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Quantifying the vulnerability of well fields towards anthropogenic pollution: The Netherlands as an example

Igor Mendizabal *, Pieter J. Stuyfzand

VU University Amsterdam, Dept. Hydrology and Geo-Environmental Sciences, FALW, Boelelaan 1085, 1081 HV Amsterdam, The Netherlands
KWR Watercycle Research Institute, PO Box 1072, 3430 BB Nieuwegein, The Netherlands

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SUMMARY

A new method is presented to asses the vulnerability of public supply well fields (PSWFs), other well fields or individual wells.

The Intrinsic Vulnerability Index towards Pollution (VIP) is based on the age, redox level, alkalinity (or acidity), and surface water fraction of the pumped water, resulting in a score ranging from 0 for old, deeply anoxic, high alkalinity ground water to 30 for young, (sub)oxic, acid ground water.

The Specific Vulnerability Index towards Pollutant X (VIP_X) combines VIP with four aspects: the current concentration of X in the pumped water; the mobility or mobilization potential of X in the hydrogeochemical environment as derived from the redox state and alkalinity of the raw water; the land use within the ground water catchment area; and the pollution risk for X, derived from its concentration in shallow groundwater and/or in the infiltrating surface water.

A national survey of all active PSWFs in the Netherlands revealed a low VIP in 50% and high VIP in 9% of them. Most PSWFs with a low VIP pump from very deep aquifers, and those with high VIP from either acidified, phreatic sandy aquifers, (sub)oxic, artificially recharged coastal dunes, (sub)oxic river banks or oxic limestone.

1. Introduction

Groundwater is of major societal significance for many well-known reasons. One of the most important ones is that groundwater normally offers a direct and hygienically safe source of drinking water for public, agricultural, industrial and individual supply (Matthess, 1990). Groundwater resources, however, are becoming extremely vulnerable to a multitude of anthropogenic pollution sources (Appelo and Postma, 2005).

The concept of groundwater vulnerability was introduced by Albinet and Margat (1970), but has repeatedly been redefined (e.g. van Duijvenbooden, 1987; Vrba and Zaporozec, 1994). Nowadays, intrinsic vulnerability is defined as the general vulnerability of groundwater to any contaminant generated by human activities, while specific vulnerability is used to define the vulnerability of groundwater to a particular contaminant or group of contaminants (Daly et al., 2002). Both terms are equivalent to the terms aquifer sensitivity and groundwater vulnerability (USEPA, 1993).

Intrinsic vulnerability assessment is usually based on either hydro(geo)logical or hydrochemical criteria. The purpose is to produce vulnerability maps, which are used for: identification of areas susceptible to contamination, groundwater protection, in environmental management, public information and education (Daly et al., 2002; Witkowski et al., 2004). Maps of the hydro(geo)logical type are mainly derived from a linear combination of a priori subjectively rated and weighted maps of different hydrological and lithological parameters (Aller et al., 1987; Civita and De Maio, 1997; Doerfliger et al., 1999; Foster, 1987; Goldscheider, 2005; Nguyet and Goldscheider, 2006; van Stempvoort et al., 1994; Vías et al., 2006). All these methods, like the frequently applied DRASTIC (Aller et al., 1987), have a predictive character and the system definition depends on the a priori selection of those parameters considered to be decisive for groundwater vulnerability assessment (Gogu and Dassargues, 2000). The hydrochemical approach is to compute a water quality index for all groundwater samples with sufficient analytical data, and map zones with distinct degrees of vulnerability on the basis of this index (Backman et al., 1998; Melloul and Collin, 1998; Saeedi et al., 2009; Stigter et al., 2006). However, this approach mostly is a hybrid of intrinsic and specific vulnerability, because the used water quality index is (also) based on specific contaminant levels.

The specific vulnerability is usually obtained by superimposing the actual pollution sources, which are subdivided on the basis of their pollution potential (urban areas, cultivated areas, waste dumps, industrial complexes etc.), on the intrinsic vulnerability map (Civita, 1994). Such methods have been especially applied to estimate the specific vulnerability to agricultural activities

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* Corresponding author at: VU University Amsterdam, Dept. Hydrology and Geo-Environmental Sciences, FALW, Boelelaan 1085, 1081 HV Amsterdam, The Netherlands. Tel.: +31 20 5987391; fax: +31 20 5989940.

E-mail address: igor.mendizabal@falw.vu.nl (I. Mendizabal).

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(Berkhoff, 2008; Boumans et al., 2005, 2008; Burkart and Feher, 1996; Burkart et al., 1999).

Assessment of both the intrinsic and specific vulnerability of public supply well fields (PSWFs), other well fields or wells also requires the characteristics of the ground water collection system, because characteristics like the depth of abstraction and the contribution of infiltrated surface water have a strong impact on the vulnerability, and may even change over time. Specific vulnerability determination of PSWFs requires the delineation of the well head protection area (WHPA) or water catchment area, and the mapping of land use within them. The delineation of such zones is considered the best way of dealing with the capacity of aquifers to transport contaminants, dilute and attenuate them in the saturated zone (Foster et al., 2002). Intrinsic vulnerability therefore not only depends on the hydrogeological and geological characteristics of the aquifer system but also on the characteristics of the well (field) itself, while remaining independent of the nature of and exposure to the contaminants. Specific vulnerability takes into account the properties of and the exposure to a particular contaminant (or group of contaminants) in addition to the intrinsic vulnerability of the well (field).

In this contribution, a new method of the hydrochemical type is presented to asses the vulnerability of groundwater towards anthropogenic inputs released at the surface, in particular for 'existing' well fields or wells. The added value of this method consists of using data from PSWFs and the structured hydrochemical approach which departs from the Hydrochemical Facies Analysis (HyFA) introduced by Stuyfzand (1990, 1999) and renamed to Hydrochemical System Analysis (HCSA) by Stuyfzand (2006), as a means to map and diagnose all major factors accounting for regional variations in hydrochemistry. This is done by addressing the spatial distribution of groundwater bodies with a specific origin (hydrosomes) and characteristic hydrochemical zones (facies) within each hydrosome. The method was modified by Mendizabal et al. (2010) in order to optimize it for mapping groundwater bodies (hydrosomes) contributing to PSWFs, by defining the hydrochemical facies as a combination of age, redox and alkalinity indices of the pumped water. These three indices are combined here into a single Intrinsic Vulnerability Index towards anthropogenic Pollution (VIP) and a Specific Vulnerability Index towards Pollutant X (VIP_X), with X being either a main constituent, trace element or organic compound.

Salinization of the pumped water due to upconing of natural, brackish groundwater is beyond the scope of this contribution, but it could be addressed in a similar way. The results of a national vulnerability assessment of all PSWFs in the Netherlands are discussed for some of the major water quality problems faced by the Dutch waterworks during drinking water production, i.e. raised levels of NO_3, SO_4, Al, Ni and bentazone (a herbicide).

2. Materials

2.1. Water quality data

The proposed method of vulnerability assessment of a well (field) requires water quality data from various sources: the raw water delivered, groundwater as sampled from shallow observation wells, and surface water, if the raw water delivered is composed of a significant fraction of surface water which infiltrated after for example artificial recharge (AR) or river bank filtration (RBF).

2.1.1. Raw water quality delivered by PSWFs

During a national sampling campaign in the first trimester of 2008, all active PSWFs in the Netherlands were sampled for chemical analysis. Samples were collected following the guidelines described in Mendizabal and Stuyfzand (2009), in order to obtain the hydrochemically most representative sample for each well field. Samples of the mixed raw water were taken from faucets on the transport mains that discharge the water from various or all pumped wells, when these wells had been active for at least a couple of hours. In well fields where the storage capacity of the pumping station limited the number of wells that could simultaneously abstract water, the most representative selection of wells was switched on for obtaining a representative sample of the well field. Variance in water quality between different wells within a PSWF were not addressed in this national survey, except for 35 PSWFs known to tap both a phreatic and confined aquifer. For those PSWFs a separate sample was collected from each aquifer. Thus, a total of 241 samples was obtained from 206 active PSWFs.

Samples were analyzed for a wide set of parameters, including amongst others, macroparameters (main cations and anions, and nutrients), trace elements and the stable isotopes δ^{18}O and δ^{2}H. Temperature, specific electrical conductivity (SEC), pH and dissolved oxygen were measured on site. Samples for analysis of cations, PO_4, SiO_2 and trace elements were collected in 100 ml polypropylene bottles, after filtration in the field through a 0.45 μm Millipore membrane filter, and acidified to pH < 2 by addition of 0.7 ml HNO_3 Suprapur 65%. They were analyzed by ICP-MS + ICP-OES. Samples for analysis of Cl, SO_4, HCO_3, NO_3, NO_2 and NH_4 were collected unfiltrated, in 100 ml polypropylene bottles and stored in a refrigerator for less than 3 days before analysis by spectrophotometry. Sulphide (HS^-) was not measured because of expected low concentration levels, expected problems with sample preservation and financial limitations. Samples for analysis of δ^{2}H and δ^{18}O were collected in 30 ml brown glass bottles without filtration and without any preservative. The bottles were fully filled and hermetically closed, to avoid atmospheric gas exchange. The samples were kept in the dark and at 4 °C until analysis by mass spectrometry.

Data on pesticides were obtained from the national PSWF data bank, an extensive database containing numerous properties of all Dutch PSWFs, annual means of their raw water quality as analyzed by the individual water utilities on a routine basis, and the annual total volumes pumped since 1898 (Mendizabal and Stuyfzand, 2009).

2.1.2. Dutch national groundwater quality monitoring network

Groundwater quality is regularly monitored in The Netherlands by means of the Dutch national groundwater quality monitoring network (LMG). LMG was established in 1979 by the Dutch National Institute for Public Health and the Environment (RIVM) in order to quantify human impacts on groundwater quality in space and time. The network comprises 400 piezometer nests evenly distributed throughout the country, with a higher density in areas relevant for drinking water production (Reijnders et al., 1998; van Duijvenboodem, 1987). All wells were constructed using a standardized drilling method, dimensions and well completion, with 2 m long screens at about 9, 15 and 24 m BS (below surface). The land use around every well is well documented. The upper (9 m BS) and lower piezometers (24 m BS) are sampled and analyzed for macro and micro constituents every 1–4 years, depending on the vulnerability of the groundwater (Wever and Bronswijk, 1998). The other piezometer is sampled occasionally. LMG is a valuable network that has been used in numerous studies to determine shallow groundwater quality on a national scale (Frapporti, 1994; Meinardi et al., 2003; Reijnders et al., 1998; van den Brink et al., 2007). Since 1989, the network has been enlarged with 12 provincial groundwater quality monitoring networks (PMG), which follow the same construction and sampling protocol for optimal integration. PMG fulfills additional purposes, like