Journal of Hydrology 450–451 (2012) 279–292

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Hydrochemical trends for public supply well fields in The Netherlands (1898–2008), natural backgrounds and upscaling to groundwater bodies

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ARTICLE INFO

Article history:
Received 12 October 2011
Received in revised form 16 April 2012
Accepted 20 April 2012
Available online 8 May 2012
This manuscript was handled by G. Syme, Editor-in-Chief, with the assistance of Craig T. Simmons, Associate Editor

Keywords:
Groundwater
Water bodies
Monitoring
Natural background
Trends analysis
The Netherlands

SUMMARY

Statistical trend analysis is applied to a 110 years long groundwater quality time series from the national network of public supply well fields (PSWFs) in The Netherlands. Such a groundwater quality monitoring network should be available in many countries, so that approaches and experiences presented here could be of interest world wide.

Trendless concentration data series measured in the early years, which should bear the least anthropogenic influences, are selected to quantify the regional natural background concentration levels (NBLs) of groundwater resources at the depth of abstraction. Trends in the period 1960–2005, which contained a more homogeneous data set, are normalized to drinking water standards, mapped in planar view and cross sections, and used to identify the responsible hydrochemical processes. Seven representative trend bundles are defined by aggregation of trends for individual chemical parameters. Trend reversals due to either environmental sanitation measures or well field adaptation measures are identified by comparing significant trends obtained for two different periods within the time series.

Natural background levels (NBLs) for individual PSWFs are upscaled to the national groundwater body level (as reported to EU), by aggregating them according to a PSWF typology based on a Hydrochemical System Analysis. This aggregation method groups together PSWFs that deliver waters of the same origin and similar hydrogeochemical environment. PSWFs delivering old groundwaters with a very stable quality are clearly differentiated from PSWFs pumping highly vulnerable aquifers characterized by strongly deteriorating water quality trends.

Results are presented on national maps of The Netherlands with NBLs and water quality trends for selected major constituents. A normalized concentration change index (NCC) is defined and mapped to relate the quality difference between a recent survey (in 2008) and calculated NBLs, to the EU drinking water standards.

1. Introduction

European legislation enforces all EU member states to monitor and assess the quality and quantity of their waters on the basis of common criteria and to identify and reverse groundwater pollution trends before 2015 (EU, 2000, 2006, 2008). For this purpose, numerous national groundwater quality monitoring networks (NGQMNs) are being developed, not only in Europe like in Denmark (Juhler and Felding, 2003), The Netherlands (van Duijvenbooden et al., 1993) and the UK (Ward et al., 2004), but also in other countries, a.o. Egypt (Dawoud, 2004), Korea (Kim et al., 1995; Lee et al., 2007), New Zealand (Daughney and Reeves, 2005), South Africa (Parsons and Tredoux, 1995) and the US (Rosen and Lapham, 2008). Such networks are regularly monitored to fulfill three main purposes: (1) establish the current groundwater quality state in relation to anthropogenic inputs, soil use, soil type and hydrogeological conditions (Boumans et al., 2005; Frapporti et al., 1993; Fraters et al., 1998; Meinardi, 2003; Pebesma and de Kwaadsteniet, 1997; Reijnders et al., 1998; van den Brink et al., 2007); (2) identify trends in groundwater quality (Batlle Aguilar et al., 2007; Boumans et al., 2005; Broers and van der Grift, 2004; Burow et al., 2007, 2008; Daughney and Reeves, 2006; Frapporti et al., 1994; Reynolds-Vargas et al., 2006; Stuart et al., 2007; Visser et al., 2009; Xu et al., 2007); and (3) establish the regional natural background (unpolluted baseline) level of concentrations in groundwater (Coetsiers et al., 2009; Edmunds et al., 2002; Edmunds and Shand, 2008; Fraters et al., 2001; Lee and Helsel, 2005; Limbrick, 2003; Wendland et al., 2008).

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0022-1694/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2012.04.050

The current groundwater quality is successfully established with data gathered via these networks. Groundwater quality trend detection and quantification of natural background levels (NBLs) are, however, hindered by insufficient length of time series, which in most cases do not cover the period of interest (Visser, 2009). Such networks are operational for 20–30 years at most, while the main groundwater quality deteriorating processes, due to intensive agriculture, urbanization, industrial activities and atmospheric pollution, threaten groundwater resources for more than a century.

Establishing the natural background composition of groundwater is crucial to identify and quantify contamination of groundwater by anthropogenic sources. The natural background level (NBL) is defined as the concentration level in water as controlled by natural geogenic, biological and atmospheric processes. The regional background levels obtained for young groundwaters normally show clear anthropogenic influences including contamination, which makes it hard today to define their NBL. The problem is usually solved through backward trend analysis of young groundwaters or by selecting, if available, a data subset from older monitoring networks that is assumed to reflect the natural composition, as evidenced by hydrological and geochemical tracers (Edmunds, 2008). In such cases, the data set selection is crucial and old analyses are the only direct reference to establish the natural background concentration (Griffioen et al., 2008).

A monitoring network that is available in most countries while being also useful to fulfill the above mentioned three purposes, is the network of public supply well fields (PSWFs), which are monitored on a regular basis as an integral part of the quality surveillance of national drinking water supply. The network has already successfully been used in The Netherlands to (1) establish the current groundwater quality status at the depth of abstraction and on the scale of groundwater bodies (GWBs; defined as a coherent, three-dimensional unit of groundwater with a specific origin) (Mendizabal et al., 2011), and (2) quantify the intrinsic vulnerability of PSWFs and their specific vulnerability towards numerous pollutants, either macro-constituents, trace elements or organic compounds (Mendizabal and Stuyfzand, 2011).

The advantages and disadvantages of this monitoring network as compared to dedicated networks that use specific monitoring (observation) wells are discussed in Mendizabal and Stuyfzand (2009). The main advantage of PSWFs is their longer period of record, which in many cases fully covers the period of interest. In The Netherlands, where the centralized monitoring of the raw water quality of PSWFs started in 1898, the earliest data provide a valuable means to assess the NBL of the aquifers they pump. In addition, they can also be considered representative for a huge volume of groundwater (0.1–20 Mm^3), the quantity of which is registered as well. The mixed character of raw water samples from a PSWF is, however, also one of the main disadvantages, due to a more laborious interpretation as compared to samples from conventional observation wells. In Mendizabal and Stuyfzand (2009), guidelines are introduced to interpret such data, based on (a) historical changes in the well field, (b) the origin of the groundwater mixture (local precipitation, river bank filtrate (RBF), artificially recharged surface water (AR) or recent/ancient sea water), and (c) the approximate age distribution of the water pumped.

In this contribution, a unique database with 110 years of water quality data from a maximum of 351 PSWFs in The Netherlands is used for the first time, to determine NBLs and hydrochemical trends for selected parameters and for individual groundwater bodies. Trends for Dutch PSWFs were investigated before (Cirkel and Stuyfzand, 2004; Reijnders et al., 1983; van Beek et al., 1990), but were limited to a much shorter time interval covering 25 years at most. This paper aims at demonstrating that PSWFs constitute a very valuable monitoring system indeed (although often neglected), and at indicating how their long records can be used to establish NBLs and show impacts of environmental pollution. New approaches presented here include simple statistics for determining NBLs, trends and trend reversals, a normalization procedure for trend mapping, the definition and mapping of so-called trend bundles and the normalized concentration change index, and a method to upscale NBLs for individual PSWFs to their national groundwater body with distinction of hydrochemical zones.

2. Materials and methods

2.1. Hydrogeological setting

The major fresh groundwater resources in The Netherlands, pumped by PSWFs, are contained in unconsolidated siliclastic sediments of Tertiary and Quaternary age, composed of alternating layers of marine, eolian, fluvial, paludal and glacial origin. Only one, moderately large fresh groundwater body is observed in hardrock, namely in Cretaceous limestone in the south-east of the country (Fig. 1). A small fresh groundwater body in sandstone located in the eastern part of The Netherlands was also used for drinking water production in the past and is still partly used by one PSWF. The major fresh groundwater bodies with active recharge are found in the Holocene coastal dunes, the northern, eastern, central and southern Pleistocene uplands, and the Cretaceous limestone hills (inset of Fig. 1). The southern Pleistocene sands are underlain by a deep confined aquifer recharged either in Flanders (Belgium) or in the Dutch province of Brabant (Fig. 4; N–S and SW–SE), with an estimated age in the order of 1000–10,000 years (Mendizabal et al., 2011).

Groundwater resources have been supplemented by AR systems mainly in the coastal dunes and by RBF along the rivers Rhine and Meuse. These particular PSWF systems are also included in this study. All PSWFs together supply about 1000 Mm^3/year (81%) of the drinking water in The Netherlands. Groundwater resources were subdivided into fairly homogeneous groundwater bodies with specific origins (hydrosomes) and characteristic hydrochemical zones (facies) within each hydrosome by Mendizabal et al. (2011). Such a Hydrochemical System Analysis (HCSA) undertaken upon all active 208 PSWFs in 2008 yielded nine hydrosomes (seven hydrosome complexes and two hydrosome types) and eleven facies parameters, defined on the base of age, redox and alkalinity indices. The main characteristics of these major hydrosomes are summarized in Table 1.

A hydrosome complex is composed of various adjacent hydrosomes with a very similar origin and recharge area and the complex members cannot be easily discerned from each other with environmental tracers. A hydrosome type is characterized by a similar type of recharge water, like river water in case of RBF or AR hydrosomes. Hydrosomes belonging to the same type may have a totally different chemistry because of different source waters (for instance the Rhine River, Meuse River or Lake Yssel) and they do not need to be adjacent.

Extension of such classification to 143 abandoned PSWFs resulted in the addition of two hydrosome complexes: (1) hydrosome complex B, a small fresh groundwater body in the so-called Bentheimer sandstone, in the eastern part of The Netherlands; and (2) hydrosome complex W, a shallow aquifer system of marine sands in the western polder area. The spatial distribution of the 11 hydrosomes is given in Fig. 1.

2.2. Data collection and preprocessing

In The Netherlands, the raw water quality and volumes pumped from all PSWFs are reported four times a year to the authorities, conform Dutch legislation (Waterleidingbesluit, 1984). These routine