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Interactive comment

Interactive comment on "Contributions of Catchment and In-Stream Processes to Suspended Sediment Transport in a Dominantly Groundwater-Fed Catchment" *by* Yan Liu et al.

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We thank S. Mylevaganam for the detailed review and the constructive remarks. In the following, the comments are set in normal fonts, and the responses are in italic.

Comments and Responses

Though the demand on water use is ever increasing due to population growth, urbanization, and climate change, it is inevitable to accept the fact that the supply is limited.

To compound this issue, the quality of water is also deteriorating due to human and natural activities. Among the activities that deteriorate the available water, sedimentation that is due to erosion, suspension, and deposition in rivers ranks at the top. Therefore, in this manuscript, the authors present an integrated sediment transport model to determine the sediment contribution from the Ammer River in Germany. Based on the review of this manuscript, the following points are highlighted:

1. The catchment input, bed erosion, and bank erosion increase with an increase in flow rates (See LN-18 P-1). Is this a generic statement? What is meant by catchment input? What is the expected relationship between the erosion and flow rate? What is mentioned in the literature? Is it possible to justify this statement (i.e., LN-18 P-1) using equation (10) and equation (11)?
   Response: By the catchment input we refer to the sum of sediments from urban areas, non-urban areas, karst system, and waste-water treatment plants (WWTP), that is, all sediments that are not generated by in-stream processes (bed and bank erosion).
   For a river with uniform cross section, we would expect a power-law relationship between the erosion and flow rate. Previous studies have shown that the bed load depends on stream power by a power-law function (Lammers and Bledsoe, 2018; Schneider et al., 2014), in which the stream power is a linear function of the flow rate for a given channel geometry. For the entire river system with non-uniform profiles along the reach, however, the cumulative erosion of the river could follow a different functional relationship on flow rate (in general, we expect that the erosion increases with the increase of flow rates, as the bottom shear stress monotonically depends on the flow rate). Equation (10) shows that bed erosion rate is a piecewise linear function of excess shear stress if the supply of bed sediments is infinite. Equation (11) indicates that the bank erosion rate increases linearly when the shear stress is greater than the threshold. Shear stress increases with the increase of flow rates. Therefore, the bed and bank erosion

increase with an increase in flow rates.
In the intended revision of the paper we will try to make these concepts clearer.

2. Bed erosion and bank erosion are negligible when flow is smaller than the corresponding thresholds of 1.5 m^3s^{-1} and 2.5 m^3s^{-1}, respectively (See LN-19 P-1). Is this statement about the rate? Moreover, the threshold values (i.e., 1.5 m^3s^{-1} and 2.5 m^3s^{-1}) need to be normalized using some of the catchment properties to understand the authors' statement. The threshold value on bank erosion (i.e., 2.5 m3 s-1) is greater than the threshold value on bed erosion (i.e., 1.5 m^3s^{-1}). What is mentioned in the literature?
Response: Yes, the statement is about the rate. To normalize the threshold values of bed and bank erosion is a very good suggestion. We will use the mean discharge to normalize the thresholds and the changes will be shown in the revised manuscript. In our manuscript, we wanted to see the effects of flow rate on the total sediment erosion of the entire river. The result indicates a higher threshold of bank erosion than that of bed erosion, which is expected and reasonable. The bank material is more coherent than be bed sediments, thus requiring larger shear stress to induce bank erosion compared with bed erosion, which results in a higher threshold of flow rate for bank erosion. The literature shows a smaller critical shear stress for bed erosion (Winterwerp et al., 2012) than for bank erosion (Clark and Wynn, 2007).

3. As per the authors, USLE and SEDD cannot estimate sediment generation by in-stream processes (See LN-15 P-2). Moreover, as per the authors, although SWAT/HSPF/HEC-RAS can simulate "physical processes", none of these models represent in-stream processes well, specifically in natural rivers (See LN-24 P-2). What are those instream processes? In think, the authors need to explain the way the sediment (e.g.., suspended) generation and transport is simulated in some of these models (e.g., SWAT) to understand the pitfalls of the existing models to solve the intended problem(s) in Germany.

Response: The in-stream processes in the manuscript are deposition of suspended sediment from the water phase to the river bed, bed erosion and bank erosion due to excess shear stress. We have given some general information of sediment generation of the listed models. We will provide more information on the in-stream processes of the existing models in the revised manuscript, including the limitations of SWAT.

4. The catchment-scale hydrological model is based on the HBV model (See LN-1 P- 4). Does this statement need a reference? Moreover, the authors have added a quick recharge component and an urban surface runoff component to explain the special behavior of discharge in the Ammer catchment (See LN-4 P-4). The special behavior of discharge in the Ammer catchment and the reason(s) for including the additional components are not understood. Is the integrated sediment transport model applicable anywhere?
   Response: We will add a reference to the HBV model. The reason for adding a quick recharge component is that in the Ammer catchment, the measured hydrograph demonstrates a rapid increase in base flow in sporadic events. We attribute this peculiar behavior to the hydrological functioning of karst with a deep unsaturated zone (distance to groundwater up to 100m at the upstream end of the catchment). In our conceptual model, we assume water storage in the deep unsaturated zone, which spills over when a threshold value is reached, causing quick groundwater recharge occur which then leads to a rapid increase of base flow.
   We have added an urban surface runoff component to obtain a surface runoff depth in urban areas in order to simulate particle wash-off from urban land surface. The integrated sediment model can be applied to other catchments with characteristics similar to the Ammer catchment. In particular, the sediments are mainly contributed by urban areas, surface runoff in the agricultural areas is so weak and sporadic that the erosion in the agricultural area can be simplified, and

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sediment production is driven by surface runoff rather than wind blow. Besides the karst-affected hydrology mentioned above, the Ammer catchment is special because the valley is too wide for the current stream flow. This stems from a different river system (River Nagold) cannibalizing the Ammer in the early Pleistocene. The valley has a size that fits to a stronger river that has lost a substantial fraction of its stream flow. This is why we observe so little erosion on the (too flat) hillslopes. While this situation is special, it is not unique. There are other rivers in South Germany that have lost their original stream flow in the course of the extension of the drainage by rivers discharging into River Rhine.
The applicability of the model is affected by data availability as well. We have access to farily detailed river-profile data facilitating the set up the HEC-RAS model. The emphasis on processes for the sediment generation also matters. Our model assumes simplified sediment generation in agricultural areas due to its small contribution. If a user was more interested in sediment generation on different types of crops, the corresponding processes could be modified.
Upon the revision, we will explain the peculiarities of the studied system somewhat better. We will also provide the entire code needed to set up the model as supporting information so that interested readers can adapt and use the code for their own purposes.

5. The HEC–RAS simulates hourly quasi-steady flow (See LN-15 P-4). What was the reason for not selecting the unsteady option in HEC-RAS? The details about the boundary conditions (e.g., Upstream/downstream) and initial states are missing in the manuscript. What types of boundary conditions you had in your model?
Response: The temporal resolution of the hydrological model and of HEC-RAS is one hour, because we have hourly gauging and meteorological data. We performed unsteady flow simulations with HEC-RAS, solving the hydrodynamic-wave form of the St.-Venant equations, and did not observe big differences. This may also be attributed to the comparably small size of the catchment so that in-

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stream retention has only a minor impact on the flow behavior. The unsteady simulations are also less stable. The key outcome of the quasi-steady flow simulations by HEC-RAS is to obtain bottom shear stresses and water depth needed for the modelling of sediment transport in the river channel. The upstream boundary condition was set to time-series of flow and the downstream was set to normal depth. We will add relevant information in the revised manuscript and provide all HEC-RAS files as supplementary material in the revision.

6. The distances between "computed" cross-sections range from 10 m to 100 m depending on the changes of river bathymetry (See LN-19 P-4). Are these the interpolated cross-section data. What was the interpolation algorithm? Did you use one of in-built (HEC-RAS) interpolation algorithms? Where did you have your observed crosssection data in your model? The details are missing in the manuscript. HEC–RAS model computes the hourly hydraulics for the all cross-sections of the main channel and two major tributaries of the Ammer River (See LN-18 P-4). Does this statement fit the section (i.e., model setup)?
   Response: We have 258 measured cross sections. We have used the built-in interpolation algorithm in HEC-RAS to obtain the additional cross sections (based on linear interpolation between cross-sections), which results in totally 385 cross sections for the entire river network. We will add relevant information in the revised manuscript and provide the bathymetry file in the supplementary material S1.

7. The section 2.3 needs to be more detailed. Many details are missing in the manuscript. The modeled river schematization needs to be included in the manuscript. How did you include the tributaries in HEC-RAS? The details on the junctions/ confluences are also needed.
   Response: Thanks for this comment. We use HEC-RAS to obtain river hydraulics, so we didn't write too much details about HEC-RAS model considering the article length. The confluence points of all smaller tributaries are points at

which the river discharge for the HEC-RAS model changes. For the few confluences of HEC-RAS modeled streams, we use the standard framework provided by HEC-RAS. We will provide all details of the HEC-RAS model in the supplementary material, and add some specifics in the main text of the revised manuscript.

8. The land use is classified into urban areas and non-urban areas (See LN-23 P-4). Impervious surfaces such as roads and roofs are regarded as urban areas, while non-urban areas consist of pervious surfaces such as gardens and "parks", agricultural areas, and forests (See LN-24 P-4). Does this statement contradict with your section 3.1(See Table 1)? Did you classify your LULC into urban and non-urban?
   Response: Table 1 shows the land cover of urban area, agriculture, and forest. It is used in the hydrological model in terms of different parameters for ET and storage. Then the agricultural area and forest are combined as non-urban areas to apply non-urban algorithm for sediment generation. Because we use two algorithms for sediment generation, one is for urban area (including particle build-up and wash-off) and another for non-urban area (surface runoff induced sediment production).

9. The sediment-generating model is used to obtain hourly sediments of different sources from the 14 sub-catchments (See LN-26 P-4). What is meant by different sources?
   Response: By "different sources" mean urban and non-urban particles. We will rewrite it to "The sediment-generating model is used to obtain hourly sediments of urban and non-urban particles from the 14 sub-catchments" in the revised version.

10. We use the urban-area algorithm of SWMM, which "performs well on particle buildup and wash-off for urban land use", to describe sediment generation from urban areas (See LN-28 P-4). Does this statement need a reference?

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Response: We will add a reference.

11. The variables in equation (1) need more description to understand the units (i.e., gm^{-2}). The definitions of the variables need to include the area. Moreover, the variable $M(t)$ is not found in the equation. Is equation (1) applicable only for urban areas? What is the reason(s)? Does the equation have a variable to show that it is applicable only for urban areas?
The unit gm^{-2} means particle mass per unit area, which indicates current particle build-up in a unit area. The area is used afterwards. After knowing the rate of change of particle mass per unit area, we can use this rate, the time interval, and the area to calculate the mass of particle build-up in the corresponding urban area. M(t) is the same as M, but indicating time dependence. We will use M instead of M(t) to make this variable consistent in the revised manuscript. This equation is only applicable for the build-up of particle in urban areas. Because the urban surface has a capacity (maximum build-up, mass per area) of particles, equation (1) leads to the capacity after several days of the dry period (particle accumulation period). But for the non-urban area, the source of particle is soil, so that we assume an "infinite" source from non-urban areas.

12. In equation (1), what is the value of "k" used in the model. What is the value of "Mmax" used in the model? The maximum buildup depends on the particle production and cleaning frequency, which is obtained through calibration (See LN-6 P-5). This statement needs more explanation.
Response: The values of "k" and "Mmax" used in our model were provided in Table 2 of the manuscript. The maximum build-up varies with cities, which affected by the particle production (such as traffic density, population density, and industry density) and cleaning frequency which takes some urban particle out of the system. Therefore it is a calibration parameter.

13. In equation (5), what is the value of your critical stress? Does the value of critical

stress vary with time? Don't you consider the particle accumulation in non-urban areas? Is equation (4) applicable for all non-urban areas? Moreover, sin(theta) is not the mean slope of the sub-catchment. Since theta is very small, you will end up saying sin(theta)=tan(theta)?
Response: The value of critical stress was provided in Table 2 of the manuscript. Yes, the critical stress could vary with time, which is affected by many factors such as the vegetation. But in our case, due to the limited contribution from non-urban areas, we simplified the sediment production from non-urban areas and used a time-independent critical stress. We don't have particle accumulation in non-urban areas, but we assume a "infinite" particle supply from non-urban areas. We would say that for the sake of simplicity the equation (4) can be used for all non-urban area to estimate shear stress. But if the users are focusing on more precise calculation of shear stress on non-urban surfaces, they should search for more precise methods. Yes, when theta is very small, $\sin(\theta) = \tan(\theta)$*. We will revise the equation (4) to use* $\tan(\theta)$ *instead of* $\sin(\theta)$*.*

14. Is equation (11) formulated by the authors? Otherwise, the reference is required. In equation (11), what is the unit of bank erosion rate? This unit needs to be compared with the unit of bed erosion rate (i.e. equation (10)). Does the bank erosion rate vary spatially along the reach? Does equation (11) cover the bank erosion in the freeboard region? In equation (11), what is the value of your critical shear stress for bank erosion? Does the value of critical stress vary with time? In equation (11), what is the equation of your bank shear stress?
Response: Yes, equation (11) was formulated based on bank erosion due to excess shear stress. The unit of the bank erosion rate is $gm^{-1}s^{-1}$*, which is the same as the unit of the bed erosion rate. Yes, the bank erosion rates vary spatially and temporally along the reach. Equation (11) is the average bank erosion for a cross section, we don't have separate erosion algorithms for freeboard regions, which needs more detailed information on the cross sections, such as vegetation*

types of freeboard regions. The critical shear stress is provided in Table 3 of the manuscript. The critical stress in our model doesn't vary with time and the shear stress is obtained through the HEC-RAS model.

15. In equation (10), the units of bed erosion rate and the specific rates of particle and mass erosion are not understood. What is meant by "specific rate"? How do you compare this (i.e., specific rate) with the bed erosion rate? What are the values of the thresholds (i.e., mass erosion threshold and particle erosion threshold)? Does the bed erosion rate vary spatially along the reach?
Response: In equation (10), the units of bed erosion and specific rates of erosion are gms^{-1}, which means how much mass of particles can be eroded per unit length (1 m) of the river channel per second. The "specific rate" is a constant. If we know the shear stress and the critical shear stress, we can calculate the excess of shear stress, multiply it with the specific rate constant, and obtain the bed erosion rate. The values of the thresholds are provided in Table 3 of the manuscript. Yes, the bed erosion rates vary spatially and temporally along the reach.

16. Does equation (9) represent the "bank" and "bed" deposition rates? What is the reason to condition based on the bottom shear stress of the river?
Response: Equation (9) represents the deposition rate of suspended sediment from the aqueous phase to the bed sediment. When the shear stress generated by the flow is smaller than a critical shear stress, it cannot maintain all sediments in the water phase in suspension, therefore some of the suspended sediments will deposit on the river bed.

17. In equation (8), what is the assumption(s) made in formulating the first component of the right-hand-side of the equation?
Response: The first component of the right-hand-side of equation (8) is the deposition of suspended sediments onto the river bed, which increases the bed

sediment mass. The assumption is similar as the response of the question 16).

18. Are your computations cells of equal size? As per LN-5 in P-6, the computation cells are formed by two cross-sections. However, your cross-sections are not equally spaced (See LN-19 P-4). Wont this influence your model outcome?
Response: Our computation cells are not equal in size. The computation cells are small in the river segments with rapidly changing bathymetry, while they are big in the river reaches with relatively stable bathymetry (maximum 100 m). The reasons why we don't use equally spaced cells are that 1) if we use cells of equal size, then the minimum spacing (10 m in our case) should be used, otherwise, we cannot well represent the river segments with fast changing geometry by using larger spacing. It makes the number of computation cells almost 10 times bigger, which results in the increase of one order of magnitude of computation time; 2) Using a bigger spacing for the river segment with stable bathymetry is feasible, because the flow characteristics are similar.

19. As per the title of the manuscript, the catchment is dominated by groundwater. However, the current version of the manuscript does not lead to understand this statement. Does the equations account in your suspended sediment transport model account for this statement (i.e., dominantly groundwater-fed catchment)?
Response: The water flux of the Ammer catchment is dominated by groundwater inputs (see the stable base flow contrasting other catchments in the area), whereas the sediment load is dominated by urban particles. The dominance of groundwater (plus the sewage treatment plant) on the hydrology is reflected in small surface-runoff contributions to the water flux, which is restricted to only a few events. The latter is the main reason why so little sediments generated in the agricultural areas. We will provide a flow duration curve in the supplementary material to demonstrate the dominantly groundwater-fed property. And we contemplate on modifying the title of the manuscript.

20. The equation (7) needs to be derived from first principles. Does this equation account for sink (i.e., flow diversion)? Is this equation formulated correctly? Considering your equation (10) and equation (11), what is the unit of the third component in equation (7)? Did you use the equations (1-6) in your equation (7)? Which component of your equation (7) accounts for your equations (1-6)?
Response: Equation (7) is formulated for the main channel, where no flow diversion exists. In our case, tributaries enter into the main channel, which are regarded as lateral flow (the source term, the last component in the right-hand-side of equation (7)). The unit of the third component in equation (7) is gs^{-1}*, which is in consistent with the unit of the change rate of suspended sediment mass. We compute the change rate of mass instead of concentration due to numerical reasons. Equation (7) does not explicitly use equations (1-6), but implicitly considers them. Equations (1-6) are used to calculate sediment from the catchment, which is the source term for the sediment transport in the river channel (*c^i_{lat} *and* Q^i_{lat} *in equation (7)).*

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