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Interactive comment on “A fluid-mechanics-based classification scheme for surface transient storage in riverine environments: quantitatively separating surface from hyporheic transient storage” *by* T. R. Jackson et al.

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Ross Woods, Editor

RE: Interactive comment on “A Fluid-Mechanics-Based Classification Scheme for Surface Transient Storage in Riverine Environments: Quantitatively Separating Surface from Hyporheic Transient Storage” By Jackson et al.

Dear Dr. Woods,

Please find below our responses to all comments and questions provided by Reviewer 1. All points have been addressed below and, where appropriate, revisions have been made to a revised version of the current manuscript. We would like to thank Reviewer 1 for his helpful suggestions and comments which will improve the quality of this manuscript.

Sincerely,

Tracie R. Jackson

Responses to Reviewer 1

This manuscript is exciting in its efforts to create a new classification scheme for ecosystem structure and function. It seeks to characterize the mean flow structure and scaled-geometry in 8 geomorphic features, referred to as surface transient storage (STS) zones, common to rivers. The STS is considered by the authors as 1 of 2 zones where solutes can reside when not in the main channel (MC) flow regime, the other zone being the hyporheic transient storage (HTS) zone. Ideally, the characterization would allow for a predictive estimate of STS residence time based on geomorphic geometry and solute breakthrough curves of total transient storage (TS), and from that scientists would be able to determine the fraction of solute residence time and volume spent in the MC, the STS, and the HTS. In prior experimental and analytical work the authors developed such a relationship between geometry and STS residence time for the river embayment STS. In this manuscript they classify the embayment as an emerged lateral cavity, which they contrast with submerged lateral cavities, both belonging to the first of the 8 geomorphic features, and provide their predictive equation. The other 7 geomorphic features are: Protruding in-channel flow obstructions (backward and forward facing); Isolated in-channel flow obstructions (emerged and submerged); Cascades and riffles; Aquatic vegetation (emerged and submerged); Pools (vertically submerged cavity, closed cavity, recirculating reservoir); Meander bends;

and Confluence of streams. The manuscript does not establish predictive relationships between these 7 geomorphic features and STS residence time. However, for most of these 7 other features the manuscript provides a list of the explanatory variables thought to control the residence time.

This study is presented as providing foundation for future studies in areas of fluid dynamics, geomorphology, and hydrology. The manuscript suggests specific terminology of geometries may help clarify discussions in hydrology about structure and function relations (pool example and the hydraulic reversal theory). The manuscript suggests the use of a fluid mechanics approach to characterize STS and use key hydromorphic parameters (mean flow structure) to influencing mean RT. Hydromorphic parameters will be used to estimate mean RT for each STS (width to length ratio, Re ranges). The authors did a wonderful job illustrating and explaining the idea around coherent structures formed in the velocity shear region by instabilities (Kelvin Helmholtz, etc), and then illustrated 3 types of free shear flows – jets, wakes, and mixing layers.

Referee 1: SUGGESTIONS

Suggestion 1.1) The manuscripts conceptual model of solute residing in the MC, STS, or HTS zones is common, however it may be flawed in the application around high turbulence zones and with unsteady flow typical to these geomorphic structures. The data collected in our field work and the subsequent testing of this MC, STS, or HTS conceptual model suggest solute spends significant time in transition through intermediary locations linking the MC and STS zones. As one example, if we propose the MC and STS are each well-mixed, we should see solute leaving one zone and entering the other, but our data show that the solute spends time in several intermediate zones along the shearing fringe. I suggest the manuscript examine the weaknesses in this conceptual model for MC-STS exchange. If the STS has indistinct boundaries with the MC and there is no exact method of delineating the zones, how do we account for significant (> than median residence time) transition times between these two zones?

Response 1.1) We thank the reviewer for bringing this point to our attention as we did not observe this phenomenon in our field work on emerged lateral cavities because the solute exchange process is fairly rapid through the shear layer interface. However, in the section on submerged aquatic vegetation, Heidi Nepf and coworkers derived a two-zone model to distinguish between two timescales of exchange: an exchange timescale through the shear layer interface, which has been provided in equation 10, and a canopy timescale representative of the STS, which has been provided in equation 12. This seems to be similar to what you have described in that the slower exchange requires an additional timescale. We did not discuss the “what if” effects of slow exchange through the interfaces of each STS because (1) after “scouring” the literature, we only found residence time relationships for emerged lateral cavities (the focus of our work) and submerged aquatic vegetation; and (2) we did not know which types of STS would have rapid versus slow exchange. We believe your point is important and have added a few sentences to section 4 of the revised manuscript to address this issue. See below:

“We hypothesize that, for each STS type (and subtype) identified in the classification scheme, mean residence time relationships can be derived for a range of flow conditions and geometries using field-measureable hydromorphic parameters. Employing dimensional analysis, nondimensional mean residence times can be related to a combination of nondimensional quantities, such as Reynolds number, Froude number, shape factors, bed roughness parameters, aspect ratios, submergence ratios, velocity ratios, and other case-specific parameters. Nondimensional mean residence times can then be compared to collected data for verification. This method was recently utilized by Jackson et al. (2013) to successfully relate the nondimensional mean residence time of a lateral emerged cavity to six nondimensional quantities. Nepf et al. (2007) also developed residence time relationships by dividing a submerged aquatic canopy into two zones: an exchange and wake zone. The exchange zone timescale (Eq. 10) is representative of solute residence time in the shear layer interface and the wake zone timescale (Eq. 12) is representative of solute residence time in the canopy (STS).

Thus, in some cases, mean residence time relationships may need to be derived for both the STS and the shear layer interface if solute exchange is not a rapid process and solute becomes entrained in the shear layer at timescales near the order of the STS timescale."

With respect to your comment: "If the STS has indistinct boundaries with the MC and there is no exact method of delineating the zones, how do we account for significant (> than median residence time) transition times between these two zones?" This is a difficult comment to address directly without an example. If the flow field is submerged, such as a submerged lateral cavity, then overtopping flow will disrupt the shear layer at the surface and can make visualization difficult. Experiments of submerged lateral cavities typically inject a visual dye at the surface and then at different depths to visualize the shear layer.

Suggestion 1.2) The reader would benefit greatly if the manuscript could provide a list of variables and their definitions that are used in the equations; this will help the reader readily find the definition of these variables.

Response 1.2) Good point. A notation section has been added to the revised manuscript.

Suggestion 1.3) The manuscript cites Bukaveckas 2007 regarding the impact of hydromorphic parameters on in-stream structure design. I caution the reference to this citation without contacting the author and asking about some odd data results where that study found the OTIS model required significant lateral inflow (q), creating huge increases in streamflow along the reach, to explain the transient storage around in-stream structures. It is not clear if the author would have a new explanation for that model result given the new research results over the past 8 years, and perhaps the new explanation would be that this large lateral inflow suggests large STS around the structure.

Response 1.3) Thank you for the information regarding Bukaveckas (2007). We were

unaware the results seemed odd. As this reference was cited only once and does not impact the main idea of the manuscript, the citation was removed.

QUESTIONS Question 1.1) The structure of the flow obstruction to STS function relationship is attractive but not enough functional examples were provided to determine if the 8 distinct flow obstruction structures are related to 8 distinct functions – are they likely to be distinct?

Response 1.1) We believe the reviewer is referring to the statement: "Eight distinct STS types are identified and some are subcategorized based on characteristic mean flow structure: (1) lateral cavities (emerged and submerged); (2) protruding in-channel flow obstructions (backward- and forward-facing step); (3) isolated in-channel flow obstructions (emerged and submerged); (4) cascades and riffles; (5) aquatic vegetation (emerged and submerged); (6) pools (vertically submerged cavity, closed cavity, and recirculating reservoir); (7) meander bends; and (8) confluence of streams." The reviewer is correct that "distinct" is not a proper adjective to be used when describing this classification scheme. We were trying to convey that eight different types of STS are identified and subcategorized based on distinctive flow features. As streams are dynamic systems, the characteristics of the STS flow field can change, such as from an open to a closed cavity (Figure 11). The word "distinct" has been removed to avoid this confusion.

Question 1.2) Eq 2 is a wonderful relationship to move from geometry to RTD, but Eq 3 is only a list of variables that are likely to influence RTD. The authors might try to determine direct vs inverse relationships for the variables. Eq 10 provides timescale of the wake zone in submerged aquatic vegetation.

Response 1.2) We believe the reviewer is stating that we should try to develop relationships between mean residence time and each of the variables presented in the functional equations for each STS type. We added a new table to the revised manuscript (Table 2) that lists all hydraulic and morphologic parameters influencing mean residence time for each STS type. Table 2 lists whether each parameter varies proportionally or inversely with mean residence time. For each STS type in section 3 we discussed in detail qualitative relationships between mean residence time and all case-specific parameters. For STS types where no data is available, we provide hypotheses and justifications for how we believe select variables relate to mean residence time. Please note that the functional equations presented are our hypotheses for the variables that most influence mean residence time. The manuscript is a compilation of all current data to date. When more detailed studies are done to relate mean residence time to variables characteristic to each STS type, the data may show some variables have more influence on mean residence time than others.

Question 1.3) Why limit the discussion to 8 flow obstruction structural classes – are there other interesting combinations that are common in natural rivers? I think of any of these structures in series or parallel.

Response 1.3) This manuscript was a 2-year work in progress. The eight STS types (and subtypes) presented are based on our own field observations and on a review of over 600 journal papers from the transient storage, sediment transport, geomorphology, and fluid mechanics literature. The STS classification presented is a compilation of the observations of what we, the authors, and others constitute a surface transient storage zone. To our knowledge, we believe the classification scheme is complete (at least in the sense that it covers a majority of the STS types one would observe in a natural fluvial system). There may be a few rare types of STS that can form in natural streams that are not covered in this manuscript, but the authors are unaware of any STS types other than those that are presented herein. To address the concern that some STS that may not precisely fit into the STS types presented due to slight variations in mean flow structure, we added an additional subsection and briefly discussed this possibility. We provide an example of one particular case and discuss the best way to deal with nonideal STS zones:

“Some STS may have flow structure characteristics that deviate somewhat from the

flow structure described in the classification. For example, one may find an emerged lateral cavity in a channel with a slightly permeable upstream boundary, such as if wood debris upstream of the cavity forms the upstream boundary. In the case that the amount of leakage through the wood debris does not significantly disrupt the flow structure (i.e., the recirculation region is pronounced), then the leakage can be assumed negligible. However, in this case that the amount of leakage through the wood debris does significantly disrupt the flow structure (i.e., flow in the upstream cavity region is disrupted while a recirculation region forms in the downstream region), then the leakage cannot be neglected. For these unique cases sensors may need to be placed in the individual STS zones and in the main channel adjacent to the STS to deconvolve the STS RTD using the method employed by Gooseff et al. (2011) to obtain the STS mean residence time.”

Question 1.4) Are the hydraulics really coherent structures? These are perhaps identified as such in very large rivers or ideal situations with flumes when the roughness of the bed and the discharge does not vary in time or space. In natural rivers the bed roughness likely varies in space and discharge often varies, so the coherence of the hydraulic structures is not certain.

Response 1.4) The hydraulics do produce coherent structures (even in natural systems). In our field work of flow past natural emerged lateral cavities, we have observed these large-scale coherent structures; however, you need to use a needle syringe with a visual dye and inject a small amount of dye to see them. You are correct that bed roughness can distort these structures and make them less idealized, but the mixing layer is always discernible and the structures are “coherent” because you can see the passage of large vortical structures downstream. While we agree that discharge is not a constant variable in time, slight changes in discharge do not prevent these structures from forming. Instead slight variations in discharge cause slight changes to the timing of passage of the structures due to slight changes to their kinetic energy. The purpose of the mean flow field descriptions and representative diagrams was to provide the audience with a visualization of the key variables driving mass and momentum exchange in order to understand the flow physics. While the natural environment will always be less ideal, the mechanisms driving the exchange are the same. I think this comment is mostly about terminology. In fluid mechanics, we also call these structures “vortical structures”. We replaced “coherent” with “vortical” to emphasize that vortical structures are being advected in the shear layers.

Question 1.5) Table 2 parameters are not consistently present in the illustrative figures; for example Figure 12 (pools), Figure 13 (meander), and 14 (confluence) have none of the case specific parameters listed in the corresponding rows of Table 2. Again, the entire suite of these parameters should be defined somewhere in the text.

Response 1.5) A notation section was added that lists are variables and definitions in the revised manuscript. Key parameters also are labeled in Figures 12, 13, and 14.

Question 1.6) Figure 2 has 4 components (3 at top in plan view, 1 at bottom in oblique view) that could be labeled A - D. When Figure 2 is introduced with the text in section 2.2 (line 25) the top plan view parts of the figure doesn’t clearly illustrate the 3 zones using the same terms – detachment, reattachment, and counter-rotating gyres; in the bottom figure it has 2 of these terms, but uses recirculation region in the text and primary gyre in the figure. Try to harmonize these elements; also consider if you need to show the adverse pressure gradient you take care to note in the same section of text. Consider illustrating the entrained vortices that cause the recirculation.

Response 1.6) Labels A-D have been added to Figure 2 and each component of the figure is appropriately referenced in the text in the revised manuscript. Figures 2A-C are labeled with slightly different terminology from figure 2D because labeling each figure with all terms is distracting. Figure 2 should convey that the recirculation region is comprised of primary and secondary gyres. We understand there are many terms used in the text, but all terms are needed to provide a full understanding of the mean flow structure. For readers with a strong fluid mechanics background, the labeling

of different flow structure components may seem superfluous. We apologize to the reviewer and to future readers with a fluid mechanics background where the labeling is unnecessary. However, the manuscript incorporates many ideas and is written to “bridge the gap” between fluid mechanics and transient storage for a broad audience.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 10, 4133, 2013.