and the Umm Rijam Chert (B4). Even lithologies with a comparably low organic carbon and/or lower phosphate content were found to be enriched with trace elements, though to a lower degree. Due to the fine dispersion of the minerals bearing the trace elements, this enrichment was linked to a synsedimentary deposition.

A study by Ahmad et al. (2020) identified elevated concentrations for Cd, Cr, Mo, Ni, Se, V and Zn in limestones and phosphorites of the Al Hisa Formation (B2) and Muwaqqar Chalk Marl (B3). For the Umm Ghudran (B1) formation no information on its trace element content was found. However, considering the closely related geological history of the Belqa-group (e.g., Bandel and Salameh, 2013), it appears likely that B1 also shows some enrichment in the aforementioned trace elements. This assumption, however, requires confirmation by geochemical analysis.

At several recent and historic locations with selenium or molybdenum violations outside of Irbid Governorate, the B3 has been eroded and lower members of the Belqa Group prevail (displayed in Annex D). In addition, the historic molybdenum violations at the Rwaished wellfield occurred in wells exploiting the B4 aquifer. We therefore conclude that while Dorsch et al. (2020) identified the B3 as the main source for molybdenum in the Wadi Al Arab, other sediments of the Belqa group (notably B2) may also have the potential to release molybdenum and selenium, though possibly in lower concentrations. This is in agreement with Wagner et al. (in prep.) who propose sediments of the lower Belqa groups, especially B2, to act as potential source for elevated selenium concentrations in the Karak region. Similarly, Al Kuisi et al. (2009) links high observed selenium concentrations in A7/B2 and A4 aquifer of the Amman Zarqa Basin mainly to the leaching from overlying phosphorite units, however, he also mentions the potential for alternative sources including the release from industrial fertilizer (especially when processed from Jordanian phosphorites).

Concerning the mobilization process, Wagner et al. (in prep.) proposes the in-situ mobilization of selenium and other oxyanion-forming trace elements in response to an aeration of the aquifer matrix as possible driver for the observed selenium concentrations. The aeration of formerly water-saturated formations favors the oxidation of immobile native selenium and/or selenium-bearing mineral phases such as sulfides and organic matter. As a result, a formerly anaerobic environment transforms to an aerobic environment, triggering the formation of soluble (Se, Mo) oxyanions, which can be mobilized by seasonal GW level fluctuations and/or infiltrating meteoric/surface water e.g., during the rainy season or from dams, ponds and irrigated areas. The aeration of formerly water saturated host rocks is probably linked to the excessive drawdown for the Karak as well as other wellfields. A comparison with the A7/B2 drawdown data from 2017 suggests that for the baseline data most locations with elevated Se and Mo concentrations fall into areas with strong decreases in groundwater level. Consequently, an aeration of the aquifer connected to excessive drawdown might be a plausible trigger for the mobilization of selenium and molybdenum concentrations at these locations. In agreement with a mobilization by aeration, Al Kuisi et al. (2010) also reports that the water for samples from the A4 aquifer (showing the peak concentrations in his study), was more aerobic than for the remaining samples (A7/B2, A1/A2 and Kurnub).

In Wadi Al Arab, direct leakage from the oilshale (B3) was identified as the most likely source for the high trace element concentrations (Al Kuisi, 2015, Dosch et al. 2020). However, we suggest that selenium and molybdenum, possibly in combination with other trace elements (As, Cd, Ni, U, V), could also be released from other members of the Belqa group, notably the B2 formation. Given the severity of this problem, further research is required to understand the trace element content of the B2 host rocks in comparison to other aquifer formations (e.g., A7) and to evaluate alternative theories for trace element release. Due to the observed correlations between Mo, Se and other trace elements, we recommend to introduce a routine monitoring suite of the correlated trace elements (As, Mo, Ni, Se, V, and U), possibly extended for cadmium, at locations showing elevated concentrations for one or more elements included in this suite. Sites with the most urgent need for more detailed attention identified in this study include especially the Tamoween and Karak wellfields.

5.6.2 Nickel and Vanadium

High nickel (Ni) concentrations were responsible for nine guideline violations in the baseline study. In four cases, these violations coincided with either selenium or molybdenum exceedances, while for the remaining five violations molybdenum or selenium concentrations were not analysed. Similarly, the five violations for vanadium (V) against the Italian standard mostly occurred together with either a selenium or a molybdenum exceedance (four cases). However, for the monitoring location with the highest vanadium concentrations (AWSA 16a/F4166, V= 0.5 mg/L, B4/B5), the selenium and molybdenum concentrations were acceptable and only salinity related parameter moderately surpassed their limits, with TDS, Na and Cl between 1.1 to 1.5 times their guideline values.

Nickel concentrations in Figure 25 were considered **unproblematic**, when they were **below half of guideline limit** for nickel (0.035 mg/L), represented by blue dots. **Noticeable** concentrations **between 0.035 mg/L and 0.07 mg/L** are represented by orange circles. These wells are acceptable regarding nickel concentrations, but should be monitored in the future. **Critical** concentrations (red circles) identify locations **exceeding 0.07 mg/L** up to a peak value of 0.215 mg/L at Abu Al Bassal 2 (AD3121). Concentration ranges for **vanadium** were subdivided according to the Italian Guideline limit for vanadium (0.140 mg/L, Arena et al., 2015) into **unproblematic** wells **below 0.07 mg/L** (blue triangles), **noticeable** wells **over 0.07 mg/L** (orange triangles) and **critical** wells **over 0.140 mg/L** (red triangles)). All elevated categories for elevated nickel and vanadium concentrations (noticeable – critical) can be considered unusually high in the Jordanian context as they represent outliers in comparison to the boxplot distribution (Figure 22).

The spatial distribution of elevated nickel concentrations were found predominantly in the Irbid (Wadi Al Arab wellfield and Abu Al-Bassal 2) and Karak (Sultani and Quatrana wellfield) region. However, elevated nickel concentrations were also reported for the Rwaished 1 (H2015) well. Nickel showed a significant weak to moderate Spearman correlation to the redox sensitive trace elements Mo, Se, U and V in Table 8. In addition, it moderately correlated with carbonate (Ca: 0.55, HCO_3^-: 0.65) as well as Antimony (0.52), Cadmium (0.66) and

Elevated arsenic concentrations were mainly scattered across northern Jordan

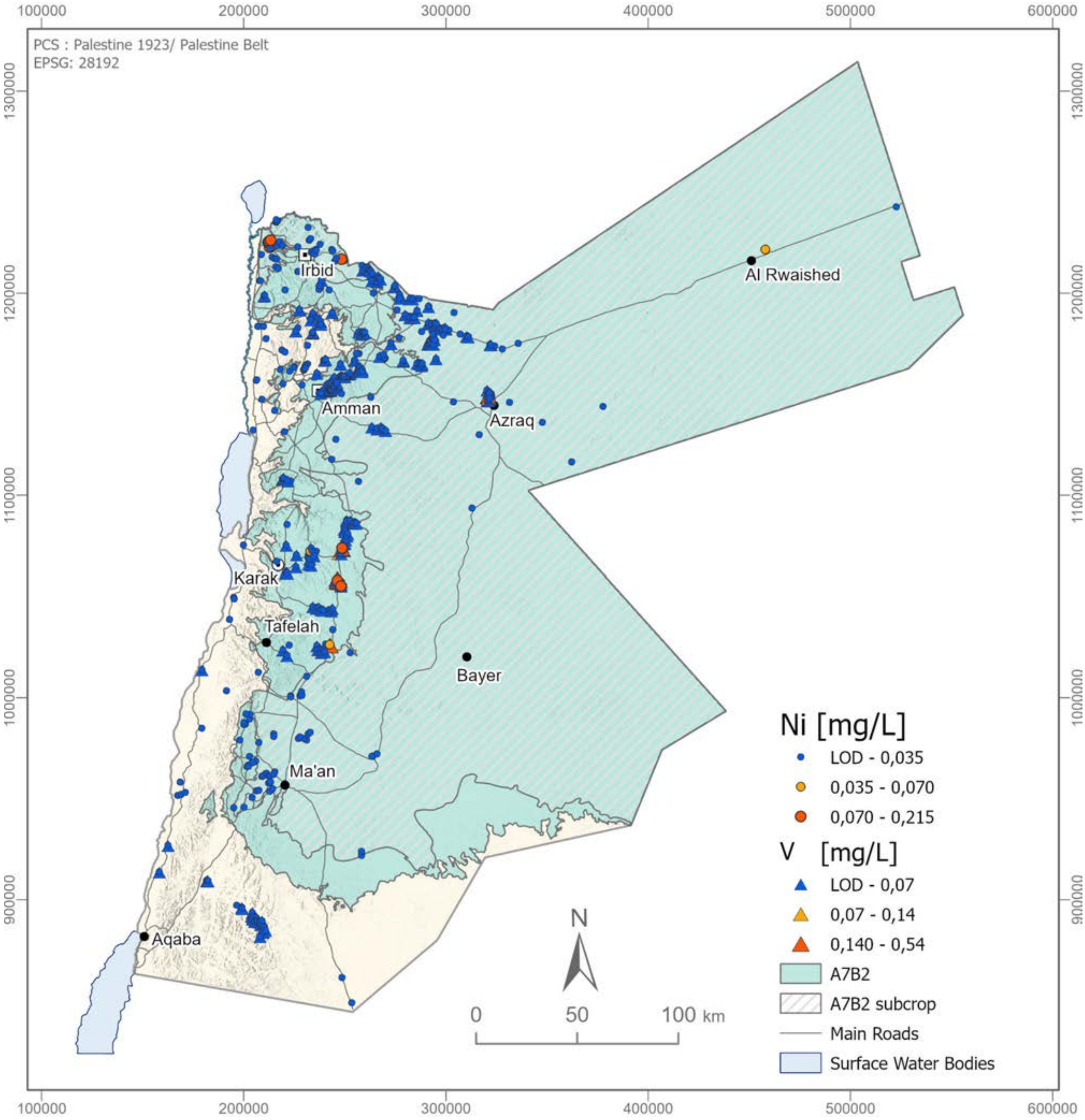


Figure 25: Nickel and vanadium concentrations observed in the baseline study.

Zinc (0.50). Elevated nickel concentrations (0.035 – 0.215 mg/L) were found at 13 wells. Most of these wells are exploiting (11) or subcropping (1) the A7/B2 aquifer and one is tapping into the B4/B5 aquifer (Rwaished 1/ H2015).

In the historic data, guideline violations for nickel concentrated on the Wadi Al Arab wellfield and the Abu Al-Bassal 2 (AD3121) and Kufr Asad 4 (AE3011) wells. These violations frequently coincided with very high molybdenum concentrations. For example, BGR & MWI (2018) reported the joint occurrence of nickel, molybdenum and arsenic violations for several wells the Wadi Al Arab wellfield. The peak concentration of the historic data was reached in 2017 for Wadi Al Arab 19 (AE3043) with 1.51 mg/L for nickel and 13.7 mg/L for molybdenum. These extraordinary levels are thought to result from a combination of anthropogenic effects (crushed rock, introduction of an oxidant by drill foam and long contact time) that reinforced the trace element release from the aquifer (Dorsch et al., 2020). Outside of Irbid, elevated historic nickel concentrations were also found for wells in the Ruseifa (AL1551, AL3656), Rwaished (H2015, H3060), Siwaqa (CD1122), Muhay (CD3480) and Za Tari (AL2710) wellfields.

Vanadium mostly follows the same pattern as nickel, except for the peak value, which occurred at the AWSA wellfield (Figure 25). Elevated vanadium concentrations (0.07 – 0.541 mg/L) were found at seven wells and most were exploiting the A7/B2 aquifer, at least partially. Three of the wells directly tapped into the A7/B2 aquifer and two of the wells completely penetrated the A7/B2 aquifer and ended in the deeper A1/A2 carbonate aquifer. The peak concentration of 0.541 mg/L and one noticeable concentration was analysed at the AWSA wellfield exploiting the Basalt/B4 aquifer. Historically, vanadium concentrations above the guideline threshold (0.174 - 0.962 mg/L) were measured for samples from the Wadi Al Arab wells 18 (AE3035) and 13a (AE3042). These vanadium violations occurred in samples that also showed critical to alarming levels of molybdenum (0.131 – 0.693 mg/L) and nickel (0.098-0.235 mg/L).

The correlation and similar spatial distribution between nickel, vanadium, selenium and molybdenum most likely indicates a common source. Several studies identified an enrichment of nickel and vanadium in combination with other trace elements (e.g. Mo, Se, Cd, Cr, U and Zn) for sediments of the Belqa group (Al-Hwaiti et al. 2013, Fleurance et al. 2013, Ahmad et al., 2020). Therefore, a similar mobilization process as the one responsible for the observed selenium and molybdenum processes is suspected. The observed correlation between nickel and cadmium could indicate a release of cadmium from the same source. However, Cd concentrations did not reach toxic levels in the baseline study.

Due to the suspected common source and a similar environmental behaviour to the other oxyanions, e.g. the stability of the dissolved form in oxygenated circum-neutral groundwater (Wright et al., 2014), high vanadium concentrations are likely to occur together with elevated levels for molybdenum and selenium. Vanadium is not included as parameter in the Jordanian drinking water guideline, however it has been observed in high concentrations and is known for its potential for detrimental health effects, especially in its pentavalent form (Assem and Levy 2009, Arena et al. 2015). In a global comparison, vanadium has not (yet) been considered relevant for drinking water purposes by WHO (WHO, 2022). However, US-EPA (2022) ranked it as a potential drinking water contaminant and the Italian water authorities introduced a limit of 0.14 mg/L (total V) in response to high vanadium concentrations caused by volcanic activity (Arena et al. 2015). We therefore recommend to include vanadium in the suite of contaminant candidates and introduce routine monitoring on vanadium for locations with elevated Se, Mo or Ni concentrations.

5.6.3 Arsenic

Arsenic concentrations above the guideline threshold of 0.01 mg/L coincided with high TDS concentrations between 2072 and 15008 mg/L in three out of six violations. The remaining three locations showed either violations for selenium, nickel, molybdenum and fluoride or strongly elevated nitrate concentrations (47 mg/L). Apart from the weak to moderate correlations with the other redox sensitive elements (Mo, Se, V, U) and Ni (Table 8), arsenic showed a moderate correlation to antimony (Sb = 0.65).

For the visualization, arsenic concentrations were sorted into three categories. Unproblematic concentrations below half of the JDWS-limit are represented as blue dots (As < 0.005 mg/L). Values higher than half the JDWS-limit were considered noticeable and marked in orange (As < 0.01 mg/L) and while all values higher than the JDWS-limit were seen as critical and marked in red (As > 0.01 mg/L). The elevated concentrations are likely to represent an underestimation, as for 77 out of the 227

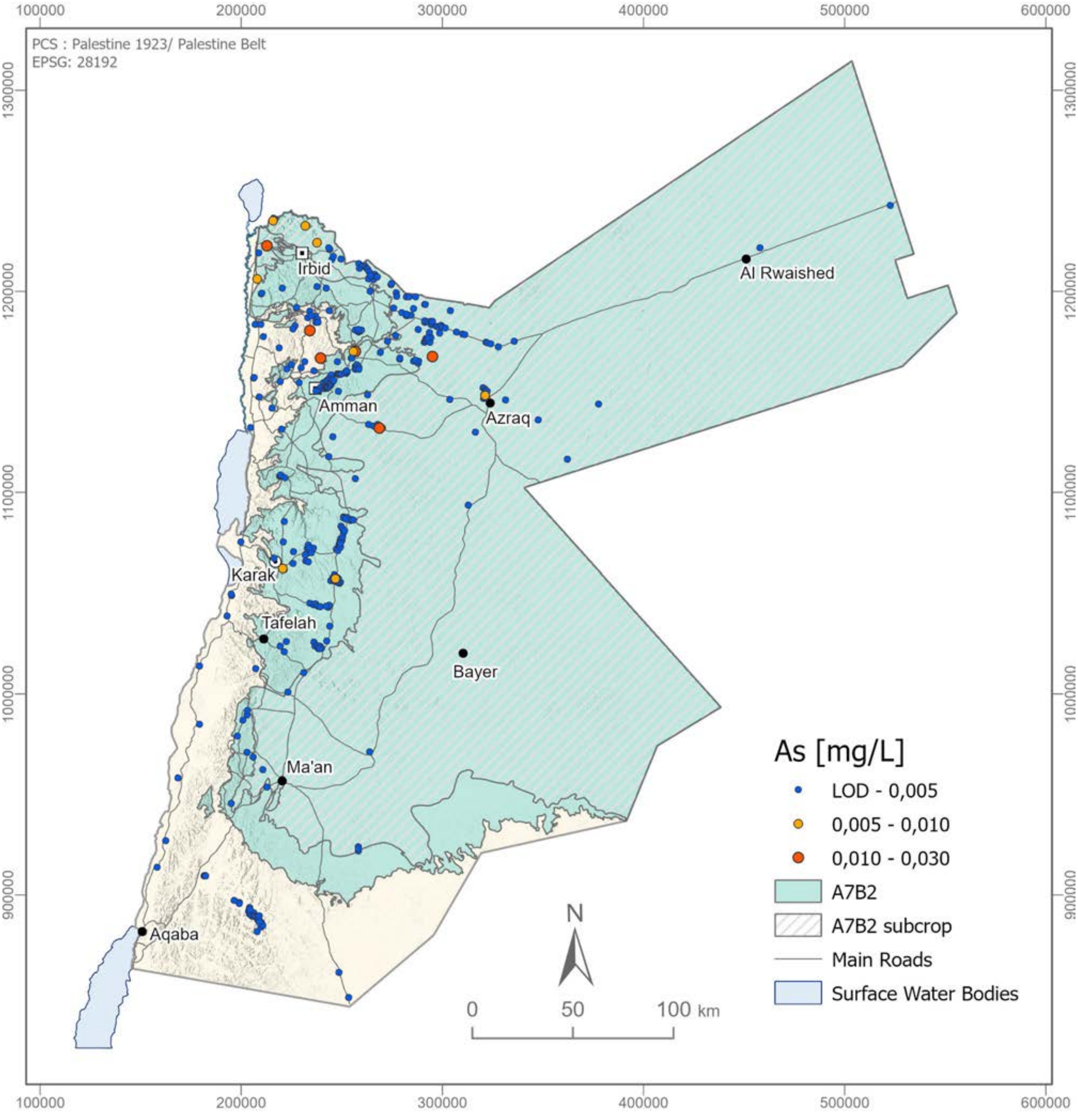


Figure 26: Arsenic concentrations observed in the baseline study.

arsenic analyses, the detection limit was equal to the guideline limit (0.01 mg/L). For three analyses, the detection limit even surpassed the guideline value with LODs of 0.02 and 0.03 mg/L. These samples were omitted in the boxplot distribution (Figure 22) and the Jordan-wide map (Figure 26).

The spatial distribution of the elevated arsenic concentrations on Figure 26 shows that the guideline violations were mainly scattered across northern Jordan. Elevated concentrations still below the guideline value clustered north of Irbid and scattered around Hashemiya, Azraq and Karak. Three of the six JDWS violations occurred at locations strongly affected by local industry (Hashimya 5/ AL1254), agriculture (Prince Faisal Nursery 1a/ AL5998) or extreme salinity (Abdelmuhsen Alwan Al Jam'an/ F4203). Of the remaining violations, one coincided with trace element violations (Wadi Al Arab 5/ AE1011), while the other two were inconspicuous except for fluoride at Muwaqqar 18 (F4196). In the past, several arsenic violations, frequently coinciding with high Ni or Mo concentrations, were reported for the Wadi Al Arab wellfield (e.g. BGR & MWI, 2018).

The box plot distribution in Figure 22 shows that arsenic was responsible for less guideline violations (indicated as gray circles above the guideline limit displayed by the red line) than other redox sensitive species known to be enriched in the Belqa sediments (Fleurance et al. 2013). A visual inspection showed that most elevated arsenic concentrations occurred close to sediments of the Belqa group or at the Kurnub outcrop (Prince Faisal Nursery 1a/ AL5998). The lower number of violations for arsenic could be caused by a different mobility in the aquifer when compared to molybdenum and selenium. Generally, arsenic shows higher mobility under anaerobic (Fe(III)-reducing) redox environments, since the As(V) species dominating aerobic redox environments has higher sorption affinity to mineral surfaces, such as Fe-, Al-, Mn-oxides and may be immobilized in presence of these minerals. Nevertheless, occurrence in areas affected by industry- and agriculture (pesticides) could be equally linked to anthropogenic contamination.

5.6.4 Uranium

Uranium (U) is not included in the Jordanian drinking water guideline, however, the WHO (2022) provisional guideline limit of 0.03 mg/L (chemotoxicity) was considered in lieu. Uranium (U) is a redox-sensitive trace element and commonly known for its radioactivity. However, due to its very long half-life the chemotoxicity of U is more relevant than its radiotoxicity. In the baseline study, uranium showed elevated concentrations (>0.015 mg/L) at five monitoring locations. At one location (Merheb 2A/AL3432, 0.0338 mg/L), the guideline limit was surpassed slightly and the violation co-occurred with a guideline exceedance by selenium (0.048 mg/L). Out of the four remaining locations with elevated U concentrations, three locations showed violations by selenium and one location had TDS and nitrate surpassing their threshold limits.

Uranium concentrations showed a weak to moderate correlation to other oxyanion forming trace elements, such as As (0.20), Mo (0.32), Se (0.53) and V (0.36) (Table 8). Additionally, it correlated with nickel (0.38) and cadmium (0.50) and is reported to occur enriched in sediments of the Belqa group, especially those associated with high phosphor concentrations (e.g. Fleurance et al. 2013). The spatial distribution of uranium concentrations is displayed in Annex E.

5.7 Fluoride

Fluoride was tested at 365 of the sampled locations with **116 wells (31.2%) showing elevated concentrations.** In contrast to previous studies, who encountered negligible amounts of fluoride (e.g. Abu Rukah & Alsokhny, 2004), **35 of these samples (9.6%)** exceeded the regular JDWS-limit and **are thus considered critical,** while **nine wells (2.5%) are considered alarming (>2.0 mg/l).** The median of F-concentrations is at 0.41 mg/L. Considering the fact that worldwide fluoridation of drinking water is common for caries prevention (US Public Health Services currently recommend 0.7 mg/L (until 2015: 0.7-1.2 mg/L)), fluoride is not (yet) to be considered a public health issue for the whole of Jordan. The geographical distribution can be seen in Figure 25.

When looking at the distribution among the aquifers, most of the fluor violations were found in the most-sampled A7/B2. Here, especially the wells in Central Jordan around Karak are affected,

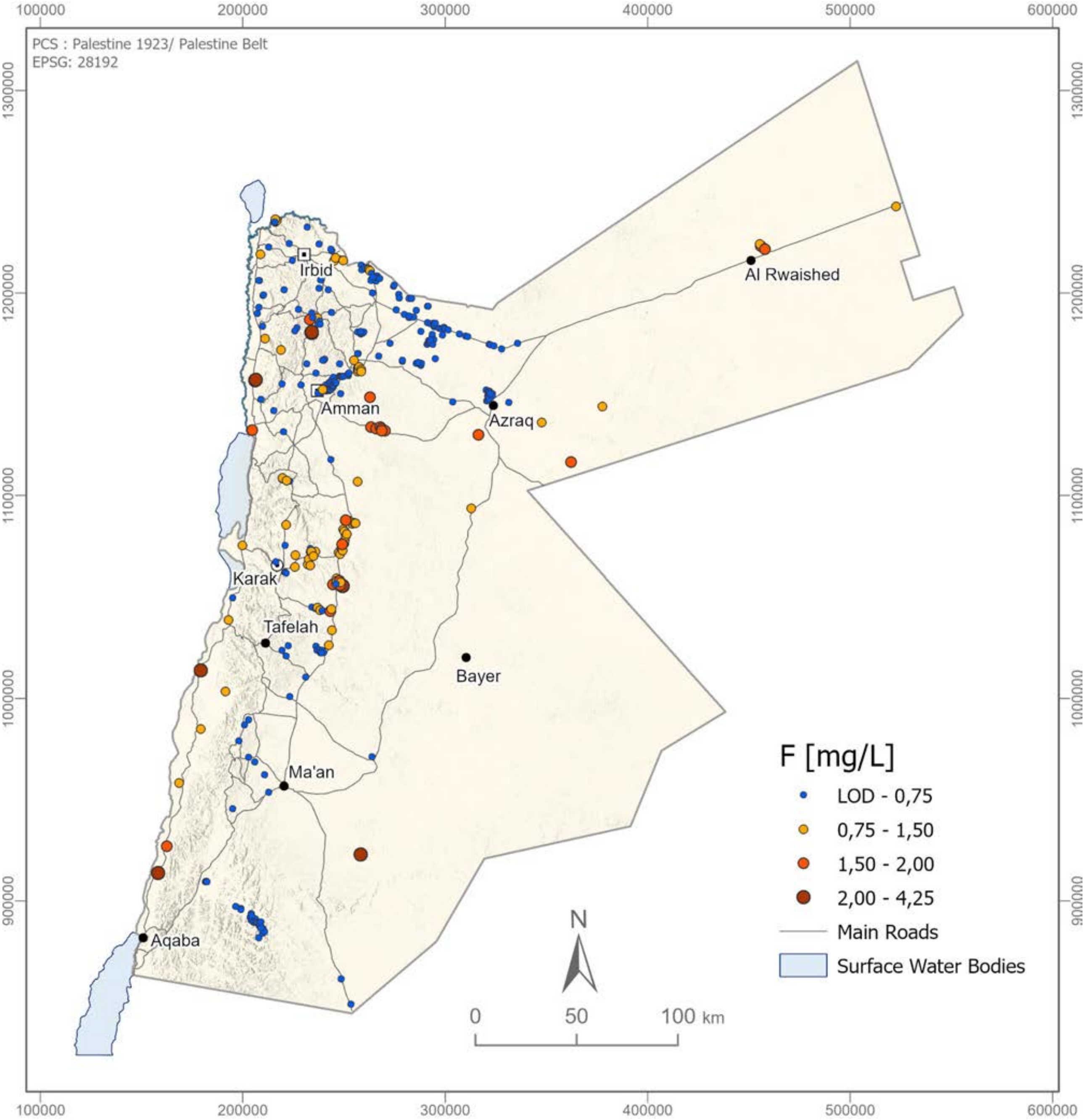


Figure 27: Fluoride concentrations observed in the baseline study.

where salinities are generally low, but elevated trace metal contents were found (see chapter 5.5). Furthermore, the Tamoween-wellfield is affected, where it coincides with severe molybdenum violations.

When looking at the ratio of affected to unaffected wells, other aquifers show relatively more violations: The Kurnub aquifer appears affected mainly in Jerash and at Mashtal Faisal, where salinities are generally high. Also the affected wells in the Alluvium – mostly in the Wadi Arabah – and in the B4/B5 – mostly in Eastern Jordan – show a combination of elevated fluoride content and high TDS.

Table 12: Number of F violations per aquifer. The percentage of affected locations are calculated for the number of violations per number of analyses. For comparison, the mean F concentrations for all samples from the affected aquifers are shown.

Aquifer	Total Locations	F Analyses	F Violations	Affected Locations	F Median	
Alluvium	26	12	5	42 %	1.04	[mg/L]
B4, B4/B5	15	1 (B4); 11 (B4/B5)	4	33%	0.99 (B4/B5)	[mg/L]
A7/B2	263	177	16	9%	0.44	[mg/L]
A4	53	42	1	2%	0.50	[mg/L]
Kurnub	26	14	8	57%	1.785	[mg/L]
RAM	33	29	1	3%	0.18	[mg/L]

Predominantly of geogenic origin

While F can be derived from industrial activities and domestic wastewater, it is more likely that in the Jordanian context it is predominantly of geogenic origin. According to Edmunds & Smedley (2013), the occurrence of F in phosphorites is closely connected to fluorapatite and carbonate-fluorapatite, one of the main resources for phosphate mining. XRF-scans by the BGR of a single core in the B2-unit found >3% of fluorite content in phosphorite layers with a $P2O5$-content of >30%, which is an indicator for the prevalence of fluorapatite over hydroxoapatite (Wagner et al., in prep.). According to Edmunds & Smedley (2013), apatites with high F-content appear more soluble in the environment than OH-dominant apatites, resulting in a predominant release of fluoride from the rock material in this case.

On the other side of the Jordan Rift Valley, elevated fluor concentrations are well known since many years: Abu Jabal et al. (2014) and Shomar et al. (2004) found the groundwater in Gaza to be significantly enriched with fluoride, leading to serious problems with dental fluorosis especially in Khan Younis, Southern Gaza strip. Furthermore, Arad et al. (1986) and Kafri et al. (1989) found elevated fluoride-contents in groundwater all over Israel, especially in the Alluvium of the Wadi Arabah/Arava, in the Nubian sandstone in the South (equivalent to the Ram aquifer) and in the Cenomanian-Turonian formations (equivalent to the A1-A7), when unconfined and below Senonian sediments (Campanium – Paleocene; equivalent to B1-B3).

Kafri et al. (1989) analysed rock samples from Cenomanium to Eocene in Israel and found the formations younger than Turonian to be enriched with fluoride (equivalent to B1-B3 in Jordan), especially the phosphate-rich rocks. Furthermore, they conducted leaching experiments on crushed rock samples and observed that <90% of the fluoride is dissolved after 1-2 hours. This indicates that contact time is of minor importance for the dissolution process. However, hydrogeological factors (pre-enrichment of groundwater with Ca or F; preferential flow paths) could not be considered in this study, so contact time might still play a role for in-situ leaching, as stated by Edmunds & Smedley (2013).

Kafri et al. (1989) plotted the logarithmic chloride-concentrations vs. the logarithmic ratio of Fl-/Cl-concentrations to calculate a linear regression, showing that rising salinities are accompanied by a decrease in relative fluoride content. The same plot was created for the data of the baseline study, which is shown in Fig. 27 for the different aquifers, where different groups can be identified:

1. Waters from the Basalt-aquifer showed generally low F/Cl-ratio, decreasing rapidly at higher salinities.
2. Waters from the sandstone units showed a rather low F/Cl-ratio at low salinities. However, with increasing salinities, this ratio remains rather unchanged, which results in a high fluoride-content in saline waters.
3. Wells, abstracting waters from the Alluvium generally show high salinities with comparably high F/Cl-ratios.
4. Waters from A1/A6 showed a high F/Cl-ratio at low salinities, decreasing rapidly at higher salinities. B4/B5 shows a similar trend, but appears even more enriched with fluoride.
5. Waters from A7/B2 show a similar behavior as A1/A6, but appear separated in two groups with differing F/Cl-ratios. One group with generally lower F/Cl-ratios appears to be affected by an anthropogenic increase in salinity, especially around Amman, Russeifa, Zarqa and Mafraq, while the other group around Irbid and Karak appears to be similarly affected by increased F-enrichment and oxyanions (see chapter 5.5).

While wells in the Basalt-aquifer are unlikely to develop fluor related problems, wells in A7/B2 and A1/A6 are prone to increased fluoride-concentrations at lower salinities. This is probably related to their hydraulic connection with the lower Belqa-units. Wells in the sandstone or in the Alluvium are rather prone to increased fluoride concentrations at higher salinities.

Edmunds & Smedley (2013) state that fluor enrichment in groundwater takes place mainly at higher pH (>6), which is the case in the Jordanian context for all samples in the baseline study. Furthermore, the solubility of fluoride in groundwater decreases with falling temperature and increasing Ca-content, due to the close relation to CaF2-solubility (Edmunds & Smedley, 2013).

Combining these information and considering the fluoride-enrichment processes, depicted by Kafri et al. (1989), fluoride will most likely remain a relevant candidate for JDWS-breaches in waters, which are unproblematic with regard to TDS. This is especially true for groundwater, which is in contact with the B1-B3 units, and where excessive pumping increases water flow through these units.

Most groundwaters in Jordan are rich in Ca, limiting the dissolution of fluoride and the average F-concentration in this baseline study was at 0.62 mg/l, which roughly matches the WHO-recommendations for caries prophylaxis (WHO, 2022). **However, in the future F-concentrations should be closely monitored in the scope of the Annual Groundwater Sampling.** Treatment of F-enriched waters is costly and blending of waters might turn out difficult, as F-concentrations tend to increase not in single wells but over rather large areas.

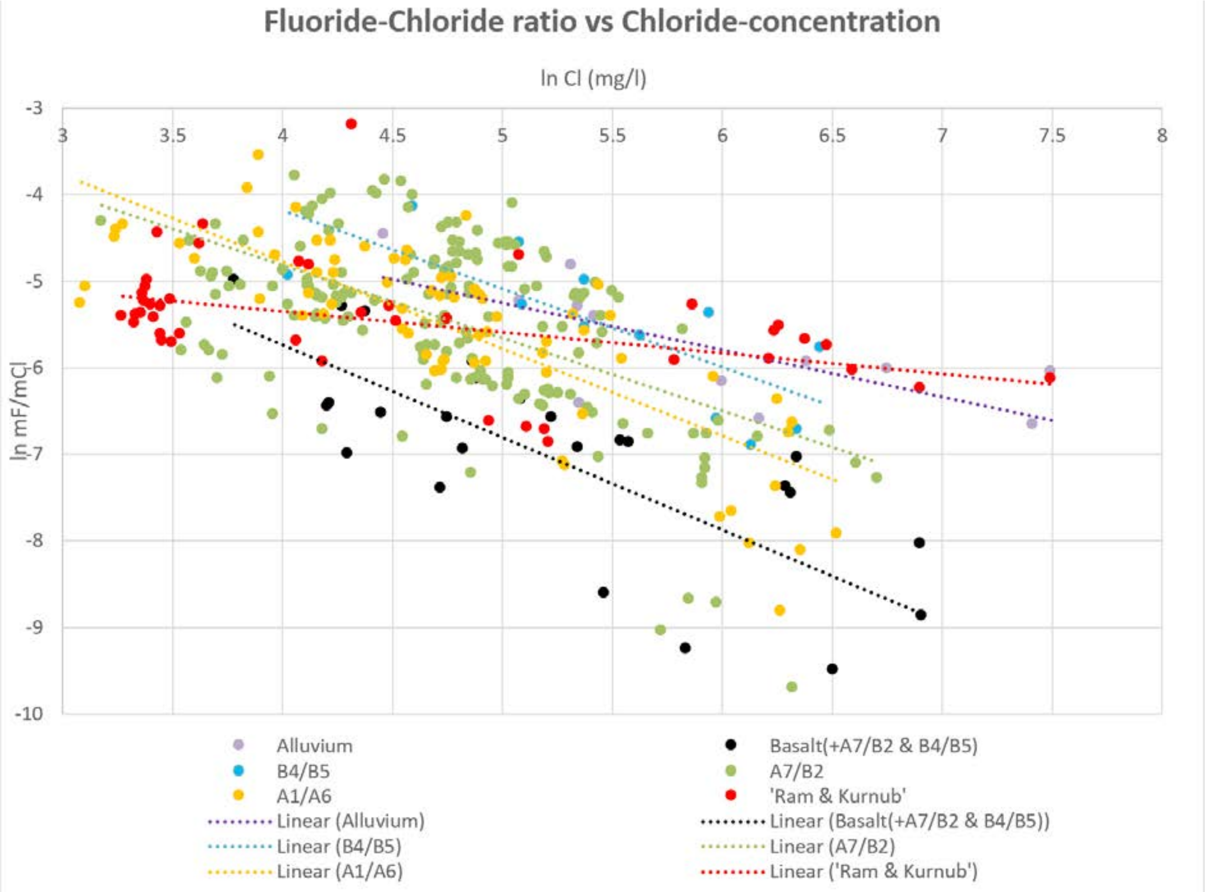


Figure 28: Plot of the logarithmic chloride concentrations against the logarithmic ratio of fluoride and chloride for the 365 water samples from the baseline study. A general trend for increasing relative fluoride concentrations is visible, indicating that fluoride is dissolved from rocks by rather non-saline water.

5.8 Aluminum

Aluminum (Al) concentrations above the guideline level (0.1 mg/L) were found at five monitoring locations in the baseline study. For the spatial visualization in Figure 29, the measured aluminum concentrations were sorted into four concentration ranges. Concentrations below 0.05 were considered unproblematic and are represented by blue dots. Concentrations between 0.05 mg/L and 0.1 mg/L were considered noticeable and are represented by orange circles. These wells are still acceptable regarding aluminum concentrations, but should be monitored in the future. Concentrations exceeding 0.1 mg/L (red circles) were considered critical, water from this category can only be used with the Ministry of Health approval, and concentrations exceeding 0.2 mg/L (brown circles) were classified as alarming, water from this category is unfit for human consumption.

Elevated concentrations of aluminum (noticeable – alarming) are scattered all across Jordan. The highest concentrations were found in the proximity of industrial activities (Abu Elzeeghan Desalinition 10/ AL3687, Shidiya Rum Deep 3 / Phosphate Mines 3 G4162), while for the areas close to critical concentrations agricultural activities could be identified.

Elevated aluminum concentrations for example can derive from an unnoticed rupture of the filter membrane during filtration or very small clay particles/colloids that passed through the filter.

industrial and agricultural activities

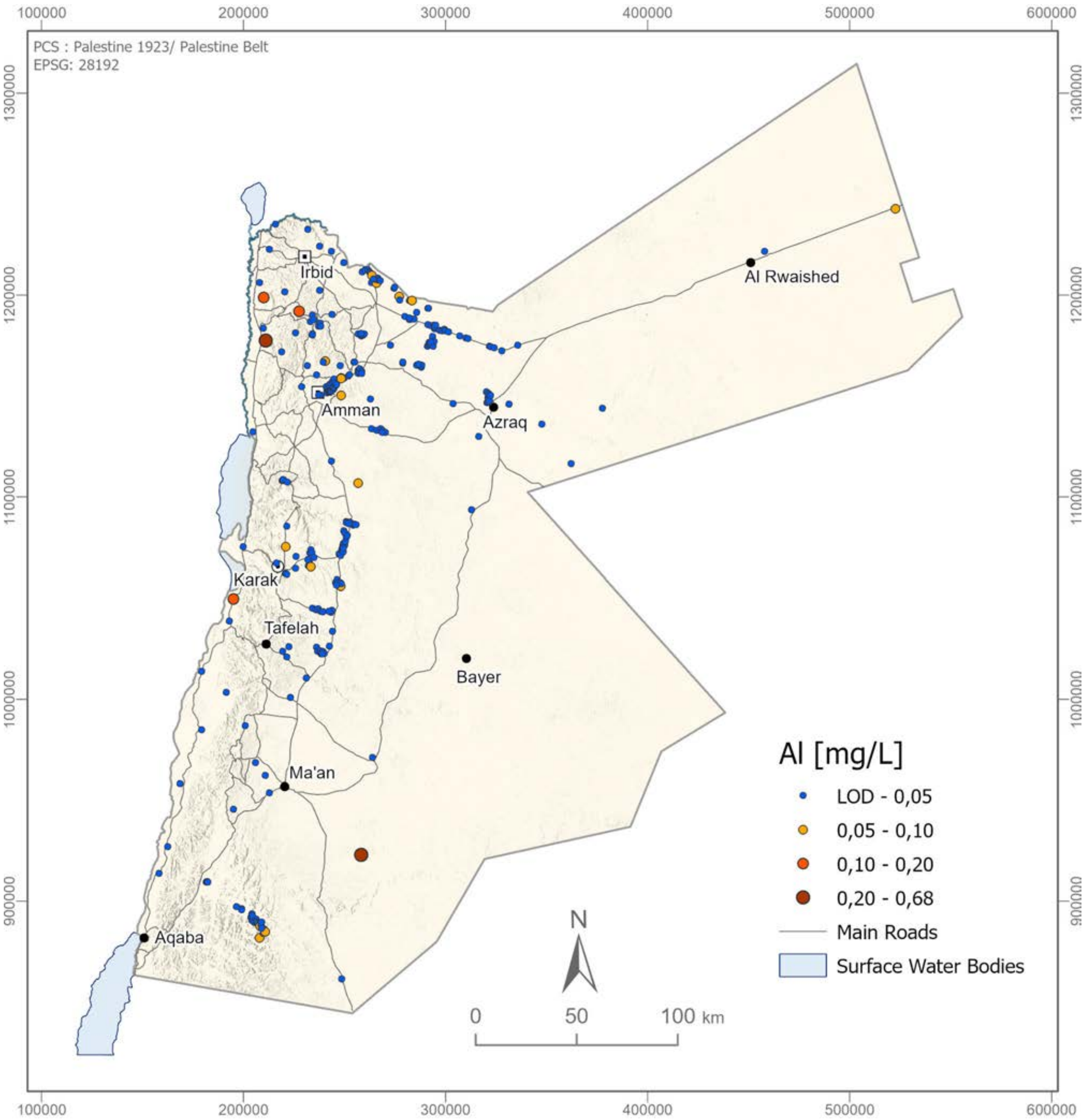


Figure 29: Aluminum concentrations observed in the baseline study.

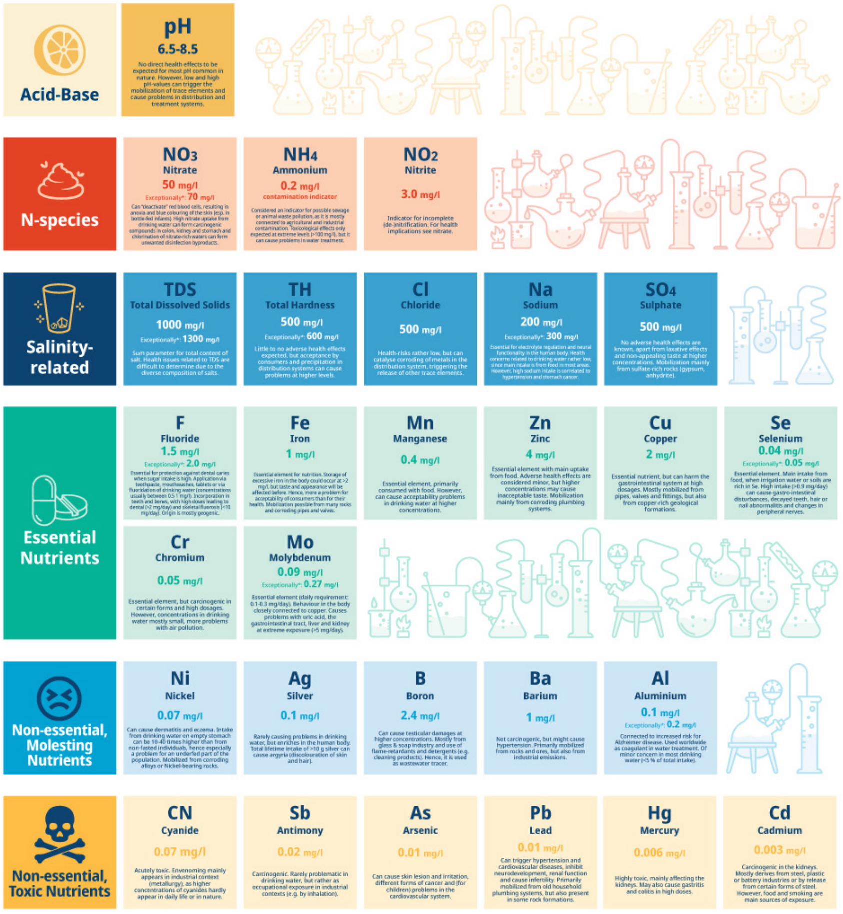
5.9 Other Trace Elements

Other trace elements analysed in the base line study include antimony, barium, cadmium, chromium, copper, iron, lead, manganese, mercury, silver and zinc. They were compared to their JDWS guideline limits and are presented as maps in the Annex of this report (Annex F). The occurrence of their guideline violations was either low, or the process leading to high concentration in groundwater was well established (iron).

Barium showed two guideline violations north of Irbid, but otherwise remained well below its threshold. Cadmium had some elevated concentrations still below guideline threshold mostly scattered in the Karak region. Chromium showed a guideline violation at the Al Jazeera for Chicken Grannys Co well (F4202). However, several wells in the area between Koum Al Mahmar on the Syrian border to the Bagdad road show noticeable concentrations and further monitoring of this area is advisable. Iron showed 12 guideline violations and several elevated concentrations. High iron concentrations mostly stem from the reduction of iron oxides present in the aquifer matrix and are known to prevail in reducing aquifers. Lead and Zinc concentrations showed isolated elevated concentration. Antimony, copper, manganese, mercury, silver, concentrations were unproblematic in the baseline study.

Inorganic Water Quality Parameters of the Jordanian Drinking Water Standard

Water that complies with the Jordanian Drinking Water Standard (JDWS) from 2015, including the amendments from 2023, is guaranteed to be potable and safe for domestic supply. The Water Authority of Jordan (WAJ) laboratory monitors all physical and chemical parameters listed in the JDWS, with examples of inorganic parameters provided below.



Category	Parameter	Name	Limit	Exceptionally*	Description
Acid-Base	pH		6.5-8.5		No direct health effects to be expected for most pH common in nature. However, low and high pH-values can trigger the mobilization of trace elements and cause problems in distribution and treatment systems.
N-species	NO_3	Nitrate	50 mg/l	70 mg/l	Can "deactivate" red blood cells, resulting in anoxia and blue colouring of the skin (esp. in bottle-fed infants). High nitrate uptake from drinking water can form carcinogenic compounds in colon, kidney and stomach and chlorination of nitrate-rich waters can form unwanted disinfection byproducts.
	NH_4	Ammonium	0.2 mg/l contamination indicator		Considered an indicator for possible sewage or animal waste pollution, as it is mostly connected to agricultural and industrial contamination. Toxicological effects only expected at extreme levels (>100 mg/l), but it can cause problems in water treatment.
	NO_2	Nitrite	3.0 mg/l		Indicator for incomplete (de-)nitrification. For health implications see nitrate.
Salinity-related	TDS	Total Dissolved Solids	1000 mg/l	1300 mg/l	Sum parameter for total content of salt. Health issues related to TDS are difficult to determine due to the diverse composition of salts.
	TH	Total Hardness	500 mg/l	600 mg/l	Little to no adverse health effects expected, but acceptance by consumers and precipitation in distribution systems can cause problems at higher levels.
	Cl	Chloride	500 mg/l		Health-risks rather low, but can catalyse corroding of metals in the distribution system, triggering the release of other trace elements.
	Na	Sodium	200 mg/l	300 mg/l	Essential for electrolyte regulation and neural functionality in the human body. Health concerns related to drinking water rather low, since main intake is from food in most areas. However, high sodium intake is correlated to hypertension and stomach cancer.
	SO_4	Sulphate	500 mg/l		No adverse health effects are known, apart from laxative effects and non-appealing taste at higher concentrations. Mobilization mainly from sulfate-rich rocks (gypsum, anhydrite).
Essential Nutrients	F	Fluoride	1.5 mg/l	2.0 mg/l	Essential for protection against dental caries when sugar intake is high. Application via toothpaste, mouthwashes, tablets or via fluoridation of drinking water (concentrations usually between 0.5 1 mg/l). Incorporation in teeth and bones, with high doses leading to dental (>2 mg/day) and skeletal fluorosis (<10 mg/day). Origin is mostly geogenic.
	Fe	Iron	1 mg/l		Essential element for nutrition. Storage of excessive iron in the body could occur at >2 mg/l, but taste and appearance will be affected before. Hence, more a problem for acceptability of consumers than for their health. Mobilization possible from many rocks and corroding pipes and valves.
	Mn	Manganese	0.4 mg/l		Essential element, primarily consumed with food. However, can cause acceptability problems in drinking water at higher concentrations.
	Zn	Zinc	4 mg/l		Essential element with main uptake from food. Adverse health effects are considered minor, but higher concentrations may cause inacceptable taste. Mobilization mainly from corroding plumbing systems.
	Cu	Copper	2 mg/l		Essential nutrient, but can harm the gastrointestinal system at high dosages. Mostly mobilized from pipes, valves and fittings, but also from copper-rich geological formations.
	Se	Selenium	0.04 mg/l	0.05 mg/l	Essential element. Main intake from food, when irrigation water or soils are rich in Se. High intake (>0.9 mg/day) can cause gastro-intestinal disturbances, decayed teeth, hair or nail abnormalitis and changes in peripheral nerves.
	Cr	Chromium	0.05 mg/l		Essential element, but carcinogenic in certain forms and high dosages. However, concentrations in drinking water mostly small, more problems with air pollution.
	Mo	Molybdenum	0.09 mg/l	0.27 mg/l	Essential element (daily requirement: 0.1-0.3 mg/day). Behaviour in the body closely connected to copper. Causes problems with uric acid, the gastrointestinal tract, liver and kidney at extreme exposure (>5 mg/day).
Non-essential, Molesting Nutrients	Ni	Nickel	0.07 mg/l		Can cause dermatitis and eczema. Intake from drinking water on empty stomach can be 10-40 times higher than from non-fasted individuals, hence especially a problem for an underfed part of the population. Mobilized from corroding alloys or Nickel-bearing rocks.
	Ag	Silver	0.1 mg/l		Rarely causing problems in drinking water, but enriches in the human body. Total lifetime intake of >10 g silver can cause argyria (discolouration of skin and hair).
	B	Boron	2.4 mg/l		Can cause testicular damages at higher concentrations. Mostly from glass & soap industry and use of flame-retardants and detergents (e.g. cleaning products). Hence, it is used as wastewater tracer.
	Ba	Barium	1 mg/l		Not carcinogenic, but might cause hypertension. Primarily mobilized from rocks and ores, but also from industrial emissions.
	Al	Aluminium	0.1 mg/l	0.2 mg/l	Connected to increased risk for Alzheimer disease. Used worldwide as coagulant in water treatment. Of minor concern in most drinking water (<5 % of total intake).
Non-essential, Toxic Nutrients	CN	Cyanide	0.07 mg/l		Acutely toxic. Envenoming mainly appears in industrial context (metallurgy), as higher concentrations of cyanides hardly appear in daily life or in nature.
	Sb	Antimony	0.02 mg/l		Carcinogenic. Rarely problematic in drinking water, but rather as occupational exposure in industrial contexts (e.g. by inhalation).
	As	Arsenic	0.01 mg/l		Can cause skin lesion and irritation, different forms of cancer and (for children) problems in the cardiovascular system.
	Pb	Lead	0.01 mg/l		Can trigger hypertension and cardiovascular diseases, inhibit neurodevelopment, renal function and cause infertility. Primarily mobilized from old household plumbing systems, but also present in some rock formations.
	Hg	Mercury	0.006 mg/l		Highly toxic, mainly affecting the kidneys. May also cause gastritis and colitis in high doses.
	Cd	Cadmium	0.003 mg/l		Carcinogenic in the kidneys. Mostly derives from steel, plastic or battery industries or by release from certain forms of steel. However, food and smoking are main sources of exposure.

6.

Aquifer-Specific Observations

Even though an exact assignment of the different wells to a certain aquifer is often difficult – due to the in-well mixing of waters caused by the long screens – certain characteristics of the different aquifers are pointed out in the following sections. Due to the non-normal distribution of most parameters, median and quartiles (+minimum & maximum) are given instead of arithmetic mean and standard deviation. The Piper-diagrams differentiate for sub- and outcrop and partly for the interacting aquifers to represent possibly mixed groundwater qualities encountered within a specific aquifer.

6.1 Alluvium

Prone to salinization Nitrate concentrations is high in Lower Jordan Valley

Figure 30 and Table 13 show the distribution of hydrochemical parameters for the Alluvium aquifer. It is only present along the Jordan Rift, in Wadi Arabah, close to the Dead Sea and in the Jordan Valley itself. Due to its young age, it is not overlain by any other aquifer and due to its situation in the low-altitude areas, it is prone to salinization, which can be seen in Figure 10. More than 50% of the wells, which tapped into the alluvium, showed TDS-concentrations critical or alarming with regard to its JDWS threshold and temporal as wells as spatial distribution of high TDS concentrations are known to vary. Total hardness is very high and more related to the high SO_4^{2-} and Cl-concentrations (permanent hardness), than to carbonates. Nitrate concentrations were found to be very high in most areas of the Lower Jordan Valley, especially close to agricultural areas, but rather low in Wadi Arabah and close to the Dead Sea. Boron-concentrations show a similar distribution, but remain mostly below the JDWS-limit, with one exception close to the King-Abdullah-channel next to Karameh dam. Fluoride, on the other hand, is more prevalent in the southern part of Wadi Arabah. All other trace elements are found in negligible amounts.

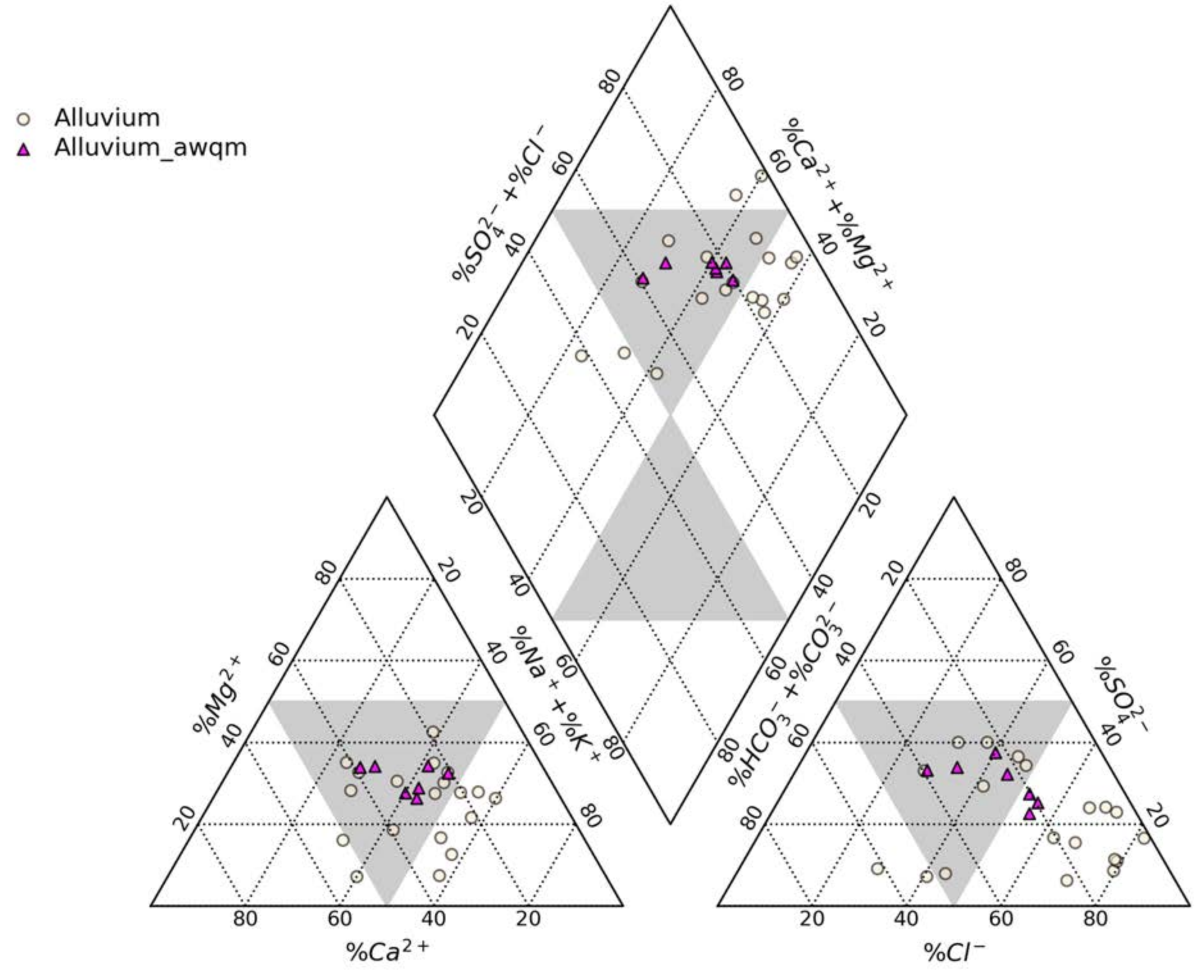


Figure 30: Piper-Diagram for samples from the Alluvium-aquifer. The category "Alluvium_awqm" consists of samples, which are part of the AGS-program and will be sampled on an annual basis in the future.

*Table 13: Observed hydrochemical parameter, major and trace element distributions for the Alluvium aquifer. Concentrations below the LOD were assumed with 0.5*LOD, except for arsenic (LODs ≥ JDWS limit discarded). Antimony (15 wells), mercury (4 wells), and silver (12 wells) not shown as all baseline concentrations stayed below 0.5* JDWS limit.*

	count	min	25%	50%	75%	max
Temp	16	22.3	26.375	27	29.225	38
pH	15	7.05	7.299	7.48	7.695	8.036
Depth	20	28	52.75	72	194	1224
EC	25	653	1298	2520	3490	8730
TDS (sum)	26	486	872	1609	2271	6846
TH	21	261	431	613	948	2177
Na	26	36.9	123.725	260.8	355.7	1281.2
K	26	1.1	5.45	13.35	42.4	109.9
Ca	26	56.3	99.3	122.55	170.025	614.3
Mg	26	22.8	38.075	72	130.325	251.7
Cl	26	70.3	205.425	507.2	820.625	1797.5
F	12	0.348	0.8475	1.035	1.755	4.25
HCO_3-	26	51.7	210.5	291.5	387.625	1127.5
SO_4^{2-}	26	30.1	206.9	267.65	321.45	1747.8
NH_4+	17	0.005	0.05	0.05	0.05	2.09
NO_3-	26	0.25	3.88	8.85	37.35	243.9
Al	15	0.005	0.005	0.01	0.0205	0.81
Fe	18	0.005	0.0155	0.05	0.15	4.04
B	14	0.05	0.1575	0.31	0.62	2.66
Ba	15	0.03	0.034	0.04	0.05	0.16
As	8	0.00012	0.00015	0.00157	0.0025	0.0025
Mo	15	0.00253	0.005	0.005	0.009965	0.02
Ni	18	0.0004	0.005	0.005	0.005	0.01
Se	14	0.00091	0.0025	0.003105	0.01	0.01
V	4	0.004	0.00475	0.0065	0.00925	0.013
Cr	18	0.00114	0.0025	0.0025	0.0025	0.008
Cd	18	0.000009	0.0015	0.0015	0.0015	0.0015
Cu	18	0.00036	0.01	0.01	0.01	0.01
Pb	18	0.00005	0.0025	0.0025	0.0025	0.0025
Zn	18	0.00244	0.01	0.01	0.01	0.159

6.2 Basalt

Table 14 shows the hydrochemical parameters for samples taken from wells which only tap in the Basalt aquifer, while the distribution of the major ions can be seen in Figure 32 (together with samples from B4/B5). Most of the Basalt aquifer is situated in the rather less-populated northeast of the country. It is mostly uncovered and hence prone to anthropogenic contamination by farms and mining activities in the area. In total, ten wells were considered to be exclusively tapping into the Basalt aquifer, while most other wells apparently communicated with other aquifers, too (see next chapter). The wells assigned to the Basalt aquifer showed very strongly differing salinities, even though 75% of the TDS-values remained below the JDWS-limit of 1000 mg/L (see Figure 17). The higher salinities are probably caused by agricultural and mining activities between Azraq and Mafraq. This can be seen by a strong correlation of TDS and NO_3- for Basalt-wells (Pearson R^2>0.9), when the Awsa-wellfield is excluded. At Awsa, where agricultural activities are minor, salinization is rather caused by the heavy pumping of groundwater upstream the Azraq wetland.

The pH is higher than in other aquifers (mostly >8), which is common for basic volcanites. On the Piper diagram in Figure 18, the concentrations from the Basalt samples appear wide-scattered. This is due to the rather low TDS-content for most wells, causing the positioning within the Piper-diagram to be heavily affected by small variations in concentrations. On the other hand, the aquifer is often hydraulically connected to either the B4/B5 or the A7/B2. Due to the higher salinities in these two layers, the different extents of mixing can heavily affect the hydrochemistry. Fluoride and trace elements were found to be unproblematic in almost all of the wells.

Prone to anthropogenic contamination by farms and mining activities

*Table 14: Observed hydrochemical parameter, major and trace element distributions for the Basalt aquifer. Concentrations below the LOD were assumed with 0.5*LOD, except for arsenic (LODs ≥ JDWS limit discarded). Antimony (4 wells), mercury (1 wells), and silver (2 wells) not shown as all baseline concentrations stayed below 0.5* JDWS limit.*

	count	min	25%	50%	75%	max
Temp	6	27.9	28.425	30.05	30.85	33
pH	7	7.7	7.915	8.39	8.412	8.671
Depth	9	61	310	357	460	515
EC	10	286	329.75	760	1606.5	6760
TDS (sum)	10	198	238.63	475	868.5	3921
TH	7	51	77.5	257	421	1766
Na	10	34.1	44.65	75.35	122.625	685.4
K	10	3.6	3.825	6.95	9.65	43
Ca	10	8.3	11.075	33.2	76.7	318
Mg	10	3.9	7.455	22.55	60.25	236.5
Cl	10	26.2	32.075	125.85	332.05	2066.5
F	3	0.041	0.059	0.077	0.0885	0.1
HCO_3-	10	78.9	91.975	101.55	120.55	315.7
SO_4^{2-}	10	15.2	23.05	63.25	120.45	289.8
NH_4+	7	0.005	0.0275	0.05	0.05	0.05
NO_3-	10	6.9	8.05	15.55	24.125	69.9
Al	4	0.005	0.010	0.014	0.016	0.02
Fe	5	0.003	0.005	0.007	0.09	0.11
B	4	0.005	0.018	0.02525111	0.046	0.1
Ba	4	0.00032	0.00083	0.003	0.00875	0.02
As	3	0.00016	0.00022	0.00028	0.00139	0.0025
Mo	4	0.00172	0.0020875	0.003605	0.00625	0.01
Ni	5	0.00038	0.00047	0.005	0.005	0.005
Se	4	0.0006	0.00138	0.00207	0.004375	0.01
V	2	0.01	0.012	0.014	0.016	0.018
Cr	5	0.0025	0.008	0.01363	0.018	0.01878
Cd	5	0.00001	0.00001	0.0015	0.0015	0.0015
Cu	5	0.00041	0.00047	0.01	0.01	0.01
Pb	5	0.00002	0.00004	0.0025	0.0025	0.0025
Zn	5	0.004	0.01	0.01	0.01	0.01

6.3 B4/B5

Generally elevated TDS-content

As many wells tap both aquifers, the distribution of the major ions of the B4/B5 aquifer is shown together with the wells in the Basalt in Figure 31, while the hydrochemical parameters in Table 15 only show the samples from wells in the outcrop areas of B4/B5. 36 samples were taken from the B4/B5-aquifer, with some wells also tapping into the Basalt aquifer. The samples show a generally elevated TDS-content, with 40% lying above the JDWS. Sulphate concentrations are slightly increased, though total hardness is similar to the underlying A7/B2 (which is lower in SO_4^{2-}). Nitrate concentrations are mostly low, except for Rahoub spring (close to Irbid), probably due to agricultural activities there. Trace element concentrations are low in most wells, except for a few single wells in the eastern part of the country, where nickel was slightly elevated (0.04 mg/L) at Rwaished 1 (H2015) and vanadium showed its peak concentration of 0.5 mg/L at Awsa 16a (F4166).

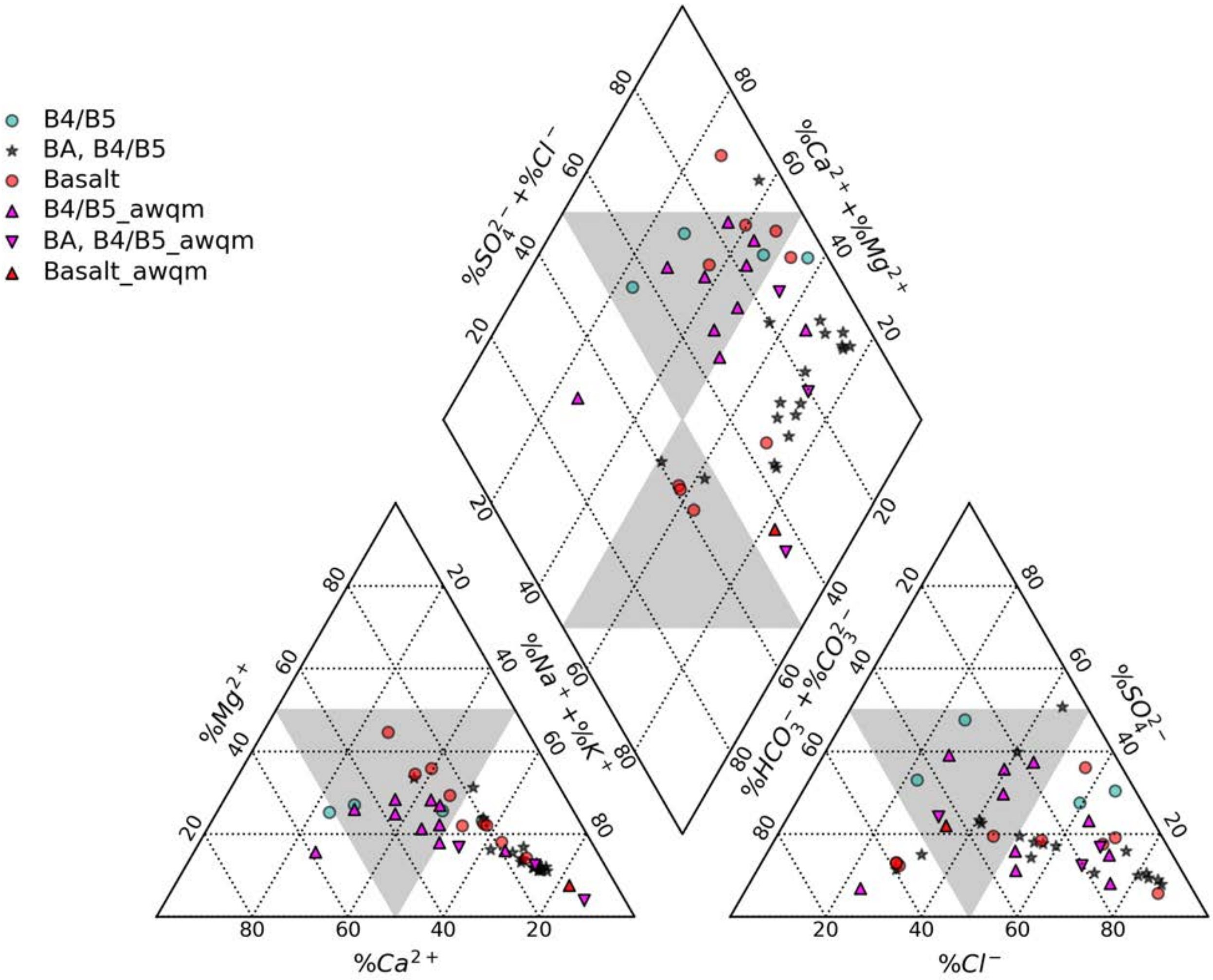


Figure 31: Piper-Diagram for samples from the Basalt- and the B4/B5-aquifer. While the categories "Basalt" and "B4/B5" refer to wells, which are withdrawing water exclusively from the Basalt or the B4/B5, samples with "BA, B4/B5" consist of mixed waters from the two aquifers. The categories ending with "_awqm" consist of samples, which are part of the AGS-program and will be sampled on an annual basis in the future.

*Table 15: Observed hydrochemical parameter, major and trace element distributions for the B4/B5 aquifer. Concentrations below the LOD were assumed with 0.5*LOD, except for arsenic (LODs ≥ JDWS limit discarded). Antimony (23 wells), mercury (4 wells), and silver (21 wells) not shown as all baseline concentrations stayed below 0.5* JDWS limit.*

	count	min	25%	50%	75%	max
Temp	24	18.2	20.975	24.75	29.55	34
pH	28	7.18	7.67	7.89	8.2325	8.6
Depth	35	0	110.5	205	221	570
EC	36	369	855	1225	2330	6400
TDS (sum)	36	263	537.845	839.015	1581.5175	3855
TH	13	90	316	337	694	1374
Na	36	39.7	104	145.5	273.1	809.4
K	36	1.4	4.675	6.8	14.85	33.5
Ca	36	7	27	69.05	142.8	256.7
Mg	36	2	13.55	34.1	53.075	178.5
Cl	36	35.8	128.75	232.3	562.85	1480.5
F	30	0.05	0.18325	0.32	0.8025	1.95
HCO_3-	36	90.7	120.2	128	218.5	435.4
SO_4^{2-}	36	19.3	60.575	102.6	198.75	1047.455
NH_4+	30	0.005	0.03	0.05	0.05	0.84
NO_3-	36	0.015	1.8625	3.96	10.025	147.6
Al	25	0.005	0.01	0.013	0.021	0.046
Fe	28	0.005	0.01	0.026	0.0515	1.52
B	25	0.005	0.042926886	0.123730437	0.272711983	0.43
Ba	25	0.001	0.03	0.06	0.088	0.26
As	11	0.0003	0.000465	0.0009	0.002505	0.01
Mo	23	0.00344	0.004665	0.005	0.01	0.03
Ni	26	0.00036	0.001	0.005	0.01	0.04
Se	24	0.0001	0.002425	0.01	0.01	0.0129
V	10	0.008	0.019	0.022	0.02925	0.5
Cr	26	0.00051	0.0025	0.0025	0.01645	0.075
Cd	26	0.000005	0.00001	0.0015	0.0015	0.0015
Cu	26	0.00039	0.0006175	0.01	0.01	0.01
Pb	25	0.00005	0.00016	0.0025	0.0025	0.0025
Zn	28	0.0035	0.007	0.01	0.01	0.43

6.4 A7/B2

The A7/B2 is the most wide-spread and thus most frequently sampled aquifer in the baseline study with 278 samples in total, with the hydrochemical parameters shown in Table 16. This included many wells in the subcrop areas, which are considered to also abstract water from the overlying B4/B5 or the Basalt-aquifer (see distribution of major ions in Figure 32). The high salinity areas presented in Hobler et al. (2001) were defined for the A7/B2.

TDS is elevated at roughly 23% and critical/alarming at 12% of all wells in A7/B2. The two most prominent cases with TDS at 7200 and even at 15,000 mg/L are shared with the Basalt-aquifer and likely influenced by leakage of saline water from the surface, possibly in form of desalination brine. High (or increasing) salinities at the remaining locations may be linked to heavy pumping and water table drawdown (e.g. at Karak or Wadi Fuheis springs) or to agricultural, industrial or mining activities. Certain areas appear to develop hotspots of salinity, especially around Russeifa and Hashimiya, significantly increasing the treatment costs for future usage of the groundwater.

Nitrate pollution is critical to alarming in wells along the Zarqa river close to Amman, and elevated in large parts of the Irbid region. Furthermore, there are distinct wells in areas with agricultural activity (e.g. around Karak or along Baghdad road) with elevated nitrate concentrations.

Fluoride concentrations are elevated in >25% of the A7/B2-wells. The cause is most probably geogenic, probably connected to the Belqa-unit (see chapter 5.6).

Notable to alarming trace element concentrations appear closely connected to the A7/B2-aquifer. Almost all of the elevated Se, Mo, Ni and V levels (0.5*LOD – max) were observed at wells interacting with this aquifer (except for the wells in B4/B5, mentioned before). In some parts (e.g. Wadi Al Arab), there seems to be a close connection to the B3-aquitard. In other parts, the trace elements appear to derive from lower parts of the Belqa-unit, especially B2, which is considered part of the aquifer (see chapter 5.5).

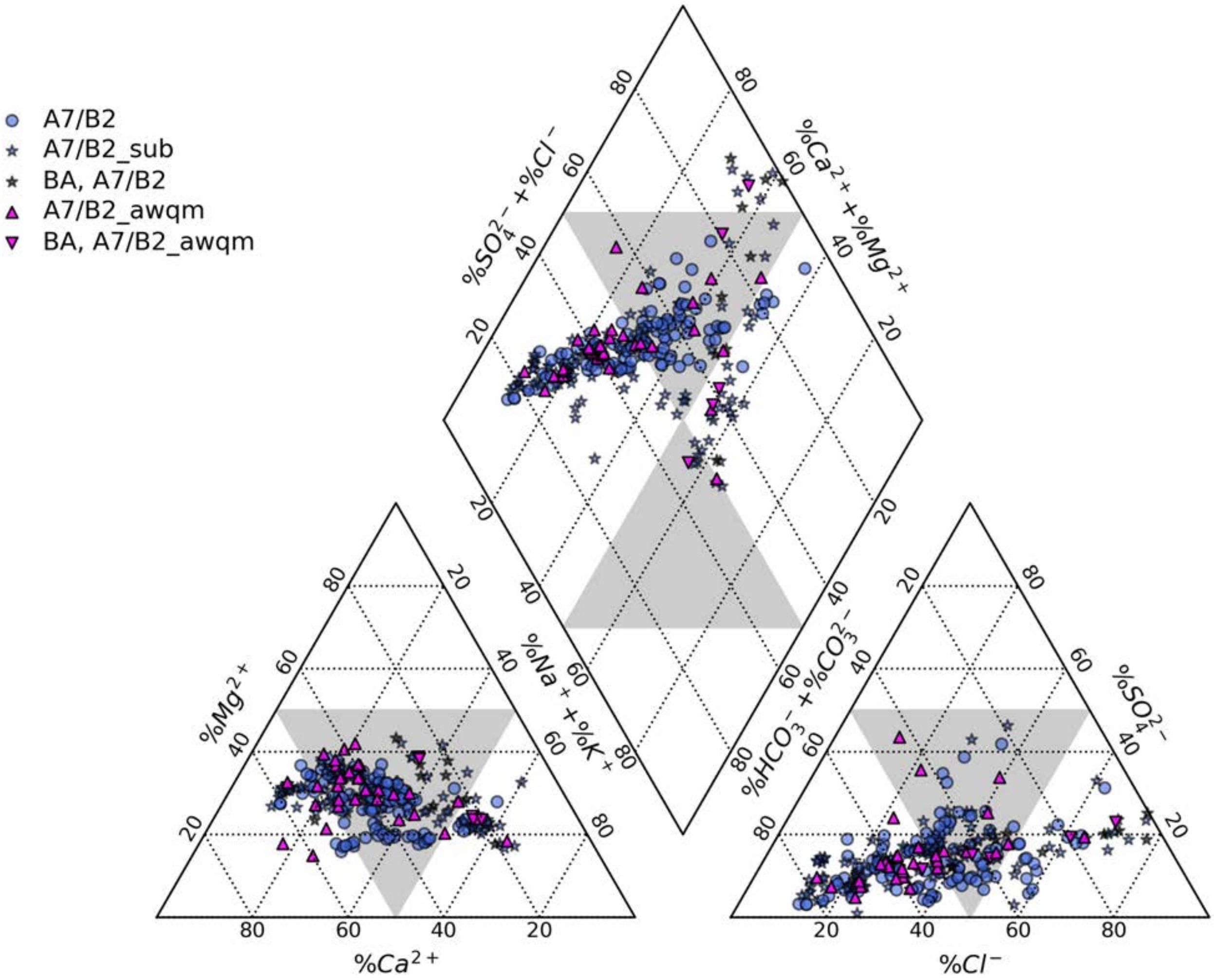


Figure 32: Piper-Diagram for samples from the A7/B2-aquifer. While the category < "A7/B2" means that the wells were situated in the outcrop areas of A7/B2 (hence, only tapping into this aquifer), "A7/B2_sub" indicates that the well was from the subcrop area (hence, potentially abstracting water mixed from different aquifers), with "BA, A7/B2" as a special case, where the Basalt-aquifer overlies the A7/B2. The categories ending with "_awqm" consist of samples, which are part of the AGS-program and will be sampled on an annual basis in the future.

*Table 16: Observed hydrochemical parameter, major and trace element distributions for the A7/B2 aquifer. Concentrations below the LOD were assumed with 0.5*LOD, except for arsenic (LODs ≥ JDWS limit discarded). Antimony (193 wells), mercury (31 wells), and silver (141 wells) not shown as all baseline concentrations stayed below 0.5* JDWS limit.*

	count	min	25%	50%	75%	max
Temp	231	18.1	22.7	25.7	29.25	43.2
pH	249	6.675	7.232	7.44	7.72	8.604
Depth	265	0	177	248	375	800
EC	277	322	696	868	1166	21900
TDS (sum)	278	218.8	513	649	823	15008
TH	135	67	273	345	401	3160
Na	278	13.7	37.35	62.95	94.05	2476
K	278	0.5	2	3.2	5.275	96.8
Ca	278	8.6	58.425	78.5	98.825	1055
Mg	278	7.38	26.4	31.95	40.3	1191
Cl	278	24	61.3	104.95	155.95	6871
F	191	0.028	0.2885	0.41	0.917	2.55
HCO_3^-	278	55.9	240.5	296.4	337.675	457.2
SO_4^{2-}	278	3.7	34.8	56.1	91.75	3143
NH_4^+	193	0.005	0.005	0.01	0.05	0.41
NO_3^-	278	0.0015	0.25	7.495	22.975	183.4
Al	199	0.0015	0.008035	0.013	0.022	0.44
Fe	264	0.001	0.01	0.0235	0.06	16.09
B	195	0.005	0.03	0.11	0.18	1.22
Ba	195	0.001	0.043	0.07	0.11	3.82
As	155	0.00005	0.00034	0.0006	0.0013	0.03
Mo	229	0.00018	0.005	0.00504	0.02	1.645
Ni	262	0.0002	0.00304	0.005	0.01	0.215
Se	231	0.00001	0.00205	0.01	0.01	0.226
V	127	0.0005	0.007	0.013	0.0215	0.254
Cr	260	0.00005	0.002285	0.0025	0.00494	0.044
Cd	261	0.000002	0.00006	0.0015	0.0015	0.002
Cu	264	0.00021	0.0008	0.01	0.01	0.72
Pb	261	0.00004	0.00017	0.0025	0.0025	0.01
Zn	264	0.0007	0.01	0.02	0.06	0.52

6.5 A1/A6

The A1/A6 aquifer was sampled in 97 wells during this study. The distribution of major ions is shown in Figure 33, while the hydrochemical parameters are presented in Table 17. Even though it is considered a single aquifer on the regional scale, the units A3 and A5/A6 are actually considered aquitards with locally differing permeabilities. Due to this, the share of water from the different units in a well depends largely on the exact location and the well setup. Furthermore, the A1/A6 outcrop is largely situated close to the densely populated areas west of Amman and Madaba on the shores of the Jordan valley and the Northern Dead Sea, where agriculture is extensive. Due to this, generally elevated nitrate levels are found.

Wells in A1/A6 with elevated concentrations in trace elements are mostly interacting with A7/B2 (e.g. the Heedan wells or in the Karak region). The same is true for fluoride, which is elevated in roughly 25% of the wells, most of which are interacting with A7/B2.

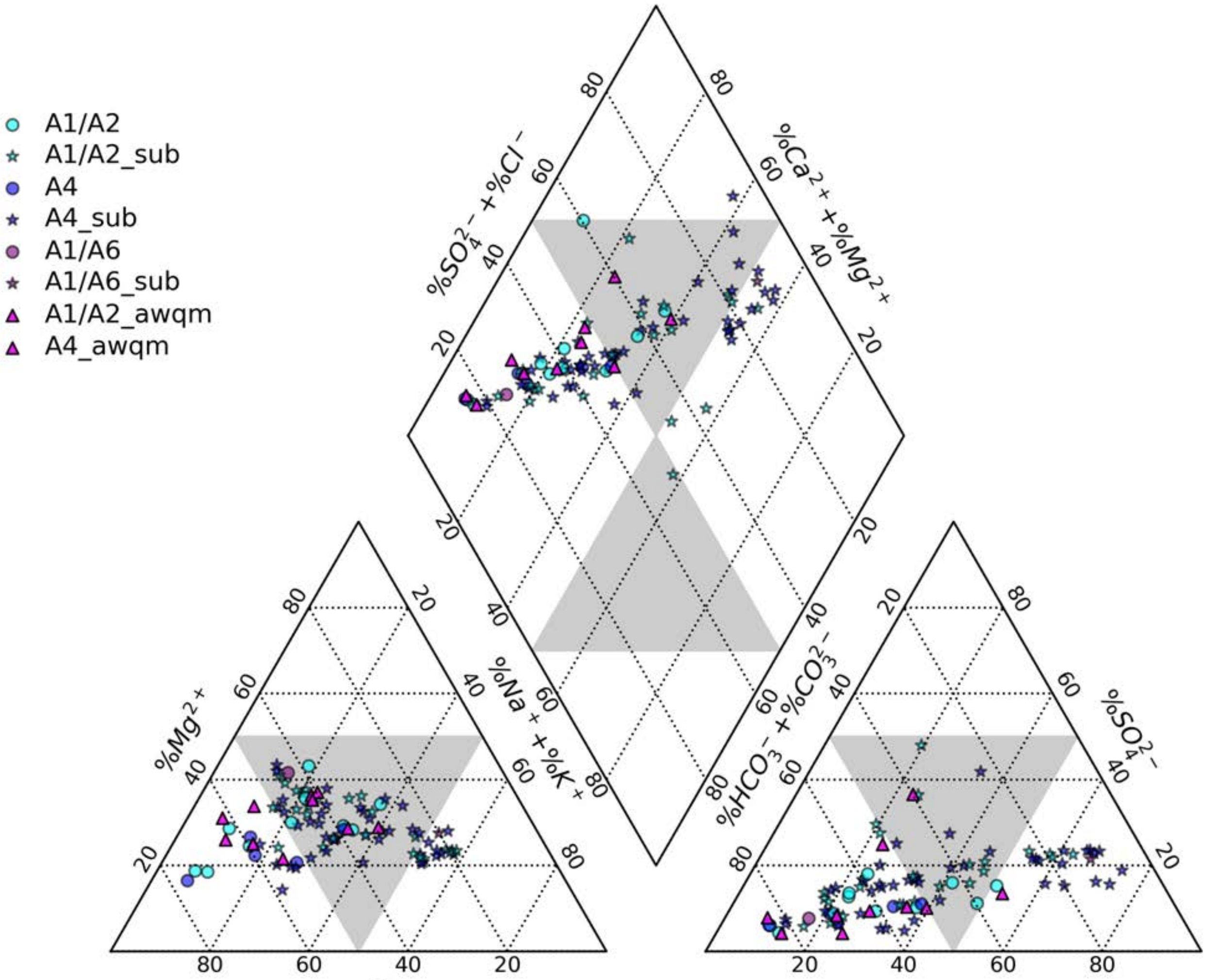


Figure 33: Piper-Diagram for samples from the A1/A6-aquifer. While the categories "A1/A2", "A4" and "A1/A6" mean that the wells were situated in the outcrop areas of the respective aquifer units (hence, only tapping into this aquifer), the "_sub"-suffix indicates that the well was from a subcrop area (hence, potentially abstracting water mixed from different aquifers). The categories ending with "_awqm" consist of samples, which are part of the AGS-program.

*Table 17: Observed hydrochemical parameter, major and trace element distributions for the A1/A6 aquifer. Concentrations below the LOD were assumed with 0.5*LOD, except for arsenic (LODs ≥ JDWS limit discarded). Antimony (78 wells), mercury (15 wells), and silver (47 wells) not shown as all baseline concentrations stayed below 0.5* JDWS limit.*

	count	min	25%	50%	75%	max
Temp	70	18.1	23.75	26.15	28.875	39
pH	77	6.6	7.36	7.526	7.787	8.4
Depth	95	0	175	283	363.5	1183
EC	97	486	760	998	1403	5490
TDS (sum)	97	375	565	753	962	3487
TH	36	248	296.25	348.5	479	1379
Na	97	10.6	33.4	69.2	118	664.5
K	97	0.5	2.6	4	6.1	67.2
Ca	97	30.3	71	89.6	103.1	263.8
Mg	97	13.4	28	35.7	51.4	175.3
Cl	97	20.6	63.6	113	206	1344.1
F	76	0.078	0.29925	0.4785	0.76175	1.79
HCO_3-	97	81.1	260	310	336	587
SO_4^{2-}	97	12.4	33.8	68.3	155	623.8
NH_4+	76	0.005	0.005	0.005	0.05	0.69
NO_3-	97	0.0015	6.72	22.8	45.3	151
Al	78	0.0015	0.01	0.01598	0.02675	0.63
Fe	90	0.005	0.011	0.02	0.03925	2.28
B	75	0.005	0.080803551	0.141406214	0.202008877	1.113573931
Ba	75	0.016	0.0565	0.07	0.087	0.244
As	68	0.00006	0.0003975	0.00057	0.00116	0.013
Mo	81	0.00065	0.005	0.00921	0.0275	1.009
Ni	88	0.00045	0.0017225	0.005	0.01	0.107
Se	80	0.000025	0.0025	0.005815	0.01243	0.348
V	57	0.0005	0.006	0.013	0.028	0.428
Cr	88	0.00005	0.0012675	0.0025	0.0033525	0.01858
Cd	88	0.000005	0.00002	0.000307	0.0015	0.00188
Cu	90	0.00037	0.0007825	0.001515	0.01	0.03
Pb	88	0.00003	0.000134	0.0003105	0.0025	0.01
Zn	90	0.004	0.01	0.024	0.068	1.29

6.6 Deep Sandstone Aquifer (Zarqa, Kurnub & Ram)

The Deep Sandstone Aquifer consists of three different units, each with varying thicknesses, permeabilities and interconnections. Furthermore, the lithology of the three layers differs substantially, as the Ram-aquifer mainly comprises pure sand, while the other two show significant contents of fines, carbonates and gypsum. Furthermore, they still contain brines, which infiltrated in the Tertiary and are slowly released, as the hydraulic pattern in the neighbouring aquifers change (Möller, 2020).

In total, 64 samples were taken from wells in the Ram (33), Zarqa (3) or Kurnub (16) aquifer or undifferentiated (12) (see Figure 35). Hydrochemical parameters are shown in Table 18. While the TDS-content of the Ram is mostly far below 750 mg/L, the Kurnub (>1500 mg/L) and the Zarqa (>3000 mg/L) show much higher salinities. Nitrate is basically non-existent in all subcrop-parts of the Ram. In the outcrop areas, though still far from any limit of the JDWS, it shows concentrations of up to 20 mg/L in some parts. This trend should be monitored closely as a connection to agricultural activity is likely.

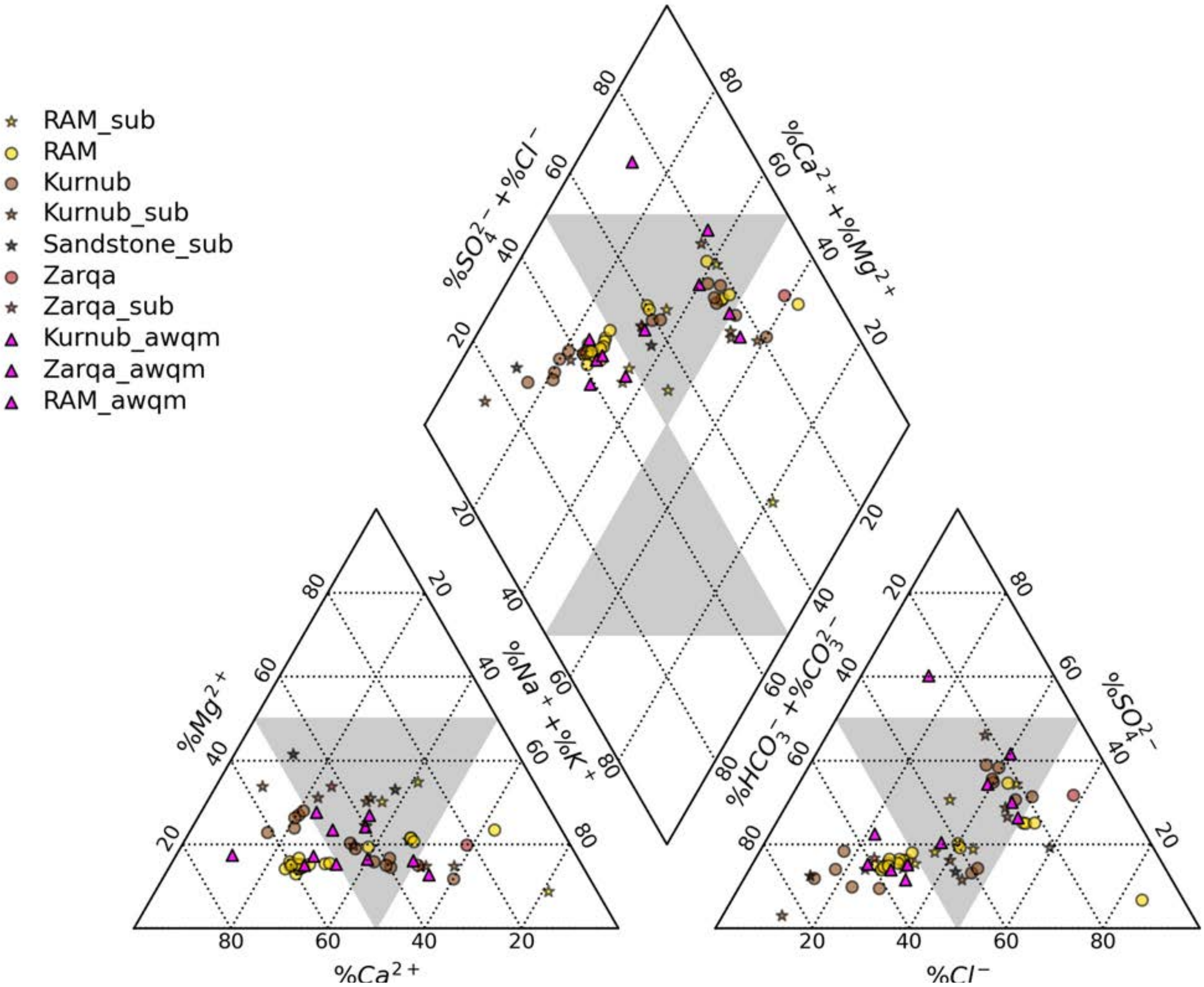
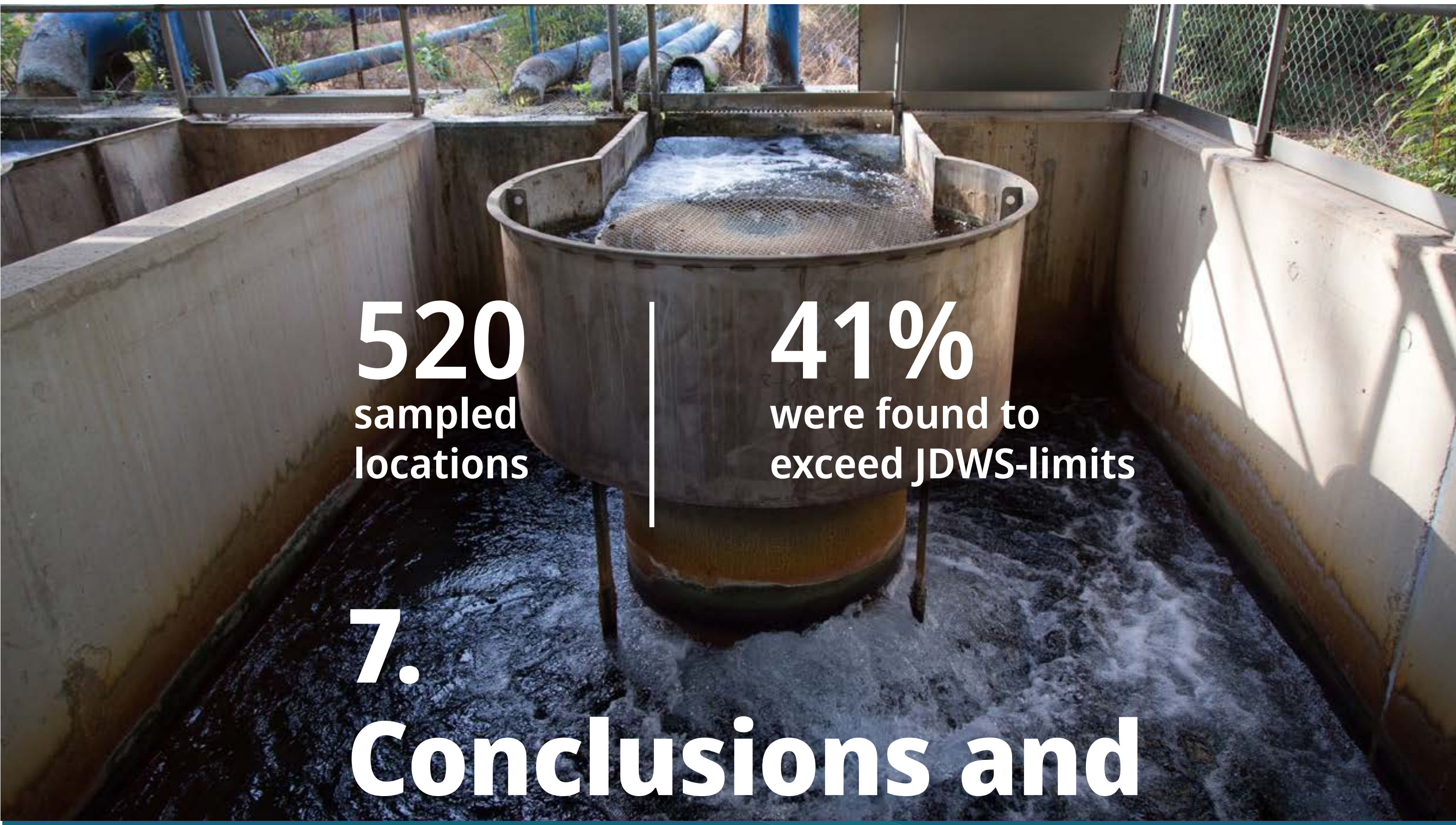


Figure 34: Piper-Diagram for samples from the sandstone aquifers. While the categories "RAM", "Kurnub" and "Zarqa" mean that the wells were situated in the outcrop areas of the respective aquifer units (hence, only tapping into this aquifer), the "_sub"-suffix indicates that the well was from a subcrop area (hence, potentially abstracting water mixed from different aquifers). The categories ending with "_awqm" consist of samples, which are part of the AGS-program.

*Table 18: Observed hydrochemical parameter, major and trace element distributions for the sandstone aquifers. Concentrations below the LOD were assumed with 0.5*LOD, except for arsenic (LODs ≥ JDWS limit discarded). Antimony (50 wells), mercury (10 wells), and silver (20 wells) not shown as all baseline concentrations stayed below 0.5* JDWS limit.*

	count	min	25%	50%	75%	max
Temp	52	21.1	26.875	27.5	28.425	61.3
pH	54	6.48	7.0205	7.8325	8.01525	8.195
Depth	63	100	232.5	400	500	1903
EC	64	291	362.75	727.5	2030	9180
TDS (sum)	64	210.32	258.75	539	1368.662	6781
TH	32	72	210.25	369	659.25	2099
Na	64	14.4	19.325	49.8	167.575	1370.8
K	64	1	1.4	3.8	7.425	129.1
Ca	64	15.3	38.575	67.5	146.025	592.1
Mg	64	4.55	6.8475	23.85	46.8	210.8
Cl	64	26.4	33.1	78.4	268.55	2113.6
F	45	0.106	0.159	0.36	1.04	3.89
HCO_3-	64	76.8	108.475	251.85	358.75	1183.3
SO_4^{2-}	64	10	25.85	57.5	244	1544.4
NH_4+	51	0.005	0.005	0.05	0.19	2.25
NO_3-	64	0.0075	0.25	8.94	11.575	310.9
Al	49	0.005	0.007	0.017	0.022	0.68
Fe	58	0.005	0.01425	0.036	1.165	14.26
B	49	0.005	0.040402	0.05555	0.17423	2.8
Ba	49	0.01	0.02	0.03	0.04	0.26
As	40	0.00005	0.0001375	0.00018	0.001075	0.011
Mo	50	0.00046	0.0010775	0.002325	0.005	0.02
Ni	58	0.00036	0.0007025	0.005	0.005	0.02
Se	50	0.000009	0.000525	0.00117	0.008125	0.01
V	30	0.0015	0.0015	0.0015	0.00375	0.004
Cr	58	0.00059	0.0025	0.0025	0.00353	0.01046
Cd	58	0.000003	0.00002225	0.0000465	0.0015	0.0015
Cu	58	0.00037	0.00071	0.00583	0.01	0.0868
Pb	58	0.000039	0.00011675	0.0017245	0.0025	0.005215
Zn	58	0.00244	0.007	0.01	0.02	3.09



520
sampled locations

41%
were found to exceed JDWS-limits

7.

Conclusions and recommendations

This study provides a baseline for the groundwater quality in Jordan between the years 2020 and 2023. **It reports the water qualities as encountered at the monitoring location prior to any treatment and is therefore not representative for the drinking water quality of a certain area.** Of the 520 sampled locations, 41% were found to exceed JDWS-limits for at least one of the 28 assessed inorganic parameters. As the study did not consider microbiological parameters, radioactivity and/or organic compounds, it is likely, that even more wells would be considered unsuitable for drinking water supply, if these parameters were included. The high percentage of compromised wells clearly highlights the challenges faced by the water suppliers in providing suitable drinking water to the public by water treatment and blending.

Rising groundwater salinities (TDS) is a major groundwater quality problem

Rising groundwater salinities (TDS) have been identified as a major groundwater quality problem for Jordan by previous studies (e.g., El-Naqa et al. 2007, Al-Kuisi et al., 2009, GIZ, 2020). In agreement with these studies, high TDS concentrations were identified as the most frequent cause for drinking water guideline violations in the baseline study and several locations with rising salinity trends have been identified. One of the main causes for salinization is the overexploitation (e.g., El-Naqa et al. 2007), leading to a depletion of the fresher groundwater and an increasing withdrawal of more saline water. If the source of higher salinity can be identified, a careful estimation of future salinity increases can be attempted. However, due to the non-linear behaviour of many underground processes, extrapolation in the future is to be conducted with extreme caution, even when trends can be identified. Furthermore, many salinity increases seem to be linked to contamination, deriving from agriculture, sewage or industrial wastewater (e.g., reverse osmosis brines). Such an increase by external sources is unpredictable and requires regulative prevention and comprehensive monitoring.

Nitrogen in the groundwater (especially in the form of nitrate) is known to create severe groundwater quality problems and increase groundwater treatment costs in many places of the world. In this baseline study it was identified as the second most frequent parameter responsible for a JDWS guideline violation after salinity and its directly related parameters (TH, Na, Cl, SO_4^{2-}). The highest nitrate concentrations were observed in the northern part of Jordan where high population density and agricultural activities prevail. Agriculture is suspected to significantly impact groundwater quality in some parts of the country, particularly affecting shallow groundwater. High pumping rates for agricultural purposes lead to drawdown, which increases the risk of

Nitrogen in the groundwater create severe groundwater quality problems and increase groundwater treatment costs

salinization and mobilization of trace metals. Irrigation return flows intensify groundwater quality issues, increasing salinity and introducing nitrates and ammonium. In addition, the improper application of fertilizer and the excessive dumping of manure on farmland can deteriorate groundwater quality. This is a common problem affecting drinking water supplies in many countries of the world. In Jordan, the situation is especially critical due to the generally low groundwater recharge and already tense water situation. In order to mitigate these potential effects of agriculture on groundwater, pumping rates for agricultural purposes as well as the application of fertilizer need to be minimized in areas with a tense groundwater supply. In addition, new development of agricultural land needs to be restricted to specific designated areas and farmers should be trained with regard to consequences of irrigation return flows and the appropriate use of fertilizers on their land. Furthermore, a nationwide assessment on nitrogen balances is needed to prevent further contamination.

Alarming concentrations of the trace elements exclusively in carbonate aquifers

Alarming concentrations of the trace elements molybdenum, selenium and nickel were found to be responsible for multiple guideline violations across wide parts of Jordan also beyond the Karak and Wadi Al–Arab region. Even though it is not considered in the JDWS, vanadium was found in high concentrations, which would severely affect the suitability for drinking water. The violations occurred exclusively in carbonate aquifers and appear to predominantly follow the A7/B2 outcrop areas (esp. for Mo and Se). Previous studies identified an enrichment for these and other trace elements in most lithologies of the Belqa group (e.g., Al-Hwaiti et al. 2013, Fleurance et al. 2013, Wagner et al. in prep.) and their release is thought to be connected to an excessive water table drawdown (Wagner et al. in prep., Dorsch et al. 2020, Brückner et al. 2021). At many location with guideline violations, the B3 as potential trace element source has been eroded. Instead, other parts of the Belqa-group (especially B2) appear responsible for the release of trace elements, possibly triggered by a change in redox conditions, e.g. by aeration during drawdown of groundwater or by introduction of other oxidation agents, e.g. nitrate. Due to the observed statistical and spatial correlation of Mo, Ni, Se, and the suspected common source, we propose to introduce routine monitoring of all three parameters at locations with recorded elevated concentrations for any of these trace elements. For the same reason, these locations should additionally be checked for chrome, cadmium, vanadium and uranium. The latter two should be considered for possible integration into the Jordanian Drinking Water Standard, as especially vanadium shows extraordinary concentrations. At sites with a known trace element violation, groundwater quality monitoring should be conducted with a higher frequency than the AGS, as they appear highly variable over time (Wagner et al., in preparation). Sites with the most urgent need for a more detailed survey identified in this study include especially the Tamoween and Karak wellfields and Wadi Al Arab (e.g., Dorsch et al. 2020, GIZ, 2020).

Given the severity of this problem, further research is required to understand the trace element content of the B2 host rocks in comparison to other aquifer formations (e.g., A7), to elucidate the mobilization process in greater detail and to evaluate alternative theories for trace element release. Finally, we recommend to intensify the exchange about these issues with neighbouring countries, who are expected to encounter similar problems due to the shared hydrogeology.

In addition to that, the Belqa-group appears to be a source **for increased fluoride-concentrations.** Even though the average concentration here is still unproblematic (<0.7 mg/l), certain areas – especially in Central Jordan – show widespread elevated F-contents in the groundwater of the A7/B2-aquifer. This development needs to be monitored closely in the future, especially in the context of falling groundwater levels.

Groundwater levels falling increasing problems

Groundwater levels all over the country are falling since many years and are predicted to decline further (Brückner et al., 2021). Considering the results from the baseline study and experiences from Wadi Al Arab wellfield (Dorsch et al. 2020, Brückner et al. 2021) their implications, this will most probably lead to increasing problems, due to the mobilization of (trace) contaminants. Especially areas in the A7/B2-aquifer where formerly confined change to unconfined conditions should be monitored closely, as this may go hand in hand with an aeration of the uppermost parts of the Belqa-unit.

On the other hand, **caution is required, when measures are implemented to counteract the falling groundwater levels as MAR with oxygen-rich, low-mineralized water could alter the hydrochemistry significantly and lead to the mobilization of fluoride or oxyanions (Se, Mo, V, etc.)** or even of elements, which at the moment do not show elevated concentrations yet (e.g. As, Cr, Cd). This does not mean that MAR should be restricted completely, but it should be connected to a rigorous hydrogeochemical monitoring.

This baseline study can only be seen as a short reference point in time, and requires continuous updates. For this purpose, 88 wells will be sampled and analysed on an annual basis in the scope of the AGS in the future. This will allow a nationwide overview on trends in groundwater quality. However, it is obvious that 88 wells for the whole Kingdom of Jordan is not sufficient and this monitoring should be complemented by a closer monitoring in areas of concern (e.g. Central Jordan, Wadi Al Arab, Russeifa).

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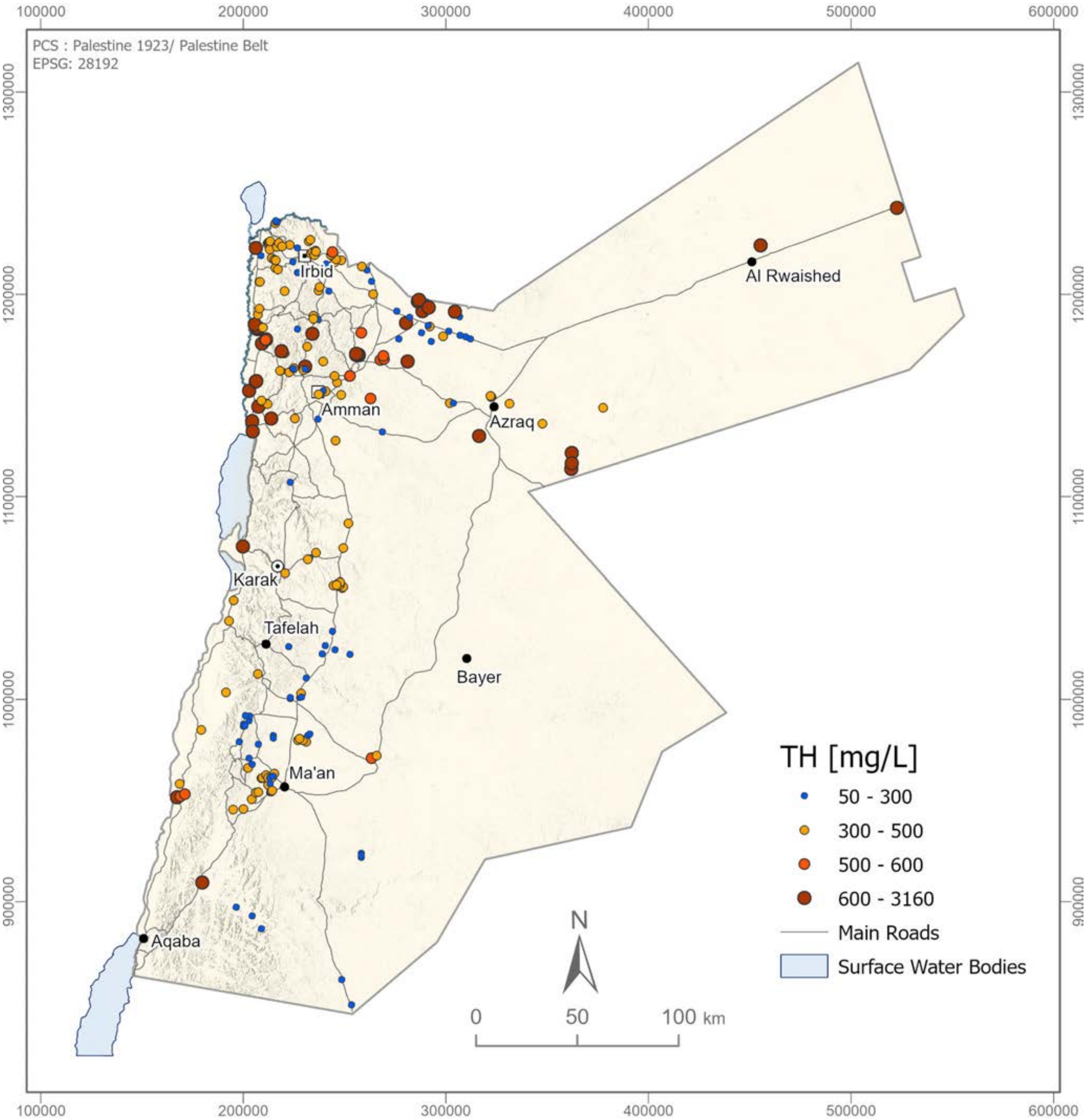
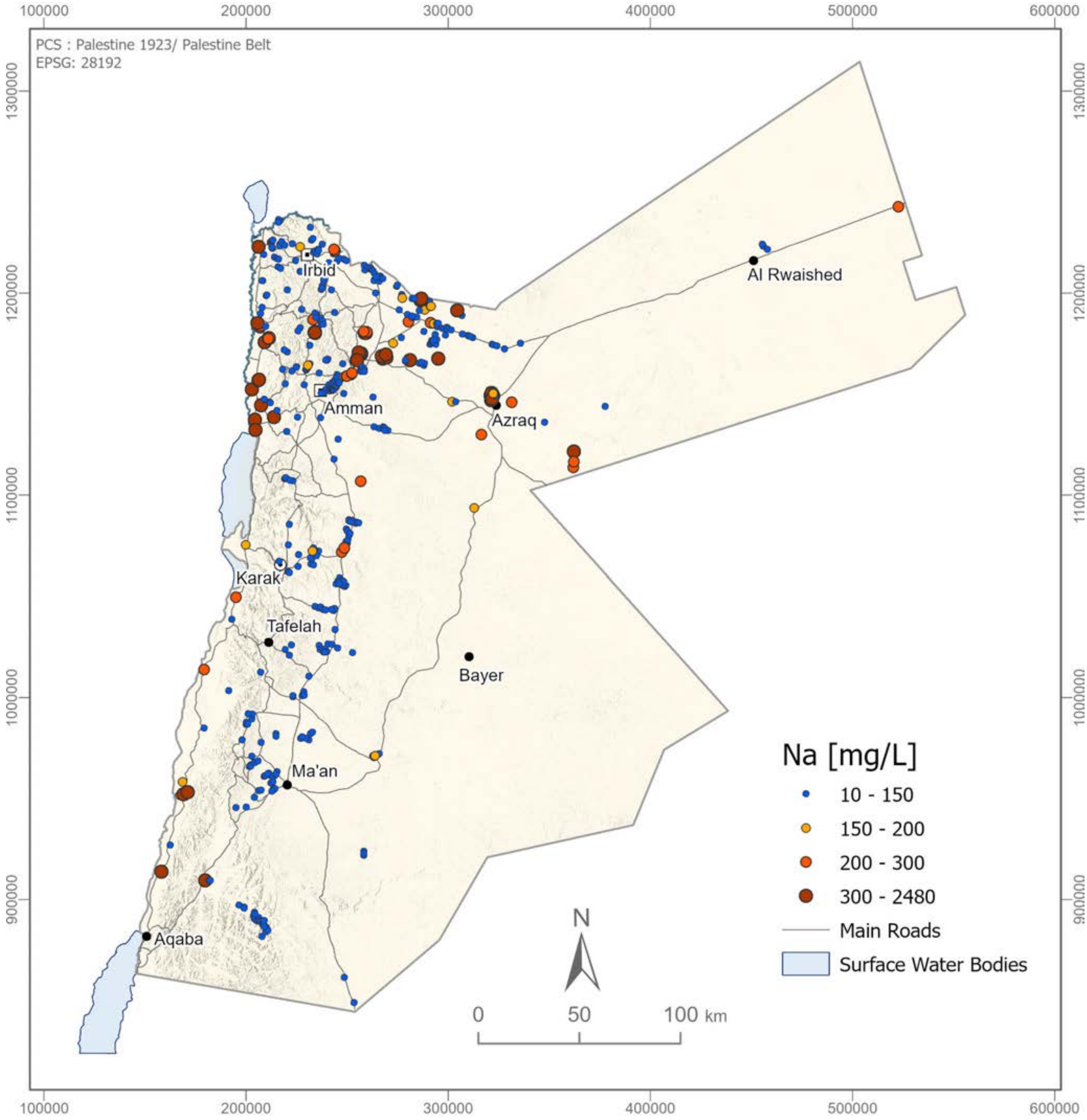
Annexe A. Salinity Related Parameters

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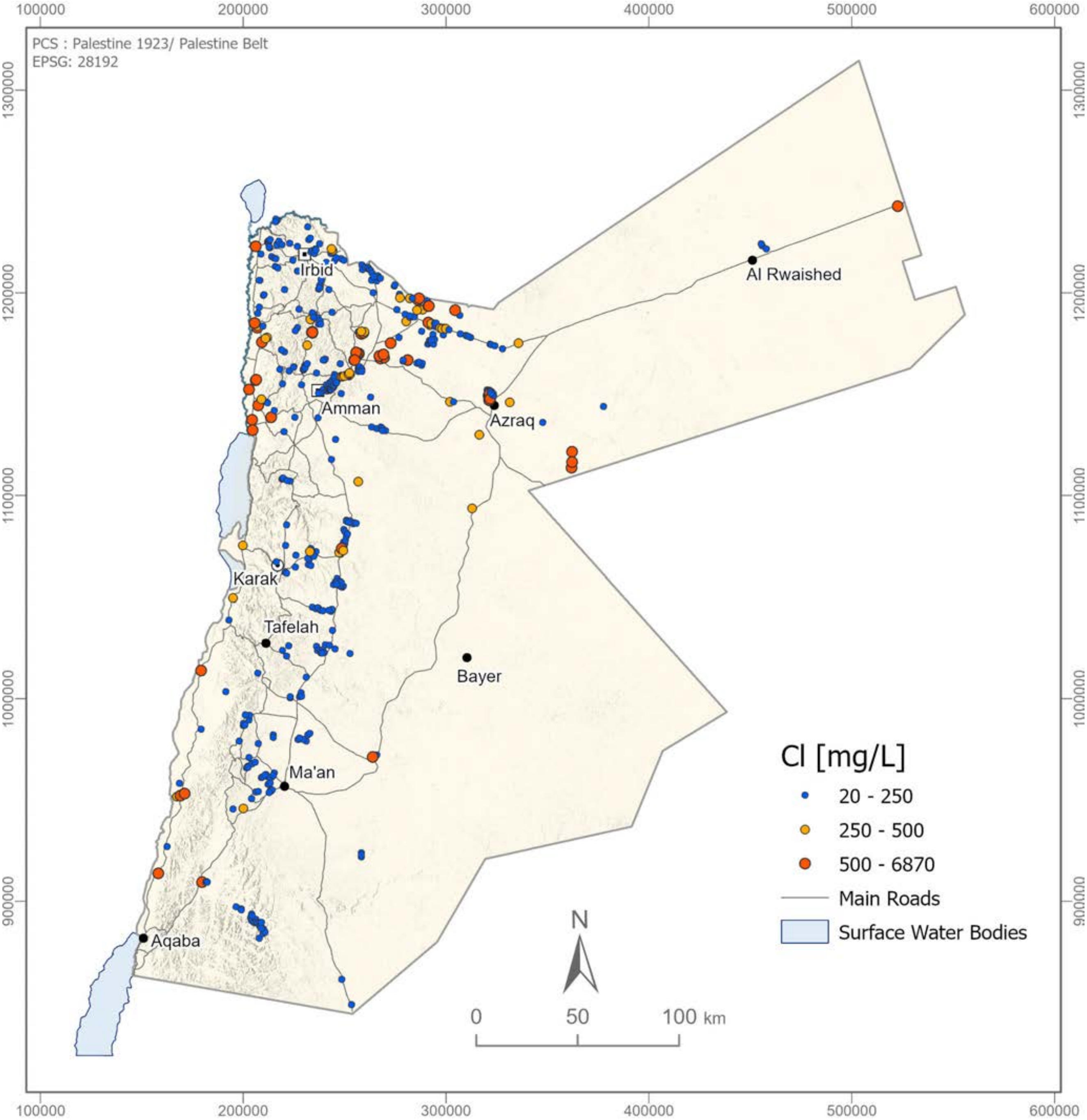
100000
200000
300000
400000
500000
600000
1300000
1200000
1100000
1000000
900000
Irbid
Amman
Azraq
Al Rwaished
Karak
Tafelah
Bayer
Ma'an
Aqaba
Na [mg/L]
10 - 150
150 - 200
200 - 300
300 - 2480
Main Roads
Surface Water Bodies
N
0
50
100 km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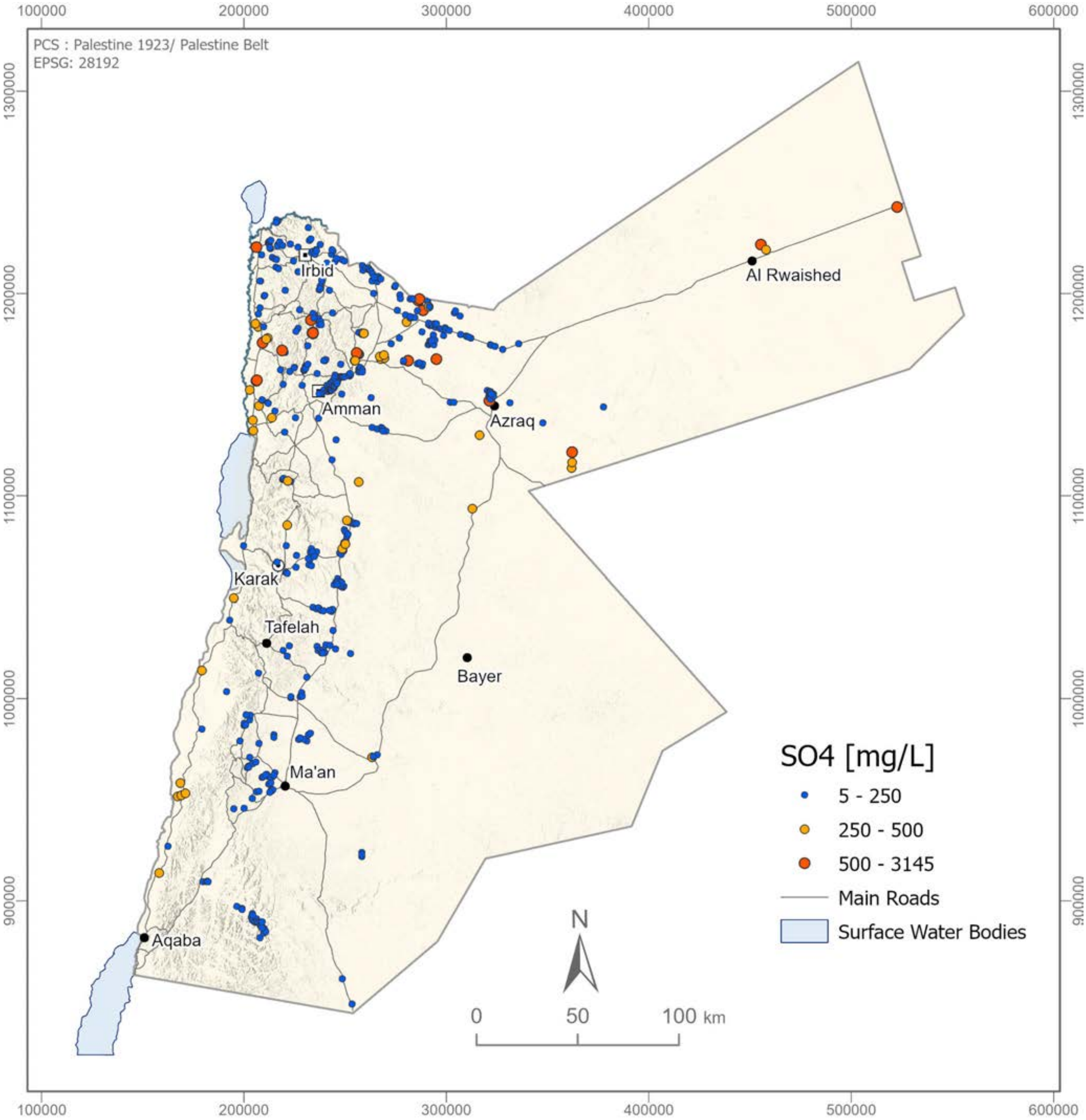
200000
300000
400000
500000
600000
900000
1000000
1100000
1200000
1300000
Irbid
Amman
Azraq
Al Rwaished
Karak
Tafelah
Bayer
Ma'an
Aqaba
Cl [mg/L]
● 20 - 250
● 250 - 500
● 500 - 6870
Main Roads
Surface Water Bodies
N
0
50
100 km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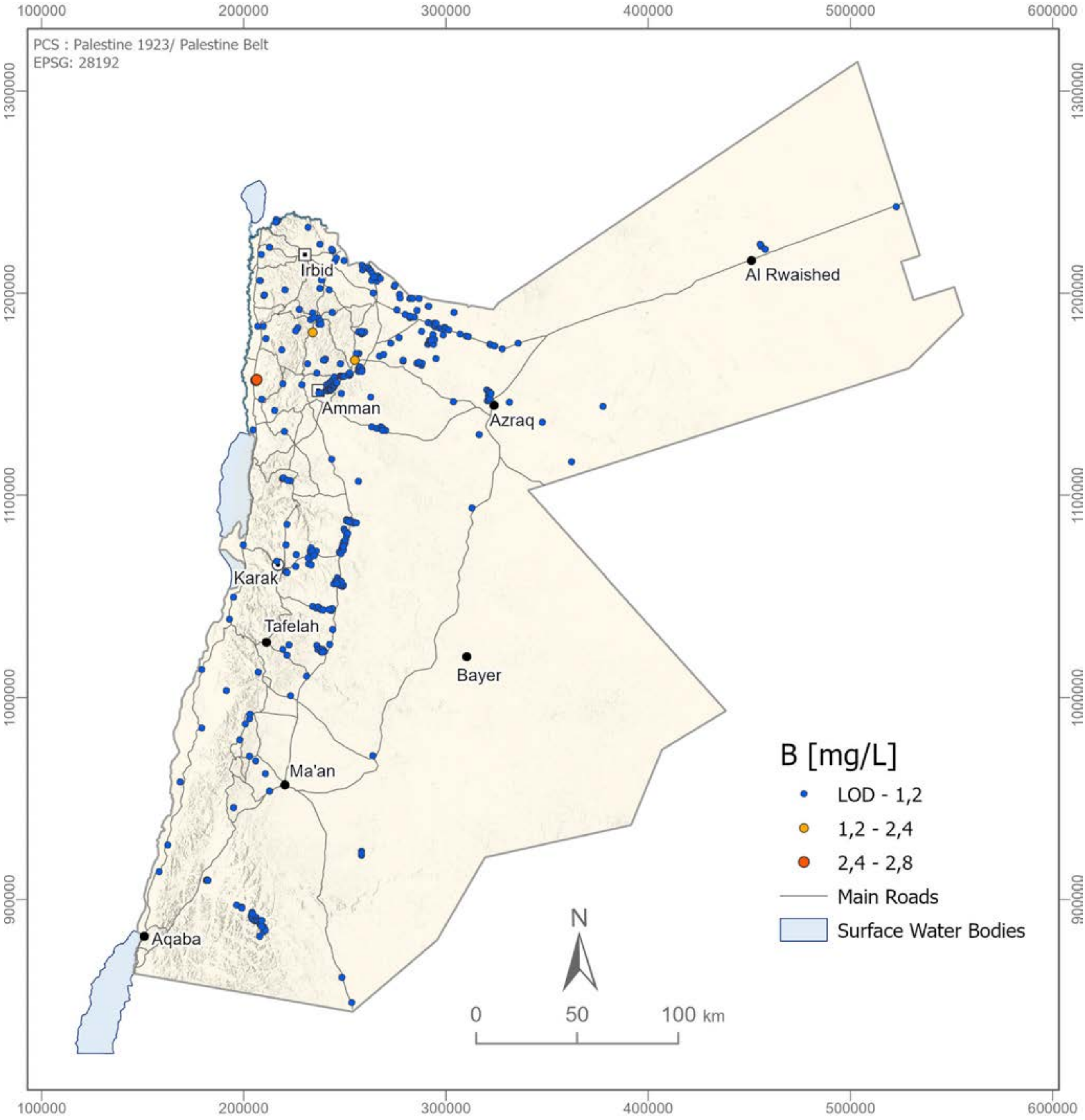
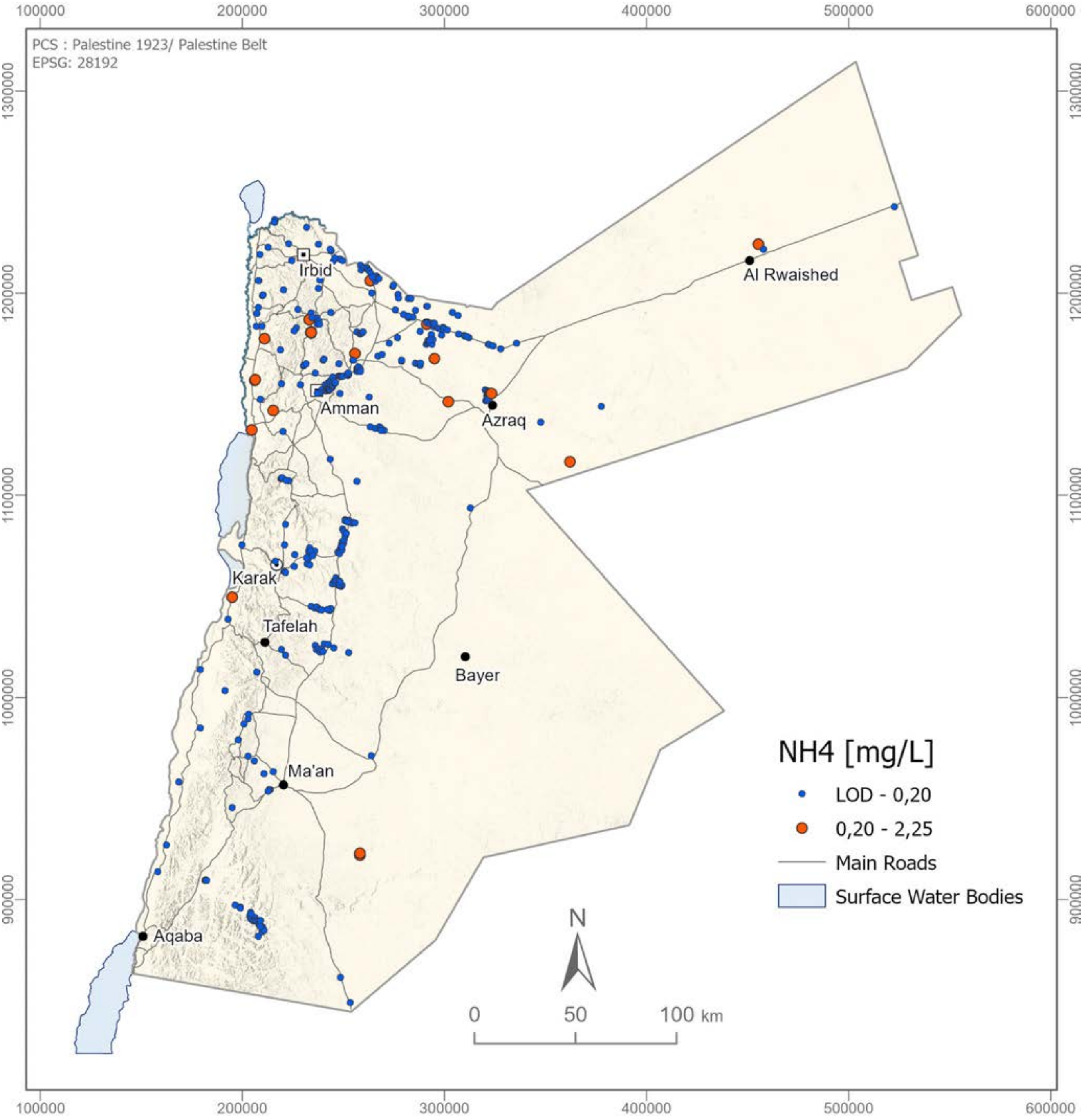
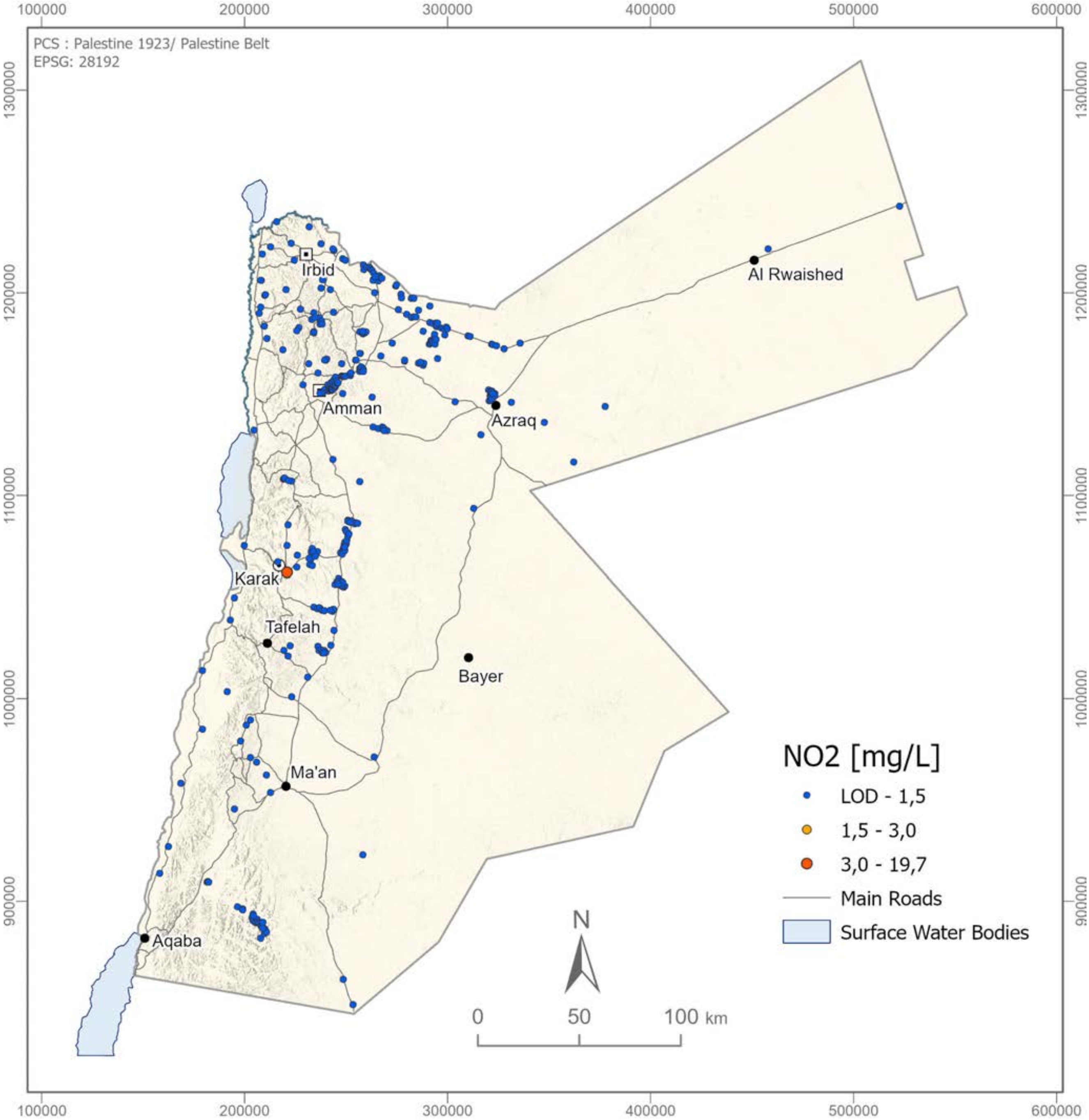
200000
300000
400000
500000
600000
1300000
1200000
1100000
1000000
900000
Irbid
Amman
Azraq
Al Rwaished
Karak
Tafelah
Bayer
Ma'an
Aqaba
SO4 [mg/L]
5 - 250
250 - 500
500 - 3145
Main Roads
Surface Water Bodies
N
0
50
100 km

Annexe B. Boron

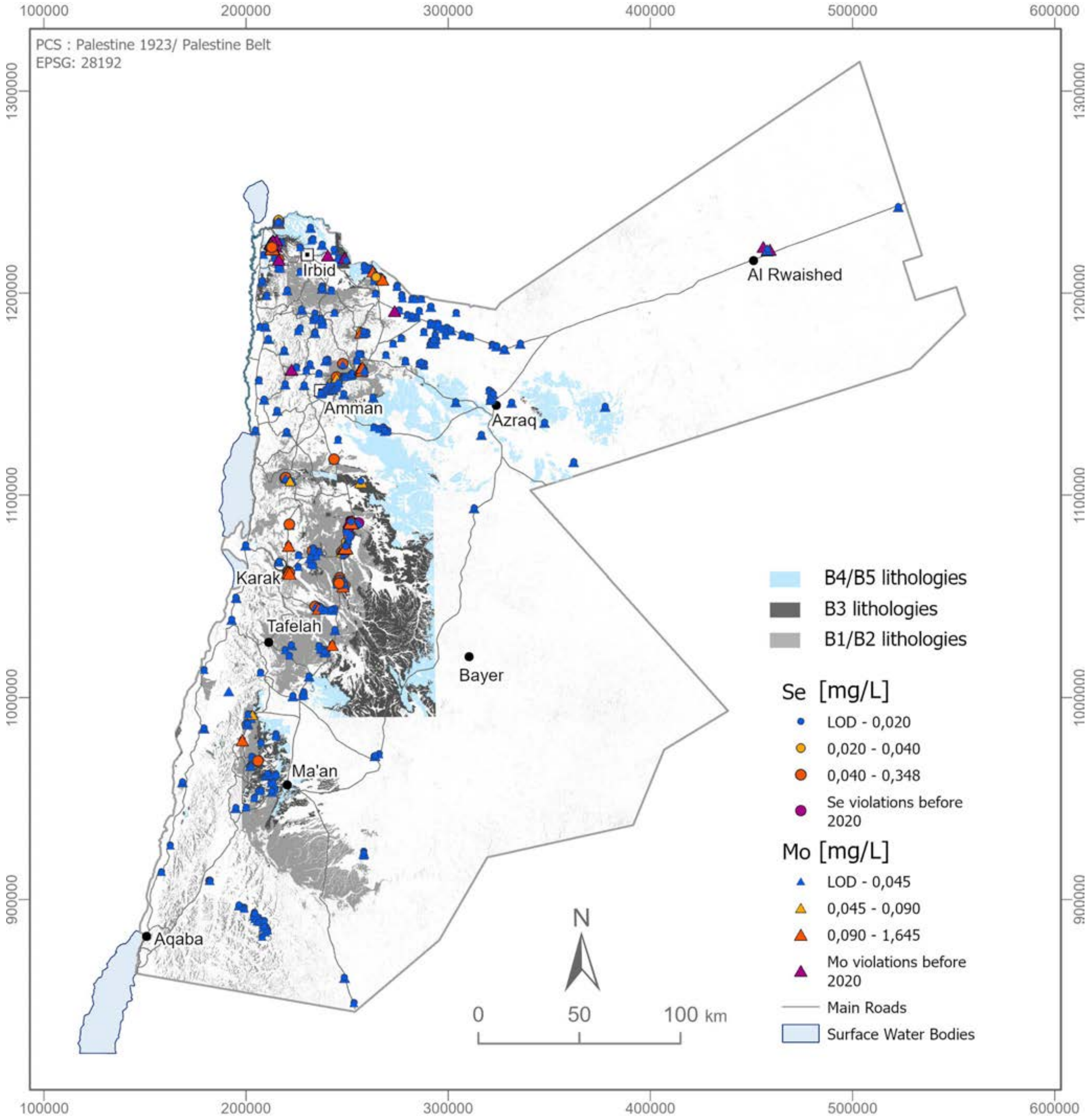


Annexe C. NH_4+ and NO_2-

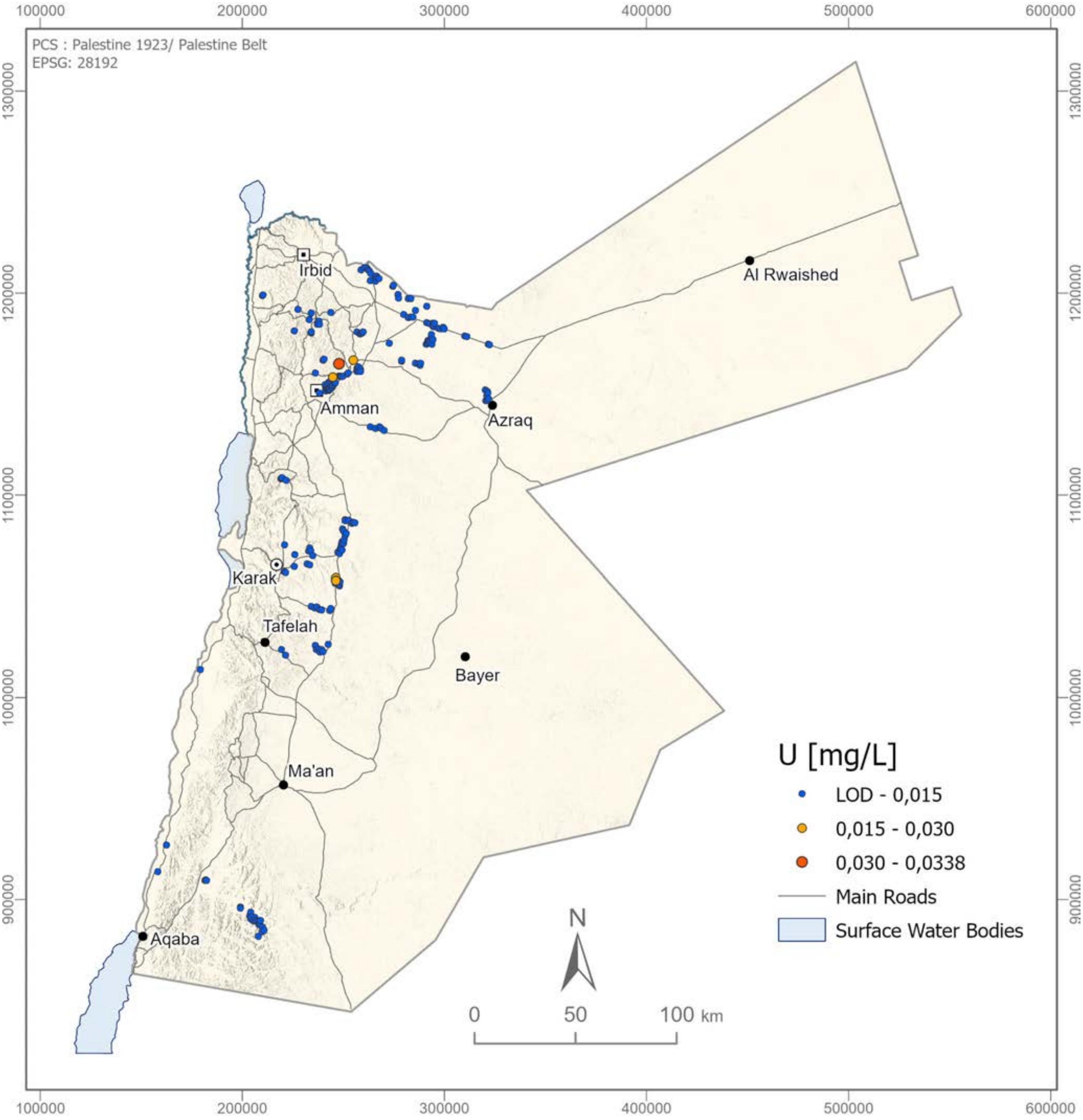



100000
200000
300000
400000
500000
600000
1300000
1200000
1100000
1000000
900000
PCS : Palestine 1923/ Palestine Belt
EPSG: 28192
Irbid
Al Rwaished
Amman
Azraq
Karak
Tafelah
Bayer
Ma'an
Aqaba
NO2 [mg/L]
LOD - 1,5
1,5 - 3,0
3,0 - 19,7
Main Roads
Surface Water Bodies
N
0
50
100 km

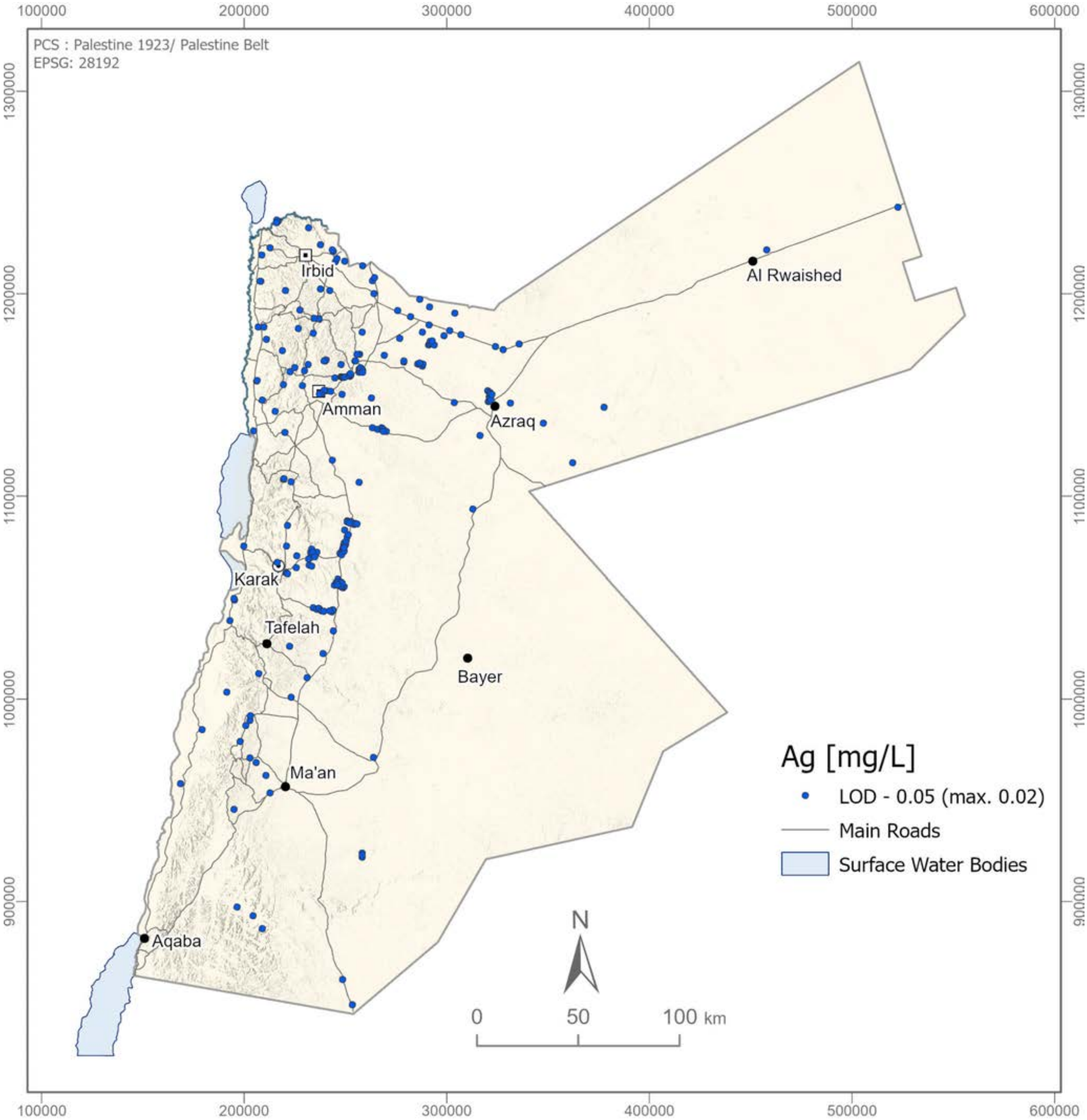
Annexe D. Belqa Sediments vs Mo and Se

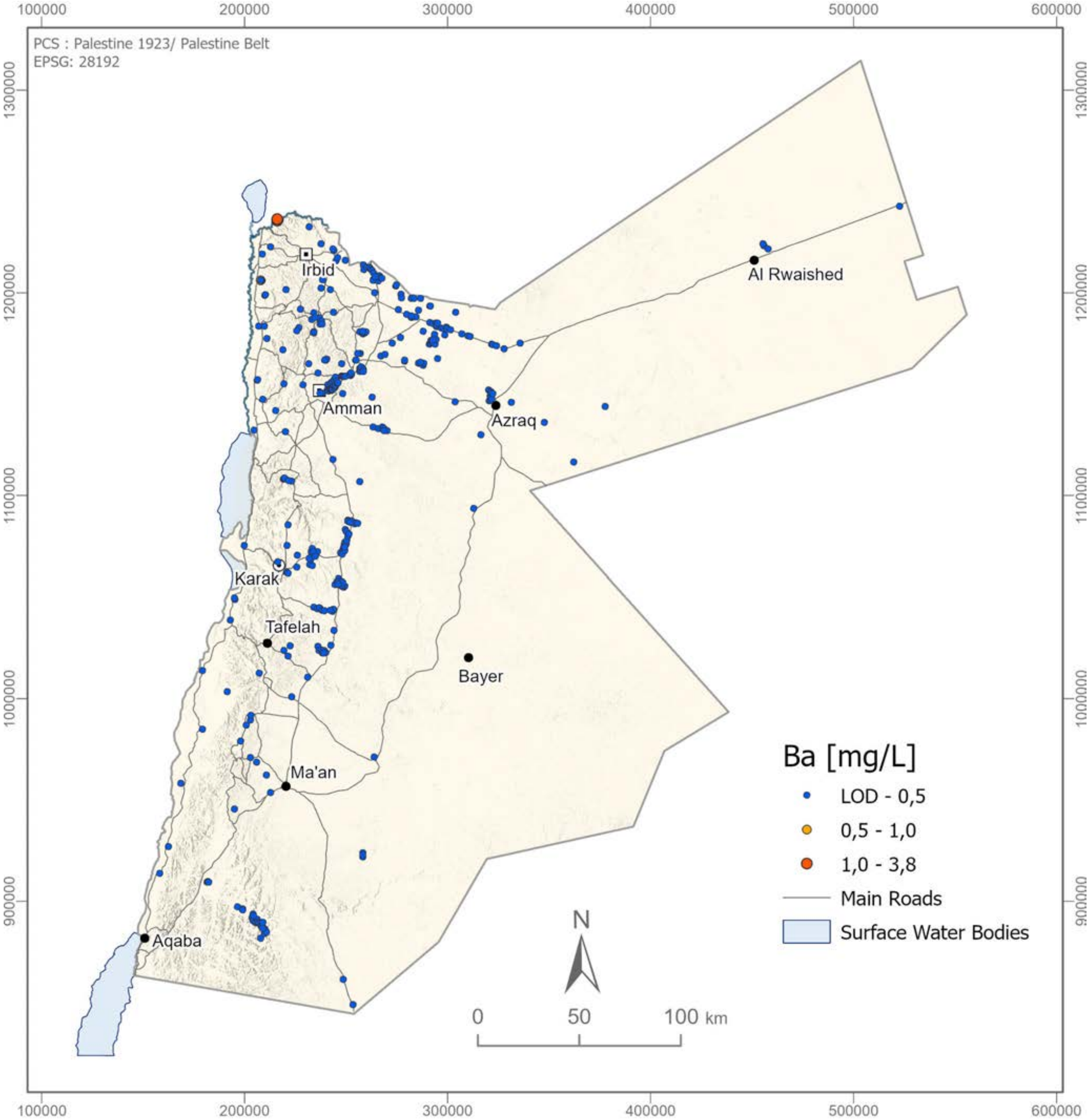


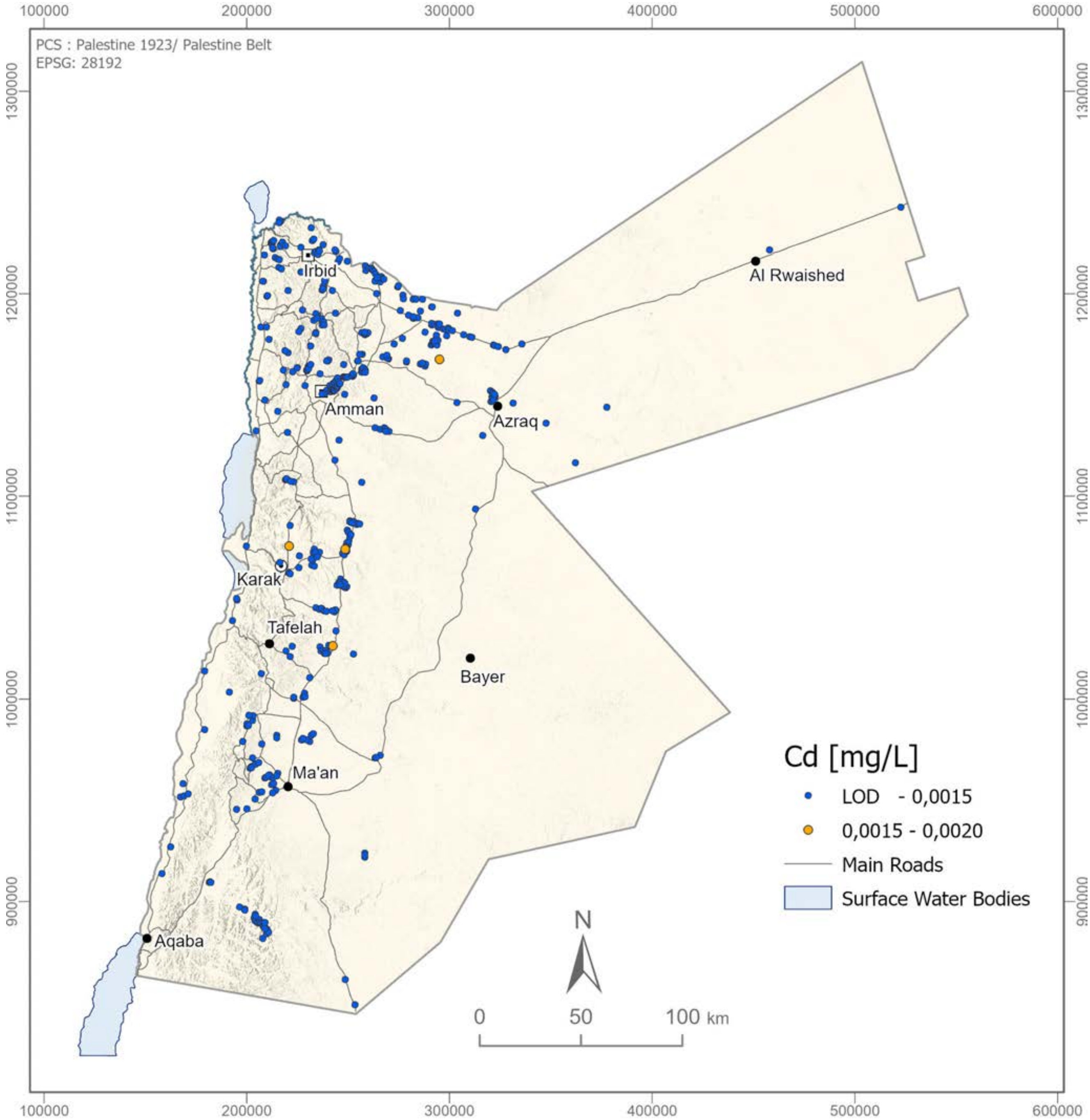
Annexe E. Uranium



Annexe F. Remaining Trace Elements (Ag, Ba, Cd, Cr, Cu, Fe, Hg, Mn, Pb, Sb, Zn)




100000
200000
300000
400000
500000
600000
1300000
1200000
1100000
1000000
900000
PCS : Palestine 1923/ Palestine Belt
EPSG: 28192
Irbid
Amman
Azraq
Al Rwaished
Karak
Tafelah
Bayer
Ma'an
Aqaba
Ba [mg/L]
● LOD - 0,5
● 0,5 - 1,0
● 1,0 - 3,8
Main Roads
Surface Water Bodies
N
0
50
100 km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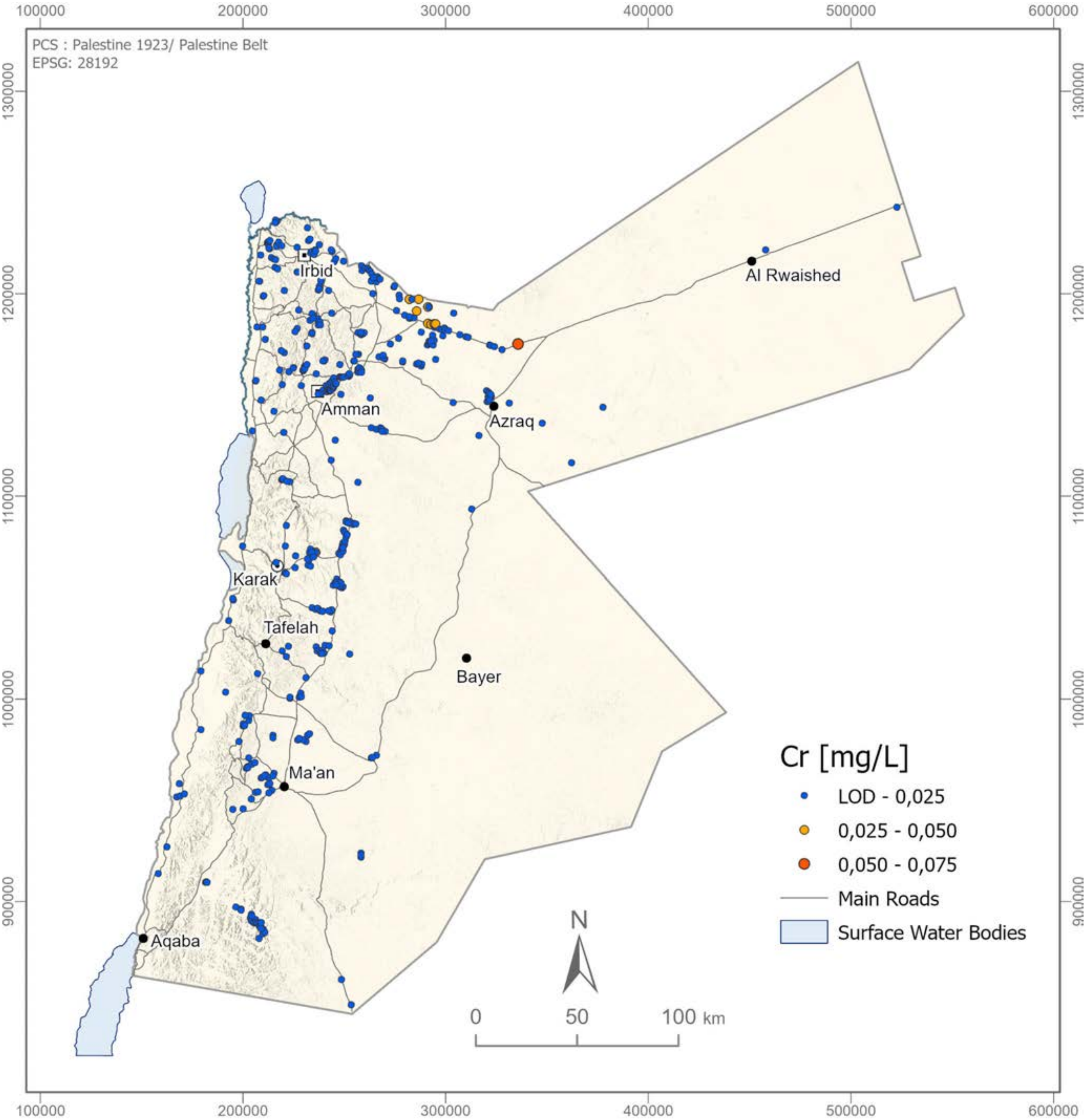
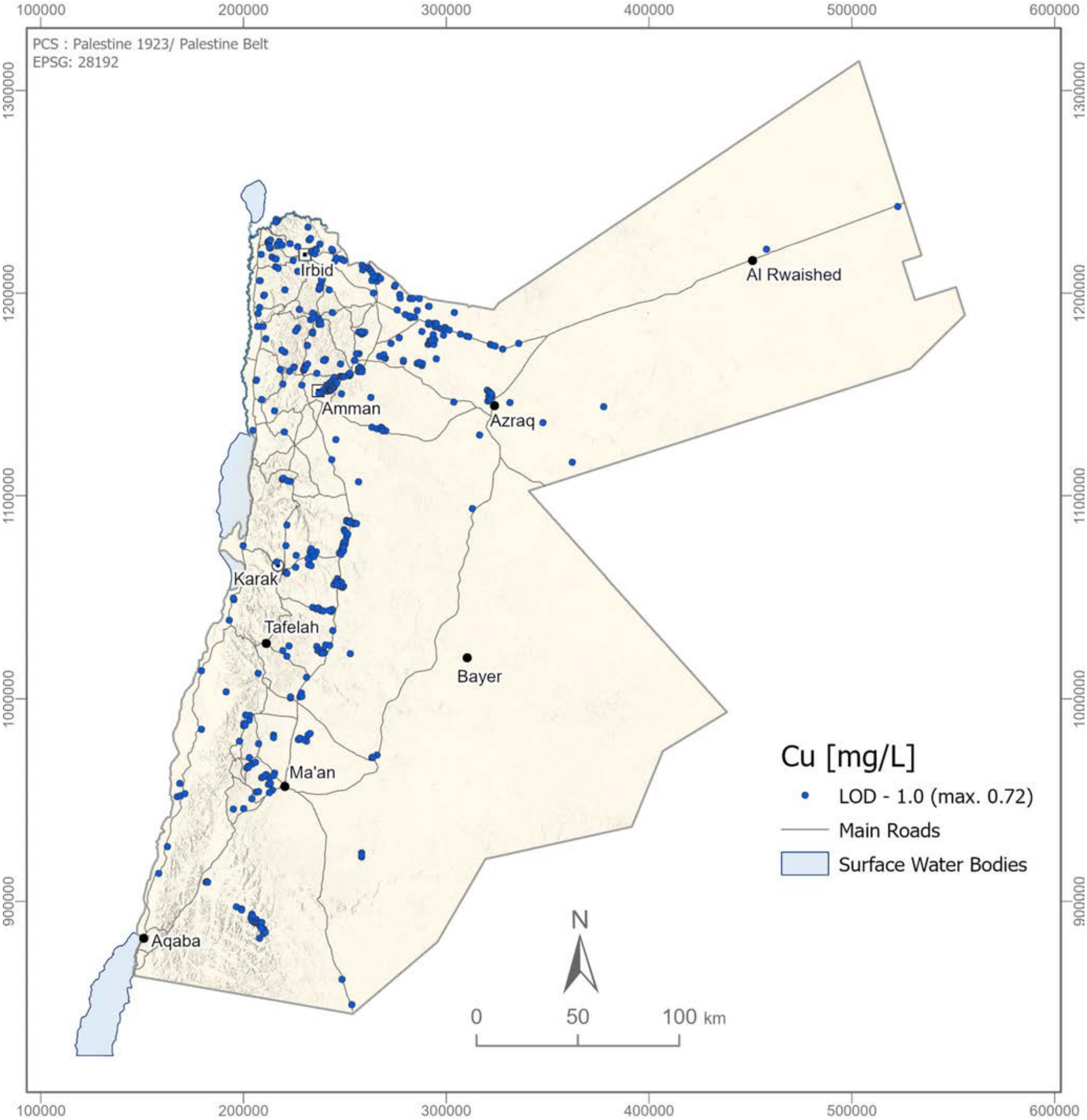
200000
300000
400000
500000
600000
1300000
1200000
1100000
1000000
900000
Irbid
Amman
Azraq
Al Rwaished
Karak
Tafelah
Bayer
Ma'an
Aqaba
Cd [mg/L]
LOD - 0,0015
0,0015 - 0,0020
Main Roads
Surface Water Bodies
N
0
50
100 km


100000
200000
300000
400000
500000
600000
1300000
1200000
1100000
1000000
900000
PCS : Palestine 1923/ Palestine Belt
EPSG: 28192
Irbid
Amman
Azraq
Al Rwaished
Karak
Tafelah
Bayer
Ma'an
Aqaba
Cr [mg/L]
● LOD - 0,025
● 0,025 - 0,050
● 0,050 - 0,075
Main Roads
Surface Water Bodies
N
0
50
100 km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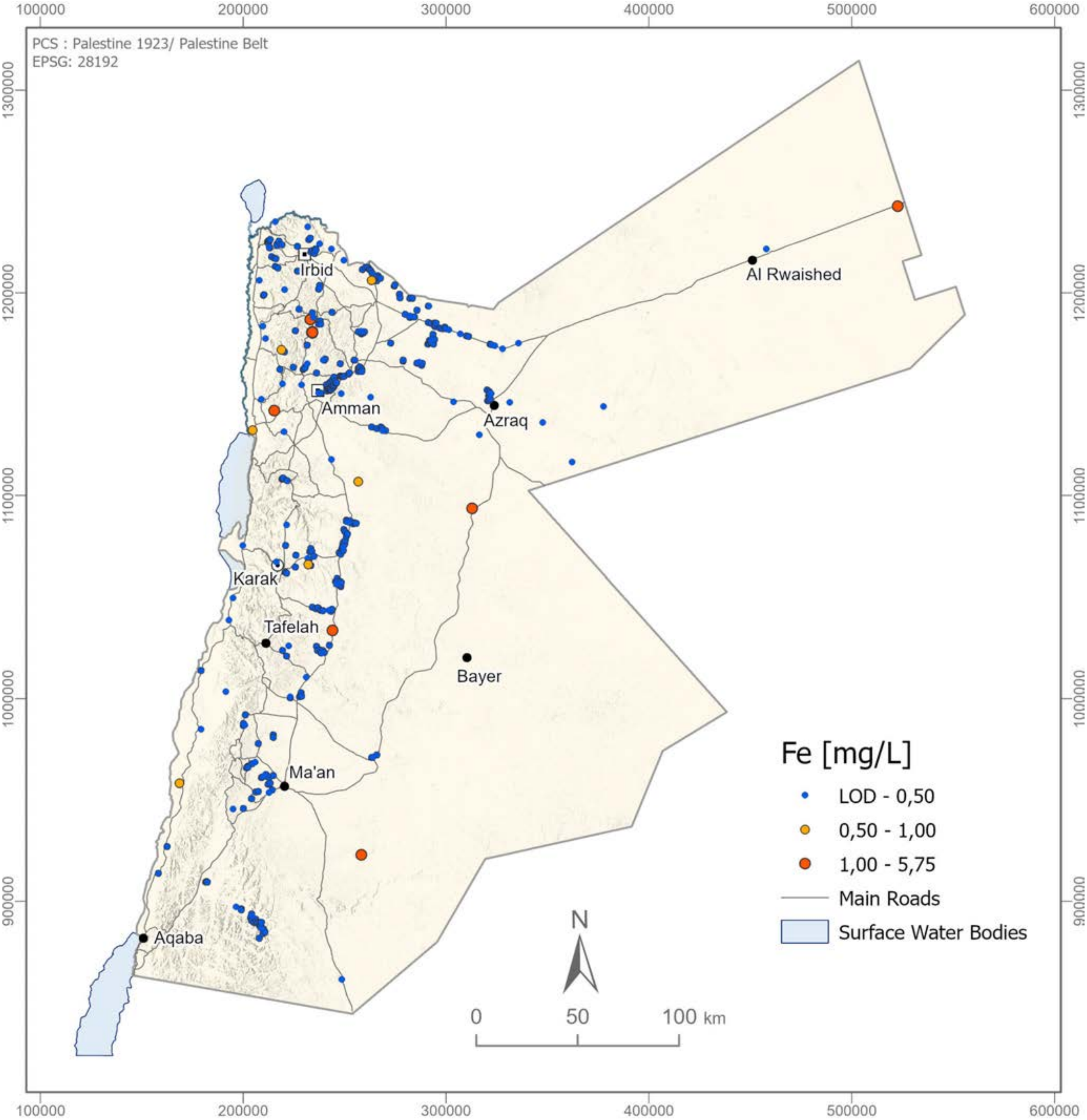
200000
300000
400000
500000
600000
1300000
1200000
1100000
1000000
900000
PCS : Palestine 1923/ Palestine Belt
EPSG: 28192
Irbid
Al Rwaished
Amman
Azraq
Karak
Tafelah
Bayer
Ma'an
Aqaba
Cu [mg/L]
LOD - 1.0 (max. 0.72)
Main Roads
Surface Water Bodies
N
0
50
100 km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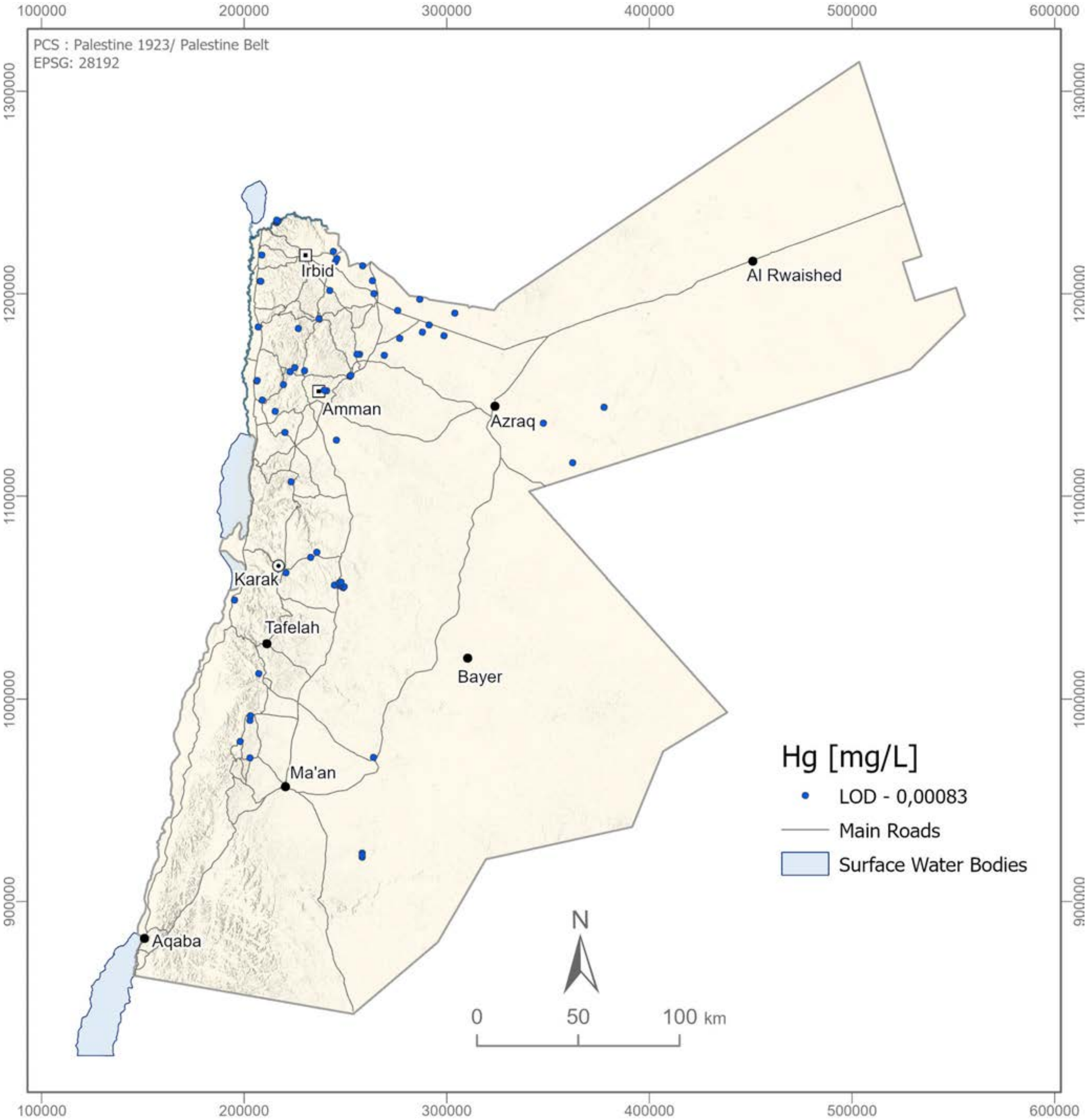
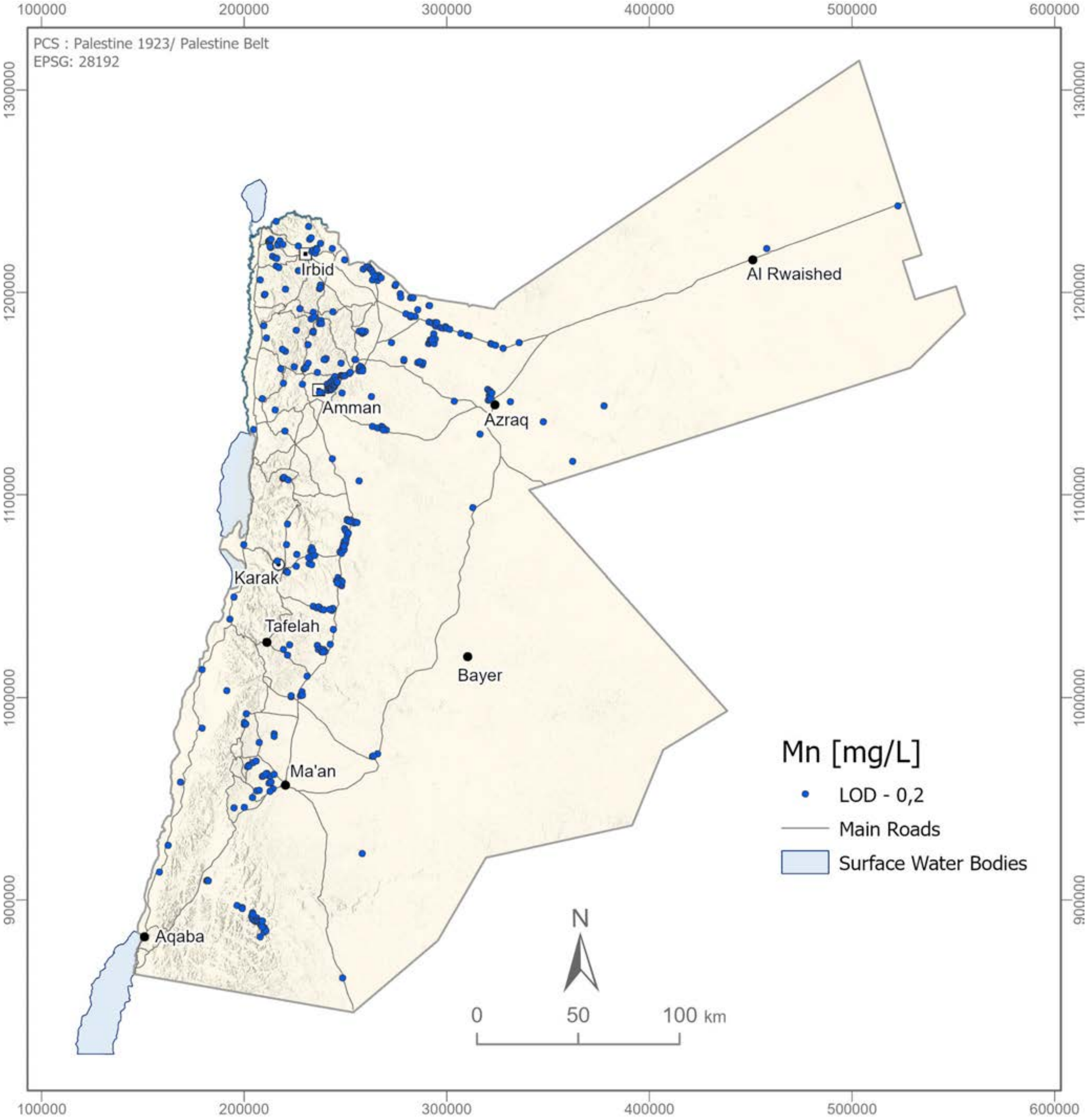
200000
300000
400000
500000
600000
1300000
1200000
1100000
1000000
900000
Irbid
Amman
Azraq
Al Rwaished
Karak
Tafelah
Bayer
Ma'an
Aqaba
Fe [mg/L]
LOD - 0,50
0,50 - 1,00
1,00 - 5,75
Main Roads
Surface Water Bodies
N
0
50
100 km



100000
200000
300000
400000
500000
600000
1300000
1200000
1100000
1000000
900000
PCS : Palestine 1923/ Palestine Belt
EPSG: 28192
Irbid
Al Rwaished
Amman
Azraq
Karak
Tafelah
Bayer
Ma'an
Aqaba
Hg [mg/L]
LOD - 0,00083
Main Roads
Surface Water Bodies
N
0
50
100 km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500000
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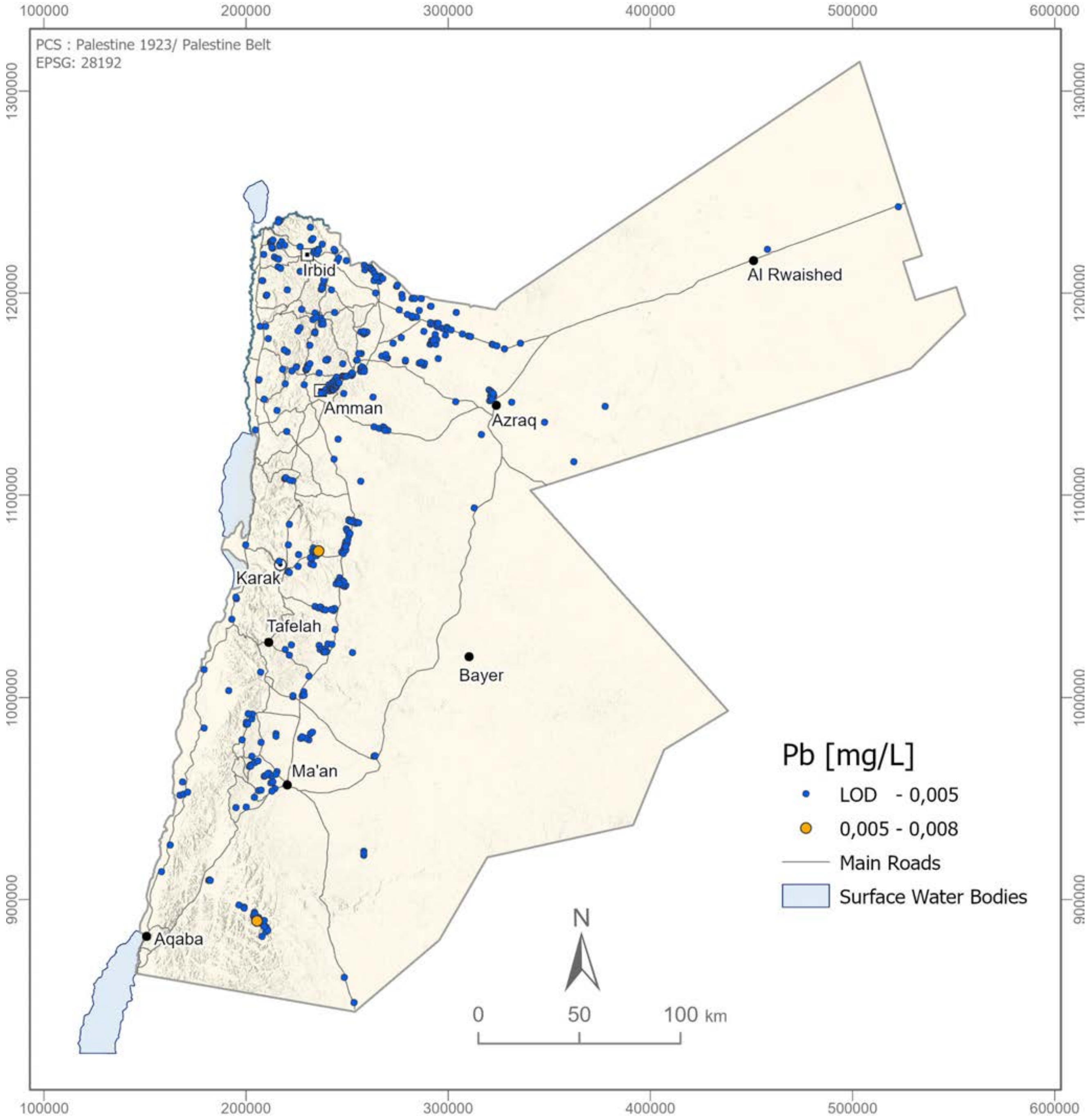
1300000
1200000
1100000
1000000
900000
PCS : Palestine 1923/ Palestine Belt
EPSG: 28192
Irbid
Al Rwaished
Amman
Azraq
Karak
Tafelah
Bayer
Ma'an
Aqaba
Mn [mg/L]
● LOD - 0,2
Main Roads
Surface Water Bodies
N
0
50
100 km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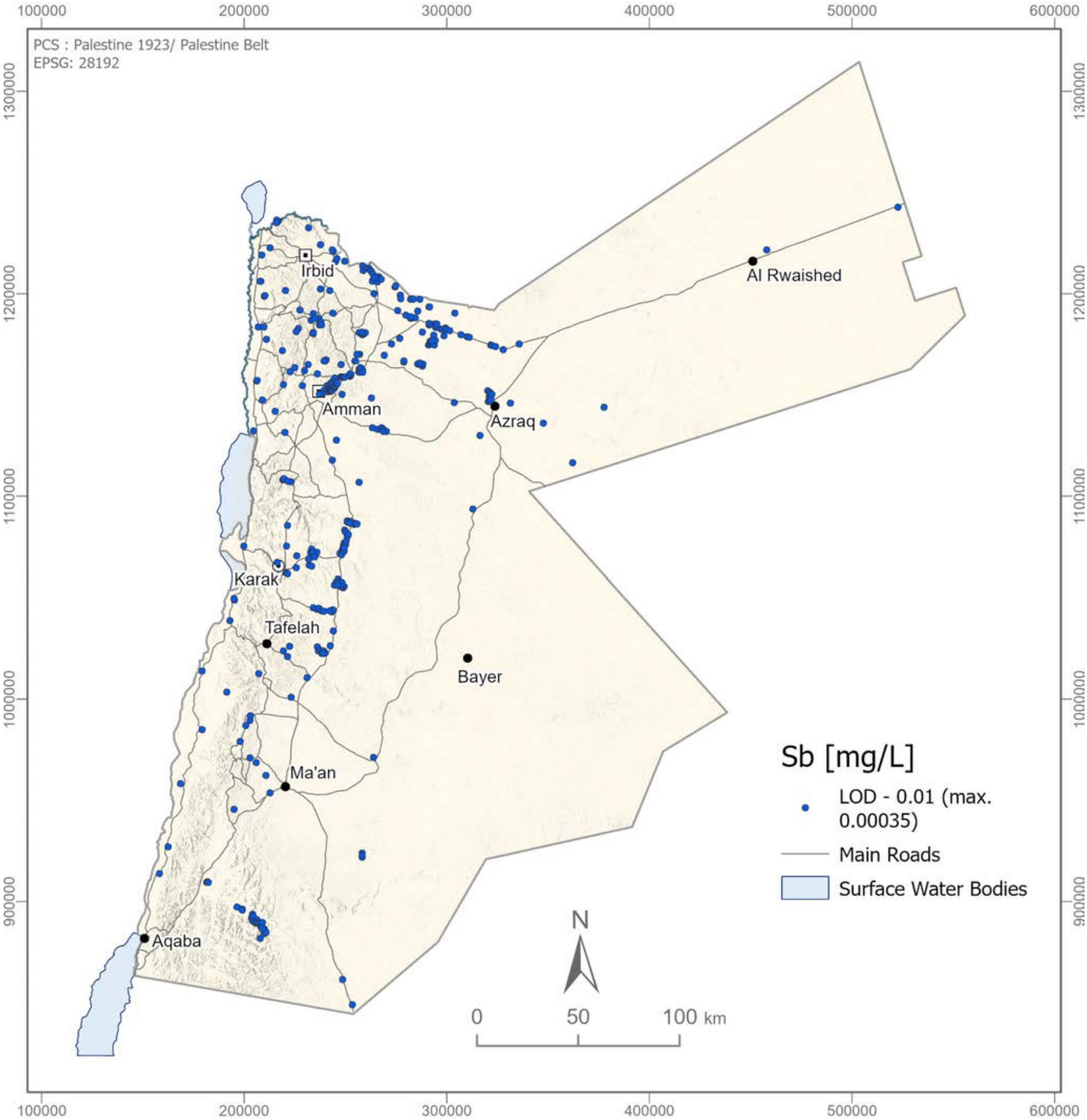
900000
PCS : Palestine 1923/ Palestine Belt
EPSG: 28192
Irbid
Al Rwaished
Amman
Azraq
Karak
Tafelah
Bayer
Ma'an
Aqaba
Pb [mg/L]
● LOD - 0,005
● 0,005 - 0,008
Main Roads
Surface Water Bodies
N
0
50
100 km


100000
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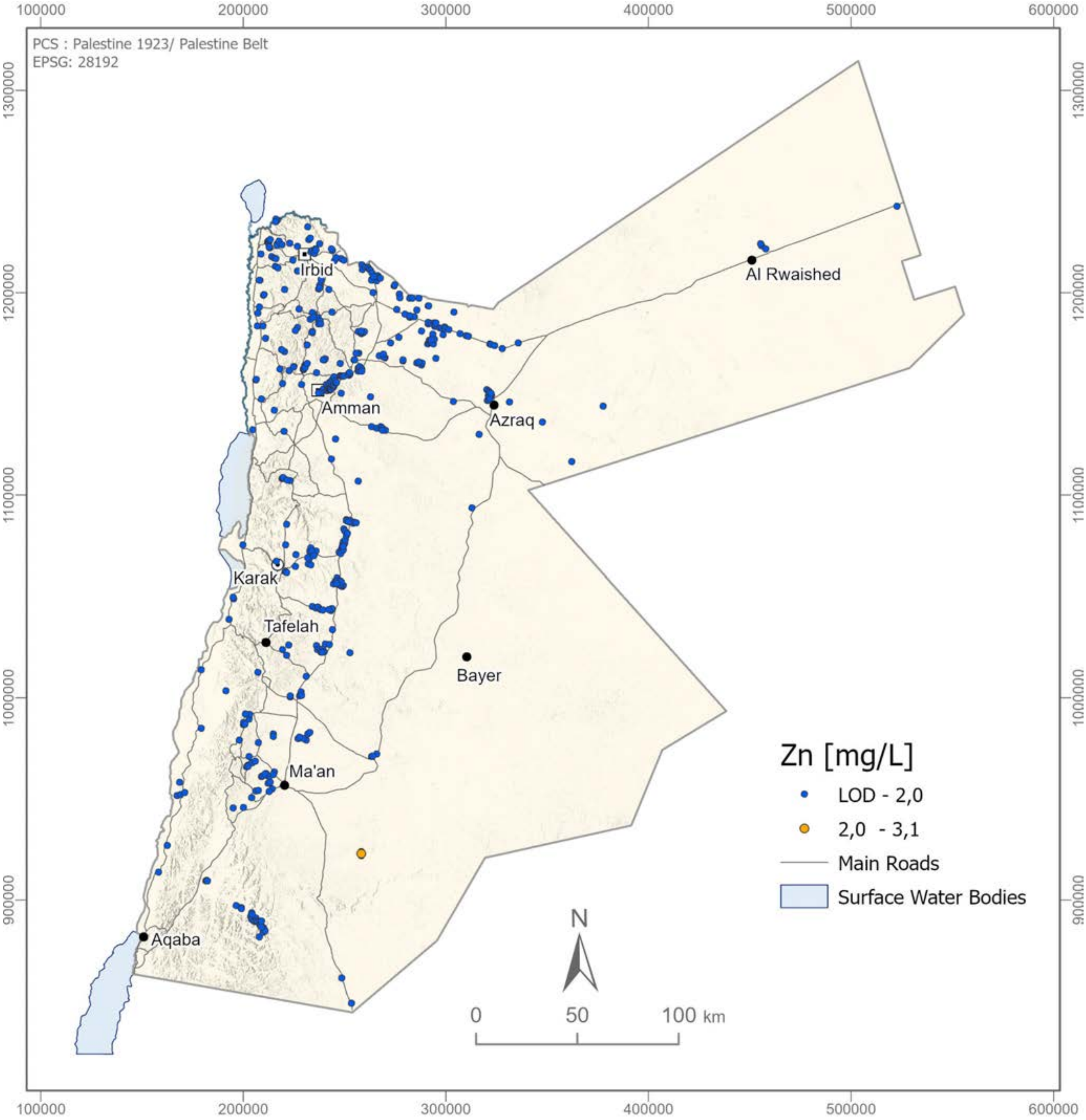
1300000
1200000
1100000
1000000
900000
PCS : Palestine 1923/ Palestine Belt
EPSG: 28192
Irbid
Al Rwaished
Amman
Azraq
Karak
Tafelah
Bayer
Ma'an
Aqaba
Sb [mg/L]
LOD - 0.01 (max. 0.00035)
Main Roads
Surface Water Bodies
N
0
50
100 km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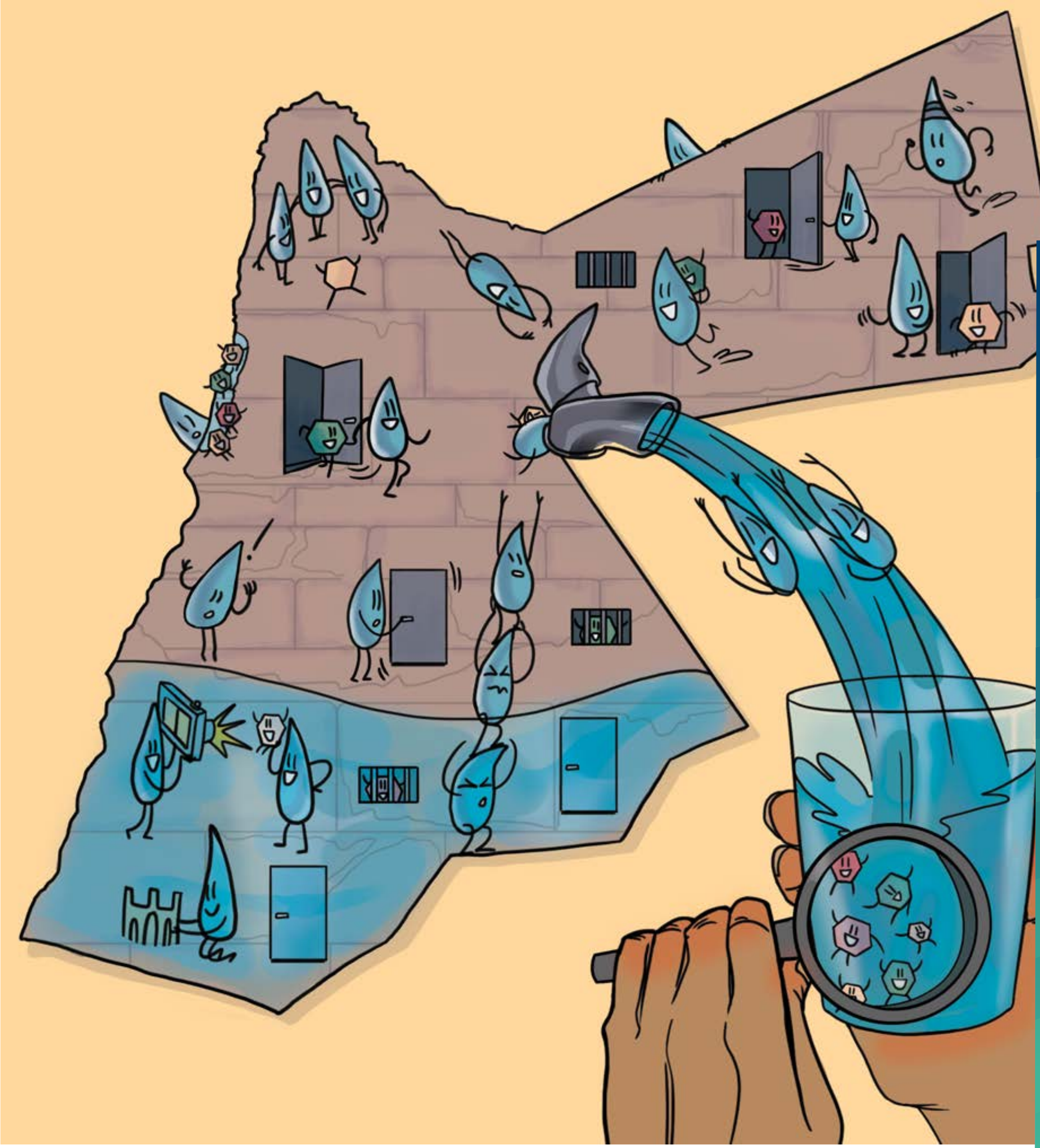
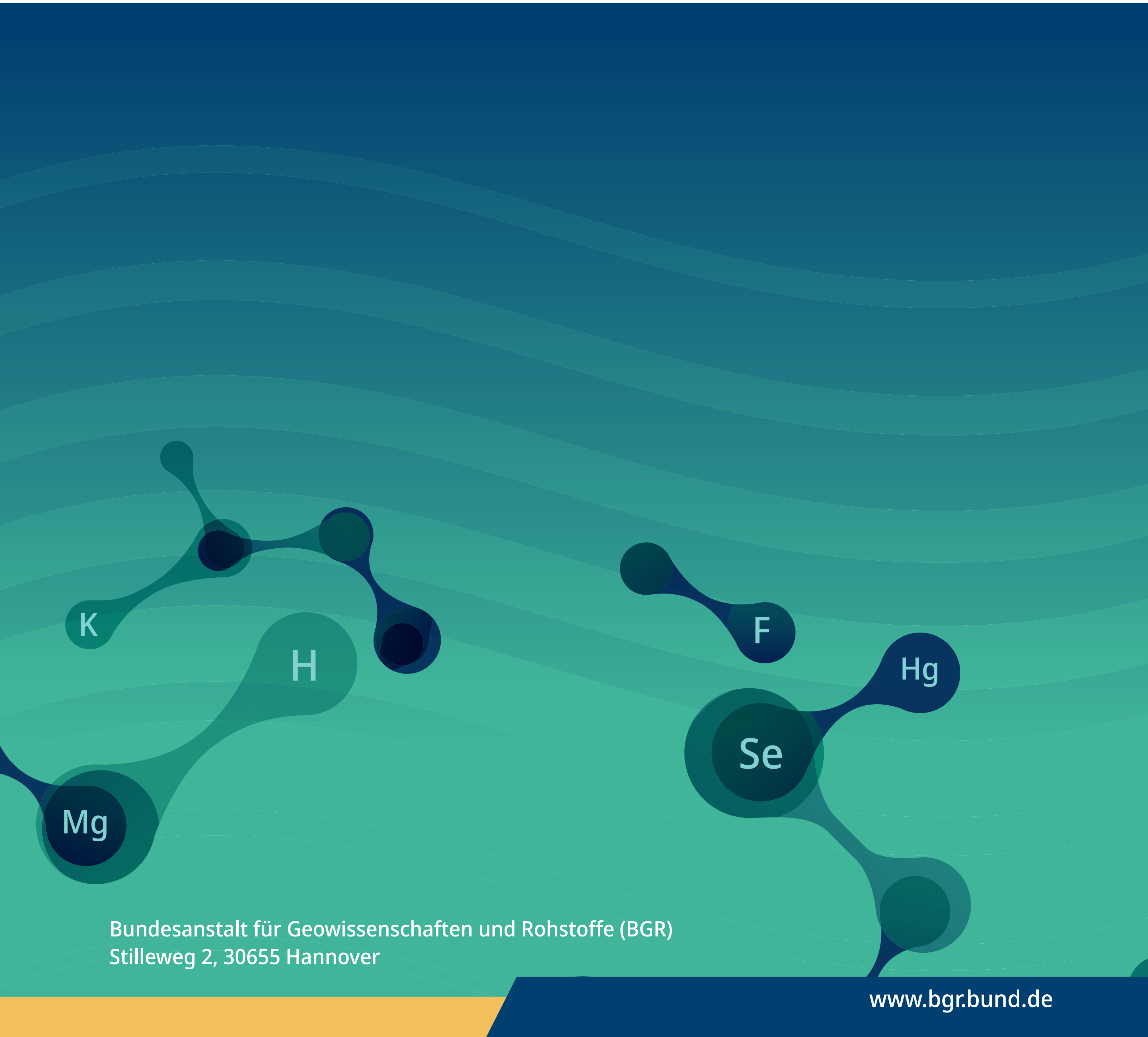
500000
600000
1300000
1200000
1100000
1000000
900000
Irbid
Amman
Azraq
Al Rwaished
Karak
Tafelah
Bayer
Ma'an
Aqaba
Zn [mg/L]
● LOD - 2,0
● 2,0 - 3,1
Main Roads
Surface Water Bodies
N
0
50
100 km





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Stilleweg 2, 30655 Hannover

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