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Hydrology and Earth System Sciences
Discussions

Interactive comment on "Are hydrological pathways and variability in groundwater chemistry linked in the riparian boreal forest?" *by* Stefan W. Ploum et al.

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General comment

This is a concise paper that compares groundwater chemistry in sub-catchments of the Kryckland observatory and asks questions about chemical variability in relation to hydrological pathway. The paper is written in a clear and concise way with not much to complain about in the introduction and results. The paper clearly shows and describes the variability of groundwater chemistry in relation to its hydro- logical activity. This is a very relevant result that is worth being published in HESS.

Answer: Thank you for evaluating the manuscript and the constructive commentary. Below we will present answers to each point that is addressed.

However, I have some point of criticism that should be addressed: Groundwater was sampled with fully screened wells which means that there is an unknown integration of water quality over depth potentially changing between sampling campaigns. The authors should carefully discuss the pros and cons of this approach.

Answer: We agree with Referee #1 that we can further elaborate on the well infrastructure, sampling protocol and the subsequent effects on the water chemistry of each sample. We will insert on page 2 in line 2 the following: 'We assumed that the water sampled from the well is a weighted average of the phreatic aquifer, down to the depth of the well. Given the exponentially decaying hydraulic conductivity with depth, this assumption would imply that, under saturated conditions, the majority of the water is therefore from the upper soil layers, referred to as the dominant source layer (Ledesma et al., 2015). We assume that the lateral flow below the well bottom is negligible compared to the flow in the shallow subsurface.'

Later on in the text there seems to be a not-outspoken assumption of vertical homogeneity of ground- water quality and a high weight on lateral heterogeneity. This needs to be made more clear and concise as this new DRIP-concept seems to stand against the former RIM- (Seibert et al. 2009) and DSL-concepts (Ledesma et al. 2015) that were derived from the same study site.

Answer: We agree that further elaboration is needed, in combination with the previous comment, regarding the vertical heterogeneity in the groundwater quality and the associated RIM and DSL concepts. Our study could be considered complimentary to the existing literature, rather than opposing. To clarify this we will add on page 2, lines 21-24: 'In terms of conceptualizing the spatial heterogeneity of groundwater inputs to streams (both hydrologically and biogeochemically), the RIM model and DSL concept have considered the vertical heterogeneity in riparian groundwater fluxes to

boreal streams (Ledesma et al., 2015; Seibert et al., 2009).'

The authors used linear mixed-effect models (LMM) to analyze spatiotemporal patterns of groundwater chemistry. There should be some effort in the text to justify the choice of this method and also on the choice of predictors. One could argue that the authors did not look hard enough to include other predictors (e.g. local TWI) but instead chose a method which can handle random effects from unaccounted factors.

Answer: The use of LMM was justified by the setup of the groundwater well network. Given that this is, to our knowledge, the first groundwater chemistry database that has been designed and compiled a priori based on three factors (hydrological condition, distance to stream and season), we deem those factors as our only true testable factors. Since the study sites were selected partly based on TWI, TWI and DRIP vs. non-DRIP are inherently correlated. Given the large improvement of the model by the inclusion of random factors which are describing spatial dependency of the samples, we discussed that there is a large part of spatial variability in groundwater chemistry left to be explained by factors that are not included by our study. We deliberately attempted to explain groundwater chemistry in a simple manner with generic and a priory set predictors, and explaining variability by unique properties of the study sites would impair any upscaling of our findings.

Finally, I have a major concern with the discussion section that is rather an implication section centered on the question what the varying groundwater quality would mean for stream chemistry. However, this was not part of the study design. So the discussion should rather be focused around the question, why the measured groundwater quality was different in different parts of the riparian zone.

Answer: We agree that the discussion is rather speculative and conceptual. We will balance the interpretation of our findings more appropriately with the potential implications. Especially, we will focus more on explaining and discussing the variation in groundwater quality in our well network while keeping the implications to stream chem-

istry to lesser extent. We will elaborate on the larger context of our work in a short conclusion.

What came into my mind here: Aren't DRIPs just an extension of the fractal stream network into the catchment. DRIPs are along topographic depressions funneling water flow in the same way as the stream network. The major difference is that they are not (permanent) pathways of surface flow but rather pathways of shallow subsurface flow. Maybe I missed that connection in earlier studies that were cited here. I however very much like the idea to refine the view on riparian zone by that type of concepts focused around major flowpaths.

Answer: We agree that in a sense DRIPs could be considered a part of the stream network especially during a high flow conditions. However, it is in our eyes essential to consider not only the hydrological definition but also the biogeochemical definition. And for the latter, the most important property of DRIPs is the highly organic substrate, and the generally high water tables. This is something that is not typical for stream channels and therefore we would argue that they are a unique landscape feature.

In essence I support this manuscript but ask for a substantial revision of the discussion section and a better justification of field and statistical methods.

Answer: Thank you for the constructive comments.

Specific comments

Abstract:

L13: This sentence is potentially misleading. What is meant by chemical variability in the riparian boreal forest? The linkage of riparian groundwater as described beforehand forest is not clear.

Answer: We will reformulate the sentence.

L20: The pairing of hydrological connection and groundwater condition cannot be un-

derstood here. Can you find a more telling factor name?

Answer: The hydrology between DRIP and non-DRIP is mostly conceptualized as different groundwater flow principles based on the water table characteristics. However we will re-evaluate how we can line up the definition and factor names better.

L20: The water provided by DRIPS – is that surface water discharging from the DRIP or groundwater within the DRIP?

Answer: Since the term DRIP covers both subsurface flows, stream-like flows and other types of confluences, we prefer to not specify whether DRIP water is surface water of groundwater. The section 2.2 clarifies this, but within the abstract this might not suffice.

L23: "chemically more stable" may be misleading. Do you mean spatially and/or temporally homogeneous?

Answer: Yes, we will reformulate this.

Introduction

P2L1: While I in general like such comparisons the idea of headwaters as "capillaries" was not immediately clear to me.

Answer: We will further clarify the sentence

P3L10-13: These two sentences need some references.

Answer: We will expand the references in this section.

Methods

Fig. 2: The catchment delineation is somewhat distracting. I suggest to limit the catchment boundaries to the catchment with studied DRIPs/ nonDRIPs. What determines the catchment outlet? A gauging station? Maybe show them to make clear that this was not completely arbitrarily chosen.

Answer: The catchments are determined by gauging stations, and we will indicate

them in the figure. We will reduce the amount of catchment boundaries to clear up the figure.

P5L6: TWI units are not [ha] – what do you mean by "topographic wetness index (2 ha threshold)"?

Answer: We aimed to specify that we used, similar to stream initiation thresholds, a 2 ha lower limit for a DRIP to be predicted as a DRIP. We will clarify this in the text.

P6L1: Can you specify the wells in terms of diameter and material? What is the meaning of a groundwater sample taken in a fully screened well? Do you expect this to be a representative sample from all depths or rather a sample from the most conductive depth? In the latter case the depths where most water is coming from may change over time with changing groundwater levels. I would like to see a critical evaluation of your sampling design and drawbacks (assets?) of the chosen methods! The methods chapter is likely not the right place.

Answer: In the discussion section we will evaluate our sampling design, and put into context with studies that consider samples from different depths (e.g. the DSL and RIM model in case of the Krycklan catchment). We will further specify the well properties in the methods section. The fully screened wells give a representative sample of the water that is laterally transported at the time of sampling, relative to the hydraulic conductivity of each soil layer which the well is in contact with. In our view this is the most representative water sample of what is drained into the stream in terms of shallow groundwater contributions. Given the exponentially decaying hydraulic conductivity profile in these soils, it is likely that our shallow well network provides a representation of the subsurface water that ends up in the headwater streams. Perhaps further down the stream network, at higher order streams, we have to consider a considerable contribution of deep groundwater flow that originates from deeper as the typical well depth of our current well network.

Results

P7L4: I don't understand why you jump in directly with that statement in the second sentence already.

Answer: The sentence aims to explain that the position relative to the stream is most explanatory, but the differences observed are not as great as the contrasts observed between DRIP and non-DRIP water. This means that in our approach we observed the chemical function of the riparian zone in a lateral context (chemical change from the upland wells to the riparian wells), but in the spatial context the DRIP/non-DRIP distinction seems to be more informative given the larger differences that we observed.

P7L26: Did you expect more distinct differences? Keep in mind that the pH is a logarithm of concentrations and small changes can mean a lot compared to DOC and EC.

Answer: In earlier work the soil pH in DRIPs were found to be distinctly higher as non-DRIPs, which was expected to be reflected in the groundwater pH (Kuglerová et al., 2014). We were aware of the pH scales sensitivity but expected perhaps more distinct differences given the field-based observations of DRIP and non-DRIP riparian areas.

P8L16: When you talk about seasonality you mean factor TIME, right? It would be helpful to stick to those factor names and provide it in brackets if other words such as seasonality are used.

Answer: We will go through the result section to ensure this terminology is used consistently

Fig. 4: I suggest that you indicate if the mean is significantly differing in individual panels. That would improve readability here. Same is true for Fig. 3 and 5

Answer: Although we agree that this would improve the figure in general, it is in combination with our statistical approach likely to cause more confusion than clarification. The significant differences of these individual sets might not be entirely representing the statistical outcome of the LMM we have used, since that tests to what degree vari-

ability in the predictor can be explained by the explanatory factors. As such, the significant differences of the boxplots is maybe confusing because we deliberately tried to avoid this type of statistic. Moreover the box plots show medians and p-values would be computed by means. Although we do provide a p-value for the Figure 3 box plots, this is a general statistic that does not do justice to the complexity of the dataset. Figures 3-5 are mostly aiming to show the elapse in variability over space and time, rather than proving significant differences at the individual plot or season level.

Discussion

The discussion makes strong links of groundwater spatial variability to stream chemistry temporal variability. But this is not what was shown in the results. I miss a discussion of why groundwater quality was as it was measured and presented above. All the discussion is rather focusing on implications.

Answer: We will expand the first paragraph to further explain the results and shorten the implications for stream water quality.

P9L23 to P10L3: I have problems following the argumentation here. Why does the contrasting chemistry of DRIPS and non-DRIPS explains why pre-event water is quickly mobilizes? Do we really need DRIPS and non-DRIPS to explain temporal variability of stream chemistry within an event? That is also covered by vertical chemical heterogeneity (taking Seibert's RIM for instance).

Answer: We argue that the vertical chemical heterogeneity is still valid, but that in a horizontal plane the hydrological conditions (or storage state) of the riparian zone are dominating the way this vertical chemical heterogeneity is translated to lateral contributions to streams. For DRIPs the mobilization can be extremely fast since there is no unsaturated zone to store more water. In contrast, non-DRIPs are presumably delayed in response due to the vertical infiltration and rise of groundwater tables before a contribution to the stream is initiated. In combination with previous comments we will elaborate on the comparison to the DSL and RIM concepts in the discussion.

P10L26: The generalization (that totally make sense) of your findings to the larger scale of the Kryckland catchment is a selling point. I suggest to base the statement made here on DRIPS in catchments on a sound and reproducible analysis and not on a personal communication.

Answer: The statement is based on a reproducible analysis which we will provide in the supporting material.

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