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Highlighting the interaction between urban infrastructure and groundwater through hydrogeological modeling, a useful tool for urban management

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Abstract: Too often the importance of the groundwater beneath cities is overlooked or passes unrecognized. Management of the urban subsurface requires understanding the relation between groundwater and infrastructure development. A number of European cities have recently analysed how their subsurface infrastructure interacts with groundwater, but still, city planning habitually ignores potential groundwater problems and city-scale hydrogeological studies are the answer to this challenge. In Bucharest, a city-district hydrogeological study emphasizes the need for responsible urban surface and groundwater management implementation. The urban water management must be based on continuous hydrogeological surveys in urban areas, considering the nested interaction between the anthropogenic and natural features.

Keywords: groundwater modelling, subsurface infrastructure, sewer network, risk.

1. Introduction

Cities are expanding underground, and reliable use of underground space is essential for various types of utilities (e.g. water supply, sewage, telephony), transportation, storage and other uses. Urban planning frequently operates in two dimensions, without including a complete analysis of the subsurface. Poor assessment of ground conditions, and in particular the failure to take into account the presence of groundwater and its dynamics in urban planning and design, is recognized as the largest cause of construction project delays and increased execution costs, as well as subsequent damage to urban infrastructure [1].

Since cities face urban hydrogeological issues that require at least as much attention as other urban planning issues, this domain must consider the entire urban water cycle and of course the groundwater cycle. Aquifer systems are closely related to

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urbanization processes and their dynamics are constantly changing with urban development. Urban development processes have an influence on groundwater and groundwater in turn has an impact on urban infrastructure.

Land use changes reduce the recharge from precipitation to aquifer systems and in urban areas artificial recharge sources appear that regroup losses from water distribution networks, sewage systems with exfiltration and urban irrigation. Water dynamics in urban aquifers are linked to catchments, drains, tunnels, as well as water supply and sewage systems. Consequently, the change in the urban water cycle directly affects groundwater levels. The increase in groundwater levels can affect many urban components, generating floods, the appearance of major infiltration areas or risks of liquefaction. The decrease in groundwater levels can generate local subsidence, affecting the integrity of buildings or in more serious cases the occurrence of subsidence. Also, the decrease in groundwater levels can cause an increase in wastewater exfiltration from sewage networks into the aquifer which can also affect surface waters such as lakes and rivers.

Nowadays, most urban water studies do not use real water balances and many of them even ignore the urban groundwater. Unfortunately, very few urban hydrogeological studies properly consider the interaction of groundwater with the urban footprint. At the same time, studies of anthropogenic strata, often composed of heterogeneous fills, are of a pioneering nature and very few technical or scientific works document their properties, distribution or geomechanical and hydraulic behavior. Very few studies quantify the hydraulic interaction between groundwater and urban infrastructure, integrating losses from the water distribution system-the main factor of recharge of aquifers in cities, existing depletion systems and the barrier effect induced by large infrastructure elements such as tunnels and metro stations, deep building foundations and others.

Fortunately, progress has been made in the scientific understanding of urban hydrogeological processes in a substantial number of European cities. Three "classic" European case studies highlight the need to initiate a predictive process based on precise and detailed knowledge of the subsurface environment, including the interaction between urban groundwater and urban infrastructure.

In the 1970s, in London, a plan to use a tidal barrage to protect against flooding during high tides on the River Thames was temporarily abandoned after it was judged that it would lead to a permanent rise in the groundwater level in the alluvial deposits, which would have flooded numerous unprotected underground structures [1]. Monitoring wells installed all along the northern side of the Thames Flood Plain revealed that this area was uniformly drained to considerably below mid-tide river level, and it was discovered that there were Victorian pumping stations pumping large volumes of shallow groundwater under each subway station across the area.

In Barcelona, groundwater abstraction to fulfil industrial needs began at the beginning of 20th century and increased to about 60–70 Mm^3/a [2]. Between 1950–75 numerous buildings and a large part of the underground railway system were built, and this period corresponded with maximum groundwater level depletion. However, from the late 1970s pumping was reduced due to groundwater contamination and the departure of industry from the city centre. Nowadays, the groundwater levels have almost recovered to those of the early 20th Century and as a result the underground infrastructure together with several building basements and cellars are pumping around 20 Mm^3/a [2].

Two city-scale hydrogeological problems are triggered by interaction between groundwater and underground infrastructure in Bucharest [3]. First, a barrier effect from an extensively channelized river and the parallel subway tunnels (of 7-23m depth) that cuts the city into two parts and causes an increase of groundwater levels in the city centre. Second, the strong hydraulic interaction between the sewer system and the groundwater causes seepage into the sewer network and an excess sewer flow of about 1 m^3/s. The problem has been studied by groundwater investigation and modelling of the shallow aquifer system (Figure 1), and the partnership of the urban water-utility and an academic centre has led to the involvement of a broad base of urban stakeholders in data collection and monitoring [3].

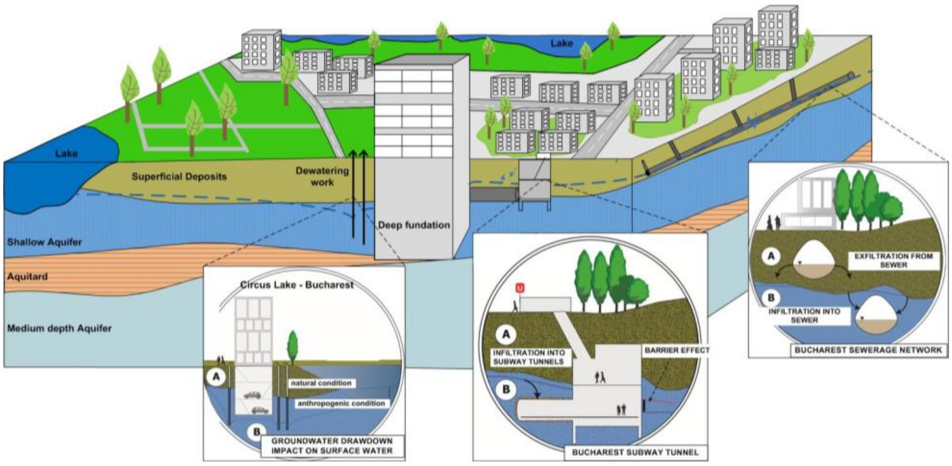

Fig. 1 Integrated approach of urban interaction between infrastructure, geology, and groundwater.

2. Urban hydrogeological analysis for the Tei area of Bucharest

The Lacul Tei area is located in the city of Bucharest, on the administrative territory of the 2nd District. With an area of 138 ha, it covers several dense urban areas, two large parks, namely Circului Park and Tei Park, and 2 lakes that are part of the two mentioned parks: Circului Lake and Tei Lake. Tei Lake is part of a system of lakes chained along the Colentina River, which crosses Bucharest from the northwest to the east. With an area of 0.75 ha, Circului Lake is an artificial lake with a recreational role, aligned with natural ecosystem services, offering benefits for human well-being. Due to its hydraulic connection with the shallow aquifer system, the lake recharges the aquifer with stormwater captured from the park's watershed. The main problem, from a hydrological point of view of this urban area, is the decrease of the groundwater level and therefore the water level in Circului Lake. This is a consequence of several hydrological and hydraulic factors that influence the zonal hydrological balance: climate change highlighted by the spatial and seasonal change in precipitation patterns, the drastic reduction in losses from the water distribution

system, and declared or undeclared permanent or temporary dewatering systems.
Starting from a 3D geological model with good accuracy [4], a hydrogeological model was developed to simulate the behavior of the urban aquifer. By intersecting the geological model with the existing urban infrastructure elements, it was possible to identify the position of the sewer pipes in the aquifers and their potential hydraulic connection with them, as well as providing the geometric parameters necessary to quantify the barrier effect on groundwater [5] induced by the presence of engineering works (tunnels and metro stations, underground parking lots, etc.).

3. Hydrogeological modeling aspects

From a hydrogeological point of view, Bucharest is situated on a Quaternary sedimentary aquifer system consisting of three units [6]. The deepest unit is known as the “Frătești strata”. Overlying this is a sequence of marl and clay layers with sand intercalations called the “Coconi layers” or the “Marly Complex”. The thickness of the “Marly Complex” varies in depth from 110 m in the north to approximately 40 m in the south of the city. The second aquifer unit is known as the “Mostiștea sands”. This can be found at depths ranging from 20m to 50m and is mainly composed of sands. The third aquifer layer called the “Colentina gravels” is composed of gravels and sands. This is a phreatic aquifer with a free level. The Colentina aquifer has a direct interaction with most of the urban infrastructure elements of Bucharest. This aquifer is covered by an aquitard layer known as "Surface Deposits". Between the Colentina aquifer and the Mostiștea aquifer there is a clayey aquitard layer called "Intermediate Deposits".

As in most major cities in the world, groundwater recharge in Bucharest is mainly from losses in the water supply system, from water losses in the sewerage pipes and of course from precipitation. The sewerage network of Bucharest collects both rainwater and wastewater in a unitary system. The sewerage pipes have hydraulic contact with the groundwater of the Colentina aquifer, which manifests itself either through the drainage of groundwater by them or through the loss of wastewater to the aquifer. The two phenomena of drainage and respectively water loss manifest themselves depending on the hydraulic gradient between groundwater and wastewater in the sewerage pipes and are due to the cracks and defects existing on these pipes. Tunnels and metro stations, parking lots and pedestrian passages as well as foundations of buildings of different sizes and depths are various elements of underground infrastructure that belong to the modeled area. These cavities, in relation to groundwater dynamics, introduce a barrier effect for the groundwater flow phenomenon, by raising the water level upstream and lowering it downstream of the underground enclosure. At the same time, these elements introduce a drainage effect, allowing groundwater to infiltrate into these cavities through cracks or areas lacking waterproofing.

The groundwater flow model focuses on the interaction between urban infrastructure and the aquifer system. It is based on the urban geological model obtained by the three-dimensional (3D) intersection of the aquifer layers with the main urban infrastructure elements (3D sewerage system, 3D metro network, and all others).

This hydrogeological model was performed in a steady flow regime for the superficial aquifer system composed of the first two aquifer layers “Colentina Gravels” and “Mostistea Sands”, separated by the aquitard layer represented by the “Intermediate Deposits”. The model uses the MODFLOW software package that uses the finite difference method [7].

The initial objective of the model was to quantitatively assess the interaction of groundwater with the sewer system. The model was built considering sewer pipes with a diameter greater than 400 mm. The datasets used for the development of the groundwater flow model are listed in Table 1.

Tabel 1. Simplified diagram of the datasets used to develop the groundwater flow model for the Tei area of Bucharest city.

No	Component	Variable	Data source
1	Aquifer system	Aquifer geometry	Geological model
		Hydraulic conductivity (horizontal and vertical)	Lithological description
			Pumping teste
2	Precipitations	Aquifer recharge	Stormwater recharge study through the urban fabric
3	Water distribution network	Aquifer recharge	Water operator estimations
4	Tunnels	Seepage into tunnels	Measurements
		Geometry	Measurements
		Hydraulic characteristic	Modelling
5	Rivers and lakes	Geometry	Database
		Hydraulic head	Measurements
6	Sewage system	Hydraulic head	Measurements and water operator estimations
		Water balance	Water operator estimations
		Hydraulic conductance of the sewer pipes (C)	Groundwater flow calibration process
		Aquifer system location	Sewer conduits intersection with Geological model
		Groundwater seepage (discharge)	Water operator estimations
7	Hydraulic head data	Hydraulic head in shallow aquifer Colentina (unconfined) Hydraulic head in middle aquifer Mostiștea (confined)	Measurements and interpolations

Given that the model is developed under steady-state flow conditions, the hydraulic calibration of the model was performed taking into account the hydraulic conductivity. The spatial distribution of the hydraulic conductivity was determined using the Pilot Point Method. Since this method requires the estimation of hydraulic conductivity values at several points, the values were obtained based on the lithological description from the boreholes as well as on the basis of hydraulic pumping tests.

4. Study on the groundwater balance in the Tei area

An urban groundwater balance was carried out for the Tei District (Fig. 2). The results of this balance serve as an example to illustrate the urban hydrogeological analysis. During the last 20 years, a slow decrease in the water level has been observed in one of the lakes of Bucharest, called Circului Lake (Fig. 3). Even though it has an anthropogenic origin, the lake is naturally recharged by the groundwater aquifer "Colentina Gravels".

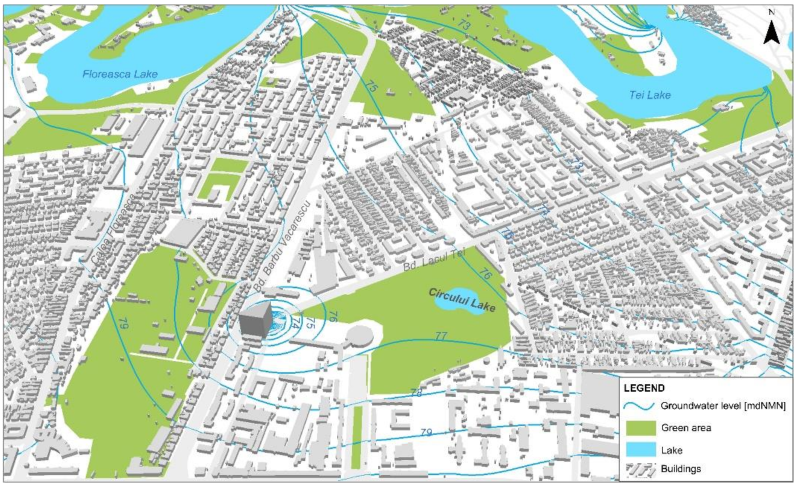

Fig. 2. Groundwater level in Circului Lake in 2015 (CCIAS, 2015).

In terms of urban infrastructure, the area is served by a water distribution system consisting of low-pressure pipes with a length of approximately 180 km. Groundwater recharge in the modeled area is largely from losses in the water supply network and to a lesser extent from the interaction with the sewage system.

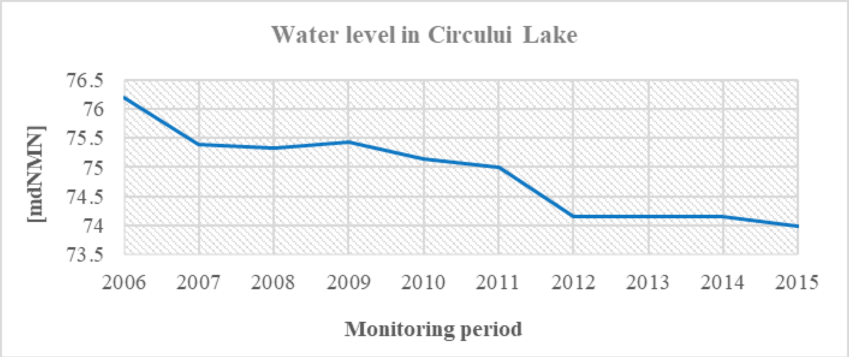

Fig. 3. Water level in Circului Lake between 2006 and 2015 [8].

The hydrogeological study [8] carried out in a first phase, covering the period 2006-2014, took into account the drastic reduction of water losses from the distribution network (Fig. 4), due to the improvement of the water distribution network in the studied area.

A reduction of the aquifer recharge from precipitation (Fig. 4) was recorded [9] between 2006 and 2014, indicating a corresponding decrease in the piezometric head in both the first unconfined aquifer (Colentina Gravels) and the second confined aquifer (Mostiștea Sands).

In this study, several urban groundwater modeling scenarios were developed to simulate the decrease in the water level of Circului Lake [10], including the recorded history of the decrease in losses from the water distribution network (2006 - 2014), the interaction with the sewage network, the barrier effect produced by the nearby metro tunnels (Ștefan cel Mare Boulevard) and the location of permanent dewatering systems.

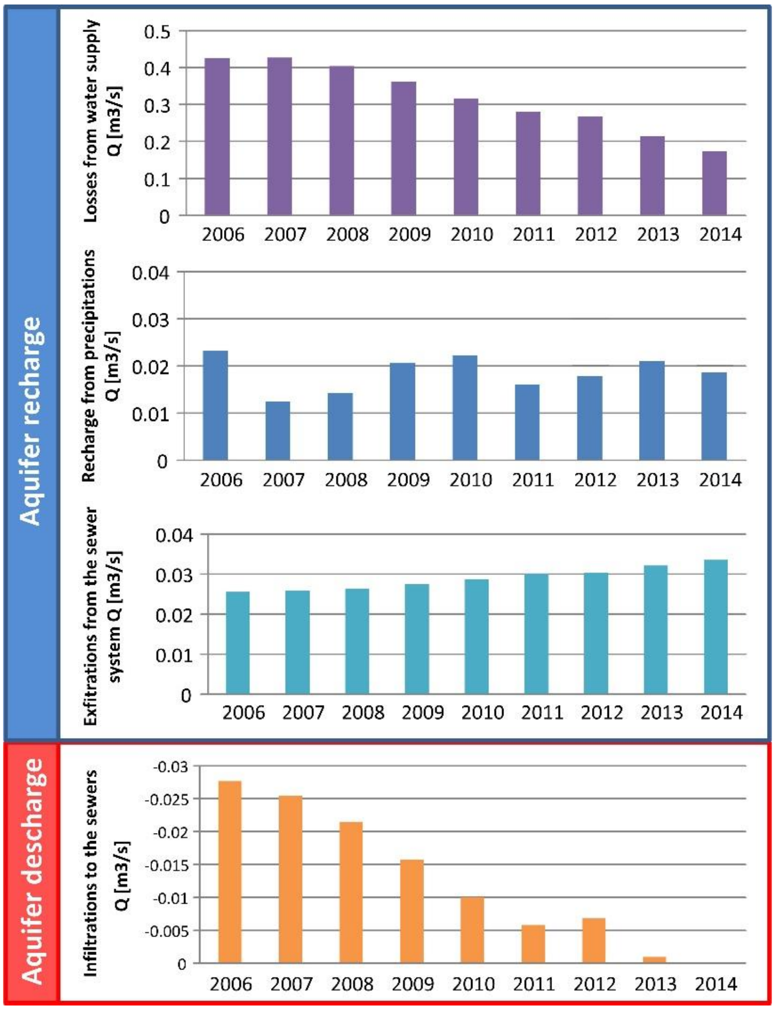

Fig. 4. The main components contributing to the aquifer recharge/discharge in the hydrogeological model.

The modeling results highlighted a clear link between the decrease in the lake water level and the permanent dewatering systems. Also, the reduction in precipitation is one of the causes of the decrease in the groundwater level, but the strong and well-marked reduction of losses (data from the Bucharest city water operator) in the water distribution network (Fig. 4) played an important role. In Fig. 4, a decrease in losses in the water distribution network in the Tei area is observed, due to the repair of the pipeline system, from 0.42 m^3/s in 2006 to 0.17 m^3/s in 2014. The strong changes in the local groundwater balance and the associated decrease in the groundwater level, produced an increase in the exfiltration of wastewater from the sewage system into the aquifer (Fig. 4).

To simulate scenarios focused on the hydraulic interaction between the aquifer system and infrastructure elements, the hydrogeological model was updated for 2019 (Fig. 5). Next, simulating the reduction of losses in the water distribution network by 50% and 100%, respectively, strong changes in the local groundwater balance are observed, with an associated decrease in the level of the shallow unconfined aquifer of up to 1.8 meters and a corresponding increase in the exfiltration of wastewater from the sewage system into the aquifer. Consequently, the water level in Circului Lake decreases accordingly, in both cases requiring additional solutions to maintain its ecological stability.

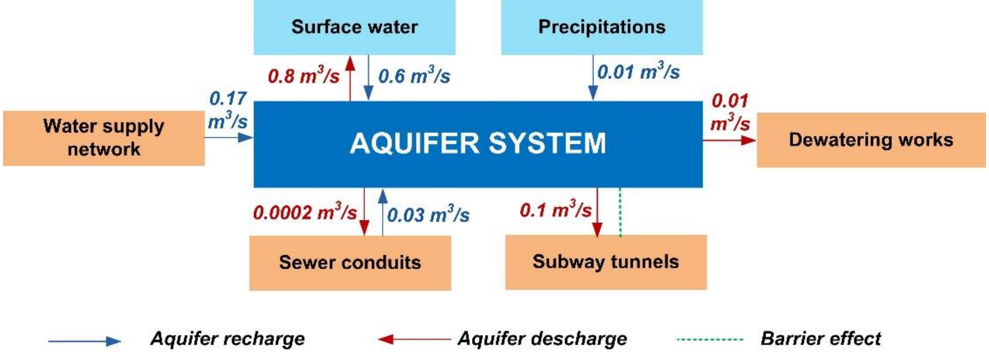

Fig. 5. Groundwater balance in the Tei area for September 2019.

5. Results and discussions

This study shows that both anthropogenic and natural causes control the decrease in the piezometric level of groundwater in the Tei district, emphasizing that several hydrological and hydraulic factors influence the hydrological balance of the area, namely the effects of climate change manifested by reduced precipitation, reduced water losses and the presence of dewatering systems. A clear correspondence is observed (Fig. 3) between the decrease in the water level of Circului Lake between 2006 and 2014, which has a direct hydraulic connection with the groundwater aquifer (Colentina Gravels) and the decrease in losses in the water supply network in the area (Fig. 4). Changes in the water balance of an urban area, by modifying the supply corresponding to anthropogenic or natural water sources or by its extractions (e.g. dewatering systems), can generate significant imbalances. Consequently, a strong reduction in losses from the water distribution network has an impact on the groundwater balance, affecting the level of the groundwater aquifer, with consequences in increasing leakages from the sewage network to the aquifer system, decreasing the water level in lakes and implicitly threatening the safety of ecosystems. At the same time, the decrease in the groundwater level (1.8 m in the case of a 100% reduction in losses from the water supply network) can trigger subsidence [11] and implicitly could generate severe geotechnical risks.

There is a need to carry out systematic hydrogeological studies in urban areas, taking into account the hydraulic interaction between anthropogenic elements and natural features. Reliable studies on surface water and groundwater in urban areas can only be produced after establishing a correct groundwater balance analysis, which must take into account water supply losses (the main component of groundwater recharge for aquifers located in urban areas), urban underground infrastructure (e.g. tunnels and metro stations, deep foundations, car parks and others) that induce a barrier effect and a drainage effect for groundwater, urban aquifer recharge from precipitation, interaction with surface water and green infrastructure as well as interaction with sewerage pipes. Since sewerage pipes can cross both the urban unsaturated zone and hydrogeological strata (aquifer, aquiclude or aquitard), their presumed exfiltration to the aquifer layer depends on the hydraulic conductivity of this stratum. The hydraulic interaction of groundwater with sewer pipes depends on the hydraulic gradient between the level of wastewater (or stormwater in the case of a divided sewer system) in the pipe and the hydraulic head in the aquifer.

Currently, very little attention is paid to the urban subsurface, although these situations are found in most cities around the world. Attention to this underground environment appears suddenly, when major accidents occur such as those related to infrastructure, significant land subsidence, or major contaminations that may involve human lives or require huge funds to solve the problems. However, these accidents can be avoided through systematic studies that can build a scientific basis necessary for the activity of responsible management in order to progressively develop the underground use of cities.

Cities should focus on interdisciplinary approaches by reflecting within urban planning guidelines the experience gained on the interaction between urban infrastructure and groundwater, hydrological processes, as well as groundwater pollution. This can be put into practice by interconnecting expertise between the disciplines of urban planning, hydrology, biology, ecology, geology, geotechnics, geothermal sciences and green infrastructure planning. Currently, there is a major trend in implementing green infrastructure in order to ensure sustainable development of cities, and most solutions are hydraulically connected to both surface and groundwater, but without being based on a correct water balance. Therefore, studies, urban planning projects and the implementation of green infrastructure elements must be based on the water balance obtained with the help of hydrogeological studies and models.

6. Conclusions

City scale groundwater monitoring and urban subsurface studies are an important component of sustainable urban development. These activities create a basis for supporting impact analysis of future underground works (e.g. tunnels, warehouses, parking lots, deep foundations, sewerage system rehabilitation, thermal energy and others), based on which their impact can be systematically assessed, and potentially costly risks can be avoided.

Urban planning should include water balance studies based on sound hydrological and hydrogeological analyses. Studies on the urban water cycle should include the analysis of the urban groundwater balance encompassing natural and anthropogenic water sources, the study of natural and allochthonous geological strata, as well as the parameters of the entire set of infrastructure elements.

Urban groundwater data is a critical dataset for the development of resilient cities [1]. Water and sewerage companies, municipal environmental departments, construction companies, public health authorities, as well as all private or public users of water wells are important beneficiaries of these data sets.

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