Journal of Hydrology 517 (2014) 791–802

Contents lists available at ScienceDirect

Journal of Hydrology

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

Role of a groundwater–lake interface in controlling seepage of water and nitrate

S. Karan [a], J. Kidmose [a,b], P. Engesgaard [a,*], B. Nilsson [b], M. Frandsen [b,c], D.A.O. Ommen [d], M.R. Flindt [d], F.Ø. Andersen [d], O. Pedersen [c]

[a] *Department of Geosciences and Nature Management, University of Copenhagen, Øster Voldgade 10, 1350 K, Denmark*
[b] *Department of Hydrology, Geological Survey of Denmark and Greenland, Denmark*
[c] *Department of Biology, University of Copenhagen, Denmark*
[d] *Institute of Biology, University of Southern Denmark, Denmark*

ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form 4 June 2014
Accepted 9 June 2014
Available online 18 June 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Christophe Darnault, Associate Editor

Keywords:
Groundwater
Lake
Nitrate
Plants
Modeling

SUMMARY

The effects of the hydraulic characteristics of a groundwater–lake interface on discharge and nitrate loading to a lake were investigated. The interface is defined as the zone separating the adjacent aquifer (10's of m) and the lake bed (10's of cm) itself. The study combines field data using several tracers (water, oxygen isotopes, and nitrate) and numerical modeling. The hydraulic head distribution, a nitrate plume and seepage rates were observed over a two-year period along a ~100 m long transect reaching from an agricultural field into the lake. The groundwater–lake interface system was simulated with a 2D steady state flow and nitrate transport model (FEFLOW). The observations showed that discharge to the lake was doubled-peaked, with a peak discharge near the shore line followed by an almost (classical) exponential decrease, and a second peak further off-shore. The nitrate plume also extended 60–80 m off-shore. By calibrating the model to measured discharge and the outline of the nitrate plume it was demonstrated that; (1) the ratio of horizontal to vertical hydraulic conductivity (anisotropy) was very important and on the order of 50 and (2) the lake bed acted as a hydraulic barrier by having a much lower hydraulic conductivity than that of the relatively homogeneous aquifer. We suggest that the barrier is formed by an extensive plant cover that can trap finer materials and produce a surface colmation layer. The simulation results show that when a barrier is present the total groundwater discharge to the lake can be up to a factor of two lower and that approximately 50% of the nitrate bypasses the barrier. This proportion of the nitrate loading will therefore also bypass the plant cover and discharge directly to the lake off-shore potentially leading to algal blooms under N-limited conditions in the lake water column.

1. Introduction

Groundwater-dominated lakes around the world are especially vulnerable to pollution by nutrients leached from agricultural areas in the catchment. It is therefore of interest to know how a groundwater–lake interface controls seepage of flow in order to quantify the loading of nutrients to the lake. The groundwater–lake interface is often regarded as a flow convergence zone of shallow and deep groundwater where groundwater originating from different sources mix near the lake shore. For example, Schafran and Driscoll (1993) found that the composition of groundwater discharging to a lake was dependent on the origin of groundwater from a small forested watershed. Near the shore line, the input of solutes was controlled by acidifying processes in the adjacent shallow soil horizons, whereas farther from the shore line, inputs were controlled by weathering processes due to transport through the aquifer sediments over longer distances. Similar mixing of groundwater of different ages was discussed by Kidmose et al. (2011), who used Chloro-Fluoro-Carbons (CFCs) to assign apparent ages in the range of a few years to >30 years to groundwater discharging to Lake Hampen, Denmark. Groundwater with apparent ages of ~10 years came from the part of the crop field nearest to the lake, mixing near the lake shore with nitrate-containing groundwater that infiltrated from the same crop field further upstream, and deeper and older nitrate-free groundwater. Lake Hampen, with close to 2/3 of the water coming from groundwater, is one of the few remaining oligo-mesotrophic lakes in Denmark with a major distribution of rosette plants and a good example of lakes, where shifts in the lake ecosystem in the past decades have been related to

* Corresponding author. Tel.: +45 23812354.
E-mail address: pe@ign.ku.dk (P. Engesgaard).

http://dx.doi.org/10.1016/j.jhydrol.2014.06.011
0022-1694/

increased inputs of nutrients from groundwater discharging from agricultural areas (Ommen et al., 2012).

The interaction between groundwater and a lake is controlled by a number of factors. If the aquifer and lake bed can be assumed to be one homogeneous unit it has been demonstrated theoretically (McBride and Pfannkuch, 1975) and in several field studies (e.g. Lee et al., 1980) that discharge (here defined as upward seepage to a lake) decreases exponentially with distance from the lake shore (Lee et al., 1980; Cherkauer and Nader, 1989; Schafran and Driscoll, 1993). Pfannkuch and Winter (1984) investigated how the geometry of a groundwater–lake interface, i.e., how an increase in the width ratio (WR, defined as half-lake width divided by aquifer thickness) or lake depth penetration ratio (LD, defined as the lake depth divided by aquifer thickness) cause stream line crowding near the lake shore under isotropic conditions. They went on to demonstrate that with anisotropy in the hydraulic conductivity (K_h/K_v, where K_h and K_v are the hydraulic conductivities in the horizontal and vertical directions, respectively) stream line crowding is less apparent and discharge occurs over a wider section of the lake bed. Similar results were obtained earlier by Lee et al. (1980) and later by Genereux and Bandopadhyay (2001).

An important control on groundwater exchange with lakes is geological heterogeneity at various scales. Cherkauer and Nader (1989) suggested that protrusions of highlypermeable sediments into lower-permeability units near the lake (as observed from seismic profiles) could be the cause of significant off-shore discharge. Kidmose et al. (2011) developed a groundwater–lake catchment model and found a better agreement with seepage data by specifying a high-permeability lake bed leakage zone near the shore line and a low-permeable leakage zone off-shore (as observed from georadar images). Likewise, Kidmose et al. (2013) showed that a low-permeable lake bed caused the majority of groundwater to flow beneath the lake and discharge at the opposite shore line. At a smaller scale, Kishel and Gerla (2002) found that discharge did not follow an exponential decrease, but rather changed irregularly controlled by small-scale (<1 m) heterogeneities in the aquifer and lake bed. Not much work has been carried out on the influence of the lake bed itself on discharge despite that this part of the interface likely is hydraulically different from the underlying aquifer unit. Rosenberry et al. (2010) discuss some of the mechanisms responsible for surface colmation (clogging of the sediment–water interface) and straining (infiltration of finer materials to pore spaces of coarse material below the sediment–water interface) and conducted seepage measurements at two lakes trying to look into the effects of disturbing the upper sediments of a lake bed on seepage from the lake to groundwater (i.e. recharge). In all cases, disturbance (e.g., by walking on the lake bed) caused a substantial increase in seepage. Another example is that of Frandsen et al. (2012) who speculated that a plant cover in the littoral zone may form hydraulic barriers by trapping finer material, which was used to explain the 7-fold increase in discharge through their in-situ growth-chambers consisting of technical sand and plants installed into lake beds (replacing the original lake bed). The hydraulic barrier could be as thin as 10–15 cm (root zone of plants). Genereux and Bandopadhyay (2001) numerically explored such effects (here a 2 m uniform thick lake bed) and found that decreasing the hydraulic conductivity caused the distribution of discharge to flatten out from the exponential trend forcing more groundwater to discharge off-shore. Rosenberry (2000) used the observations of an unsaturated-zone wedge beneath a lake to calibrate a variable-saturated flow model by changing the hydraulic properties of the aquifer and lake bed. He found that the contrast in hydraulic conductivity between the aquifer and lake bed (or barrier effect) and the anisotropy were correlated and the simulated extension of the unsaturated-zone wedge sensitive to changes in these parameters.

Despite these many investigations, of which most have been of a modeling character, only a few have included reactive or non-reactive tracers (e.g., Lee et al., 1980; Schafran and Driscoll, 1993). Very few studies have included solute transport modeling; examples are Lee et al. (1980), Kang et al. (2005) and Schuster et al. (2003), who used 1D analytical models to estimate fluxes across a lake bed from Chloride and $^{18}\delta O$ profiles. Cherkauer et al. (1992) and Sacks et al. (1992) applied 2D groundwater flow and transport models to simulate groundwater–lake interactions for complete lake systems, while Krabbenhoft et al. (1990) used 3D models to simulate $^{18}\delta O$ plumes on the down-gradient/up-gradient side of a lake. Most of these modeling studies have been at spatial scales, where it was not possible to use tracer information to resolve how discharge through the lake bed takes place. An exception is the work by Lee et al. (1980), who performed a salt tracer experiment below a 600 m^2 lake bed and tracked the movement of the salt with an extensive network of multi-level sampling wells and seepage meters (length scale <10 m). A 2D flow model was subsequently used to estimate flow patterns (and anisotropy ratio) and a 1D model was used to estimate longitudinal dispersivity based on estimated fluxes.

The objective of the current study was to use water, oxygen stable isotopes, and nitrate as tracers to improve our understanding of how a groundwater–lake interface affects flow and transport processes. Our main motivation was to examine if and how a lake bottom with underwater vegetation (where plant uptake of nitrate and nitrate reduction may occur) may act as a barrier to seepage and control the loading of nitrate to the lake. Our investigation methods were; (a) two years of monitoring of a nitrate plume at the groundwater–lake interface, (b) small-scale measurements of discharge using water (seepage meters) and $^{18}\delta O$ (diffusion sampler) as tracers, and (c) 2D numerical simulation of flow and nitrate transport.

2. Field site and methods

2.1. Site description

Lake Hampen is located in the Western part of Denmark, Fig. 1A, just east of the main advance of the last glacier of the Late Weichselian glacial maximum (Houmark-Nielsen, 1989). The lake was formed as a kettle hole. When the ice cover retreated, it left behind a 15–35 m layer of coarse melt water sands and gravels in the area close to the lake with tertiary marine silty clays present below the glacial sediments (Kidmose et al., 2011). Groundwater flows to the lake from the North–East, East and South–East directions and lake water recharges the aquifer mainly in the West, Fig. 1. The lake is characterized as a flow-through lake. Precipitation was measured to 901 mm/yr in 2008. Average lake stage was around 79 m above sea level (m a.s.l.) in 2008, and fluctuates in normal years by about 0.3 m (Kidmose et al., 2011). Two small inlets from Lake Krag and Lake Trold to the North–East and South–East (not shown in Fig. 1A) contribute with negligible inflows only during winter seasons. A small outlet drains the lake on the Western side corresponding to about 200 mm/yr (Kidmose et al., 2011), which is roughly 6% of the total flow out of the lake (i.e., recharge and evaporation; Ommen et al., 2012).

The lake catchment is approximately 912 ha (excluding Lake Hampen; Ommen et al., 2012) comprised of forested and agricultural areas. A farm is located on the north-eastern shoreline and farm land covers 6 % of the lake perimeter or about 300 m, Fig. 1A. Very high nitrate concentrations have been measured in groundwater in the area between the farm land and lake (Ommen et al., 2012).