Groundwater quality management for urban supply security

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Water utilities have a key role to play in managing groundwater if this resource is to contribute fully to water supply security in the face of climate change. ***Stephen Foster***, ***Susie Mielby***, ***Ricardo Hirata***, ***Aleksandra Tubic*** *and* ***Julia Gathu*** *set out the core principles they should follow.*

Climate change stress means better use of water reserves will be critical for urban water supply security. Aquifers, with their large natural groundwater storage, offer a cost-effective option to improve urban water supply resilience. For the most part, groundwater is naturally of excellent quality, requiring only precautionary disinfection before it is put into public supply. Two key exceptions are:

- Where groundwater quality is impacted or threatened by a pollution load generated by man-made activities on the land surface
- Where groundwater quality is affected by natural trace contaminants mobilised from soils and rocks.

Both cases mean that improved water quality management for groundwater is needed if aquifers are to contribute sustainably to resilience. The potential for concern is illustrated by the very large body of data on the chemical quality of groundwater bodies, collected under the European Union's Water Framework Directive. This is periodically summarised in reports by the European Environment Agency (EEA). In its July 2018 summary, it is clear that by far the most serious problem is nitrate – and sometimes ammonium – mostly derived from agriculture. This is very industrial solvents (such as trichloroethylene, tetrachloroethylene and trichloromethane), and certain heavy metals (nickel, lead and cadmium).

Globally, water utilities are the major stakeholders in groundwater as a primary low-cost, high-quality source. They, therefore, need to promote widely a more balanced approach to achieving long-term sustainable water quality. However, the contribution of urban water utilities – with some notable exceptions, including those discussed here – has been limited to date. This has prompted the writing of this article, summarising the principles of groundwater quality management.

Pollution protection for groundwater sources

Given the high capital and operational costs of treatment plants to remove contaminants, the preferred approach must be to protect groundwater by applying selective land-use controls. Groundwater pollution can occur where the subsurface contaminant load generated by man-made discharges and leachates is inadequately controlled and certain components exceed the natural attenuation capacity of the underlying soil and rock profile (Figure 1).

Figure 1. Land-use activities commonly generating a groundwater pollution hazard

The concept of groundwater source protection zones (SPZs), known in the US as wellhead protection areas (WHPAs), is long established. They have been part of legal codes in some European countries for many decades. However, increasing hydrogeological knowledge and changes in the level of pollution threat mean that the concept has had to evolve significantly. Certain EU countries have been at the forefront in the practical deployment of SPZs – notably Denmark, but also, more locally, Germany and the UK. There are also scattered examples from the Latin America and Caribbean region, but their introduction in Southern Europe, Asia and Africa has lagged seriously.

In Denmark, SPZs based on detailed hydrogeological investigation have been promoted strongly in the past 15-20 years through partnerships between water companies, municipal authorities and nature conservation agencies (Thomsen et al., 2004; Jorgensen and Stockmarr, 2009). The idea has been to improve the quality of groundwater recharge, and avoid the need for advanced water treatment, by reducing fertiliser applications and prohibiting pesticide use in critical areas, as well as making significant investment in afforestation, which has the added benefit of providing recreational zones.

Delineation of SPZs

SPZs have to defend against degradable contaminants (for which subsurface residence time is the best counter-measure) and non-degradable contaminants (for which flowpath-dependent dilution must be provided). The key factors influencing the hazard posed by any land-use activity to a given groundwater supply source (well or spring) are the vulnerability of the aquifer concerned to pollution, and the location of the potentially polluting activity in relation to the capture area of the groundwater supply. Figure 2 gives an indication of the land areas required for complete protection of groundwater abstraction in different climatic settings.

As socio-economic pressure for development often makes it untenable to eliminate potentially polluting activities, a subdivision of recharge capture zones is required so that the most stringent land-use restrictions are applied only in areas closer to groundwater sources. A series of generally concentric land-surface zones around the groundwater source is thus defined, through knowledge of – and assumptions about – hydrogeological conditions and contaminant behaviour. These include the total source recharge capture area and the microbiological protection zone (usually the

The SPZ concept is a simple and powerful one, which is readily understood by land-use planners and others who need to make the often-difficult public decisions generated by groundwater protection policies. However, there are a number of hydrogeological situations where the concept encounters significant complications:

- When aquifers are subject to heavy seasonal pumping (usually for agricultural irrigation), as this produces complex unstable zones
- For aquifers whose long-term abstraction considerably exceeds their long-term recharge, with continuously falling groundwater levels and unstable zones
- Where 'losing' surface watercourses occur within the capture zone, through which potentially polluting activity in the upstream catchment could affect groundwater quality
- The presence of multilayered aquifers, where vertical hydraulic gradients may develop, inducing leakage between aquifer units.

Figure 2. Variation in land area needed for complete protection of a groundwater or wellfield source with climatic type

The SPZ concept is equally valid in all environments, but significant problems often occur in defining and implementing them in the urban environment. This is because of the complexity of aquifer recharge processes in urban areas, the frequently large number of wells for various uses, and the fact that the defined SPZs will often already be occupied by industrial and/or residential development. Nevertheless, the delineated zones will serve to prioritise groundwater pollution hazard assessments and quality monitoring, the inspection of industrial premises, and groundwater pollution mitigation measures, such as changes in industrial effluent handling or chemical storage, and the introduction of mains sewer coverage in areas that are highly vulnerable to aquifer pollution.

There are a number of steps in the process of delineating an SPZ. The most important is data acquisition, as information is required not only on aquifer properties, but also on well construction, the operational regime for the source, groundwater levels, recharge processes and rates, and aquifer interaction with surface watercourses. When the primary data have been compiled, they should be synthesised into a conceptual model to provide a clear statement of the groundwater setting. An integrated GIS is a useful means of organising the data, offering visualisation to check for inconsistencies.

The SPZ can be delineated subsequently, using a variety of methods ranging from simple analytical tools to numerical aquifer modelling. One of the most common simplifications involved is to render complex 3D systems to simplified 2D models.

Use of numerical models to address uncertainty

Numerical aquifer modelling is recommended where reasonable hydrogeological data are available, and conditions cannot be readily simplified for use of analytical codes. Where possible, numerical aquifer models with a 'particle-tracking routine' – with small time steps tracking the movement of groundwater toward a source – are preferred.

Models have to be calibrated by comparing their outputs to observed aquifer head conditions. The most rigorous approach to sensitivity analysis is to use a Monte Carlo (statistical-based) approach to define the maximum protection perimeter, which is the envelope of all credible zones (Figure 3). In general terms, the definition of an SPZ becomes less reliable as the groundwater travel time overlap of all plausible combinations, and a zone of uncertainty, defined by the outer envelope of plausible combinations.

The output from the delineation process has to be translated into final source protection zone maps (at scales of 1:25,000 or 50,000), which can be superimposed on aquifer vulnerability maps for the purpose of well pollution hazard assessment.

Natural groundwater quality hazards

Figure 3. Aquifer numerical modelling for SPZ delineation, incorporating zones of confidence and uncertainty

Trace elements make up only about 1% of the naturally occurring dissolved constituents in groundwater, but they can sometimes make it unfit or unacceptable for consumption. The reaction of rainwater in the soil/rock profile during infiltration and percolation gives groundwater its essential mineral composition, as it takes up carbon dioxide, and the resultant weak acid dissolves soluble minerals.

Certain trace elements, notably arsenic and fluoride (Table 1), are discussed here because they are known to occur naturally in some groundwaters at concentrations above WHO drinking water guidelines, with long-term health implications for water consumers. Two recent developments have raised public health concerns. One is the capacity to analyse ever-smaller amounts of dissolved constituents in water, moving from the mg/l (ppm) to µg/l (ppb) level and below. The other is that epidemiological research has advanced, with better understanding of the longer-term health effects of prolonged ingestion of trace contaminants.

If excessive concentrations of trace elements are discovered in groundwater used for domestic water supply, an immediate emergency plan to cope with the potential problem must be defined, and a longer-term strategy identified and outlined. The emergency plan is likely to comprise the following elements:

- Hydrogeochemical evaluation at an appropriate level of detail to enable affected wells to be identified and a reasonable diagnosis of the problem made
- Community guidance on use restrictions and safe locations for wells
- A community health programme to look for symptoms of any health conditions related to drinking water, and immediate patient management.

A number of critical issues are likely to arise. One is that short-term mitigation by closing wells will imply provision of quality-assured bottled or tankered water supplies. The cost of this can be highly sensitive to the ‘action trigger level’ adopted, given the uncertain epidemiology over a range above WHO guidelines. Another is the promotion of a public awareness campaign about the groundwater quality hazard.

A further issue will be the definition of the scale of the investigation, based on the hydrogeological framework, the health hazard from the trace element levels initially encountered, the number of existing wells, and public health criteria, such as the population involved, the probable period of exposure and the protocol for diagnosis of incipient symptoms.

Long-term mitigation

Long-term mitigation of naturally occurring groundwater quality problems raises important issues regarding institutional arrangements and organisational structure. The approach to finding a long-term solution will depend considerably on the scale of the water supply required, the seriousness feasibility need to be considered carefully. A particularly pertinent question, therefore, is how and where to invest for the greatest unit benefit in terms of overall health improvement.

Caution is needed with solutions involving surface water supply and/or water treatment, especially at smaller scale. One reason for this is that inexpensive robust treatment methods to remove trace contaminants at small town, village and household levels are not yet available in developing countries, even if they are now routine in large centralised water treatment plants of the industrialised world. So, bottled water for drinking and food preparation – while using lower quality water for other uses – may be the only feasible solution.

Also, the most cost-effective solution will often be to identify and develop alternative groundwater sources. This, however, will require aquifers containing elevated trace element concentrations to be reliably delineated (both spatially and in depth), with special attention to well design and aquifer monitoring where the preferred solution is to drill deeper to exploit better quality groundwater.

While some large water utilities in developing countries offer fluoride treatment by reverse osmosis, the cost is prohibitive for most small-scale utilities. This has led to 'local innovations' to reduce fluoride concentrations, such as using animal bone or seed cake in storage tanks.

Improved hydrogeological investigation and data management are also needed to help site any wells in areas of high fluoride or arsenic concentrations, together with training of well drillers and the provisions of water quality testing equipment.

Final remark

Groundwater resources are much less vulnerable to quality degradation than surface water bodies. However, once contaminated, aquifer clean-up is a problematic and costly process. So, if best use is to be made of groundwater resources for public water supply, then parallel investments in their management are essential, in terms of systematic quality monitoring and proactive quality protection. It is only with such actions that their critical role in climate change adaptation can be assured. l

Further reading

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***Stephen Foster**, University College London, UK. **Susie Mielby**, Geological Survey of Denmark (GEUS). **Ricardo Hirata**, University of São Paulo, Brazil. **Aleksandra Tubic**, University of Novi Sad, Serbia. **Julia Gathu**, Drilling for Life, Nairobi, Kenya. All are on the IWA Groundwater Management Specialist Group Committee (with **S Foster** as chair).*