

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

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11
12 **Abstract**

13 Composite agricultural systems with permanent maize cultivation in the uplands and irrigated
14 rice in the valleys are very common in mountainous Southeast Asia. The soil loss and fertility
15 decline of the upland fields is well documented, but little is known about reallocation of these
16 sediments within the landscape. In this study, a turbidity-based linear mixed model was used
17 to quantify sediment inputs, from surface reservoir irrigation water and from direct overland
18 flow, into a paddy area of 13 hectares. Simultaneously, the sediment load exported from the
19 rice fields was determined. Mid-infrared spectroscopy was applied to analyze sediment
20 particle size. Our results showed that per year, 64 Mg ha⁻¹ of sediments were imported into
21 paddy fields, of which around 75% were delivered by irrigation water and the remainder by
22 direct overland flow during rainfall events. Overland flow contributed one third of the
23 received sandy fraction, while irrigated sediments were predominantly silty. Overall, rice

1 fields were a net sink for sediments, trapping 28 Mg ha⁻¹ a⁻¹ or almost half of total sediment
2 inputs. As paddy outflow consisted almost exclusively of silt- and clay-sized material, 24 Mg
3 ha⁻¹ a⁻¹ of the trapped amount of sediment was estimated to be sandy. Under continued
4 intensive upland maize cultivation, such a sustained input of coarse material could jeopardize
5 paddy soil fertility, puddling capacity and ultimately also food security of the inhabitants of
6 these mountainous areas. Preventing direct overland flow from entering the paddy fields,
7 however, could reduce sand inputs by up to 34%.

8

9 **Key words**

10 Sediment budget, sediment particle size distribution, sediment yield, maize, irrigated rice,
11 composite swiddening

12

1 **1. Introduction**

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

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

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

1 In shifting cultivation systems, forest plots are cleared and burned followed by cultivation of
2 subsistence crops. Cultivation lasts for one to three seasons, after which the plots are left
3 fallowed for a prolonged time to recover soil fertility (often a minimum of six times the
4 cropping duration (Ziegler *et al.*, 2009)). Traditional shifting cultivation systems are very
5 extensive in space and time, generating very limited runoff and erosion at the watershed scale
6 (Ziegler *et al.*, 2009). Gafur *et al.* (2003) reported soil losses amounting to 30 Mg ha⁻¹ a⁻¹ for
7 an upland area with shifting cultivations, while the regional average sediment yield was 1.2
8 Mg ha⁻¹ a⁻¹, as 43% of soil loss from upland areas was captured by filtering elements in the
9 lower area of the watershed. Chaplot and Poesen (2012) similarly found large sediment
10 accumulations downslope in a slash and burn system in Southeast Asia, pointing towards the
11 lower impact of the land use at the watershed scale. In recent years, under the influence of
12 market mechanisms and population pressure, the traditional shifting cultivation systems on
13 the slopes have been replaced by permanent upland cultivation (Ziegler *et al.*, 2009).
14 Implications of these land use changes have been studied in detail on the upland fields, and
15 the increased erosion due to these changes are well documented. Chaplot *et al.* (2007) found
16 water erosion rates of 6 to 24 Mg ha⁻¹ a⁻¹ in an intensifying slash and burn system in Northern
17 Laos. Lacombe *et al.* (2015) determined that conversion of fallow into teak plantation versus
18 forest communities has opposite effects on catchment hydrology. Infiltration increased and
19 runoff decreased for the forest communities, while the opposite was true for the teak
20 conversion, illustrating how the effects of disappearing fallow strongly depend upon the
21 replacing vegetation. In our study area, maize and maize-cassava intercropping on steep
22 slopes with clay topsoil texture resulted in plot-level erosion rates in bounded plots of up to
23 174 Mg ha⁻¹ a⁻¹ (Tuan *et al.*, 2014), coupled with a loss of soil organic matter reaching 1 Mg
24 ha⁻¹ a⁻¹ (Häring *et al.*, 2014). Additionally, changes in texture occurred as fertile silt and clay
25 fractions were exported from the upper and middle slope positions whereas sandy material

1 was deposited at foot slope positions (Clemens *et al.*, 2010). Differences in amount and
2 texture of eroded material from upland fields could therefore entail a shift in matter exchange
3 between upland cultivation and valley paddy rice.

4

5 Increased erosion may therefore not only jeopardize the continued production of the cash
6 crop maize on upland fields, but also adversely affect the long-term sustainability of the food
7 crop production in the paddies. Schmitter *et al.* (2010) showed that soil fertility in paddy
8 cascades varies with distance to the irrigation channel, and thus established a link between
9 sedimentation processes and soil properties. R uth and Lennartz (2008) and Schmitter *et al.*
10 (2011) found that variability of paddy soil texture and yield were a function of position along
11 the catena, related to differential settling of sediments in irrigation water. If soil properties
12 and yield are closely linked to sedimentation processes, then changes in amount and texture
13 of the sediment inputs have a potential effect on long-term soil fertility and crop production,
14 and hence on food security in the area, as rice is the main staple food crop.

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

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

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

17

18 **2. Material and Methods**

19 **2.1 Study site**

20 The study was conducted in a small agricultural watershed, located in Chieng Khoi
21 commune, Yen Chau district, Son La province, North-West Vietnam (21°7'60''N,
22 105°40'0''E, 350 m a.s.l., Figure S1). The catchment is 200 ha in size, and sediment
23 reallocation in a sub-catchment of 50 ha which consists of 13 ha of paddy rice and 27 ha of
24 upland fields was monitored in greater detail. In the area, the dominant soil types are Alisols

1 and Luvisols (Clemens *et al.*, 2010) and the climate is monsoonal, with a rainy season from
2 April till October and average annual rainfall of around 1200 mm. Land use in the watershed
3 is characterized by maize and maize-cassava intercropping on the slopes, and irrigated rice in
4 the valleys. The source of irrigation water is a surface reservoir that feeds a concrete
5 irrigation channel, ensuring two rice crops per year: a spring crop from February till June,
6 followed by a summer crop planted in July and harvested in October. The reservoir was
7 formed by the damming of a river that originates in the karst mountains of the area. It has a
8 capacity of 10^6 m^3 and a contributing area consisting of 490 ha of intensively cultivated
9 upland fields and forest. The channel splits in two, just below the reservoir, and feeds two
10 paddy rice areas (6.5 ha each), on the banks of a river that intersects the paddy fields. The
11 irrigation water flows from the channel into the paddy fields, which drain into the river
12 (Figure 1).

13 2.2 Hydrological monitoring

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

21 Discharge was monitored using pressure sensors (Ecotech, Germany) and the stage-discharge
22 relationship was established using the salt dilution method for the channel and the area-
23 velocity method for the river (Herschy, 1995). Rainfall was measured with a tipping-bucket

1 rain gauge (0.1 mm accuracy, Campbell Scientific, USA) in the upper part of the catchment.
2 The water level of the lake was recorded on a daily basis.

3 2.3 Sediment concentration predictions

4 Water samples were collected manually with a storm-chasing approach, where more samples
5 were taken when water level and turbidity were rapidly changing. The sampling interval
6 depended on the hydrograph. During rapid changes in turbidity, samples were taken more
7 frequently (up to two minutes apart) than at the end of the falling limb (up to 15 minutes
8 apart). A typical sampled rainfall event thus consisted of ten to twenty water samples,
9 depending on the duration of the event. Additionally, base-flow samples were collected every
10 two weeks. Total sample sizes for each location are shown in Table 1 and ranged from 71 to
11 327 samples. Each sample consisted of a 500 ml bottle. Sediment concentration in the
12 samples was determined gravimetrically (ASTM, 2013) as recommended for samples with
13 very high Suspended Sediment Concentration (SSC), by letting the sediment settle overnight
14 in cold storage ($<4^{\circ}\text{C}$) and then siphoning off the supernatant followed by oven-drying of the
15 sediment at 35°C until the sample weight remained constant.

16 Field calibration of the sensors resulted in continuous statistical predictions of sediment
17 concentration for the two year study period (temporal resolution of two minutes) which were
18 obtained from a linear mixed model (Slaets *et al.*, 2014). The linear mixed model is a
19 regression-type model with SSC as response variable and turbidity, discharge and cumulative
20 rainfall as predictor variables. As the storm-based approach resulted in samples taken at very
21 short consecutive time intervals (i.e. 2 min), the assumption required for a traditional
22 sediment rating curve of independence of errors was not fulfilled in this dataset. Similarly, we
23 found the variance to increase with increasing sediment concentration, violating the
24 assumption of homoscedasticity. To account for temporal correlation in the observations, an

1 error with a first-order autoregressive covariance structure was fitted to the data. The
2 response variable was log-transformed to stabilize the variance, as were the predictor
3 variables discharge and turbidity. The models were validated with five-fold cross validation
4 using a SAS macro described in Slaets *et al.* (2014).

5 2.4 Separating sediment sources

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

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

$$4 \quad Q_{in} = Q_{irr} + Q_{out}, \quad (\text{Eq. 1})$$

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

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

$$14 \quad Q_{in} + Q_{pp} + Q_{of} = Q_{irr} + Q_{out}, \quad (\text{Eq. 2})$$

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

22

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

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

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 $\text{m}^3 \text{s}^{-1}$ 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 the time series consisted of two minute intervals. As such, the estimated monthly or annual sediment load $\hat{L}_{1 \text{ to } t}$ in grams can be computed by summing up the instantaneous loads, across t measurement intervals of turbidity and discharge:

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

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

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

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 L_{in} , L_{irr} and L_{out} in Equation 5 computed using Equation 4. The sediment load from direct runoff during rainfall is then the only remaining unknown in Equation 5: 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

1 watershed at Location 3, assuming full mixing. The sediment load from overland flow can
2 then be calculated from

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

4 In the river, the water sources are paddy outflow and reservoir overflow. The measurement
5 stations were installed in a similar manner as they were in the irrigation channel, with one
6 station upstream and one downstream of the paddy fields (Locations A and B in Figure 1).
7 The only sediment input between these two locations was drainage from paddy fields and fish
8 ponds in the paddy area. The river receives outflow from both banks of paddy fields, and we
9 only monitored the overland flow entering the right bank. Therefore, in order to quantify the
10 net sediment balance for the paddy fields, the assumption is made that the upland fields on
11 the left bank of the river generated the same amount of erosion as those on the right bank, as
12 the areas are very similar in land use, slope and size (17 and 20 hectares of contributing area).
13 There was one additional measurement location in the river further downstream (overall
14 outlet, Figure S1), at the outlet of a larger watershed of 2 km² in which the monitored paddy
15 area was nested, in order to assess scaling effects on paddy watershed sediment losses.

16 In order to calculate 95% confidence intervals on the sediment load, a bootstrap method was
17 used that accounts for uncertainty in the discharge and sediment concentration predictions
18 (Slaets *et al.*, under review; Appendix A). The number of bootstrap replicates was 2000. As
19 the direct sediment load estimation described in Equation 3 is typically biased downwards
20 when concentration and discharge are predicted on the log-transformed scale (Ferguson,
21 1986), taking the medians of the bootstrap replicates is a simple approach to bias-correct the
22 estimates (Efron and Tibshiriani, 1993). Therefore, the estimated sediment loads reported in
23 this study are the medians of the bootstrap empirical distribution, rather than the direct
24 estimates from Equation 3 (Slaets *et al.*, under review; Appendix A).

1

2 2.6 Sediment texture with mid-infrared spectroscopy

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

22 Sand, silt and clay were predicted from the spectral data using Partial Least Squares
23 Regression (PLSR; Wold, 1966). All spectral manipulation and model selection was
24 performed using Quant2 package within the software Opus 7.0 (Bruker Optik, Germany).

1 Models were evaluated with leave-one-out cross validation. Opus offers several spectral
2 processing techniques to enhance spectral information and reduce noise. The selection of the
3 most suitable method can be automatized using the Optimization function, which selects the
4 method resulting in the highest r^2 of observed versus predicted values after cross-validation.
5 For sand, the pre-processing method was the calculation of the second derivative of the
6 spectra, which can help to emphasize pronounced but small features over a broad
7 background. After validation, an r^2 of 0.81 was obtained. For silt, multiplicative scattering
8 correction was applied, which performs a linear transformation of each spectrum for it to best
9 match the mean spectrum of the whole set, and the model resulted in an r^2 of 0.83. For clay,
10 no satisfactory model could be obtained, and so the clay percentage was calculated as the
11 remaining amount of sediment after subtracting the sand and silt fractions.

12

13 **3. Results**

14 3.1 Hydrological processes driving sediment flows

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

19 In 2010, a total of 920 mm of rainfall was measured between April and October with the
20 onset of the rainy season in April, whereas in 2011, 961 mm fell but rains were delayed,
21 resulting in less rainfall in April- May and a precipitation peak in July, and 780 mm of the
22 annual rain falling between June and October. The lower amount of precipitation in the
23 spring of 2011 resulted in a lower amount irrigated during that period (Figure 2). Although
24 the total amount of water irrigated to the 13 ha of paddy fields was similar, i.e. $3\,978 \cdot 10^3 \text{ m}^3$

1 in 2010 and $4\,021 \cdot 10^3 \text{ m}^3$ in 2011, the seasonal distribution of the irrigated amounts varied
2 between the study years. As the rainy season started late in 2011, there was more water
3 irrigated during the first rice season (February-June) in 2011 ($913 \cdot 10^3 \text{ m}^3$) than in 2010
4 ($700 \cdot 10^3 \text{ m}^3$). The opposite was true for the summer crop (July-October), during which
5 $1\,308 \cdot 10^3 \text{ m}^3$ was irrigated in 2011 compared with $1\,448 \cdot 10^3 \text{ m}^3$ in 2010. As the rains came
6 late in 2011, the reservoir was not filled up yet in July at the start of the summer crop, and so
7 there was less irrigation water available.

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

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

1 concentrations were higher and varied from 29 to 94% with an average of 72% for the 14
2 measured events.

3 In the river, the median of the suspended sediment concentration predictions was 300 mg L^{-1}
4 during periods of no rainfall (data not shown). There were no differences in base-flow
5 concentrations between Locations A and B. The river sediment concentrations were very
6 little affected by overland flow as the paddy fields buffered inputs from Hortonian overland
7 flow, and so the maximum concentrations in the river only reached up to $5\,000 \text{ mg L}^{-1}$. Water
8 samples of Location A in the river, upstream of the paddy fields, had on average 61 % sand,
9 22% silt and 17% clay (n=12, Table 2). After paddy discharge, the river sediment texture on
10 average had 47% sand, 33% silt and 20% clay (n=13, Table 2).

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

22

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

1 water. But during July 2011, the month in the study which had the highest rainfall (247 mm),
2 direct overland flow provided almost as much sediments to the paddy fields as irrigation
3 water from the reservoir (62 Mg versus 71 Mg).

4

5 3.3 Sediment budget for paddy fields

6 Irrigation water from the surface reservoir removed 806 Mg of sediment from the reservoir in
7 2010 (Table 3). Of this amount, 646 Mg entered paddy fields through irrigation and 160 Mg
8 were exported from the sub-watershed, as the irrigation channel crosses the watershed border
9 into a neighboring catchment. In 2011, the sediment load from the irrigation water was
10 similar with 762 Mg, of which 612 Mg entered the rice fields, and 150 Mg were exported to
11 the next catchment. Using the average textural class percentages of the surface reservoir
12 outflow, irrigation water can be estimated to have contributed 208 Mg of sand, 208 Mg of silt
13 and 196 Mg of clay to the paddy rice fields in the watershed in 2011 (Table 4). As there were
14 not enough samples analyzed to obtain continuous predictions of the different particle size
15 classes using a regression model, simple averages were used for the texture loads. In this
16 sense, all sand, silt and clay loads are more a semi-quantitative estimate that provides an
17 order of magnitude, rather than an exact figure.

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

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

3 The sediment load exported from the paddy fields on both banks of the river, calculated as
4 the difference between Location A and Location B, was 469 Mg in 2011 (Table 3), of which
5 60% was exported during the spring cropping season, and 40% during the summer crop. As
6 the monitoring station in Location B was only installed in 2011, data for 2010 are not
7 available. Combining all of these loads, the difference between inputs and export from the
8 paddy resulted in a sediment yield of 363 Mg in total, or 28 Mg ha⁻¹ that remained in the
9 paddy fields in 2011. Since the load exported and the net paddy load are differences between
10 positive numbers (loads measured at Location A minus B for the export, and inputs minus
11 export for the net load), the lower limit of the confidence interval for these two estimates can
12 become negative (Table 3). Negative load estimates can be interpreted as net sediment
13 trapping of the paddy area. Looking at the texture-specific loads (Table 4), the sediments
14 exported from the paddies consisted mostly of finer material. Thus, in 2011 approximately
15 326 Mg of silt and 141 Mg of clay were exported from the rice fields. Combining inputs and
16 losses, 315 Mg of sand and 99 Mg of clay remained behind in the paddy fields over the whole
17 year, while a net amount of 52 Mg of silt was lost from the 13 ha paddy area (Table 4).

18

19 3.4 Watershed sediment yield

20 The total sediment yield of the sub-watershed, ending at Location B, was 2 234 Mg in 2011.
21 This amount was exported via two pathways. First, the irrigation canal distributed 150 Mg
22 from the reservoir and 59 Mg from the upland area through overland flow into the
23 neighboring catchment (Table 3, Figure 6). Second, the river exported 2 026 Mg from the
24 sub-watershed at Location B. Of these 2 026 Mg, a total of 469 Mg consisted of runoff from

1 the paddy fields. The remaining 1 556 Mg that was lost through the river, originated from the
2 surface reservoir as water released via the reservoirs spill-over, which allows excess water to
3 flow into the river whenever the reservoirs maximum capacity is reached. For the larger
4 watershed of 200 ha, which contains the aforementioned sub-catchment, the annual sediment
5 yield was 6 262 Mg in 2010 and 5 543 Mg in 2011.

6

7 **4. Discussion**

8 4.1 Upland sediment contribution to the irrigation system

9 The largest peak of suspended sediment concentration found in this study was two to five
10 times higher compared to the highest values found in other SE Asian studies (Ziegler *et al.*,
11 2014; Valentin *et al.*, 2008) and the corresponding event contributed 23% of the total annual
12 sediment load transported by overland flow to the irrigation channel in 2011. The difference
13 in sediment concentration with other studies is most likely due to the more gentle slopes (8 to
14 15 %) present in the watershed study of Valentin *et al.* (2008), whereas steep slopes up to
15 65% are found in our watershed. Both other studies, however, which contain the highest
16 values found for Southeast Asia in literature, also used a storm-based sampling strategy,
17 underscoring the importance of capturing the highest events in order to reliably assess the
18 erosivity of mountainous catchments. Horowitz *et al.* (2014) reported that calendar-based
19 sampling typically underestimates constituent transport, while event-based sampling does
20 not. Capturing the highest peaks is crucial, as the importance of single, high-intensity storms
21 for sediment yield in tropical areas is increasing due to climate change. In the monsoon
22 climates of Southeast Asia, a rise in extreme, high intensity rainfall events is expected (IPCC,
23 2013) and as single large storms already have such a substantial effect on the annual sediment
24 load, in the future they can be expected to dominate annual sediment loads.

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

21

22 4.2 Sediment trap efficiency of paddy fields

23 Surface reservoir water was the largest contributing source to suspended sediment inputs for
24 the paddy fields, with only one quarter of sediment inputs to the paddy fields coming from

1 overland flow in both years. When looking at the sediment quality rather than sediment loads,
2 however, the importance of overland flow increased for sand, with 34% of the total paddy
3 inputs originating from erosion in 2011. Therefore, while irrigation was the main driver
4 behind water and sediment fluxes in this irrigated catchment, overland flow plays an
5 important role in transfers that could affect plant production and long-term soil fertility.

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

16 Comparing inputs to paddy field exports suggests that the rice area trapped 44% of the
17 combined re-allocated sediments from reservoir irrigation water and direct runoff from the
18 upland areas. Similarly, Mingzhou *et al.* (2007) found that the sediment load in the irrigation
19 water resulted in a net deposition, rather than erosion from paddy fields, which led to an
20 additional 4 cm of top soil through irrigation deposits after fifty years of irrigation. While the
21 paddies in our study were a net overall sediment sink, results also showed that the sand
22 fraction was preferentially deposited and was in fact almost entirely captured in the paddies,
23 forming a net deposition of 23 Mg ha⁻¹ a⁻¹. About half of the imported clay remained behind
24 in the fields, or a total of 8 Mg ha⁻¹ a⁻¹. For silt, the overall balance was negative, with 5 Mg
25 ha⁻¹ of silt exported on an annual basis. This preferential deposition is likely to have

1 consequences, as long-term fertility of paddy fields is contingent upon the particle size
2 distribution of the soils for physical soil properties, e.g. clay content exceeding 20% is
3 favorable for puddling (De Datta, 1981). In our study area, top soil in the paddy fields is
4 predominantly silty, with an average of 19% sand, 68% silt and 13% clay (Schmitter *et al.*,
5 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
6 paddies, and a removal of 4 Mg ha⁻¹ a⁻¹ of silt, textural changes can be expected to take place
7 over time. While the clay fraction is expected to add sediment-associated nutrients to the
8 paddies, and thus increase the indigenous nutrient supply for rice, the sand deposits are much
9 larger (76% of all inputs) and will thus drive the long-term fertility changes in paddy topsoil.
10 Assuming a puddling depth of roughly 25 cm and a bulk density of 1.2 g cm⁻³, the sand
11 fraction would dominate after approximately fifty years of these continued inputs. But not all
12 fields would have the same longevity, as sediment inputs do not affect the fields equally.
13 Previous research has shown that sedimentation in rice cascades shows spatial variability, and
14 that fields closest to the water source receive most of the coarse material, the yield declining
15 with decreasing distance to the water source (Schmitter *et al.*, 2010). Thus for certain fields
16 closer to the water source, sand content would increase more rapidly, which is indeed already
17 visible in the study area: paddies higher up on the cascades were often seen to display poor
18 water holding capacity.

19 Similar composite agricultural systems with permanent upland cultivation on the hills and
20 irrigated rice in the valleys contain 60% of the total paddy area in Northern Vietnam (Rutten
21 *et al.*, 2014). Consequently, a large agricultural area is potentially affected by such upland-
22 lowland linkages. Eliminating the direct entry of Hortonian overland flow into the irrigation
23 channel, for example by runoff ditches, is one way to prevent up to one third of the total sand
24 inputs from entering the rice fields and thus to protect the food security of the people in the
25 mountainous areas of Northern Vietnam, who depend on rice as their staple food. This

1 solution is not sustainable in the long run from a systems-approach perspective, as the
2 fertility loss of the uplands would affect income when the cash crop income is declining. But
3 with the current high maize prices, it is challenging to identify sustainable hillside land uses
4 that are attractive to local stakeholders (Keil *et al.*, 2008), and deviating direct runoff from
5 entering the paddies would at least be an interim solution. It would, however, also lead to
6 substantial losses of nutrients (Dung *et al.*, 2008) which could not be recycled.

7

8 4.3 Buffer capacity of the reservoir

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

21 The water in the reservoir also had a lower sand and higher silt and clay content, and
22 sediment profiles in the lake indeed confirmed this preferential settling of coarse material.
23 Weiss (2008) showed that soil profiles taken at the lake bottom had a sediment texture of
24 between 40 and 75% sand, 20 to 50% silt and 5 to 14% clay. The reservoirs filtering effect

1 can be expected to be stronger beyond the watershed, as coarser particles will be trapped
2 preferentially in closer vicinity to the source. While large enough to substantially affect rice
3 production, the amount of sediments trapped by the paddy fields is moderate (12%) compared
4 to the total amount exported from the watershed by reservoir spillover export. In light of
5 these proportions, effects of climate change and declining soil fertility in upland areas will
6 not remain on-site but can be expected to propagate beyond the watershed, and also affect
7 areas further downstream.

8

9 **5. Conclusion**

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

23 Our results show the importance of quantifying upland-lowland linkages within and between
24 watersheds, and can be used by scientists, policy makers and extension services to give

1 suitable recommendations to the large group of people in mountainous Southeast Asia who,
2 under influence of population pressure, have gone from practicing composite swidden
3 agriculture to an intensified cropping system with permanent maize cultivation on the hills.
4 Preventing overland flow from reaching the paddy fields, for example, could prevent up to 8
5 Mg ha⁻¹ a⁻¹ of sand per year, or one third of the total sand deposits, from entering the rice
6 fields. More diversified, sustainable and acceptable approaches, however, benefitting both
7 upland fields as well as downstream paddies, need to be developed at the same time.

8

9 **6. Data availability**

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

14

15

16

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3

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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,

1 resulting in 2000 bootstrap sediment rating curves, and thus 2000 time series
2 predictions of continuous suspended sediment concentration;

3 3. Adding a simulated error term to the concentration predictions to account for inherent
4 residual scatter in the data and to facilitate the back-transformation from the log-scale.

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1 **10. Tables**

2 Table 1: Number of observations (n), coefficient of determination (R^2) and method used for
 3 stage-discharge relationship (Q); and number of observations and Pearson’s correlation
 4 coefficient (r^2) after five-fold cross-validation for suspended sediment concentration
 5 predictions (SSC). Details on the linear mixed model development can be found in Slaets *et*
 6 *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 |

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8

- 1 Table 2: Average sediment particle size distribution measured at the different measurement
- 2 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 |

3

4

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

| Sediment source | Sediment load (Mg a^{-1}) | | | | | |
|-----------------------------|--------------------------------------|-------------------|------|-------|---|-------|
| | 2010 | | | 2011 | | |
| | 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 $\text{Mg ha}^{-1} \text{ a}^{-1}$ | |

6

7 nd = not determined

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1 Table 4: Texture -specific sediment inputs from irrigation water and overland flow from the
 2 37 ha upland area in the sub-watershed, and texture-specific sediment export and trapping by
 3 the 13 ha paddy area (Figures 1 and S1).

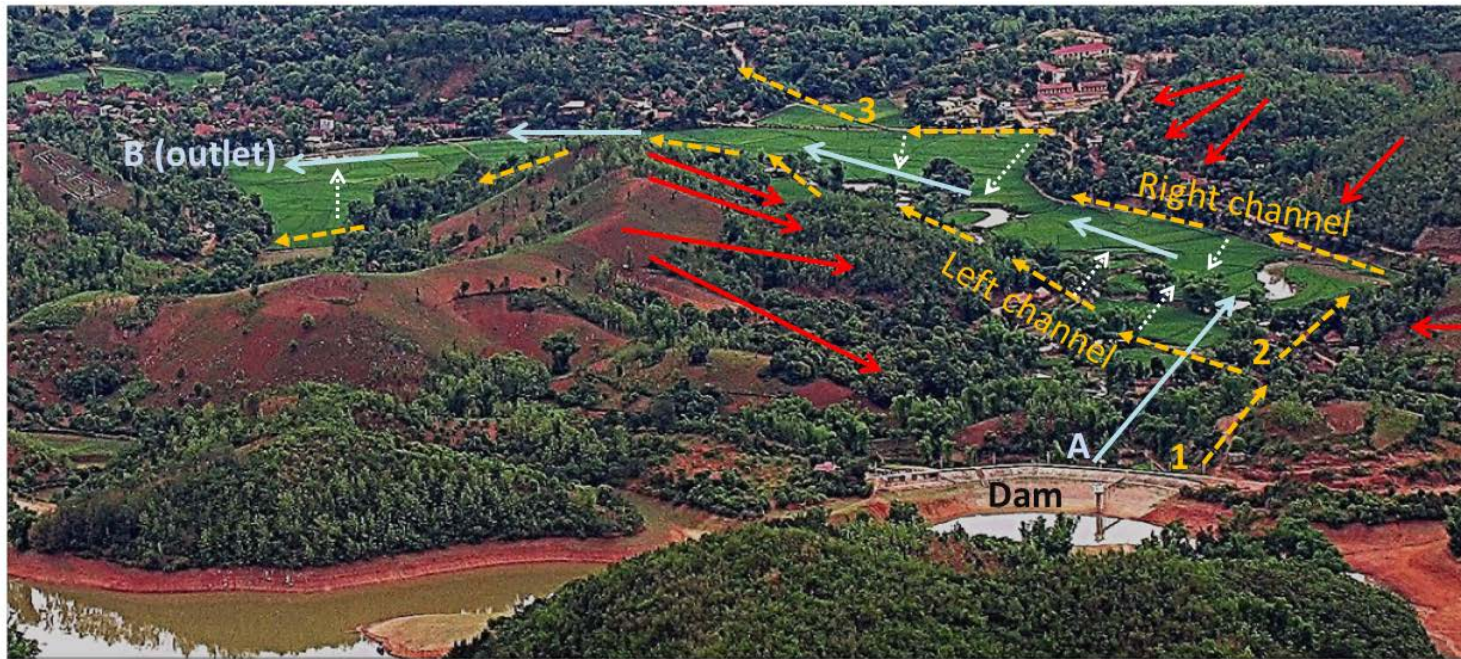
| Sediment source | Load (Mg a⁻¹) | | | | | |
|-----------------------------|---------------------------------|-------|-------|------------|-------|-----------|
| | 2010 | | | 2011 | | |
| | Sand | Silt | Clay | Sand | Silt | Clay |
| Reservoir water: | | | | | | |
| Total to channels ... | 274 | 274 | 258 | 259 | 259 | 244 |
| ... irrigated to paddies | 220 | 220 | 207 | 208 | 208 | 196 |
| | (70%) | (79%) | (84%) | (66%) | (76%) | (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 | 58 | 39 | 109 | 66 | 44 |
| | (30%) | (21%) | (16%) | (34%) | (24%) | (18%) |
| ... exported via channel | 28 | 17 | 11 | 30 | 17 | 12 |
| Paddy input (100%) | 316 | 278 | 246 | 317 | 274 | 240 |
| Paddy outflow | nd | nd | nd | 2 | 326 | 141 |
| Net paddy balance | nd | nd | nd | +315 (99%) | -52 | +99 (40%) |

4

5 nd = not determined

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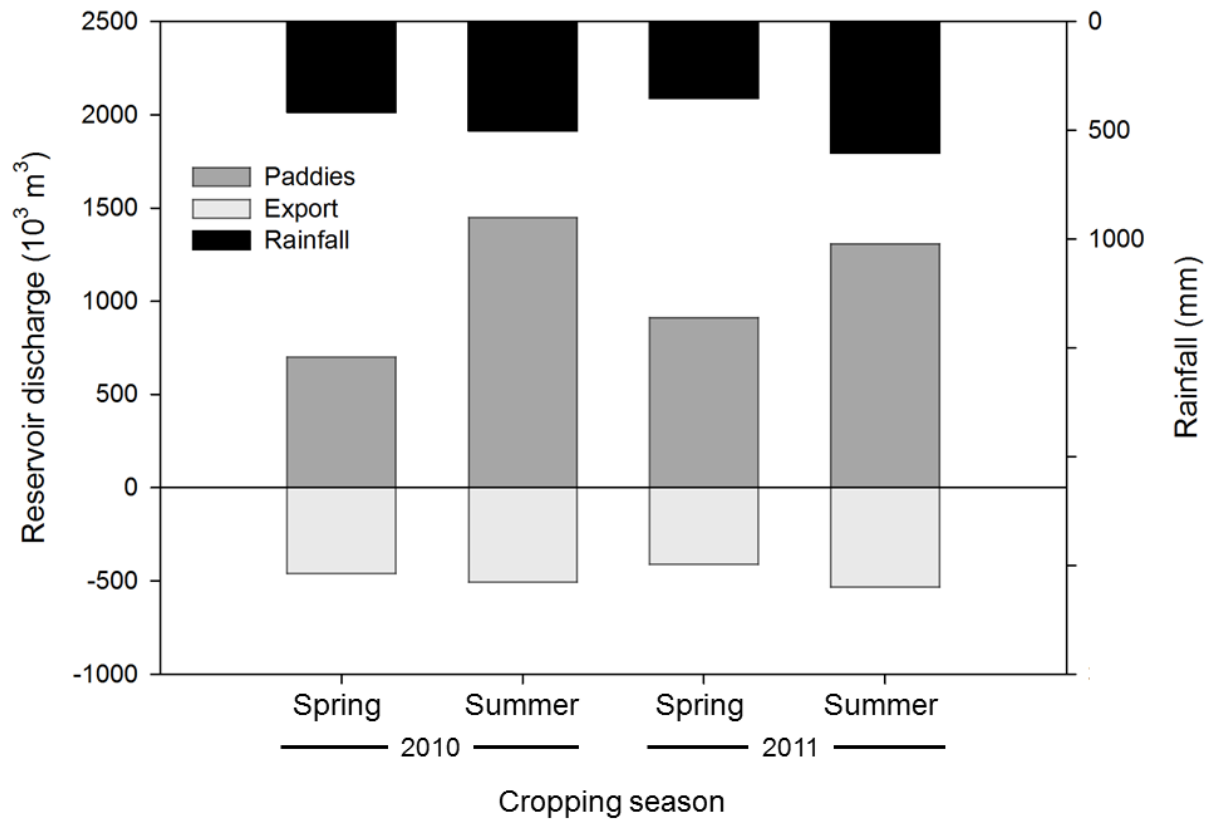
1 **11. Figures**



2

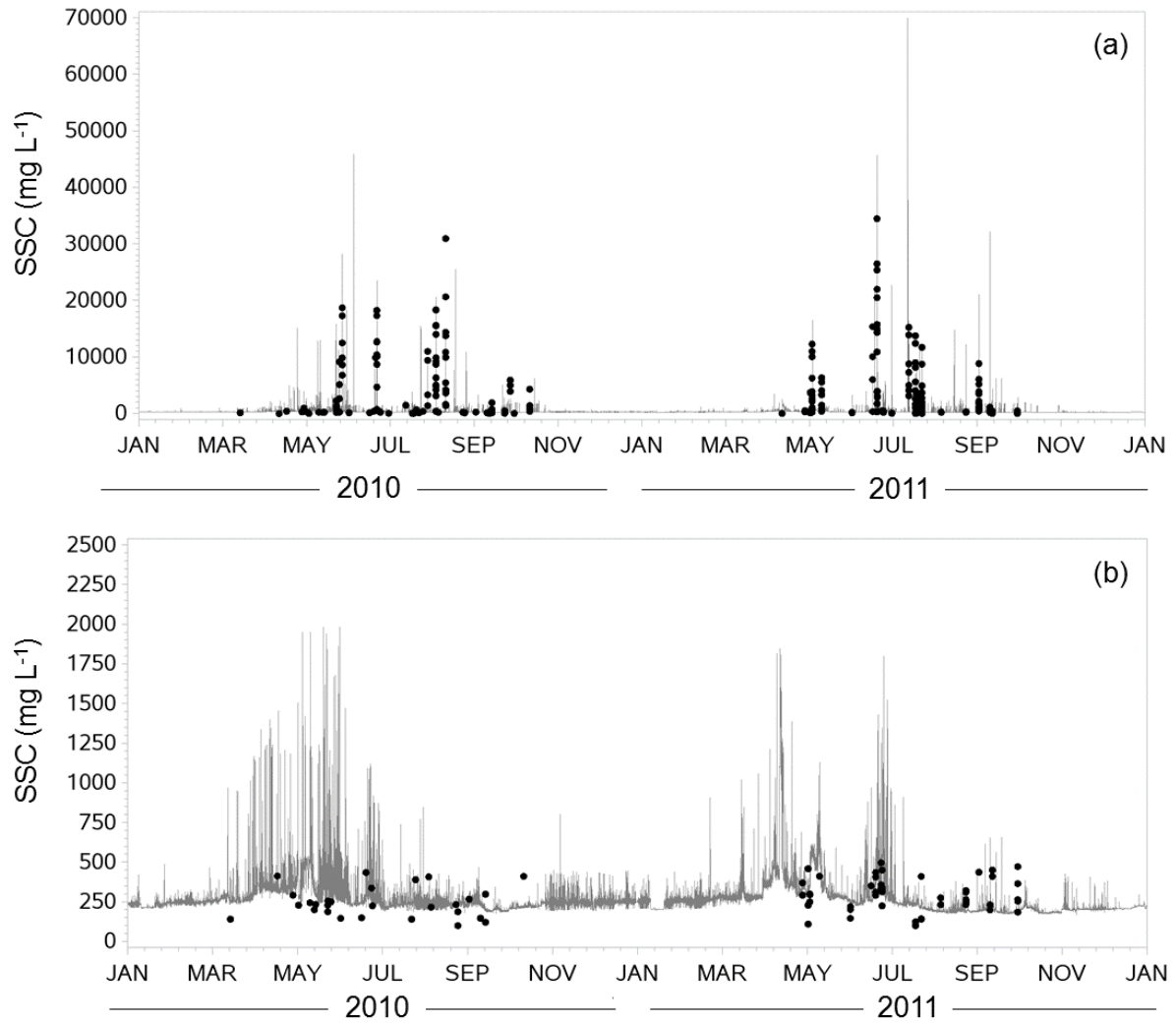
3 Figure 1: Sediment sources and water flows into and out of paddy rice fields in Chieng Khoi watershed. The dotted yellow arrows show the
4 irrigation channel leaving the reservoir and splitting in two, feeding the two banks of paddy rice. The rice fields subsequently drain into the river,
5 which is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

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



1

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



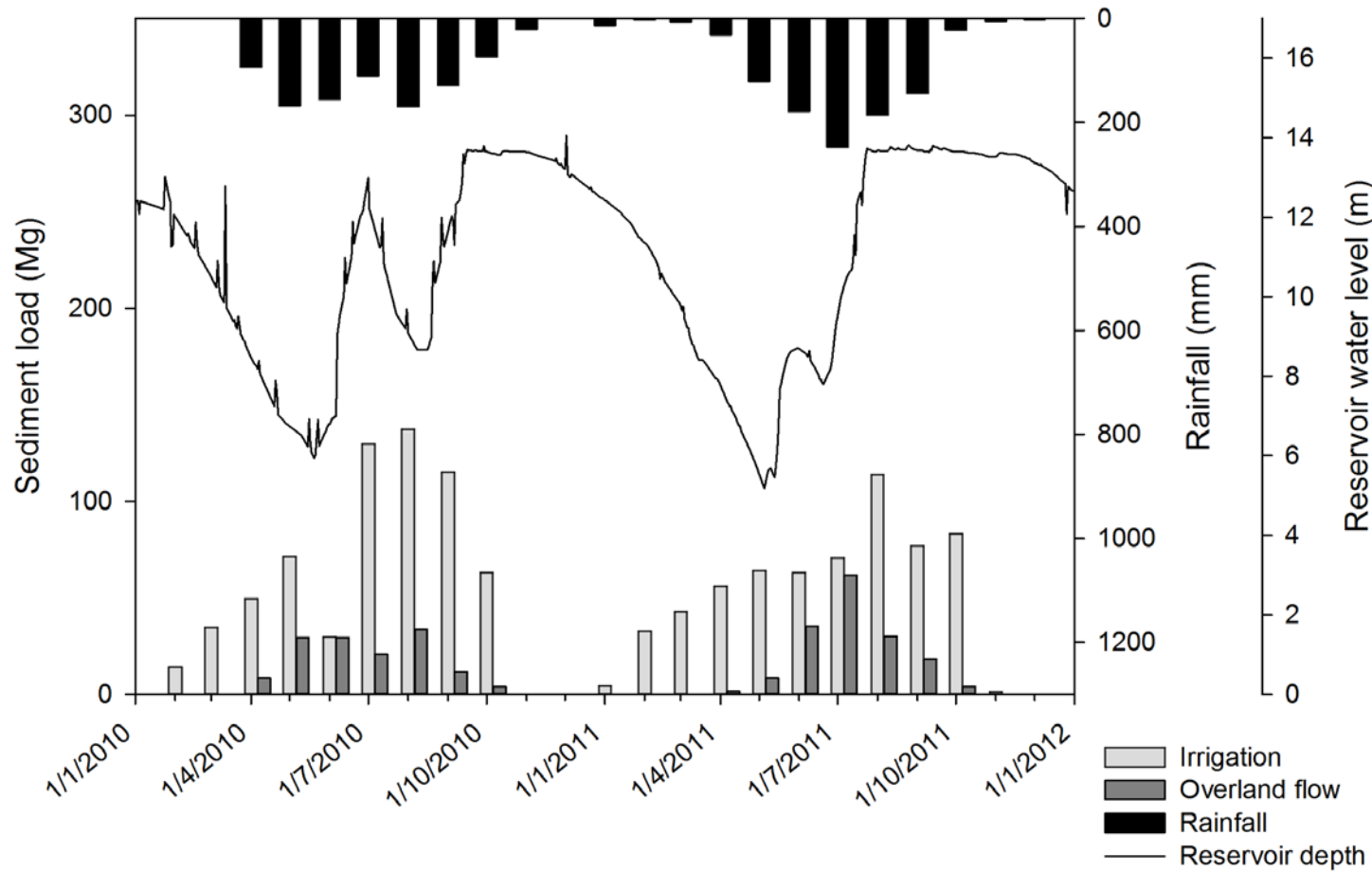
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2 Figure 3: Observed and predicted sediment concentrations (in mg L⁻¹) for Location 3 in the
 3 irrigation channel (a), and zooming in on base-flow, showing only non-event samples and
 4 concentration predictions (b).

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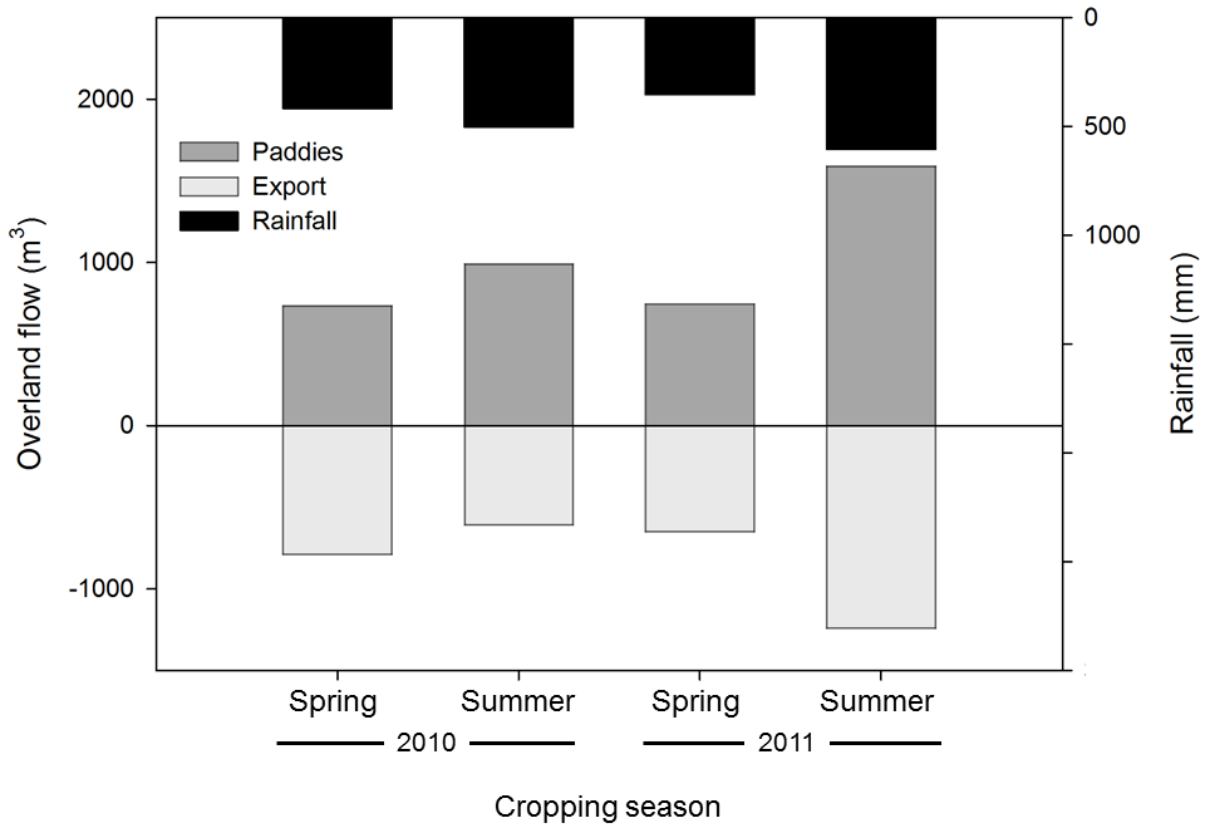
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2 Figure 4: Monthly variations in rainfall, reservoir water level, and sediment load inputs to the paddy fields, both from the surface reservoir and
 3 from overland flow.

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

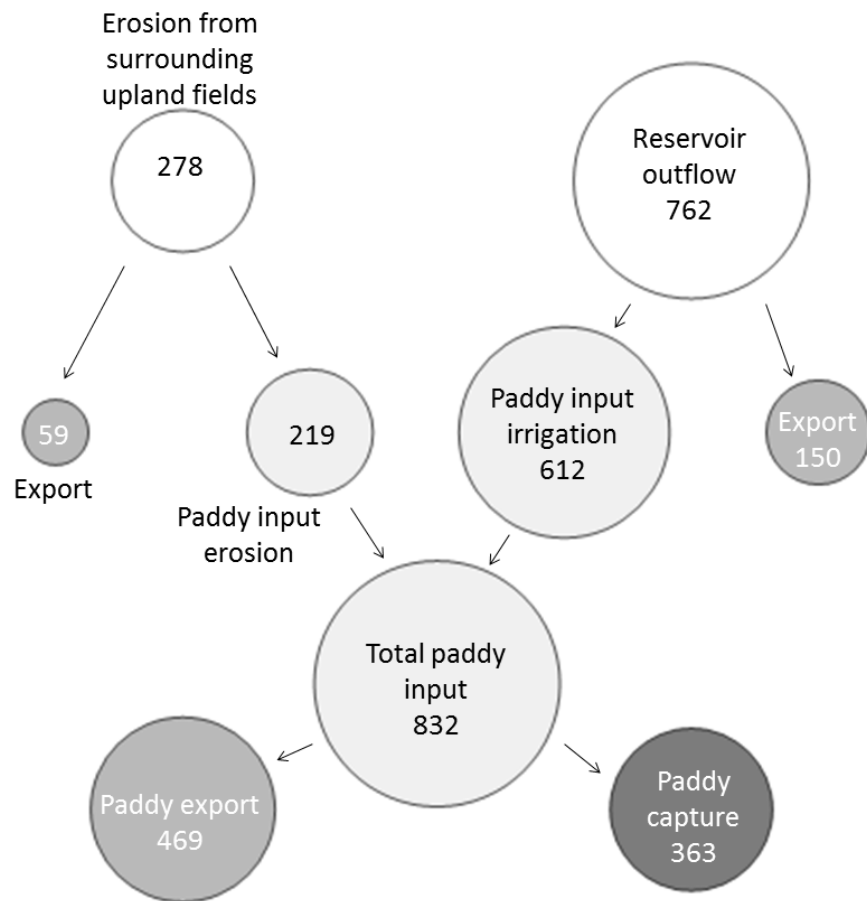
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3 Figure 6: Sediment flow chart for 2011. Bubble size corresponds to size of the sediment load
 4 (in Mg a^{-1})