Reply to Referee #1

Wenlong Wang on behalf of all co-authors

The manuscript entitled "Spatial-temporal changes in flow hydraulic characteristics and soil loss during gully headcut erosion" is a study of gully head evolution under controlled conditions belonging to a set of papers presented by the authors in the last years on this subject. Since the authors aim in this manuscript is to investigate the hydraulics changes in the flow through the gully and its impact on energy consumption it fits into the journal scope. My general comments on the manuscript are that it covers a topic of interest, and it is well structured with clear Tables and Figures. Not been a native English speaker I find hard to suggest specific changes in the English usage, but there are sections that are hard to follow and expressions that does not seem the most appropriate (e.g. line 146 "artificially planted forest: : :"). In my opinion the most valuable part of the manuscript is the experimental dataset presented by the authors, which are scarce in gully erosion studies. However, the results are mostly a confirmation of the previous knowledge, some hardly novel like the transition in hydraulic regime trough the gully headcut, which limits the significance of the manuscript. This might be compensated with a more critical discussion of the results, which currently is mostly a comparison of previous papers. The analysis and discussion of the issue of energy dissipation (consumption in the authors wording), which might be the most innovative part of the manuscript is not deep enough, and does not try to link with previous studies on optimization of energy dissipation in drainage networks which might be enlightening.

Response: First of all, we would like to thank you for your recognition of our work that is a topic of interest and fits within the scope of the journal. As for the language, we will revise it carefully several times, and then invite researchers who have been working in Europe for a long time to revise the manuscript, hoping to make the language smoother. Also, we thank you for your recognition of our research work on gully erosion and the value of the data. We also agree your comments about "the results are mostly a confirmation of the previous knowledge, some hardly novel like the transition in hydraulic regime trough the gully headcut, which limits the significance of the manuscript. This might be compensated with a more critical discussion of the results, which currently is mostly a comparison of previous papers.". We will reduce the comparison with previous studies and compensate the discussion in more depth about what our results show and why this is the case than the simple comparison with previous studies. One of the important reasons why the process of gully erosion is more complicated than that of slope erosion is that the existence of gully head changes the runoff characteristics and erosion dynamic mechanism of slope. For a complete gully system, the flow characteristics of upstream area, gully head runoff and gully bed are completely different, and the erosion process and hydro-dynamic mechanism of the corresponding three landform parts are also completely different. Therefore, this is also the reason why we study the change of flow properties along upstream area - gully head - gully bed and its influences on runoff energy consumption and soil loss in the process of gully headcut erosion. We believe that understanding the erosion process and hydrodynamic mechanism of different landforms units is conducive to a deeper understanding of the process and mechanism of gully erosion, and provides some references for the development and establishment of gully erosion process models.

In addition, as you mentioned, the energy dissipation may be the most innovative part of the manuscript. We also found the soil loss due to gully headcut erosion had closer correlation with energy dissipation than other hydraulic parameters. So, we will intensify this in-depth analysis and discuss it with previous studies on optimization of energy dissipation in drainage networks. The more detailed explanation is also provided in Q3 and specific revision will be reflected in further revised manuscript. We are particularly grateful to you for your valuable suggestions, which will make our work more in-depth and excellent.

Some specific comments that might be of help to the authors for improving the manuscript are:

Q1. Better description in material and methods of the flume conditions in the gully bed section. It is apparent in Figure 3e that this is a short section with lateral walls, and so it is a situation far off from which might appear on gully in real world conditions, where gully walls will expand at a different rate and energy dissipation might take place for a longer section. Although this does not invalidate the experiment performed by the authors, it clearly conditions the expected results and the conditions to which we could extrapolate the results. This should be considered in the discussion.

Response: First of all, we are very grateful for your valuable suggestions for amendments. (1) We will add more descriptions about the gully bed in the “2.2.1 Plot set-up” in “2 materials and methods” section. (2) Gully erosion has three sub-processes, including gully headcut erosion, gully bank expansion and gully incision. Our research mainly focuses on gully headcut erosion, which is consistent with the research of many people such as Bennet et al. (1999, 2000, 2001, 2006), Gordon et al. (2007), Wells et al. (2009a, 2009b), Su et al. (2013, 2014) and Zhang et al. (2016, 2018). So, in this study only when the gully head migrates upstream, the gully channel and gully bank will be formed, so the gully bed section designed in this experiment does not include the gully bank. In this study, the gully bed was set up for the development of plunge pool, and also for clarifying the changes in the runoff characteristics of the upstream area and the gully bed and their impact on the erosion dynamic mechanism due to the existence of the gully heads. We also did some pre-experiments and found that the length of the gully bed can meet the morphological development of the plunge pool, and it can also stabilize the water flow after it comes out of the plunge pool (because the most of flow energy was consumed in plunge pool, so the flow energy and velocity are very low and easy to stable). As you stated, indeed, when gully head migrates, the flow energy dissipation might take place for a longer section than the designed gully bed section. In our study, we treated this as the result of gully head migration, and thus the energy dissipation due to gully walls expand was included in the range of gully head energy consumption. Of course, to some extent, this does clearly condition the expected results and the conditions to which we could extrapolate the results. We will add the above related content to the Discussion section according to your suggestion. Thanks again.

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- Zhang, B.J., Xiong, D.H., Zhang G.H., Zhang, S., Wu, H., Yang, D., Xiao, L., Dong, Y.F., Su, Z.A., Lu, X.N.: Impacts of headcut height on flow energy, sediment yield and surface landform during bank gully erosion processes in the Yuanmou Dry-hot Valley region, southwest China, Earth Surface Processes & Landforms, 43(10), 2271-2282, https://doi.org/10.1002/esp.4388, 2018.

Q2. 2- The discussion of results seems to be mostly a comparison of results for previous papers, with little additional insight. A deeper discussion, which might include, for instance, implications for modelling gully erosion, scale effects (for larger or smaller gullies), or restoration efforts might be included.

Response: We thank you for your useful comments and valuable suggestions regarding the discussion. We have also realized the shortcomings of the discussion part, and we will reduce some comparison with previous studies, and also supplement and improve each discussion part to increase the intrinsic significance of our research results. We will add some aspects about the explanation about how the hydraulic characteristics of three landform units with gully headcut, the effect of gully headcut on variation of hydraulic properties from upstream to gully bed, and clarify the difference in hydrodynamic mechanism of three landform units during headcut erosion. In addition, we will add a section (**4.4 Implications and significance of this study**) focusing on the implications and significance of our research about gully erosion for improving the significance and value of this study. This section will refer to some points including modeling gully erosion, scale effect of gully erosion, establishment of gully erosion model and gully erosion control practice, etc.

Q3. 3- The analysis if energy dissipation does not seem in depth enough. Firstly, there is no any attempt to provide an overall energy analysis of the system, there are energy losses in the water depth which are not mentioned (like the one dissipated as heat and noise) and it is not clear how much of the original energy available to the flow (which I guess is the potential energy at the reservoir located at the top of the upstream section) is dissipated and how much remains at the end of the flume. The authors do not try to analyze the results to seek if some kind of optimization of energy dissipation (as suggested by previous papers on river and rill network development) is apparent. For instance calculating the energy losses by wetted section or by unit flow or sediment discharge, like previous studies. These are ideas, among others in that line, that the authors may want to explore to take advantage of the very detailed dataset that they have developed.

Response: We fully agree with your comment. Indeed, we have not provided the overall energy analysis of the system in the original submission. As you guessed, the original energy available to flow is the potential energy based on the zero-potential surface (the bottom of the gully bed section), which was calculated by Eq. (9). We will add the analysis about the "how much of the original energy available to the flow is dissipated and how much remains at the end of the flume". The following figure shows the total flow energy, total energy consumption and the rest flow energy under different flow discharge conditions. The added Fig. 1 will combinate with Figure 10 in "3.2 Spatial-temporal change of energy consumption".

In addition, we indeed have not analyzed the results to seek if some kind of optimization of energy dissipation (as suggested by previous papers on river and rill network development).

Previous studies showed that the similarity between rill/gully networks and river drainage networks is not surprising since rills belong to the same drainage network that river sections do, and some lab studies have documented similarity between river and rill network (e.g., Mosley, 1974; Ogunlela, et al., 1989) as well as the similarity between drainage networks at basin and small scales (Helming et al., 2006). That is why that, in the soil erosion field, the flow dynamic knowledges/theory of river systems are always used to understand and model rill/gully network or hillslope erosion processes. At present, the theory of minimum rate of energy dissipation have been used to describe channels in equilibrium with water and sediment based on analogy with thermodynamic systems (Yang, 1971a, 1971b; Yang et al., 1981) and also was used in the studies on the hydro-dynamic mechanism of soil erosion due to above-mentioned similarity. The theory of minimum rate of energy dissipation was expressed as following equations (Yang, 1971a, 1971b) and also employed in our study.

The flow energy and unit flow power are:

$E=\rho \cdot g \cdot l \cdot Q \cdot J$

$P = V \cdot J$

Where ρ is water density, l is channel length, Q is the unit flow discharge, V is flow velocity, J is the slope gradient.

In our study, the calculation of flow energy in different landform units (Eqs. (9-12)) is consistent with the two principles.

In addition, we also analyzed the temporal change in the ratio of total energy dissipation to total flow energy with experimental time (Figure 2 as following) and find the similar trend with the published article by Gomez et al. (2003) who found that the theory developed for river networks might explain the evolution of rill networks at hillslope scale. Therefore, we also further confirmed that the flow energy dissipation in our study followed the theory of minimum rate of energy dissipation.

To be honest, nevertheless, many studies distinguished between rill/gully and river scales because there are significant differences between them due to their different sizes and the more discontinuous and ephemeral character of the rill/gully compared with rivers. This difference in size implies that some mechanisms involve in the evolution of rill/gully networks may seldom be present in the evolution of river networks. For that reasons, the interpretation of rill/gully networks process form the experimental and theoretical studies of river networks may not be straightforward, in same way that the interpretation of the evolution of river networks form small-scale rill studies has its shortcomings. Throughout the current researches on the hydrodynamic mechanism of soil erosion, most of the hydrodynamic calculations are carried out according to the river dynamics formula, and in terms of energy consumption, the principle of minimum energy consumption is used.

We will analyze the results to clarify which kind of optimization of energy dissipation is available and build the connection between soil loss and energy dissipation for the “UA-GH-GB” gully system in our study and promise to revise the related content in further MS (Fig. 3).

Also, our research team will do our best to study the hydrodynamic mechanism of gully erosion to replace the theory of river dynamics.

References:

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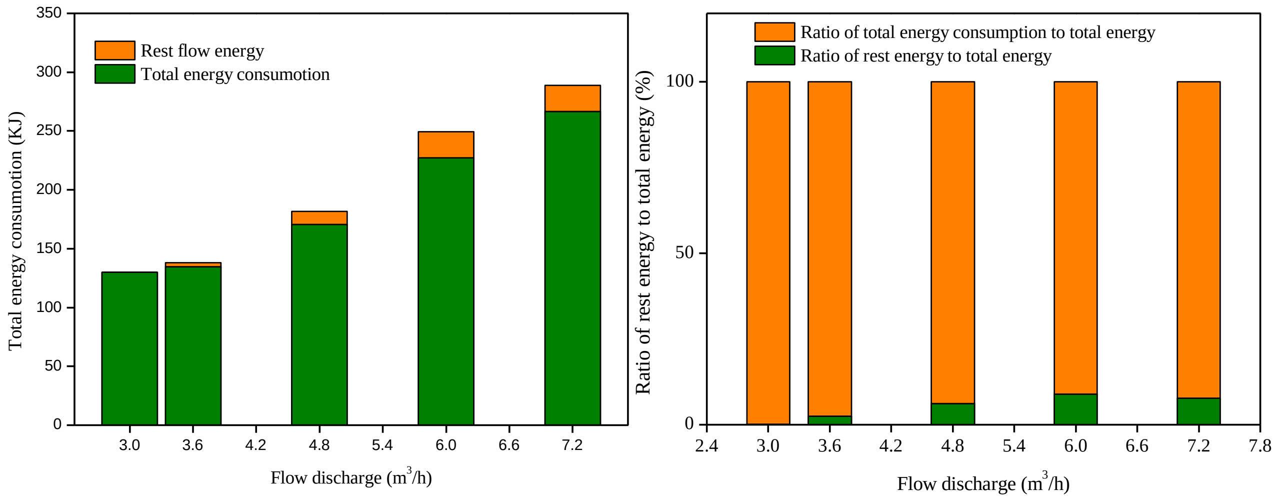

Fig. 1 Variations in total energy consumption and rest flow energy with flow discharge and their ratios to total energy

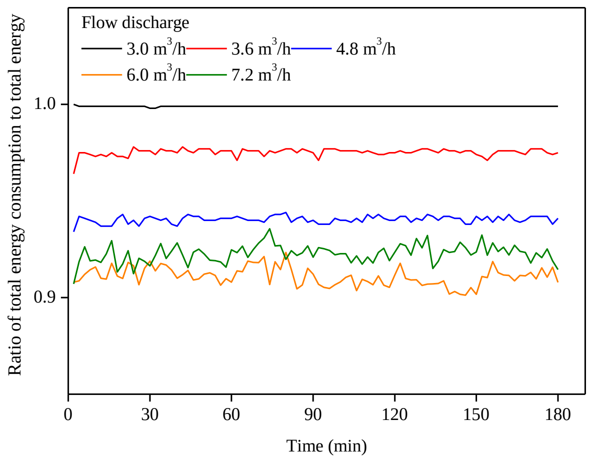

Figure 2 The ratio of total energy consumption to total flow energy

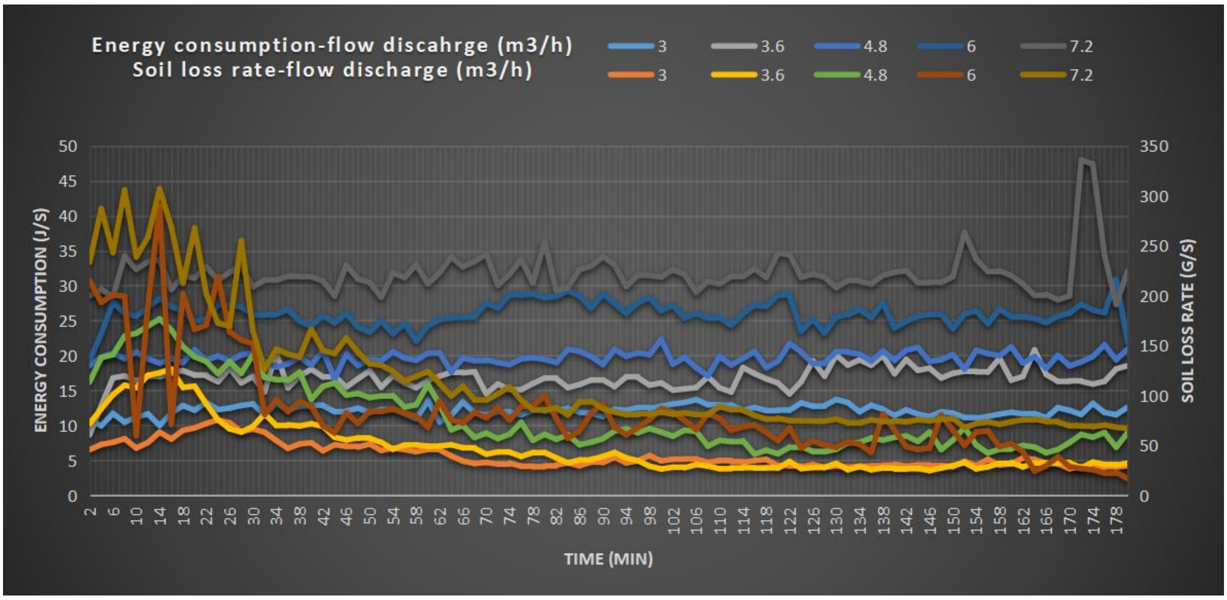

Fig. 3 Relationship between soil loss rate of "UA-GH-GB" system and energy dissipation during headcut erosion

Q4. 4- Data availability. Although in this case it is beyond the authors responsibility to decide on data availability, it is a good practice to provide at least the ancillary data from which the graphs have been developed. For this I mean the values of the data plotted in the graphs. In this way you facilitate use to other colleagues of the information that might be retrieved scanning and plotting the graphs. I recommend the authors to seek permission for this.

Response: We fully understand your comment. As you mentioned in general comments, "In my opinion the most valuable part of the manuscript is the experimental dataset presented by the authors, which are scarce in gully erosion studies.". At present, indeed, the datasets about gully erosion process are scarce. After a careful consideration, we obtain the permission and can provide the data information of all figures in the manuscript. In the future revision, we will provide the data plotted in the figures for other colleagues.

Some other minor technical corrections that I might add are:

Q5. 1- Title. Perhaps "Spatial-temporal changes in flow hydraulic characteristics and soil loss during gully headcut erosion under controlled conditions" might be more descriptive of the manuscript.

Response: We thank you for your pertinent suggestion. Indeed, our study was designed and completed under controlled conditions. We accepted your suggestion and will revised the title as "Spatial-temporal changes in flow hydraulic characteristics and soil loss during gully headcut erosion under controlled conditions". Thank you again.

Q6. 2- Lines 62-64. Not very clear, please edit for clarity.

Response: We thank you for your careful review. We will revise the sentence in future revised MS as "Moreover, the different landform units (upstream area, UA; gully head, GH; gully bed, GB) of gully system exhibited completely different erosion processes and mechanisms during gully headcut erosion (Zhang et al., 2018; Guo et al., 2019; Shi et al., 2020a).". We hope our amendments will be satisfactory to you.

Q7. 3- Lines 85-86. Reduces soil losses as and headcut retreat as compare to what, bare soil? Please clarify

Response: We are so sorry for the unclear expression. As you said, the reduced soil losses were compared with bare soil. We will revise the sentence as "Guo et al. (2019) concluded that the grass (Agropyron cristatum) could reduce soil loss and headcut retreat distance by 45.6–68.5%, 66.9–85.4%, respectively, compared with bare soil, and the roots of 0–0.5 mm in diameter showed the greatest controlling influence on headcut erosion." in the future revision. Thank you very much for your careful review.

Q8. 4- Lines 133-134. You probably do not need two references to indicate elevation range in the area.

Response: We are sorry for it. In fact, we should insert the two references in the last sentence. We will revise the sentence as "The mean annual precipitation is 546.8 mm (1954 - 2014), of which precipitation from May to September accounts for 76.9% of the total precipitation (Xia et al., 2017; Guo et al., 2019). The elevation ranges from 1050 to 1423 m.". Thank you very much.

Q9. 5- Check English usage in line 145-146.

Response: We thank you for your careful review. We will revise the sentence as "The plants are primarily artificially planted arbors and herbaceous vegetation and shrubs" in the future revision.

Q10. 6- Line 215. Please provide a bit more information on the LS300-A measuring principle.

Response: We thank you for your valuable suggestion. We will add the more information on the measuring principle. The specific revision is "The runoff velocity (V_J) before runoff arrived at the brink of headcut was measured 5 – 8 times by the flow velocity measuring instrument (LS300-A). The instrument was firstly placed perpendicular to the flow section but does not touch the underlying surface. When the flow passes through the turbine, the flow velocity can be measured by the rotating velocity of the turbine with the accuracy of 0.01 m s^{-1} and measuring error of < 1.5%, Also, the runoff width at the headcut brinkpoint was measured (Fig. 3d).".

Q11. 7- section 2.2.2. Could you indicate the corresponding upslope area for the different flow discharge used, according to the runoff coefficient, and storm intensity used?

Response: We thank you for your meaningful comment. In fact, the five different flow discharges were selected from a range values (3.12 to 9.68 m^3 h^{-1}) that was calculated according to the runoff coefficient, storm intensity and upstream area. The runoff coefficient was confirmed based on the data of standard runoff plots; the storm intensity was calculated by Eq. (1). For the upstream area, our research team investigated 45 upstream areas in the study area. The upstream area (A) and width (W) are 0.15-8.69 km^2 and 0.53-1.64 km, respectively. **Then, the inflow discharge was calculated by Eq. (2) and ranged from 3.12 to 9.68 m^3 h^{-1}. Before the study, we first conducted some preliminary experiments under some flow discharges, and meanwhile considering the pre-experiment effect, finally, we selected the five inflow discharge levels (3.0, 3.6, 4.8, 6.0, and 7.2 m^3 h^{-1}) from the calculated ranges (3.12 to 9.68 m^3 h^{-1}). Therefore, the five discharges had not the investigated corresponding upslope area in the study, but the five flow discharges are bound to happen in the real situation. In fact, the same upslope drainage area may correspond different unit width flow discharges due to the different length or width of catchment area.**

$$RI = \frac{5.09N^{0.379}}{(t+1.4)^{0.74}} \quad (1)$$

where RI is the average rainfall intensity during t minutes, mm min^{-1}; N is the recurrence period of rainstorm, yr; and t is the rainfall duration, min.

$$q = \frac{60\alpha \cdot A \cdot RI \cdot w}{W} \quad (2)$$

where w is the plot width, m; and α is the runoff coefficient of bare land and is identified as 0.167 by analyzing the runoff and rainfall data of standard runoff plots (Li et al., 2006).

Q12. 8- Lines 241-241. Error in X-Y dimension or in Z dimension? Please clarify.

Response: We are so sorry for the unclear expression. We will revise the sentence as "The root mean square errors for the altitudes (Z axis) of the target points are 0.0037, 0.0045, 0.0024, 0.0052 and 0.0030 m on average, respectively,".

Q13. 9- Discussion on soil losses. A mention of the sediment concentration measured in the upstream and flume outlet might be quite helpful to understand the erosion/deposition processes.

Response: We are particularly grateful to you for your valuable suggestions on the revision of our manuscript. As you mentioned, we indeed measured/calculated the sediment concentration of upstream area and flume outlet. The sediment concentration of upstream area and flume outlet was showed as following figures (Fig. 4) under different flow discharge conditions. In fact, the sediment concentration of flume outlet can reflect the erosion process of the "upstream area - gully head – gully bed" system. Compared with the soil loss process of the upstream area and the system (Figure 11a, 11b), we found the change in sediment concentration with time is consistent with the temporal change of soil loss rate. Moreover, in Figure 11, we exhibited the soil loss/deposition process of three landform units as well as the "upstream area - gully head – gully bed" system, which can reflect the erosion/deposition process of each landform unit.

We also think the mention of sediment concentration is worth adding. However, given this similar change trend between soil loss process and sediment concentration process, we carefully considered and decided not to add it in the results section. Of course, We respect the suggestions of reviewers very much, and thus, we will add some related discussion in Discussion section about soil losses.

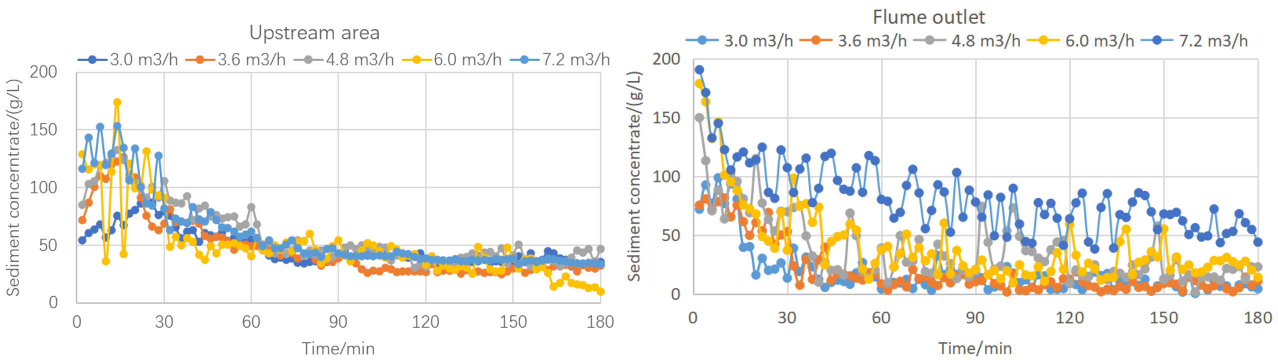

Fig. 4 Temporal change in sediment concentration of upstream area and flume outlet

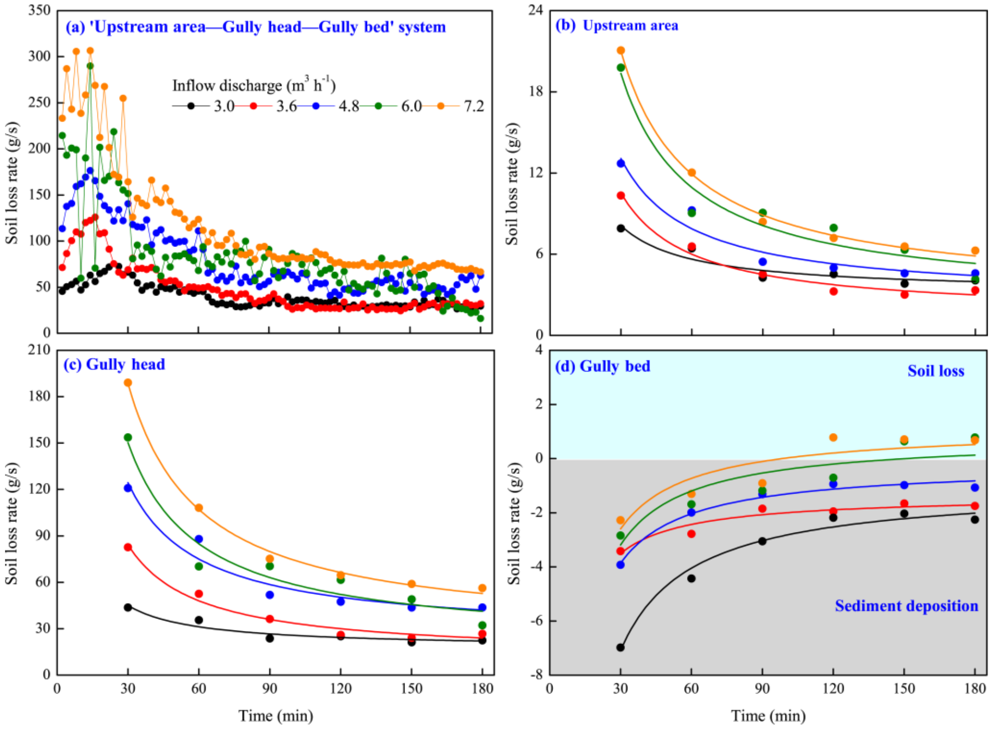

Figure 11 (original MS)