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Weekly variations of discharge and groundwater quality caused by intermittent water supply in an urbanized karst catchment

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SUMMARY

Leaky sewerage and water distribution networks are an enormous problem throughout the world, specifically in developing countries and regions with water scarcity. Especially in many arid and semi-arid regions, intermittent water supply (IWS) is common practice to cope with water shortage. This study investigates the combined influence of urban activities, IWS and water losses on groundwater quality and discusses the implications for water management. In the city of As-Salt (Jordan), local water supply is mostly based on groundwater from the karst aquifer that underlies the city. Water is delivered to different supply zones for 24, 48 or 60 h each week with drinking water losses of around 50–60%. Fecal contamination in groundwater, mostly originating from the likewise leaky sewer system is a severe challenge for the local water supplier. In order to improve understanding of the local water cycle and contamination dynamics in the aquifer beneath the city, a down gradient spring and an observation well were chosen to identify contaminant occurrence and loads. Nitrate, *Escherichia coli*, spring discharge and the well water level were monitored for 2 years. Autocorrelation analyses of time series recorded during the dry season revealed weekly periodicity of spring discharge (45 ± 3.9 L s^{-1}) and NO_3-N concentrations (11.4 ± 0.8 mg L^{-1}) along with weekly varying *E. coli* levels partly exceeding 2.420 MPN 100 mL^{-1}. Cross-correlation analyses demonstrate a significant and inverse correlation of nitrate and discharge variations which points to a periodic dilution of contaminated groundwater by freshwater from the leaking IWS being the principal cause of the observed fluctuations. Contaminant inputs from leaking sewers appear to be rather constant. The results reveal the distinct impact of leaking clean IWS on the local groundwater and subsequently on the local water supply and therefore demonstrate the need for action regarding the mitigation of groundwater contamination and reduction of network losses from sewer leakage. Furthermore, these investigations contribute to an improved understanding of urban water cycle systems in the Middle-East which may help water managers in the region to conserve precious resources.

1. Introduction

Worldwide, water managers of urban systems face severe challenges related to inefficient infrastructure. Urban areas and the process of urbanization strongly affect groundwater recharge processes in underlying subsurface layers and the quality of local natural water resources. Anthropogenic inputs and outputs create new water qualities and quantities through complex mixing processes accompanied by temporally and spatially highly variable dynamics (Lerner, 1986, 2002; Martinez et al., 2011; Schirmer et al., 2013). Large amounts of artificial recharge are thereby generated through leaks in water supply, sewerage, and storm drainage systems. This leads to contamination by effluents on the one hand and dilution effects by high losses of drinking water on the other hand (Eiswirth et al., 2004; Rutsch et al., 2006; Wolf et al., 2004). Commonly water mains losses in developed countries range from 5% to 25%, whereas in developing countries losses greater than 30% are common (Hibbs and Sharp, 2012). However, the urban environment makes it difficult to identify individual recharge sources, pathways and processes affecting the chemical and microbiological quality (Barrett et al., 1999; Vazquez-Sune et al., 2010). Leaky sewer and distribution networks are often closely spaced. Therefore, a mobilization of contaminants originating from sewage and dilution with drinking water leaking from the water supply pipes might occur at the same time.

Developing countries typically experience water scarcity and an increasing water demand due to population growth. In particular, urban centers nowadays establish a demand-based management instead of a supply based management (Vairavamoorthy et al.,

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2008). Hence, the infrastructure of potable water and sanitation becomes an even more critical factor in the urban water cycle depending on the degree of inefficiency. In most developing countries, these circumstances have led water authorities to resort to intermittent water supplies (IWS). Here, a mostly regular, but interrupted water supply is forcing consumers to collect and store water for the non-supply hours and days (Hardoy et al., 2014; Kumar et al., 2013; McIntosh, 2003; Thompson et al., 2002).

Leaks from urban water supply systems are a major source of inefficient water infrastructure. Therefore, the IWS strategy, amongst others, is applied to reduce leakage losses. In the Middle East, the intermittent mode of water supply is an important factor contributing to the deterioration of potable water quality (Tokajian and Hashwa, 2003). Current literature on water quality of IWS has already illustrated the risk of contamination, which has many causes like supply rationing, polluted sources, leaky or poorly-functioning water storage, treatment or distribution systems (Kumpel and Nelson, 2013, 2014).

In Jordan, the sanitation systems are not sufficiently managed and provide ample potential for improvements towards sustainability. Leaky sewerage and water distribution networks are often an enormous problem. In most urban centers of Jordan, municipally-piped water is provided by a network of different distribution zones and is only intermittently available (for 12–60 h per week). Consequently, it is common practice to draw water off from the distribution system for the total duration of supply (Abu-Shams and Rabadi, 2003; Bonn, 2013; Rosenberg et al., 2008).

High population areas, such as Al Balqa or the cities of Amman or Irbid, are located in the mountains at the eastern margin of the Lower Jordan Rift Valley (LJV). Over history, these urban centers relied on groundwater from springs and shallow wells as sources of clean potable water (Suleiman, 2004). Karst aquifers dominate in these mountains in Jordan, and as well as in the Palestinian territories (West Bank) along the western margin of the LJV. A similar hydrogeology applies to Syria and Lebanon further north (Al-Charideh, 2011; Bakalowicz et al., 2008; Mimi and Assi, 2009). Regional water resources such as these have been exploited since historical times, but are nowadays often rendered unusable due to unregulated waste management (Amiel et al., 2010; Schmidt et al., 2013; Werz, 2006).

Karst aquifers are generally well known for responding rapidly to hydrological events, such as rainfall, but also to urban artificial recharge processes (Daher et al., 2011; Ford and Williams, 2007). Their focused flow and specific heterogeneity results in complex flow systems comprising dual or multiple porosities, that are characterized by a high susceptibility and vulnerability to pollution (Goldscheider, 2010; Gutierrez et al., 2014; White, 2002). Concentrated infiltration and rapid contaminant transport in the phreatic zone are characteristic, because karstified carbonates contain fast flow through conduits and enlarged fractures and slow flow components through the surrounding rock matrix (Atkinson, 1977; Schmidt et al., 2013; Toran and Reisch, 2013). This mixing of slow and fast flow components makes it difficult to determine pathways, residence times, and recharge areas. Protection of karst groundwater resources is notoriously challenging in urban settings.

In order to maintain a good groundwater quality, ambitious measures in water treatment and management have to be undertaken, such as protection zoning, reduction and fast detection of polluting activities. If practiced properly, permanent water-quality monitoring and contamination event detection is an inevitable measure for protection against pollutants and anthropogenic impacts.

This study focused on a karst aquifer contaminated with dissolved nitrate and fecal coliforms that underlies the city of As-Salt in Jordan. As-Salt had 88,900 inhabitants in 2011, and is located approximately 30 km northwest of Amman (Fig. 1a). As-Salt was founded about 300 BC and was the first capital of Jordan before Amman.

Two observations sites have been chosen for this case study. The first is a well that lies about 500 m down-gradient from the city center, and the second is Hazzir Spring that lies about 2.25 kilometers (km) down-gradient and represents resurgence from the karst aquifer. For a better understanding of the temporal variability of the contaminants, a spectrometric sensor for continuous high-resolution nitrate monitoring was installed. The nitrate sensor was combined with grab samples manually collected for fecal coliforms, including total coliforms and *Escherichia coli*. Dissolved nitrate is commonly used as an indicator for groundwater pollution (Fenech et al., 2012; Wakida and Lerner, 2005) and also frequently used as a monitoring parameter in karst studies (Huebsch et al., 2014; Katz, 2012; Panno et al., 2001).

The aim of this monitoring campaign was to improve the understanding of urban subsurface mixing processes and contamination dynamics in relation to discharge and groundwater level fluctuations. The study site can be considered as a blueprint for research into the impact of urban recharge processes controlled by leaky sewer and water distribution networks (specifically with IWS). To determine urban dilution and mobilization effects in groundwater, we considered high-resolution time series only for the dry season to avoid natural recharge impulses such as rain events. Time series of two summer seasons were studied by using correlation analyses on chemographs (spring nitrate and *E. coli*) and hydrographs (spring discharge and well water level). Correlation functions, such as autocorrelation, spectral analyses and cross-correlation, have already been applied many times to assess the relation between rainfall and discharge in karst systems (e.g. Fiorillo and Doglioni, 2010; Massei et al., 2006; Valdes et al., 2006; Zhang et al., 2013), but not for urban-influenced karst aquifers during dry periods.

2. Materials and methods

2.1. Study site

The Lower Jordan River Basin is characterized by a distinctive relief (416 m below and up to 1100 m above sea level) featuring a network of wadis distributed down the western slopes of the Transjordanian Mountains towards the LJV. Wadi Shueib is one of the sub-catchments, wherein the investigated springs' capture zone of approximately 4 km^2 is located (Fig. 1a). It lies in the upper part of the Wadi and is characterized by a rather steep valley with dense drainage network (Fig. 1b and c). The local climate is semi-arid with typical Mediterranean short rainy winter and long dry summer. Annual rainfall varies from approximately 500 to 700 mm.

Within this catchment, the city As-Salt is faced with severe water management problems due to several reasons. The water supply infrastructure is prone to high rates of losses and the average unaccounted for water (UFW) is estimated as 50–60% of the annual network supply, of which equal shares are assumed to physical and administrative losses due to metering failures (MWI and GTZ, 2004; Riepl, 2012). In As-Salt the water supply network is divided into 13 distribution zones which shift according to a weekly schedule. In each zone, water is available for 24, 48 or 60 h per week. In the area nearby the observation well and spring, the distribution network allocates five zones, that are supplied for 24 h (zone 1, 2), 48 h (zone 3, 4) and 60 h (zone 5) on different days of the week (Fig. 1d). The supply duration depends on the housing density, and no flow occurs in the distribution infrastructure