HESS 2018-42: Contributions of Catchment and In-Stream Processes to Suspended Sediment Transport in a Dominantly Groundwater-Fed Catchment
- Rebuttal Letter -

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We thank the reviewers and the editor for their comments helping us to improve our manuscript. In the following, comments are in normal fonts, and our point-by-point replies are in italic.
Upon revision we have made the following major changes to the manuscript and Supporting Material:

1. *We performed a local sensitivity analysis of sediment transport regarding the coefficients of sediment generation in urban and rural areas to verify whether the parameter-set of the manuscript is the local optimal. The sensitivity analysis is mentioned in Sect. 3.6 of the revised manuscript. Details are provided in the Supplementary Material (Table S1).*

2. *We provide several pieces of additional information to support the small contribution of rural particles to the total suspended-sediment load and small and sporadic rural surface runoff in the Ammer catchment. The supporting information consists of the source diagnosis of suspended sediments through an end-member-mixing analysis based on sediment-bound Polycyclic Aromatic Hydrocarbons (PAH) with different origins (Table S2 and Equations S1-S7), the soil erosion map (Fig. S1) of our study area from the state geological survey of Baden-Württemberg (`http://maps.lgrb-bw.de/`), the implications of small rural surface runoff and weak connection between soils and streams from the study of Schwientek et al. [2013], and the measured and modelled flow duration curve (Fig. S2). The mentioned figures, tables, and equations above have been included in the Supplementary Material. The corresponding discussion has been added in Sect. 4.2 of the revised manuscript.*

3. *We provide a figure (Fig. S3) on the relationships between measured turbidity and discharge for the summer and winter periods to show that temporal variation of the critical shear stress may not be relevant in our catchment. Together with the information mentioned in point 1, we discuss the reasons why refining the sub-model for sediment generation in rural areas does not pay off. Therefore, we kept the simplified approach for rural areas to model the average rural sediment delivery, but the shortcomings of this approach are discussed in Secs. 3.4.2 and 4.2 of the revised manuscript. We also provide detailed time series of suspended-sediment concentrations for a few events (Fig. S4) in the Supporting Material to demonstrate that our model is capable to predict suspended-sediment concentrations for different size of events.*

4. *We provide the entire files for the HEC-RAS model setup in the Supplementary Material. We also make the sediment transport code open so that interested readers can modify the code for their own purposes.*

5. *We adjusted the manuscript structure by introducing the study area first before describing our sediment transport models.*

6. *We changed Fig. 5 to a semilogarithmic plot. The colors of figures 6, 7 and 9 have been changed to more distinguishable colors. The filled areas of Fig. 10 were changed to lines in order to better show the net deposition and erosion. The schematic text on suspended-sediment sources under different flow conditions in Sect. 4.3 has been replaced by Table 4 of the revised manuscript.*

1 Reply to the Comments of the Editor

Thank you for submitting the responses to the three comments regarding your manuscript "Contributions of Catchment and In-Stream Processes to Suspended Sediment Transport in a Dominantly Groundwater-Fed Catchment".

You have addressed most of the comments in a manner such that I suggest to revise the manuscript accordingly. however, there are two overarching aspects – the erosion from agricultural land and the source apportionment - that are not convincingly treated. There are several aspect of these themes that require a more thorough improvement.

I list these aspects below:

1. Rev. 1 and 2 expressed doubts that the small contribution by erosion from arable fields was actually true. In your respective response to Rev. 2 you suggest to search for further studies supporting your findings. I highly recommend to do so and would like to point out that there is a high-resolution erosion risk map for Germany available Auerswald et al. [2009]. Additionally, it might be worth contacting local practitioners to obtain region specific knowledge that is not available in the scientific literature.

   Response: Thanks for the suggestion on the soil-erosion map, which we now include in the Supplementary Material together with two additional pieces of supporting information. We have modified Sect. 4.2 of the revised manuscript to discuss these issues and added material to the Supplementary Material. Specifically, we provide the following evidence:

   (a) We diagnosed the source of suspended sediments based on their content of Polycyclic Aromatic Hydrocarbons (PAHs) by an end-member-mixing analysis. Elevated PAH contents are indicators of urban origin. This analysis implies a small contribution of rural particles in the suspended sediments, which is in good agreement with our model results. Please see the calculation in Table S2 and Equations S1-S7 of the Supplementary Material.

   (b) Schwientek et al. [2013] investigated the hydrological drivers of nitrate export dynamics in the Ammer catchment based on one-year measurements. They observed dilution patterns of nitrate in the Ammer catchment under both summer and winter conditions. According to their analysis the Ammer catchment could be described as a two-component system, dominated by a base flow rich in nitrate and a very fast, diluting component from urban areas. Connectivity between soils and the stream network was lacking. This finding is in agreement with a small surface-runoff component from rural areas.

   (c) We obtained the soil erosion map of our study area from the state geological survey of Baden-Württemberg (`http://maps.lgrb-bw.de/`), which is provided in Fig. S1 of the Supplementary Material. Sites with very high erosion risks in the state of Baden-Württemberg are found in northern (Kraichgau) and southeastern (Oberschwaben) areas as well as along the western slope of the black forest. By contrast, most of our study area exhibits the lowest level of soil-erosion risk according to this survey. These finding support our model results.

2. Rev. 1 expressed concerns (point 3) about the low value of the Ch parameter and asked for a sensitivity analysis that would show how robust your findings about the relevance of urban versus rural sediment sources would be. You explain that due to the computational burden (please provide quantitative information), the model uncertainty was only calculated for the hydrological part but you ignore the comment on the sensitivity analysis. I think this request by Rev. 1 is solid and you have to provide some calculations that demonstrate the robustness of your findings.

   This directly links to one major concern raised by Rev. 2, which is the non-identifiability of model parameters and model structure based on the available data (Point 2). This severely limits the possibility to actually infer the sediment sources from your model results. It is possible that the results in section 4.2 simply reflect your prior knowledge because you could tune the model such as to produce what you expected to find. You argue that you will provide further evidence that the model assumptions were plausible. While this is very welcome, it should be complemented by a (local) sensitivity analysis demonstrating how the modeled sediment sources vary (or don't vary) with changing model parameters. With such a sensitivity analysis you respond properly to the comments/request by Rev.1 (see Point 3 there) and Rev. 2 (Points 2).

   Response: The computation time of one complete model run is 2.5 hours. As suggested, we performed a local sensitivity analysis of the sediment transport model, the description of which is now included in Sect. 3.6 of the revised manuscript. The model contains 4 parameters related to the urban and rural inputs. In the sensitivity analysis, we regarded the calibrated parameter set as the base case, we then changed each parameter by -90%, -70%, -50%, -30%, -10%, +30%, +50%, +100%, +200%, +300% to obtain 40 scenarios plus the base case in total (see Table S1 of the Supplementary Material). By running the model

scenarios we obtained the fraction of the rural contribution to the annual suspended sediment load, Nash-Suttcliff coefficient of efficiency for the entire suspended sediment data (NSE_e), and the NSE values for high suspended sediment concentrations ($\geq$ 30 mgL^{-1}, NSE_h).
Table S1 in the Supplementary Material shows the result of the local sensitivity analysis. It can be seen that with changing model parameters, the modelled rural contributions changed, ranging between 0.1% and 12.3%. The corresponding NSE_e and NSE_h also change (-3.29 to 0.50).

- *By decreasing the parameter M_{max}, the rural contribution to the suspended sediments increases. However, by changing M_{max} from the base case, the values of both NSE_e and NSE_h decrease.*
- *As similar response can be observed by adjusting parameter K_w.*
- *By increasing the parameter C_h, we also increase the rural contribution to the suspended particles. However, the NSE_e decreases to negative values even though NSE_h slightly increases.*
- *Finally, the rural contribution to the suspended sediment increases when decreasing τ_c, but the NSE_e values decrease (with a little increase of NSE_h).*

The local sensitivity analysis shows that the parameter set of the base case is at least locally optimal. In the base case the rural contribution to the annual sediment load is 3.5%, which is similar to the result of the PAH-based sediment-source analysis (see the reply to editor comment 1). The range of C_h in the manuscript is taken from Gilley et al. [1993]. This range is strongly affected by soil properties. We also found the study of [Romero et al., 2007] listing smaller C_h-values. Therefore we have adjusted the range of C_h in the revised manuscript.
To increase the transparency of the paper, we now provide the HEC-RAS files and the Matlab-code of the sediment transport model in the Supplementary Material so that interested readers can use and potentially modify the code.

3. Along a very similar line, Rev. 2 commented (point 15) that the infiltration rates were high in his opinion and asked how the results would change upon lowering these values. Although you provide a reference for these infiltration rates you fail to provide the more important answer which concerns how your findings would change upon less effective infiltration. Please provide simulation-based evidence for the robustness of your findings (or its absence!).

   Response: Please see the detailed response to point 15 of Rev. 2 below. Of course, less infiltration at identical precipitation levels would increase surface runoff and thus the risk of soil erosion. A key question in this regard is whether the rain intensity exceeds the infiltration capacity of the soil. Therefore a robust hydrological model is the basis of modeling sediment transport. We carried out an uncertainty analysis of the hydrological model in the manuscript, then calibrated and validated the hydrological model to the measured discharge. The model shows a good fit. We also provided flow duration curves of measurements and model results (Fig. S2 of the Supplementary Material), which indicates that the distributions of high and low flow of the model results are consistent with the measurements. They both imply that our hydrological model is robust. The hydrological model is auto-calibrated and -validated. In essence, if the infiltration was less effective, we would have higher discharge peaks and less base flow; but this is not observed.
   The results of the hydrological model indeed confirm our prior believes (very little surface runoff on agricultural land). In the manuscript we compared precipitation intensity and infiltration rates of different types of soil in order to find a reason to explain why so little rural surface runoff occurs. Perhaps the statement is not very clear so that the reviewers thought infiltration rates were parameters of our model. However, in the hydrological model, the infiltration rates are model results based on other parameters. We didn't perform simulations in which we deliberately adjusted parameters to obtain less infiltration because the corresponding parameter variations have already been included in our uncertainty analysis of the hydrological model.
   We have revised the statement on infiltration rates in the manuscript to make the point clearer.

4. Several times, you defend the model structure for erosion on arable land by your prior knowledge saying that runoff hardly occurs (because of low rainfall intensity compared to the infiltration rates and flat topography) and that therefore urban sources dominate sediment input into the stream network (e.g., responses 4 and 13 to S. Mylevaganam, response 4 to Rev. 1, responses 1 and 2 to Rev. 2). This creates a (potentially) vicious circle because you set up the model structure based on your prior knowledge in such a way that the model prevents proving your wrong.
   One example illustrating this issue relates to the comment by S. Mylevaganam about the temporal invariance of the critical shear stress (point 13). You mention in your response that you implemented your simplified approach because of the limited non-urban contributions. However, by doing so, you may actually miss important non-urban fluxes, e.g., during winter when for example cereal fields may

be very prone to erosion even under low intensity rain (e.g., [Prasuhn, 2011]) due to high water saturation. Also the German Environmental Protection Agency points out that low intensity rain may be relevant for triggering erosion (see `https://www.umweltbundesamt.de/themen/boden-landwirtschaft/bodenbelastungen/erosion#textpart-3`). Inspection of Fig. 5 in the manuscripts reveals an event where the model severely underestimates the observed sediment load (winter 2016). This might be potentially such a case where due to the seasonal conditions erosion on arable fields may have been relevant. Hence, a critical shear stress that varied with time might have led to a different result regarding the relevance of different sources for sediment delivery.

Response: We agree that the critical shear stress may vary with time in some catchments. However, in our catchment, we didn't see relevant effects. The following observations support our assessment:

- *Figure 1 of this rebuttal letter shows the relationships between measured turbidity and discharge for the summer and winter periods. It can be seen that high-discharge events in winter are smaller than in summer. However, for the same discharge, we don't observe higher turbidity values in winter compared to those in the summer season. The latter reveals that the erosion is similar in winter and summer given the same flow rate. Hence, temporal variation of the critical shear stress may not be relevant in our catchment. Therefore, using a time-independent critical shear stress does not introduce a bias in estimating the average sediment delivery.*

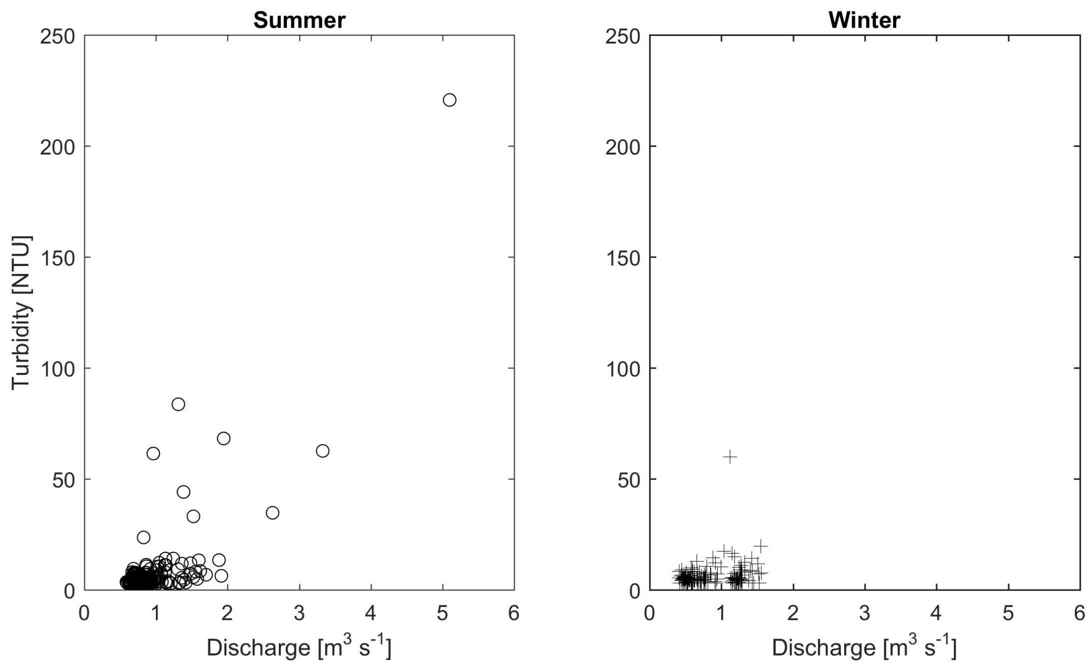

Figure 1: Relationships between measured turbidity and discharge for summer season (Left) and winter season (Right).

- *Low-intensity rain may trigger erosion in some regions of Germany with high erosion risk. But the soil-erosion risk of most of the Ammer catchment is in the lowest range (please see the soil-erosion risk maps of the Ammer catchment and state of Baden-Württemberg in the Supplementary Material, Fig. S1), which means that erosion in low-intensity rainfall events is unlikely in the Ammer catchment.*
- *The small and sporadic rural surface runoff is not only our prior knowledge but also the result of the hydrological model, which is well calibrated by and validated against the discharge measurements. Please see our reply to point 1 on other information supporting the small erosion potential in the agricultural land within the Ammer catchment.*

5. Several times, you defend the model structure with the low contribution from arable fields due to sufficient infiltration capacities of the soil such that no critical runoff would occur. This argument is based on the assumption that overland flow is the only relevant trigger for erosion on arable fields. However, splash erosion (e.g., [Fernández-Raga et al., 2017]) may initiate erosion (and with it overland flow) if the soil structure is not sufficiently stable and rain drops cause surface sealing. Upon surface sealing, infiltration rates may drop substantially causing erosion even if on intact soils the infiltration capacity would be sufficient. Because such aspects are neglected, the chosen model structure cannot prove your prior knowledge/assumptions wrong.

Response: We have carefully checked the articles on splash erosion. Detachment of soil particles by splash erosion is the first stage of soil erosion. Then the detached soil particles have to be transported by surface runoff to the receiving streams. Splash erosion is affected by many factors such as rain drop size, kinetic energy, rain amount and intensity, and soil properties. It is difficult to measure and validate splash erosion. We also realized that with surface runoff occurring, the splash erosion decreases because surface runoff prevents splash erosion happening. To conclude it, splash erosion may increase the risk of soil erosion at the beginning of the events, which can be partly included by giving a smaller critical shear stress. Finally surface runoff is functioning as carriers for soil particles. The critical shear was obtained through calibration in our study. The simplified approach was chosen to estimate average rural particle delivery by surface runoff, which simulates how many particles can be transported to streams. Given several information to support small rural particle delivery (see point 1), we hope it is fair to use this approach to estimate particles from rural areas even it has some shortcomings. We have discussed this approach in Sect. 4.2 in the revised manuscript.

6. In this context, it is also peculiar that for the priors of the critical shear stress on fields you refer to a non-published Master thesis Bones [2014] developed in the context understanding scouring around foundations of bridges causing failures. There is no argument not to use such information, however given the large numbers of papers specifically dealing with critical shear stress on crop soils (e.g., as a random selection [Léonard and Richard, 2004]).

   Response: Bones [2014] listed a full table of critical shear stresses ranging from very erodible soil to very resistant soil. In the revised manuscript, we now cite the published article of Léonard and Richard [2004] to set the range of the critical shear stress.

7. As a minor comment I'd like to add about your argument that crop rotations – for which you don't have specific information in time - would make it difficult to incorporate more complex agronomic aspects into the model (e.g., Rev. 1, point 2). Given the fact that farm size (0.2 – 0.4 km^2, I guess for this region) is much lower that the size of your sub-catchments (1.6 – 10.7 km^2 agricultural land) and on single farms the crop mix is rather stable across years (just single fields are cropped differently) cropping patterns for the scale of interest for your model approach would be rather stable in time.

   Response: We agree that the cropping pattern in our catchment would be rather stable for the simulation period. After providing additional information (see reply to point 1) to support the rather small contribution of rural particles, we think that using our simplified approach to simulate the average sediment delivery from the catchment is feasible. Introducing more parameters to the model would increase the model complexity and make calibration more difficult. Therefore, we kept the simplified approach for agricultural land but we have discussed the shortcomings and limitations of this approach in Sect. 4.2.

2 Reply to the Comments of Reviewer #1

The manuscript illustrates a coupled catchment-stream model for water quantity and sediment productions and transport developed for the Ammer River Basin (Germany), which has some important karstic contribution to baseline flow and suspended sediments. The physics-based model that is proposed includes a complex one-dimensional hydraulic component for calculating shear stress. Erosion rates are then based on shear stress concepts applied to erosion of bed and bank material (either deposited sediments or consolidate beds), as well as in-stream deposition. The model was developed to tackle Ammer Basin hydrology in particular, however, it is proposed as an integrated model of general applicability. The model is built on components of other hydrological and sediment models. It appears to be very focused on in-stream processes. Conversely, sediment sources from land processes (soil erosion) seems too simplified. I have some concerns about the paper and its content.

1. First of all, it is not true that existing models do not account for in-stream processes (P2 L24). For example, I know that SWAT model offers several ways to tackle in-stream sediment transport and erosion, including some physics based approaches based on shear stress and the possibility to include cross section of reaches. Some literature has shown that these SWAT approaches work well. The authors should therefore revise their statements.

   Response: The reviewer is right that SWAT has a sediment routine in stream channels for sediment transport. We have given a more precise statement on the SWAT model and also sharpened the advantages of using HEC-RAS for calculating river hydraulics of the Ammer River in Sect. 1 of the revised manuscript.

2. Sediments from urban land is modelled with a well-known wash off/build up approach. Instead erosion from non-urban areas is tackled with a (to my point of view overly) simplified approach (eqs. 4-6) whose main drivers are runoff and slope. Only one shear stress threshold is considered despite agricultural land diversity, which includes a variety of crops like cereals, vegetables, and natural vegetation. This approach

does not consider any variability in soil erodibility, or changes in crop cover during the year, which instead impact soil erosion from agricultural land especially among seasons. This flaw limits very much results drawn from the model especially in terms of seasonality and 'hot moments' of erosion.

Response: Many factors could affect sediment delivery from rural areas such as land use, soil properties, and rainfall properties. In our study, we used a simplified approach described by Piro and Carbone [2014] to estimate the average sediment delivery from rural areas to streams. Equation 4-6 partly consider the dependence of land use and soil property by slope and flow depth in the formulation. We have the following reasons for choosing this approach:

- *The end-member-mixing analysis of sediment-bound PAH, the study of Schwientek et al. [2013], and the soil-erosion maps of the state geological survey reflect the small contribution from rural areas to suspended sediments. This information has been added to the Supplementary Material. The discharge-turbidity pattern doesn't differ between summer and winter (see reply to the editor's comment 4). Hence, we don't think that refining the sub-model for rural sediments would have a major impact on the overall behavior.*
- *As pointed out in the response to the editor, there is clear evidence that rural surface runoff is sporadic and small. This is supported by a good match of the hydrological model component and the measured hydrograph. The explanation for the small surface-runoff component is that the slopes of Ammer catchment are very mild. The river valley is too wide for the current river discharge because the river has lost its former head-water catchment in the early Pleistocene. The present upstream end of the catchment is a karstified limestone plateau of the middle Triassic Muschelkalk formation with some loess cover but little topography. This geomorphological setup makes surface runoff on agricultural land and the associated contribution to suspended sediments rather small. Therefore we doubt that refining the model component related to agricultural sediment generation would pay off.*

Of course, other catchments behave differently and require thus a different focus of a sediment-generation and -transport model. We discuss the limitations of our method in Sect. 4.2 of the revised manuscript.

3. I have some concerns about the calibration and validation of the model. The model has 14 calibration parameters and is calibrated vs 1 single station at the outlet of the Basin. I also note that calibrated parameter Ch (Table 2) which regulates the non-urban sediment loads, is lower than its initial range. The risk of over parameterization of this model is very high. Some sensitivity analysis should be shown and discussed as this represent a limit of potential conclusions of the paper. Calibration was driven by a LHS scheme but conducted manually. The authors state that calibration parameter sets were retained to derive 90 % confidence intervals. However these confidence intervals are not shown nor further commented expect for a vague comment at P 11 L 14. The model runs at hourly time step. At what time step calibration and validation were conducted? Water discharge was calibrated for 2013- 2014 and validated for 2015-2016. Sediments were calibrated for 2014 and validated for 2016. Why data for 2015 was not used in this exercise? Data was available as shown in fig 5 but model simulations are not shown. However, model simulations are used for sediment balance considerations e.g. figures 6 and 7. Please explain. The model missed simulation of 2 large rainfall events (one in 2014 and one in 2016), where the highest sediment concentrations occurred. The explanation offered (P11 L 14, p12 L1-2) is that rainfall precipitation measurements 'may be missing'. This should be verified in the input data. In any case, these 2 events were the most important for sediment load, so all sediment balance is flaw as it cannot consider these main events. It would also be good to see some events in more details given the high temporal discretization of the model.

   Response: We used the LHS scheme to calibrate the hydrological model because this model runs very fast. By contrast, the sediment transport model was calibrated manually due to the high computation time (2.5 hours for a single run). 90 % confidence intervals were calculated for the hydrological model and are shown in Fig. 4 of the manuscript. The models were calibrated and validated to the daily data. The reason for not using data of 2015 in the sediment transport model is that we don't have measurements in 2015. In Fig. 5 of the manuscript, the red dashed line represents measurements and blank solid line indicates model results. The red dashed line shows a data gap in 2015. The model results of 2014 and 2016 were used to compute the sediment balance. Even though the peak suspended-sediment concentrations were not well reproduced by the sediment transport model, the model predicted high suspended sediment concentrations for these two events. In the revision we have changed Fig. 5 to a semilogarithmic plot.
   Fig. 2 below shows details of several events. It demonstrates that the sediment transport model in the manuscript has the capability to predict suspended-sediment concentrations for different size of events. Events are affected very much by the input data such as precipitation, which drives the surface runoff. We have added this figure to the Supplementary Material of the revised manuscript (Fig. S4).
   As suggested, we performed a local sensitivity analysis of the sediment transport model. Please see our

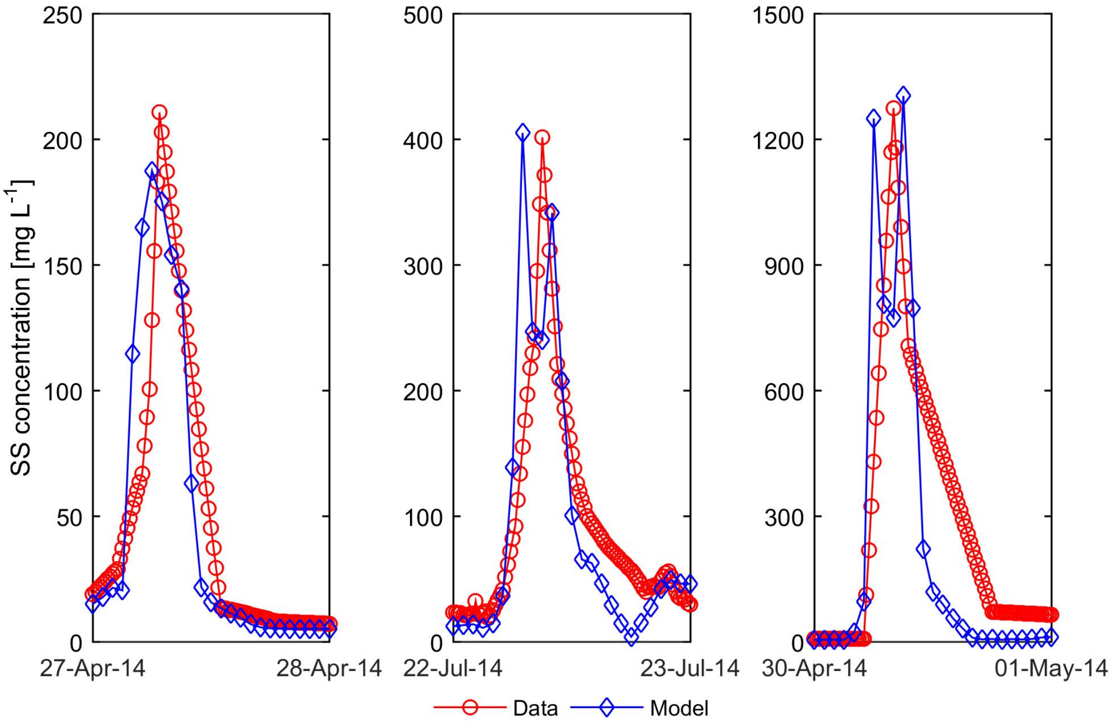

Figure 2: Measured and modelled suspended-sediment concentrations for different events (the magnitude of the events increases from the left to right of the figure).

detailed response to the editor comment 2.
The reason why we used a smaller value of C_h than the initial range in the manuscript is that, when we used the value of 0.001, the model showed a much higher NSE value than when using the lower limit of the initial range. The range of C_h in the manuscript was taken from Gilley et al. [1993], which was very much affected by specific soil properties. In the meantime, we found the study of [Romero et al., 2007] showing a smaller C_h. We have modified the range of C_h in the revised manuscript accordingly.

4. The results of the model indicate that urban land is the major source of sediments in the catchment. This is possible, but I find hard to believe that 67 % of the basin (agricultural land) contributes almost nothing to sediment loads. Even if runoff production is very low and land is gentle sloping (P 21 Lines 10-12), I would expect more contribution. The authors should check with other lines of evidence (e.g., literature of soil erosion from agricultural land in the region) if their results are realistic.

   Response: As detailed in the response to the editor's comments , we have several lines of evidence pointing to small rural contributions to the suspended-sediment load: the elevated PAH concentration in the suspended sediments, the nitrate dynamics, the existing soil-erosion-risk map, and the good agreement of the hydrological model to the measured hydrograph. Above, we have also given explanations for the small rural erosion, to which we want to refer here.

5. Fig 8 indicates an increase of sediment sources following a power-law with discharge, which may make sense. However, I wonder if an excess of sediment transport capacity of the stream was considered in the model. This may regulate deposition when sediment sources are very high. I do not see this being considered in the model (but I may be wrong). Please discuss.

   Response: The sediment-transport capacity is important for bed load transport. For a given discharge, the flow can only transport a limited bed load by rolling, sliding, and hopping, which is regulated by the transport capacity. The bed-load material is mainly sand and gravel. The transport of cohesive sediments (fines) is different. The transport capacity of cohesive sediments always exceeds supply [Brunner, 2016]. The transport of suspended sediments of our study relates to the cohesive sediment transport. Therefore, we transferred the algorithm for cohesive sediments of HEC-RAS to our matlab model of simulating suspended sediment transport. This algorithm is based on shear stress. This is in line with previous studies using shear-stress related processes to model suspended sediment transport [e.g., Li et al., 2009].

6. What data was used to set karstic sediment loads?

Response: We clarified this in Sect. 2.1 of the revised manuscript. We measured a turbidity of 3 NTU under base-flow conditions in the Ammer River. Rügner et al. [2013] showed that karst springs in the Ammer catchment contribute to turbidity. Other studies also showed that karst systems can contribute suspended sediments [Bouchaou et al., 2002, Meus et al., 2014]. For the Ammer River, the subsurface flow through the karst system dominates the river flow in periods without rainfall events. Therefore, the turbidity under base-flow conditions is potentially generated by subsurface flow through the karst matrix. We set a constant suspended-sediment concentration to the subsurface flow. The subsurface flow is obtained from the catchment hydrological model. Then the karstic sediment load was calculated by subsurface flow rates and constant suspended sediment concentrations.

7. Section 3.1 should precede model description. The model was built for the Ammer and some important information driving model conceptualization is given in this section, so this should come first. Information about measurement data should be given in this section. Please move P 9 Lines 14-17 and P10 Liens 18-25 to after current P 8 line 14.

   Response: Thanks for the suggestion. We have revised the manuscript accordingly. We now introduce the study area first and then describe the model.

8. Please change color of $Load_{urb}$ and $load_{bed}$ in figs 6 and 7 to better distinguish them.

   Response: We have used distinguishable colors for Figures 6 and 7, and changed the corresponding colors of Fig. 9 as well.

9. Schematic text at P 18-19 lines 12 onward should be given as a table.

   Response: We summarized the schematic text in Table 4 of the revised manuscript.

10. Reference in the conclusion to events with 2-year return period (P 22 L 2) is surprising. No reference to return period is done before in the manuscript. Given that model failed to simulate two large rainfall events of the region, I find it hard to believe this statement.

    Response: We have checked the flood return period on the state discharge monitoring website (LUBW, http://www.hvz.baden-wuerttemberg.de/) and give the reference in Sect. 2.2 (data source). The 2-year return period was modified to 2-year to 10-year return period in the conclusions. The model does not well capture the peak concentrations of the two events, but the model gives high concentrations (even though it does not reach the peak concentration of measurements). We provided several events with details in the supplementary material (Fig. S4) to show that the model can predict high suspended-sediment concentrations. After providing additional evidences such as flow duration curve (Fig. S2), end-member-mixing calculation based on pollutants (PAHs) on different particles (Table S2 and Equations S1-S7), nitrate dynamics implication [Schwientek et al., 2013], and local soil erosion map (Fig. S1), we hope that the statement is sufficiently supported.

3 Reply to the Comments of Reviewer #2

The manuscript presents an integrated sediment transport model including hydrological, hydraulic, sediment-generating and an in-stream transport model for the Ammer catchment in Germany. The attempt to assemble a fully integrated model and explain sediment dynamics fits nicely in the recent efforts to support integrated water resources management, the topic is absolutely timely.

I see two significant points that absolutely require improvement.

1. First is the conceptual explanation and model representation of overland sediment transport, where there is a gap between soil mobilisation (erosion) and reaching the streams. Retention during overland transport and its dependence on vegetation cover is generally neglected and not included in any form, except if we consider it to be deeply hidden in the parameters of equations 4-6. This formulation makes sediment loads independent from landcover, which partially violates the Critical Source Area principle (not wholly, because slope and flow depth are still there), and makes the model unable to identify the impact of different cultivation patterns. Although the optimal solution would be to change the non-urban sediment-generating submodel to something more appropriate for such a large and diverse catchment, the absolute minimum is to mention this deficiency in the discussion.

   Response: This remark is similar to the comment 2 of reviewer #1, please see our arguments listed there (and in the response to the editor) why we believe that the rural contribution to the suspended-sediment load is indeed so low that further differentiation does not pay off. Equations 4-6 (adopted from Piro and Carbone [2014]) are a simplified approach to estimate the average sediment delivery from rural areas to *streams. This formulation does not explicitly consider all known processes on the hillslope scale, but partly considers the dependence of land use and soil property by slope and flow depth in the formulation. We have discussed the limitations of this method in Sect. 4.2 of the revised manuscript. We definitely agree that other catchments will require more elaborate parameterizations of rural soil erosion.*

2. The second major issue is the problem of identification and the credibility of model results. TSS concentrations were measured at a single site, the Pfäffingen gauge. All subcatchments and their various landcover classes contributed to this single data series through various transport processes including in-stream retention or resuspension. The identification of the contribution of each class requires specifying contrasting behaviour for all source types a priori, otherwise one cannot decide about the importance of each process from a single aggregate TSS series. Here it was done through the model specification, which one can partially debate, but that's not a principal issue. The problem is that the results, e.g., the importance of processes is finally conditional on the model specification, which is not mentioned here at all. Thus, the identified (and thoroughly analysed) contribution of each source is only true when the model assumptions are correct. This must be explicitly stated in the manuscript, considering that the applied model equations are not obviously the right ones (which is not a real problem, it just reflects the subjective decisions of the authors), and the outcome seems a bit strange (negligible agricultural contribution with 60 % arable land). An additional point to this concern is the imperfect fit of the model to the observed data. While the fit is not worse than what one can usually achieve with TSS modelling, the uncertainty is large enough to make identification of different sources practically impossible.

   A more objective decomposition of sediment dynamics could have been the analysis of time-dynamics, that is the identification of slow-medium-fast responding components and their precipitation or discharge trigger thresholds, and binding known mechanisms to them afterwards. In the manuscript the same happened in mathematical sense, but it is now stated with high confidence that a certain response pattern is obviously the effect of a certain process, which is simply not proven by fitting a model to the TSS data. Emphasising the subjectiveness of results is therefore advisable.

   A logical follow-up study could aim at repeating the same exercise using multiple TSS time-series from different locations possessing different shares of sediment sources. This would strengthen the basis for attributing certain sediment dynamics to specific sources.

   Response: The reviewer points to the important general issue that parametric model uncertainty does not cover the conceptual uncertainty and bias of a model. For a rigorous analysis of conceptual model uncertainty one would need several competing models and a tremendously large and informative data set. In our study catchment, only one gauge was installed at the outlet of the catchment, where we can obtain time-series of turbidity (which can be converted to suspended sediment concentrations). Then the time-series data were used as the reference to calibrate and validate the combined sediment contributions from different sources. At the time being, we don't have data for sub-catchments, which makes it difficult to verify the sediment dynamics from different sub-catchments. We have started a coordinated project in the catchment last year, which includes installing more measurement stations, so that future data can be used to validate the assumptions regarding the assumed behavior of at least a few sub-catchments.
   However, our conceptual prior that rural particles play a (surprisingly) low role in the Ammer River does not come out of the blue. The arguments have been given in the responses to preceding comments above. We have extended Sec. 4.2 and the Supplementary Material to present and underline them. The actual motivation of the present study was to develop a mechanistic model of sediment-bound PAH transport in the Ammer River, which shows surprisingly high concentrations of PAH (and PCBs) which can only be explained with a high contribution of urban particles (see Table S2 and Equations S1-S7 and Schwientek et al. [2013]). While we may be able to come up with an alternative model in which more particles come from agricultural land, we would have big difficulties to get the PAH load right without making unreasonable assumptions about PAH contamination of rural particles. While the presentation of the PAH model is reserved for a follow-up paper, we have recognized that the arguments based on the PAH need to be properly stated already in the present manuscript. Please notice also the other pieces of evidence supporting little rural surface runoff and associated soil erosion listed in the reply to editor comment 1.
   As for parametric uncertainty, we have followed the suggestion of reviewer #1 and performed a local sensitivity analysis (already discussed above).

Specific Comments

1. P2 L12 and L15: USLE is an empirical model of soil loss on the plot scale, it is not applicable to entire subcatchments, but not because of the lack of in-stream mechanisms. USLE cannot deal with heterogeneities along the transport pathways of soil particles, so it cannot model how much retention will occur during overland transport. So if we don't speak about a homogeneous plot stretching right down to

the stream, with the same soil quality, cultivation method, slope, rainfall exposure, USLE will be a bad approximation.

Response: We have modified the statement on USLE accordingly in the revised manuscript.

2. P3 L7: "Towards this ends" sounds strange.

   Response: We revised it to "In this study" in the revised manuscript.

3. P3 L11-12: Dry weather sediments from a WWTP are much different from "normal" particles due to their different particle size distribution and much higher organic carbon content. Would this spoil the estimation of TSS from turbidity?

   Response: Particle size and composition can affect turbidity and TSS. The sediment transport model computes suspended-sediment concentrations. We set suspended-sediment concentrations of WWTP effluent as an input to the model. The TSS-turbidity relationship is obtained at the river gauge, which has already taken different particles from different sources into account. Moreover, because of the small contribution to total discharge from the WWTP and the small suspended-sediment concentrations, the influence of WWTP particles has been smoothed out.

4. Figure 1: Would "Rural" be a better alternative to "Non-urban"?

   Response: Thanks for the suggestion. We have used "rural" instead of "non-urban" in the revised manuscript.

5. P4 L1: It would be reasonable to introduce the Ammer first, as the following sections contain a lot of specific information, which cannot be judged without knowing the basic characteristics of the catchment and river.

   Response: Thanks for the suggestion. We have adjusted the corresponding structure. We now introduce the Ammer catchment first, and then describe the model setup.

6. P4 L7: When the aquifer is a karst, is "groundwater" the right term? Wouldn't "fracture-water" be a better description? Or is this a mix of karst and non-karst?

   Response: It is a mix of karst and non-karst. Water in a karst aquifer is still called "groundwater" (refer to the Karst Hydrogeology and Geomorphology book [Ford and Williams, 2007] and other hydrogeology textbooks).

7. Equation 1: This must assume that it is always restarted at the beginning of the accumulation phases. If this is the case, please mention. Equations 4-6: This formulation ignores that (i) overland flow path lengths have a serious influence on sediment delivery [>90 % of the mobilised sediment accumulates during overland transport], and (ii) surface roughness, permeability, flow concentration affect yield. How does landcover quality affect sediment transport here? How would buffer zones work in such a model? Given these shortcomings, please comment whether the landcover conditions in the Ammer catchment make these equations usable.

   Response: Yes, it is restarted at the beginning of every accumulation period considering the remaining particles after the flush period. We have added this explanation to equation 1 of the revised manuscript. Several factors may affect sediment yield from agricultural land, such as flow path lengths, different land use (reflecting surface roughness), and soil permeability. But in our study, we used a simple method (Equations 4-6) to estimate sediment delivery to streams by surface runoff in rural areas. The method and formulation are described in the study of Piro and Carbone [2014]. Equations 4-6 don't explicitly account for all processes mentioned above, but implicitly consider the dependence of land use and soil property by slope and flow depth in the formulation. We have given detailed explanations why we believe that the simplified model is sufficient in our application in the reply to comment 2 of reviewer #1.

8. Figure 2: Given that cross-sections were 100 m away from each other, travel time between cross-sections must have been between 50 to 200 seconds. Then the hourly time step means that this model was solved for a series of quasi steady states. How did the dynamics of sediment sources relate to these times? Wouldn't this mean that some dynamics of the rapidly responding urban sources was lost due to improper numerical resolution?

   Response: The integrated sediment transport model consists of the catchment-hydrological model, the catchment sediment-generating model, and the river sediment-transport model. The time resolution of the catchment hydrological and the sediment generating models is one hour, because we have precipitation data with one-hour resolution. The river hydraulics adapt comparably quick to changing discharge, so that the quasi-steady state mode of HEC-RAS (neglecting in-stream retention of water) with hourly resolution was considered sufficient to calculate river hydraulics. We use ODE23s/ODE45 to solve the system of *diffrential equations arising from spatial discretization of the model for sediment transport in the river channel. In the discretization of advection, we use upwinding. ODE23s/ ODE45 includes an adaptive time-step scheme, which uses small steps when needed; we have set the maximum time-step size to five minutes. While the river sediment transport model can simulate rapid responses, we keep the output only at hourly resolution to be consistent with the output of the flow model.*

9. P7 L9: A significant part of TSS and turbidity comes from the wash load, which practically never deposits. So it is a rather significant simplification that all fractions deposit at the same rate. Did this cause problems in the model fits?

   Response: In our model, we simulate particles with a single, average size, so that the settling velocity is the same for all particles. This is a simplification. A model with distributions of particle sizes would require additional processes such as flocculation, which would make the model more complex. This beyonds the scope of our study.

10. P9 L 11-12: It would be logical to mention the peak NSE value besides the threshold.

    Response: We calculated NSE value for high flows, which are important for sediment transport, and the corresponding values has been added in Sect. 3.6 and 4.1. We also kept NSE values in the revised manuscript because the Ammer River is mainly groundwater-fed. The relatively high baseflow affects sediment deposition during low flow conditions. NSE values can reflect the goodness of fit for both high and low flow.

11. Table 2: The applied value of Ch (0.001) is out of the specified range (0.003-0.05). Why?

    Response: In the manuscript, the specified range (0.003-0.05) was taken from Gilley et al. [1993], but the NSE-value was much higher with a parameter value of 0.001. As Romero et al. [2007] showed even smaller values of C_h, we have modified the range of C_h in the revised manuscript. The new sensitivity analysis of the sediment-generating model confirmed our parameter choice.

12. Figure 4: Baseflow is perfect (which is a big achievement in a karstic catchment), but discharge peaks are seldom met. What does this mean for the TSS calculations? Most of TSS likes to travel with discharge peaks.

    Response: In our case, baseflow and peak flow are both important for the sediment transport in the Ammer catchment. Baseflow has a big influence on sediment transport in our study catchment because 65 % of discharge is less than the annual mean discharge (1 $m^3 s^{-1}$) and only 1.5 % of discharge is greater than 2 $m^3 s^{-1}$, which makes the contribution of suspended sediments under low flow conditions a relevant fraction to the total sediment transport (around 25 %). Honestly some peaks are missing in the model. Several factors can affect prediction of flow rates, the most important is precipitation. While the model reproduced many events, some thunderstorms in summer months have not been captured well because the rain gauge missed the spatially localized precipitation event. This is a very common problem. We did a sensitivity analysis for the catchment hydrological model in the manuscript and obtained the best parameter set for discharge simulation. For the revision, we also calculated the NSE for high flows, which indicates an acceptable fit by using hourly precipitation data.

13. Figure 5: Please use log scale for TSS, this linear scale isn't very informative, the reader can't figure out if the model was right or wrong.

    Response: We adopted the suggestion and presented log-scale concentrations of suspended sediments in the revised manuscript.

14. P14 L4-5: Urban and karstic dominance in TSS loads would be exceptional with 60 % arable land (which - with its barren soil surface in certain months - is generally considered as the most erosion-prone land use class, besides construction sites). Can you find specific reasons for this?

    Response: We have provided additional information to support the small contribution from arable land in the Supplementary Material and in Sec. 4.2 of the revised manuscript. Please see also the reply to similar comments (editor comment 1 and comment 4 of reviewer #1).

15. P14 L9: These infiltration rates seem to be a bit high. Design values (for example: `https://stormwater.pca.state.mn.us/index.php?title=Design_infiltration_rates`) for loam are around 8 mm/hr, for clay loam around 1-5 mm/hr, which would change the runoff picture significantly. Can you bring up a reference in support of these high rates?

    Response: We have given a reference from FAO in the revised manuscript (`http://www.fao.org/docrep/S8684E/s8684e0a.htm`). The dominant soil type in the catchment is a luvisol on loess, the state geological (and pedological) survey maps deep infiltration (to a large extent via karst) as the dominant *recharge process with some west-east oriented stripes along individual depressions in which surface runoff is considered possible. A lower infiltration capacity would of course lead to more surface runoff and a higher risk of soil erosion, provided that the precipitation exceeds the infiltration capacity. Perhaps the statement on infiltration rates was not clear in the manuscript. In the hydrological model, the infiltration rates are a model outcome. If there was more surface runoff, we would have higher river-discharge peaks and less base flow. However, the hydrological model has been well calibrated and validated to discharge measurements so that we consider it to be robust. In the revision, we have provided additional information in the Supplementary Material such as flow duration curves (Fig. S2) and the PAH-based analysis of particle sources (Table S2 and Equations S1-S7), which all can support little surface-runoff generated soil erosion (in good agreement with our prior knowledge of this catchment). We have revised the statement on infiltration rates to make it clearer.*

16. Figure 10: Would be better to show the NET rate and slope along the river, because the present legend is confusing. Where can one see "NET EROSION"?

    Response: We have revised the manuscript as suggested. The dash-dotted lines highlight NET rates along the river in Fig. 10. Since the net erosion is too small and sporadic in the simulation period, the red dash-dotted line (representing net erosion) is very close to the X axis.

17. P22 L5-9: This paragraph is speculative. First it should be shown with further measurements that the model was right.

    Response: For the revision, we have searched for additional studies to support our results because the direct measurements of turbidity/suspended sediment concentrations are not available. We provided the flow duration curves (Fig. S3), particle source diagnosis based on end-member-mixing calculation of sediment-bound PAHs (Table S2 and Equations S1-S7), some implications from nitrate dynamics [Schwientek et al., 2013], the state soil erosion map (Fig. S1), and a sensitivity analysis (Table S1) to further support our statements. After doing so, we believe the conclusion is reasonable and fair.

4 Response to the Comments of Reviewer #3 (S. Mylevaganam)

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, rural areas, karst system, and waste-water treatment plants (WWTPs), 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 rates. 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 the 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.

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 m^3s^{-1}) is greater than the threshold value on bed erosion (i.e., 1.5 m^3s^{-1}). What is mentioned in the literature?

   Response: Thanks for the good suggestion. The threshold values of bed and bank erosion have been normalized by the mean discharge, leading to critical values that are 1.5 and 2.5 times the mean discharge, respectively. In the manuscript, we studied 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 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. Also the literature shows a smaller critical shear stress for bed erosion [Winterwerp et al., 2012] than for bank erosion [Clark and Wynn, 2007].

3. Asper 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 the deposition of suspended sediment from the water phase to the river bed, bed erosion, and bank erosion due to excess shear stress. We discuss the shortcomings of empirical and physically based models in the revised manuscript. We have also added a statement on the advantages of using HEC-RAS for river hydraulics.

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 have added Lindström et al. [1997] as reference to the HBV model. In Sec. 3.2 we have tried to clarify the explanation for adding additional components. We 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. 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 to 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 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 fairly detailed river-profile data facilitating the setup of 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 should be modified.

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: We added the boundary conditions of HEC-RAS model in Sect. 3.3 of the revised manuscript. We also provide all of the HEC-RAS files in the supplementary material. The reason for choosing a quasi-steady state mode is described below. 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-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.

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 cross section 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 added "We have 258 measured cross sections and we used the built-in interpolation algorithm in HEC-RAS to obtain the additional cross sections, which results in totally 385 cross sections for the entire river network." in Sect. 3.3 of the revised manuscript. The sentence, "HEC–RAS model computes the hourly hydraulics for all of cross-sections of the main channel and two major tributaries of the Ammer River" was deleted. More detailed information can be found in HEC-RAS files in the Supplementary Material.

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: We provided additional details in Sect. 3.3. All HEC-RAS files are provided in the Supplementary Material. We use HEC-RAS to obtain river hydraulics, so we didn't write too much details about the 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.

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 rural areas to apply rural algorithm for sediment generation. We use two algorithms for sediment generation, one is for urban areas (including particle build-up and wash-off) and another for rural areas (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" we mean urban and rural particles. We revised it to "The sediment-generating model is used to obtain hourly sediments of urban and rural particles from the 14 sub-catchments".

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?

    Response: We added two references [namely Wicke et al., 2012, Gong et al., 2016] in Sect. 3.4.1.

11. The variables in equation (1) need more description to understand the units (i.e., g m^{-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?

    Response: We revised equation (1) to make the variable M consistent by using M instead of $M(t)$. The meaning of build-up, "particle mass per unit area", was also added in the context. The unit g m^{-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, and we have changed M(t) to M. This equation is only applicable for the build-up of particles 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 rural area, the source of particle is soil, so that we assume an "infinite" source from rural areas.

12. In equation (1), what is the value of "k" used in the model. What is the value of "M_{max}" 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 "M_{max}" used in our model were provided in Table 2 of the manuscript. For the statement on the maximum build-up, we added the information, "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. It is obtained through calibration.", into the corresponding paragraph.

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 is provided in Table 2 of the manuscript. The critical stress may vary with time in some catchments and is affected by many factors such as vegetation. However, it is not relevant in the Ammer catchment. From the discharge-turbidity patterns (Fig. 1 in the reply to editor comment 4), we don't observe higher turbidity values in winter compared to that in the summer season for the same discharge. This finding reveals that the erosion is similar for winter and summer given the same flow rate, thus the temporally variable critical shear stress may not relevant in our studied catchment. Therefore, using time-independent critical shear stress is plausible to estimate the average sediment delivery. For more detailed information please refer to the reply to editor comment 4. We don't have particle accumulation in rural areas, but we assume an "infinite" particle supply from agricultural soils. We would say that for the sake of simplicity the equation 4 can be used for all rural areas to estimate shear stress. But if the users are focusing on more precise calculation of shear stress on rural surfaces, they should search for more precise methods. Yes, when theta is very small, $sin(\theta) = tan(\theta)$. We has revised 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 $gm^{-1}s^{-1}$, which means how much mass of particles can be eroded per unit length (1 m) of the river channel per second. The "specific rate constant" 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 the critical shear stress, the river cannot maintain all sediments in the water phase in suspension, therefore some of the suspended sediments will be deposited 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 in the response to 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). Won't 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 would run into problems in river segments with fast changing geometry. Using fine cells everywhere would increase the number of computation cells by almost a factor 10, resulting in a similar increase of computation time; 2) Using a bigger spacing for the river segment with stable bathymetry is feasible, because the flow characteristics are similar. We have added the information on cross-section interpolation in Sect. 3.3. We also provided all of HEC-RAS files in the Supplementary Material.*

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 flow duration curve was provided in the supplementary material (Fig. S3). It indicates that 65 % of discharge is less than the annual mean discharge (1 $m^3 s^{-1}$) and only 1.5 % of discharge is greater than 2 $m^3 s^{-1}$, demonstrating the dominantly groundwater-fed property. 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.

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: We have revised the description of Equation (7) to make it clear that this equation is used 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 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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Contributions of Catchment and In-Stream Processes to Suspended Sediment Transport in a Dominantly Groundwater-Fed Catchment

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Abstract. Suspended sediments impact stream water quality by increasing the turbidity and acting as a vector for strongly sorbing pollutants. Understanding their sources is of great importance to develop appropriate river management strategies. In this study, we present an integrated sediment transport model composed of a catchment-scale hydrological model to predict river discharge, a river-hydraulics model to obtain shear stresses in the channel, a sediment-generating model, and a river sediment-transport model. We use this framework to investigate the sediment contributions from catchment and in-stream processes in the Ammer catchment close to Tübingen in South-West Germany. The model is calibrated to stream flow and suspended-sediment concentrations. We use the monthly mean suspended-sediment load to analyze seasonal variations of different processes. The contributions of catchment and in-stream processes to the total loads are demonstrated by model simulations under different flow conditions. The evaluation of shear stresses by the river-hydraulics model allows identifying hotspots and hot moments of bed erosion for the main stem of the Ammer River. The results suggest that the contributions of suspended-sediment loads from urban areas and in-stream processes are higher in the summer months, while deposition has small variations with a slight increase in summer months. The ~~catchment~~ sediment input from agricultural land and urban areas~~,~~ as well as bed ~~erosion,~~ and bank erosion increase with an increase in flow rates. Bed ~~erosion~~ and bank erosion are negligible when flow is smaller than the corresponding thresholds of ~~1.5 m^3 s^{-1} and 2.5 m^3 s^{-1}~~1.5 and 2.5 times ~~of~~ the mean discharge, respectively. The bed-erosion rate is higher during the summer months and varies along the main stem. Over the simulated time period, net sediment trapping is observed in the Ammer River. The present work is the basis to study particle-facilitated transport of pollutants in the system, helping to understand fate and transport of sediments and sediment-bound pollutants.

1 Introduction

Suspended sediments are comprised of fine particulate matter (Bilotta and Brazier, 2008), which is an important component of the aquatic environment (Grabowski et al., 2011). Sediment transport plays significant roles in geomorphology, e.g., floodplain formation (Kaase and Kupfer, 2016), and transport of nutrients, such as particulate phosphorus and nitrogen (Haygarth et al., 2006;Slaets et al., 2014;Scanlon et al., 2004). Fine sediments are important for creating habitats for aquatic organisms (Amalfitano et al., 2017;Zhang et al., 2016). Conversely, high ~~suspended~~ suspended-sediment concentrations can have negative impacts on water quality, especially, by facilitating transport of sediment-associated contaminants, such as heavy metals (Mukherjee, 2014;Peraza-Castro et al., 2016;Quinton and Catt, 2007) and hydrophobic organic pollutants such as polycyclic aromatic hydrocarbons (PAH~~s~~) (Rügner et al., 2014;Schwientek et al., 2013;Dong et al., 2015;Dong et al., 2016), polychlorinated biphenyls (PCB~~s~~), and other persistent organic pollutants (Meyer and Wania, 2008;Quesada et al., 2014). Without understanding the transport of particulate matter, stream transport of strongly sorbing pollutants cannot be understood.

An efficient approach to estimate suspended-sediment loads is by rating curves, relating concentrations of suspended sediments to discharge. By this empirical approach, however, we cannot gain any information on the sources of suspended sediments, which is important for the assessment of particle-bound pollutants. Therefore, a model considering the various processes leading to the transport of suspended sediments in streams is needed. Numerous sediment-transport models have been developed during the past decades, including empirical and physically based models. Commonly used empirical models include the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) and the Sediment Delivery Distributed (SEDD) model (Ferro and Porto, 2000). The USLE was designed to estimate soil loss on the plot scale. It is incapable to deal with heterogeneities along the transport pathways of soil particles~~,~~ and thus cannot be applied to entire sub-catchments. ~~the long-term average annual rate of erosion on a field slope.~~ The SEDD model considers morphological effects at annual and event scales. The two models ~~are capable to estimate sediment production from hillslopes, but~~ cannot distinguish different ~~estimate sediment generation by~~ in-stream processes. Among the models simulating physical processes, the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995), the EUROpean Soil Erosion Model (EUROSEM) (Morgan et al., 1998), the Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2011), the Storm Water Management Model (SWMM) (Rossman and Huber, 2016), the Hydrological Simulation Program Fortran (HSPF) model (Bicknell et al., 2001), and the Hydrologic Engineering Center's River Analysis System (HEC–RAS) (Brunner, 2016) are widely used. WEPP and EUROSEM are applied to simulate soil erosion from hillslopes on the timescale of single storm events. The two models do n~~'~~ot have the capability of estimating urban particles. SWAT uses a modified USLE method to calculate soil erosion from catchments. SWMM aims at simulating runoff quantity and quality from primarily urban areas, including particle accumulation and wash-off in urban areas. HSPF considers pervious and impervious land surfaces. All of these models estimate sediment productions from the catchment and model the transport in the river channel with simplified descriptions of in-stream processes by simplifying the shape of cross sections. ~~None of these models represent in-stream processes well, especially not in natural river channels.~~ Various sediment-transport models for river channels exist that rely on detailed river hydraulics, particularly the bottom shear stress, which controls the onset of erosion and the transport capacity of a stream for a given grain diameter (Zhang and Yu, 2017;Siddiqui and Robert, 2010). HEC–RAS solves the full 1-D St. Venant equation for any type of cross-section including cases with changes in the flow regime, which is beneficial ~~can be used~~ to obtain detailed information on river hydraulics.

In this study, we present a numerical modeling framework to understand the combined contributions from catchment and in-stream processes to suspended-sediment transport. The main objectives of this study were: (i) to develop an integrated sediment-transport model taking sediment-generating processes (e.g., particle accumulation and particle wash-off), and river sediment-transport processes (e.g., bed erosion and bank erosion) into consideration; (ii) to understand annual load and seasonal variations of suspended sediments from different processes; (iii) to investigate how the contributions of suspended sediments from catchment and in-stream processes change under different flow conditions; and (iv) to identify hotspots and hot moments of bed erosion. The model is applied to a specific catchment introduced in the next section, implying that model components that control the behavior of suspended sediments in this catchment are given specific attention, whereas processes of less relevance are simplified in the model formulation. All model components are made available in the Supplementary Material to facilitate modifications that may be needed when applying the framework to catchments with different controls.

2 Study Area~~Application to the Ammer Catchment, Germany~~

2.1 ~~Study Area~~The Ammer Catchment, Germany

We applied the integrated sediment transport model to the Ammer catchment, located in southwest Germany (Fig. 1~~Fig. 3~~). The River Ammer is a tributary to the River Neckar within the Rhine basin. It covers approximately 130 km^2, dominated by agricultural land use that accounts for 67~~.35~~ % of the total area. The hydrogeology is dominated by the middle-Triassic Upper Muschelkalk limestone formation which forms the main karstified aquifer (Selle et al., 2013). In this catchment, annual precipitation is 700-800 mm. The Ammer River, approximately 12 km long, is the main stem with a mean discharge of ~1 m^3 s^{-1}. It has two major tributaries, the Kochhart and Käsbach streams. Two wastewater treatment plants (WWTPs), Gäu-Ammer and Hailfingen, also contribute flow and suspended sediments to the Ammer River. During dry weather conditions, the discharge of WWTP Gäu-Ammer is 0.10–0.12 m^3 s^{-1}, and the effluent turbidity is approximately 3 NTU (Nephelometric Turbidity Units). The WWTP in Hailfingen is comparatively small with flow rates of 0.012–0.015 m^3 s^{-1}, and its turbidity is in the same range as that of the WWTP Gäu-Ammer.

With the exception of a small stripe at the north-eastern boundary of the study domain, highlighted by the forest land-use in Fig. 1, the topography of the catchment is only slightly hilly (with mean slope of 4.2 degrees), which agrees with the bed rock being a carbonate platform, partially overlain by upper Triassic mudstones and loess. Soils are dominated by luvisols on loess with mostly high probability of deep infiltration and low risk of soil erosion according to the state geological survey of the state of Baden-Württemberg (LGRB, http://maps.lgrb-bw.de).

~~Only one gauging station is installed in the main channel of the Ammer River at the outlet of the studied catchment (red triangle in~~ Fig.1 ~~Fig. 3); here, hourly discharge and turbidity measurements are available, which are used for model calibration and validation. The hydrograph was converted by rating curves, whereas the suspended sediment concentrations are derived from continuous turbidity measurements (Rügner et al., 2013). The water levels and turbidity data were measured by online probes (UIT GmbH, Dresden, Germany). The linear relationship between suspended-sediment concentrations and turbidity is robust in the Ammer River (Rügner et al., 2013;Rügner et al., 2014). Based on the updated measurements, the conversion factor of 2.02 (mg L^{-1} NTU^{-1}) was used to convert turbidity to suspended-sediment concentrations. We also observed turbidity values~~

of ~3 NTU for the periods without runoff events. Many studies have shown that karst systems can contribute suspended sediments (Bouchaoua et al., 2002;Meus et al., 2013). The study of Rügner et al. (2013) also showed that karst springs in the Ammer catchment contribute to turbidityMany studies have shown that karst systems can contribute suspended sediments (Bouchaoua et al., 2002;Meus et al., 2013).. For the Ammer River, the subsurface flow through the karst system dominates the river flow in periods without rainfall events. Thus, the turbidity under base-flow conditions is potentially generated by subsurface flow through the karst matrix.. The karstic sediment flux was calculated by subsurface flow rates and constant suspended sediment concentrations. Based on the digital elevation model (DEM) of the Ammer catchment, we delineated 14 sub-catchments using the watershed delineation tool of the Better Assessment Science Integrating point & Non-point Sources (BASINS) model (see Fig. 1Fig. 3). Table 1 shows the proportions of different land-use types and the areas of each sub-catchment.

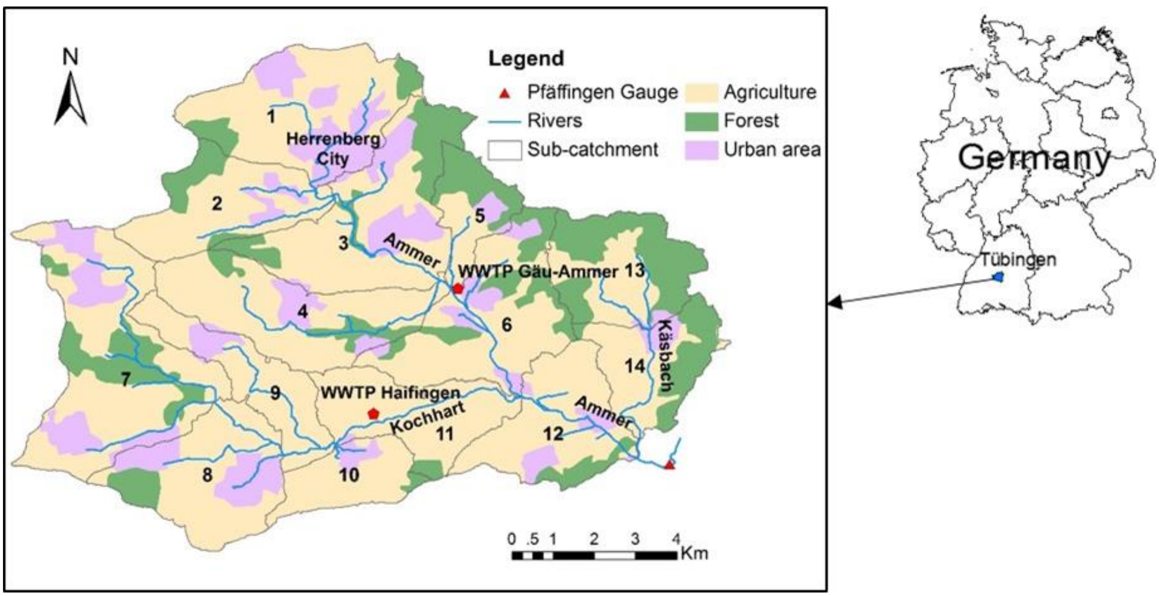


Figure 1: Location of the Ammer catchment and its sub-catchments, rivers and land-use. The numbers show identifiers (ID) of 14 sub-catchments that are characterized in more detail in Table 1. Two red regular pentagons represent two WWTPs in the study domain. The red triangular indicates the gauge at the catchment outlet.

Table 1. Properties of the Ammer sub-catchments.

ID of sub-catchment	Area of sub-catchment [km^2]	Urban Area [km^2]	Agriculture* [km^2]	Forest [km^2]
1	12.70	3.78	7.80	1.13
2	8.13	0.70	6.06	1.38
3	13.53	2.47	8.13	2.92
4	11.15	1.19	8.70	1.25
5	3.97	0.46	1.62	1.89
6	11.80	1.53	7.69	2.59
7	17.12	3.30	10.65	3.16
8	10.10	2.41	6.74	0.95
9	6.14	0.66	5.48	0.00
10	4.55	0.50	3.87	0.18
11	7.74	0.05	7.39	0.30
12	8.66	1.04	6.73	0.89
13	8.36	0.21	3.39	4.76
14	6.60	0.58	3.66	2.35
Area of land use [km^2]	130.54	18.87	87.92	23.75
Proportion of land use [%]	100	14.45	67.35	18.19

*The agricultural land in the Ammer catchment is dominated by non-irrigated arable land (80.2 % of the total agricultural areas), the crop of which is mainly cereals with annual rotation, and complex cultivation land (e.g., vegetables, 17.5 %). The rest (2.3 %) is principally agricultural area with natural vegetation. Therefore, we summarize the three types of arable land and use the same parameterization to estimate soil erosion.

2.2 Data Sources

Hourly precipitation and air-temperature data are the driving forces of the hydrological model. We use hourly precipitation data of the weather station Herrenberg, operated by the German weather service DWD (CDC, 2017), whereas air temperatures are taken from the weather station Bondorf of the agrometerological service Baden-Württemberg (BwAm, 2016). The generation and transport of sediments behave differently for different land use and topography. We use the digital elevation model with 10m resolution and land-use map of the state topographic service of Baden-Württemberg and Federal Agency for Cartography and Geodesy (BKG, 2009;LUBW, 2011). The river-hydraulics model requires bathymetric profiles of River Ammer and its main tributaries. We use 230 profiles at 100 m spacing, obtained from the environmental protection agency of Baden-Württemberg (LUBW, 2010).

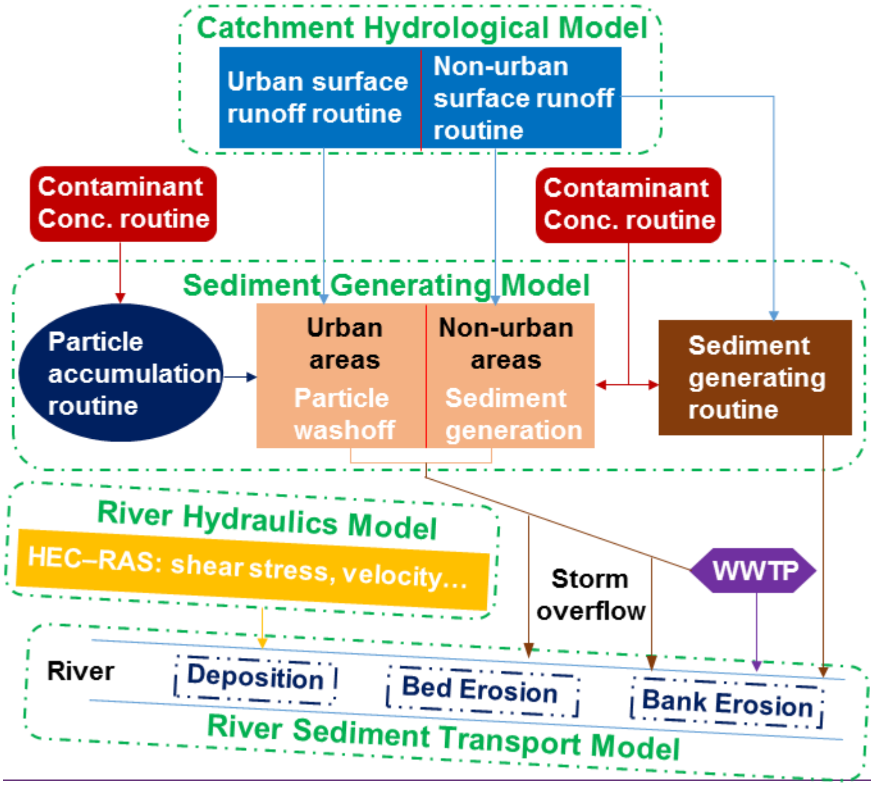
Only one gauging station is installed in the main channel of the Ammer River at the outlet of the studied catchment in Pfäffingen (red triangle in Fig.1); here, hourly discharge and turbidity measurements are available, which we used for model calibration and validation. The water levels and turbidity data were measured by online probes (UIT GmbH, Dresden, Germany). The hydrograph was converted to discharge time series by rating curves, whereas the suspended sediment concentrations are derived from continuous turbidity measurements (Rügner et al., 2013). The linear relationship between suspended-sediment concentrations and turbidity with a conversion factor of 2.02 (mg L^{-1} NTU^{-1}) has been reported to be robust in the Ammer River (Rügner et al., 2013;Rügner et al., 2014).

~~Discharge and suspended-sediment concentration at the gauge Pfäffingen are used for model calibration and validation. The hydrograph was converted by rating curves, whereas the suspended sediment concentrations are derived from continuous turbidity measurements (Rügner et al., 2013). The water levels and turbidity data were measured by online probes (UIT GmbH, Dresden, Germany). For t~~The simulation period covers the years 2013-2016. In this time, the maximum ~~event is~~discharge reflected an event with ~~between~~ 2-~~year and~~ 10- year return period according to the long-time statistics of the gauging station (LUBW, http://www.hvz.baden-wuerttemberg.de/).

3 Model Setup

3.1 Model Structure and Assumptions

The integrated sediment-transport model consists of a catchment-scale hydrological model, a river-hydraulics model, a catchment sediment-generating model and a river sediment-transport model (Fig .2~~Fig. 1~~). The catchment-scale hydrological model is used to estimate river discharge along the entire stream. The river-hydraulics model uses the discharge of the hydrological model and the river bathymetry to compute the river stage, cross-sectional area, velocity, and bottom shear stress, which are needed for the river-transport model. ~~Towards this ends,~~ In this study we use HEC–RAS in quasi steady-state mode. The catchment sediment-generating model is used for simulating particle accumulation in urban areas during dry weather periods, particle wash-off during storms, and erosion from rural~~non-urban~~ areas during rain periods. The river sediment-transport model is used to simulate in-stream processes (advection, dispersion, deposition, as well as bank and bed erosion). Wastewater treatment plants (WWTPs) are treated as point inputs with constant discharge and sediment concentration during dry weather periods. Under low-flow conditions, when no soil erosion and urban particle wash-off occur and the suspended sediment concentrations in the streams are relatively small, we use a constant concentration to represent the sediment input under these conditions. Based on our prior knowledge of the Ammer catchment, ~~the~~ soil erosion is very limited (the information supporting this statement ~~information~~ will be discussed ~~in details~~ in Sect. 4.2), thus a well-known approach and a simplified method are used to simulate particles from urban and rural areas, respectively. ~~P~~Mobilization of particles from different sources ~~are very much conditional on the corresponding~~depends on different processes, ~~such as~~e.g., input of urban particles depends~~ing~~ on the build-up and wash-off processes, rural particles rely~~ing~~ on ~~the rural sediment generating process~~soil erosion, ~~and~~whereas bed and bank erosion are substantially affected by river hydraulics. Considering these processes enables us to well diagnose~~Proving model assumptions,~~ the importance of different sediment sources ~~can be well diagnosed~~.


Catchment Hydrological Model
Urban surface runoff routine
Non-urban surface runoff routine
Contaminant Conc. routine
Contaminant Conc. routine
Sediment Generating Model
Particle accumulation routine
Urban areas
Particle washoff
Non-urban areas
Sediment generation
Sediment generating routine
River Hydraulics Model
HEC–RAS: shear stress, velocity…
Storm overflow
WWTP
River
Deposition
Bed Erosion
Bank Erosion
River Sediment Transport Model

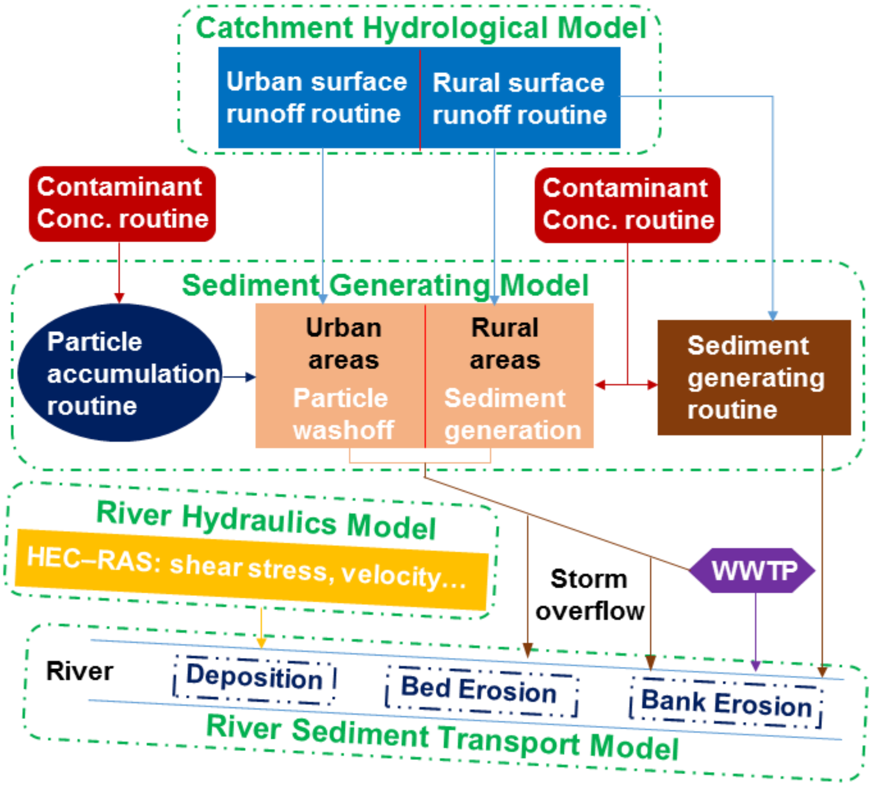


Figure 2: Integrated sediment transport model, consisting of a catchment-scale hydrological model, a river-hydraulic model, a sediment-generating model, and a river sediment-transport model.

3.2 Catchment-Scale Hydrological Model

~~3.3~~ The catchment-scale hydrological model is based on the HBV model (Hydrologiska Byråns Vattenbalansavdelning) (Lindström et al., 1997). However, ~~by~~ we have ~~adding~~ added a quick recharge component and an urban surface runoff component to explain the special behavior of discharge in the Ammer catchment (see Sect. 2.1)~~, which is the catchment where we apply the model~~. The main Ammer springs are fed by groundwater from the karstified middle-Triassic Muschelkalk formation. The measured hydrograph indicates a rapid increase of base flow in sporadic events. We explain this behavior with a model that contains three storages of water in the subsurface: soil moisture in the top soils, a subsurface storage in the deeper unsaturated zone, and groundwater in the karstic aquifer. ~~When the storage in the subsurface layer reaches a threshold, quick groundwater recharge occurs, which causes a rapid increase of base flow.~~ 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 to occur which then leads to a rapid increase of base flow. An urban surface runoff component is used to obtain surface runoff depths in urban areas in order to simulate particle wash-off from urban land surface. Details of the hydrological model are given in ~~the~~ Appendix A. The temporal resolution of the hydrological model is one hour. We use the catchment-scale hydrological model to simulate discharge contributions from the 14 sub-catchments shown in Fig. 1 (detailed information see Sect. 2.1-).

3.43.3 River-Hydraulics Model

In order to better understand in-stream processes, we feed the discharge data of the hydrological model into the river-hydraulics model HEC–RAS (Brunner, 2016), which solves the one-dimensional St.-Venant equations. The HEC–RAS model simulates hourly quasi-steady flow using. The the hourly discharge of the 14 sub-catchments simulated by the hydrological model is as the input of HEC–RAS as change - of of discharge input. The locations where the discharge from 14 sub-catchments enters into the main channel are set to the corresponding cross sections. The upstream boundary condition was set to time-series of flow and the downstream was setone to normal depth. Then HEC–RAS model computes the hourly hydraulics for the all cross-sections of the main channel and two major tributaries of the Ammer River.We have 258 measured cross sections and we used the built-in interpolation algorithm in HEC-RAS to obtain the additional cross sections, which results in totally 385 cross sections for the entire river network. The distances between computed cross sections range from 10 m to 100 m depending on the changes of river bathymetry. The model requires river profiles in regular cross-sections along the river channel and yields detailed information for each cross section along the river channel, such as the water-filled cross-sectional area, the water depth, flow velocity, and shear stress, among others, as model output, which are needed in the river sediment-transport model. The detailed settings of HEC–RAS can be found in the sSupplementary mMaterial.

3.53.4 Sediment-Generating Model

The land use is classified into urban areas and ruralnon-urban areas as well as forested areas. Impervious surfaces such as roads and roofs are regarded as urban areas, while ruralnon-urban areas consist of pervious surfaces such as gardens, and parks, and agricultural areasland, and forests. The sediment generating processes are different for the two types of land use. The sediment-generating model is used to obtain hourly sediments of different sources from the 14 sub-catchments Sediment generation in forested areas is considered to be negligible. The sediment-generating model is used to obtain hourly sediments of urban and rural particles from the 14 sub-catchments.

3.5.13.4.1 Urban Areas

We use the urban-area algorithm of SWMM, which performs well on particle build-up and wash-off for urban land use (Wicke et al., 2012;Gong et al., 2016), to describe sediment generation from urban areas. The corresponding processes are described below.

(1) Particle Accumulation

An exponential function is used to simulate particle accumulation during dry periods under the assumption that particles in the urban areas have a capacity, which is governed by the accumulation process during dry periods.

$$\frac{dM}{dt} = kM_{max}e^{-kt} \quad (1)$$

in which ~~$M(t)$~~ M [g m^{-2}] and M_{max} [g m^{-2}] represent the particle build-up at ~~a given~~the current time and the maximum build-up (particle mass per unit area), respectively; k [s^{-1}] is the rate constant for particle accumulation, and t [s] denotes ~~current~~ time since the last wash-off event. ~~The maximum buildup depends on the particle production and cleaning frequency, which is obtained through calibration.~~The maximum build-up ~~varies~~depends ~~with cities~~on the location ~~, which affected by~~because the particle production (such as traffic density, population density, and industry density) and cleaning frequency ~~which takes~~(removing ~~some~~ urban particle ~~out of the systems~~) differ in different urban areas. In our model it is obtained as uniform value for the entire catchment by ~~through~~ calibration. The particle accumulation is restarted at the beginning of every accumulation period considering remaining particles after the flush period.

(2) Particle Wash-Off

A power function is used to simulate particle wash-off during rain periods. The particle wash-off quantity is a function of surface runoff and the initial buildup of the corresponding rain period.

$$\frac{dM}{dt} = r_w = -k_w q^{n_w} M \tag{2}$$

$$c_{sw} = -\frac{r_w}{q} \tag{3}$$

in which r_w [g m^{-2} s^{-1}], q [m s^{-1}], and c_{sw} [mg L^{-1}] are the rate of wash-off, the surface runoff velocity, and the concentration of washed suspended sediment, respectively; k_w [$s^{n_w-1}\ m^{-n_w}$] and n_w [-] represent a wash-off coefficient and a wash-off exponent.

~~3.5.2~~3.4.2 Rural ~~Non-Urban~~ Areas

In contrast to urban areas, the supply of suspended sediments from ~~non-urban~~rural areas can be seen as “infinite” because they mainly originate from eroded soils. Soil erosion is assumed to linearly depend on shear stress, provided that the shear stress generated by surface runoff is larger than a critical shear stress. The sediment generation from ~~non-urban~~rural areas is based on the study of Patil et al. (2012).

$$\tau = \rho_w g R_{surface}\, tan~~sin~~\theta \tag{4}$$

$$y_h = \begin{cases} C_h(\tau - \tau_c) & if\ \tau > \tau_c \\ 0 & otherwise \end{cases} \tag{5}$$

$$c_{sed} = \frac{y_h}{q} \tag{6}$$

in which τ [N m^{-2}] is the mean shear stress generated by the average depth of surface runoff $R_{surface}$ [m], ~~sin~~tan θ [-] is the mean slope of the sub-catchment, ρ_w [kg m^{-3}] is the density of water, and g [m s^{-2}] is the gravitational acceleration constant. The rural~~non-urban~~ sediment load y_h [kg m^{-2} s^{-1}] is directly proportional to the difference between the mean shear stress τ and the critical rural~~non-urban~~ shear stress τ_c [N m^{-2}]. C_h [s m^{-1}] is a proportionality constant. c_{sed} [kg m^{-3}] is the concentration of sediment generated in ruralnon-urban areas, and q [m s^{-1}] is, like above, the surface runoff velocity. This is a simplified approach to estimate the average sediment delivery from rural areas to streams. It has shortcomings fordoes not explicitly considering all processes on the hillslope scale. In particularly, we don't consider the dependence of the coefficients on the crop type and time-dependent phenology of the crops. Instead, all rural areas are treated the same. We justify this strong simplification by an overall low sediment input from rural areas discussed further below. In catchments with larger sediment load from rural areas, distinctions should be made.but partly considers the dependence of land use and soil property by slope and flow depth in the formulation.

3.63.5 River Sediment-Transport Model

We consider two types of sediment: suspended sediment in the aqueous phase (mobile component) and bed sediment (immobile component). Fig. 3 Fig. 2shows a schematic of the river sediment-transport model, which considers advection, dispersion, deposition, bank erosion, bed erosion, and lateral input of suspended sediments. We use this model to calculate the average concentration of the mobile component and the mass of the immobile component for every computation cell (formed by two cross-sections) every hour.

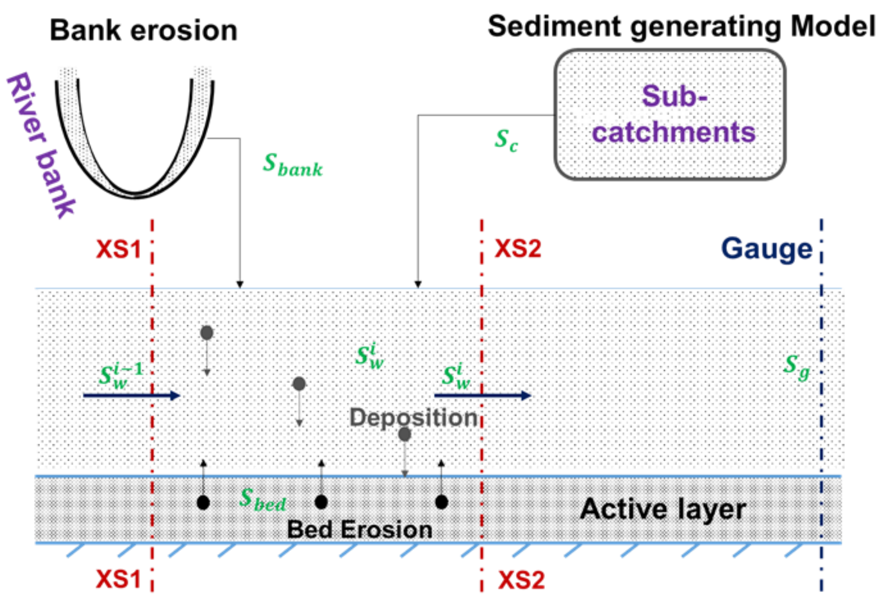


Figure 3: In-stream processes of the river suspended-sediment transport model considering deposition, bed erosion, bank erosion, and input from the catchment. XS1 and XS2 are the two cross sections bounding a cell in a Finite Volume scheme. $\boldsymbol{S_c}$ and $\boldsymbol{S_{bank}}$ are sediments from the catchment and bank erosion. $\boldsymbol{S_{bed}}$ indicates the bed sediment mass. $\boldsymbol{S_w^i}$ stands for the concentration of suspended sediments in the i-th cell. $\boldsymbol{S_g}$ is the suspended-sediment concentration at a river gauge.

(1) Mobile Component

We use a Finite Volume discretization for suspended-sediment transport for the main channel, considering storage in the aqueous phase, advection, dispersion, bed and bank erosion, deposition, and lateral inputs (tributaries and WWTPs):

$$\frac{\partial(c_w V)}{\partial t} = -\frac{\partial(c_w Q)}{\partial x}\Delta x + AD\frac{\partial^2 c_w}{\partial x^2}\Delta x + (r_{bed} + r_{bank})\Delta x - r_d V + \sum c_{lat}^i Q_{lat}^i \quad (7)$$

in which c_w [mg L^{-1}] is suspended-sediment concentration; V [m^3] is the cell volume; Δx [m] is the cell length; Q [m^3 s^{-1}] and A [m^2] are the flow rate and cross sectional area; D [m^2 s^{-1}] is the dispersion coefficient; c_{lat}^i [mg L^{-1}] and Q_{lat}^i [m^3 s^{-1}] represent the suspended-sediment concentration and flow rate of the i-th lateral inflow; r_d [mg L^{-1} s^{-1}], r_{bank} [g m^{-1} s^{-1}], and r_{bed} [g m^{-1} s^{-1}] indicate the deposition, bed-erosion, and bank-erosion rates, respectively. For the advective term, we use upstream weighting, whereas the second derivative of concentration appearing in the dispersion term is evaluated by standard Finite Differences.

This model component requires the sediment concentrations in the lateral inputs (tributaries and WWTPs) as well as in the Ammer spring as boundary conditions. The lateral inputs are computed by the sediment-generating model. For the sediment input by the Ammer spring, we consider the turbidity of ~3 NTU measured under base-flow conditions. Rügner et al. (2013) showed that the karst springs in the Ammer catchment contribute to turbidity, which is in agreement with many previous studies showing that karst systems can contribute suspended sediments (Bouchaoua et al., 2002;Meus et al., 2013). Thus, the turbidity under base-flow conditions is potentially generated by subsurface flow through the karst matrix. The karstic sediment flux was calculated by subsurface flow rates and constant suspended sediment concentrations.

(2) Immobile Component

For simplification, we account for one active layer only in the bed sediment per cell, and consider only the average grain size. Deposition of suspended sediments leads to a mass flux from the aqueous phase to the bed layer, whereas bed erosion causes a mass flux in the opposite direction:

$$\frac{\partial M_{bed}}{\partial t} = r_d \frac{V}{\Delta x} - r_{bed} \quad (8)$$

in which M_{bed} [g m^{-1}] is the sediment mass per unit channel length in the active layer on the river bed.

a. Deposition

The deposition rate r_d of particles can be calculated by (Krone, 1962):

$$r_d = \begin{cases} \left(1 - \frac{\tau_b}{\tau_e}\right)\frac{v_s c_w}{y} & \text{if } \tau_b < \tau_e \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

in which τ_b [N m^{-2}] and τ_e [N m^{-2}] represent the bottom shear stress of the river and the threshold shear stress of particle erosion (see below); y [m] denotes the water depth; and v_s [m s^{-1}] is the settling velocity.

b. Bed Erosion

We consider two types of bed erosion, namely particle erosion and mass erosion, which correspond to two thresholds of the bottom shear stress. The bed erosion rate r_{bed} can be calculated by (Partheniades, 1965):

$$r_{bed} = \begin{cases} M_{me}\left(\frac{\tau_m}{\tau_e} - 1\right)\left[\frac{\tau_b}{\tau_m} - 1 + \frac{M_{pe}}{M_{me}}\left(\frac{\tau_m}{\tau_e} - 1\right)\right] & \text{if } \tau_b > \tau_m \\ M_{pe}\left(\frac{\tau_b}{\tau_e} - 1\right) & \text{if } \tau_e < \tau_b \leq \tau_m \\ 0 & \text{otherwise} \end{cases} \quad (10)$$

in which r_{bed} [g m^{-1} s^{-1}] is bed erosion rate; τ_m [N m^{-2}] represents the mass erosion threshold; whereas M_{pe} [g m^{-1} s^{-1}] and M_{me} [g m^{-1} s^{-1}] are rate constants, denotinge the specific rates of particle and mass erosion.

c. Bank Erosion

In our model, the bank erosion rate r_{bank} is calculated by:

$$r_{bank} = \begin{cases} \kappa\rho L y(\tau_{bank} - \tau_{bc}) & \text{if } \tau_{bank} > \tau_{bc} \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

in which τ_{bank} [N m^{-2}] and τ_{bc} [N m^{-2}] are the bank shear stress and critical shear stress for bank erosion. κ [m^3 N^{-1} s^{-1}] is the erodibility coefficient. ρ [kg m^{-3}] is density of bank material. L [km] is length of the river bank.

3.73.6 Parameter Estimation

For the estimation of parameters, we used the well-known Nash-Sutcliffe Efficiency (NSE) as model performance criterion:

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(O_i - M_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (12)$$

in which O_i and M_i are the i-th observed and modelled values, $\bar{O}$ is the mean of all observed values. An large NSE-value approaching unity, indicates good agreement between model and data, whereas NSE-value smaller than zero imply that the model performs worse than taking the mean of all observations. We obtained the best set of parameters by systematically scanning the parameter space.

The hydrological model was applied to 14 sub-catchments. Each sub-catchment has three types of land use: agricultural areas, forest, and urban areas. We used daily average discharge data of 2013–2014 and 2015–2016 for calibration and validation, respectively. We generated 1000 realizations of the 14 parameters bBy Latin Hypercube Sampling (LHS) we generated 1000 realizations of the 14 parameters for calibration and calculated the corresponding NSE-value for each parameter set. If NSE was ≥ 0.55, the parameter set was regarded acceptable. In the same way, we used the accepted parameter sets for validation. ThenSubsequently , we calculated these sets were used to calculate the 90 % confidence intervals and the NSE value for high flows (flow rate greater than the mean discharge) using the accepted parameter-sets was calculated. Finally, we identified identify the best-fit parameter values were identified.

For the calibration and validation of the sediment generating and the river sediment-transport models, we performed a literature survey to identify the a referenceexpected range of each parameter. We performed a manual calibration of the corresponding parameters within the given range, Then the parameter values were identified manually based upon the reference range and optimized by fitting the modelled and measured suspended sediment concentrations at the river gauge. Subsequently, we used Then the identified parameter-set were used as the reference case, we performedbase values in a local sensitivity analysis, to see the model response and performance in order to verify if the identified parameter is optimal.the Ddetails of the sensitivity analysiswhich can be foundare given in the Table– S1 of the sSupplementary mMaterial. Within the given parameter variations, It turns out tthe manually calibrated identified parameter-sets represents the optimal onewere confirmed as optimal. All The parameters of the sediment-generating model and the river sediment-transport models are listed in Tables 2 and 3 for the sediment-generating model and the river sediment-transport model, respectively. Suspended sediment concentrations were estimated from turbidity. The linear relationship between suspended-sediment concentrations and turbidity is robust in the Ammer River (Rügner et al., 2013;Rügner et al., 2014). Based on the updated measurements, the conversion factor of 2.02 (mg L^{-1} NTU^{-1}) was used to convert turbidity to suspended-sediment concentrations. We also observed turbidity values of ~3 NTU for the periods without runoff events. Many studies have shown that karst systems can contribute suspended sediments (Bouchaoua et al., 2002;Meus et al., 2013). The study of Rügner et al. (2013) also showed that karst springs in the Ammer catchment contribute to turbidity. For the Ammer River, the subsurface flow through the karst system dominates the river flow in periods without rainfall events. Thus, the turbidity under base-flow conditions is potentially generated by subsurface flow through the karst matrix.

Table 2. Parameters of the sediment-generating model

Parameter symbol	Definition	Unit	Range	Reference	Value
M_{max}	Maximum accumulation load	g m^{-2}	7.5–50	(Piro and Carbone, 2014;Modugno et al., 2015;Bouteligier et al., 2002)	23
k	Accumulation rate constant	d^{-1}	0.16–0.46*	(Rossman and Huber, 2016)	0.33
K_w	Wash-off coefficient	$d^{0.5}$ $m^{-1.5}$	50–500**	(Rossman and Huber, 2016)	80
n_w	Wash-off exponent	-	0–3	(Wicke et al., 2012;Modugno et al., 2015;Rossman and Huber, 2016)	1.5
C_h	Proportionality constant	s m^{-1}	0.0003–0.05	(Gilley et al., 1993;Romero et al., 2007)	0.001
τ_c	Critical non-urban shear stress	N m^{-2}	0–2110***	(Bones, 2014;Léonard and Richard, 2004)	0.3

*The range of k is calculated under the assumption that it takes 5–30 days to reach 90 percent of the maximum buildup;

**The range of K_w, 50–500 (1–10, U.S. units), is sufficient for most urban runoff;

***It is for the very erodible to resistant soil, not including very resistant soilthe most of time, but depends on soil propertiesy.

Table 3. Parameters of the river sediment-transport model

Parameter symbol	Definition	Unit	Range	Reference	Value
v_s	Settling velocity	m s^{-1}	10^{-6}–10^{-4}*	(Brunner, 2016)	4×10^{-6}

τ_e	Particle erosion threshold	N m^{-2}	0.1–5	(Winterwerp et al., 2012)	2.5
τ_m	Mass erosion threshold	N m^{-2}	$>\tau_e$	(Partheniades, 1965;Brunner, 2016)	3.5
M_{pe}	Particle erosion rate	kg m^{-1} d^{-1}	0.8–43.2	(Winterwerp et al., 2012)	30
M_{me}	Mass erosion rate	kg m^{-1} d^{-1}	$>M_{pe}$	(Partheniades, 1965;Brunner, 2016)	40
κ	Erodibility coefficient	m^3 N^{-1} d^{-1}	0.0001–0.32	(Clark and Wynn, 2007;Hanson and Simon, 2001)	0.0018
τ_{bc}	Critical bank shear stress	N m^{-2}	0–21.91	(Clark and Wynn, 2007)	5
ρ	Density of bank material	kg m^{-3}	2190-2700	(Clark and Wynn, 2007)	2650

*This range is calculated for the suspended sediment with average diameter 1–50 µm;

4 Results and Discussion

4.1 Quality of Model Calibration and Validation

The best-fit parameter set of the hydrological model resulted in NSE values of 0.63 and 0.59 for calibration and validation, respectively. Fig.4 shows the measured and simulated hydrographs for the calibration and validation periods with 90 % confidence intervals. It can be seen that the discharge was reproduced quite well, both in the general trend and the dynamics. The measured discharge data almost all fall within the 90 % confidence interval of the simulation. The NSE value for high flows (greater than the mean discharge, 1 m^3 s^{-1}) of the simulation period is 0.43, implying an acceptable fit of high flows. Only ~~a~~ few events cannot be reproduced by the model. These events occurred in the summer months and probably resulted from thunderstorms, which are very local and precipitation measurements may ~~may be~~ miss~~ing in the~~them~~ precipitation measurements~~, so that the resulting flow peaks could not be predicted by the hydrological model.

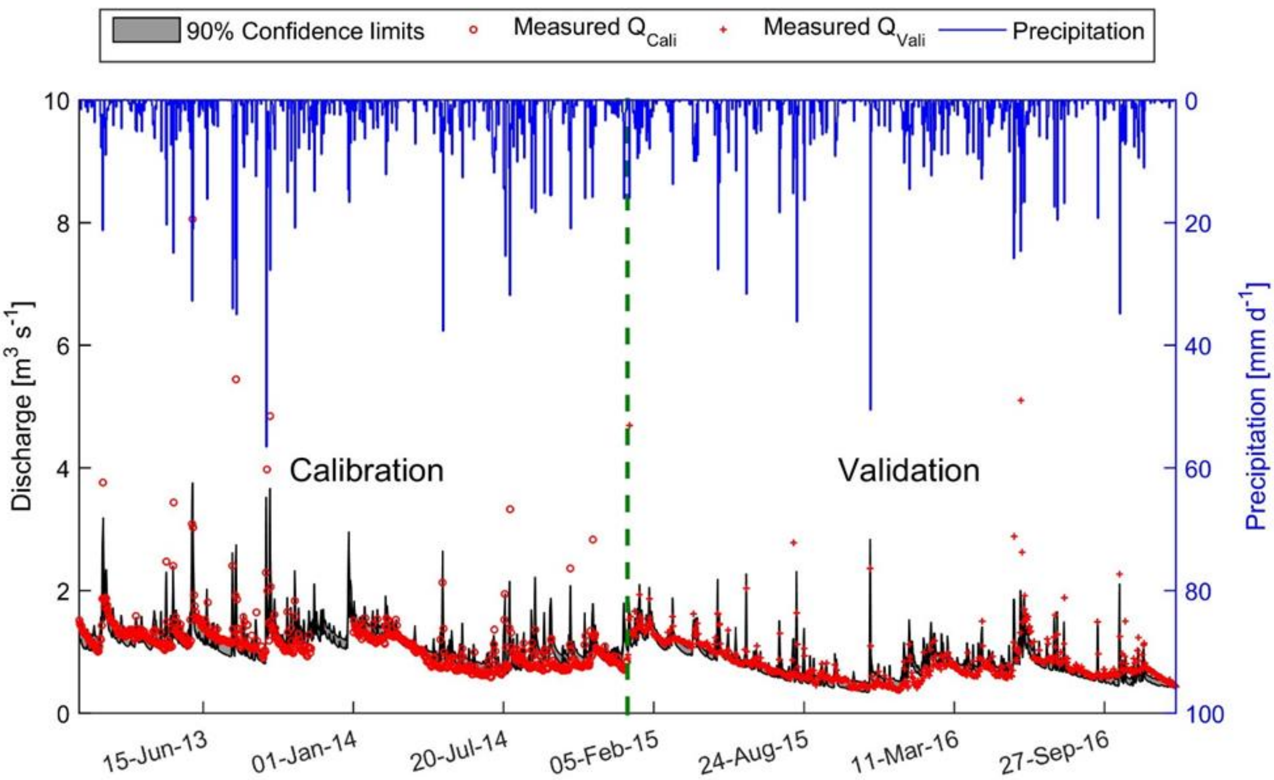
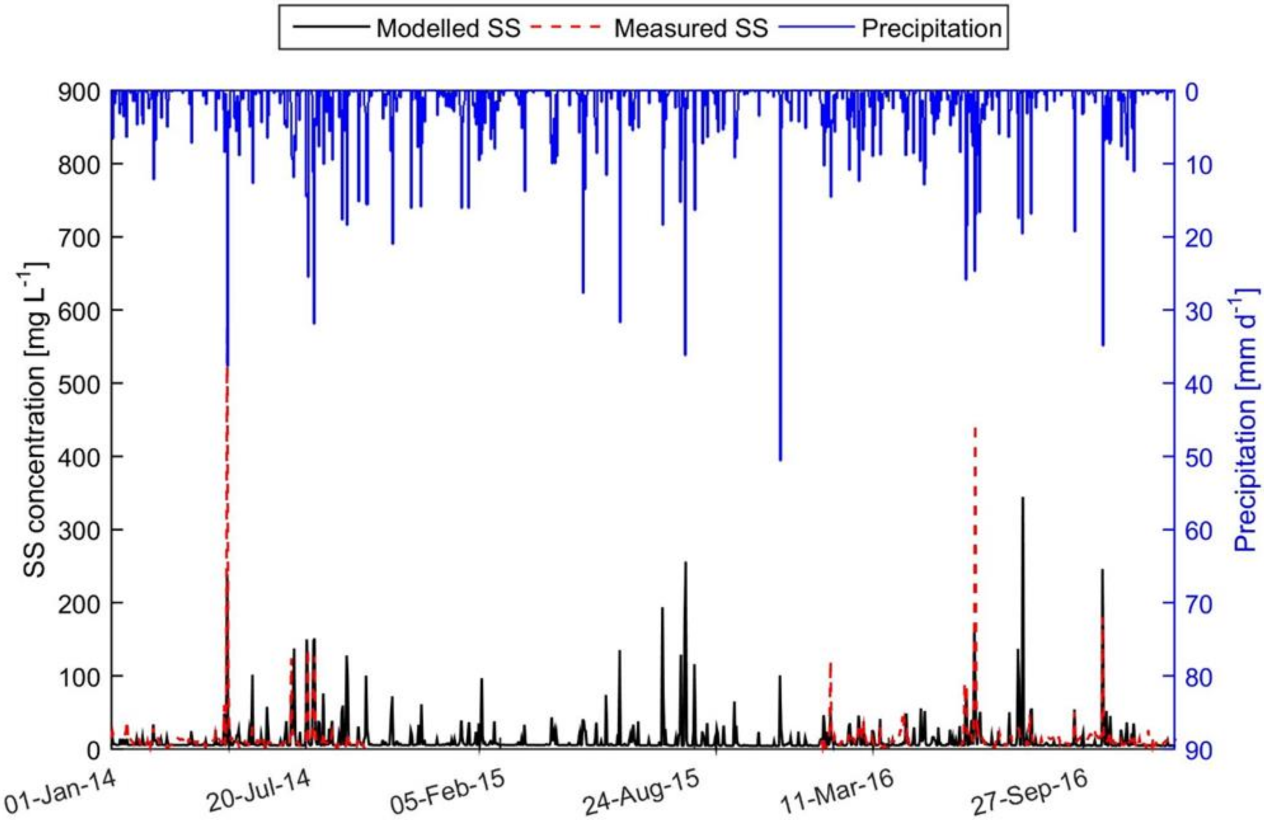


Figure 4: Calibration (left, year 2013–2014) and validation (right, year 2015–2016) of hydrological model, $\boldsymbol{Q_{Cali}}$ and $\boldsymbol{Q_{Vali}}$ are measured discharges used for calibration and validation, respectively.

Figure 5 depicts measured suspended-sediment concentrations and the simulation results of the sediment-transport model during the calibration (year 2014) and validation (year 2016) periods. The corresponding NSE values are 0.46 and 0.32, respectively, which indicates an acceptable fit, albeit not as good as for the hydrograph. The integrated sediment transport model can capture the dynamics of the suspended sediment concentrations. Especially, the model captures the concentration peaks well. However, two events~~ with very high suspended sediment concentrations~~, one in the calibration and the other in the validation period, were not well fitted. These are events which were also not captured by the hydrological model, occurring in the summer months and due to thunderstorms.


Modelled SS
Measured SS
Precipitation
SS concentration [mg L^{-1}]
Precipitation [mm d^{-1}]
900
800
700
600
500
400
300
200
100
0
10
20
30
40
50
60
70
80
90
01-Jan-14
20-Jul-14
05-Feb-15
24-Aug-15
11-Mar-16
27-Sep-16

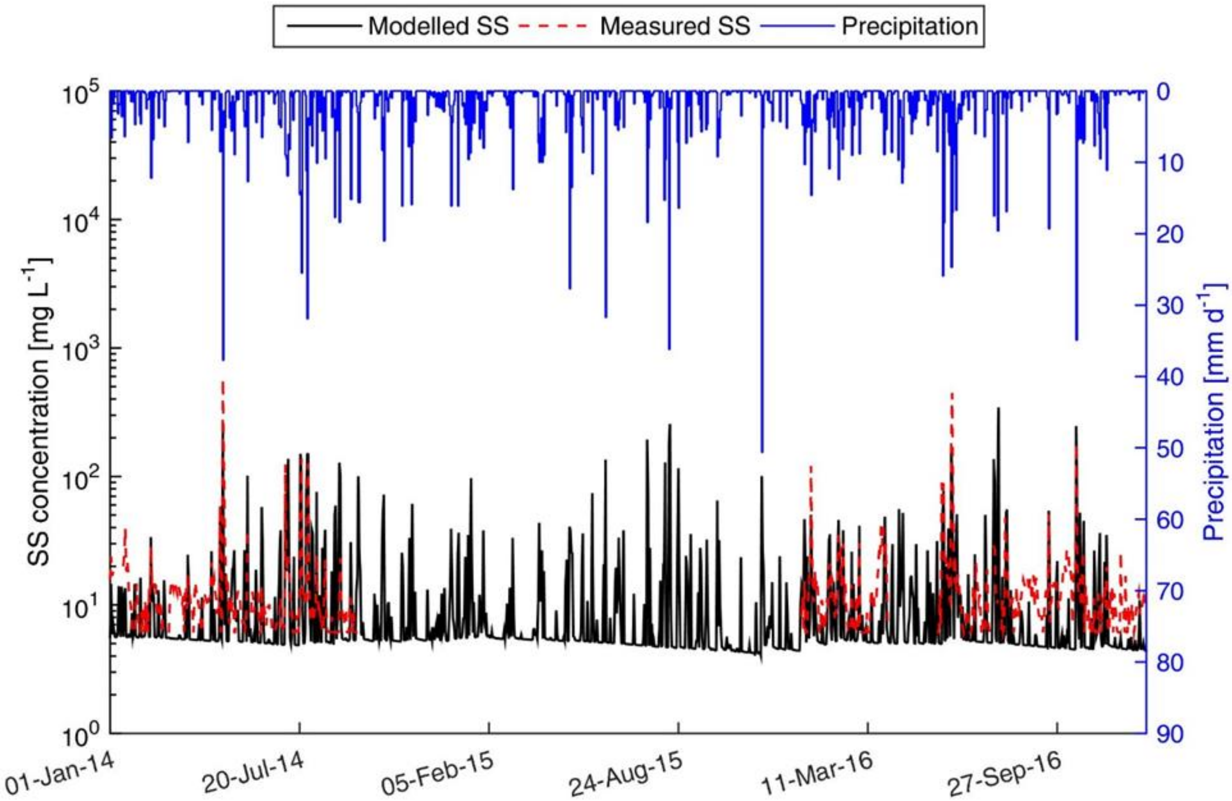


Figure 5: Modelled and measured suspended sediment concentrations used for calibration (year 2014) and validation (year 2016) of the sediment transport model. A data gap exists for year 2015.

4.2 Annual and Monthly Suspended Sediment Loads from Different Processes

After calibrationng and validatingion the model and providing further supporting information (see the supplementary material) to support model assumptions, the model results can be used to analyze the importance of different sediment sources. Fig. 6 displays the modelled annual suspended suspended-sediment loads from catchment and in-stream processes for the entire Ammer River network. The annual suspended suspended-sediment load at the gauge ranges between 410 and 550 ton yr^{-1}. Equation 13 describes the overall mass balance of sediments in the entire catchment:

$$Load_{gauge} = (Load_{urban} + Load_{ruralnon-urb} + Load_{karst})_{Catchment} + \left(Load_{bde} + Load_{bke} - Load_{dep} - \Delta S\right)_{Stream} \quad (13)$$

in which $Load_{gauge}$ [ton yr^{-1}] indicates the suspended-sediment load at the river gauge. $Load_{urban}$ [ton yr^{-1}], $Load_{ruralnon-urb}$ [ton yr^{-1}], and $Load_{karst}$ [ton yr^{-1}] denote the suspended-sediment loads from urban areas generated by surface runoff and WWTP effluent, non-urbanrural areas generated by soil erosion, and karst system carried by subsurface flow, respectively. These three terms represent the catchment processes. $Load_{bde}$ [ton yr^{-1}], $Load_{bke}$ [ton yr^{-1}], $Load_{dep}$ [ton yr^{-1}], and ΔS [ton yr^{-1}] are the suspended-sediment loads from bed erosion, bank erosion, deposition, and the change of sediment storage in the entire river channel, respectively. These four terms represent the in-stream processes.

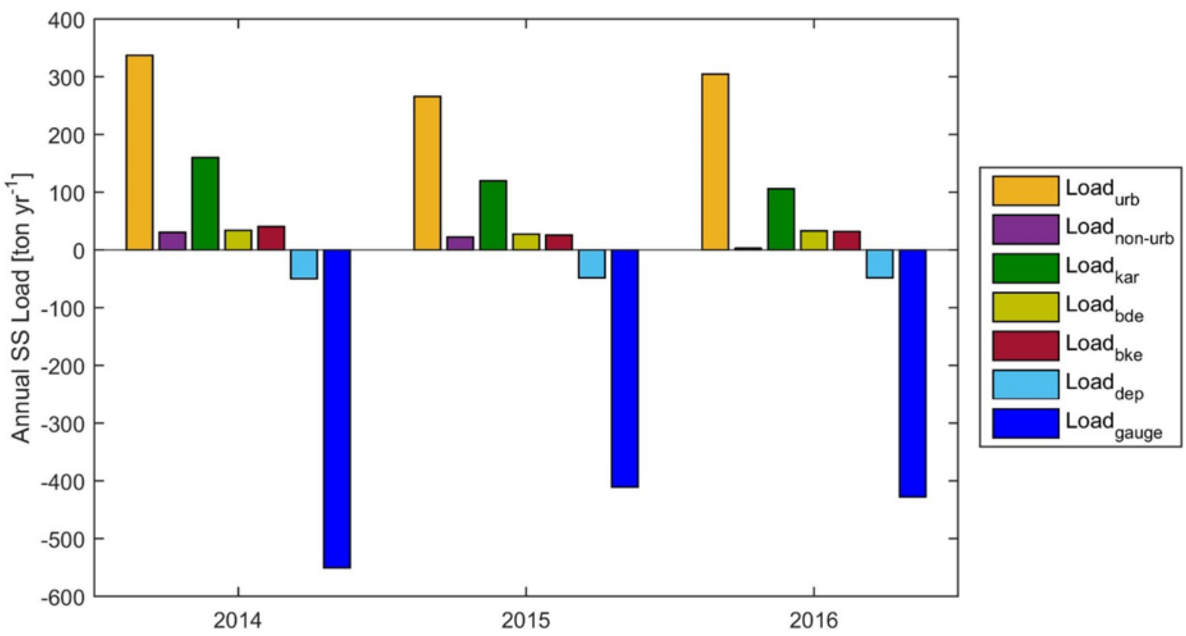
In the Ammer catchment, urban particles (266–337 ton yr^{-1}) and the sediment input from the karst system (106–160 ton yr^{-1}) dominate the annual suspended sediment load, accounting for 59.1 % and 24.9 %, respectively. Bed erosion, bank erosion, and rural~~non-urban~~ sediment contribute much less, namely 6.2 %, 6.3 %, and 3.5 % of the total annual load, respectively. The contribution of rural~~non-urban~~ runoff sediment in the Ammer catchment was very small, which may occur surprising at first. We have collected several independent lines of evidence that support these findings and included them in the Supplementary Material:

1. The suspended sediments of the Ammer River are strongly contaminated by polycyclic aromatic hydrocarbons (PAH) and other persistent organic pollutants (Schwientek et al., 2013). Table S2 and Equations S1-S7 of the Supplementary Material present an end-member-mixing analysis indicating a fraction of rural particles amounting to only 3%.
2. The state geological survey of the state of Baden-Württemberg has developed a ~~, which is confirmed by the sediment source diagnosis based on the end-member-mixing of sediment-bound PAHs (the calculation is given in Table S2 and Equations S1-S7 of the supplementary material)~~. ~~The~~ soil~~-~~-erosion risk map ~~(~~shown Fig. S1~~, in the supplement)~~putting most of Ammer catchment into the class of lowest soil-erosion risk.~~ also indicates that the soil erosion risk of the Ammer catchment is mostly in the lowest level compared with northern and southeastern part of the state Baden-Württermberg.~~ ~~It~~This is so because the surface runoff from agricultural areas is ~~very~~ small due to a comparably flat topography. The same agency associates most of the catchment with deep infiltration as main discharge mechanism.
3. Schwientek et al. (2013a) found a lacking connection between soils and streams in the Ammer catchment. The catchment has a large water storage capacity due to the karst and the slopes of this catchment are mild. During the simulation period, the precipitation intensity was not large enough to exceed the maximum infiltration rates or to reach storage capacity of the subsurface. Compared with literature values of maximum infiltration rates (10–20 mm h^{-1} and 5–10 mm h^{-1} for loamy soil and clay loamy soil, respectively. http://www.fao.org/docrep/S8684E/s8684e0a.htm.), only few events exceed 10 mm h^{-1} of with the precipitation intensity during the simulation period. Thus, hardly any surface runoff occured in the rural area, so that sediment generation and transport from rural areas to the river channel were small.

The comparably flat topography can be explained by the geological formation. The Muschelkalk limestone is a carbonate platform that is partially overlain by mudstones of the upper Triassic. ~~Within~~Along the Ammer ~~catchment~~main stem, there is only a small stretch where the river is somewhat deeper incised into the limestone rock. The river has lost its former headwater catchment in the early Pleistocene to river Nagold so that the currently existing small river has a too wide valley given its discharge.~~during the simulation period. Schwientek et al. (2013a)(Schwientek et al., 2013a) found that the connection between soils and streams is lacking in the Ammer catchment. The possible reasons are the formation of the~~

Ammer catchment results in a very wide valley and a small river (the Ammer River) due to rerouting of the former head-water catchment in the early Pleistocene;

As discussed above, we used a simplified approach to simulate the average sediment delivery from rural areas in our study The catchment has a large water storage capacity due to the karst and the slope of this catchment is mild; The precipitation intensity was not large enough to exceed infiltration rates or to reach storage capacity of the subsurface. Compared with literature values of infiltration rates (10–20 mm h^{-1} and 5–10 mm h^{-1} for loamy soil and clay loamy soil, respectively. http://www.fao.org/docrep/S8684E/s8684e0a.htm.),During the simulation period, annual precipitation was low, averaging 700 mm per year and there were only only few events with the precipitation intensity excessing exceed 10 mm h^{-1} during the simulation period., while infiltration rates of loamy soil and clay loamy soil are 10–20 mm h^{-1} and 5–10 mm h^{-1}, respectively. Thus, hardly any surface runoff can occur in the ruralnon-urban area, so that sediment generation and transport from ruralnon-urban areas to the river channel are small. Bbecause of the small contribution of rural areas to sediment delivery , a simplified approach was usedwas so small to simulate the average sediment delivery from rural areas in this study. In particular, we did not distinguish between different crop types and seasons It cannot explicitly consider all influence factors such as crop types and flow length, but and givesestimated the average sediment load that reaches the streams instead. In other catchments, where the rural contributions to the sediment load are considerably higher, the description of soil erosion processes would require more differentiations.It is special in the Ammer catchment that urban particles dominate. Therefore, if the purpose is to differentiate sediments from different cropland or to focus on the soil erosion processes, the other methods considering detailed processes should be used.



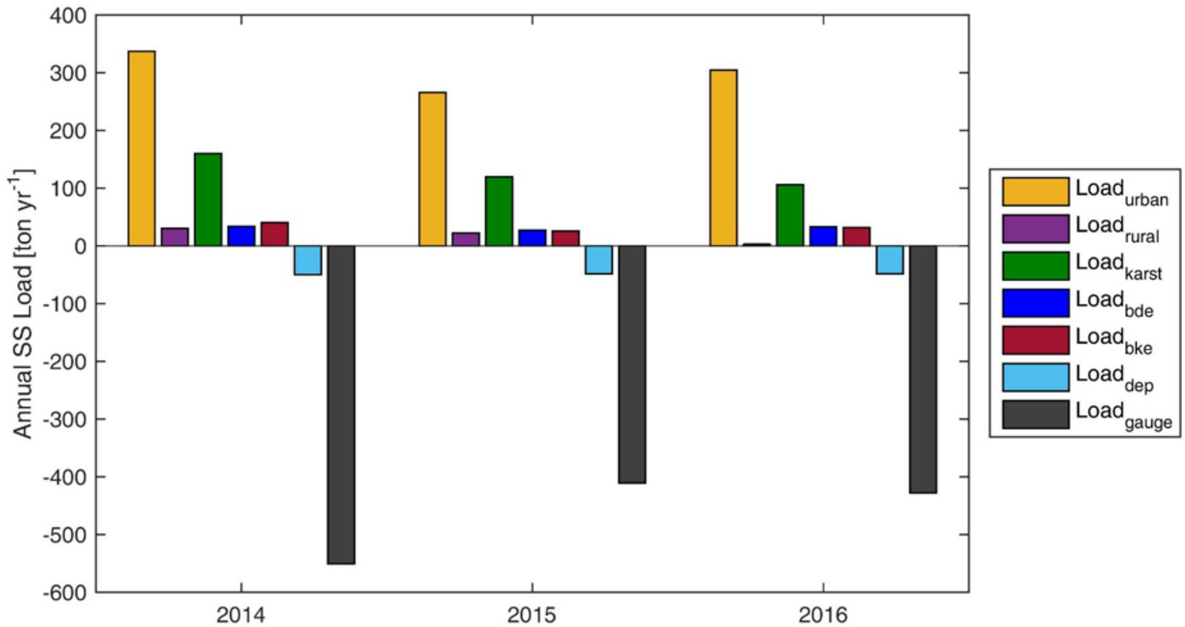
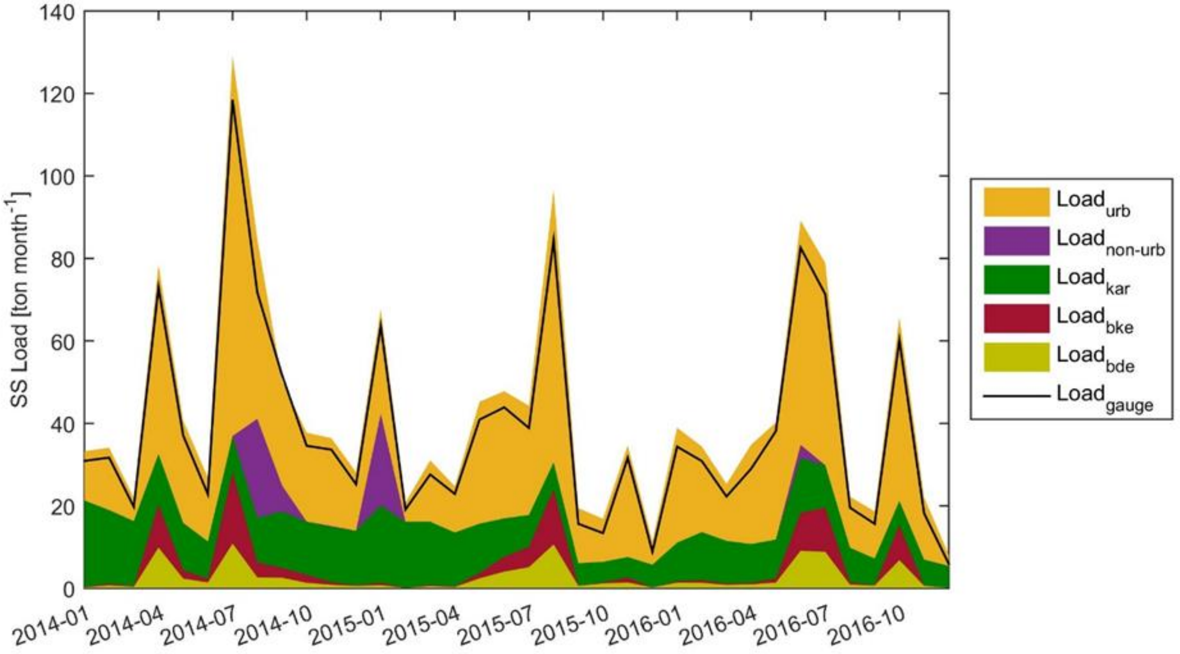


Figure 6: Annual suspended sediment loads from different processes. $\boldsymbol{Load_{gauge}}$ is calculated by modelled discharge and suspended sediment concentrations at catchment outlet. $\boldsymbol{Load_{urban}}$, $\boldsymbol{Load_{rural}}$~~$_{non-urb}$~~, and $\boldsymbol{Load_{karst}}$ are calculated using the results of sediment generating model. $\boldsymbol{Load_{dep}}$, $\boldsymbol{Load_{bde}}$, and $\boldsymbol{Load_{bke}}$ are the sum of deposition load, suspended sediments eroded from river bed and river bank of the entire river network for a whole year, respectively. In this figure, the positive values represent sediment input to the river channel, while negative values denote sediment output from the river channel.

To identify seasonal variations of suspended sediment loads originating from different processes, we used the model results of 2014–2016 to analyze the monthly mean suspended sediment loads from the urban areas, rural~~non-urban~~ areas, karst system, bed erosion, bank erosion, and deposition (Fig. 7). More suspended-sediment loads from urban areas and at the gauge can be observed in June and July (summer months). In summer months ~~the~~ events with high rain intensity ~~is normally higher~~are more common than in winter months, which results in higher discharge peaks, more sediments generated in urban areas, and higher suspended-sediment loads at the gauge. Monthly suspended-sediment loads at the gauge have similar dynamics as the monthly urban particle contributions. The suspended-sediment load from the karst system is higher in winter months because the subsurface flow in the Ammer catchment is higher in winter months. Rural~~Non-urban~~ particles contribute to the overall particle flux only during few months ~~only to the overall particle flux since~~because annual precipitation and rainfall intensity were relatively small so that surface runoff generated from rural~~non-urban~~ areas was also low.

In the model simulation period, the seasonal patterns of bed erosion and bank erosion are obvious. High bed erosion and bank erosion occur from June to August due to increased bed shear occurring during big events. The area above the line of $Load_{gauge}$ indicates ~~the~~ net deposition, which shows small variations with a slight increase in July and August. The slight increase in summer is due to increased suspended-sediment concentrations during summer months. Comparing monthly mean bed erosion and deposition shows that bed erosion was greater than deposition in July, which indicates that accumulated bed sediment can be partly eroded in July.



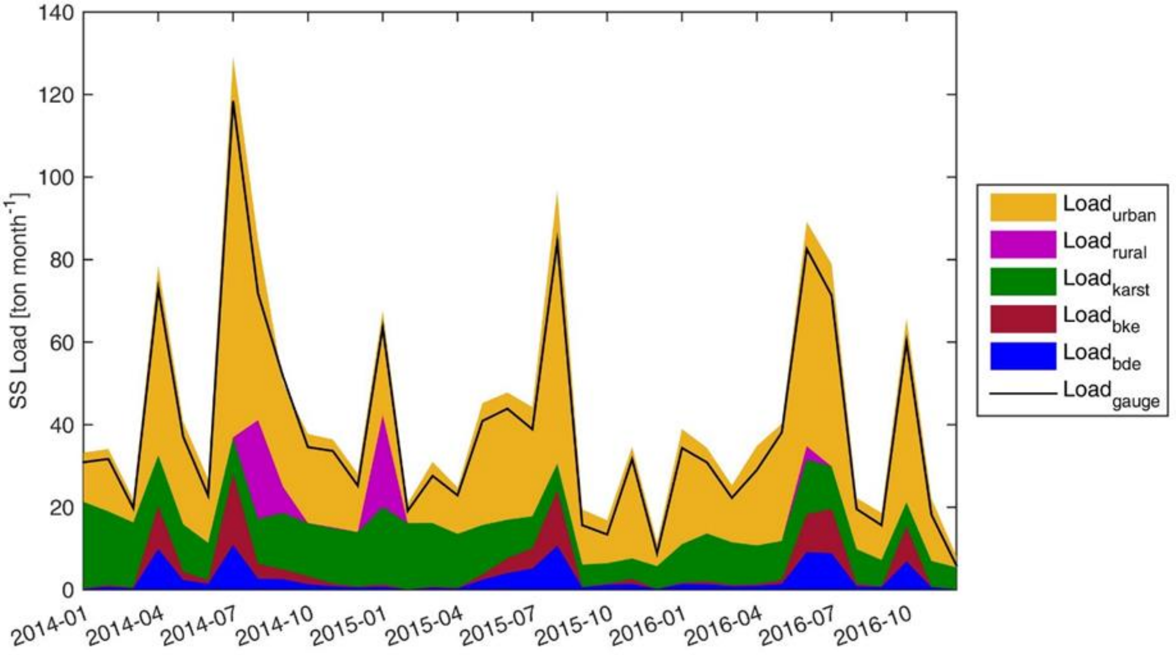


Figure 7: Monthly mean suspended-sediment load from different processes, calculated using the model results of 2014-2016. $\boldsymbol{Load_{gauge}}$, $\boldsymbol{Load_{urban}}$, $\boldsymbol{Load_{rural\,non-urb}}$, and $\boldsymbol{Load_{karst}}$ are the monthly mean suspended-sediment load at the gauge and from urban areas, rural~~non-urban areas~~, and karst system. ~~$\boldsymbol{Load_{bde}}$ and~~ $\boldsymbol{Load_{bke}}$ and $\boldsymbol{Load_{bde}}$ represent monthly mean suspended-sediment load from ~~bed~~ bank erosion and bed~~ank~~ erosion for the entire river network, respectively. The area above the line of $\boldsymbol{Load_{gauge}}$ is the monthly mean deposition, $\boldsymbol{Load_{dep}}$.

4.3 Suspended-Sediment Sources under Different Flow Conditions

Fig. 8 shows ~~The~~ the relationship between hourly mean discharge and the simulated hourly suspended sediment loads from catchment, bed erosion, and bank erosion~~ is demonstrated by the model simulations (Fig. 8)~~. The hourly suspended-sediment load from the catchment monotonically increases with increasing hourly mean discharge by a power-law relationship (Fig. 8a), which is consistent with the particle wash-off rate being a power-law function of discharge. Bed erosion requires that the bed shear stress exceeds a critical value, so that bed erosion is almost 0 when hourly mean flow is smaller than 1.5 m^3 s^{-1}, namely 1.5 times mean discharge (Fig. 8b). For discharge larger than this threshold (1.5 m^3 s^{-1}), bed erosion increases approximately linearly with discharge. The simulated hourly bed-erosion loads for a given flow rate vary substantially because bed erosion is not only influenced by the shear stress, which directly depends on discharge, but also on the bed sediment storage, which depends on previous deposition and erosion events. Bank erosion occurs when the hourly mean flow rate is larger than 2.5 m^3 s^{-1}, i.e., 2.5 times mean discharge (Fig. 8c). The relationship between bank-erosion related loads and discharge is more unique than that of bed-erosion loads because we assume an infinite source for bank erosion.

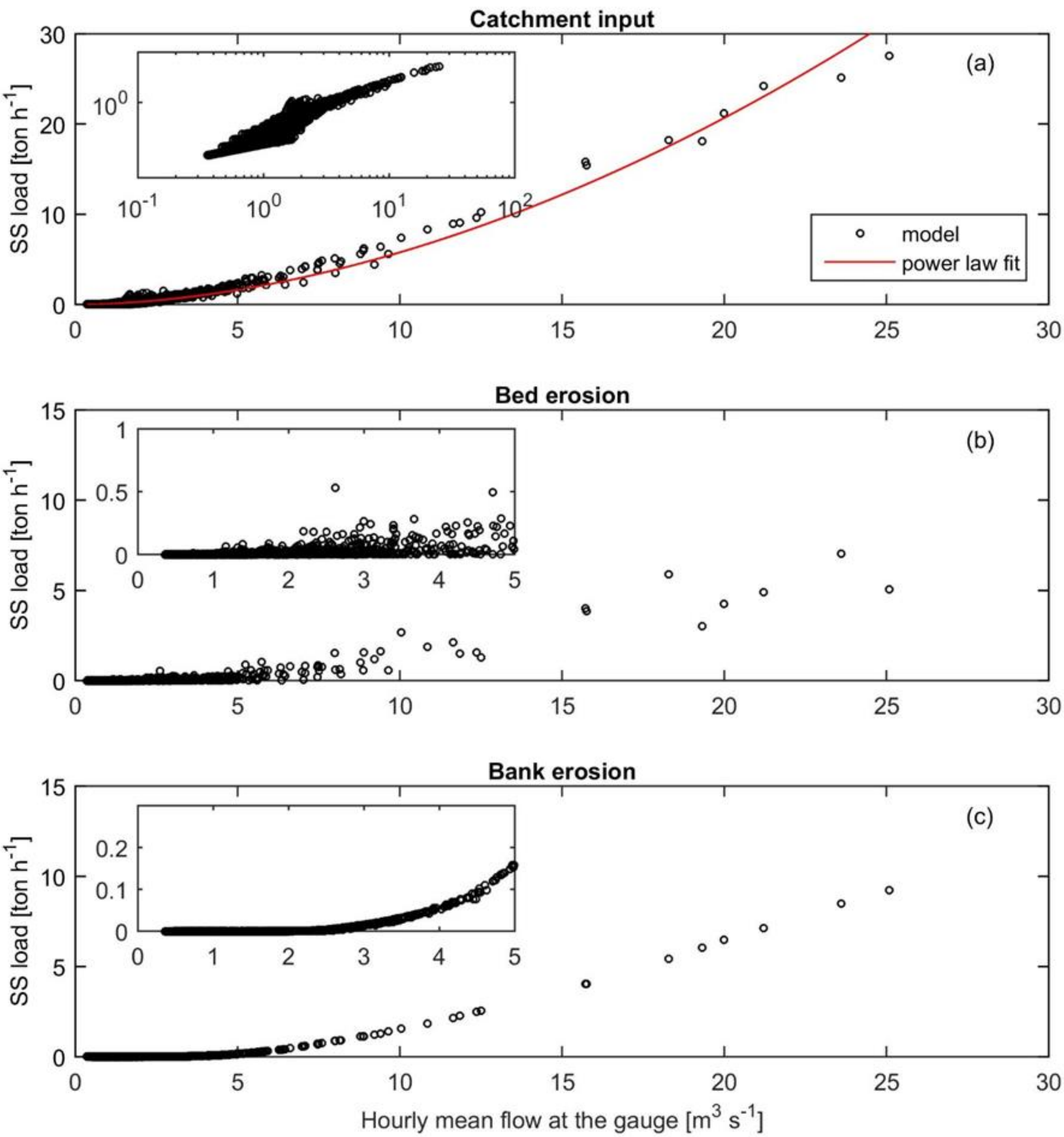
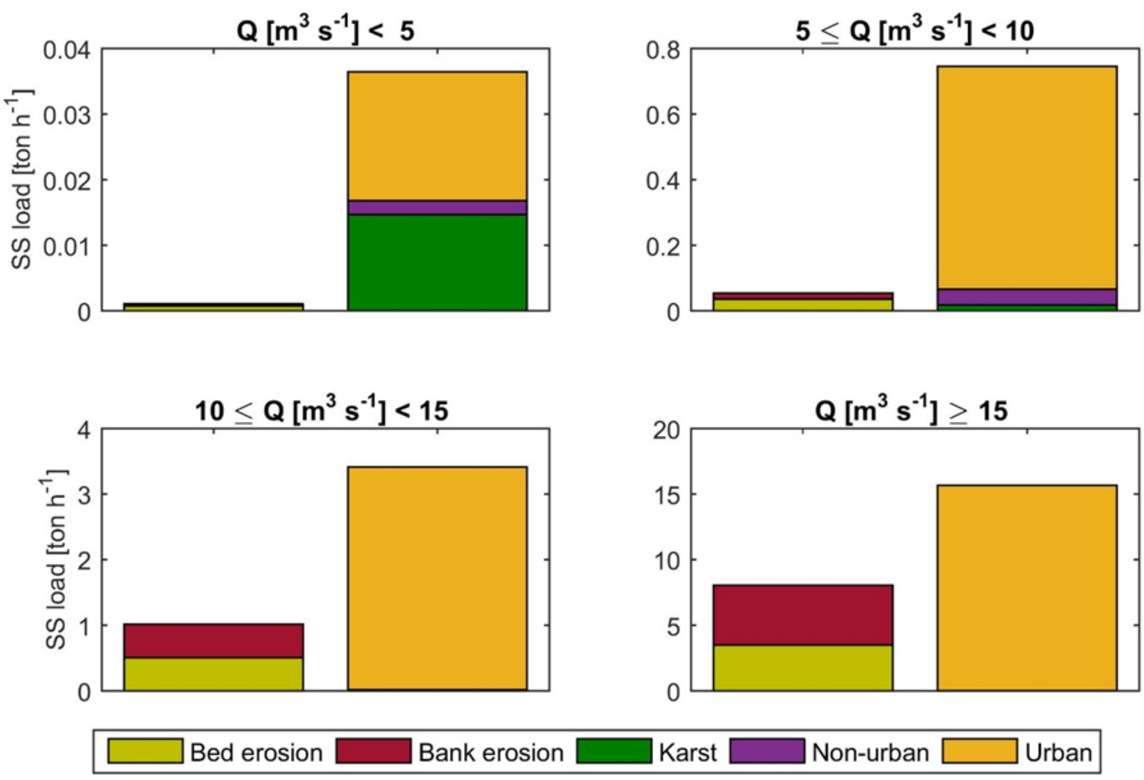


Figure 8: Relationship between simulated hourly mean flow and hourly suspended-sediment loads from the catchment (a), bed erosion (b), and bank erosion (c), in which bed erosion and bank erosion are sums over all computation cells. Loads from catchment is the sum of contributions from urban areas, non-urban areas, and karst system.

Figure 9 shows the suspended sediment loads from in-stream (bed erosion and bank erosion) and catchment processes (input from karst system, urban areas, and ~~non-urban~~rural areas) under different flow regimes. The fractions of suspended-sediment contributions from different processes change with flow regimes. The contributions of in-stream processes are negligible in the flow regime of discharge smaller than 5 $m^3 s^{-1}$. With the discharge increasing, the contributions of in-stream processes increase. The in-stream processes play significant roles in high flow regimes, which contribute 23 % and 34 % of total suspended sediment loads under flow regimes of $10 \leq Q$ [$m^3 s^{-1}$] < 15 and Q [$m^3 s^{-1}$] ≥ 15, respectively. The relative contribution of the karst system is high in the low flow regime (Q [$m^3 s^{-1}$] < 5), while it can be neglected under high flow regimes (Q [$m^3 s^{-1}$] > 10). With the increase in flow rates, the contribution of urban particles becomes dominant in terms of catchment processes, especially when discharge is larger than 10 $m^3 s^{-1}$.



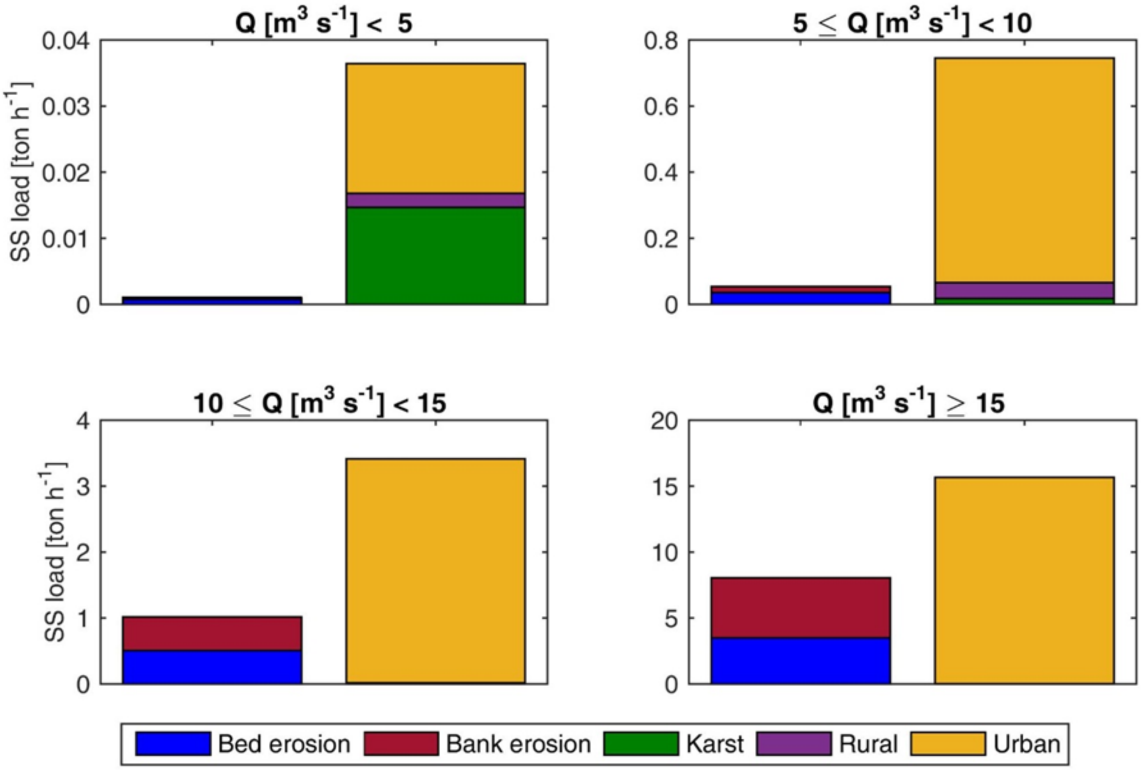


Figure 9: Simulated suspended sediment load from bed erosion, bank erosion, karst system, rural~~non-urban~~ areas, and urban areas (including suspended sediment from WWTPs) under different flow regimes, the suspended sediment loads are the mean values for the specific flow regimes.

From above observations, we can see that the sources of suspended sediments differ under different flow conditions in the following way (Table 4):

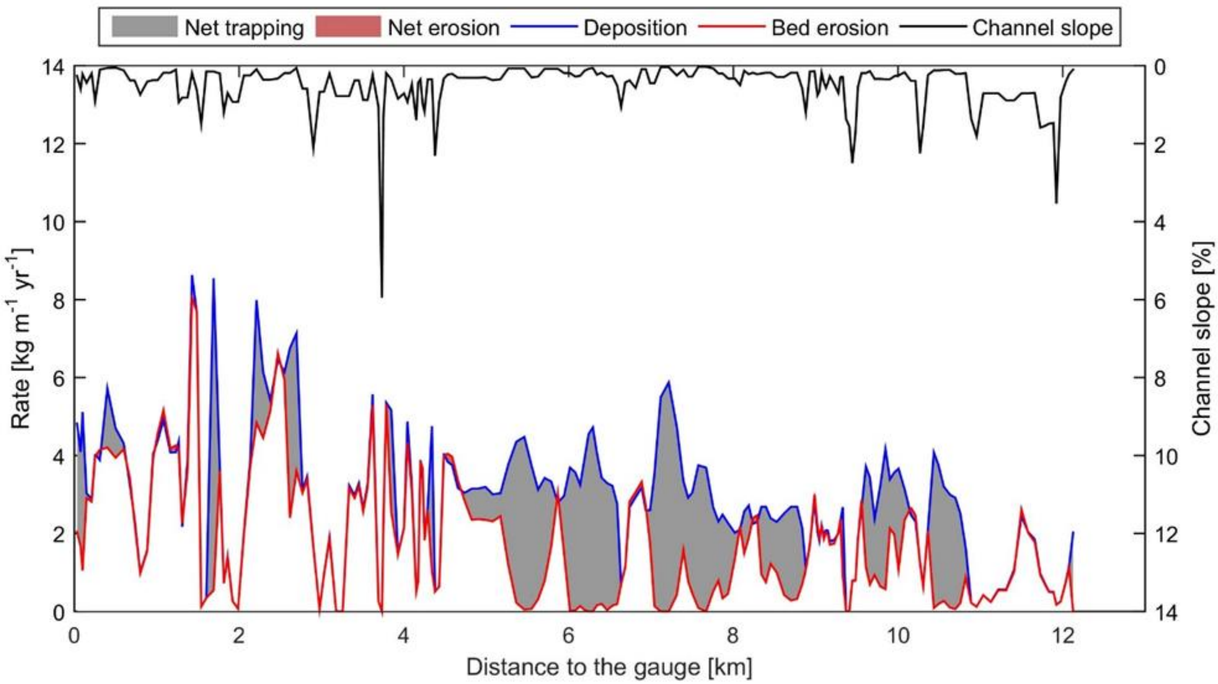
Table 4. Summary of suspended-sediment sources under different flow conditions.

Flow (Q) [$m^3 s^{-1}$]	Description of main suspended-sediment sources
Q < 1.5	Suspended sediment load is dominated by contributions from the catchment (karst system, ~~non-urban~~rural areas, and urban areas), while bed erosion and bank erosion can be neglected.
1.5 ≤ Q < 2.5	Bed erosion starts contributing.
2.5 ≤ Q < 5	Bank erosion starts contributing, but the contributions from bed and bank erosion are still negligible. Contributions from urban areas and karst system are dominant.
5 ≤ Q < 10	Bed and bank erosion contributes more, but the major contribution is still from catchment, especially from urban areas. Bed erosion contributes less than 5 % and bank erosion contributes less than 3 %. The relative contribution from karst system becomes very small.
Q ≥ 10	Suspended sediment contributions from bed and bank erosion are significant. The contribution of in-stream processes can be up to 35 % of the total suspended sediment load when discharge is larger than 15 $m^3 s^{-1}$. The contribution from urban areas is largest, which dominates the catchment input.

~~Q [$m^3 s^{-1}$] < 1.5:~~	~~Suspended sediment load is dominated by contributions from the catchment (karst system, non-urban areas, and urban areas), while bed erosion and bank erosion can be neglected;~~
~~1.5 ≤ Q [$m^3 s^{-1}$] < 2.5:~~	~~Bed erosion starts contributing;~~
~~2.5 ≤ Q [$m^3 s^{-1}$] < 5:~~	~~Bank erosion starts contributing, but the contributions from bed and bank erosion are still negligible. Contributions from urban areas and karst system are dominant;~~
~~5 ≤ Q [$m^3 s^{-1}$] < 10:~~	~~Bed and bank erosion contributes more, but the major contribution is still from catchment, especially from urban areas. Bed erosion contributes less than 5 % and bank erosion contributes less than 3 %. The relative contribution from karst system becomes very small;~~
~~Q [$m^3 s^{-1}$] ≥ 10:~~	~~Suspended sediment contributions from bed and bank erosion are significant. The contribution of in-stream processes can be up to 35 % of the total suspended sediment load when discharge is larger than 15 $m^3 s^{-1}$. The contribution from urban areas is largest, which dominates the catchment input.~~

4.4 Hotspots and Hot Moments of Bed Erosion in the Ammer River

The annual mean rates of bed erosion and deposition (mass per unit length per year) along the main channel can be used to identify hotspots of bed erosion and net sediment trapping (Fig. 10). The rates of deposition and bed erosion vary substantially along the main stem, ranging from essentially zero to a maximum of 8.6 kg m yr^{-1} and 8.0 kg m yr^{-1}, respectively. Bed erosion is higher in the river segment close to the gauge because the flow rate is higher due to the contributions of the tributaries. Bed erosion is rather low in the river segments of 5–6.5 km, 7–8 km, 8.5–9 km, and 10–11 km to the gauge, where the channel slope is very mild. The river sections with the steepest channel slope typically don't show the highest bed erosion because there is not enough sediment available for erosion, which is caused by insufficient deposition. Fig. 10 also shows that when the channel slope is very mild, the deposition rate is very high, while the bed erosion rate is nearly zero. These are sections where net sediment trapping (~~grey shaded areas~~b~~u~~lue dash-dotted line) was observed. With increasing ~~the~~ channel slope ~~increasing~~, bed erosion rates increase and deposition rates decrease. In a small range of channel slopes, deposition rates ~~are~~ equal to erosion rates, resulting in a local ~~equilibrium~~steady state. If the channel slope continues increasing, the erosion rate will be higher than the deposition rate, which results in net sediment erosion if the~~re are available~~ sediment storage~~s~~ in the channel is large enough (~~pink shaded areas~~red dash-dotted line, very few in Fig. 10). Where the channel slope is very steep, both sediment deposition and erosion rates are very small.



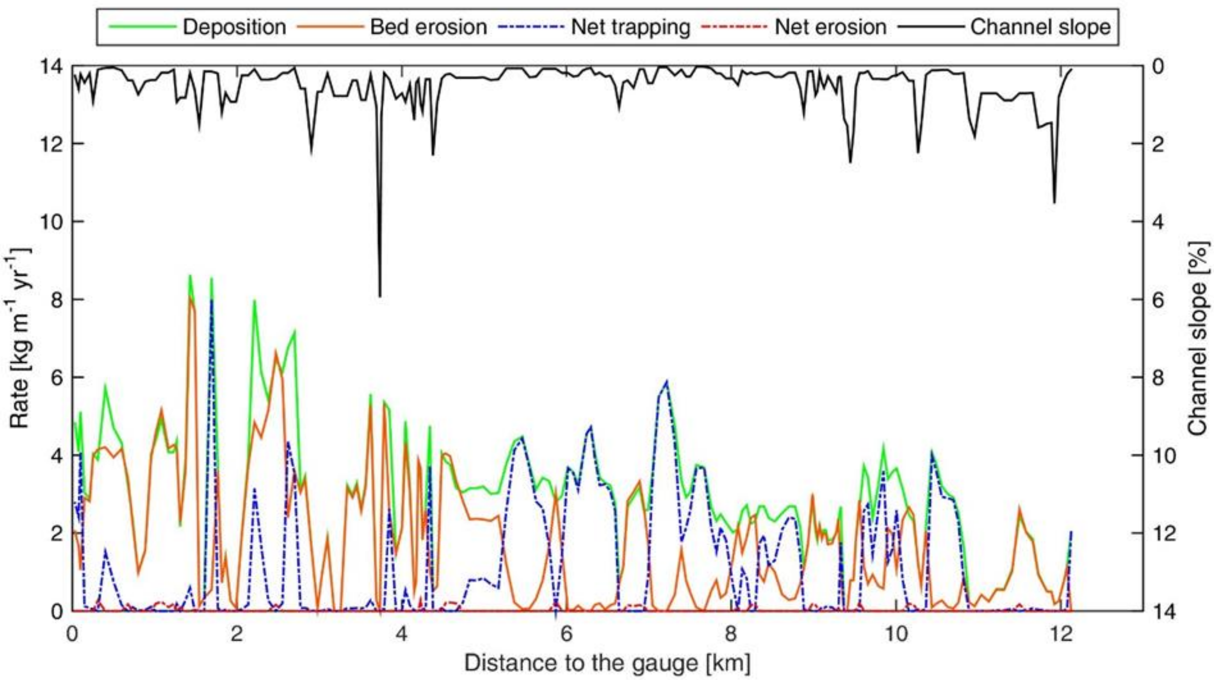


Figure 10: The distribution of the annual mean deposition, bed erosion, net sediment trapping, net sediment erosion, and channel slope along the main channel of the Ammer River (flow direction from right to left). The ~~grey~~ blue and ~~pink~~ red ~~shaded areas~~dash-dotted lines highlight ~~represent~~ net sediment trapping and net erosion, respectively.

Figure 11 shows monthly means of the bed erosion rates along the Ammer main stem, computed for the simulated years 2014 to 2016. Bed erosion is stronger in the summer months, especially in July, which is consistent with the monthly load of suspended sediments discussed in Sect. 4.2. The hot moments of bed erosion are the extreme events caused by summer thunderstorms. The downstream river segments close to the gauge show higher bed erosion rates than the sections further upstream because flow rates and thus bed shear stresses are higher even with identical channel slope.

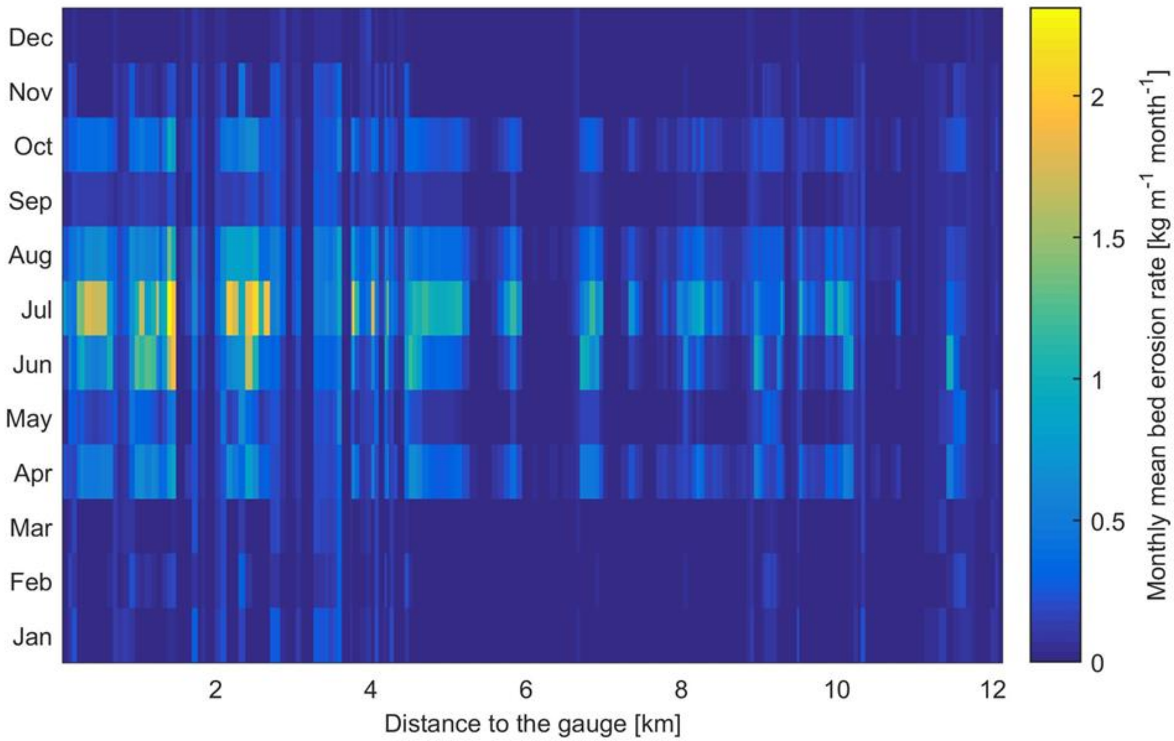


Figure 11: Monthly mean bed erosion along the channel of the Ammer River upstream of the gauge (flow direction from right to left).

5 Conclusions

Suspended sediment transport is of great importance for river morphology, water quality, and aquatic ecology. In this study, we have presented an integrated sediment-transport model, combining a conceptual hydrological model with a river-hydraulics model, a model of sediment generation, and a shear-stress dependent sediment-transport model within the river, which enables us to investigate the major contributors to the suspended-sediment loads in different river sections under different flow conditions.

In the dominantly groundwater-fed Ammer catchment, annual suspended-sediment load is dominated by the contributions of urban particles and sediment input from the karst system. The contribution from ~~non-urban~~rural areas is small because the topography is comparably flat and the infiltration capacity of the soils is high~~low annual precipitation and intensity~~ in this region resulting in a very weak surface runoff from ~~non-urban~~rural areas, thus very few ~~non-urban~~rural particles are generated and transported to the river channel. In-stream processes, i.e. bed erosion and bank erosion, play significant roles in high flow ~~regimes~~ conditions ($Q > 10$ m^3 s^{-1}). The flow rate governs the contributions of different processes to the suspended sediment loads. Especially, bed erosion and bank erosion take place when flow rates reach the corresponding thresholds, 1.5 and 2.5 times ~~of~~ the mean discharge~~1.5 m^3 s^{-1} and 2.5 m^3 s^{-1}~~, respectively. The channel slope has significant effects on the deposition and bed erosion rates. Net sediment trapping was found in the river segments with very mild channel slopes in the Ammer River during the simulation period with events of a 2-year to 10-year return period. Finally, the river hydraulics model is necessary to differentiate sediment sources and sinks of in-stream processes i.e. shear stress related deposition, bed erosion and bank erosion.

The model and results of this study are useful and essential for further research on the fate and sediment-facilitated transport of hydrophobic pollutants like PAHs, and for the design of optimal sampling regimes to capture the different processes that drive particle dynamics. In addition, the analysis of deposition and bed erosion in the Ammer main stem provides information on the distribution of net sediment trapping within the channel, which would be a good indicator for channel dredging to improve water quality.

Code availability

The full code is ~~available on request.~~provided in the Supplementary Material.

Appendix A. Catchment-Scale Hydrological Model

The hydrological model in the integrated sediment transport model is composed of three storage zones in vertical direction with a quick recharge component and an urban surface runoff component. Detailed processes are shown below.

We applied this model to 14 sub-catchments of the study domain. Each sub-catchment includes three different land use: urban area, agriculture and forest. For urban area, we consider effective urban area such as roads and roofs and ineffective urban area such as parks and gardens. We use the same parameters of agriculture for ineffective urban area.

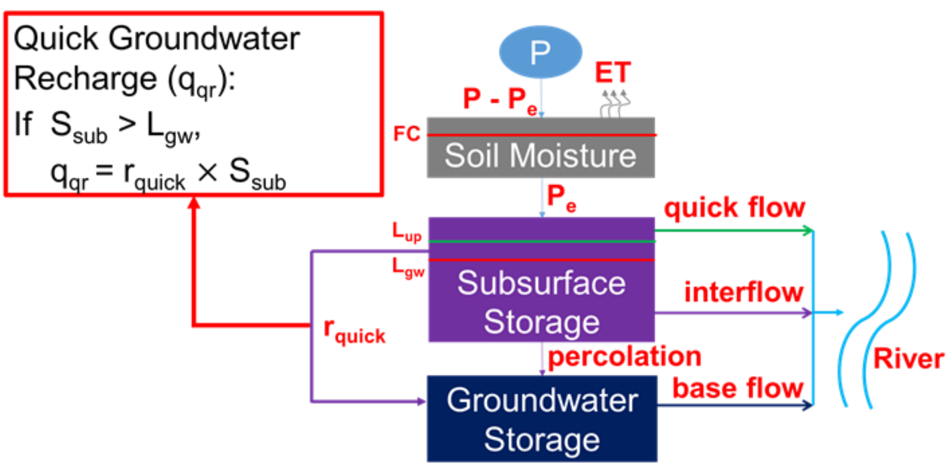


Figure A1: The hydrological model for the Ammer catchment with three storage zones (soil moisture, subsurface storage and groundwater storage), a quick groundwater recharge and an urban surface runoff component

The effective urban area is used for surface runoff component, the ratio is calculated by:

$$r_{eff} = \frac{A_{eff}}{A_{urb}} \quad \text{(A1)}$$

in which r_{eff} [-] is the ratio of effective urban area over total urban area, A_{eff} [km^2] and A_{urb} [km^2] represent areas of effective urban area and total urban area, respectively.

The effective precipitation to the subsurface storage for agriculture, forest and ineffective urban area is calculated below:

$$P_e = \left(\frac{SM}{FC}\right)^{\alpha} P \quad \text{(A2)}$$

in which P_e [mm d^{-1}] indicates effective precipitation, P [mm d^{-1}] is precipitation, SM [mm] and FC [mm] are soil moisture and maximum soil storage capacity, respectively, α [-] is a shape factor.

We use long-term monthly mean evapotranspiration to calculate the actual evapotranspiration with a temperature adjustment.

$$L_{et} = FC c_{et} \quad \text{(A3)}$$

$$ET_t = [1 + c_t(T - T_m)]ET_m \quad \text{(A4)}$$

$$ET_a = \begin{cases} ET_t, & SM \geq L_{et} \\ \frac{SM}{L_{et}} ET_t, & SM < L_{et} \end{cases} \quad \text{(A5)}$$

in which L_{et} [mm] is a threshold for maximum evapotranspiration, c_{et} [-] is a factor to calculate L_{et}. ET_t [mm d^{-1}] represents the maximum evapotranspiration at temperature T [°C]. ET_m [mm d^{-1}] and T_m [°C] indicate long-term monthly mean evapotranspiration and long-term monthly mean temperature, respectively, c_t [°C^{-1}] is a temperature adjustment factor. ET_a [mm d^{-1}] represents actual evapotranspiration, which reaches maximum evapotranspiration when soil moisture is greater than the threshold for maximum evapotranspiration. Otherwise, it increases linearly with soil moisture.

The top storage layer, soil moisture, is calculated by:

$$\frac{dSM}{dt} = P - P_e - ET_a \quad \text{(A6)}$$

in which $\frac{dSM}{dt}$ [mm d^{-1}] represents the change rate of soil moisture. It is used for agriculture and forest. The change rate of soil moisture for urban area is $\frac{dSM}{dt}\left(1 - r_{eff}\right)$, because we assume that precipitation on the effective urban area will directly become urban surface runoff.

The surface runoff in the effective urban area, overflow and interflow are calculated by:

$$q_{effurb} = P \quad \text{(A7)}$$

$$q_{of} = \begin{cases} 0, & S_{up} < L_{of} \\ k_{of}\left(S_{up} - L_{of}\right), & S_{up} \geq L_{of} \end{cases} \quad \text{(A8)}$$

$$q_{if} = k_{if} S_{up} \quad \text{(A9)}$$

$$q_{bf} = k_{bf} S_{gw} \quad \text{(A10)}$$

in which q_{effurb} [mm d^{-1}] is surface runoff in the effective urban area. q_{of} [mm d^{-1}] represents overflow when subsurface storage S_{up} [mm] is greater than an overflow threshold L_{of} [mm]. It is used for agriculture, forest and ineffective urban area. q_{if} [mm d^{-1}] represents interflow. k_{if} [d^{-1}] is a rate constant. q_{bf} [mm d^{-1}] represents base flow, S_{gw} [mm] is groundwater storage, k_{bf} [d^{-1}] is a base flow recession coefficient.

The two equations below are used to calculate percolation and quick recharge.

$$q_{perc} = k_{perc} S_{up} \quad \text{(A11)}$$

$$q_{qr} = \begin{cases} 0, & S_{up} < L_{qr} \\ k_{qr}\left(S_{up} - L_{qr}\right), & S_{up} \geq L_{qr} \end{cases} \quad \text{(A12)}$$

in which q_{perc} [mm d^{-1}] represents percolation from soil moisture to subsurface storage. k_{perc} [d^{-1}] is a rate constant. q_{qr} [mm d^{-1}] represents quick recharge, which occurs when subsurface storage reaches a quick recharge threshold L_{qr} [mm]. k_{qr} [d^{-1}] is a rate constant.

The subsurface storage and groundwater storage are calculated by:

$$\frac{dS_{up}}{dt} = \begin{cases} P_e - q_{perc} - q_{qr} - q_{of} - q_{if}, & agriculture\ and\ forest \\ P_e\left(1 - r_{eff}\right) - q_{perc} - q_{qr} - q_{of} - q_{if}, & urban\ area \end{cases} \quad \text{(A13)}$$

$$\frac{dS_{gw}}{dt} = q_{perc} + q_{qr} - q_{bf} \quad \text{(A14)}$$

in which $\frac{dS_{up}}{dt}$ [mm d^{-1}] is the change rate of subsurface storage. In the urban area, only precipitation in the ineffective area can partly become recharge to the subsurface storage. $\frac{dS_{gw}}{dt}$ [mm d^{-1}] represents the change rate of groundwater storage.

Competing interests

The authors declare that they have no conflict of interest.

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