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Dilution and volatilization of groundwater contaminant discharges in streams

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ABSTRACT

An analytical solution to describe dilution and volatilization of a continuous groundwater contaminant plume into streams is developed for risk assessment. The location of groundwater plume discharge into the stream (discharge through the side versus bottom of the stream) and different distributions of the contaminant plume concentration (Gaussian, homogeneous or heterogeneous distribution) are considered. The model considering the plume discharged through the bank of the river, with a uniform concentration distribution was the most appropriate for risk assessment due to its simplicity and limited data requirements. The dilution and volatilization model is able to predict the entire concentration field, and thus the mixing zone, maximum concentration and fully mixed concentration in the stream. It can also be used to identify groundwater discharge zones from in-stream concentration measurement. The solution was successfully applied to published field data obtained in a large and a small Danish stream and provided valuable information on the risk posed by the groundwater contaminant plumes. The results provided by the dilution and volatilization model are very different to those obtained with existing point source models, with a distributed source leading to a larger mixing length and different concentration field. The dilution model can also provide recommendations for sampling locations and the size of impact zones in streams. This is of interest for regulators, for example when developing guidelines for the implementation of the European Water Framework Directive.

1 . Introduction

The discharge of contaminated groundwater into streams may impact surface water quality, with contaminant loads originating from contaminated sites e.g., chlorinated solvents and other xenobiotic organic compounds (Chapman et al., 2007; Conant et al., 2004; Westbrook et al., 2005), old landfill sites (Milosevic et al., 2012) or agricultural application of pesticides (McKnight et al., 2012). Due to the implementation of the European Water Framework Directive (WFD) and the increasing exploitation of stream water and groundwater, an increasing effort is made to understand the linkage between these two systems and assesses the effect of groundwater contaminants on surface water ecosystems and chemical quality (Hancock, 2002; McKnight et al., 2010, 2012; Schmidt et al., 2010). Proper tools for quantification of pollutant transport from groundwater seepage into streams and the inherent transport and dilution are essential for risk assessment and management of groundwater–surface water systems affected by contaminated sites.

Mixing in rivers and streams has been actively studied since the middle of the 20th century and many researchers have been interested in modeling the transport of pollutants. The mixing process of pollutants in natural rivers and streams is complicated due to irregularities of the velocity, bed configuration, river shape etc. Most existing modeling studies focus on predicting the pollutant transport from a point pollutant release, characterized by continuous or instantaneous discharge or injection of a known pollutant mass with a low or high (waste water discharge, individual jet) initial velocity (Fischer et al., 1979; Kalinowska and Rowinski, 2012; Lung, 1995; Rutherford, 1994; Sanders et al., 1977). These models use

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the advection–dispersion equation to predict the concentration distribution in the stream from a point pollutant release and to describe the mixing length, i.e. the downstream distance required to ensure uniform concentration across the river, and have been proved to be suitable in many studies (e.g., Jirka and Weitbrecht, 2005; Lung, 1995; Pujol and Sanchez-Cabeza, 2000). One-dimensional models have also been developed to cater for the retention of pollutant in so-called dead zones (e.g., Runkel, 1998) and take into account the changes of the factors affecting the pollutant transport (such as water flow rate, channel width and depth and stream bed slope) along a short stream length (Ani et al., 2009). These models describe mixing from a single point discharge release and do not consider the groundwater discharge plume width and the spatial distribution of the source along the stream. Since a distributed groundwater discharge source is very different from a point source, it is essential to incorporate these features in a model of the transport of pollutants in streams.

A limited number of recent studies deal with mixing downstream of multiport diffusers where pollutants are emitted in a line across a river (Kalinowska and Rowinski, 2012; Zhang and Zhu, 2011). For example, Zhang and Zhu (2011) studied the mixing downstream of a multiport diffuser in a wide shallow river. They tested the sensitivity of the modeling results to different initial spatial distributions of the pollutant in the vertical and lateral direction (homogeneous versus Gaussian concentration distributions), and showed that it had little effect on the results. However, the location of pollutant emission in the river, the spatial concentration distribution along the river (in the longitudinal direction) and the small velocity of discharge, which are characteristics of the groundwater seepage, are not considered in this model.

A model that predicts the pollutant dilution and volatilization in a stream due to contaminated groundwater discharge is currently unavailable. In contrast to the point pollutant release and the multiport diffuser, the effluent in the groundwater seepage scenario enters the stream as a continuous source from a larger area, most likely from the side of the stream or half of its bottom and with a very small velocity and thus small initial dilution. In this study we aim to develop an analytical model for groundwater contaminant discharge mixing in a stream that considers transport, dilution and volatilization processes. The model should be used in a regulatory context for risk assessment where simple screening models with limited data requirement are necessary (e.g., Chambon et al., 2011). The solution of Fischer et al. (1979) for point pollutant release is modified to include volatilization and all the conditions necessary to describe the concentration distribution of contaminated groundwater recharges into streams. It considers a range of boundary conditions enabling the risk assessment of various practical cases; for example different locations of groundwater seepage in the stream and different spatial concentration distributions of the pollutant along the groundwater seepage zone. The paper focuses on describing various options for the solution for its application to the groundwater discharge problem.

Field experimental studies have attempted to identify the surface water–groundwater interaction zones, quantify the inflow (Milosevic et al., 2012; Westbrook et al., 2005), and study the processes in the sediment bed during groundwater seepage (e.g., Bianchin et al., 2006; Chapman et al., 2007; Conant et al., 2004; Ellis and Rivett, 2007; McKnight et al., 2010; Milosevic et al., 2012). In field studies the contaminant discharged from a groundwater plume was rarely detected in the stream due to rapid dilution by clean stream water and there is little published work on the resultant concentration distribution along the stream. In this study the developed models are compared to the field data provided by McKnight et al. (2010) and Nielsen et al. (2014) from two Danish streams. The applicability of the models for location of water quality sampling points and risk assessment in streams exposed to groundwater contamination is discussed with respect to current EU regulations, uncertainty, and potential for further model development.

2 . Conceptual model

Fig. 1a illustrates the conceptual model for the physical system considered in this study, where a groundwater plume of width equal to W_{plume} is discharged into a stream of depth d and width W. The model aims to predict contaminant concentration in the stream.

The groundwater plume can be discharged along half of the bottom of the stream (Fig. 2a), or along a length of the stream's bank (Fig. 2b). Numerical simulations were performed to investigate what is the location of the groundwater plume discharge in typical conditions. The governing parameters affecting whether the plume is discharged at the bank or through the stream bed are the aquifer depth and hydrogeology, the recharge rate, and the contaminated source location. A 2-D model of the catchment of the stream was developed to model the groundwater flow at steady state conditions using COMSOL Multiphysics 4.3, a finite element tool. Fig. 3a shows the conceptual model and boundary conditions used. The simulations were repeated for different stream depths and widths, recharge rates and catchment sizes representing a range of typical values for streams and aquifers (further details in supporting information). A sand aquifer was used with vertical and hydraulic conductivities of 10^{-4} and 10^{-5} m/s, respectively. The depth of the aquifer did not affect the results. Fig. 3b shows the streamlines discharging to the stream through the bank (white streamlines) and the stream bed (black streamlines). For each scenario, x_{critical} was estimated, where the x_{critical} is the maximum distance from the stream of a contaminated source where the plume resulting from the source will discharge to the stream through its bank (Fig. 3b). For typical conditions, x_{critical} is always larger than 0.5 km, i.e. any contaminated source located closer than 0.5 km from the stream will discharge to the stream through its bank (see Supporting Information S1 for more details). Since many contaminated sources posing a risk to streams are located closer than 0.5 km from the stream, the model considering the plume discharge from the bank is the most appropriate in most scenarios and was applied in the model.

The scenario where the groundwater seepage is from a length of the bank (W_{plume}, Fig. 2b) was compared with point discharge at the bank of the stream (Fig. 2c). Finally, for the case (Fig. 2b) where the plume was discharged over a width (W_{plume}) the effect of the contaminant mass distribution of the plume was studied (Fig. 4), with the mass being distributed: