URBAN HYDROGEOLOGY

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Summary

The fundamental processes that affect urban hydrogeology are not essentially different from those of rural environments. There are however differences relating to time and space scales. Moreover, a number of new problems relating to groundwater and the urban environment arise:

- Disruption of the groundwater cycle in urban areas. Rainfall infiltration is reduced, but this is counterbalanced by reductions in evapotranspiration and losses from the sewage and water distribution systems.
- Anthropic fluctuations of groundwater levels. Changes in urban patterns often lead to dramatic changes in water levels.
- Effects on urban structures. Structures designed and built without a proper acknowledgement of groundwater are suffering seepage and flooding. Large areas in some cities are suffering subsidence and flooding.
- *Groundwater contamination.* Industrial spills, sewage losses, mobilization of pollutants by rising groundwater levels, and so on lead to water pollution.

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Moreover, mixing chlorinated water with sewage water and partial degradation may lead to new pollutants.

- Quantification and modeling of problems 1 to 4 is difficult, because of lack of experience and because their time and spatial scales are often much smaller than in conventional models.
- The usual attitude is one of responding to urgent problems rather than preventing them.
- Difficulties in communication between the scientific community and city managers/policy makers. The latter are subject to pressures on a wide range of urgent matters, so they normally lack the level of motivation and specialized dedication of regional or national water agencies.

These problems are being faced by many cities worldwide. They have been addressed by researchers and municipal managers, but usually as separate problems. The challenge in the future is to provide a unified framework to confront them.

1. Introduction

During the twentieth century there was a very significant change in all the issues related to demography. The two most important changes were the increase in overall population and the demographic flow from rural environments to cities. As a consequence, at present (2002) more than 50% of the world's population lives in urban centers, with around 60 cities with over 5 million inhabitants (Mhab) and a few in the range of 15 to 20 Mhab. These large populations are huge predators of natural or elaborated resources, including water, electricity, gas, and so on. As a consequence, water supply and water resources management are major concerns in urban areas worldwide.

The amount of water that needs to be provided to any large or medium-sized city is generally much larger than the surface water resources available at that same city. We have to keep in mind that the total urban area (more than 3500 Mhab) occupies less than 1% of the Earth's surface. The net result is that in most of the large cities in the world, water has to be diverted from locations that are quite far away, causing significant social, economic, and environmental costs.

However, a huge amount of water lies beneath most cities, filling the voids left by the granular skeleton of the underlying geological formations. This groundwater is in many cases neglected, either because of cultural or technical reasons, or because it is considered unsuitable for human consumption (as it is polluted). Despite this, groundwater has a number of characteristics that make it favorable for exploitation and inclusion in a global water management analysis. Some of these are the huge volumes of the groundwater reservoirs, the sustainability of the resource in the medium mid and long term, and its widespread availability, which creates the possibility of extracting water in the same places as it is consumed, thereby minimizing the length of conduit needed. Even if the quality of groundwater in a particular city is not very good, this water could be used for other than drinking purposes, thereby reducing the demand for high-quality water. In summary, groundwater can be considered in most large urban areas as an alternative source for particular uses in the city, thus reducing the amount of

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water that needs to be imported, and eliminating the economic and environmental cost of making water potable.

There is a fundamental difference in the way urban groundwater needs to be viewed depending on the economy of the country. In nondeveloped or developing countries the most important priority is to be able to provide quality (safe) water to the population. In most cases the population is growing at a high rate, and therefore the objective is to increase the available water resources. The sources must be reliable as far as possible when related to climate, because most of the cities in non-developed or developing countries are located in arid or semiarid areas, and groundwater can be considered an interesting alternative.

In developed countries the situation is generally different. Most cities (not all of them) have a stable population, and the water supply is guaranteed. In these cases the problem is to look for cleaner, more ecological sources, which could provide better quality water for drinking purposes in a sustainable way.

Another important characteristic of cities, particularly in developed countries, is the widespread presence of underground structures. The relationship between groundwater and urban subsurface structures is quite complex, as will be discussed later. These interactions are of social and economic importance for both individuals and social agents.

Figure 1 shows some of the relations between groundwater and a city in a developed country at the end of the twentieth century. In nondeveloped countries the problems are quite different in nature.

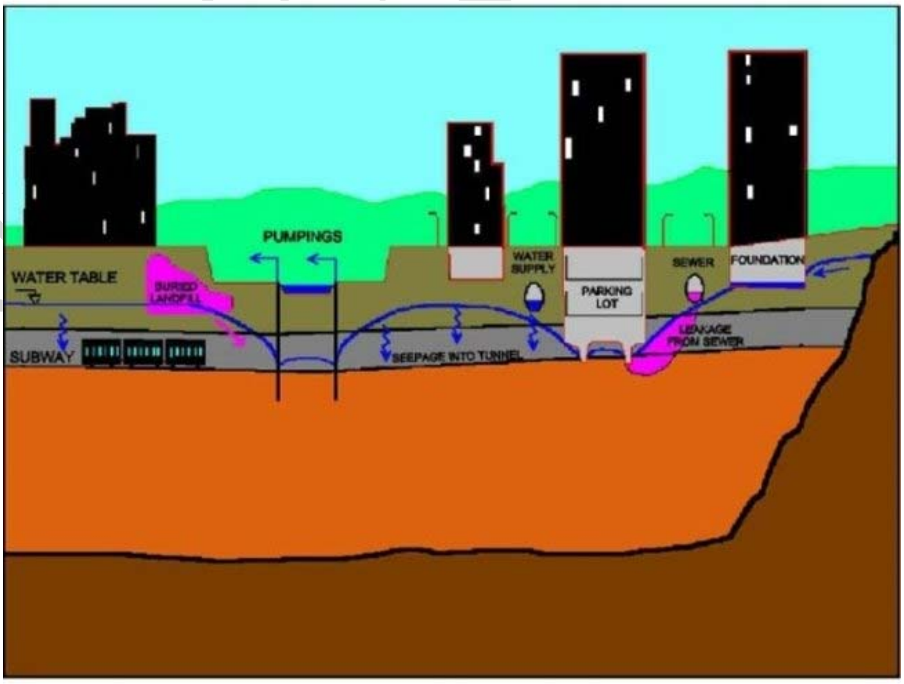

Figure 1. General sketch of some particular aspects of urban groundwater in developed countries

The focus of this article is to analyze the particularities of hydrogeology in urban areas, including environmental, social, and economic aspects. This will lead progressively to the idea of global groundwater resources management in urban areas.

2. A Quick Glance at Urban Hydrogeology

2.1. The Close Link between a City's Historical Development and Urban Groundwater

There is an obvious correlation between the urban development of a city and the physical and chemical characteristics of the groundwater present beneath the city. Urbanization affects not only the availability but also the quality of groundwater resources. These effects can be summarized as follows:

- Changes in soil uses because of urban development lead to significant changes in the natural hydrological cycle, singularly in the total recharge to the system. These changes are mostly related to climate conditions. Paving decreases direct rainfall infiltration; in dry climates this effect is, or can be, counterbalanced by the reduction in evaporation plus transpiration from plants, leading to a larger total recharge. In wet or cold climates the reduction in infiltration could lead to a depletion in groundwater levels. It must be noted that urban development changes with time and has a clear, usually well known, history.
- Losses in the supply and sewage systems are the main input of water to the aquifers in most cities. The amount of recharge coming from losses in the main water supply system depends on the size of the city (through the total amount of water supplied), the hydrogeological setting (whether the water supply pipes are located below or above the groundwater levels), the topographical setting (steep slopes would mean the need for higher pressure in the water-conducting pipes, and therefore higher losses), and the historical development of the city and the wealth of the country (good indicators of how well maintained the pipes are). The percentage of water lost can be as little as 8% in places like Hong Kong, or as high as 60% in some parts of Lima, Peru. Most cities in Europe are in the range of 20% to 25%. Assuming an average supply of 200 liters per inhabitant per day, that would lead to 15–20 hm^3 per year in a city with a population of 1 million. In most parts of Asia and South America the average water supply per person is less, but the percentage of losses is higher, leading to similar numbers. Losses in the sewage system are not that high, as water usually flows by gravity rather than by pressure. Losses also depend on the type of sewage system. When the system is separated (storm waters flow through a different pipe system than wastewaters) the amount of wastewater infiltrated is rather small, due to biofilm clogging. When the system is unitary, storm water can wash the biofilm, enhancing direct infiltration of waste water right after storms. This will condition water quality, as will be discussed later.
- The history of groundwater evolution is directly linked to the history of industrialization in many cities in developed countries. In general, at an early stage of city development urbanization was related to the increase in industrial activity (with the exception of suburbs). Industry became in most cases a great water consumer, and in some cases industries favoured the use of groundwater, either for economic reasons, or simply because there was a lack of an adequate

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(and reliable) water supply system. The proliferation of industries, and the subsequent increase in groundwater extraction (in most cases uncontrolled), led to a gradual but significant decrease in piezometric levels (namely water mining). An important consequence of water mining in the presence of clayey layers below the city is subsidence. Dramatic examples of this phenomenon can be found in Mexico City, Venice, Shanghai, and Bangkok, among others. A case in point is Venice, where the present subsidence problems are caused by groundwater extraction for industrial purposes after the Second World War. Industries were also a potential source of pollution, particularly during the nineteenth and most of the twentieth century, when groundwater pollution control was not a priority.

- When urbanization is in a certain stage of development in these types of industrial city, the opposite effect takes place. The pressure of urbanization can cause industries to move away from the urban area and relocate outside the city. Other causes of the reverse effect are economic crises that send a number of industries out of business (such as the one that took place in the early 1970s), and the quality of groundwater becoming inadequate and forcing some industries to connect to the supply system. A consequence of these and other causes is that piezometric levels increase again, tending to return to the situation previous to the industrial settlement, or simply achieving a new equilibrium level.

An impressive example of this falling and rising of the groundwater levels is that of the confined chalk aquifer underlying the city of London, UK. Measurements extending in time over one and a half centuries show groundwater level variations of several tens of meters. Groundwater levels clearly reflect the industrial evolution of the city: first, industrial expansion leading to water abstraction and falling groundwater levels; second, industrial maturity after the Second World War, where levels are practically constant in time; and third, industrial recession, following the 1970 economic crisis, with spectacular rising water levels on the order of 2 m y^{-1}.

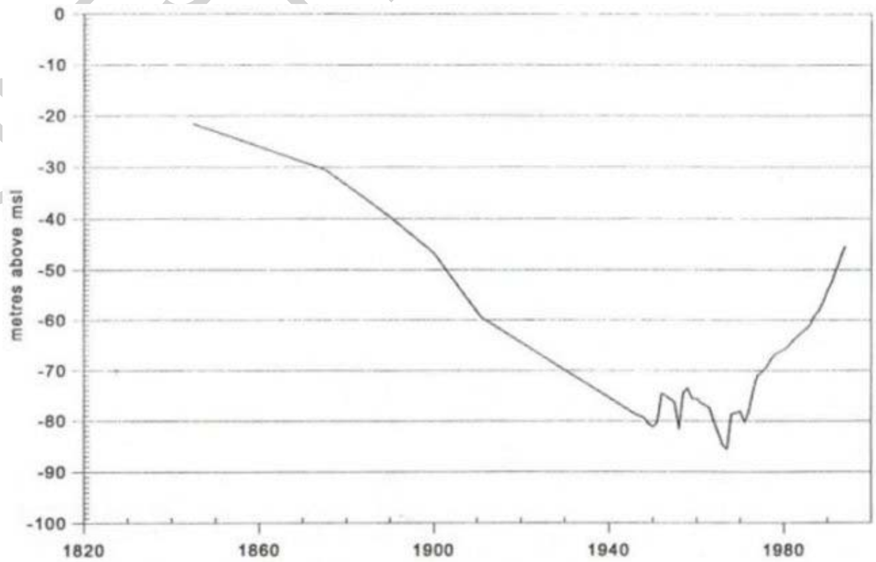

Figure 2. Falling and rising of the groundwater level evolution in the chalk aquifer underlying London

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- This particular evolution of the groundwater levels has been observed in several cities in Europe such as London, Milan, and Barcelona. A related problem is the interaction of groundwater with subsurface structures. The period of low piezometric levels corresponds to 1950–1970, a period of reconstruction in some countries, or simply a time of construction boom. A large number of underground structures were built during that time, most probably without taking into account that the groundwater level could rise appreciably. Now such structures are facing water pressures or chemical attacks that were not considered in the original design. Many urban areas are currently suffering this situation, which affects all underground facilities, such as metro tunnels, underground parking lots, cellars, and communication lines. The breakdown of some of the materials used in these urban subsurface structures is a double cause of concern, as not only can it be a potential focus of pollution, but also it can lead to construction failures because of a reduction in the thickness of concrete or a chemical attack on steel reinforcement bars.
- The previous point was devoted to the effect of water on structures. It should be noted, nevertheless, that urban structures could also affect the direction and magnitude of groundwater flow, as they can act as artificial barriers. Any new structure will potentially influence the local groundwater flow. The net effect is a local change in the piezometric levels, which could now affect new structures, remobilize contaminants that were fixed in the soil, or simply change the water balance in the city. The effect is more significant when it is a large structure, such as a new railroad, subway line, or a large urban tunnel.
- Groundwater can be polluted from different sources. The most important source is water leaking from the sewage system. Additional polluting sources can be septic tanks and/or materials buried or deposited in the soil. In poor countries wastewater is simply dumped to the street or to surface water bodies nearby, which act as groundwater pollutant sources. The mixture of wastewater (with a great organic content) and water from the supply system (free chlorine) can lead to other pollutants (such as chlorinated hydrocarbons) with quite different chemical properties. Furthermore, changes in the chemical composition of water can mobilize toxic components, like heavy metals. On the other hand a significant increase in the quality of water may be achieved through the oxidation of organic material.
- At present there are no examples of integrated water management at the city level. Most studies consider in detail either surface or subsurface water resources. A proper urban groundwater study would deal with a complete subsurface water balance, leading to an estimation of recharge to and discharge from the system. It would also include quality aspects, which can be evaluated by characterizing the sources of urban groundwater, and polluting episodes. Information, which usually is scattered in space and time, needs to be integrated in a conceptual model that could be the first step towards a full-integrated management model, which in the future could be used as a tool for decision makers.

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Biographical Sketch

Xavier Sánchez-Vila received a M.S. degree in Civil Engineering from the University of California at Berkeley in 1990 and a Ph.D. in Civil Engineering from the Technical University of Catalonia (UPC) in 1995. He is now Assistant Professor at the UPC. He has authored more than 60 papers on different aspects of hydrogeology such as groundwater modeling, stochastic hydrogeology, and urban groundwater. He received the Harry Bolton Seed Award from the Civil Engineering Department in UC Berkeley in 1990, and the Best Thesis Award from the UPC in 1997. At present he is the President of the Spanish Chapter of the International Association of Hydrogeologists.

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