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Current research in urban hydrogeology – A review

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ABSTRACT

Urban groundwater is a heritage at risk because urban land use practises puts enormous and highly complex pressure on this resource. In this article, we review urban groundwater studies in the context of urban water management, discuss advances in hydrogeological investigation, monitoring and modelling techniques for urban areas and highlight the challenges. We present how techniques on contaminant concentration measurements, water balancing and contaminant load estimation were applied and further developed for the special requirements in urban settings. To fully understand and quantify the complex urban water systems, we need to refine these methods and combine them with sophisticated modelling approaches. Only then we will be able to sustainably manage our water resources in and around our urban areas especially in light of growing cities and global climatic change. We believe that over the next few years much more effort will be devoted to research in urban hydrogeology.

1. Introduction

Urbanisation is an emerging issue with ecological, economic and social implications. Currently half of the world's and 70% of Europe's population is living in urban areas. According to the United Nations, by 2050 these numbers are going to rise to 70% and 84%, respectively [1]. In the year 2000 urbanised areas made up 3.7% of Europe's surface. Between the years 1990 and 2000 the annual land consumption by housing, services and recreation was 50,000 ha which refers to half of the total land consumption (based on Corine land cover 1990 and 2000 for 23 European countries, http://www.eea.europe.eu/). Of course, there are positive aspects of this development such as more efficient use of land resources and more effective public transport and centralised waste treatment, reducing per capita emissions of contaminants [2]. Nevertheless, urban land use leads to enormous pressure on the environment. Aside from drastic changes in the water balance, manifold and often diffuse and poorly regulated emissions have had a negative impact on the quality of air, soil and urban water resources [2]. On one hand, this environmental stress is likely to increase with further urban growth at an unprecedented rate. On the other hand, the stress factors will change as urban areas undergo dramatic changes, like shrinking or large migration as seen in many cities in the former Eastern Bloc.

Urban water usage as well as urban water quantity and quality problems are closely linked to the city's development [3]. The different states of development can be seen in all major cities of the world [4]. Over history, settlements often relied on groundwater from springs and shallow wells as a reliable source of clean potable water. With industrialisation and an accelerated urbanisation, water demand has increased. Due to the heavy abstraction, groundwater supplies beneath cities have been declining and as a consequence of unregulated waste management, groundwater quality has become more and more degraded [5]. Cities have increasingly become importers of water from remote sources. Overexploitation of groundwater beneath urban areas, declining water levels, the resulting land subsidence and, for coastal cities, salt water intrusion, still are major concerns in many cities of the world [3,5,6]. However, over recent decades, in the developed world, abstraction volumes have been reduced and groundwater levels are rising again. Consequently, pumping has to be increasingly employed to prevent flooding of underground structures [7].

Maintaining the quality and quantity of urban water resources is recognised as a very complex task including different spatial and temporal scales. The key to understand the deterioration of urban water resources is the knowledge of the tremendous impact of urbanisation on the entire water balance (Fig. 1). The deterioration of the water balance can develop very differently in contrasting urban areas and even within heterogeneous cities. Often, surface sealing in urban areas leads to an increase of surface runoff and thus to a reduction of water infiltrating into the subsoil. On the other hand, water is imported into the urban areas by water mains and transported after usage within the sewage system. Water can

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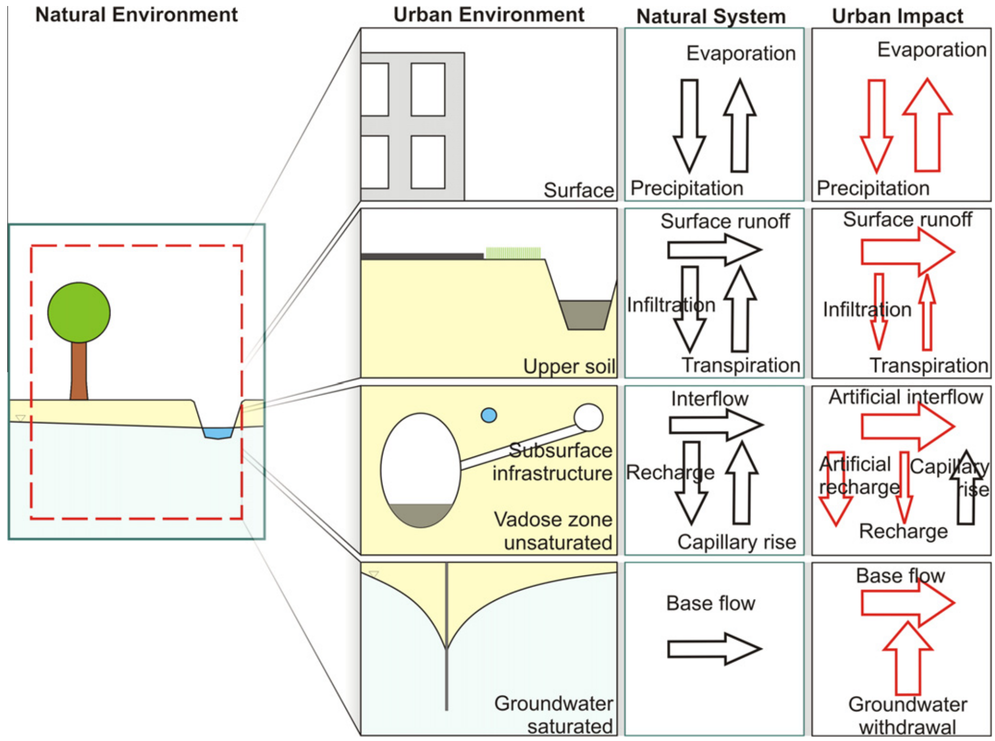

Fig. 1. Simplified urban impact on the water balance. The red arrows represent water flow which has been modified or newly introduced by urbanisation.

leak from these subsurface infrastructures as artificial groundwater recharge, increasing the net recharge beneath urban areas [8]. Storm water runoff can also be transported in the sewage system as artificial interflow and mix with wastewater in combined sewers. When the water amount exceeds the capacity of the sewage system, this contaminated storm water can discharge into surface waters (combined sewer overflow, CSO). In urban settings streams as major receivers for groundwater as well as for treated and untreated wastewater are often degraded by a multitude of stressors [9]. This degradation is summarised as the "urban stream syndrome" and comprises amongst others the "flashier" hydrograph with shorter lag times to peak flow, changed base flow magnitude and impaired channel morphology. These effects most likely influence the magnitude and quality of groundwater-surface water interactions. In general the manifold interactions of the different urban water compartments are complex in time and space and still leaves many questions open [10–14].

The disturbance of the natural water balance is closely connected with deteriorating quality, since new pathways for contaminants are introduced. Probably most challenging is the variety of chemicals from human and industrial activities released via different wastewater sources. We live in a "chemical society" with thousands of chemical compounds available in the products of our daily life [15]. Due to the concentrated accumulation, and the transport and treatment of wastewater in urban areas, urban water resources are at particular risk. The waste-water-borne contaminants are often present in waters in low concentrations ranging from pg L^{-1} to ng L^{-1} and are therefore termed "micropollutants" [16]. Examples of micropollutants are pharmaceuticals and personal care products (PPCP) and endocrine disrupting chemicals (EDC) [17–19]. These compounds are now frequently found in wastewater treatment plants and surface water bodies [20–23], and although in the last few years several research groups have begun to study these chemicals in urban groundwater (e.g., [17,24–29]), they are not usually the focus of groundwater investigations.

Despite the fact that urban-source micropollutants are of concern, urban areas are also often associated with industrial activities which potentially introduce *macro*pollutants such as chlorinated solvents, polycyclic aromatic hydrocarbons (PAHs) and gasoline constituents. In addition, agricultural practises within cities and sewer leakages have contaminated urban aquifers with large amounts of nitrate and phosphate which are still of great concern (e.g., [30]).

The present and future tasks concerning the management of urban water resources are not new. The urban population needs a reliable supply of clean drinking water on the one hand, and on the other hand, urban groundwater contamination and wastewater have to be treated and storm water has to be managed. This task has a substantial overlap with the concept of Integrated Urban Water Management (IUWM). In an IUWM approach water supply, drainage and the sewage systems are seen as parts of an integrated physical system [31]. This approach is a logical consequence of the connection of the water compartments in the urban water balance. Nevertheless, groundwater is often not sufficiently integrated into IUWM concepts [32,33]. This does not mean we only have to manage the negative effects such as land subsidence, infiltration to the sewage system or building damage by high groundwater levels. Urban groundwater is a heritage and deserves protection and sustainable management in the same way as other water resources. Although being affected by urban land use and anthropogenic activity, a growing number of publications show the value and usability of urban groundwater resources as part of water resources management in urban areas (e.g., [34]).

Urban groundwater can be utilised for potable and non-potable water production (e.g., [35]). Managed and cost-effective aquifer recharge and aquifer storage and recovery methods can be used to recycle storm water or treated sewage for non-potable and indirect potable reuse [36,37]. Bank filtration of surface water provides potable water for cities like Berlin (Germany) [38]. Foster et al. [39] report the extensive and unregulated usage of shallow urban groundwater in many developing cities as a low-cost alternative