Hydrol. Earth Syst. Sci. Discuss.,
https://doi.org/10.5194/hess-2020-121-AC1, 2020

Hydrology and Earth System Sciences
Discussions
Open Access

Interactive comment on "Linking groundwater travel times to stream chemistry, isotopic composition and catchment characteristics" *by* Elin Jutebring Sterte et al.

Elin Jutebring Sterte et al.

eljs@dhigroup.com

Received and published: 9 July 2020

Introduction comment from reviewer #1 In this study the authors used a physically-based distributed model in combination with a particle tracking approach to determine groundwater travel times in the well-studied Kryklan catchment in northern Sweden. They compared the modeled mean travel times (MTTs) with average winter values of stable isotopes, pH, base cations and found significant correlations for all of them. Furthermore they tried to relate MTTs to certain catchment characteristics. The only strong and significant correlation they found was between MTTs and the fraction of low conductive sediments.

- Authors response: On behalf of all authors, I, would like to thank reviewer #1 for his/her constructive criticism and suggestions which will improve the next version of the manuscript. The main concern raised was the need to improve the analysis and discussion part, which, we agree will progress the manuscript further. Our explanations and responses to all the reviewer's comments and questions are listed below. All the comments have been included unabridged in this document, together with our response following each comment.

The use of particle tracking approaches to determine travel time distributions with numerical models becomes more and more common in catchment hydrology. And although some of these approaches still suffer from certain simplifications (missing dispersion component, particles disappearing after temporary exfiltration, etc.) they can already shed light on general catchment dynamics. Having said that I am missing a more detailed description of both the model setup with Mike SHE and the particle tracking approach in particular (one or two additional figures would not hurt).

- Authors response: We understand the reviewers concerns regarding the method sections. A main reason for this is that the present model is based on the model that already has been thoroughly described in a previous paper by Jutebring Sterte et al. (2018), which is cited in the manuscript. However, we realize the need to provide the readers of this manuscript with a more proper background. We will incorporate a schematic figure in the method section as well as adjust the text to make the method description easier to follow and understand. Figure 2 is a preliminary example of an additional of the particle tracking procedure. We will also add a more descriptive text of the Mike She water flow model in the revised manuscript.

Language, style and structure throughout the manuscript are quite good and easy to follow.

- Authors response: We appreciate the specific language comments listed below which helps to increase the understandability and language quality.

In the introduction the authors present their hypotheses regarding the relationships between travel times and catchment characteristics. However, it seems that the review of relationships that have already been determined in former studies is a little short. I would like to point out that it is already quite well established that MTT saretime-variant and going along with this the strength of relationships between MTTs and certain physical catchment characteristics changes as well (this should be discussed at least in a little more depth than just mentioning it in line 49 once). Also research over at least the last 10 years has stressed the fact that it is in most cases a combination of multiple characteristics that control a catchment's MTTs. A comprehensive (short) summary of the state of art would be really helpful.

- Authors response: We appreciate the reviewer's comment and will add a section that better describes the state of art regarding this in the introduction of the revised manuscript. We have read the suggested literature and will use these to extend the introduction and discussion. Reviewer #2 also addressed this issue and we do agree that our hypothesis used in the original version of the manuscript was not the best way to present the results of our study. As responded to reviewer #2 comment, we decided to focus our study on the connection between baseflow travel times and stream chemistry (base cation and isotopes). We do believe we have a unique opportunity to distinguish the baseflow in the streams due to the prolonged winter, which gives little to no new input of water to the system during almost 6 months. The baseflow in turn, can be a very important signature for the amount and quality of groundwater.

I am also missing a more detailed analysis of the modeled travel time distributions. I am especially intrigued by the very steep initial rise of the cumulative distributions. Given the fact that the TTDs are related to baseflow conditions, this seems particularly puzzling to me. Therefore I would like to see more explanation and discussion in this part. A figure of the modeled (not cumulative) TTDs would also be interesting/helpful.

- Authors response: The groundwater in Krycklan is relatively shallow, especially around the mires. The till has a marked decreasing hydraulic conductivity with depth. The main flow of water occur therefore in the shallow part of the till, resulting in fast groundwater flow especially during snow melt in the spring. TTD:s is the travel time of the groundwater for the whole simulated period, and thereby the steep initial rise of the TTD:s are mainly connected to the spring snowmelt. This emphasize the importance of conducting thorough investigations of TTDs and MTTs in different climate regions. We assume that the "true" baseflow can be represented by the groundwater reaching the streams during the winter period since there is no new input of precipitation to the soil during this time. This period also has an older age (gMTT). We will add a figure with monthly groundwater age distribution and the partition of groundwater and direct surface flow, and also change the TTD:s figure to show only the particles related to the baseflow (winter flow), see example figure 6.

The discussion and conclusion sections are straightforward and quite easy to comprehend. This may, unfortunately, be due to the fact that the results are not really new. Catchment size is not related to MTTs; hydraulic conductivity, slope and flow path length are related to MTTs. In the end I am left wondering whether there is enough novelty (maybe relating pH and base cations to MTTs?). A more in depth discussion of the modeled TTDs could help or maybe additional analyses on the interdependencies of how different catchment characteristics combined control MTTs. Still, I believe that in the end the authors will manage to add more analysis and discussion to justify a publication in HESS.

- Authors response: We will extend the evaluation regarding the TTDs and the chemistry data and give more focus to the unique opportunity to analysis the baseflow due to the prolonged winter conditions at the site. We will also add a figure that show the monthly groundwater age distribution to the streams and add a discussion towards the importance of baseflow for the different sub-catchment. Additionally, we will add a section in the discussion part that highlights the unique set of data and models available, which enables a coupled analysis of chemistry and hydrology in order to understand the complex integrated surface-subsurface water system of the Krycklan catchment. It should be noted that in contrast to many previous studies this study was conducted in a snow-dominated catchment in the boreal forest region, which implies that one could expect differences in the hydrology and transit time distributions compared to more temperate regions where the majority of previous work has been conducted. We believe that the extended winter season conditions allow great opportunities to address the role of the base flow, its TTDs and relationship to water isotopes and water chemistry. Furthermore, we must also emphasize the comprehensive background data that was used for the setup and testing of the results, e.g. continuous discharge measurements and measurements of stable water isotopes and stream chemistry at 14 streams. Combined this should strengthen the reliability of the modelled TTDs.

Specific comments from reviewer #1

Authors disclosure: We agree with most specific suggestions and comments from reviewer #1. However, some sections of the introduction and discussion will be re-written with the help of this input and some sentences might end up being different in the revised manuscript.

Line 23: ‘...to investigate...’

- Authors response: We will change this according to the reviewer’s suggestion.

Line 23: Better write: ‘...the travel time of the input to 14 [...] sub-catchments via groundwater to the stream...’.

- Authors response: We will change this according to the reviewer’s suggestion.

Line 30: Move this sentence up to Line 27 just after ‘...stream water.’.

- Authors response: We agree to this change and we will change this according to the reviewer’s suggestion.

Line 31: I would add whether these were positive or negative correlations.

- Authors response: We agree that this would make the manuscript easier to follow and

we will therefore change it accordingly.

Line 34: I would not call this a ‘landscape characteristic’. Maybe better call it ‘physical catchment characteristic’.

- Authors response: We will change it to “physical catchment characteristic” in the revised version of the manuscript to make the text clearer.

âĂČ Line 35: ‘...to positively correlate with MTT.’ - Authors response: We agree to this change and we will change this according to the reviewer’s suggestion.

Line 50: These referenced papers deal mainly with mean travel times, not with travel time distributions. Appropriate references for variations in TTDs would be for example Botter et al. (2010), Heidbüchel et al. (2012), Hrachowitz et al., (2013). Line 87: Again, I would not use ‘landscape’ factors since the term landscape refers to the visible landforms rather than to physical properties or subsurface features.

- Authors response: We like to thank the reviewer fort the suggested references. We have read and will add these to the introduction.

Introduction: This section lacks the mention/discussion of previous work that is very relevant to the study. Especially concerning research on the connection of travel time and catchment characteristics. Your hypothesis is that catchment size correlates with travel time, but what about any other catchment properties? So far travel times have been related to slope, flow path length, soil thickness, antecedent moisture content, hydraulic conductivity, just to name a few. I recommend expanding the short introduction a bit more to include a brief discussion of potential travel time controlling factors (Ameli et al., 2016; Birkel et al., 2016; Haitjema et al., 1995; Heidbüchel et al., 2013; Hrachowitz et al., 2010; McGuire et al., 2005; Yang et al., 2018).

- Authors response: We appreciate the reviewer’s suggestion and will extend the introduction using the suggested material. We will also focus more on the connection between stream chemistry compared to model results. The long winter with no input of precipitation to the groundwater makes it possible to distinguish the baseflow from the discharge affected by new input of water to the system. Krycklan has a significant amount of empirical data and long-term observations that provides a unique opportunity to analyze a northern snow-dominated catchment.

Line 106: '...type OF regolith...'?

- Authors response: We agree with this change and we will add "of" to this sentence.

Line 123: I would like to see a figure of the stratigraphy and how it is displayed in the model.

- Authors response: We will add a map over the typography and a soil map in the manuscript, as well as a more descriptive text about the Mike SHE flow model.

Line 172: Are these winter GW travel times travel times of particles that entered the catchment during the winter or exited the catchment during the winter (are they from 'forward' or from 'backward' TTDs)? This is a very important and interesting question since it could be very different catchment characteristics that control forward or backward travel times.

- Authors response: We agree that this could be better described to make it clearer. It is the age of particles exiting the catchment through stream discharge during winter regardless when they entered the groundwater as recharge, i.e. it is backwards TTDs. We will improve the clarity throughout the manuscript regarding weather it is forward or backward TTDs. Note that practically all precipitation falls as snow during the winter so typically there is little or no addition of water to the system during this period. Therefore, there is no addition of particles to the model during the winter months. Consequently, we doubt that it would be meaningful to trace the small amounts of water that might be added during the winters in these systems.

Line 215: According to this equation a mire coverage of 100% would result in an infinitely large adjusted cation concentration which is quite unrealistic (this is equivalent to a scenario where mires do not contribute any cations whatsoever). How do you justify this relationship?

- Authors response: The adjustment of the cation concentrations is based on observations of how mires affect the stream water concentrations of a wide range of elements. This has been described in detail by Lidman et al. (2014), which is cited in the manuscript. A general pattern was that the concentration of predominately weathering-derived elements such as the base cations decreased with the mire coverage. For the base cations, which do not sorb particularly strongly to peat, the decrease corresponded well with the decrease in mineral soils. This was therefore interpreted as dilution by mire water, since weathering does not occur in peat. For example, if 20% of the mineral soils in catchment was replaced by 20% peat, the weathering should be expected to decrease by approximately 20%, eventually causing approximately 20% lower concentrations in the runoff. (In practice, somewhat higher specific discharge from mires would increase the dilution effect, but then a slight addition of base cation with the precipitation would counteract this effect so the net effect is approximately 1% dilution by 1% wetland.) This is illustrated by Na in figure 3 with data from Lidman et al. (2014), where these matters are discussed in more detail for Na and other elements. We believe that this justifies the need to adjust the base cation concentrations for the effect of the mires in order to make a fair comparison to the modelled transit times, which include the mires. In principle, however, the Reviewer is correct in stating that this adjustment would be problematic in cases where the mire coverage approaches 100%. One reason, as the Reviewer points out, is that the adjustment would lead to unrealistically high concentrations if the mire coverage were close to 100%. This is, however, only a theoretical problem, since the mire coverage in the investigated sub-catchments never exceeds 44%. There is therefore no need to make such unrealistic and also unsupported adjustments. We find it hard even to envisage how a catchment with much higher mire coverage would be able to develop in this area, but since no such sub-catchments exist in the present study we believe that this discussion could be left for another context. Another reason why we would be reluctant to use this type of adjustment for such extreme cases where the mire coverage was close to 100% (had it for some reason been necessary) is that it would require extrapolation far outside the observed range. In this case the relationship to the concentration is significant between in the range 0-44% mire coverage (as in figure 3). The observations were made in the same streams that were investigated in this study so there is clearly a justifiable relationship between base cation concentrations and mire coverage.

Line 220: What exactly do you mean by this ('...less impacted...', '...also considered.')?

- Authors response: What we meant to express was that there is a fundamental difference between the water isotopes, on the one hand, and the stream chemistry, on the other. The interpretation of the water isotopes is based on the characteristic variation in the input signal throughout the year. Consequently, the important parameter is the variation in the water isotope signature in the runoff, as given in the manuscript. The annual average, however, is not a meaningful parameter. In the case of pH and base cation concentrations, the major drivers are processes within the catchment, e.g. weathering rates and transit times, and it is therefore meaningful to look also at the annual averages in this case. Apparently, we will need to explain this clearer in a revised manuscript.

Line 239: But the simulated specific baseflow is not included in Table 4.

- Authors response: Information about the specific discharge was omitted from Table 4 at a late stage. It must however still be left in the text. This needs to be corrected.

Line 243: Again it would be important to know whether these are forward or backward times.

- Authors response: We agree with this comment and will check and adjust the entire text accordingly. To answer the question, it is backwards times, i.e. the age of a particle when it reaches a stream and exits the model, regardless of when they were first introduced to the groundwater. Since the system is frozen during the winters, there

is only negligible addition of water. Hence, it would not be very meaningful to study the forward times for the winter period.

Line243: I would some how indicate that the means are geometric instead of arithmetic when you write MTT (maybe something like 'gMTT'?). Because one will automatically assume that MTT is the arithmetic mean of the travel times.

- Authors response: Thank you for the comment, we will adjust this in the next version since it will improve the clarity of the text and use the suggested gMTT.

Line 245: This is not a complete sentence (verb missing).

- Authors response: Thank you, we will change this in the next version

Line 248: 'Over the course of a year...'; '...may enrich or dilute...'

- Authors response: We agree with this change and change this in the next version

Line 259: Winter baseflow or winter groundwater fraction?

- Authors response: Winter groundwater fraction is the winter discharge divided by total yearly discharge. We will change this text.

Line272: Instead of 'decreased' I would rather write'...became more negative/became more enriched in the lighter isotope...'

- Authors response: We agree with this and change this in the next version

Line 277: '... averages...'

- Authors response: Thank you, we will change this in the next version

Line 292-294: It would be good to add 'positive' or 'negative' before 'correlations', so you immediately know the direction of the relationship.

- Authors response: We agree that this would add to the manuscript and make it easier for the reader to directly understand the relationship without having to look at the figures.

Line 297: How do these equations show that LCS is the most significant parameter?

- Authors response: The reviewer has a valid point here. It is hard to justify based only on the equations in questions that LCS is the single most important parameter for controlling the MTTs in the investigated catchment. This should clearly be rephrased in a more stringent way. The message we were trying to convey is that it seems hard to get around the impact of the LCS when looking at the MTTs throughout the landscape. As in this example, it is difficult to replace LCS by any other parameter and obtain equally good correlations, which indicates that it probably plays an important role for controlling MTTs. We will improve this explanation in the next manuscript version.

Line 304: ‘Percentage of low conductive sediments...’

- Authors response: We agree with this change and will adjust it in the revised manuscript.

Line 314: ‘...on the other...’?

- Authors response: We checked this and ”. . .on the other. . .” should be removed.

Line 318: ‘...and a gamma distribution transfer function (convolution) method...’

- Authors response: We agree with this edit and will change it in the revised manuscript.

Line 318: ‘In a conceptual, non-distributed modeling study...’

- Authors response: We agree with this edit and will change it in the revised manuscript.

Line 319: Some more details would be helpful (‘another travel time distribution technique’).

- Authors response: We will add more details regarding this technique.

Line 361: This section is a bit unstructured. You start out by stating that slope and hydraulic conductivity are the main factors controlling MTTs, then you state that the

fraction of LCS is the most important factor adding travel distance to the mix before arguing that the steeper small C20 behaves differently maybe also because of the fluvial deposits fraction... Since these are some of your main findings it would be good to clarify the section. Also, what about the fact that you released the particles at the top of the transient groundwater table? That means that depending on the groundwater table a larger or smaller part of the regolith was not taken into account for the MTT calculations. If the water table was high a larger proportion of the regolith was considered, if it was low the particles started somewhere else in the profile. What are the implications of this? Would that influence your results?

- Authors response: Please check the new figure 2 and new figure 1. Most of the calculated groundwater table has a level between 0-3 m below the ground. The vertical discretization of the saturated zone follows the soil layers and are a few meters in depth close to the surface and increasing in thickness with depth. Note that the horizontal grid-size is 50*50 m and therefore the MTT will be bias to long travelling groundwater. Peatlands are generally the areas with an average groundwater table above 1 m, while the till areas have a depth between 2-3 m in average. However, at C14, the deep esker has a lower water table than on other locations in the catchments. The esker has the highest vertical hydraulic conductivity, and thereby the fastest route from infiltration to recharge. Although the horizontal distance is still larger than the distance to the groundwater table and the vertical hydraulic conductivity is large, one should note that this could impact the results and give C14 and C16 older MTT than if the phreatic surface was at the same level around the whole catchment. It can be noted that the areas were the MTTs mainly could be suppressed by this limitation in the modelling tools are areas with relatively long MTTs. This effect therefore somewhat counteracts the general patterns that were observed in this study. Hence, the observed patterns are not a result of the differences in groundwater depth. On the contrary, we would have expected patterns that are even more distinct if it had been possible to account for the time it takes for the water to percolate to the groundwater surface. We will add a discussion about this, since it is an interesting subject and relevant for the interpretation of the results and try to make the section more structured.

Line 380: It would be good to point out more the novel aspects of your work. What did you find out that was really new? The fact that Darcy's law works? Catchment size has been ruled out as a MTT control since quite a while now. Or is it mainly a study that confirms the applicability of the particle tracking of your model by comparing results to time series of pH, base cations and stable isotopes?

- Authors response: Reviewer #2 also indicated that we need to highlight more clearly the novelty of this study so this is one of the major concerns we would have to address in a revised manuscript. The original manuscript was organized around the hypothesis that MTTs are controlled by catchment size, but based on the comments of both Reviewers and the available literature, we agree that the results of this study could be presented in a better way by omitting this hypothesis as a rationale for the study and instead focus on other more novel aspects of this work. This includes emphasizing the implication of the northern landscape setting where the hydrology processes are dominated by prolonged winter conditions, and a dominating spring flood. Krycklan is one of the most well-investigated and well-instrumented catchments in the boreal region with a large database of empirical observations that allow multiple ways to test the predictions of hydrological models. In our opinion, the discussion about MTTs, TTDs and their variation at different scales in the landscape is far from finished, and we believe that this study could contribute significantly to the understanding of the hydrology of the snow-dominated boreal forest landscape, the coupling between hydrology and water quality and, not least, the role of winter base flow in a changing climate. It is far from obvious that MTTs and TTDs would look the same and be controlled by the same factors in different types of landscapes and climates, so we believe that this type of studies from different areas of the world are necessary to improve our understanding of these matters. We further believe that should highlight the role of the base flow better in a revised version of the manuscript, since the long winters make these boreal systems particularly suitable for addressing their role. We should also try to emphasize better the large amount of data that were used to set up and test the model, e.g. the continuous discharge measurements in the streams and the extensive monitoring of water isotopes and stream chemistry. Combined we believe that this background data significantly strengthens the credibility of the conclusions we present.

Figure specific comments: Figure 1: Why do you call the sub-catchments subareas in this figure? Also, all subcatchments (not only the green ones) connect before reaching the main outlet at C16.

- Authors response: We will change sub-areas to sub-catchments in the figure. Yes, all streams connect before they reach C16. However, the color code was used to illustrate which areas connect before they reach the white area. We will try to clarify this in the figure text.

Figure 2: I am confused by the y axis label. Why does it start with 100% and then decrease to 0%? Isn't this a cumulative TTD (that should start with 0%)? Also, you never mention how you construct this TTD. Do you record the time the particles that arrive in the stream in the winter needed to travel through the catchment (backward TTD) or do you record the time that particles that are released during winter need to travel through the catchment (forward TTD)? I am curious since the cumulative TTDs exhibit a shape I would not have expected since the initial rise is very steep although you use a logarithmic x axis. For a groundwater TTDs in particular, this extremely high initial values are quite unusual. How do you explain this?

- Authors response: Thank you for pointing this out! There was an error in this figure, the number of particles should start at 0 % and increase to 100 %, so the y-axis should change, see figure 4. The TTD is the age of particles when they reached a stream for the whole simulated period, winter has not been selected in this figure. However, we will clarify the text, change the y-axis and pick out only the winter period. The reason for the initial rise is due to that it includes particles coming to the streams during the whole year (Jan-Dec). The snowmelt impacts the groundwater travel time age and therefore there is a rapid start. Given that a substantial portion of the annual precipitation leaves the catchments during a few weeks of spring flood, we do not think that the initial steepness of the distribution is surprising. This is probably one of the characteristics of boreal systems compared to other types of systems and emphasizes the importance of conducting this type of studies in different climate regions.

Figure3: So if youre place the geometric MTT with thec ommonly used arithmetic MTT, how does that change the correlations? In case they become weaker you could argue for the general use of the geometric MTT.

- Authors response: The arithmetic MTT is often used when looking at the gamma convolution distributions using isotopic data. It has been argued that the MTT should not be used for MTT older than 5 years because the amplitude signals are lost (Kirchner, 2016). Therefore, the aMTT is less impacted by the “old tail”. For particle tracking or modelling methods the median or the geometric MTT may describe the bulk of the particles better than aMTT, because one particle (even though there are hundreds of particles in total) with a very old age may cause significant differences in the MTT estimation. This is undesirable, since the age of these very old particles becomes increasingly uncertain and are very hard to validate. The gMTT is less dependent on a few old particles but does still take them into account. In our case, the aMTT correlates well with the gMTT (see figure 5) and aMTT is shown in the supporting information but we will move them to a table in the main manuscript. Kirchner, J. W.: Aggregation in environmental systems – Part 1: Seasonal tracer cycles quantify young water fractions, but not mean transit times, in spatially heterogeneous catchments, Hydrol. Earth Syst. Sci., 20, 279–297, https://doi.org/10.5194/hess-20-279-2016, 2016.

Supplements Supplements S1: Check again for typos and misuse of words throughout the supplement (in particular in the table captions and the table foot notes).

- Authors response: We will check this in the revised version

S1, line 3: What does that mean that the table includes both non-transformed and

log-normal transformed data? Which is which?

- Authors response: We will check this and make the table easier to understand.

S1, line 4: What happened to the other 44% of particles?

- Authors response: These particles reached a model sink, either the model boundary through groundwater outflow, or reached the unsaturated zone/surface water that is not connected to a stream or a lake.

S1, line 8: ‘Artesian’ mean? And why ‘back-transformed’?

- Authors response: We will make this text and corresponding table easier to read. “Artesian” should be arithmetic

S1, line 19: ‘...as well as the precipitation (P)’

- Authors response: We will change this according to the suggestion

S2, line 3: What does ‘The statistics are based on...’ mean?

- Authors response: We will make this text and corresponding table easier to read and explain more in the text what the table show.

S2: The tables are not that helpful. Many of the abbreviations are not explained

- Authors response: We will make this text and corresponding table easier to read and explain more in the text what the table show as well as explain all abbreviations.

Add to literature: Literature Ameli, A. A., Amvrosiadi, N., Grabs, T., Laudon, H., Creed, I. F., McDonnell, J. J., and Bishop, K.: Hillslope permeability architecture controls on subsurface transit time distribution and flow paths, J. Hydrol., 543, 17–30, https://doi.org/10.1016/j.jhydrol.2016.04.071, 2016. Birkel, C., Geris, J., Molina, M. J., Mendez, C., Arce, R., Dick, J., et al.: Hydroclimatic controls on non-stationary stream water ages in humid tropical catchments, J. Hydrol., 542, 231–240, https://doi.org/10.1016/j.jhydrol.2016.09.006, 2016. Botter, G., Bertuzzo, E., and Rinaldo, A.: Transport in the hydrologic response: Travel time distributions, soil moisture dynamics, and the old water paradox, Water Resour. Res., 46, https://doi.org/10.1029/2009WR008371, 2010. Haitjema, H. M.: On the residence time distribution in idealized groundwatersheds, J. Hydrol., 172, 127–146, https://doi.org/10.1016/0022-1694(95)02732-5, 1995. Heidbüchel, I., Troch, P. A., Lyon, S. W., and Weiler, M.: The master transit time distribution of variable flow systems, Water Resour. Res., 48, https://doi.org/10.1029/2011WR011293, 2012. Heidbüchel, I., Troch, P. A., and Lyon, S. W.: Separating physical and meteorological controls of variable transit times in zero-order catchments, Water Resour. Res., 49, 7644–7657, https://doi.org/10.1002/2012WR013149, 2013. Hrachowitz, M., Soulsby, C., Tetzlaff, D., Malcolm, I. A., and Schoups, G.: Gamma distribution models for transit time estimation in catchments: Physical interpretation of parameters and implications for time-variant transit time assessment, Water Resour. Res., https://doi.org/10.1029/2010WR009148, 2010. Hrachowitz, M., Savenije, H., Bogaard, T. A., Tetzlaff, D., and Soulsby, C.: What can flux tracking teach us about water age distribution patterns and their temporal dynamics?, Hydrol. Earth Syst. Sci., 17, 533–564, https://doi.org/10.5194/hess-17-533-2013, 2013. McGuire, K. J., McDonnell, J. J.,Weiler, M., Kendall, C., McGlynn, B. L., Welker, J. M., and Seibert, J.: The role of topography on catchment-scale water residence time, Water Resour. Res., 41, https://doi.org/10.1029/2004WR003657, 2005. Yang, J., Heidbüchel, I., Musolff, A., Reinstorf, F., and Fleckenstein, J. H.: Exploring the dynamics of transit times and subsurface mixing in a small agricultural catchment, Water Resour. Res., https://doi.org/10.1002/2017WR021896, 2018.

- Authors response: We thank the reviewer for these literature suggestions which can be used to especially improve the introduction section further. We will read these suggestions and incorporate them were they seem to be most fitting.

Please also note the supplement to this comment:
https://www.hydrol-earth-syst-sci-discuss.net/hess-2020-121/hess-2020-121-AC1-

supplement.pdf

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2020-121, 2020.

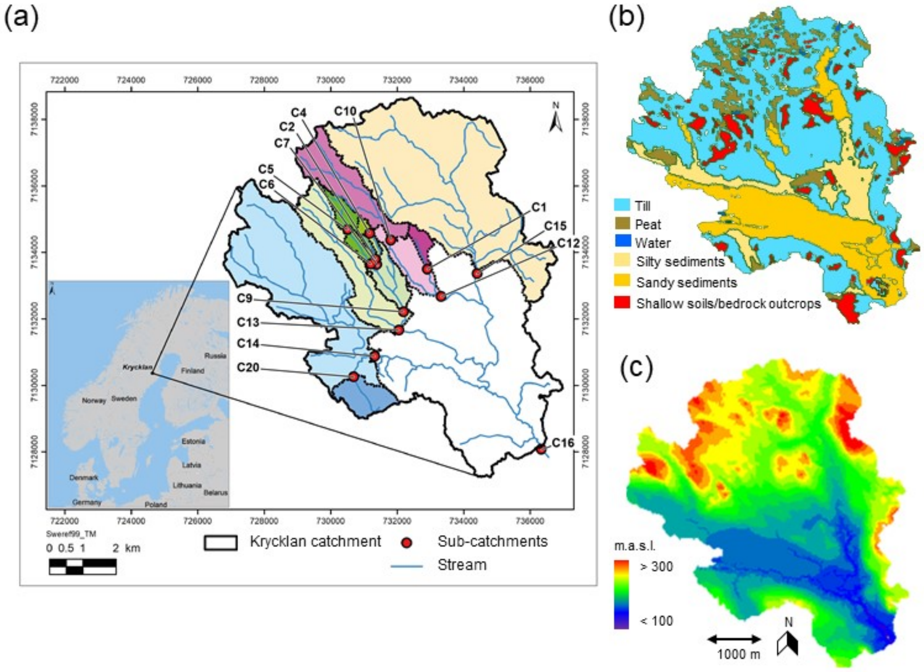
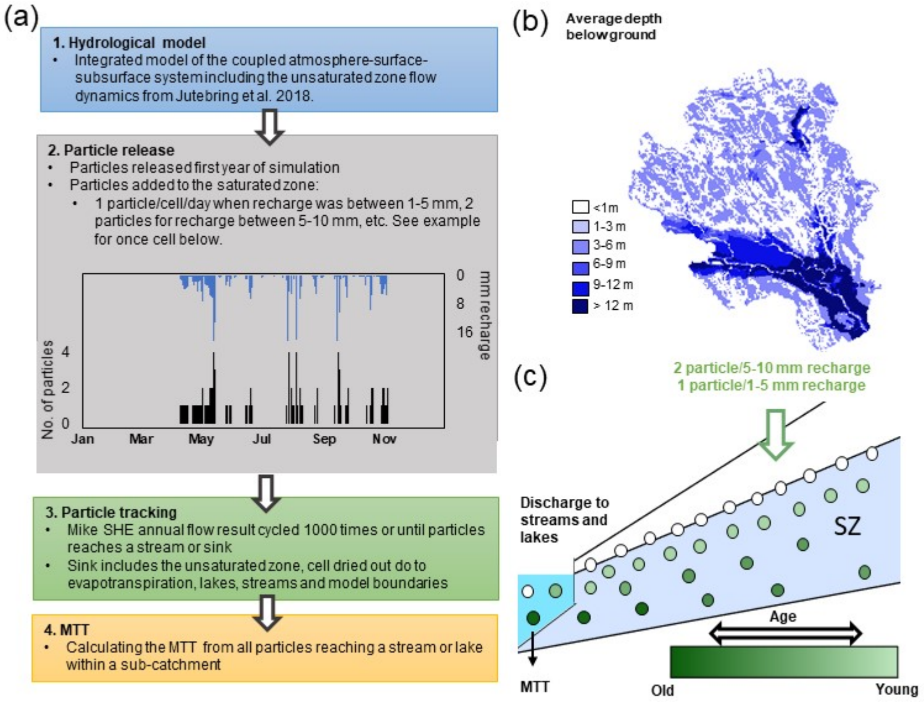


Fig. 1. The Krycklan catchment



1. Hydrological model
- Integrated model of the coupled atmosphere-surface-subsurface system including the unsaturated zone flow dynamics from Jutebring et al. 2018.

2. Particle release
- Particles released first year of simulation
- Particles added to the saturated zone:
  - 1 particle/cell/day when recharge was between 1-5 mm, 2 particles for recharge between 5-10 mm, etc. See example for once cell below.

3. Particle tracking
- Mike SHE annual flow result cycled 1000 times or until particles reaches a stream or sink
- Sink includes the unsaturated zone, cell dried out do to evapotranspiration, lakes, streams and model boundaries

4. MTT
- Calculating the MTT from all particles reaching a stream or lake within a sub-catchment

Fig. 2. Model setup

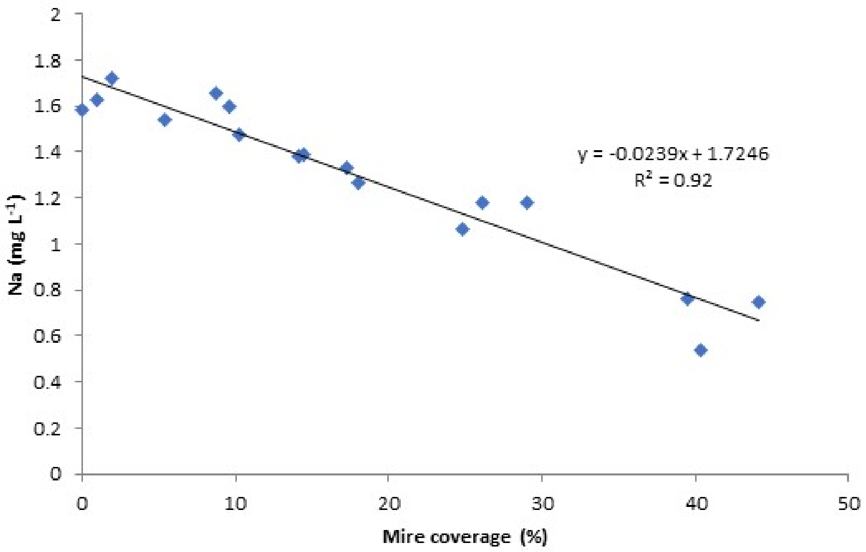


Fig. 3. Na concentrations

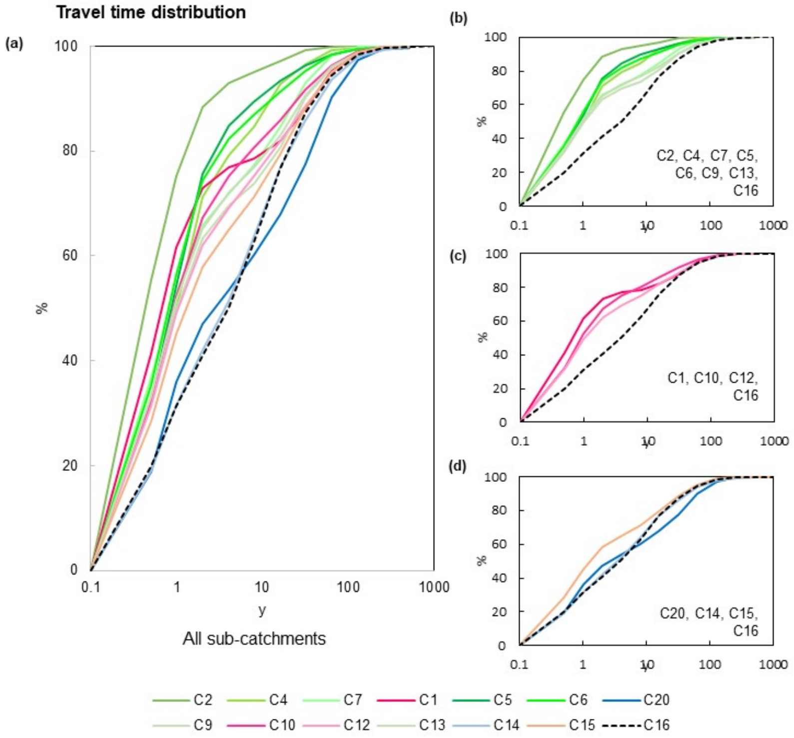


Fig. 4. TTD

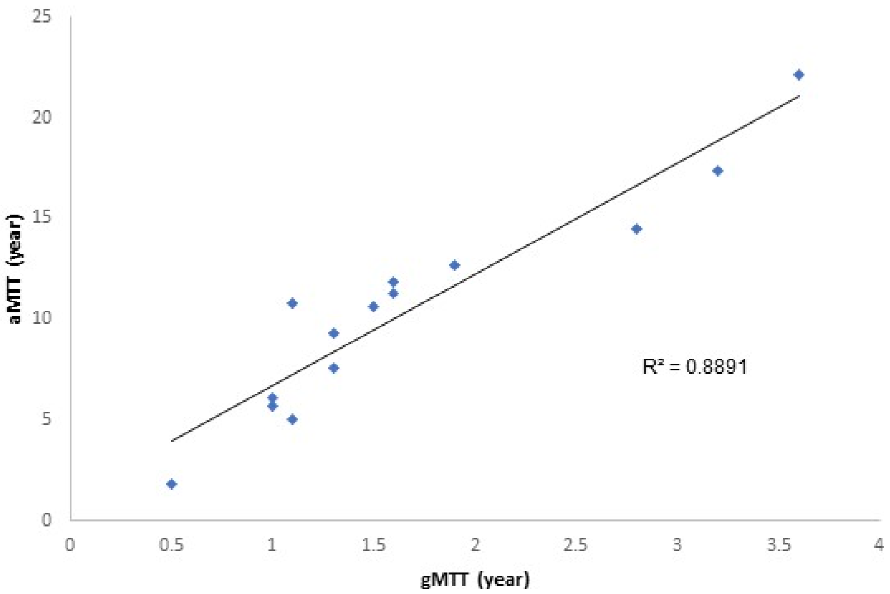


Fig. 5. aMTT and gMTT relationship

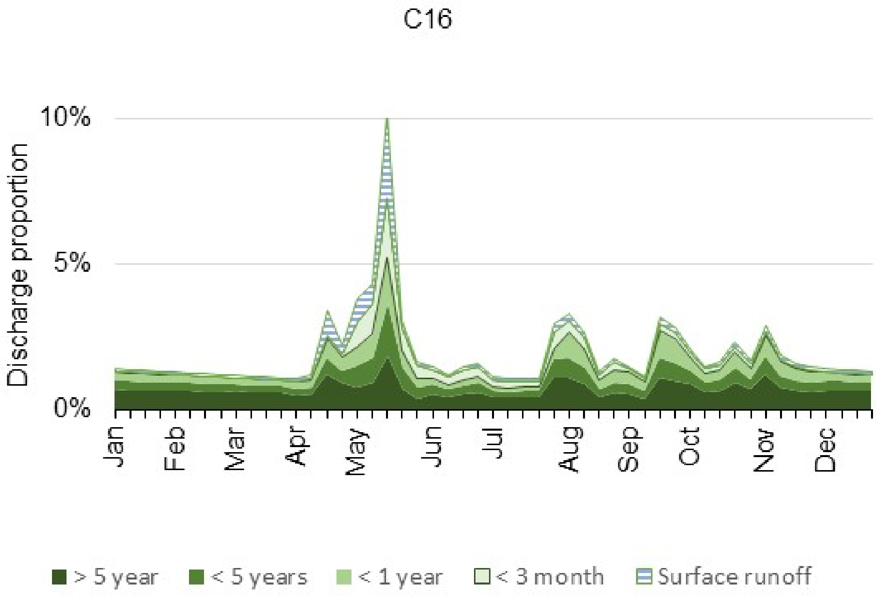


Fig. 6. Discharge distribution

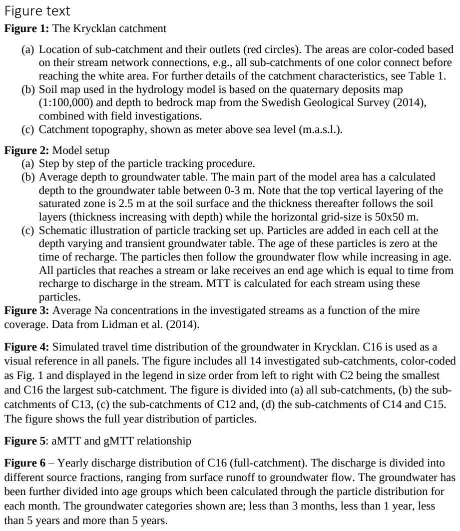


Figure text

Figure 1: The Krycklan catchment

(a) Location of sub-catchment and their outlets (red circles). The areas are color-coded based on their stream network connections, e.g., all sub-catchments of one color connect before reaching the white area. For further details of the catchment characteristics, see Table 1.
(b) Soil map used in the hydrology model is based on the quaternary deposits map (1:100,000) and depth to bedrock map from the Swedish Geological Survey (2014), combined with field investigations.
(c) Catchment topography, shown as meter above sea level (m.a.s.l.).

Figure 2: Model setup
(a) Step by step of the particle tracking procedure.
(b) Average depth to groundwater table. The main part of the model area has a calculated depth to the groundwater table between 0-3 m. Note that the top vertical layering of the saturated zone is 2.5 m at the soil surface and the thickness thereafter follows the soil layers (thickness increasing with depth) while the horizontal grid-size is 50x50 m.
(c) Schematic illustration of particle tracking set up. Particles are added in each cell at the depth varying and transient groundwater table. The age of these particles is zero at the time of recharge. The particles then follow the groundwater flow while increasing in age. All particles that reaches a stream or lake receives an end age which is equal to time from recharge to discharge in the stream. MTT is calculated for each stream using these particles.

Figure 3: Average Na concentrations in the investigated streams as a function of the mire coverage. Data from Lidman et al. (2014).

Figure 4: Simulated travel time distribution of the groundwater in Krycklan. C16 is used as a visual reference in all panels. The figure includes all 14 investigated sub-catchments, color-coded as Fig. 1 and displayed in the legend in size order from left to right with C2 being the smallest and C16 the largest sub-catchment. The figure is divided into (a) all sub-catchments, (b) the sub-catchments of C13, (c) the sub-catchments of C12 and, (d) the sub-catchments of C14 and C15. The figure shows the full year distribution of particles.

Figure 5: aMTT and gMTT relationship

Figure 6 – Yearly discharge distribution of C16 (full-catchment). The discharge is divided into different source fractions, ranging from surface runoff to groundwater flow. The groundwater has been further divided into age groups which been calculated through the particle distribution for each month. The groundwater categories shown are; less than 3 months, less than 1 year, less than 5 years and more than 5 years.

Fig. 7. Figure text