Point-by-point response to Interactive comment on “Sediment trap efficiency of paddy fields at the watershed scale in a mountainous catchment in Northwest Vietnam” by J. I. F. Slaets et al.

Original comments in italic
Responses in non-italic

Anonymous Referee #1

Received and published: 19 January 2016

General Comment
The manuscript deals with sediment fluxes and budgets of paddy rice areas at watershed scale which are not studied enough in the mountainous southeast Asia and published much in the literatures. And the paper has significant contribution on how to track the type sediment texture in the landscape. It is based on primary field data with appropriate analysis procedure to achieve the objective of the paper. The data in this paper are carefully collected, well described, analyzed and interpreted accordingly. The measurement points are also professionally selected and used to identify the influence of each part of the sub-watershed. It is also written in simple language to understand easily and I found it very good. Here under I put comments by each section that may improve the paper readability.
One of my general comment on the manuscript is the assumption of Hortonian overland flow from the contributing upland area to the paddy fields. On what bases are these assumption is made?

We thank Referee 1 for his expressed appreciation of the manuscript. The open-channel irrigation systems are adjacent to paddy fields on one bank, and upland area on the other bank. Slopes are steep and fast draining while rainfall intensities are high. The infiltration rate is frequently exceeded. Furthermore, the irrigation channels are not located in valley bottoms that are saturated, but rather at the footslope of the hills. Additionally, the groundwater level in the paddy fields is still significantly lower than the plough layer due to the topography (see picture) and soil profiles are not fully saturated, as paddy fields drain several metres above the bed of the river.

Specific comment:

Introduction
Page 20438 line 24: is it Bray, 1996 or 1994?
Thanks for catching this! The correct reference is “Bray F. 1986. The rice economies: technology and development in Asian societies. London, (UK): B. Blackwell” and the manuscript has been updated to reflect this.

Page 20438 line 26: Put Dobermann, 1998 in the reference list.
The reference “Dobermann, A., Cassman, K., Mamaril, C., Sheehy, J., 1998. Management of phosphorus, potassium, and sulfur in intensive, irrigated lowland rice. Field Crops Research, 56(1): 113-138.” has been added to the reference list.

Page 20439 Line 19 and 20: There may be a disagreement between the sentences “paddy systems have located in the valleys” and “60% paddy cultivation is located in such hilly areas”.
The manuscript has been updated to “In Northern Vietnam, 60% of paddy cultivation is located in valleys of such hilly areas, on terraces that form cascades (Rutten et al., 2014).”

Page 20439 Line 21: what does it mean traditional shifting cultivation system? you may need to define some of the terms in your manuscript for those readers outside of Southeast Asia.

The manuscript has been adjusted to clarify this point: “In shifting cultivation systems, forest plots are cleared and burned followed by cultivation of subsistence crops. Cultivation lasts for one to three seasons, after which the plots are left fallowed for a prolonged time (often a minimum of six times the cropping duration (Ziegler *et al.*, 2009)).”

Page 20439 Line 28: The erosion in the study area is too much with 174 ton per ha. What is the texture of the soil on the agricultural fields?
These are field scale measurements in bounded plots, which explains the high estimates, and this has been clarified: “In our study area, maize and maize-cassava intercropping on steep slopes with clay topsoil texture resulted in plot-level erosion rates in bounded plots of up to 174 Mg ha^{-1} a^{-1} (Tuan et al., 2014).”

Materials and Method
The material and method section need to be clear about the number of samples collected for each analysis. In the result section, you reported the number of data without telling in this section those quantities.
Sample size for discharge and sediment concentration were shown in Table 1 for each monitoring location, which has been clarified in the Material and Methods: “Discharge and sediment concentration were monitored at five different locations in the catchment (Figure 1, Figure S1 and Table 1).”

Page 20442 Line 23- 27: During a manual water sampling, do you have a specific time interval you followed during the rainfall event? every 10, 20, 30 minutes?
The variation in sampling interval was clarified in the Material and Methods: “The sampling interval depended on the hydrograph. During rapid changes in turbidity of the stream, samples were taken more frequently (up to two minutes apart) than at the end of the falling limb (up to 15 minutes apart).”

why you want to take two 500ml bottles?
The second bottle was in the frame of a study looking at nutrient transport in the same system, and has now been removed from this manuscript.

Page 20444 Line 19: why the assumption of irrigated discharge to the paddy fields are the same before and after the rain? While there is rain, the amount of irrigated discharge from reservoir should be less?
Storms are often short-lived and unpredictable in this tropical mountainous catchment, and experience in the field showed that irrigation management was typically not adjusted during the short duration of rainfall events, leading to the assumption in the flow component separation that the reservoir discharge remained constant to the pre-event amount (Schmitter *et al.*, 2012). We have clarified that this specifically refers to reservoir outflow remaining constant within-event compared to pre-event, and does not refer to periods of rain versus dry spells: “Assuming that the irrigated discharge to the paddy fields prior to the onset of the a particular rainfall event remained constant during the duration of that specific rainfall event, Q_{of} can be calculated using Equation 2.”

Page 20444: what is the computation time interval for equation 1 and 2? daily? or what time scale?
Thanks for bringing up this point, the flow component separation was done at the same temporal resolution as the discharge and sediment concentration time series, hence Equation 1 and 2 are at the two-minute time scale, which has been added to that section.

Page 20446: is equation 6 used to estimate the sediment load from overland flow? If this is the case, please say it within the section.
Yes, Equation 6 is indeed used to estimate the load from overland flow: “…with each load in the L_{in}, L_{irr} and L_{out} sediment balance in Equation 6 computed using Equation 5. The sediment load from direct runoff during rainfall is then estimated from Equation 6.”

Page 20447: I am not clear about sources of sediment samples for the texture analysis mentioned in section 2.6? and how they are sampled?
Texture analysis was performed on the sediment obtained from a selected subset of the water samples collected for sediment concentration analysis. After gravimetrically determining sediment weight for the concentration, the sediment was then additionally analysed with mid-infrared spectroscopy. Samples in the subset were selected to cover the full range of seasons and flow regimes. "From the samples collected for sediment concentration analysis, the sediments of total of 152 samples were selected to cover analyzed for texture, covering the full range of locations, seasons and flow regimes, and analyzed for texture."

Page 20447: It is better to write the long forms of the acronyms QUANT2 and OPUS in addition to their short forms.
The terms refer to the name of the software (Opus) and the analytical package within the software used (Quant2), and are not abbreviations of long forms, therefore we have switched to the notation Opus and Quant2 to avoid confusion.

Results

Page 20448 line 10: why irrigation pattern difference if you assume the irrigation discharge is the same before and after rain? On page 20444 line 19, you assume the same discharge.
The assumption of reservoir outflow remaining constant (p20444, line 19) refers to individual rainfall events, during which the discharge is assumed not to be changed by the irrigation manager in the short duration of the event. The irrigation pattern difference is referring to seasonal changes in amounts irrigated, where less water is available during spring when the reservoir has not yet been replenished by rains, and differences between years, where a late onset of the rains in 2011 resulted in reduced water availability in the first half of the year. We have clarified the section to reflect this: "The lower amount of precipitation in the spring of 2011 resulted in a lower amount irrigated during that period se differences in rainfall pattern led to differences in irrigation patterns between the two years (Figure 2)."

Discussion Page 20 line 2: mention USDA, 2012 in the reference list.
Thank you for pointing this out, this reference has been corrected to "Schertz, D. L.: The basis for soil loss tolerances, Journal of Soil and Water Conservation, 38, 10-14, 1983."

Page 22 line 11: is it Keil et al., 2009 or 2008; different in citation and in reference.
Thank you for pointing this out, the correct reference was 2008.

Page 22 line 13: is it Dung et al., 2008 or 2009; different in citation and in reference.
Thank you for pointing this out, the following reference was added to the reference list: "Dung, N. V., Vien, T. D., Lam, N. T., Tuong, T. M., and Cadisch, G.: Analysis of the sustainability within the composite swidden agroecosystem in northern Vietnam. 1. Partial nutrient balances and recovery times of upland fields, Agriculture, Ecosystems and Environment, 128, 37-51, 2008."

Tables
Table 1: It would be better to show the eqns (for stage-discharge and suspended sediment concentration) than simply showing the n and R2 value
As a linear mixed model was used for the sediment concentration, which is explained in detail and parameter estimates for model coefficients are shown in Slaets *et al.* (2014), we prefer to not repeat them here as estimates for a mixed model involve an autocorrelation parameter and a residual error additional to the fixed effects, which we believe would drive away the focus of the reader in this applied paper. Instead, we refer the reader to the methodological paper: "Details on the linear mixed model development can be found in Slaets *et al.* (2014)."

Table 2: How did you determine the texture of sediment from overland flow?
Thank you for raising this point. As sediment concentrations during rainfall events were several orders of magnitude higher than those from irrigation water, the textural distribution of sediment during rainfall events was determined to be driven by the erosion fraction, and thus sediment texture from overland flow was equated to sediment texture from samples taken during storm events at the end of the channel.

Table 3 and 4: Balance are not ok for some columns because of may be digits
This is a good point. The reason some columns do not sum up exactly in Table 3, is because we use bootstrap medians rather than direct estimates of differences, in order to remove bias. This has been clarified in the table caption: "Loads are estimated as the median of the bootstrap estimates (Med) and therefore do not always sum up exactly within columns,, and 95% confidence intervals are shown (LL=lower limit, UL=upper limit) in Mg per year." Two rounding errors in Table 4 have been corrected.

Figures
Figure 2: the x-axis legend is missing.
The legend "Cropping season" has been added to the X-axis.

Figure 2 and Figure 5: the y-axis for flows should be in mm so that one can compare with the rainfall measurements. and what is the negative axis is telling?
The negative loads refer to water exported from the catchment via the irrigation channel, which has been added to the figure captions: "Total discharge from the reservoir irrigated to the 13 ha paddy area draining between Locations A and B in the river, and (negative on the Y-axis) total discharge exported from the sub-watershed via the irrigation channel at Location 3, per rice crop (spring, summer) per year, and amount of rainfall per rice crop per year."
To convert from cubic metres to millimetres, we would have to divide by an area, and the question is which area to choose. The surface of the reservoir, on which the rain falls? The area of the paddies, to which the irrigation water goes? In order to avoid this issue, we opt to leave the amounts in a pure volume measure, so interpretation is relevant for reservoir replenishment, rice irrigation and watershed losses.

Anonymous Referee #3

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The present article "Sediment trap efficiency of paddy fields at the watershed scale in a mountainous catchment in Northwest Vietnam" investigates a major issue in soil conservation (soil erosion and sedimentation) with key implications for soil fertility and food security in high land tropical ecosystems (loss of fine soil particles in the uplands, siltation in the low lands). This paper is well illustrated and well written.

Despite that I found it did not acknowledge the existing literature on the subject (impact of land use change on soil erosion in the uplands of South-East Asia with numerous papers such as by Ingram et al. 1996; Gafur et al. 2003; Chaplot et al. 2007; : : :: : :: : :: : :: : :: : :.) and on sedimentation in basins (Gafur et al. 2003, Lapon, 2010, Chaplot and Poesen, 2012; Schmitter et al. 2012, Nunkaew, 2012,: : :: : :: : :: : :: : :..: : :)

We thank reviewer #3 for his interest in our research question. We have added an additional selection of literature relating land use change, soil erosion and scaling effects in sedimentation to the introduction.

and faces a major flaw (continuous inputs of sediments occur in irrigation canals from dam to paddy field outlet which are not considered.

The irrigation channel is fed by the surface reservoir via an outlet in the dam, and the amount of sediments that leave the surface reservoir were quantified by measurement location 1, and this sediment concentration was the same that entered the paddies as in a concrete lined fast-flowing channel, during no-rain there are no additional inputs or losses. Additional sediment inputs from upland area adjacent to the channel was quantified as the load difference between measurement location 1 and measurement location 2. The channel effectively isolates the paddies from surrounding areas, as the entire rice area is separated from upland fields by the channel. There are no additional inputs to the paddy area that do not pass the irrigation channel system first. The dam does trap sediments, but we are measuring past the dam outflow and therefore these processes do not affect the paddy area nor our experimental setup: as the spillover flows into the river, there is no direct dam overflow to the paddies.

The authors made other methodological choices which are very difficult to defend such as the use of MIRS for evaluating sediment texture for 100 samples and Laser, an broadly accepted and accurate methods for 50 samples, while all the 150 samples could have been analyzed by laser and the whole paragraphs dedicated to MIRS modeling could have been deleted.

Texture analysis with conventional methods typically requires a minimum of one gram of sample. Collecting this amount can be unpractical when the sediment is obtained from water samples which have a very low sediment concentration. The base-flow sediment concentrations in this study fluctuated around 250 mg L-1, which would mean that samples of approximately 4 L would have to be collected, transported, refrigerated for storage and analysed in order to have enough material for conventional analysis, which was deemed not feasible given the large dataset collected. Diffuse reflectance Fourier transform mid-infrared spectroscopy (MIRS) is a practical alternative to determine particle size distribution on sediment samples, as only 25 mg is needed for analysis and the measurement is not destructive (Cobo et al., 2010; Demyan et al., Schmitter et al., 2010, Towett et al., 2015). The MIRS method was calibrated and validated with the laser diffraction, which is as reviewer #3 points out a broadly accepted and accurate method, but in order to have enough material for samples at low concentrations, up to ten base-flow samples needed to be bulked. It was not feasible to obtain this many samples at each time point of the sampling campaign where concentrations were low, and additionally bulking results in a loss of temporal information which is undesirable.

We have clarified the need for MIRS with regard to available material and required sampling volume in the material and methods section: “Texture analysis with conventional methods typically requires a minimum of one gram of sample. Collecting this amount can be unpractical when the sediment is obtained from water samples which have a very low sediment concentration. The base-flow sediment concentrations in this study fluctuated around 250 mg L-1, which would mean that samples of approximately 4 L would have to be collected, transported, refrigerated for storage and analyzed. Diffuse reflectance Fourier transform mid-infrared spectroscopy (MIRS) is a practical alternative to conventional methods for determining particle size distribution on sediment samples, as only 25 mg is needed for analysis and the measurement is not destructive (Schmitter et al., 2010).”

All of this gives the impression that the authors put more emphasis on the tool they had at their disposal, going in different directions (why a sediment prediction part in this paper?)

The sediment concentration predictions in p20443, Line 6 are statistical predictions in the sense of predicted values of the response variable (sediment concentration) based on the predictor variables (turbidity and discharge). In other words, we are continuously estimating sediment loads using turbidity and discharge as a proxy, while simultaneously analysing the uncertainty introduced by using that method. The predictions provide us with an estimate of the sediment concentration every two minutes of the two year study period, which allows the estimation of the annual sediment load. These predictions as such are therefore not predictions in the future, but rather interpolations within the monitored period. This terminology was clarified in the manuscript: “Continuous statistical predictions of sediment concentration for the two year study period (temporal resolution of two minutes) were then obtained from a linear mixed model (Slaets et al., 2014), which is a regression-type model with SSC as response variable and turbidity, discharge and cumulative rainfall as predictor variables.”

while they lacked setting up a proper experimental scheme.

We are not certain what the reviewer means with ‘lacked setting up a proper experimental scheme’. As mentioned by reviewer one and addressed in an earlier comment of this reviewer, each of the potential sediment entering and exiting points was measured using field validated and published measurement strategies for both water quantity and quality. Based on these measurements, the SSC function was developed in order to calculate loads with a higher accuracy while aiming at minimizing laboratory costs. Additionally the paper discusses the potential sources of uncertainty and their effect on the overall load estimates.

Below are some additional comments:

Page 4 line 5 : “Implications of these land use changes have been studied in detail on the upland fields, and the increased erosion due to these changes are well documented.” A proper literature review on these aspects should be performed

We have added additional references to the section on erosion and sedimentation affected by land use change, as suggested: “In shifting cultivation systems, forest plots are cleared and burned followed by cultivation of subsistence crops. Cultivation lasts for one to three seasons, after which the plots are left fallowed for a minimum of six times the cropping duration (Ziegler *et al.*, 2009). Traditional shifting cultivation systems are very extensive in space and time, generating very limited runoff and erosion at the watershed scale (Ziegler *et al.*, 2009). Gafur *et al.* (2003) reported soil losses amounting to 30 Mg ha^{-1} a^{-1} for an upland area with shifting cultivations, while the regional average sediment yield was 1.2 Mg ha^{-1} a^{-1}, as 43% of soil loss from upland areas was captured by filtering elements in the lower area of the watershed. Chaplot and Poesen (2012) similarly found large sediment accumulations downslope in a slash and burn system in Southeast Asia, pointing towards the lower impact of the land use at the watershed scale. In recent years, under the influence of market mechanisms and population pressure, the traditional shifting cultivation systems on the slopes have been replaced by permanent upland cultivation (Ziegler *et al.*, 2009). Implications of these land use changes have been studied in detail on the upland fields, and the increased erosion due to these changes are well documented. Chaplot *et al.* (2007) found water erosion rates of 6 to 24 Mg ha^{-1} a^{-1} in an intensifying slash and burn system in Northern Laos. Lacombe *et al*. (2015) determined that conversion of fallow into teak plantation versus forest communities has opposite effects on catchment hydrology. Infiltration increased and runoff decreased for the forest communities, while the opposite was true for the teak conversion, illustrating the effects of disappearing fallow depend strongly upon the replacing vegetation."

P 7 from line 10: how many samples, when, what calibration/validation procedure for the turbiditimeter?

The number of samples for each location is given in Table 1, which was clarified in the corresponding section: "Total sample sizes for each location are shown in Table 1." The relationship between sediment concentration and predictor variables turbidity, discharge and cumulative rainfall (the field calibration) was established using a linear mixed model, which is a regression-type model that can take into account the serial correlation between the within-storm samples. The validation was performed with five-fold cross validation. The manuscript was updated to re-emphasize this: "Field calibration of the sensors resulted in continuous statistical predictions of sediment concentration for the two year study period (temporal resolution of two minutes) which were obtained from a linear mixed model (Slaets et al., 2014). The linear mixed model is a regression-type model with SSC as response variable and turbidity, discharge and cumulative rainfall as predictor variables. … The models were validated with five-fold cross validation using a SAS macro described in Slaets et al. (2014)."

Why "and then 16 siphoning off the supernatant followed by ovendrying of the sediment at 35_C." ? does not seem standard procedure! Should have been 100_C

This study was part of a larger project where reallocation of organic carbon and nitrogen via sediment transport to irrigation systems was also studied. As oven drying over 40°C would render the samples purposeless for those analyses, the choice was made to dry all samples at 35°C until sample weight remained constant. This clarification was added to the methodology: "Sediment concentration in the samples was determined gravimetrically (ASTM, 2013) as recommended for samples with very high Suspended Sediment Concentration (SSC), by letting the sediment settle overnight in cold storage (<4°C) and then siphoning off the supernatant followed by oven-drying of the sediment at 35°C until the sample weight remained constant."

Why "Continuous predictions of sediment concentration were then obtained from a linear mixed 18 model (Slaets et al., 2014) with SSC as response variable and turbidity"? Prediction for what purpose?

The sediment concentration predictions here refer to statistical predictions, as in predicted values for the response variable (sediment concentration) based on the continuously measured (every two minutes) predictor variables turbidity and discharge. They are therefore not future concentration predictions, but rather interpolations to obtain estimated sediment concentrations for each time point of the two year study period based on a regression type model (the linear mixed model). This terminology was clarified in the manuscript: "Field calibration of the sensors resulted in continuous statistical predictions of sediment concentration for the two year study period (temporal resolution of two minutes) which were obtained from a linear mixed model (Slaets et al., 2014). The linear mixed model is a regression-type model with SSC as response variable and turbidity, discharge and cumulative rainfall as predictor variables."

Same for "To account for temporal correlation in the observations, an error with a first-order autoregressive covariance structure was fitted to the data. The response variable was log-transformed to stabilize the variance, as were the predictor variables discharge and turbidity. Model fit was evaluated with five-fold cross validation using a SAS macro described in Slaets et al. (2014)."

As the storm-based sampling strategy resulted in samples taken very closely together in time, a normal sediment rating curve, which is a linear regression model that assumes independent observations, is not a suitable approach. Samples taken closely together in time are autocorrelated, and we took this into account by fitting a first-order autoregressive structure to the residual error, which allows an observation to be correlated to the previous sample.
Similarly, linear models assume constant variance, while in sediment data the variability typically increases with increasing sediment concentration. The purpose of the log-transformation was to take this into account.
Five-fold cross validation was used as a tool to validate the performance of the statistical model of the sediment concentrations.
This has been clarified as follows: "As the storm-based approach resulted in samples taken at very short consecutive time intervals (i.e. 2 min), the assumption required for a traditional sediment rating curve of independence of errors was not fulfilled in this dataset. Similarly, we found the variance to increase with increasing sediment concentration, violating the assumption of homoscedasticity. To account for temporal correlation in the observations, an error with a first-order autoregressive covariance structure was fitted to the data. The response variable was log-transformed to stabilize the variance, as were the predictor variables discharge and turbidity. The models were validated with five-fold cross validation using a SAS macro described in Slaets et al. (2014)."

"2.4 Separating sediment sources" was not introduced There are different sources of water and sediments in the catchment as exposed by authors "ponds in the paddy area. The river receives outflow from both banks of paddy fields, and we only monitored the overland flow entering the right bank. Therefore, in order to quantify the net sediment balance for the paddy fields, the assumption is made that the upland fields on the left bank of the river generated the same amount of erosion as those on the right bank,"
There are only two sources of sediment inputs to the paddy area: sediments in irrigation water from the surface reservoir, and overland flow which enters the paddies via the channel. Our choice of monitoring locations enabled us to separate these two sources by the same flow component separation published by Schmitter et al (2012): the measurement location in the channel just below the reservoir quantified sediment outflow whereas the measurement location at the point where the channel exits the channel allows to calculate the load entering the both paddy banks.
Inputs from overland flow to the right bank of paddies could be calculated as the difference between location 1 (just downstream of the reservoir) and location 2 (channel watershed exit) during rainfall. As the land use, slopes and area of the upland area on both banks is very similar in our study area, hence our assumption of similar inputs from overland flow to both banks of the paddy area.
Paddy outflow was calculated as the difference between the two river locations (one upstream, one downstream of the paddy area). There is a very small percentage of the paddy area which is actually fish ponds (<1%) and therefore indeed, some part of the sediment outflow into the river may also originate from these ponds. The outputs are thus combined lowland activities of paddy and pond systems rather than solely rice fields. Local knowledge shows that often, ponds are kept closed with no in-and outflow, and this in combination with their much smaller area leads us to attribute the paddy hydrology as the driving force of sediment redistribution in that area. Furthermore, paddy and pond sediments originate from the same source (surrounding upland area) and therefore consist both of the same quality and texture of material. While ponds are deeper, they are kept full so they have low buffering capacity, and therefore freeboard volume as well as overflow are very similar for ponds and paddies.
The manuscript has been updated to reflect these clarifications: "There are only two sources of sediment inputs to the paddy area: sediments in irrigation water from the surface reservoir, and overland flow which enters the paddies via the channel. The paddies are isolated from surrounding uplands by the channel, and no overland flow enters the paddies without passing through the irrigation channel (Figure 1). The monitoring locations in the concrete irrigation channel were chosen in order to separate these contributions of irrigation water from the surface reservoir, and Hortonian overland flow, to the paddy fields. The station situated furthest upstream in the channel (Location 1 in Figure 1) was placed directly below the reservoir outlet, and thus monitored the discharge and water quality of

the surface reservoir, which equals the sediment concentration of paddy inflow when it is not raining. … Thus, sediment inputs from reservoir outflow to both banks of the paddy area could be quantified."

2.6 Sediment texture with mid-infrared spectroscopy ?
"As the MIRS method requires a subset of the samples to be analyzed with conventional wet analytical methods for calibration and validation, laser diffraction with a Coulter LS 200 (Beckman Coulter, Germany) was performed on 50 samples." Laser diffraction also needs to be calibrated. Can understand why using MIRS when laser available. Lots of work for so little samples: "Sand, silt and clay were predicted from the spectral data using Partial Least Squares Regression (PLSR; Wold, 1966). All spectral manipulation and model selection was performed using QUANT2 package within software OPUS 7.0 (Bruker Optik, Germany). Models were evaluated with leave-one-out cross validation. OPUS offers several spectral processing techniques to enhance spectral information and reduce noise. The selection of the most suitable method can be automatized using the OPTIMIZATION function, which selects the method resulting in the highest r2 of observed versus predicted values after cross- validation. For sand, the pre-processing method was the calculation of the second derivative of the spectra, which can help to emphasize pronounced but small features over a broad background. After validation, an r2 of 0.81 was obtained. For silt, multiplicative scattering correction was applied, which performs a linear transformation of each spectrum for it to best match the mean spectrum of the whole set, and the model resulted in an r2 of 0.83. For clay, no satisfactory model could be obtained, and so the clay percentage was calculated as the remaining amount of sediment after subtracting the sand and silt fractions."
The choice for MIRS was driven by the amount of material available per sediment sample. Most conventional methods including laser diffraction require a minimum of one gram of soil or sediment. For our concentration range in the water samples, which fluctuated around 250 mg L-1, samples of approximately 4 L would have to be collected, transported, refrigerated for storage and analysed in order to have enough material for conventional analysis, which was deemed not feasible given the large dataset collected. Diffuse reflectance Fourier transform mid-infrared spectroscopy (MIRS) is a practical alternative to determine particle size distribution on sediment samples, as only 25 mg is needed for analysis and the measurement is not destructive (Schmitter et al., 2010). The MIRS method was calibrated and validated with the laser diffraction, which is as reviewer #3 points out a broadly accepted and accurate method, but in order to have enough material for laser diffraction analysis at low concentrations, up to ten base-flow samples needed to be bulked, and it was not feasible to obtain this many samples at each time point of the sampling campaign where concentrations were low.
We have clarified the need for MIRS with regard to available material and required sampling volume in the material and methods section: "Texture analysis with conventional methods typically requires a minimum of one gram of sample. Collecting this amount can be unpractical when the sediment is obtained from water samples which have a very low sediment concentration. The base-flow sediment concentrations in this study fluctuated around 250 mg L-1, which would mean that samples of approximately 4 L would have to be collected, transported, refrigerated for storage and analyzed. Diffuse reflectance Fourier transform mid-infrared spectroscopy (MIRS) is a practical alternative to conventional methods for determining particle size distribution on sediment samples, as only 25 mg is needed for analysis and the measurement is not destructive (Schmitter et al., 2010)."

Table 1: 6 of water flux observations only? "Table 1: Number of observations (n), coefficient of determination (R2) and method used for stage-discharge relationship (Q); and number of observations and Pearson's correlation coefficient (r2) after five-fold cross-validation for suspended sediment concentration predictions (SSC)."
How were 6 data points used to estimate yearly loads?

These are the number of observations obtained to establish the stage-discharge rating curve which allowed calculating loads from the concentration data. As the channel is concrete lined with a fixed cross section and slope, and the salt dilution method was used, very few observations are required to obtain a reliable discharge rating curve, as can be seen from the resulting R^2 which ranged from 0.96 to 0.99 for the channel locations. It is not the case for this study that loads were calculated based on load measurements at certain time points which were then integrated over the monitoring period, in which case six load measurements would be an inadequate sample size. Rather, we used the continuous discharge and sediment concentration data to obtain instantaneous loads at each measurement time point of the water level and turbidity sensors (which was every two minutes). As the discharge rating curve is highly accurate, sampling strategies in such a program focus on the sediment concentration dataset, which has a much higher uncertainty as can be seen from Table 1.

Table 3: "Sediment inputs from irrigation water and overland flow from the 37 ha upland area 1 in the sub-watershed, and sediment export and trapping by the 13 ha paddy area (Figures 1 2 and S1). Loads are estimated as the median of the bootstrap estimates (Med), and 95% 3 confidence intervals are shown (LL=lower limit, UL=upper limit) in Mg per year. 4 Sediment load (Mg a-1)" What is Mg a-1 ?

The unit of this table is Megagrams (or tons) per year (a^{-1}), the abbreviation has been specified in the figure caption: "Loads are estimated as the median of the bootstrap estimates (Med) and therefore do not always sum up exactly within columns, and 95% confidence intervals are shown (LL=lower limit, UL=upper limit) in Mg per year (Mg a^{-1})."

Where is dam? How can sediments not be settled in dam? Sediments obviously come from slope nearby paddy fields, how to discriminate between the two origins?

"Figure 1: Sediment sources and water flows into and out of paddy rice fields in Chieng Khoi watershed. The dotted yellow arrows show the 3 irrigation channel leaving the reservoir and splitting in two, feeding the two banks of paddy rice. The rice fields subsequently drain into the river"

The dam creates the surface reservoir that feeds the irrigation channel, and is thus located upstream of channel, river and paddy area. We have added the location of the dam to Figure 1. The dam does trap sediment, but these inputs originate from the 490 ha contributing area of the reservoir which does not contain paddies. Part of the sediments is trapped in the reservoir, and part is released to the paddies, the latter being what we monitor at Location 1. The component of overland flow that directly enters the paddies via the irrigation system is the contributing upland area between Locations 1 and 2. This contribution is what we quantify with the flow component separation and differences between the sediment loads at Locations 1 and 2.

How many data points to generate: Figure 2: Total discharge from the reservoir irrigated to the 13 ha paddy area draining between Locations A and B in the river, and total discharge exported from the sub-watershed via the irrigation channel at Location 3, per rice crop (spring, summer) per year, and amount 4 of rainfall per rice crop per year.

Total reservoir discharge inputs to the paddy area are calculated as the difference during base-flow conditions between Locations 1 and 2 (upstream and downstream of the paddies in the channel). The discharge is based on water height measurements with automatic pressure sensors which register the data every two minutes, and the establishment of a discharge rating curve with the salt dilution method for each location with the number of stage-velocity measurements indicated in Table 1. As the concrete lined channel has a fixed cross section and slope, a small number of stage-velocity measurements suffices to obtain highly accurate stage-discharge rating curves, as is evidenced by the resulting R^2 values in Table 1.

References

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Sediment trap efficiency of paddy fields at the watershed scale in a mountainous catchment in Northwest Vietnam

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Abstract

Composite agricultural systems with permanent maize cultivation in the uplands and irrigated rice in the valleys are very common in mountainous Southeast Asia. The soil loss and fertility decline of the upland fields is well documented, but little is known about reallocation of these sediments within the landscape. In this study, a turbidity-based linear mixed model was used to quantify sediment inputs, from surface reservoir irrigation water and from direct overland flow, into a paddy area of 13 hectares. Simultaneously, the sediment load exported from the rice fields was determined. Mid-infrared spectroscopy was applied to analyze sediment particle size. Our results showed that per year, 64 Mg ha^{-1} of sediments were imported into paddy fields, of which around 75% were delivered by irrigation water and the remainder by direct overland flow during rainfall events. Overland flow contributed one third of the received sandy fraction, while irrigated sediments were predominantly silty. Overall, rice fields were a net sink for sediments, trapping 28 Mg ha^{-1} a^{-1} or almost half of total sediment inputs. As paddy outflow consisted almost exclusively of silt- and clay-sized material, 24 Mg ha^{-1} a^{-1} of the trapped amount of sediment was estimated to be sandy. Under continued intensive upland maize cultivation, such a sustained input of coarse material could jeopardize paddy soil fertility, puddling capacity and ultimately also food security of the inhabitants of these mountainous areas. Preventing direct overland flow from entering the paddy fields, however, could reduce sand inputs by up to 34%.

Key words

Sediment budget, sediment particle size distribution, sediment yield, maize, ~~paddy~~ irrigated rice, composite swiddening

1. Introduction

Paddy cultivation is one of the most long-term sustainable cropping systems, as irrigated rice is the only major crop cultivated in monoculture for centuries without severe soil degradation (Bray, 1986; Uexkuell and Beaton, 1992). Two mechanisms facilitate this continuing productivity: first, flooding applies suspended particles and soluble nutrients to the fields that contribute to the indigenous nutrient supply (Dobermann, 1998; Schmitter *et al*., 2011). Second, puddling creates an environment of high input and low breakdown of organic matter (Cao *et al.*, 2006; Gong *et al.*, 2007; Huang *et al.*, 2015). As nutrient content of sediments is closely related to sediment particle size, and puddling is favored by high clay content (De Datta, 1981), the potential for long-term sustainable rice production is related to the soil texture in paddy fields.

Irrigated paddy fields, however, are not isolated elements in a landscape, as they are connected to surrounding upland areas. They receive sediments from those upland areas, both directly through overland flow, and indirectly from irrigation water released through surface reservoirs (Schmitter *et al*., 2012). These processes bring sediments into the rice fields, which can alter paddy soil texture (Schmitter *et al*., 2011). The vast majority of paddy fields in Vietnam are subject to these processes: 97% of Vietnamese rice is irrigated, and the main water source for irrigated rice in Southeast Asia is water from surface reservoirs (FAO Aquastat, 2014). Therefore, most paddy areas receive sediment-conveying irrigation water.

The amount and nature of sediments in irrigation water depends on their source, i.e. the upland fields surrounding both the paddy fields and the surface reservoirs. Traditionally, in the mountainous regions of Northern Vietnam, Thailand and Laos as well as Southern China, paddy systems have been located in the valleys, surrounded by shifting cultivation on the hills. In Northern Vietnam, 60% of paddy cultivation is located in valleys of such hilly areas, on terraces that form cascades (Rutten *et al*., 2014).

In shifting cultivation systems, forest plots are cleared and burned followed by cultivation of subsistence crops. Cultivation lasts for one to three seasons, after which the plots are left fallowed for a prolonged time to recover soil fertility (often a minimum of six times the cropping duration (Ziegler *et al.*, 2009)). Traditional shifting cultivation systems are very extensive in space and time, generating very limited runoff and erosion at the watershed scale (Ziegler *et al.*, 2009). Gafur *et al.* (2003) reported soil losses amounting to 30 Mg ha^{-1} a^{-1} for an upland area with shifting cultivations, while the regional average sediment yield was 1.2 Mg ha^{-1} a^{-1}, as 43% of soil loss from upland areas was captured by filtering elements in the lower area of the watershed. Chaplot and Poesen (2012) similarly found large sediment accumulations downslope in a slash and burn system in Southeast Asia, pointing towards the lower impact of the land use at the watershed scale. In recent years, under the influence of market mechanisms and population pressure, the traditional shifting cultivation systems on the slopes have been replaced by permanent upland cultivation (Ziegler *et al.*, 2009). Implications of these land use changes have been studied in detail on the upland fields, and the increased erosion due to these changes are well documented. Chaplot *et al.* (2007) found water erosion rates of 6 to 24 Mg ha^{-1} a^{-1} in an intensifying slash and burn system in Northern Laos. Lacombe *et al.* (2015) determined that conversion of fallow into teak plantation versus forest communities has opposite effects on catchment hydrology. Infiltration increased and runoff decreased for the forest communities, while the opposite was true for the teak conversion, illustrating how the effects of disappearing fallow ~~depend~~ strongly depend upon the replacing vegetation.

In our study area, maize and maize-cassava intercropping on steep slopes with clay topsoil texture resulted in plot-level erosion rates in bounded plots of up to 174 Mg ha^{-1} a^{-1} (Tuan *et al.*, 2014), ~~In our study area, maize and maize-cassava intercropping on steep slopes resulted in erosion of up to 174 Mg ha^{-1} a^{-1} (Tuan *et al.*, 2014),~~ coupled with a loss of soil organic

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matter reaching 1 Mg ha^{-1} a^{-1} (Häring *et al.*, 2014). Additionally, changes in texture occurred as fertile silt and clay fractions were exported from the upper and middle slope positions whereas sandy material was deposited at foot slope positions (Clemens *et al.*, 2010). Differences in amount and texture of eroded material from upland fields could therefore entail a shift in matter exchange between upland cultivation and valley paddy rice.

Increased erosion may therefore not only jeopardize the continued production of the cash crop maize on upland fields, but also adversely affect the long-term sustainability of the food crop production in the paddies. Schmitter *et al.* (2010) showed that soil fertility in paddy cascades varies with distance to the irrigation channel, and thus established a link between sedimentation processes and soil properties. Rüth and Lennartz (2008) and Schmitter *et al.* (2011) found that variability of paddy soil texture and yield were a function of position along the catena, related to differential settling of sediments in irrigation water. If soil properties and yield are closely linked to sedimentation processes, then changes in amount and texture of the sediment inputs have a potential effect on long-term soil fertility and crop production, and hence on food security in the area, as rice is the main staple food crop.

In order to assess these risks, there is a need for reliable data not only on the amount and texture of sediments entering the paddy fields, but also on the quantity and quality of the material exported from the paddies. Because of their terraced structure, paddies can function as a sediment filter in the landscape (Maglinao *et al.*, 2003). But few studies have assessed both inputs and exports. Dung *et al.* (2009) monitored a watershed in Northern Vietnam with shifting cultivation in the upper area of the catchment and paddy rice in the valley. Annually, for an experimental plot of 0.3 ha, between 11 and 29 Mg of sediments entered the paddies, and from this amount, 27 to 63% was trapped within the field and the remainder was exported with the runoff. The proportion that remained behind was mostly sandy, and hence altered the soil texture in the experimental paddy plots.

While these results indicate that paddy fields act mainly as a net sediment trap, their function might differ when up-scaled to a larger area as sediment deposition changes over cascade length (Schmitter *et al.*, 2010). Thus, at the watershed level, it is not clear whether paddy fields act as sediment sources or sinks. For example, Mai *et al.* (2013) found that paddies acted as a green filter, reducing runoff peaks, when their water storage capacity was not yet fully used by irrigation at the onset of the runoff event. But if the maximum storage capacity was already reached, runoff increased, as full paddies are not able to retain any water and so all overland flow was propelled through them, causing high runoff peaks at the catchment outlet.

Therefore, there is a need for a more detailed understanding of sediment fluxes and budgets in paddies at watershed-scale. Our specific aims were to (i) quantify the contribution of overland flow and irrigation water to the sediment inputs of a paddy rice area, (ii) determine if paddy fields are a net sediment source or a sink, (iii) assess the particle size distribution for the sediment input and export from paddy fields, and (iv) evaluate the potential effects of within-watershed sediment reallocation on long-term soil fertility in Chieng Khoi watershed, Northwest Vietnam.

2. Material and Methods

2.1 Study site

The study was conducted in a small agricultural watershed, located in Chieng Khoi commune, Yen Chau district, Son La province, North-West Vietnam (21°7’60’’N, 105°40’0’’E, 350 m a.s.l., Figure S1). The catchment is 200 ha in size, and sediment reallocation in a sub-catchment of 50 ha which consists of 13 ha of paddy rice and 27 ha of upland fields was monitored in greater detail. In the area, the dominant soil types are Alisols and Luvisols (Clemens *et al*., 2010) and the climate is monsoonal, with a rainy season from April till October and average annual rainfall of around 1200 mm. Land use in the watershed is characterized by maize and maize-cassava intercropping on the slopes, and irrigated rice in the valleys. The source of irrigation water is a surface reservoir that feeds a concrete irrigation channel, ensuring two rice crops per year: a spring crop from February till June, followed by a summer crop planted in July and harvested in October. The reservoir was formed by the damming of a river that originates in the karst mountains of the area. It has a capacity of 10^6 m^3 and a contributing area consisting of 490 ha of intensively cultivated upland fields and forest. The channel splits in two, just below the reservoir, and feeds two paddy rice areas (6.5 ha each), on the banks of a river that intersects the paddy fields. The irrigation water flows from the channel into the paddy fields, which drain into the river (Figure 1).

2.2 Hydrological monitoring

Discharge and sediment concentration were monitored at five different locations in the catchment (Figure 1, ~~and~~ Figure S1 and Table 1). As the irrigation management in the catchment disturbed the relationship between discharge and sediment concentration, a turbidity-based method was used to monitor the sediment concentration. Self-cleaning turbidity sensors (NEP395, McVan, Australia) were installed, with the optical eye down, in a vertically suspended pipe that could float with water level fluctuations, ensuring that the sensor remained approximately at the center point of flow.

Discharge was monitored using pressure sensors (Ecotech, Germany) and the stage-discharge relationship was established using the salt dilution method for the channel and the area-velocity method for the river (Herschy, 1995). Rainfall was measured with a tipping-bucket rain gauge (0.1 mm accuracy, Campbell Scientific, USA) in the upper part of the catchment. The water level of the lake was recorded on a daily basis.

2.3 Sediment concentration predictions

Water samples were collected manually with a storm-chasing approach, where more samples were taken when water level and turbidity were rapidly changing. The sampling interval depended on the hydrograph. During rapid changes in turbidity~~ of the stream~~, samples were taken more frequently (up to two minutes apart) than at the end of the falling limb (up to 15 minutes apart). A typical sampled rainfall event thus consisted of ten to twenty water samples, depending on the duration of the event. Additionally, base-flow samples were collected every two weeks. Total sample sizes for each location are shown in Table 1 and ranged from 71 to 327 samples. Each sample consisted of ~~two ~~a500 ml bottle~~s~~. Sediment concentration in the samples was determined gravimetrically (ASTM, 2013) as recommended for samples with very high Suspended Sediment Concentration (SSC), by letting the sediment settle overnight in cold storage (<4°C) and then siphoning off the supernatant followed by oven-drying of the sediment at 35°C until the sample weight remained constant.

~~Continuous~~Field calibration of the sensors resulted in continuous statistical predictions of sediment concentration for the two year study period (temporal resolution of two minutes) ~~were then~~which were obtained from a linear mixed model (Slaets *et al.*, 2014). The linear mixed model is a regression-type model with SSC as response variable and turbidity, discharge and cumulative rainfall as predictor variables. As the storm-based approach resulted in samples taken at very short consecutive time intervals (i.e. 2 min), the assumption required for a traditional sediment rating curve of independence of errors was not fulfilled in this dataset. Similarly, we found the variance to increase with increasing sediment concentration, violating the assumption of homoscedasticity. To account for temporal correlation in the observations, an error with a first-order autoregressive covariance structure was fitted to the data. The response variable was log-transformed to stabilize the variance, as were the predictor variables discharge and turbidity. ~~Model fit was evaluated with~~The models were validated with five-fold cross validation using a SAS macro described in Slaets *et al.* (2014).

2.4 Separating sediment sources

There are only two sources of sediment inputs to the paddy area: sediments in irrigation water from the surface reservoir, and overland flow which enters the paddies via the channel. The paddies are isolated from surrounding uplands by the channel, and no overland flow enters the paddies without passing through the irrigation channel (Figure 1). The monitoring locations in the concrete irrigation channel were chosen in order to separate these contributions of irrigation water from the surface reservoir, and Hortonian overland flow, to ~~the sediment inputs into~~ the paddy fields. The station situated furthest upstream in the channel (Location 1 in Figure 1) was placed directly below the reservoir outlet, and thus monitored the discharge and water quality of the surface reservoir, which equals the sediment concentration of paddy inflow when it is not raining. An additional station (Location 2 in Figure 1) was installed directly below the split of the concrete channel, and monitored only discharge, as the water quality here was the same as at Location 1. This second location quantified how much of the irrigation was flowing to the left arm of the irrigation channel after the split, and how much was going to the right arm. As the water in the left channel was fully irrigated to the paddy fields in this watershed, no further measurements were conducted in this branch of the channel. But the right channel leaves the watershed, exporting part of the irrigation water from the catchment. Therefore, a measurement station was installed downstream in the channel, at the point where the irrigation channel crosses into a neighboring watershed (Location 3 in Figure 1). Thus, sediment inputs from reservoir outflow to both banks of the paddy area could be quantified.

In the absence of rainfall, Location 3 received water with the same sediment concentration as the reservoir outflow (Location 1). As there were no other water sources entering the concrete-lined waterway, the hydrological balance when it is not raining can be described by

$$Q_{in} = Q_{irr} + Q_{out}, \qquad \text{(Eq. 1)}$$

where Q_{in} is the discharge measured at Location 2, consisting of the irrigation water originating from the reservoir, Q_{irr} the irrigated discharge to the paddies, and Q_{out} the discharge measured at Location 3, as not all irrigation water in the channel was used up fully in this catchment, but a part was transported further to irrigate rice in a watershed downstream. Since Q_{in} is the discharge measured at Location 2 and Q_{out} is the discharge measured at Location 3, Q_{irr} can be calculated as the difference in discharge between those two sites.

During rainfall events, Hortonian overland flow entered the channel directly from the upland fields (Figure 1), changing the water balance to

$$Q_{in} + Q_{pp} + Q_{of} = Q_{irr} + Q_{out}, \qquad \text{(Eq. 2)}$$

where Q_{pp} is the direct rainfall into the channel and Q_{of} the overland flow that enters the channel from the upland area between the upstream and downstream locations. During rainfall, Q_{pp} could be calculated directly from the rainfall intensity and the surface area of the channel. Assuming that the irrigated discharge to the paddy fields prior to the onset of ~~the~~ a particular rainfall event remained constant during the duration of that specific rainfall event, Q_{of} can be calculated using Equation 2. Flow component separation was performed with the statistical software R. Details of the procedure can be found in Schmitter *et al.* (2012).

~~The calculation of sediment loads for these sources requires that not only discharge, but also sediment concentration of each component is known. Rainfall does not contain sediment, so Q_{pp} makes no contribution to the sediment load. The sediment concentration c_{in} of Q_{in} was monitored at Location 1, and c_{out} of Q_{out} at Location 3. The irrigated discharge to the paddy fields, Q_{irr}, had the same sediment concentration as the discharge exported from the watershed at Location 3, assuming full mixing. The sediment load from overland flow can then be calculated from~~

$$L_{of} = [(Q_{irr} * c_{out}) + (Q_{out} * c_{out}) - (Q_{in} * c_{in})]. \qquad \cancel{\text{(Eq. 3)}}$$

~~In the river, the water sources are paddy outflow and reservoir overflow. The measurement stations were installed in a similar manner as they were in the irrigation channel, with one station upstream and one downstream of the paddy fields (Locations A and B in Figure 1). The only sediment input between these two locations was drainage from paddy fields and fish ponds in the paddy area. The river receives outflow from both banks of paddy fields, and we only monitored the overland flow entering the right bank. Therefore, in order to quantify the net sediment balance for the paddy fields, the assumption is made that the upland fields on the left bank of the river generated the same amount of erosion as those on the right bank, as the areas are very similar in land use, slope and size (17 and 20 hectares of contributing area).~~

~~There was one additional measurement location in the river further downstream (overall outlet, Figure S1), at the outlet of a larger watershed of 2 km^2 in which the monitored paddy area was nested, in order to assess scaling effects on paddy watershed sediment losses.~~

2.5 Sediment load estimates

Instantaneous sediment loads at a time *i* (*i*=1 to *t*) are generally estimated from the continuous discharge data and the continuous sediment concentration predictions according to

$$\hat{L}_i = \hat{Q}_i * \hat{C}_i \, , \qquad \text{(Eq. } \cancel{4}3\text{)}$$

where $\hat{L}_i$ is the estimated instantaneous load at time i in g s^{-1}, $\hat{Q}_i$ is the estimated discharge at time i in m^3 s^{-1} and $\hat{C}_i$ is the estimated concentration at time i in g m^{-3}. These concentrations for each specific location were derived from the continuous sediment predictions using the location specific SCC regression function, where ~~T~~the time series consisted of two minute intervals. As such, the estimated monthly or annual sediment load $\hat{L}_{1\,to\,t}$ in grams can be computed by summing up the instantaneous loads, across t measurement intervals of turbidity and discharge:

$$\hat{L}_{1\,to\,t} = \sum_{i=1}^{t}(\hat{L}_i * 120). \qquad \text{(Eq. ~~5~~4)}$$

Rainfall does not contain sediment, so Q_{pp} makes no contribution to the sediment load. The full sediment load balance for the irrigation channel then equals

$$L_{in} + L_{of} = L_{irr} + L_{out}, \qquad \text{(Eq. ~~6~~5)}$$

where L_{in} is the sediment load at Location 2, L_{of} is the sediment load brought into the channel by direct runoff during rainfall events, L_{irr} is the load irrigated to the paddies, and L_{out} is the sediment load exported from the channel at Location 3, with ~~each load in the~~ L_{in}, L_{irr} and L_{out} ~~sediment balance~~ in Equation ~~6~~ 5 computed using Equation ~~5~~4. The sediment load from direct runoff during rainfall is then the only remaining unknown in Equation 5: ~~The calculation of sediment loads for these sources requires that not only discharge, but also sediment concentration of each component is known. Rainfall does not contain sediment, so~~ ~~Q_{pp}~~ ~~makes no contribution to the sediment load.~~ The sediment concentration c_{in} of Q_{in} was monitored at Location 1, and c_{out} of Q_{out} at Location 3. The irrigated discharge to the paddy fields, Q_{irr}, had the same sediment concentration as the discharge exported from the watershed at Location 3, assuming full mixing. The sediment load from overland flow can then be calculated from

$$L_{of} = [(Q_{irr} * c_{out}) + (Q_{out} * c_{out}) - (Q_{in} * c_{in})]. \qquad \text{(Eq. ~~3~~6)}$$

In the river, the water sources are paddy outflow and reservoir overflow. The measurement stations were installed in a similar manner as they were in the irrigation channel, with one station upstream and one downstream of the paddy fields (Locations A and B in Figure 1). The only sediment input between these two locations was drainage from paddy fields and fish ponds in the paddy area. The river receives outflow from both banks of paddy fields, and we only monitored the overland flow entering the right bank. Therefore, in order to quantify the net sediment balance for the paddy fields, the assumption is made that the upland fields on the left bank of the river generated the same amount of erosion as those on the right bank, as the areas are very similar in land use, slope and size (17 and 20 hectares of contributing area).

There was one additional measurement location in the river further downstream (overall outlet, Figure S1), at the outlet of a larger watershed of 2 km^2 in which the monitored paddy area was nested, in order to assess scaling effects on paddy watershed sediment losses.

In order to calculate 95% confidence intervals on the sediment load, a bootstrap method was used that accounts for uncertainty in the discharge and sediment concentration predictions (Slaets *et al.*, under review; Appendix A). The number of bootstrap replicates was 2000. As the direct sediment load estimation described in Equation ~~4~~ 3 is typically biased downwards when concentration and discharge are predicted on the log-transformed scale (Ferguson, 1986), taking the medians of the bootstrap replicates is a simple approach to bias-correct the estimates (Efron and Tibshiriani, 1993). Therefore, the estimated sediment loads reported in this study are the medians of the bootstrap empirical distribution, rather than the direct estimates from Equation ~~4~~ 3 (Slaets *et al.*, under review; Appendix A).

2.6 Sediment texture with mid-infrared spectroscopy

Texture analysis with conventional methods typically requires a minimum of one gram of sample. Collecting this amount can be unpractical when the sediment is obtained from water samples which have a very low sediment concentration. The base-flow sediment concentrations in this study fluctuated around 250 mg L^{-1}, which would mean that samples of approximately 4 L would have to be collected, transported, refrigerated for storage and analyzed. Diffuse reflectance Fourier transform mid-infrared spectroscopy (MIRS) is a practical alternative to conventional methods for determining particle size distribution on sediment samples, as only 25 mg is needed for analysis and the measurement is not destructive (Schmitter *et al.*, 2010). ~~A~~ From the samples collected for sediment concentration analysis, the sediments of a total of 152 samples were selected to cover ~~analyzed for texture, covering~~ the full range of locations, seasons and flow regimes, and analyzed for texture. A Bruker Tensor-27 mid-infrared spectroscope (Bruker Optik, Germany) was used and three analytical replicates were measured per sample. Baseline correction and atmospheric compensation were performed on each spectrum before averaging the analytical replicates. As the MIRS method requires a subset of the samples to be analyzed with conventional wet analytical methods for calibration and validation, laser diffraction with a Coulter LS 200 (Beckman Coulter, Germany) was performed on 50 samples. Organic matter and carbonates were destroyed prior to laser diffraction analysis and samples were shaken overnight with a dispersing agent (5 ml 2% sodium metahexaphosphate for 5 g soil). Three analytical replicates were done per sample.

Sand, silt and clay were predicted from the spectral data using Partial Least Squares Regression (PLSR; Wold, 1966). All spectral manipulation and model selection was performed using ~~QUANT2~~ Quant2 package within the software ~~OPUS~~ Opus 7.0 (Bruker Optik, Germany). Models were evaluated with leave-one-out cross validation. ~~OPUS~~ Opus offers several spectral processing techniques to enhance spectral information and reduce noise. The selection of the most suitable method can be automatized using the ~~OPTIMIZATION~~ Optimization function, which selects the method resulting in the highest r^2 of observed versus predicted values after cross-validation. For sand, the pre-processing method was the calculation of the second derivative of the spectra, which can help to emphasize pronounced but small features over a broad background. After validation, an r^2 of 0.81 was obtained. For silt, multiplicative scattering correction was applied, which performs a linear transformation of each spectrum for it to best match the mean spectrum of the whole set, and the model resulted in an r^2 of 0.83. For clay, no satisfactory model could be obtained, and so the clay percentage was calculated as the remaining amount of sediment after subtracting the sand and silt fractions.

3. Results

3.1 Hydrological processes driving sediment flows

Model fit for the discharge rating curves varied between locations, with the coefficient of determination ranging from 0.96 to 0.99 (Table 1). As expected, accuracy of the sediment rating curves was lower than that of the discharge rating curves, and explained between 52 and 72% of variability in the data after cross-validation.

In 2010, a total of 920 mm of rainfall was measured between April and October with the onset of the rainy season in April, whereas in 2011, 961 mm fell but rains were delayed, resulting in less rainfall in April- May and a precipitation peak in July, and 780 mm of the annual rain falling between June and October. The lower amount of precipitation in the spring of 2011 resulted in a lower amount irrigated during that period ~~se differences in rainfall pattern led to differences in irrigation patterns between the two years~~ (Figure 2).

Although the total amount of water irrigated to the 13 ha of paddy fields was similar, i.e. 3 978·10^3 m^3 in 2010 and 4 021·10^3 m^3 in 2011, the seasonal distribution of the irrigated amounts varied between the study years. As the rainy season started late in 2011, there was more water irrigated during the first rice season (February-June) in 2011 (913·10^3 m^3) than in 2010 (700·10^3 m^3). The opposite was true for the summer crop (July-October), during which 1 308·10^3 m^3 was irrigated in 2011 compared with 1 448·10^3 m^3 in 2010. As the rains came late in 2011, the reservoir was not filled up yet in July at the start of the summer crop, and so there was less irrigation water available.

Variation in rainfall throughout the year was also reflected in the sediment concentration of the irrigation water. In the irrigation channel, the median sediment concentration during base-flow regime was 240 mg L^{-1}. The predicted base-flow sediment concentration fluctuated seasonally, peaking in April and May 2010 and in April, May and June 2011 (Figure 3b), and resulting in a higher median in those months, between 350 and 430 mg L^{-1}. As for sediment texture, the sand content of the sediments in the irrigation channel during base-flow regime (n=18) varied between 0 and 50% with an average of 34% over the whole study period (Table 2). The silt content ranged from 14 to 58% with an average of 34%. For clay, the minimum measured content was 0%, the maximum was 86% and the average clay content of the sediments was 32%.

The median sediment concentration in the irrigation channel during rainfall events was 1 200 mg L^{-1}, and the concentration reached a maximum of 70 000 mg L^{-1} (Figure 3a) during the rainfall event on 12th of July 2011, during which 70 mm of precipitation fell in just over one hour. The water samples taken during rainfall events in the channel (n=109) showed a different particle size distribution than those taken during base-flow, with higher proportions of coarser particles: on average, 50% of sand, 30% of silt and 20% of clay were measured during the full duration of rainfall event sampling (Table 2). When only looking at the peak sediment concentration of each event (thus excluding rising and falling limb samples), sand concentrations were higher and varied from 29 to 94% with an average of 72% for the 14 measured events.

In the river, the median of the suspended sediment concentration predictions was 300 mg L^{-1} during periods of no rainfall (data not shown). There were no differences in base-flow concentrations between Locations A and B. The river sediment concentrations were very little affected by overland flow as the paddy fields buffered inputs from Hortonian overland flow, and so the maximum concentrations in the river only reached up to 5 000 mg L^{-1}. Water samples of Location A in the river, upstream of the paddy fields, had on average 61 % sand, 22% silt and 17% clay (n=12, Table 2). After paddy discharge, the river sediment texture on average had 47% sand, 33% silt and 20% clay (n=13, Table 2).

In the river at the overall outlet of the larger catchment, the median base-flow concentration was 190 mg L^{-1} (data not shown). Between Location B and the overall outlet, an additional 47 ha of paddy rice drain into the river, adding filtered irrigation water with lower sediment content to the river, resulting in a lower sediment concentration during base-flow at the overall outlet compared with Location B. During rainfall events, concentration increased at the overall outlet, with a maximum peak of 22 000 mg L^{-1} on June 5th 2010 when 46 mm of rain fell in 160 minutes. These peak concentrations during rainfall events were higher than those measured at the same time at Location B. As there are point sources of overland flow that reach the stream directly at the overall outlet, the river is not completely isolated from overland flow as it is in Location B where the paddy fields buffered the input of runoff from upland fields, explaining the difference in peak concentrations between these two stations.

3.2 Seasonal sediment load trends in the irrigation system

Monthly sediment loads from irrigation water (Figure 4) reflected changes in the suspended sediment concentration (Figure 3b), related to fluctuations in the level of the surface reservoir (Figure 4) as well as changes in amount of water irrigated to the paddy fields. The first rice crop (from February till June) received about half the water volume of the second crop (Figure 2), as a smaller area of the paddy fields was cultivated during the spring season, resulting in a lower sediment input from irrigation during the spring season (200 Mg in 2010, 263 Mg in 2011) compared with the summer season (445 Mg in 2010, 346 Mg in 2011). The difference in load between the spring crop and the summer crop was smaller in 2011, as the rains came late that year. Consequently, the reservoir was depleted during the first rice crop and the first rains fell on a much smaller volume of water, increasing the sediment concentration in the reservoir, thus causing the higher sediment load compared with 2010. In the summer season of 2011, the irrigated amount of water was 10% less than in 2010 (Figure 2), as the rains came late and the irrigation manager wanted to preserve water. Overall, the largest sediment inputs from irrigation occurred in August in both years of the study (Figure 4), with 137 Mg of sediments in 2010 and 114 Mg in 2011.

Even though the sediment concentration in the overland flow was orders of magnitude higher than the concentration in the irrigation water (Figure 3), over a full year, the contribution of irrigation water was about three times larger than the contribution of overland flow (Table 3). As the rainy season starts in April, paddy water inputs from overland flow play a more important role during the second rice crop. The contribution of overland flow was almost negligible during the first rice crop, particularly in 2011 when the onset of the rains was late and the volume of overland flow was much smaller during the first crop (Figure 4). During that spring cropping season of 2011, the contribution of overland flow to the sediment input of the paddy fields was negligible, reaching only 46 Mg compared to 263 Mg from irrigation water. But during July 2011, the month in the study which had the highest rainfall (247 mm), direct overland flow provided almost as much sediments to the paddy fields as irrigation water from the reservoir (62 Mg versus 71 Mg).

3.3 Sediment budget for paddy fields

Irrigation water from the surface reservoir removed 806 Mg of sediment from the reservoir in 2010 (Table 3). Of this amount, 646 Mg entered paddy fields through irrigation and 160 Mg were exported from the sub-watershed, as the irrigation channel crosses the watershed border into a neighboring catchment. In 2011, the sediment load from the irrigation water was similar with 762 Mg, of which 612 Mg entered the rice fields, and 150 Mg were exported to the next catchment. Using the average textural class percentages of the surface reservoir outflow, irrigation water can be estimated to have contributed 208 Mg of sand, 208 Mg of silt and 196 Mg of clay to the paddy rice fields in the watershed in 2011 (Table 4). As there were not enough samples analyzed to obtain continuous predictions of the different particle size classes using a regression model, simple averages were used for the texture loads. In this sense, all sand, silt and clay loads are more a semi-quantitative estimate that provides an order of magnitude, rather than an exact figure.

For the upland area bordering both irrigation channels (37 ha), overland flow generated a sediment load of 249 Mg in 2010 and 278 Mg in 2011. Of this total amount, 193 Mg of overland flow sediments actually entered the paddy fields in 2010 and 219 Mg in 2011. The remainder of the sediments was exported from the watershed through the irrigation channel (Table 3). Again assuming average texture values, the input of overland flow to the paddy fields in 2011 hence consisted of 109 Mg of sand, 66 Mg of silt and 44 Mg of clay (Table 4).

Thus the combined addition to the paddy fields from reservoir outflow and overland runoff amounted to 318 Mg of sand, 274 Mg of silt and 240 Mg of clay (Table 4).

The sediment load exported from the paddy fields on both banks of the river, calculated as the difference between Location A and Location B, was 469 Mg in 2011 (Table 3), of which 60% was exported during the spring cropping season, and 40% during the summer crop. As the monitoring station in Location B was only installed in 2011, data for 2010 are not available. Combining all of these loads, the difference between inputs and export from the paddy resulted in a sediment yield of 363 Mg in total, or 28 Mg ha^{-1} that remained in the paddy fields in 2011. Since the load exported and the net paddy load are differences between positive numbers (loads measured at Location A minus B for the export, and inputs minus export for the net load), the lower limit of the confidence interval for these two estimates can become negative (Table 3). Negative load estimates can be interpreted as net sediment trapping of the paddy area. Looking at the texture-specific loads (Table 4), the sediments exported from the ~~paddy fields~~paddies consisted mostly of finer material. Thus, in 2011 approximately 326 Mg of silt and 141 Mg of clay were exported from the rice ~~paddies~~fields. Combining inputs and losses, 315 Mg of sand and 99 Mg of clay remained behind in the paddy fields over the whole year, while a net amount of 52 Mg of silt was lost from the 13 ha paddy area (Table 4).

3.4 Watershed sediment yield

The total sediment yield of the sub-watershed, ending at Location B, was 2 234 Mg in 2011. This amount was exported via two pathways. First, the irrigation canal distributed 150 Mg from the reservoir and 59 Mg from the upland area through overland flow into the neighboring catchment (Table 3, Figure 6). Second, the river exported 2 026 Mg from the sub-watershed at Location B. Of these 2 026 Mg, a total of 469 Mg consisted of runoff from the paddy fields. The remaining 1 556 Mg that was lost through the river, originated from the surface reservoir as water released via the reservoirs spill-over, which allows excess water to flow into the river whenever the reservoirs maximum capacity is reached. For the larger watershed of 200 ha, which contains the aforementioned sub-catchment, the annual sediment yield was 6 262 Mg in 2010 and 5 543 Mg in 2011.

4. Discussion

4.1 Upland sediment contribution to the irrigation system

The largest peak of suspended sediment concentration found in this study was two to five times higher compared to the highest values found in other SE Asian studies (Ziegler *et al.*, 2014; Valentin *et al.*, 2008) and the corresponding event contributed 23% of the total annual sediment load transported by overland flow to the irrigation channel in 2011. The difference in sediment concentration with other studies is most likely due to the more gentle slopes (8 to 15 %) present in the watershed study of Valentin *et al.* (2008), whereas steep slopes up to 65% are found in our watershed. Both other studies, however, which contain the highest values found for Southeast Asia in literature, also used a storm-based sampling strategy, underscoring the importance of capturing the highest events in order to reliably assess the erosivity of mountainous catchments. Horowitz *et al.* (2014) reported that calendar-based sampling typically underestimates constituent transport, while event-based sampling does not. Capturing the highest peaks is crucial, as the importance of single, high-intensity storms for sediment yield in tropical areas is increasing due to climate change. In the monsoon climates of Southeast Asia, a rise in extreme, high intensity rainfall events is expected (IPCC,

2013) and as single large storms already have such a substantial effect on the annual sediment load, in the future they can be expected to dominate annual sediment loads.

Our estimated upland sediment load of 278 Mg a^{-1} in 2011 translates into an annual soil loss of 7.5 Mg ha^{-1}, but this result should be interpreted as an average yield at the watershed level, not as a representative erosion rate at the plot level. This estimate is well within the order of magnitude reported by watershed-scale measurements. For instance, Valentin *et al.* (2008) monitored sediment yield from 27 catchments in mountainous Southeast Asia and found an average total annual sediment yield of 3.4 Mg ha^{-1}. Plot scale studies, however, frequently report larger erosion rates than the 7.5 Mg ha^{-1} found in our study. Also in the Chieng Khoi commune, Tuan *et al.* (2014) recorded an erosion rate averaging 44 Mg ha^{-1} a^{-1} for sediment fences in unbounded plots for maize-cassava intercropping systems. This discrepancy is typical when upscaling erosion rates (de Vente and Poesen, 2005), as processes are not linear. Erosion can be concentrated at certain hotspots and rill erosion, and internal deposition and filtering processes (e.g. hedges) leave part of the eroded sediments behind within the watershed (Verstraeten and Poesen, 2001). Indeed, in our watershed, the mix of homesteads, maize and maize-cassava cropping and trees on the hills affect both sediment delivery pathways and re-deposition opportunities. The plot-level soil loss on upland fields can thus be expected to exceed the value of 7.5 Mg ha^{-1} that enters the irrigation channel, as a proportion of eroded sediments will be deposited before ever reaching the channel. Nevertheless, even using the conservative estimate of 7.5 Mg and assuming a bulk density of around 1.2 g cm^{-3}, this result entails a loss of around 0.6 mm of soil per year, a value that is well above the soil loss of 2.5 Mg ha^{-1} a^{-1} that is generally considered tolerable (~~USDA, 2012~~Schertz, 1983).

4.2 Sediment trap efficiency of paddy fields

Surface reservoir water was the largest contributing source to suspended sediment inputs for the paddy fields, with only one quarter of sediment inputs to the paddy fields coming from overland flow in both years. When looking at the sediment quality rather than sediment loads, however, the importance of overland flow increased for sand, with 34% of the total paddy inputs originating from erosion in 2011. Therefore, while irrigation was the main driver behind water and sediment fluxes in this irrigated catchment, overland flow plays an important role in transfers that could affect plant production and long-term soil fertility.

Paddy runoff amounted to a total of 469 Mg for the 13 ha area in 2011, or 36 Mg ha^{-1} a^{-1} of sediments leaving the rice fields. The majority of paddy sediment export (60%) took place during the spring season, and can thus be related to overland runoff flowing through the paddies early in the year, when upland fields were bare as the maize crop was not yet established. Hence, intensive land preparation for maize planting and lack of soil cover in spring resulted in a large supply of readily erodible material on the hills. Short-duration, high-intensity spring storms combined with this sediment supply, led to rapid and large inputs of sediment which passed through the paddies. As a result, sediments had little time to settle, thus reducing filter effectiveness of the rice fields and culminating in less trapping and more sediment export from the paddies during the first crop.

Comparing inputs to paddy field exports suggests that the rice area trapped 44% of the combined re-allocated sediments from reservoir irrigation water and direct runoff from the upland areas. Similarly, Mingzhou *et al.* (2007) found that the sediment load in the irrigation water resulted in a net deposition, rather than erosion from paddy fields, which led to an additional 4 cm of top soil through irrigation deposits after fifty years of irrigation. While the paddies in our study were a net overall sediment sink, results also showed that the sand fraction was preferentially deposited and was in fact almost entirely captured in the paddies, forming a net deposition of 23 Mg ha^{-1} a^{-1}. About half of the imported clay remained behind in the fields, or a total of 8 Mg ha^{-1} a^{-1}. For silt, the overall balance was negative, with 5 Mg ha^{-1} of silt exported on an annual basis. This preferential deposition is likely to have consequences, as long-term fertility of paddy fields is contingent upon the particle size distribution of the soils for physical soil properties, e.g. clay content exceeding 20% is favorable for puddling (De Datta, 1981). In our study area, top soil in the paddy fields is predominantly silty, with an average of 19% sand, 68% silt and 13% clay (Schmitter *et al.*, 2010). With an estimated deposition of 23 Mg ha^{-1} a^{-1} of sand and 8 Mg ha^{-1} a^{-1} of clay in the paddies, and a removal of 4 Mg ha^{-1} a^{-1} of silt, textural changes can be expected to take place over time. While the clay fraction is expected to add sediment-associated nutrients to the paddies, and thus increase the indigenous nutrient supply for rice, the sand deposits are much larger (76% of all inputs) and will thus drive the long-term fertility changes in paddy topsoil. Assuming a puddling depth of roughly 25 cm and a bulk density of 1.2 g cm^{-3}, the sand fraction would dominate after approximately fifty years of these continued inputs. But not all fields would have the same longevity, as sediment inputs do not affect the fields equally. Previous research has shown that sedimentation in rice cascades shows spatial variability, and that fields closest to the water source receive most of the coarse material, ~~and~~ the yield declining with decreasing distance to the water source (Schmitter *et al.*, 2010). Thus for certain fields closer to the water source, sand content would increase more rapidly, which is indeed already visible in the study area: paddies higher up on the cascades were often seen to display poor water holding capacity.

Similar composite agricultural systems with permanent upland cultivation on the hills and irrigated rice in the valleys contain 60% of the total paddy area in Northern Vietnam (Rutten *et al.*, 2014). Consequently, a large agricultural area is potentially affected by such upland-lowland linkages. Eliminating the direct entry of Hortonian overland flow into the irrigation channel, for example by runoff ditches, is one way to prevent up to one third of the total sand inputs from entering the rice fields and thus to protect the food security of the people in the mountainous areas of Northern Vietnam, who depend on rice as their staple food. This solution is not sustainable in the long run from a systems-approach perspective, as the fertility loss of the uplands would affect income when the cash crop income is declining. But with the current high maize prices, it is challenging to identify sustainable hillside land uses that are attractive to local stakeholders (Keil *et al.*, ~~2009~~2008), and deviating direct runoff from entering the paddies would at least be an interim solution. It would, however, also lead to substantial losses of nutrients (Dung *et al.*, 2008) which could not be recycled.

4.3 Buffer capacity of the reservoir

For the sediment yield measured at Location B, the outlet of the sub-watershed, the vast majority of sediments (1 557 Mg out of 2 064 Mg) stem from the reservoir which spills over into the river when it reaches maximum capacity. In that sense, the bulk of sediments are merely passing through the sub-watershed, having been captured in the reservoir after runoff from the surrounding 490 hectares of upland fields. Reservoir outflow is thus not only the largest contributor to sediment transport in our paddy area within the watershed, but also has a propagating effect beyond the watershed scale: the river water leaving the watershed is either re-used for irrigating paddies in downstream catchments, or will finally end up in the Da river. In either case, the surface reservoir buffers direct sediment inputs that could negatively affect paddy production and river water quality, as average sediment concentrations released from the reservoir were much lower than those measured during rainfall events in the channel (240 mg L^{-1} versus 1 200 mg L^{-1}).

The water in the reservoir also had a lower sand and higher silt and clay content, and sediment profiles in the lake indeed confirmed this preferential settling of coarse material. Weiss (2008) showed that soil profiles taken at the lake bottom had a sediment texture of between 40 and 75% sand, 20 to 50% silt and 5 to 14% clay. The reservoirs filtering effect can be expected to be stronger beyond the watershed, as coarser particles will be trapped preferentially in closer vicinity to the source. While large enough to substantially affect rice production, the amount of sediments trapped by the paddy fields is moderate (12%) compared to the total amount exported from the watershed by reservoir spillover export. In light of these proportions, effects of climate change and declining soil fertility in upland areas will not remain on-site but can be expected to propagate beyond the watershed, and also affect areas further downstream.

5. Conclusion

The sediment budget for a 13 ha paddy area in a composite agricultural system with permanent maize cultivation on the uplands showed that rice fields at the watershed level are a net sink for sediments, i.e. trapping 46% of the total sediment inputs. Irrigation water, providing 74% of the total inputs of 832 Mg, was a larger contributor than direct overland flow from the surrounding upland fields. The irrigation water, however, provided predominantly silty material, while direct runoff sediments had a sandy texture. In the past, extensive swiddening systems with their diverse landscape patterns would have delivered little and mostly fine, fertile sediments to paddy fields via direct overland flow. Recent intensification of upland cropping has transformed these previously beneficial inputs into an increased risk for the long-term sustainability of rice production, ~~thus~~ threatening productivity of ~~both~~ upland cropping and paddy yields. The reservoir, however, acts as a buffer by protecting both the rice fields within the watershed, and paddies and water quality further downstream, from unfertile sediment inputs – thus expanding the life time of the paddies.

Our results show the importance of quantifying upland-lowland linkages within and between watersheds, and can be used by scientists, policy makers and extension services to give suitable recommendations to the large group of people in mountainous Southeast Asia who, under influence of population pressure, have gone from practicing composite swidden agriculture to an intensified cropping system with permanent maize cultivation on the hills. Preventing overland flow from reaching the paddy fields, for example, could prevent up to 8 Mg ha^{-1} a^{-1} of sand per year, or one third of the total sand deposits, from entering the rice fields. More diversified, sustainable and acceptable approaches, however, benefitting both upland fields as well as downstream paddies, need to be developed at the same time.

6. Data availability

The source code for the bootstrap analysis with the SAS software that was used for the load estimates and corresponding confidence intervals is freely available at https://www.uni-hohenheim.de/bioinformatik/beratung/index.htm together with necessary input files for testing. The full dataset is available from the authors upon request (hanna.slaets@gmail.com).

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9. Appendix A

Calculating a measure of uncertainty on a sediment load is not trivial. The final value is a sum of instantaneous loads, and those loads are the product of two predicted values, concentration and discharge, which are not independent of each other, as discharge is a predictor variable for concentration. Additionally, the predicted values are on the transformed scale, and there is serial correlation in the sediment concentration data, as samples are taken closely together in time.

In order to calculate 95% confidence intervals on the sediment loads, a bootstrap method was developed that addresses all of these issues (Slaets *et al.*, under review). The bootstrap is a Monte Carlo-type method that generates the sampling distribution of a statistic by resampling a large number of times, either from the original observations or from a parametric distribution, to obtain new bootstrap datasets, on each of which the sediment load is calculated. This large number of bootstrap sediment loads provides an empirical distribution, which can be used to estimate the 2.5th and 97.5th percentiles. These percentiles are the limits of the 95% confidence interval (Efron and Tibshiriani, 1993). In our dataset, 2000 bootstrap replicates resulted in smooth histograms and reproducible percentiles. The developed method thus accounts for uncertainty in the parameter estimates of both the discharge and sediment rating curves, and uncertainty due to residual scatter in the sediment concentrations. In this approach, the final bootstrap process consists of three steps:

1. Non-parametric bootstrapping of the (stage, discharge) pairs in order to obtain 2000 bootstrap stage-discharge equations, and thus 2000 time series predictions for bootstrapped discharge;
2. Non-parametric bootstrapping of the sediment concentration dataset, by drawing whole events (to keep the serial correlation intact) and individual base-flow samples, resulting in 2000 bootstrap sediment rating curves, and thus 2000 time series predictions of continuous suspended sediment concentration;
3. Adding a simulated error term to the concentration predictions to account for inherent residual scatter in the data and to facilitate the back-transformation from the log-scale.

10. Tables

Table 1: Number of observations (n), coefficient of determination (R^2) and method used for stage-discharge relationship (Q); and number of observations and Pearson's correlation coefficient (r^2) after five-fold cross-validation for suspended sediment concentration predictions (SSC). Details on the linear mixed model development can be found in Slaets *et al.* (2014).

	Stage-discharge relationship (Q)			Suspended sediment concentration (SSC)	
	n	**R^2**	**Method**	**n**	**r^2**
Channel (1)	6	0.99	Salt dilution	Identical to location 3	
Channel (2)	6	0.99	Salt dilution	Identical to location 3	
Channel (3)	6	0.96	Salt dilution	327	0.72
River (A)	9	0.99	Area-velocity	145	0.52
River (B)	8	0.98	Area-velocity	71	0.66
River (main outlet)	15	0.98	Area-velocity	228	0.56

Table 2: Average sediment particle size distribution measured at the different measurement locations for the different components of the paddy area sediment balance

Sediment source	**% sand**			**% silt**			**% clay**		
	min	av	max	min	av	max	min	av	max
Reservoir water – Location 1	0	**34**	50	14	**34**	58	0	**32**	86
Overland flow	0	**50**	100	0	**30**	61	0	**20**	61
River – Location A	29	**61**	89	9	**22**	40	0	**17**	80
River – Location B	1	**47**	74	17	**33**	47	9	**20**	53

Table 3: Sediment inputs from irrigation water and overland flow from the 37 ha upland area in the sub-watershed, and sediment export and trapping by the 13 ha paddy area (Figures 1 and S1). Loads are estimated as the median of the bootstrap estimates (Med) and therefore do not always sum up exactly within columns, ~~;~~ and 95% confidence intervals are shown (LL=lower limit, UL=upper limit) in Mg per year (Mg a^{-1}).

	Sediment load (Mg a^{-1})					
	2010			2011		
Sediment source	LL	Med	UL	LL	Med	UL
Reservoir water:						
Total to channels …	617	806	1123	587	762	1331
… irrigated paddy area	492	**646 (77%)**	903	496	**612 (74%)**	1085
… exported via channel	124	160	222	117	150	248
Spill-over to river	nd	nd	nd	917	1556	18128
Overland flow:						
Total to channels …	121	249	303	129	278	516
… irrigated to paddy area	119	**193 (23%)**	302	110	**219 (26%)**	517
… exported via channel	36	56	88	35	59	135
Total paddy input		**839 (100%)**			**832 (100%)**	
Paddy outflow	nd	nd	nd	-361	**469 (56%)**	2555
Net paddy balance	nd	nd	nd	-1625	**363 (44%)**	1586
Paddy balance per ha					**28 Mg ha^{-1} a^{-1}**	

nd = not determined

Table 4: Texture -specific sediment inputs from irrigation water and overland flow from the 37 ha upland area in the sub-watershed, and texture-specific sediment export and trapping by the 13 ha paddy area (Figures 1 and S1).

	Load (Mg a^{-1})					
	2010			2011		
Sediment source	Sand	Silt	Clay	Sand	Silt	Clay
Reservoir water:						
Total to channels …	274	274	258	259	259	244
… irrigated to paddies	220 (70%)	220 (79%)	207 (84%)	208 (66%)	208 (76%)	196 (82%)
… exported via channel	54	54	51	51	51	48
Spill-over to river	nd	nd	nd	950	343	265
Overland flow:						
Total to channels …	124	75	50	139	83	56
… irrigated to paddies	96 (30%)	58 (21%)	39 (16%)	109 (34%)	66 (24%)	44 (18%)
… exported via channel	28	17	11	30	~~18~~17	12
Paddy input (**100%**)	316	278	246	~~318~~317	274	240
Paddy outflow	nd	nd	nd	2	326	141
Net paddy balance	nd	nd	nd	+315 (99%)	-52	+99 (40%)

nd = not determined

11. Figures

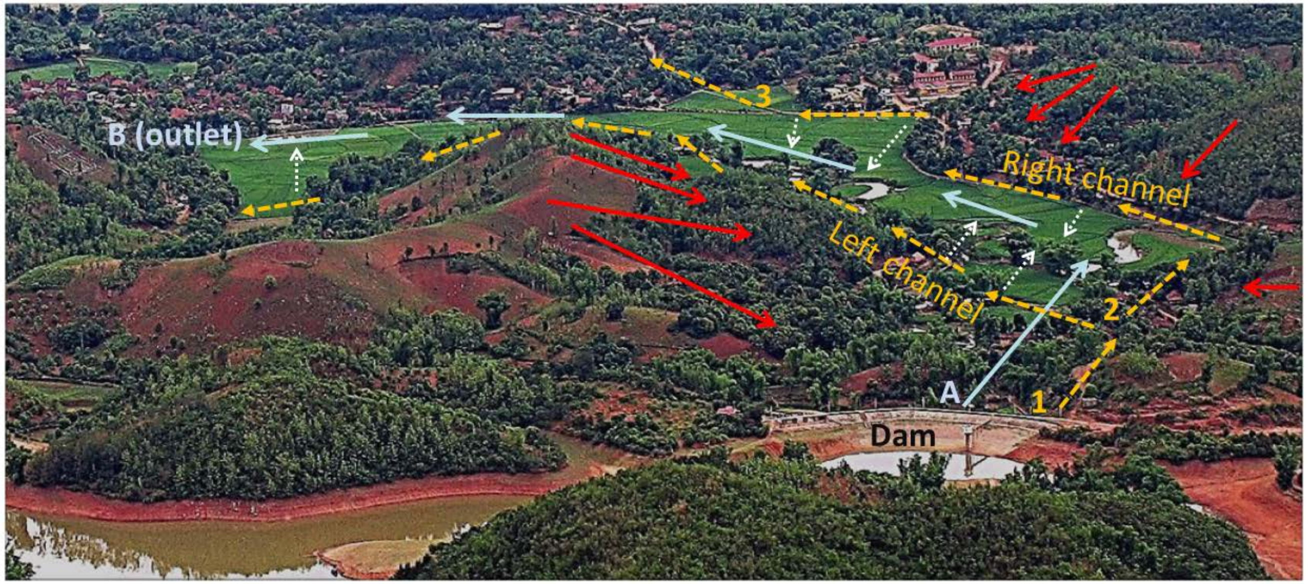

Figure 1: Sediment sources and water flows into and out of paddy rice fields in Chieng Khoi watershed. The dotted yellow arrows show the irrigation channel leaving the reservoir and splitting in two, feeding the two banks of paddy rice. The rice fields subsequently drain into the river, which is indicated by the blue arrows. During rainfall, runoff generated on the uplands flows into the irrigation channel and the paddy fields (red arrows).

Measurement locations are indicated with numbers in the channel (1: reservoir outflow, 2: channel split, 3: channel leaving watershed) and with letters in the river (A: river before paddy fields drainage, B: river after paddy fields drainage).

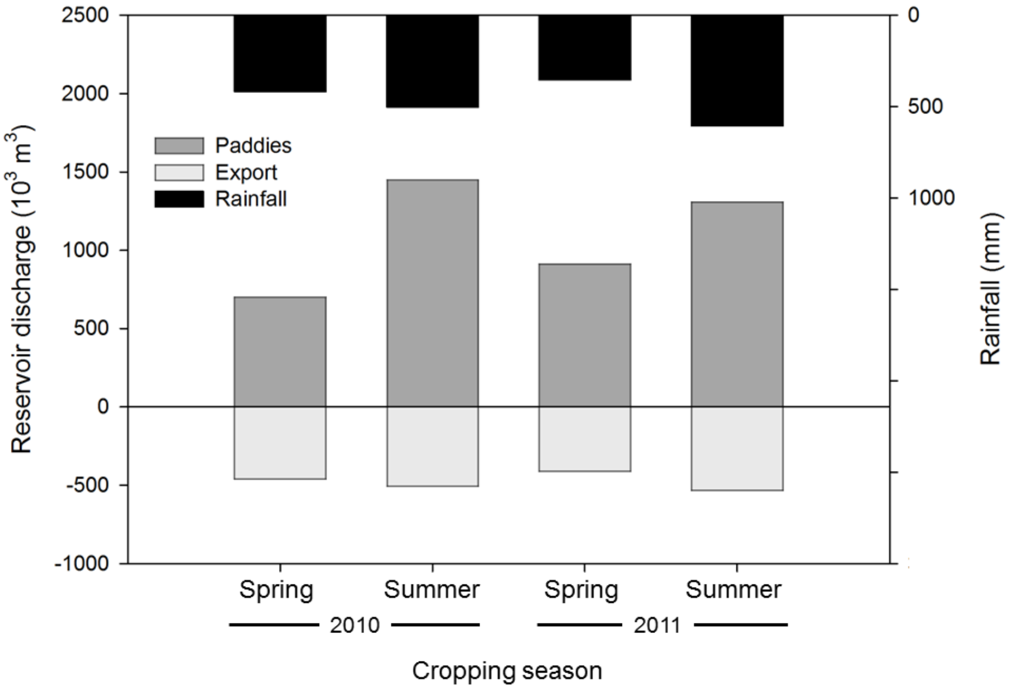

Figure 2: Total discharge from the reservoir irrigated to the 13 ha paddy area draining between Locations A and B in the river, and ~~(negative on the Y-axis)~~ total discharge exported (negative on the Y-axis) from the sub-watershed via the irrigation channel at Location 3, per rice crop (spring, summer) per year, and amount of rainfall per rice crop per year.

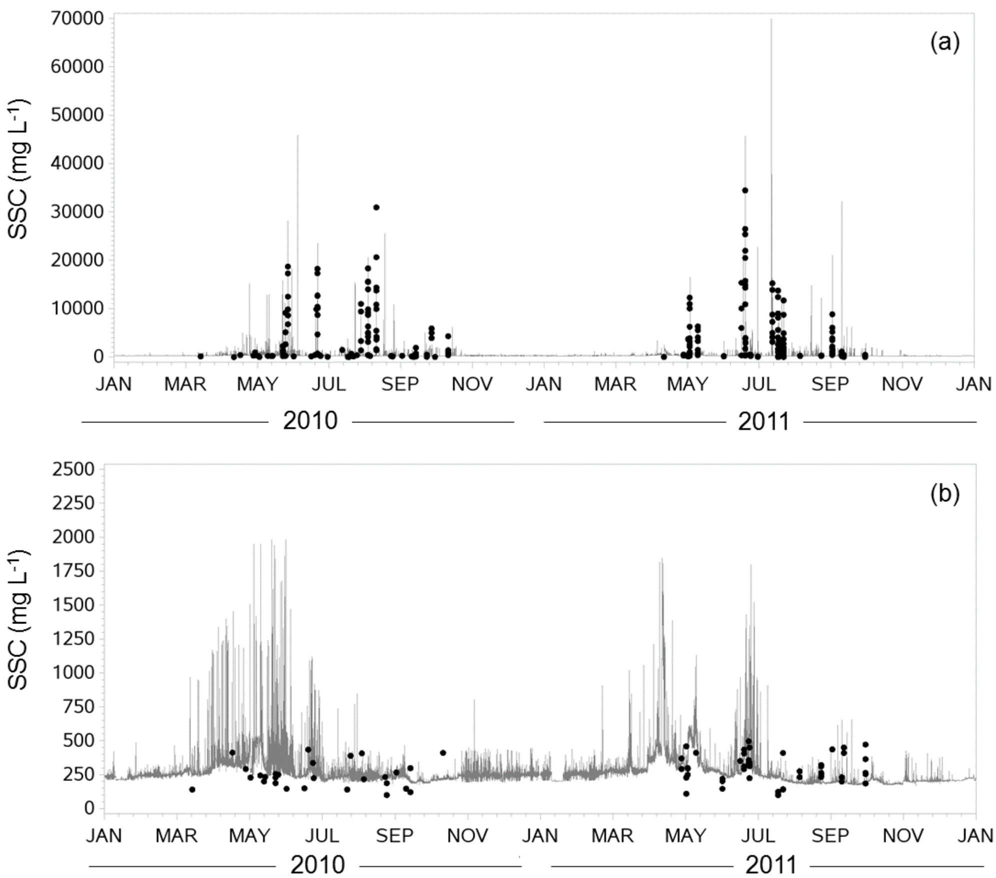

Figure 3: Observed and predicted sediment concentrations (in mg L^{-1}) for Location 3 in the irrigation channel (a), and zooming in on base-flow, showing only non-event samples and concentration predictions (b).

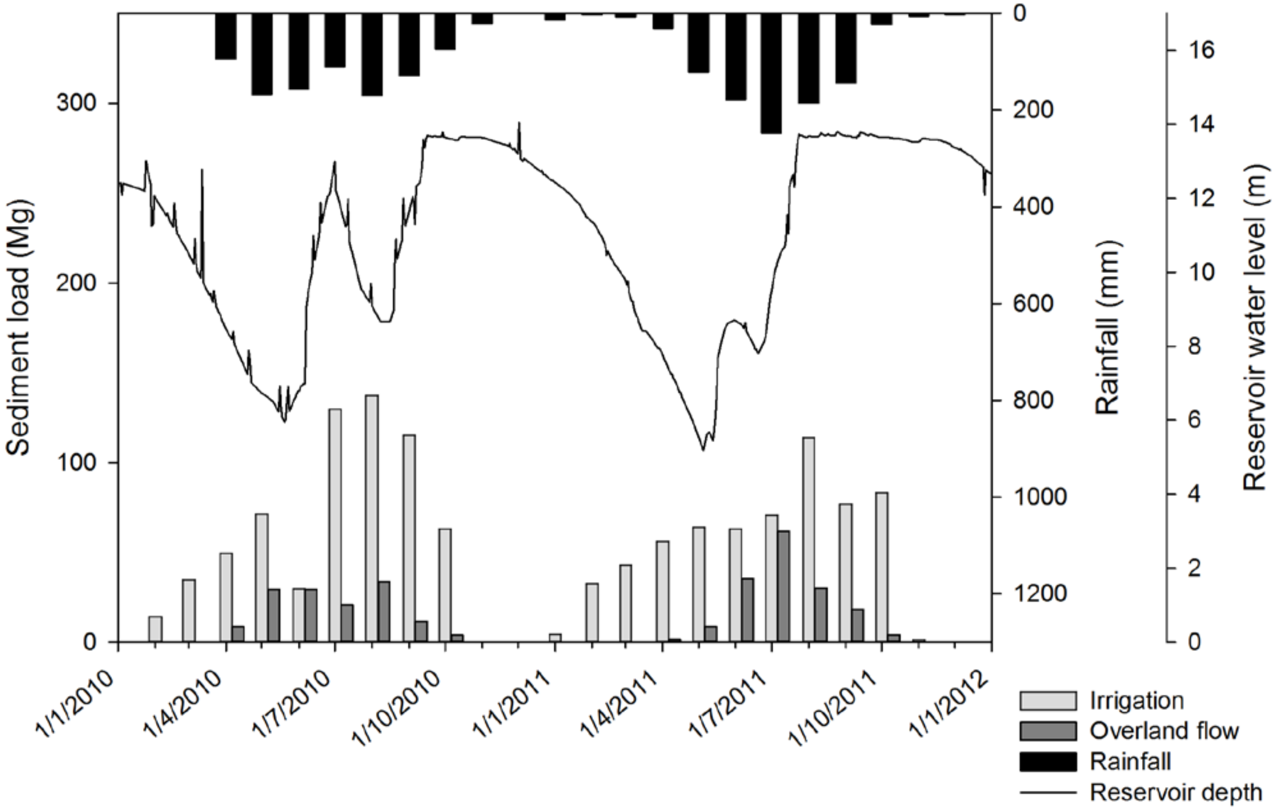

Figure 4: Monthly variations in rainfall, reservoir water level, and sediment load inputs to the paddy fields, both from the surface reservoir and from overland flow.

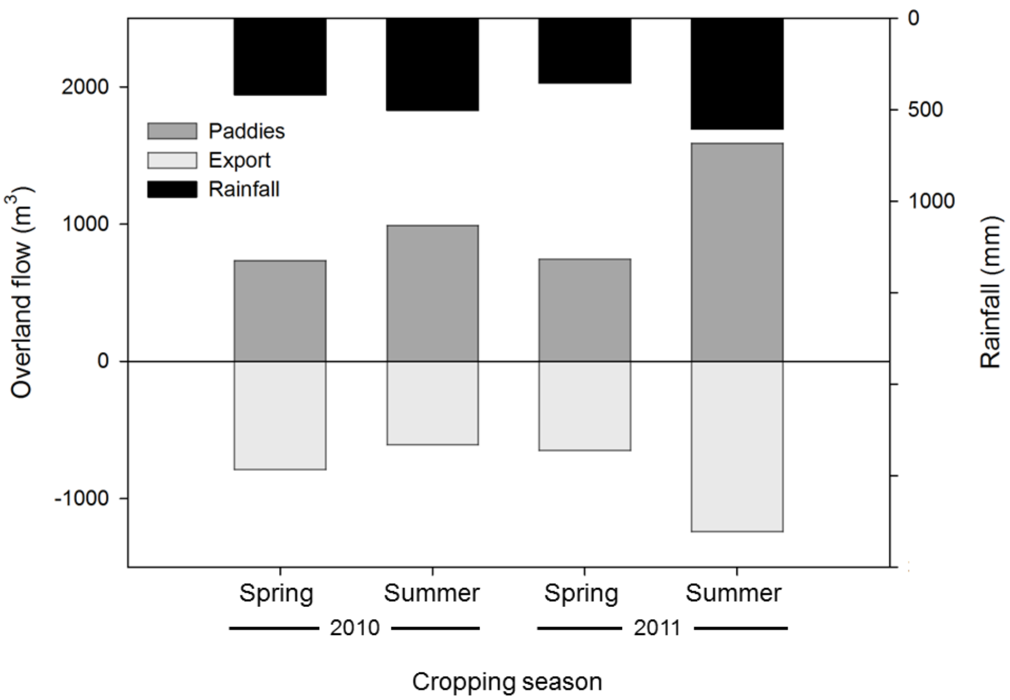

Figure 5: Total amount of water from overland flow during rainfall events, irrigated to the paddy fields and ~~(negative on the Y-axis)~~ exported (negative on the Y-axis) out of the sub-watershed via the irrigation channel per rice crop per year, and amount of rainfall per rice crop (note the different units on the Y-axis compared to Figure 2).

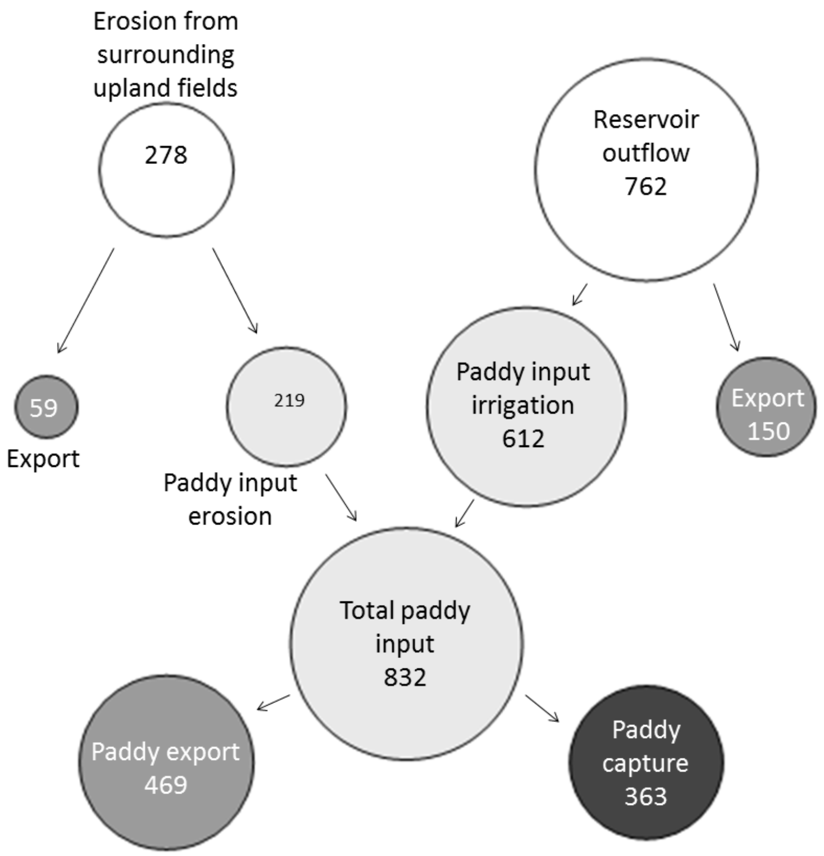

Figure 6: Sediment flow chart for 2011. Bubble size corresponds to size of the sediment load (in Mg a^{-1})