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Conceptual modelling of land cover change effects on groundwater quality in the Amman-Zarqa Basin, Jordan

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Abstract: The Amman-Zarqa Basin, a critical groundwater resource in Jordan, has experienced substantial land cover changes over recent decades due to accelerated urbanisation, industrial development, and agricultural intensification. This study assesses the effects of these changes on groundwater quality by employing an integrated methodological framework that combines Geographic Information Systems (GIS), remote sensing (RS), and conceptual hydrogeochemical modelling. Multitemporal satellite imagery (2002–2022) was analysed to detect land cover transformations using supervised classification techniques and change detection algorithms. Groundwater quality data, collected from monitoring wells across the basin over the same period, were subjected to hydrochemical analysis, including the evaluation of major ions and trace metals. Spatial overlays were used to correlate groundwater quality trends with specific land cover changes, identifying pollution hotspots and vulnerable zones. Hydrogeochemical characterisation was performed using Piper, Durov, Wilcox, and Schoeller diagrams to classify water types and assess its suitability for various uses. Results indicate a marked deterioration in groundwater quality, particularly increased concentrations of total dissolved solids (TDS), chloride, sulphate, and heavy metals such as chromium, lead, and manganese–especially near industrial and agricultural zones. The methodology proved effective in capturing both spatial and temporal dynamics of groundwater degradation. The integration of GIS and RS tools with long-term hydrochemical data provided a robust framework for understanding the interactions between land use change and groundwater quality. These findings emphasise the urgent need for implementing sustainable land and water management strategies to protect the Amman-Zarqa Basin from further environmental stress and ensure long-term water security.

Keywords: deterioration, groundwater quality, heavy metal, hydrochemical assessment, land cover changes

INTRODUCTION

As Jordan's population continues to grow rapidly, exceeding 10 mln people by 2021 (Khatatbeh *et al.*, 2021). This growing demand and limited water resources make the basin an essential groundwater source for agricultural, industrial, and domestic purposes. Moreover, the Amman Zarqa basin serves as a critical source of groundwater, which is essential for agricultural, industrial, and domestic purposes. Groundwater extraction from this basin accounts for a substantial portion of Jordan's total water supply, particularly in light of limited surface water resources and unreliable rainfall patterns (Mohammad *et al.*, 2018; Shatanawi *et al.*, 2022; Mohammad and Odeh, 2024). Furthermore, the basin's geographical location within the arid and semi-arid regions of Jordan accentuates its importance. In these water-stressed environments, effective management of groundwater resources is paramount for ensuring the sustainability of ecosystems, safeguarding agricultural productivity, and meeting the needs of urban populations (Haddadin (ed.), 2006; Mohammad and Odeh, 2016).

Thus, understanding the dynamics of land cover changes and their impact on groundwater quality in the Amman Zarqa basin is crucial for implementing sustainable water management strategies and has not been sufficiently elucidated. Geospatial analysis of land use and land cover (LULC) changes is crucial for understanding the dynamics of urban development and its impacts on the environment (El-Naqa and Ibrahim, 2001; Odeh *et al.*, 2022; Mohammad and Odeh, 2024; Dai *et al.*, 2025). Hence, the aim of this study is to examine the impacts of changing land cover dynamics on groundwater quality, aiming to guide the formulation of sustainable water management approaches. An integrated approach combining Geographic Information Systems (GIS) and remote sensing (RS) will be employed to analyse the spatial distribution of groundwater quality (Kaushik *et al.*, 2019). Additionally, a conceptual modelling framework will be presented to provide a clearer understanding of the processes influencing groundwater quality deterioration, integrating key hydrological, geological, and anthropogenic factors. This model will help illustrate the cause-and-effect relationships between land cover changes and groundwater contamination. Following this analysis, customised interventions will be developed to address environmental degradation and enhance the long-term resilience of the basin. However, developing a numerical hydrochemical model requires extensive and high-quality datasets to accurately simulate groundwater flow and contaminant transport (Naz *et al.*, 2024; Chowdhury *et al.*, 2025).

MATERIALS AND METHODS

MATERIALS

The Amman Zarqa basin, situated in the heart of Jordan (Fig. 1), characterised by a diverse array of geographical features, topography, and geological formations that significantly influence its hydrological characteristics and ecological importance (Bender, 1975). This basin spans an area encompassing Amman's capital city and Zarqa's industrial city, forming a crucial socio-economic centre for the country. Geographically, the basin is nestled within the arid and semi-arid regions of Jordan, characterised by sparse vegetation and limited rainfall (Haddadin (ed.), 2006; Al-Omari *et al.*, 2009; Mohammad *et al.*, 2024). The basin's landscape is shaped by various landforms, such as undulating plains, hills, and valleys, which contribute to its hydrological complexity and influence water distribution patterns. Topographically, the Amman Zarqa basin exhibits a varied terrain, with elevations ranging from low-lying areas to moderately elevated plateaus (Mohammad and Odeh, 2016; Odeh *et al.*, 2023; Odeh *et al.*, 2024). The basin's topography plays a significant role in controlling surface runoff, groundwater recharge, and the formation of hydrological networks, influencing water flow pathways and storage capacities (Shatanawi *et al.*, 2022). Geologically, the basin is underlain by diverse rock formations, including sedimentary deposits, limestone, and sandstone layers, contributing to its aquifer systems and groundwater storage capacities. These geological formations (Fig. 2) influence groundwater flow dynamics, aquifer recharge rates, and water quality parameters, shaping the hydrogeological characteristics of the basin (El-Naqa and Ibrahim, 2001). These factors collectively determine the availability, quality, and sustainability of water resources within the basin, making it a critical area for Jordan's environmental management and socio-economic development.

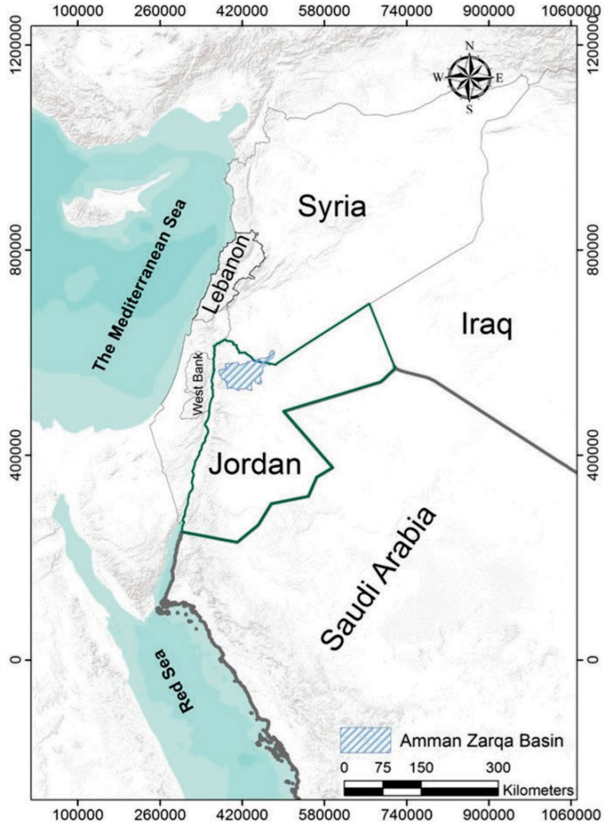

Fig. 1. Location of study area; source: data from ArcGIS Open Data Portal

The Amman Zarqa basin holds significant importance due to its pivotal role in sustaining both the environment and human populations in Jordan (Al-Omari *et al.*, 2009). This basin encompasses the capital city of Amman and the industrial city of Zarqa, making it a vital economic and social hub for the country.

METHODS

The study area comprises 25 hydrogeological points, encompassing both wells and springs, which are spatially distributed in a balanced manner, as illustrated in Figure 3. Groundwater quality data are available from government agencies, research institutions, and environmental monitoring programmes. Accessing these existing datasets can save time and resources compared to collecting and analysing new data. In this study, we obtained groundwater quality data for the samples from the Water Authority of Jordan. The chemical analysis of these samples includes a range of physico-chemical parameters, major ions, nitrate, and ortho-phosphorus concentrations. The data spans a period of 20 years, from 2002 to 2022, providing a comprehensive overview of groundwater quality trends over time.

A comprehensive Geographic Information System (GIS) database for groundwater quality samples is crucial for effective water resource management. Such a database serves as a repository for organising spatial and attribute data related to groundwater quality, enabling thorough analysis of trends and correlations with environmental factors (Kaushik *et al.*, 2019). By integrating geographic and water quality data, decision-makers can identify areas vulnerable to contamination and pinpoint pollution sources. This information is vital for develop-

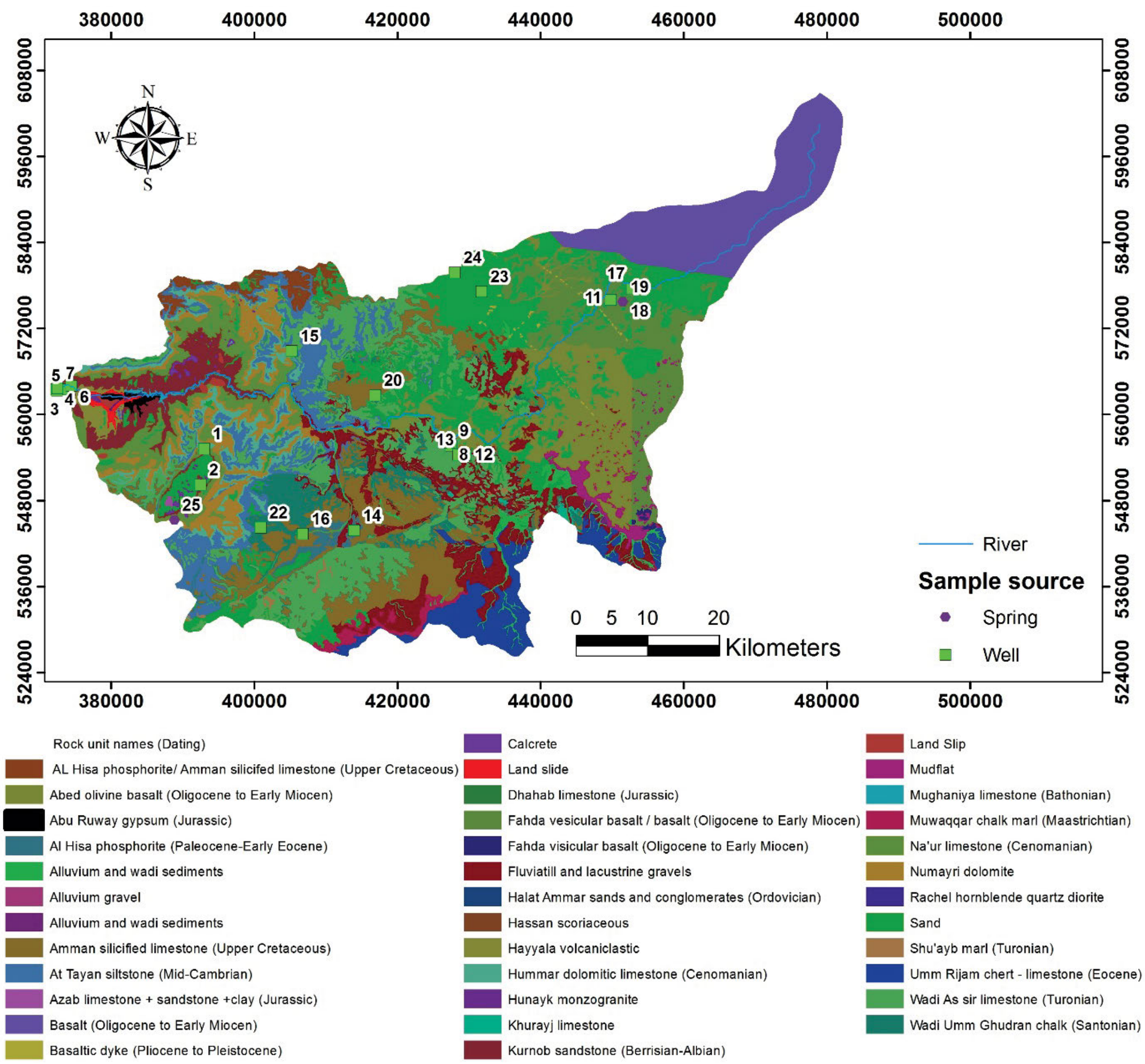

Fig. 2. The geological layers overlayed by groundwater samples; 1–25 = hydrogeological points; source: Bender (1975), modified

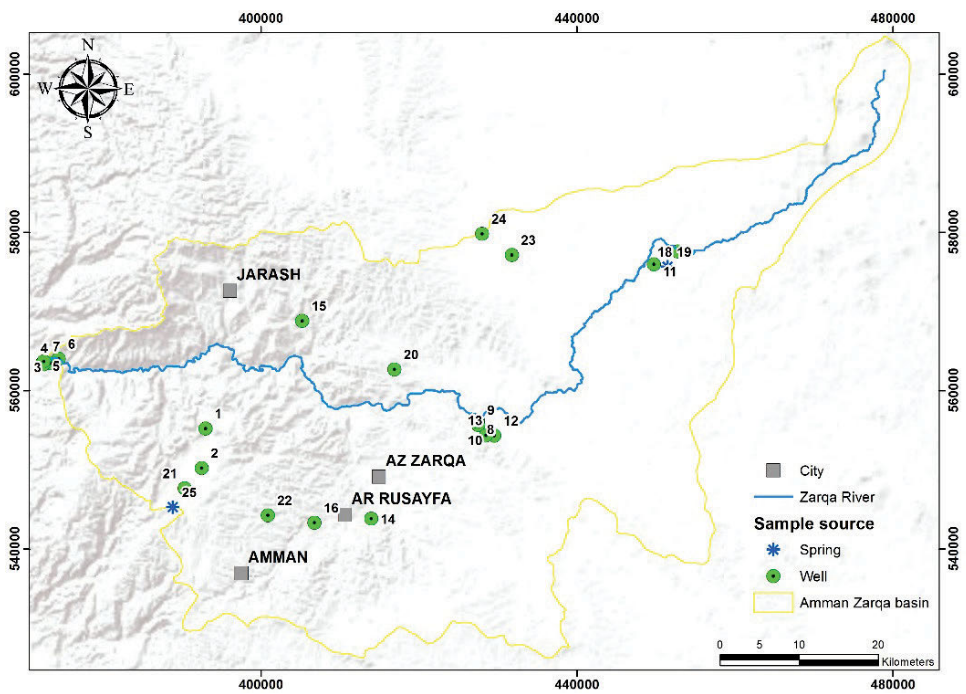

Fig. 3. Location of the groundwater samples; source: own elaboration

ing targeted remediation strategies that protect public health and preserve freshwater resources (El-Rawy *et al.*, 2024). Moreover, a robust GIS database facilitates the visualisation of spatial data, aiding in the communication of findings to stakeholders, policymakers, and the public. This promotes informed decision-making and supports sustainable water management practices (Rather *et al.*, 2022). Therefore, this study developed a geodatabase using coordinates of hydrogeological points and chemical analysis obtained from Water Authority of Jordan, processed with ArcGIS 10.3. In addition, we used an integrated approach based on remote sensing and GIS to evaluate how water quality changes as a result of land cover changes (Fig. 4). This approach allows for a thorough investigation of the spatial distribution of chemical composition changes linked to land cover alterations, providing valuable insights into the impacts of environmental changes on groundwater quality. However, overlaying is the process of combining multiple layers of spatial data to create new information or analyse relationships between different geographic features. By overlaying layers, GIS users can identify spatial patterns, detect correlations, and make informed decisions based on the relationships between different geographic phenomena (Khouni, Louhichi and Ghrabi, 2021; Rather *et al.*, 2022). For our research, the first step involved overlaying the hydrogeological points layer onto the rock unit layers with their corresponding chemical analysis data as attributes. This allowed us to evaluate the influence of the mineralogical composition of rock units on groundwater quality. In the next phase, we overlaid the hydrogeological points layer with land cover maps from different periods to investigate how changes in land cover have impacted groundwater quality. This approach enabled us to assess the spatial relationship between land use changes and variations in groundwater chemical composition, providing valuable insights into the effects of anthropogenic activities and natural processes on water quality over time.

Piper and Durov diagrams are essential tools in hydrogeochemistry for visualising the chemical composition of groundwater and understanding its quality. Both diagrams play distinct but complementary roles in analysing groundwater samples, particularly in the context of ion concentrations and water quality degradation. These diagrams help identify the dominant hydrochemical facies or types of water present in a groundwater system. By plotting the concentrations of major ions, such as bicarbonate, chloride, sulphate, sodium, calcium, and magnesium, hydrogeochemists can classify groundwater into different categories like bicarbonate water, chloride water, sulphate water, etc. This classification contributes to under-

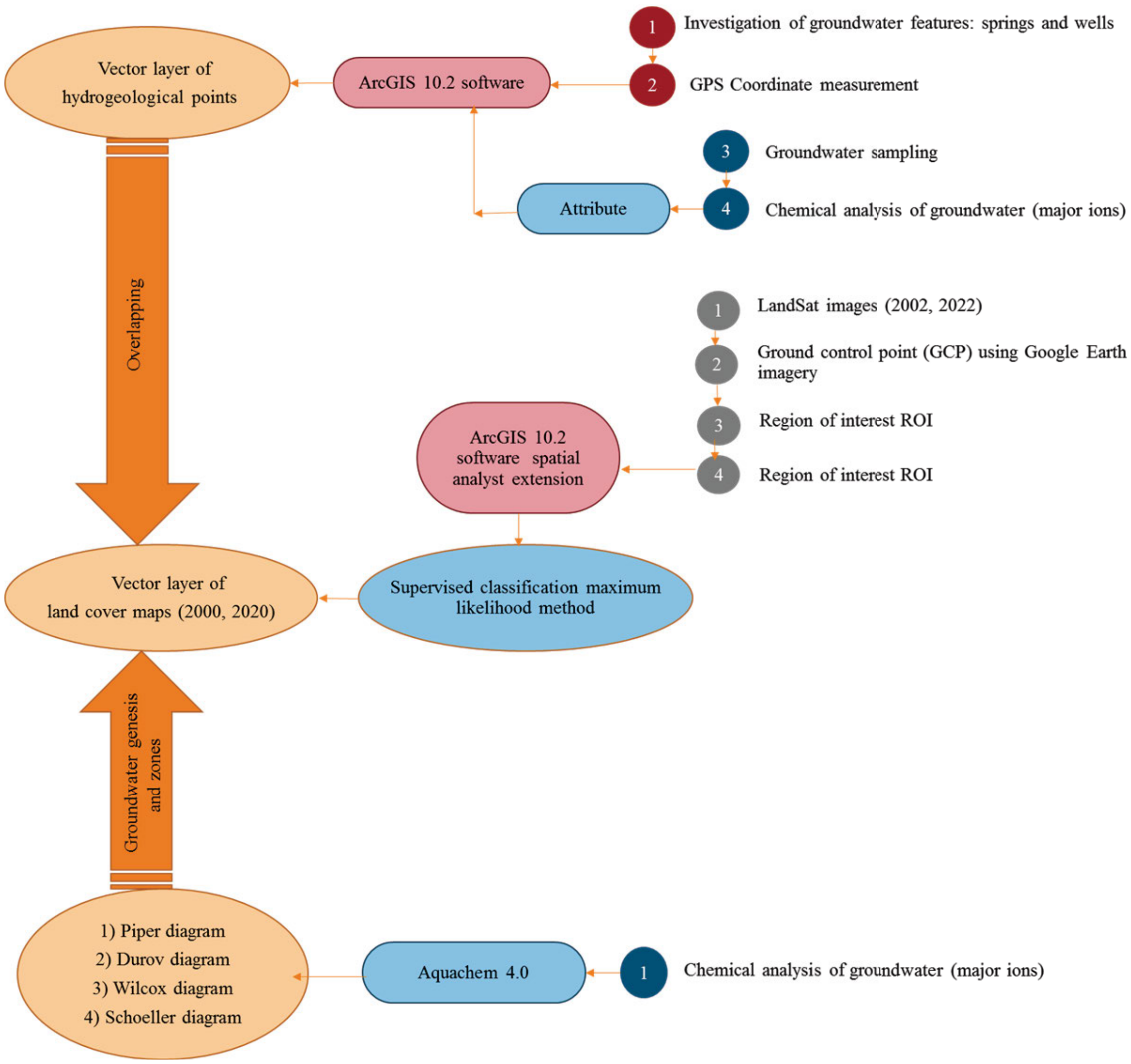

Fig. 4. The flow chart of the methodology; ROI = region of interest; source: own elaboration

standing the hydrochemical characteristics and origin of the groundwater. Therefore, we use these two diagrams to define how the groundwater chemistry changed. They were generated by Aquachem 4.0. However, this software able us to produce Wilcox and Schoeller diagrams that helped to clarify the water quality degradations. Piper and Durov diagrams are essential tools for hydrogeochemists in the classification and understanding of groundwater chemistry. When combined with Wilcox and Schoeller diagrams, they offer a comprehensive approach to assessing water quality and potential degradation. By using these tools, researchers can track changes in water chemistry, identify sources of contamination, and make informed decisions regarding water resource management and remediation strategies.

RESULTS AND DISCUSSIONS

Groundwater quality assessments are critical for understanding environmental and public health risks, particularly in regions dependent on limited water resources (El-Rawy *et al.* 2024). This section presents an overview of the chemical analysis of groundwater samples, with data from two distinct time periods: 2000 and 2020 are presented in Tables S1 and S2. However, the data obtained from the Water Authority of Jordan (WAJ) was not consistent in terms of time and location. Considerable efforts were made to organise and present data in a clear and structured manner, as sufficient and consistent data was unavailable for all hydrogeological points. The variability in data coverage posed challenges in ensuring the analysis was thorough and representative of the overall groundwater conditions. The accuracy and reliability of the chemical analysis of groundwater samples can be influenced by several factors, which may lead to discrepancies or errors in the results. These factors include sampling technique and location, contamination during collection or analysis and laboratory errors (Sundaram *et al.*, 2009). Even for those samples that are in consistency in time and locations, some discrepancies were observed when estimating the total ion balance. This introduced further uncertainties in the data. As a result, only 14 samples from each period were ultimately included in the final chemical classification after accounting for these issues. While the efforts to standardise and correct the data were extensive, these limitations highlight the challenges inherent in groundwater quality assessments and the need to consider data reliability and consistency when interpreting results carefully.

Based on the cropped rock units in the study area and the locations of the samples, the Amman-Zarqa basin was subdivided into three zones: A, B, and C (Fig. 5). Zone A was characterised by the predominance of limestone and marl, zone B was dominated by sandstone, and zone C was a mixed zone where sandstone and evaporate deposits, such as gypsum, were prevalent. The solubility of minerals in these rock formations is known to significantly influence groundwater chemistry (Elango and Kannan, 2007). To investigate the effects of land cover changes on groundwater chemistry over the past 20 years, we created Figure 6.

Additionally, Figure 7a illustrates the groundwater genesis based on the Piper diagram, showing the classification of the water samples in terms of their chemical composition. The results of this classification provide valuable insights into the geochemical processes shaping the groundwater quality in each zone as follows:

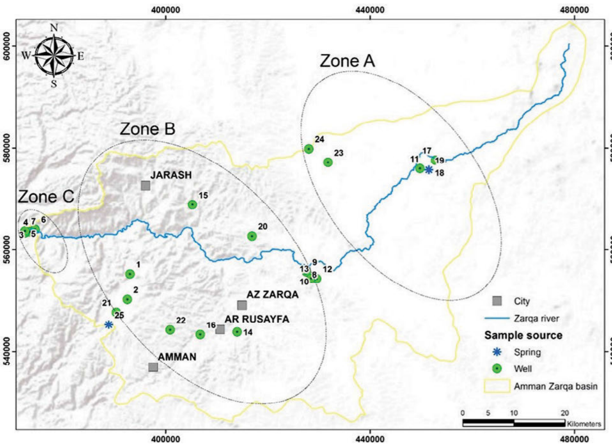

Fig. 5. Zones of groundwater samples locations; source: own study

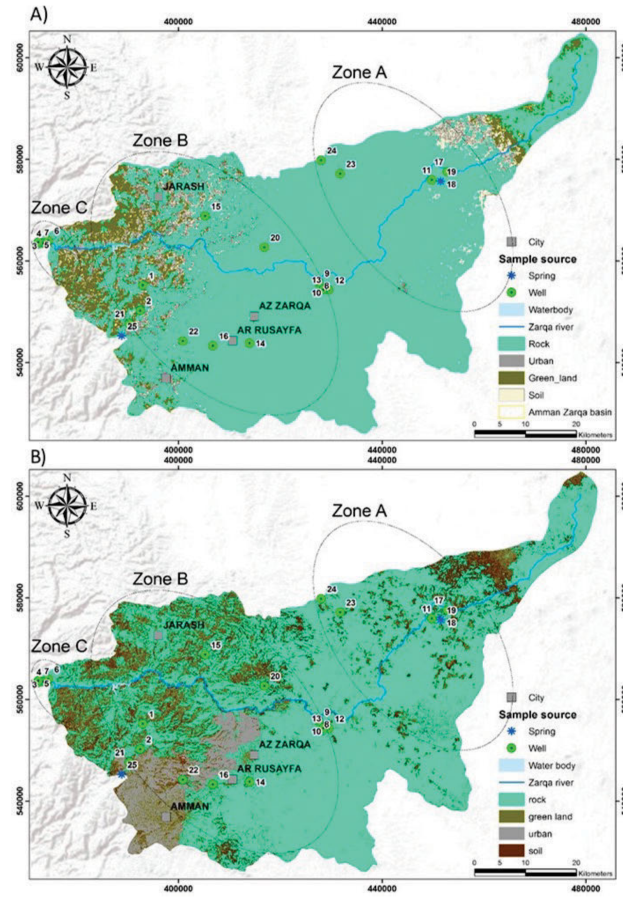

Fig. 6. Groundwater samples and landcover units in: A) 2002, B) 2022; source: own study

- Zone A: magnesium bicarbonate type as a result of the carbonate rocks mainly limestone and dolostone where the mineralogical component of calcite and dolomite generate the carbonate and magnesium by the solubility.
- Zone B: mixed type (magnesium bicarbonate type + sodium chloride type) as a result of mixing between Zone A and Zone B by faults (Odeh *et al.*, 2013).
- Zone C: sodium chloride type as a result of Halite abundant within the matrix of sandstone (Schneider, 1984).

The groundwater composition has shifted after 20 years due to land cover changes—such as groundwater over-pumping and

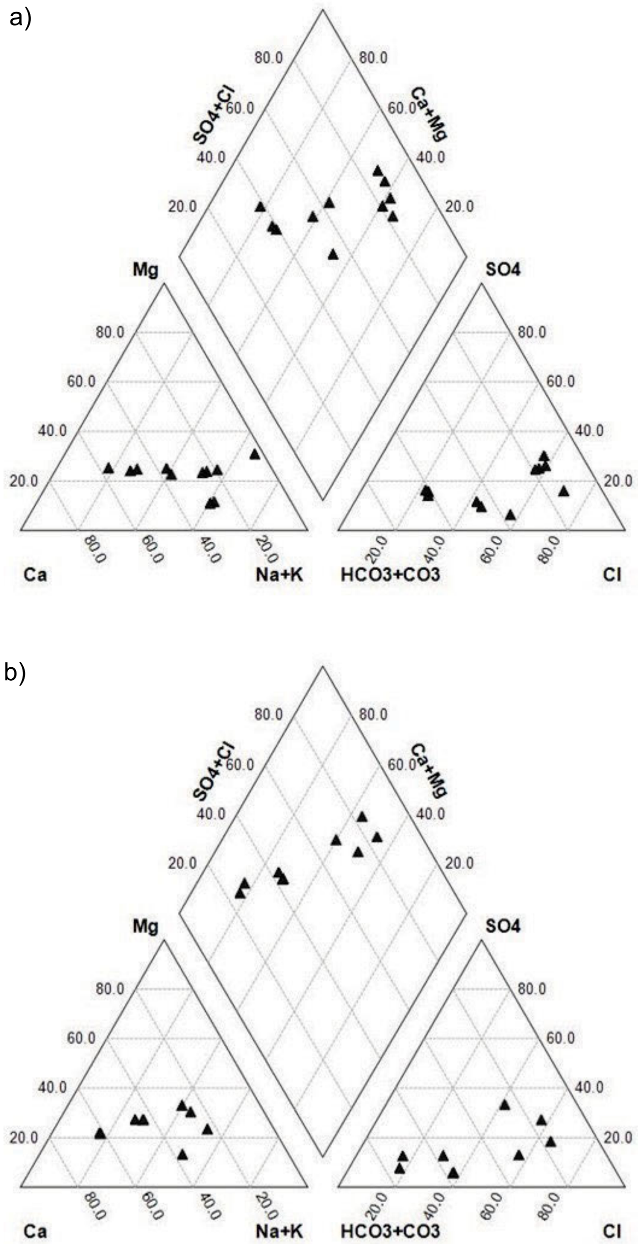

Fig. 7. Piper diagram for the chemical analysis for: a) 2002, b) 2022; source: own study

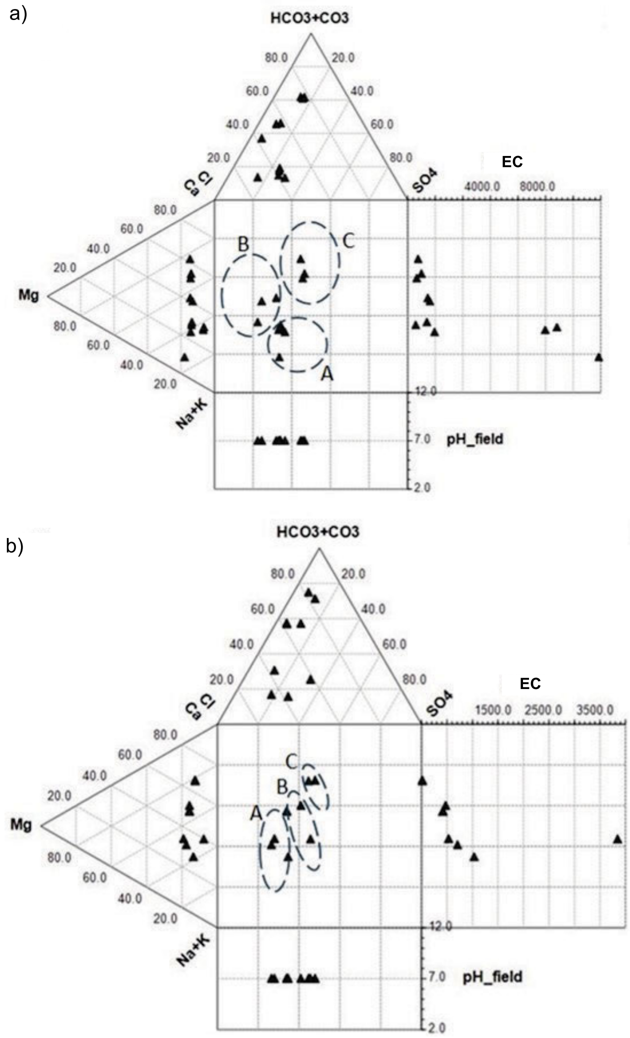

Fig. 8. Durov diagram for the chemical analysis for: a) 2002, b) 2022; *EC* = electrical conductivity; source: own study

soil salinisation caused by improper irrigation practices (Al-Omari *et al*., 2009), as illustrated in Figure 7b. This shift is characterised by an increase in total dissolved solids (TDS) and higher chloride content, indicating a deterioration in water quality over time. The data highlights the significant impact of unsustainable water management and agricultural practices on groundwater chemistry in the region.

The Durov diagram (Fig. 8) is a powerful graphical tool for analysing and interpreting the chemical composition of water samples, particularly in water-rock interactions (Elango and Kannan, 2007). It plots the concentrations of major ions (such as calcium, magnesium, sodium, potassium, bicarbonate, sulphate, and chloride) in water samples on a triangular diagram, also known as a ternary diagram. Each axis of the triangle represents the concentration of one specific ion, and the points plotted on the diagram correspond to the relative concentrations of these ions in a given water sample. Hydrochemists can gain valuable insights into the underlying geochemical processes occurring within the hydrological system by analysing the spatial distribution of points on the diagram and their relationships. These processes may include mineral weathering, ion exchange, precipitation, and evaporation, which are key factors influencing the composition and quality of groundwater and surface water. The Durov diagram thus provides essential information about the geochemical evolution of water, helping to identify sources of contamination, track changes in water chemistry over time, and assess the overall quality of water resources (Elango and Kannan, 2007; Sundaram *et al*., 2009). It is a handy tool for understanding complex hydrogeochemical systems where multiple processes influence water composition.

In the case of our study, the Durov diagram of the water samples reveals some significant trends. Notably, the diagram shows that the water samples do not exhibit any significant influence from ion substitution processes, as evidenced by their locations outside the expected straight-line patterns that would indicate ion exchange or mixing. This suggests that ion substitution does not drive the primary processes influencing water chemistry in the basin. However, the diagram also highlights a concerning trend. There has been a substantial increase in total dissolved solids (TDS) over the past 20 years, particularly in chloride and sulphate concentrations. This rapid rise in TDS indicates a growing deterioration in water quality, likely due to increased salinity, pollution, and over-extraction of groundwater. This shift in water chemistry is a critical indicator of the escalating environmental stress on the Amman-Zarqa basin's groundwater resources, underscoring the urgent need for sustainable water management practices.

The Wilcox diagram (Fig. 9) typically divides the plot into zones or categories representing different water qualities ranging from excellent to unsuitable for irrigation. This diagram represents a plot of the Sodium Absorption Ratio (*SAR*) on the *Y*-axis against Electrical Conductivity (*EC*) on the *X*-axis. According to the Wilcox diagram, water can be classified into four types based on *EC* and four types based on *SAR*. The classifications based on *EC* (or salinity hazard) are: C1 (low salinity hazard), C2 (medium salinity hazard), C3 (high salinity hazard), and C4 (very high salinity hazard); whereas the second classifications based on *SAR* (or sodium hazard) are: S1 (low sodium hazard), S2 (medium sodium hazard), S3 (high sodium hazard), and S4 (very high sodium hazard) (Wilcox, 1955; Mohammad *et al*., 2020). Water samples falling within certain zones are considered suitable for irrigation, while those falling outside these zones may require treatment or may not be suitable at all due to potential negative effects on soil structure and plant growth (Sundaram *et al*., 2009). In our case study, the Wilcox diagram clearly illustrates a concerning trend: the groundwater in the Amman-Zarqa basin has been moving toward higher salinity and sodium hazards over the years. This shift toward higher *EC* and *SAR* values signifies deteriorating water quality, which could seriously affect agricultural practices in the region. This trend is further supported by the Scholler diagram (Fig. 10), which shows a rapid increase in the concentration of sodium and chloride over the past 20 years, particularly on a logarithmic scale. The data highlights a growing salinity problem in the groundwater, emphasising the urgency of addressing these water quality issues

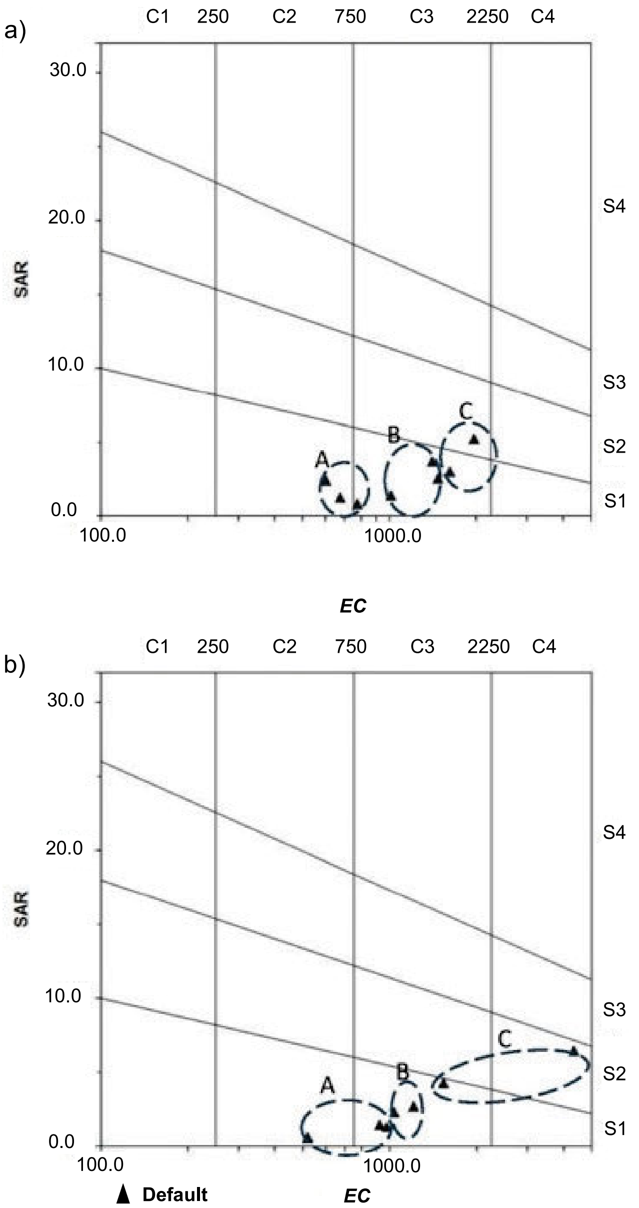

Fig. 9. Wilcox diagram for the chemical analysis for: a) 2002, b) 2022; sodium (alkali) hazard: S1 = low, S2 = medium, S3 = high, S4 = very high, salinity hazard: C1 = low, C2 = medium, C3 = high, C4 = very high, *SAR* = sodium absorption ratio, *EC* = electrical conductivity; source: own study

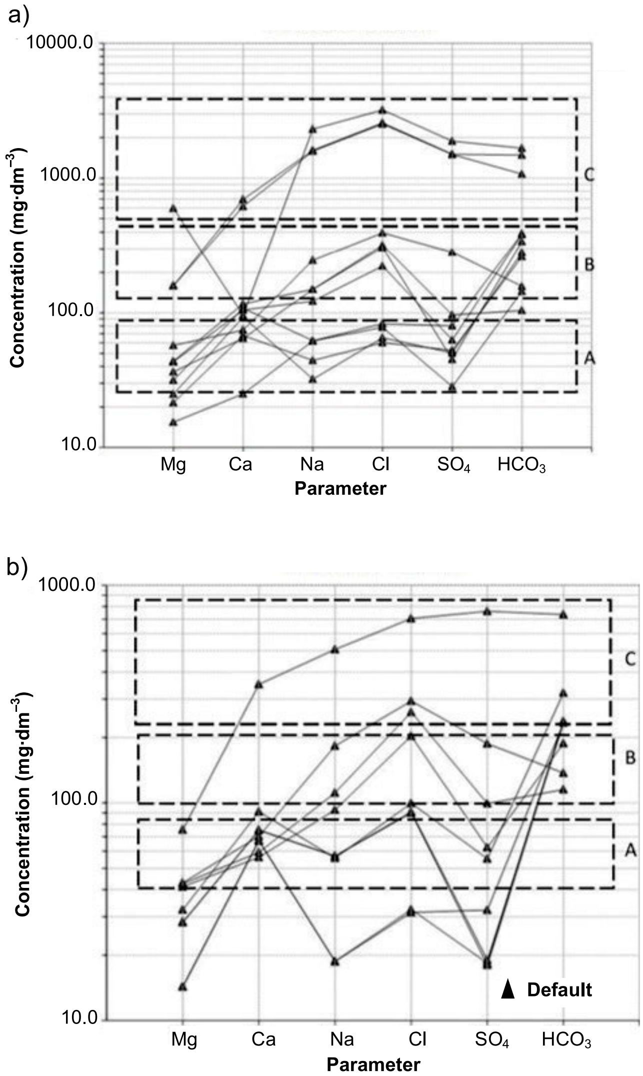

Fig. 10. Schoeller diagram for the chemical analysis for: a) 2002, b) 2022; A, B, C = zones described in page 223; source: own study

to safeguard irrigation practices and long-term agricultural sustainability in the basin.

Over the past 15 years, in the study area, the availability of chemical analysis for trace elements has unfortunately been inconsistent. However, data for vital heavy metals, including chromium, lead, manganese, nickel and copper shows good spatial coverage (Tabs. S3 and S4). As a result, these elements were selected to evaluate groundwater deterioration in terms of contamination by heavy metals. We found a significant increase in the concentrations of these heavy metals over the past 15 years, particularly in zones B and C (Fig. 11). These zones are characterised by point sources of pollution, such as food

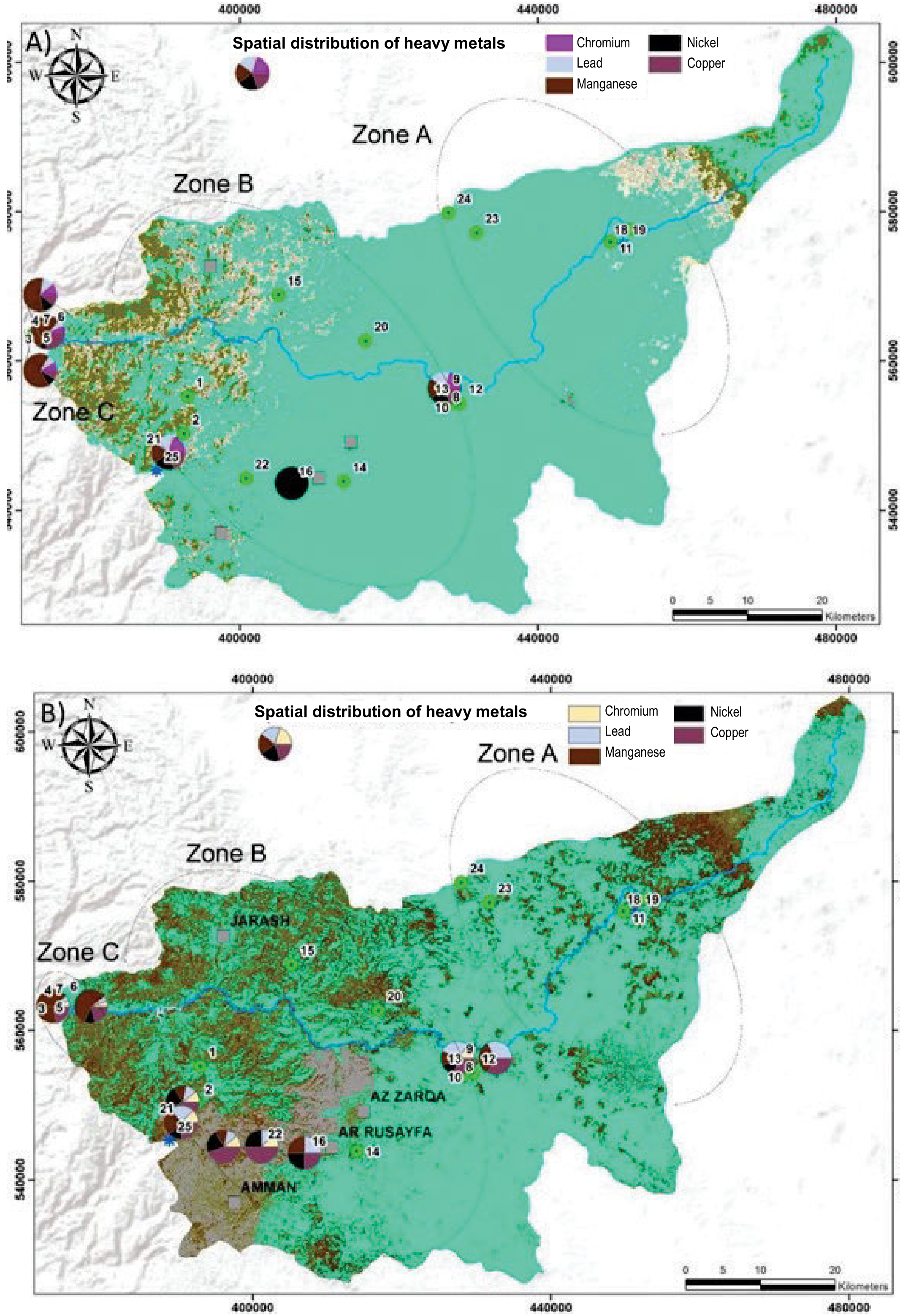

Fig. 11. Type of heavy metals in selected well water samples from: A) 2002, B) 2022; 1–25 = sampling points, A, B, and C = zones described in page 223; source: own study

processing and construction factories, and non-point source pollution resulting from agricultural activities. The concentration growth of these metals is not uniform across the study area, with chromium, lead, and manganese emerging as the dominant contaminants (Fig. 12). This uneven distribution suggests that specific industrial and agricultural practices may contribute disproportionately to groundwater contamination in these zones. The varying trends in the concentration of each metal also indicate the need for further hydrochemical and environmental research to enhance the understanding of underlying causes of this deterioration. A more in-depth investigation into the sources, transport mechanisms, and long-term trends of heavy metal contamination is crucial for developing effective strategies to mitigate groundwater pollution and protect public health and the environment.

A conceptual model illustrating the impact of industrial expansion and agricultural development on groundwater quality deterioration is presented in Figure 13. The figure highlights how rapid population growth, reaching up to 3.6% in the Amman-Zarqa Basin, has driven the expansion of industrial sites and agricultural activities, both of which contribute to groundwater contamination. The increased number of industrial facilities has led to the proliferation of cesspools, which serve as point sources for pollutants such as heavy metals and nitrates. Simultaneously, the expansion of agricultural lands translates into more intensive application of fertilisers and pesticides, generating widespread non-point source of contamination for groundwater with similar pollutants. The combined impact of these two contamination sources plays a crucial role in the ongoing degradation of groundwater quality, posing significant environmental and public health challenges.

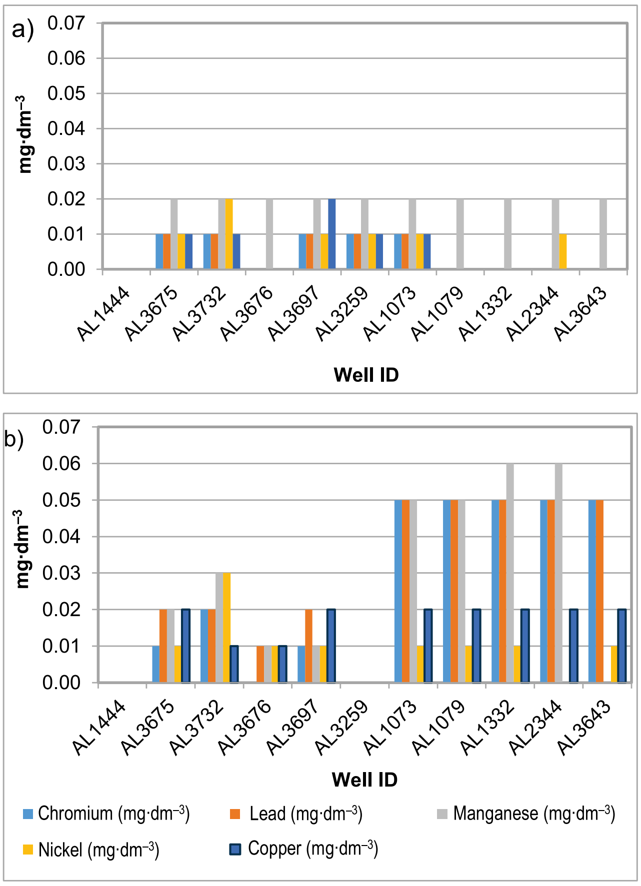

Fig. 12. Comparison of heavy metal concentrations for some well water samples collected in: A) 2002 and B) 2022; source: own study

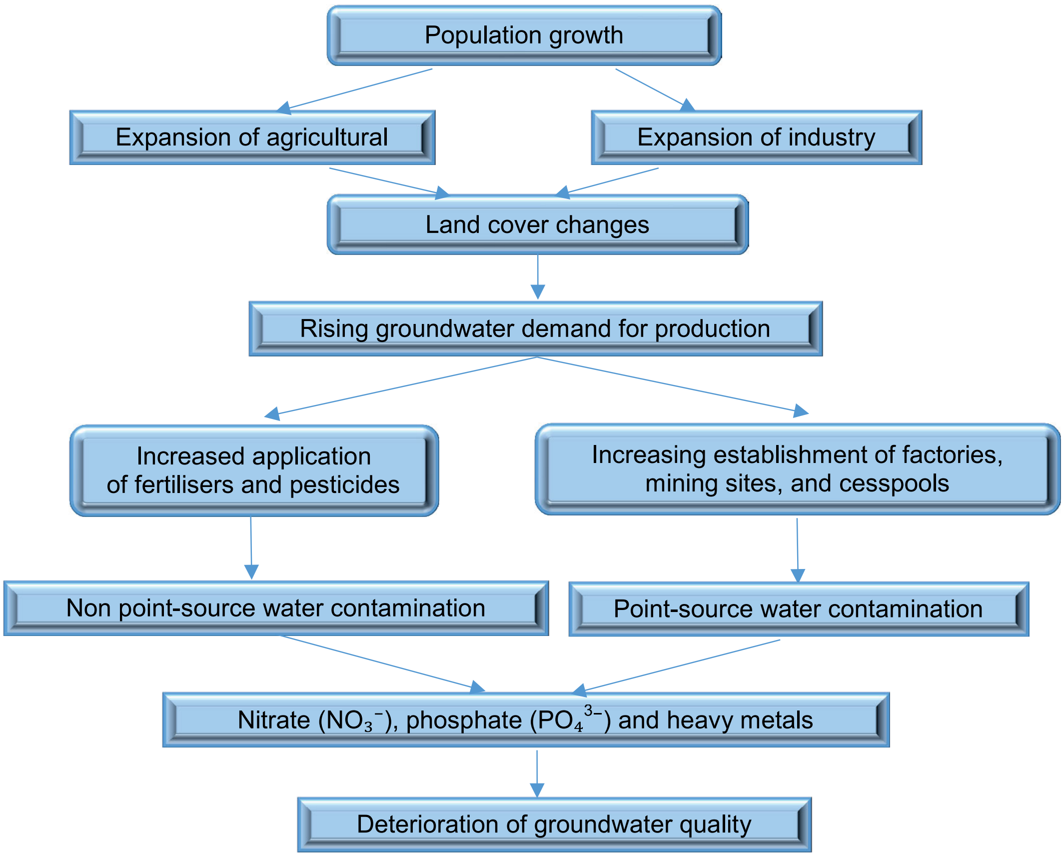

Fig. 13. Conceptual model depicting groundwater quality degradation from land cover changes; source: own study

CONCLUSIONS

Land cover changes have significantly impacted groundwater quality. The integration of GIS, remote sensing, and hydrochemical analyses provided clear evidence of water quality deterioration, particularly in areas experiencing rapid urbanisation, industrial activity, and agricultural expansion. Piper, Durov, Wilcox, and Schoeller diagrams confirm increasing salinity and contamination, with rising concentrations of TDS, chloride, and sulphate indicating both anthropogenic influences and natural geochemical processes. Spatial analysis further reinforces the link between land use changes and groundwater degradation, particularly in zones affected by industrial and agricultural runoff. There is an urgent need for sustainable water resource management. Mitigation strategies such as improved wastewater treatment, stricter regulation of industrial discharge, and controlled groundwater abstraction must be prioritised to prevent further deterioration. Additionally, environmentally sustainable agricultural practices should be adopted to minimise the impact of irrigation-induced contamination. The integration of geospatial analysis with hydrochemical techniques proves to be an effective approach for assessing groundwater in arid and semi-arid regions. The insights derived from this study offer a valuable foundation for policymakers and water resource managers in formulating targeted strategies for groundwater conservation. Future research should expand on these findings by incorporating predictive hydrochemical modelling to better evaluate long-term contamination trends and strengthen groundwater sustainability in Jordan and similar regions.

SUPPLEMENTARY MATERIAL

Supplementary material to this article can be found online at: https://www.jwld.pl/files/Supplementary_material_65_Odeh.pdf.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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