

# Modelling hyporheic processes for regulated rivers under transient hydrological and hydrogeological conditions

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## Referees comments

1. RC Doble (Referee)

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The manuscript presents an analysis of the effects of hydrological controls (bank slope, river bed Ksat, and river discharge wave characteristics) on bank storage and hyporheic exchange in the Lule River, Sweden. The paper is well written, concise and clear. It provides a new insights into understanding what kind of river discharge wave provides optimal hyporheic exchange and therefore stream ecological benefit. It is specific to the site, but should be universally applicable to rivers worldwide.

My general comments are: It is complicated to have both site specific and generally applicable information together in a paper and both maintain relevancy to the study site and not limit general modelling observations by the site conditions. While the balance of the paper feels good, there are some places that could be either more specific in outlining the site specific results (p 9340). It would be good to have a little more separation of general and site specific work – particularly in the scientifically interesting section 5.1 discussing hyporheic exchange (see below). It would be good to have 3 or so clear points stating why the paper is different from some of the other literature you have included – specifically Doble et al. 2012 a and b. This study seems to combine the results from these two papers and discuss how it impacts hyporheic exchange, particularly for the Lule River. I suspect there are more distinguishing features and it would be good to specify these up front.

I would also like to see a conceptual figure of what type of discharge wave (duration, amplitude etc) would provide the optimal ecological conditions, for the Lule River (and other if possible) hydrogeological conditions. Specific comments include: Abstract – line 24 – spawning potential of riverbeds. Might be clearer as ‘potential of river beds as fish spawning locations’, if that is what is meant.

P 9329 – Lines 9 to 12. This is a bit unclear. Could you simplify these sentences and explain what type of severe modification of neighbouring ecosystems this refers to? P 9334 - Line 24 – how does having multiple waves impact the output, especially for short duration waves? This would vary initial soil saturation conditions. P 9335 – Line 9 – how long did it take for steady state to be reached for the initial conditions run? P 9336 – Lines 8 to 10 – did you recalibrate the model to the different recharge values, or just run the model using the original calibration? P 9337 – line 1 – the increase in exchange flux was not ‘linearly’ proportional to ..... Was it logarithmically related, or somehow non-linearly related? P 9337 – line 11 – and duration on bank storage: add ‘volume’ if this is what you mean. P 9338 – line 1 – how do you define residence time? Is it for 50% of bank storage water to return to the river, or 90% or 100%? It may be 100% since you have diffuse recharge in the model, but I have seen it defined differently where there is no diffuse recharge, therefore no baseline flow toward the river

– hence not all bank storage water returns to the river. It might be good to specify this. Section 5.1 – this is really the crux of the paper I think. P 9339 – line 18, 20 and throughout – more steeply sloping banks. I assume steep banks to be close to vertical, but I think you are referring to flatter banks here (slope angle close to 0 degrees). I'm not sure if there is an international convention for the description of slope, but it may be better to refer to high and low bank slope angles. You have defined these in a figure at least. P 9340 – line 12 onward (to line 5 on next page). Is it possible to include a figure of the Lule River hydrograph, or a representative section of it? I would almost make this a new section from line 12 onwards, as you have started to discuss the Lule River specifically. It is also a very interesting discussion. I would love to see some kind of conceptual figure showing what the key parts of ecologically important flows – perhaps two conceptual hydrographs with one supporting ecologically important flows and the other not with notation why this is so. P 9341 – line 12 –Can you say what this optimal wave configuration is for the site that you have studied?

## 2. Anonymous Referee #2

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General comments: The presented analyses of the effects of hydrological and hydrogeological controls influencing the hyporheic exchange in the Lule River (Schweden) is whether a case study not a parameter or scenario study. Therefore the authors made a decision what they want to say. Nevertheless, is the topic of great interest especially in direction of managing impounded river systems according to the Water Framework Directive? The most important suggestion is: concentrate more in detail in one of the two parts which are described in the manuscript: site specific description and results or scenario analyses. Therefore a more specific discussion part would be possible and more helpful for the readers. Specific comments: - The site description is too short. It would be helpful to know more about the surrounding aquifer situation in respect to the boundary conditions. - The same applies to the Data collection part. For example a description of the method to analyze the conductivity of the clogging layer. - It is not clear what you mean with a conceptual model – is it an analytical model with a simplified Aquifer? A description of the calculation behind would be useful. - The boundary condition in the conceptual model may influence the model output significantly. - It is not clear why a numerical model was used. If it was used as comparison to the conceptual model, the comparison is to show. But then a question is, why you need a conceptual model for the scenario study. - It is not clear how you calculate the bank storage (Flux multiplied by the time step), when comparing in the results Fig. 6 and Fig 7. In Fig. 6 you have minus values for the flux and you don't have this in Fig.7. Maybe this needs an explanation. - In general it is confusing if the scale in the figures are not the same. - It would be helpful in the discussion to refer this part more to the questions in the introduction.

## Response to reviewers

### 1. RC Doble (1 September 2014)

Dear Rebecca,

Thank you for your constructive judgement and comments to our manuscript. We agree with most of your review points and altered the manuscript accordingly. General and specific comments are responded below, whereas all changes were tracked in the uploaded .doc file.

*General comments:*

- You and referee#2 suggested a better separation between site specific and general work would improve the paper. We have made respective changes, mainly for the discussion part (reorganised structure).
- Why the paper is different from some other literature:
  - o By doing site specific calibration we demonstrate the importance of conceptualisation. We test theoretical scenarios of different model settings like (wave duration, amplitude, hydraulic conductivity and bank slope) based on a calibrated numerical model that is intended to represent the site specific reality. The realistic simulation was based on number of assumptions that create limitations for this type of modelling. The major difference to earlier studies is, therefore, an attempt to demonstrate possible limits of the surface water-groundwater models and data necessity.
  - o We demonstrate application of numerical surface water-groundwater exchange modelling in a highly dynamic environment with frequently oscillating river stage. This type of discharge pattern is common for many other regulated rivers in the world. This kind of model approach can be used in different applications such as river restoration projects, improvement of ecological status of watercourse, environmental flows, integration with and/or input to regional models etc.
  - o Furthermore, current manuscript shows that ecosystem requirements in terms of river-aquifer exchange flux are satisfied by 40% of the wave events with this type of discharge pattern (using 2012 data). This portion, however, guarantees neither a sufficient residence time nor an effective biogeochemical exchange to reset hyporheic water composition. The share of ecologically beneficial flows is therefore even lower.
  - o Investigation of theoretical scenarios is a natural extension of site specific simulations and creates a platform for development of more environmental friendly river regulation strategies. A simple estimate of water residence time included in our scenarios is a useful proxy for hyporheic geochemical processing.
- A conceptual figure of what type of discharge wave would provide the optimal ecological conditions based on the site specific conditions was difficult to setup. We were more specific instead on pointing out how many of discharge waves across an ice-free season are actually ecologically significant. It is also possible to say that the hyporheic zone stress increases with increasing amplitude and duration where amplitude has a leading impact.

*Specific comments:*

Abstract Line 24 – modified as suggested

P9329 Lines 9-12 – Added an additional sentence and changed the following one to clarify the type of modifications expected in the neighbouring ecosystems.

P9334 Line 24 – As you noticed, having multiple waves affects the initial saturation conditions and will eventually shorten the filling time of the unsaturated zone and increase the bank storage. The return processes are expected to remain unchanged though.

P9335 Line 9 – It took less than **30 days** to reach steady state for the initial conditions run.

P9336 Lines 8-10 – The original calibration was used for all scenarios including changes in boundary conditions.

P9337 Line 1 – The increase in exchange flux was **logarithmically** proportional to...

P9337 Line 11 – “volume” added

P9338 Line 1 – Residence time is defined as a sum of fill and return times or the time it takes for the bank storage volume to reach its maximum and return back into the river. In other words, it accounted for complete (100%) bank storage return.

P9339 Line 18 and onwards – modified as suggested

## 2. Anonymous referee #2 (2 November 2014)

Dear reviewer,

Thank you for the critical comments. We reply to every comment that in our opinion required a response. Please, let us know if we missed or misinterpreted anything.

We clarified the manuscript in separating site specific modelling and scenario analyses. Despite the criticism, we kept both but attempted to improve the structure of the discussion section, which improves the readability. The reason for this is that site specific modelling is a demonstration of model capabilities to adequately simulate bank hyporheic exchange, which is essential for the next step – scenario modelling. To meet the suggestions of both reviewers, we improved the discussion part with respect to both site specific and scenario simulations.

The topic is without doubts of interest from the perspective of improvement of ecological status of impacted watercourses as requested by Water Framework Directive. Understanding and coupling of river-aquifer functioning to the transfer of nutrients across their interface and the impact on sediment transport and biological migration are all essential for improved ecological status of regulated rivers, which are today severely impacted by disruption of flows and related biogeochemical consequences for their channels. This type of modelling offers a platform for further investigations and demonstrates the importance of conceptualisation (e.g. process consideration, boundary conditions, data necessity) and limitations of numerical models.

The site description was enhanced by adding information about the floodplain, hillslope position, and the aquifer depth in the area.

Description of the method to analyse the conductivity of the clogging layer is given in Siergieiev et al. (2014a) and was intentionally not repeated here. We have, however, added additional information on the performance of the test.

In response to the comment on the necessity of a conceptual model, we would like to clarify that the conceptual model used in this study it to provide qualitative and subjective interpretation of the model space by describing the limits of our restricted understanding of the model domain and its boundaries. Based on the conceptual model we could also delineate model’s major limitations. It is, therefore, not an analytical model but rather a simplified and abstracted representation of the

domain and its boundaries. Further, the conceptual model represents the solid base for subsequent numerical modelling to simulate the realistic case and different scenarios.

The bank storage was calculated as the cumulative exchange flux multiplied by the time step assuming the flux being either positive or negative for in- or outflow from the model, respectively, while bank storage always positive.

As you noticed, boundary conditions may influence the model output significantly. Therefore, we provide the result of boundary conditions sensitivity analysis where we test the extent of the “aquifer” no-flux and “precipitation” flux BCs. We acknowledge the limitations of chosen strategy and lack of data, especially when it comes to the aquifer boundary, but conclude that the choice of BCs (50% precipitation on top of the domain and no flux at the right hand-side boundary) is reasonable. Future modeling should account for conceptual uncertainty and additional data are required to adequately reflect issues related to conceptualisation.