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Isotopic constraints on water source mixing, network leakage and contamination in an urban groundwater system

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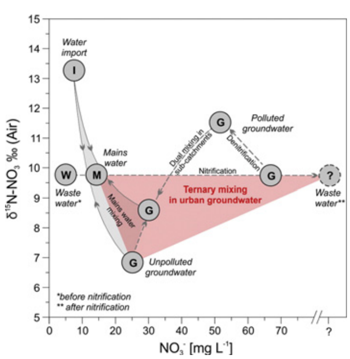
HIGHLIGHTS

- A multiple tracer approach was used to study urban water source partitioning and mixing.
- First nitrate $\delta^{15}N$ and $\delta^{18}O$ isotope data of a groundwater in Jordan are presented.
- Distinct water δD and $\delta^{18}O$ signatures allowed source identification in an urban water cycle.
- Endmember mixing calculations revealed significant contributions of city effluents to groundwater.
- Leaky networks and sewers contribute between 32% and 71% to polluted groundwater.

GRAPHICAL ABSTRACT



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ABSTRACT

Water supply in developing countries is prone to large water losses due to leaky distribution networks and defective sewers, which may affect groundwater quality and quantity in urban areas and result in complex subsurface mixing dynamics. In this study, a multi-stable isotope approach was used to investigate spatiotemporal fluctuations of surface and sub-surface water source partitioning and mixing, and to assess nitrogen (N) contamination in the urban water cycle of As-Salt, Jordan. Water import from the King Abdullah Canal (KAC), mains waters from the network, and wastewater are characterized by distinct isotopic signatures, which allowed us to quantify city effluents into the groundwater. Temporal variations in isotopic signatures of polluted groundwater are explained by seasonally fluctuating inflow, and dilution by water that originates from Lake Tiberias and enters the urban water cycle via the KAC. Isotopic analysis (N and O) and comparison between groundwater nitrate and nitrate from mains water, water imports and wastewater confirmed that septic waste from leaky sewers is the main contributor of nitrate contamination. The nitrate of strongly contaminated groundwater was characterized by highest $\delta^{15}N_{NO3}$ values (13.3 ± 1.8‰), whereas lowest $\delta^{15}N_{NO3}$ values were measured in unpolluted groundwater (6.9‰). Analogously, nitrate concentration and isotopic ratios were used for source partitioning and qualitatively confirmed δD_{H2O} and $\delta^{18}O_{H2O}$-based estimates. Dual water isotope endmember mixing calculations suggest that city effluents from leaky networks and sewers contribute 30–64% to the heavily polluted groundwater. Ternary mixing calculations including also chloride revealed that 5–18% of the polluted groundwater is wastewater. Up to two thirds of the groundwater originates from mains, indicating excessive water loss from the network, and calling for improved water supply management.

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1. Introduction

Urban water management involves multiple aspects related to water supply, wastewater treatment and water resources management (Almeida et al., 2014). Consequently, urban hydrogeology encompasses an interdisciplinary understanding of the sources, transport, distribution and mixing of water and contaminants in the context of urban growth, societal changes, and climate variability (Howard, 2007; Lerner, 2002).

Urban sprawl alters the environment, often with deteriorating effects on groundwater, both at different scales (Hibbs and Sharp, 2012). In order to safeguard against water shortages and to reduce contamination, it is crucial to control water losses in both supply and sewer networks. In this context, it is important to quantify recharge from leaky utility systems and to assess the relative contribution of individual sources and their impacts on groundwater quality (Schirmer et al., 2013). Effects of urbanization on aquifers are spatially and temporally multifaceted, rendering the identification of water sources and inputs intricate (Christian et al., 2011). Urban groundwater management requires indicators that allow the detection and tracing of man-made impacts (e.g. leakage from water pipelines, septic waste) (Strauch et al., 2007). The identification of artificial recharge processes from leaky utility systems is challenging because of its variability in time and space, often with multiple sources being involved (e.g. Barrett et al., 1999; Rutsch et al., 2006; Vazquez-Sune et al., 2010; Wolf et al., 2006).

Densely populated areas in developing countries often suffer from poor water availability and/or defective infrastructure (Armstrong, 2009; Kumar et al., 2013), causing problems that are likely to be exacerbated with increasing water scarcity in the future (Vairavamoorthy et al., 2008). Furthermore, detailed information on urban groundwater dynamics is often lacking, hampering the implementation of remediation measures.

In Jordan, freshwater supplies rely primarily on groundwater (El-Naqa and Al-Shayeb, 2009), which is a limited resource. As a consequence of political crises in the Middle East, Jordan's population has grown strongly and intensified the stress on water resources. Most of the population (9.5 million in 2016) lives in urban centers located in the mountainous northwest of Jordan, such as the cities of Amman, Zarqa and As-Salt. Groundwater from nearby mountain aquifers is an important water source for these densely populated areas.

To cope with their extensive freshwater demands, these urban centers import large amounts of surface water from the Yarmouk River and Lake Tiberias, which are transferred 110 km via the King Abdullah Canal (KAC) along the Lower Jordan Valley (LJV) (Alkhoury et al., 2010; Jiries et al., 2004) (Fig. 1A).

Numerous studies highlight increased nitrate (NO_3^-) concentrations in aquatic environments worldwide as widespread problem in urban and rural areas (e.g. Pasten-Zapata et al., 2014; Umezawa et al., 2008; Wakida and Lerner, 2005). Nitrate contamination can have a cascading set of negative consequences for aquatic environments, such as eutrophication, oxygen consumption and anoxia (e.g. Lehmann et al., 2015), and biodiversity loss. High nitrate concentrations in aquifers can lead to the deterioration of drinking water supplies. For several decades, nitrate N (and more recently O) isotopes have been used to trace nitrogen sources, including point sources (e.g., sewage plants), multipoint sources (e.g., leaky sewers), and diffuse sources (e.g., fertilizer inputs) (e.g. Aravena et al., 1993; Hale et al., 2014; Widory et al., 2005). Pinpointing the origin of N contamination is complicated, because nitrogen sources are partly not distinguishable based on their isotopic composition alone (Xue et al., 2009) (e.g. sewage and animal

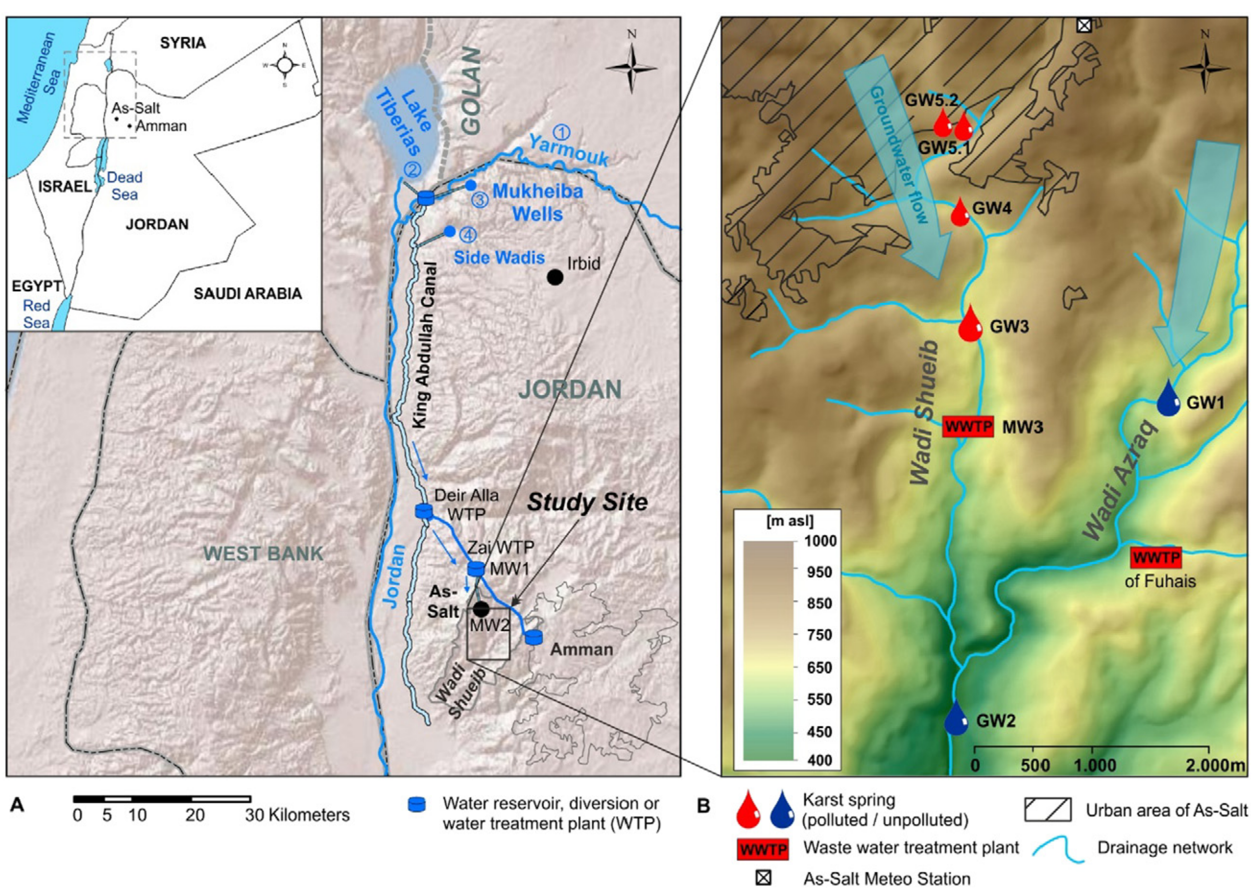

Fig. 1. Location of the study area (A) and sampling sites (B). Number 1 to 4 in (A) refer to water resources contributing to King Abdullah Canal. Abbreviations refer to groundwater sites (GW) and mixed surface water sites (MW). The karst springs GW1–2 are used for drinking water supply, and GW3–4 for irrigation. GW5.1 and 5.2 are not used.