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Evaluación de la influencia del flujo hiporréico en el transporte de solutos mediante el uso de un modelo numérico

Evaluating the influence of hyporheic flows on solute transport using a numerical model

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Abstract

El transporte de solutos en cuerpos fluviales es afectado por múltiples mecanismos y procesos que incluyen la morfología del río, fenómenos de turbulencia, re-aireación y área de almacenamiento temporal tales como zonas de recirculación, flujos hiporreicos y zonas muertas. La zona hiporréicaes un ecotono activo entre el flujo superficial y el agua subterránea. En la zona vadosa se producen importantes intercambios de agua, nutrientes y material orgánico, los cuales son función de las variaciones de descarga, así como también de propiedades del lecho del río como la topografía y porosidad. Es en esta zona donde masas de agua experimentan un intercambio continuo entre el cauce principal y aquel proveniente de la sub-superficie del lecho del río, lo que hace que la zona hiporréica funcione como un set de puntos continuos que conectan el cauce principal de un río y su cuenca. La zona muerta es aquella región de un río donde el agua está estancada o tiene una velocidad mucho menor que el cauce principal, como por ejemplo la zona más profunda de pozones o el flujo que escurre a través de vegetación densa. Junto a la zona hiporréica las zonas muertas controlan la calidad del agua, por ejemplo afectando la concentración de oxígeno disuelto, lo que se influye directamente en el hábitat disponible de especies acuáticas y ribereñas. Para evaluar la influencia, efectos e importancia de la zona hiporréica en el transporte de solutos se realizó una campaña en terreno, donde una serie de descargas de Rodamina fueron medidas en diferentes ubicaciones a lo largo de un tramo de 271 m en el río Bear Valley Creek, ubicado en el estado de Idaho, Estados Unidos. El análisis de las zonas de flujo hiporreicoy muertas se realizó usando el modelo OTIS (One-Dimensional TransportwithInflow and Storage, USGS), el cual se basa en los procesos de advección y dispersión y que además incluye el almacenamiento temporal y decaimiento de los solutos. Los resultados del modelo muestran que las zonas del almacenamiento temporal, en este caso zonas muertas y flujo hiporreico deben ser explícitamente incluidas a la hora de hacer predicciones del comportamiento del transporte de solutos en cuerpos fluviales que presentan algún grado de permeabilidad en su lecho.

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Abstract

Transport of solutes in streams are affected by multiple mechanisms and processes that include river morphology, turbulence, reaireation, and transient storage areas which include re-circulation zones, hyporheic flows and dead zones. The hyporheic zone is an active ecotone between the surface stream and groundwater. In this zone important exchanges of water, nutrients, and organic matter occur in response tovariations in discharge and bed topography and porosity. Is in this zone where water that is flowing in the stream channel flows into the subsurface materials of the streambed and then returns to the main stream, making the hyporheic zone a continuous link between the stream's channel and catchment. The dead zone is defined as a region of static or slowly moving water (i.e. backwater eddies, stagnant water at the bottom of pools, and flow through vegetation). Dead and hyporheic zones play a key role in controlling the water quality, for instance affecting the stream dissolved oxygen concentration, which ultimately controls the habitat suitability for a number of aquatic and riparian species. To evaluate the influence, effects and importance of hyporheic zone in the transport of solutes a field camping was conducted, where a series of Rhodamine injections were monitored in along a 271 m reach in Bear Valley Creek, ID, USA. The analysis of the dead zones and hyporheic flows was performed using the OTIS Model (One-Dimensional Transport with Inflow and Storage, USGS) where the governing equation underlying the model is the advection-dispersionequation with additional terms to account for transient storage, and first-order decay. Results showed that the includingtransient storage areas, in this casehyporheic and dead zones must be explicitly included in order to describe how solutes are transported in a stream whose bed present some degree of permeability.

1. Introduction

Transport of solutes in rivers and streams is affected by retention of the solutes in transient storages, where temporal isolation of the solutes from the main channel in stagnant water zones such as pools, dead-end side channels or adjacent wetland areas happens (De Smedt, 2007 [1]). This can cause that a large amount of water and solute is interchangedwithin the dead zone, which are regions of static or slowly moving water (i.e. backwater eddies, stagnant water at the bottom of pools, flow through vegetation), and the hyporheic zone, causing a delay of the solute migration and a skewed concentration profile in the main channel that may differs from that of a classic mathematical formulation of advection-dispersion processes. The dead zone is characterized by a low oxygen content (hypoxic), caused primarily by eutrophication, which is a process where an increase of in-stream chemical nutrients exists (e.g. nitrogen and phosphorus).They also play a key role in water quality dynamics, for instance controllingthein-stream dissolved oxygen concentration and habitat suitability for many riverine and riparian species.

Winter el al., (1998) [2] defines the hyporheic exchange flow as one of several mechanisms of the interaction between the groundwater and surface water. In the hyporheic zones of streams, water that is flowing in the stream channel flows into the subsurface materials of the streambed and then returns to the stream. Hyporheic zones function as a link between the stream's channel and catchment allowing a permanent interchange of water and solutes (Bencala, 1984 [3]). As a region of transition from the stream to the surrounding aquifer, the hyporheic zone has been identified as a critical component of the stream ecosystems, although still is less understood than surface flow. Hyporheic mixing occurs via circulation cells that move river water into the alluvium (downwelling) and back again (upwelling) (Tonina and Buffington, 2009 [4]) and ultimately affects thechannel geomorphology and groundwater and riverine habitat for aquatic and terrestrial organisms (Bencala, 2000 [5]; Vaux, 1962 [6]). Sharp gradients in physical, chemical, and biological conditions produce an extreme diversity of natural processes in the hyporheic zone that do not occur anywhere else in the overlying stream or underlying aquifer. As a result, fluxes through the hyporheic zone tend to influence a very wide range of ecologically relevant substances, including nutrients, carbon, and contaminants (Brunke and Gonser, 1997 [7]; Winter et al., 1998 [2]; Jones and Mulholland, 2000 [8]). Upwelling subsurface water supplies stream organisms with nutrients while downwelling stream water provides dissolved oxygen and organic matter to microbes and invertebrates in the hyporheic zone.

To understand how the hyporheic flows and dead zones affects the transport of solutes several models have been formulated, usually considering the advection-dispersion processes coupled with a mass exchange module. Transient storage can be included by means of two parameters, a mass exchange rate coefficient and the volume or cross sectional area of the transient storage zone (Runkel et al., 2003 [9]). One example of thesetype of models is the OTIS model (Runkel and Chapra, 1993 [10]), developed by the USGS and the Transient Storage Model (TSM) (Bencala, 2006 [11]), which is the one used in this study. OTISuses an approximate finite difference solution of advection-dispersionequationsand it has been extended with a parameter optimization technique, OTIS-P, to estimate transient storage characteristic in rivers [see for example Choi et al., 2000 [12]; Lees et al., 2000 [13], Fernald et al., 2001 [14]; Laenen and Bencala, 2001 [15]; Keefe et al., 2004 [16]; De Smedt et al., 2005 [17]). The importance of including transient storage is analyzed using Rhodamine injections in a 271 m long reach of the Bear Valley Creek. Here it is hypothesize than the importance of the transient storage zone can be indirectly estimated by the ratio cross-sectional area of the storage zone to the main channel cross-sectional area. A specific threshold for this ratio has not been stablished but it is assumed that if both are in the same order of magnitude the storage zone plays an important role in controlling the dynamic of the solute transport.

2. Study Site

The study was conducted in Bear Valley Creek, a headwater tributary to the Middle Fork of the Salmon River watershed in central Idaho (Figure 1).

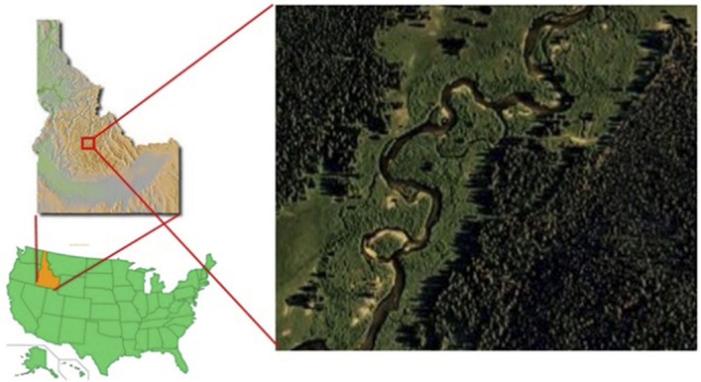

Figure 1: Location of the study site

According to Richards and Bacon, (1994) [18] the stream flows through subalpine meadows and lodgepone pine forest on a granitic batholith. Alluvial deposits of erosive sandy soils typify the region. Stream substrates have high proportions of fine sediments in many areas as a result of both point and non-point sources along the length of the stream (Konopacky et al., 1986 [19]). The field site is located in the coordinates Lat: 44.3774° and Long:-115.392° and the study reach length is about 271 m.In this specific location the river features sharp bends and a relatively large and flat floodplain (Figure 2).r

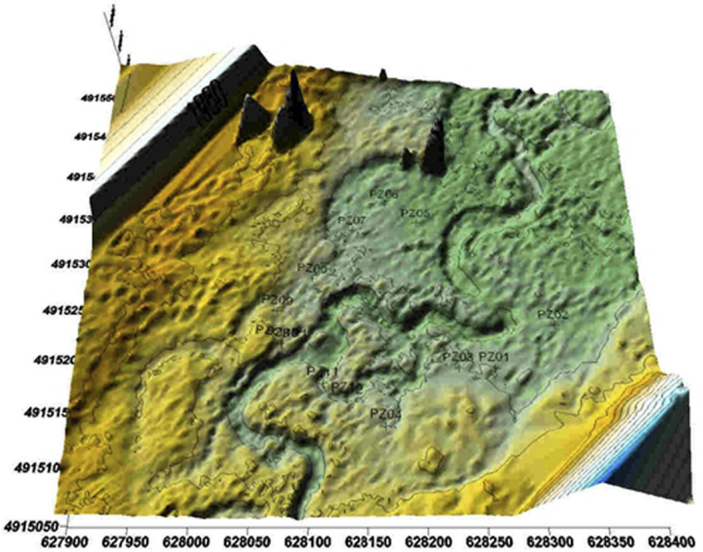

Figure 2: Bed Surface elevation at the study site. Coordinates are shown in UTM, vertical is North and horizontal is Eas

3. Methods

3.1 Field Measurements

During August 2011 a series of Rhodamine injections were performed in the study site. Concentrations of Rhodamine were measured in two locations, at 143.45 and 271.34 m starting from the injection place. Measurementsstarted before the injection and finishing long time after the concentration did not exhibit significant change and its value was practically equal to zero. The Rhodamine tracer has been used in several studies as it is a conservative solute.The river model considers a 127.9 m reach length, where the upstream boundary (x=0 m in the model) is locatedwhere the first Rhodamine measurement was taken (x'=143.45 m, where ' denotes the original coordinate system) and the downstream end (x=127.9 m, x' = 271.34 m) is where the second measurement was taken. The first location (x = 0 m) was chosen to allow the river to well mix the Rhodamine with the original flow. All measurements were corrected by temperature. The model was set as time=0 hrs when the injections were executed in order to make an easier comparison (Figure 3).Because of the correction for temperature in the measured concentrations, there were some values that exhibited negative concentrations, which is physically impossible. In those cases the corrected values were set equal to zero.The reach cross sectional area and mean discharge were 3.27 m2 and 0.927 m3/s respectively and they were obtained by averaging thee cross sections, specifically where the Rhodamine was injected and measured(x = 0, 143.45 and 271.34 m).The discharge exhibited some grade of variation (-0.04 to +0.06 m3/s from the mean value) in the three locations while it was measured. For the purpose of this work the mean discharge (0.927 m3/s) is a good representation for the studied reach.

Inputs required by OTIS and OTIS-P (see section 3.3) where taken from the measured curve and interpolated linearly every 0.02 hrs in the upstream end and 0.04 in the downstream.This difference in the time step is due the requirements of OTIS and OTIS-P.

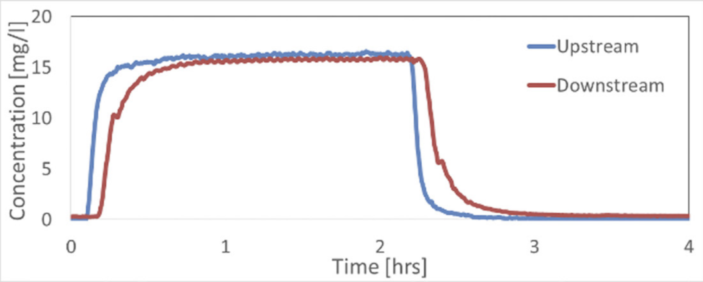

Figure 3: Measured Rhodamine concentration at the upstream and downstream ends.

3.2The OTIS Model

A brief summary of the OTIS model is described below, for further details see Runkel (1998) [20]. OTIS solves a set of equations that describe the physical processes of advection, dispersion and transient storage. Two conceptual areas are defined within the model: (i) the main channel is defined as the portion of the stream in which advection and dispersion are dominant mechanisms, and (ii) the storage zone is the portion of the stream that contributes to transient storage (i.e. hyporheic zone, pools and eddies). The exchange of solute mass between the main channel and the storage zone is modeled as a 1st-order mass transfer process (Runkel, 2002[21]).

The spatial and temporal variations in solute concentration are given by:

$$\begin{aligned}\frac{\partial C}{\partial t} = -\frac{Q}{A}\frac{\partial C}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left(AD\frac{\partial C}{\partial x}\right)& \\ + \frac{q_L}{A}\left(C_L - C\right)& \\ + \alpha\left(C_L - C\right) - \lambda C&\end{aligned} \qquad \text{Eq. 1}$$

$$\frac{dC_S}{dt} = \alpha\frac{A}{A_S}\left(C - C_S\right) - \lambda_S C_S \qquad \text{Eq. 2}$$

where is the main channel cross-sectional area (m2), is the cross-sectional area of the storage zone (m2), is the main channel solute concentration (mg/L), is the storage zone solute concentration (mg/L), is the lateral inflow solute concentration (mg/L), is the dispersion coefficient (m2/s), is the volumetric flow rate (m3/s), is the lateral inflow rate on a per length basis (m3/s/m), t is time (s), x is distance (m), is the storage zone exchange coefficient (s-1), λ the main channel first-order decay coefficient (s-1) and λ_S the storage zone first-order decay coefficient (s-1).Solutions for Eq. 1 and Eq. 2 are based on a numerical solution using Finite Differences and the well-known Cranck-Nicolson Method. For more details on the numerical strategy to solve the set of equations Runkel (1998) [20].

3.3 OTIS-P

According to Runkel (1998) [20] one of the goals in many solute transport studies is that of parameter estimation; given a set of observed concentrations, determine a set of parameters values that aptly describes the system under the study. The OTIS model is distributed along with OTIS-P, a model that uses a parameter-estimation technique known as Nonlinear Least Squares (NLS) that automatically determine a set of optimal parameter estimates that tries to match simulated and measured solute concentrations. Specifically, OTIS-P determines an optimal set of parameter estimates that minimize the squared differences between the simulated and observed concentrations, thereby automating the parameter estimation process. For more details see Runkel (1998) [20].OTIS-P is relatively quick, compared to a manual iteration, although care must be taken with the selection of both initial guessed values and the final solution in order to be inside a realistic range of values. OTIS-P was used to obtain a first approximation of the optimal set of parameters, in this case , , , , and .The full parameter estimation of OTIS-P can modify up to 10 parameters. Once OTIS-P found a solution the influence of this set of parameters was analyzed varying independently some of them.

3.4 Parameter Estimation

In thisstudy 5 parameters of OTIS and OTIS-P models were estimated to match the predicted and measured concentration at the downstream end (located at 271.34 m). Two set of runs were performed until the predicted concentration matched the measured one and also the parameter values given by OTIS-P remained constant. In the first set of run the dispersion coefficient(), storage zone cross-sectional area (), and exchange coefficient (were allowed to change while main channel first-order decay coefficient (and storage zone first-order decay coefficient () were fixed. After they converged to a solution with values inside a physically feasible range the second set of runs was performed, this time fixing , , and varying , and .

In the first set of runs (variable: , , ; fixed: ,), and were set as 10 m2/s, 0.1 m and 0s-1 respectively. Notice that can't be set equal to zero otherwise the model is bad conditioned. = 10 m2/s was estimated using the values and shape (in time) of the concentration in the downstream end and the approximation , where is the time where the peak concentration was measured.After the solution converged, the remaining 2 parameters (and) were calibrated, this time using the calibrated set of , , .

4. Results

4.1 Transient storage modeling

After the calibrations was completed the set of parameters that best describe the measured concentrationin the Bear Valley Creek was: = 5.28 m2/s, = 1.75 m2, = 2.44·10-4 s-1, =9.44·10-6 s-1, and =1.79·10-5 s-1.Under these conditions the predicted concentration, calculated with OTIS, and the measured one showed a fairly accurate match (Figure 4). The coefficient of determination was R2 = 0.999. Goodness of fit is summarized in Table 1.

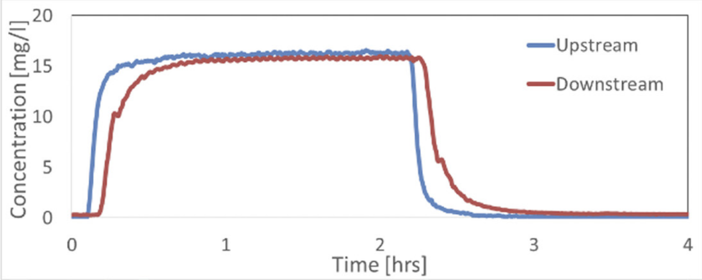

Figure 4: Predicted and measured Rhodamine concentration at the downstream point.

RMSE	0.2816 mg/l
R^2	0.9985
Nash efficiency coefficient	0.9985
Absolute error	0.2132 mg/l

Table 1: Goodness of fit in the downstream point

The cross-sectional area of storage is almost a half of that of the main channel which indicates that this component is really important in the transport of solute within this reach of the Bear Valley Creek and suggests that hyporheic and dead zones play an important role in the dynamics of solute transport.

5. Results and Discussion

Model results shows that the use of a simple advection-dispersion formulation under these river conditions is not a realistic assumption and will give erroneous results, which could lead to negative consequences if decisions were taken considering this scenario. Including storage areas allow to have a better representation of the mechanics of the solute transport and the processes that affect it. OTIS, a fairly simple, physically based, numerical model that accountsfor the main processes that occurs within a stream, is a very useful tool to predict how solutes are being transported and also how are affectedby some external processes. Although in this area Bear Valley Creek features meanders and sharp curves (Figure 1) this one dimensional model accurately predicted the transport of a conservative tracer (Figure 4, Table 2), suggesting that the main and most important processes in the solute transport problem are being considered.

The storage zonein this section of the Bear Valley Creek is controlled mainly by , , , , and . Interchange of solutes between the main channel and the transient storage zone is limited by and, where the exchange coefficient (is related with the rate at which this process occurs and the ratio controls the concentration that is interchanged between these two entities. The effects of and are especially significant when sharp gradients in the rate of concentration are observed, such as during the rising and falling curve. With the available information is not possible to separate between dead and hyporheic zone, however the ratio = 0.54 suggest that transient storage is very important in this case. Field observations suggest that most of the water at any cross section was in motion, which indicates that both component, hyporheic and dead zones, exist.

Although this model has the ability to include the main components of the solute transport, many of the local processes are not captured. Assuming the transport of solutes as a one-dimensional phenomenon does not allow to fully understand the effect of more complex flow structures such as local variations of velocity and turbulence intensities, and neither their effect in habitat suitability. The advection-dispersion equation is solved using the main channel cross-sectional area () and the volumetric flow rate (), which in cases of complex or variable geometries can induce over or under estimation of some parameter. A module that accounts for surface roughness and reach slope to compute the hydraulics would add a greater degree of accuracy, maintaining the one-dimensional assumption and its efficiency. However, it has been proved that the model is able to accurately represent the mixing process in large scales with a relatively short execution time and enough flexibility to be used in very different flow and channel conditions.

6. Conclusion

Solute transport in a reach of the Bear Valley Creek was studied using the OTIS model and the extension for parameter estimation OTIS-P. Results showed that this simple model is able to reproduce with a high degree of accuracythe solute transport in a rivers that features large floodplains and bends. This model is powerful tool which can be used for better management of water and aquatic resources. Model's results show that including storage areas allow to have a better representation of the mechanics of the solute transport.The ratio cross-sectional area of the storage zone to the main channel cross-sectional area was in the order of 0.5, indicating the importance of transient storage zones. Although is not possible to split between the effects dead and hyporheic zones with the data presented here, field observation of the flow indicates that both component, hyporheic and dead zones, exist.

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