Journal of Hydrology (2008) 362, 220–233

available at www.sciencedirect.com

ScienceDirect

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

Use of environmental isotopes to define the capture zone of a drinking water supply situated near a dredge lake

Willibald Stichler [a], Piotr Maloszewski [a,*], Bruno Bertleff [b], Ralph Watzel [b]

[a] Helmholtz-Zentrum München — German Research Center for Environmental Health, Institute of Groundwater Ecology, Ingolstädter Landstrasse 1, D-85764 Neuherberg, Bavaria, Germany
[b] Geological Survey of Baden-Württemberg, Albertstrasse 5, D-79104 Freiburg, Germany

Received 10 December 2007; received in revised form 17 August 2008; accepted 26 August 2008

KEYWORDS
Surface—groundwater interaction;
Stable isotopes;
Capture zone;
Drinking water supply;
Mathematical modelling;
Lake Leis

Summary Lake—ground water interactions in the vicinity of a dredge lake (Lake Leis; SW Germany) were studied by means of the stable isotopes (^{18}O, ^{2}H) mainly to determine the capture zone of a pumping well for the drinking water supply to the nearby town of Baden-Baden. The water supply is situated in a Quaternary gravel aquifer of the Rhine Valley. Numerical simulation performed using a two-dimensional water flow model was not able to characterise the capture zone uniquely. Several best fit options were possible by applying the values of hydraulic conductivities obtained from the pumping tests. As a result it was not possible to define whether Lake Leis is situated either completely inside or fully outside of the capture zone. To overcome this problem and to define the shape of the catchment area of the water supply precisely, a two-dimensional water flow and tracer transport model was established using both hydraulic heads and isotope data. The isotope data were applied to determine the proportion of lake water in down-gradient pumping and observation wells. Additionally, the isotope compositions of lake water and those in observation wells, measured as a function of time, were used to determine the mean water velocity ($v = 0.6$ m/d) along some selected 200 m long flow-paths. Based on known porosity and hydraulic gradient values, a hydraulic conductivity of about $k = 6 \times 10^{-4}$ m/s was determined for the central area down-gradient of the lake. This hydraulic conductivity and the proportion of lake water in the groundwater were used to calibrate a numerical two-dimensional regional scale transport model. The study demonstrates that it is possible to calibrate a water flow model in the vicinity of a dredge lake uniquely, only when

* Corresponding author. Tel.: +49 89 3187 2583; fax: +49 89 3187 3361.
E-mail address: maloszewski@helmholtz-muenchen.de (P. Maloszewski).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2008.08.024

stable isotope signals measured in a time series in both the lake and groundwater are taken into consideration. The calibrated model finally enables the capture zone of the production well to be precisely defined.

Introduction

In many densely populated regions of the world groundwater resources can no longer meet the demand for drinking water. Additionally, the requirements for the protection of drinking water are often in conflict with industrial, agricultural or human activities. This is especially true in the case when existing activities have to be shifted into the capture zone of the water supply. In such cases, the responsible authority needs an estimate of the vulnerability of the water supply to potential pollution before it can give permission for the implementation of any such activity.

The present study focuses on the groundwater flow surrounding an artificial lake dredged for gravel production and on the interaction between surface and groundwater. The local decision makers intend to use existing dredged lakes for recreation, which may cause pollution of the groundwater and consequently the drinking water supply. The focus of the study was to determine the capture zone of the water supply situated in the neighbourhood of a selected dredge lake. The study was done initially using only hydrological and geological data, which were later combined with stable isotope measurements.

Lake—groundwater interactions have been the subject of much attention in the literature, however the focus has been mainly on: (1) traditional modelling of the water flow in the surrounding lakes (e.g. Winter, 1978, 1983; Cheng and Anderson, 1994; Kacimov, 2000, 2007; Abbo et al., 2003) and (2) application of environmental tracer data to calculate water balance in lakes (e.g. Zuber, 1983; Gonfiantini, 1986; Herczeg and Imboden, 1988; Yehdegho et al., 1997; Katz et al., 1997 or Kumar et al., 2001). Only a few papers focus on the application of environmental isotope data for estimating flow parameters in bank filtration studies (e.g. Stichler et al., 1986; Maloszewski et al., 1987). Even fewer reports discuss the application of isotope data to calibrate or to constrain a numerical groundwater flow model (e.g. Krabbenhoft et al., 1990 or Turner and Townley, 2006).

The present study was performed as a part of a general research program conducted in the Rhine Valley by the State of Baden-Württemberg, Germany. The main purpose of this program was the estimation of surface—groundwater interactions in the surroundings of dredge lakes in the valley. This large-scale program included lakes possessing various geometric properties (ratio of water surface area to depth of the lake) as well as lakes with various hydraulic connections to the groundwater flow system. Studies of stable isotopes, the hydro-chemical situation in lake water and surrounding groundwater were used to estimate the spatial and temporal variations of lake water influx into the aquifer. The ability to define the proportion of lake water in the down-gradient aquifer at a specific location and time is the basis for the evaluation of possible changes in groundwater quality due to lake water influx. A summary of hydrological, geological, isotope and chemical data obtained so far has been published by Bertleff et al. (2001). In that paper, Lake Leis in the Rhine Valley (Fig. 1) is analyzed in detail to determine whether or not it lies within the capture zone of the drinking water supply for the town of Baden-Baden.

Area of investigation

Lake Leis is located in the central section of the Rhine Valley in Southwest Germany near the town of Baden-Baden (population 55,000) (Fig. 1). Its volume was estimated to be 1.16×10^6 m^3. The lake covers a surface of 87,500 m^2 and has an average depth of 13.3 m. Its maximum depth is 20 m. The groundwater inflow rate to the lake, estimated from hydrogeological data, varied between 4 and 50 l/s, while, based on isotope data, it was found to be 45 l/s. There is neither surface inflow nor run-off from the lake. The mean turnover time of water in the lake, based on isotope data, is estimated to be 0.82 years. The lake resulted from the excavation of an Upper Quaternary sandy gravel layer, which represents the most important aquifer in the valley. These layers are underlain by almost impermeable fine-grain deposits (Fig. 2). Several ground water observation wells are situated in the vicinity of the lake as well as the drinking water facility of Baden-Baden. The facility has an average production rate of Q = 80 l/s. It consists of one horizontal pumping well (HORI) and a line of 20 vertical wells (VERTI 1—10 and 11—20) penetrating the aquifer completely. The vertical wells constructed for water production were however, never used, and these are considered here as observation wells. The horizontal pumping well (HORI) consists of eight horizontal screened tubes with lengths varying between 30 and 45 m. They are situated at a depth of 28 m below the surface. The radius of the drain-system is 60—75 m. Fig. 1 presents a regional map of the piezometric head lines of the gravel aquifer before the pumping well was installed. Lake Leis is situated between the lines of observation wells (36—39) and (69—72), respectively. The hydraulic heads decrease from 121 m a.s.l. in the up-gradient of the gravel aquifer to 115 m a.s.l. northwest of the lake, with a mean natural hydraulic gradient of i = 0.002. The natural hydraulic gradient indicates a southeast—northwest direction of regional ground water flow. The mean thickness of the saturated zone of the gravel beds (m) varies between 5 m (southeast) 30 m (northwest), as shown in the geological cross-section (A—A′) in Fig. 2. The effective porosity was estimated to be approximately n = 0.125. The transmissivity T, estimated from several pumping tests, lies between 1×10^{-2} m^2/s and 2×10^{-2} m^2/s. These values correspond to a hydraulic conductivity range between $k = (3$—$40) \times 10^{-4}$ m/s. For the assumed porosity and hydraulic gradient this yields a mean regional groundwater velocity (v) between 0.4 m/d and 4 m/d. In the area under investigation the mean annual precipitation is 950 mm/a, while the