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Water flow and nitrate transport through a lakeshore with different revetment materials

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SUMMARY

As an important part of a transition zone surrounding a lake, lakeshore plays a critical role in connecting hydrology and biochemistry between surface water and groundwater. The shape, slope, subsurface features, and seepage face of a lakeside slope have been reported to affect water and nutrient exchange and consequently the water quality of near-shore lake water. Soil tank experiments and Hydrus-2D model simulations were conducted to improve our understanding of the influence of slope revetment materials (SRMs) on water flow and solute transport in a lakeshore zone. The low hydraulic conductivity of SRMs affected flow patterns in the lakeshore zone and resulted in a local increase of the groundwater table near the slope face. Water and solute flux distributions on the slope face under bare-slope conditions followed an exponential function. Fluxes were concentrated within a narrow portion of the slope surface near the intersection point between the lake water level and the slope face. Surface pollutants (for example from fishponds and paddy fields surrounding a lake) were transported into the lake along shallow groundwater through both unsaturated and saturated zones. The SRMs on the slope face affected the ratio of water and solute fluxes in the unsaturated zone, increasing along with the decline of the hydraulic conductivity of SRMs. Furthermore, as the hydraulic conductivity of SRMs decreased, the retention time and the potential for oxygen reduction correspondingly increased, which affected the nitrogen transport and transformations in the lakeshore zone. Simulated and experimental results indicate that if concrete along the shoreline of Lake Taihu is replaced with a relatively high-conductivity lime or the slope is left bare, water fluxes will increase less than solute fluxes, which will rise significantly, in particular in the unsaturated zone and along the seepage face. On the other hand, the largest water and solute fluxes along the shoreline for the bare and lime-slope conditions will be located higher at the slope than for the concrete-slope conditions. Hydrus-2D provided a good description of complicated hydrodynamic and solute transport/transformation conditions in the lakeshore zone.

1. Introduction

Lakeshore is an important component of the transitional zone surrounding a lake and plays a critical role in connecting hydrological and biogeochemical cycles of near- and off-shore regions (Ostendorp, 2004). Lake water, groundwater, and soil water mutually interact in the lakeshore zone, while pollutants are subject to concurrent transport and transformation processes under these complex hydrological conditions. The lakeshore zone is often considered an effective buffer region that retards pollution from surrounding land areas before it enters into lake water (Howarth et al., 2011). Recently, increasing attention has been given to the importance of a riparian zone (including a lakeshore) and attenuation of nitrates and other pollutants in this region (Ostendorp, 2004; Burgin and Groffman, 2012). A large number of studies have been carried out evaluating the effects of the slope, width, and shape of a lakeshore on hydrological and solute cycles in this zone (Cey et al., 1998; Genereux and Bandopadhyay, 2001; Li et al., 2007; Zhu et al., 2012). However, the effects of different slope revetment materials (SRMs) used on a lakeshore slope on hydrological and biogeochemical processes still have not been thoroughly studied.

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In essence, SRMs used on the waterside slope affect local hydraulic conductivities (Mohamed, 2006) and consequently the flow direction and fluxes, flow pathways, retention times, and even the soil reduction–oxidation potential (Lee, 2000; Lassabatere et al., 2004; Bouazza et al., 2006). The hydraulic conductivity of the near shore region significantly affects inflow/outflow hydrodynamics of a shoreline (Lee, 2000). Genereux and Bandopadhyay (2001) reported for inflow lakes that adding low-conductivity lake sediments, and decreasing their conductivity, produced a shift of groundwater seepage further offshore. Increasing the anisotropy of the surrounding porous medium had the same effect.

SRMs used in China mainly include concrete (with an extremely low conductivity), but also other materials such as ecological concrete (with a medium–high conductivity), lime with geotextiles (with a relatively low conductivity), and other materials (Wang and Luo, 2006; Yao and Yue, 2012). The present shoreline of Lake Taihu, the third largest freshwater lake in China, is almost entirely covered by a concrete material on the waterside slope in order to protect people and agricultural crops against floods (Hu et al., 2011). During the past several decades, the importance of the concrete lake shoreline to prevent erosion due to floods and wind waves could not been questioned. Nevertheless, as public preference for natural landscaping increased in importance and the near-shore lake water quality decreased, detrimental functions of the concrete lakeshore started to be discussed and questioned. Some researchers have suggested that the concrete shoreline should be replaced with materials that are more natural in order to rebuild the connection between near-shore and off-shore zones. Some have suggested that the lake shoreline should be returned to natural conditions (namely natural soils with grass) (Yang et al., 2005; Shaw et al., 2011). Others have insisted that the flood control function of the lake shoreline should be preserved by using a low conductivity material with embedded geotextiles (Nahlawi et al., 2007; Lamy et al., 2013). However, it is not well understood how such changes would alter hydrological and biogeochemical processes in the lakeshore zone. Hydraulic coupling between Lake Taihu and groundwater is difficult to assess through in-situ observations because of the presence of the concrete material at the lake shoreline. Therefore, before making any engineering decisions, preliminary studies have to be carried out to evaluate the effects of different SRMs on hydrological and biochemical processes in the lakeshore zone. More research is also definitely needed to evaluate the effects of the lake water level on shoreline groundwater processes (Schneider et al., 2005).

The exchange of water and solutes between groundwater and lakes is a complex process, and it is still a challenge to understand its temporal and spatial variability (Kidmose et al., 2011). Models are useful tools for identifying various hydrological factors that affect groundwater and solute discharge fluxes into sensitive surface water bodies such as lakes and wetlands (Lee, 2000; Simpson et al., 2003). The Hydrus-2D model, which has been used widely in similar research studies (e.g., Lee, 2000), was therefore used to simulate these processes in order to improve our understanding of water flow and nitrate transport processes in the lakeshore zone.

To improve our understanding of environments of lakeshore zones, we have conducted both laboratory soil tank experiments and corresponding numerical simulations using the Hydrus-2D model. Obtained data were analyzed to reveal general characteristics of water and nitrogen regimes in the lakeshore zone covered using three different SRMs. The effects of SRMs on distributions of water and solute fluxes on the slope face were studied in particular. Furthermore, relative fractions of water and solute fluxes passing through seepage face and submerged zones on the slope face were compared for the three SRM-cover conditions in order to better understand the transport pathways from land surface pollutant sources (for example from fish ponds or paddy fields).

2. Material and methods

2.1. Soil tank experiment

2.1.1. Design and set-up

A large soil tank (Fig. 1a) was used to simulate water flow and solute transport in the lakeshore zone. The tank was filled with soil layer by layer; each evenly compacted using a heavy object. The lakeside slope (α) was set at about 35°. Two thin PVC (Polyvinyl chloride) panels vertically divided the tank into three sections with different surface covers (Fig. 1b). Namely, one section was covered with a concrete material (with a low hydraulic conductivity), another section with a lime material (with a moderate conductivity), and the center section remained bare (additional soil was added to have the same embankment thickness). The SRMs (lime or concrete) only covered the upper section of the slope, while the lower section of the slope (beneath 30 cm) was filled with rocks. The groundwater table (GWT) was constant upstream (the HP boundary in Fig. 1a), supplied by two submerged pumps with flow meters. The lake water level (LWL, the AO boundary in Fig. 1a) was kept constant as well, controlled using overflow troughs with flow meters. The fishpond was set up on the land surface 95 cm away from the upstream boundary and its leaching flux (10 cm day^{-1}) with pollutants was controlled by one micro pump. Before the experiments, steady-state water flow conditions in the soil tank were established by maintaining constant water levels upstream (GWT) and downstream (LWL) for about one month. Selected soil physical and chemical properties are listed in Table 1.

Multiple experiments were concurrently carried out in three sub soil tanks, in order to better understand the effects of different SRMs on flow patterns and solute transport in the lakeshore zone. Based on field observations carried out in the lakeshore zone of Lake Taihu, average groundwater gradients were set at three typical values of 0.063, 0.043, and 0.022 m m^{-1}, corresponding to the dry (a LWL was 30 cm), normal (40 cm), and wet (50 cm) seasons, respectively (Fig. 1c). The GWT at the upstream boundary (line HP in Fig. 1a) was kept constant (60 cm) in all experiments. The ratio d/D represents the ratio between the relative distance from point O to the entire length of the slope face (D). Variables d_{30}, d_{40}, and d_{50} represent the distances on the slope face from point O to the intersection points B, C, and D of LWLs with the slope face, respectively (Fig. 1c).

Solutes were mixed into the assumed fishpond (or a paddy field) after a steady state water flow was reached. A solution of $NaNO_3$ and NaCl was mixed into the fishpond along with pumped water. The concentrations of chloride and nitrate were 10.0 mg L^{-1}. The experiment representing dry-season conditions was conducted first. After the experiment was finished, the soil tank was slowly flushed for about one month until solute concentrations at all observation points stabilized. Then, the experiment representing the normal season was carried out, followed by the experiment representing the wet season.

2.1.2. Measurements and analysis

Inflow fluxes through the upstream boundary (the HP line in Fig. 1a) were recorded using flowmeters connected with pumps. Groundwater table data were observed from scales connecting stainless steel tubes in the soil tank. The tubes were installed beneath the groundwater table 100, 200, 290, 420 and 465 cm away from the upstream boundary (Fig. 1a). Soil solutions were collected every ten days using porous ceramic suction cups at S_1–S_{11} (Fig. 1a). The residual solution in the suction cups was cleansed using an injector each time before sampling. The cups were then evacuated to about 80 kPa by a vacuum pump with a