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Redistribution of carbon and nitrogen through irrigation in intensively cultivated tropical mountainous watersheds

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Abstract This study aimed at tracing and quantifying organic carbon and total nitrogen fluxes related to suspended material in irrigation water in the uplands of northwest Vietnam. In the study area, a reservoir acts as a sink for sediments from the surrounding mountains, feeding irrigation channels to irrigate lowland paddy systems. A flow separation identified the flow components of overland flow, water release from the reservoir to the irrigation channel, direct precipitation into the channel, irrigation discharge to paddy fields and discharge leaving the sub-watershed. A mixed effects model was used to assess the C and N loads of each flow component. Irrigation water had an average baseline concentration of 29 ± 4.4 mg l^{-1} inorganic C, 4.7 ± 1.2 mg l^{-1} organic C and 3.9 ± 1.6 mg l^{-1} total N. Once soils were rewetted and overland flow was induced, organic C and total N concentrations changed rapidly due to increasing sediment loads in the irrigation water. Summarizing all monitored events, overland flow was estimated to convey about 63 kg organic C ha^{-1} and 8.5 kg N ha^{-1} from surrounding upland fields to the irrigation channel. The drainage of various non-point sources towards the irrigation channel was supported by the variation of the estimated organic C/total N ratios of the overland flow which fluctuated between 2 and 7. Nevertheless, the majority of the nutrient loads (up to 93–99%) were derived from the reservoir, which served as a sediment-buffer trap. Due to the overall high nutrient and sediment content of the reservoir water used for irrigation, a significant proportion of nutrients was continuously reallocated to the paddy fields in the lowland throughout the rice cropping season. The cumulative amount of organic C and total N load entering paddies with the irrigation water between

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May and September was estimated at 0.8 and 0.7 Mg ha^{-1}, respectively. Therefore deposition of C and N through irrigation is an important contributor in maintaining soil fertility, and a process to be taken into account in the soil fertility management in these paddy rice systems.

Keywords C and N flows · Flow proportional · Irrigation · Overland flow · Paddy fields · Vietnam · Water quality

Introduction

In tropical mountainous regions of southeast Asia, increasing population pressure and enhanced market access resulted in a rapid deforestation and land use intensification on steep slopes (Dung et al. 2008; 2005; Valentin et al. 2008; Ziegler et al. 2009). In Vietnam, from a total land area of 33 million ha, 75% are located in mountainous and hilly regions off which 50% are used for agriculture (The World Bank & The Danish Agency for International Development 2002). One of the most common agro-ecosystems in northern Vietnam is composite swidden agriculture (Dung et al. 2008; Lam et al. 2005; Ziegler et al. 2009) which consists out of an alternation of fallow and cash crops in the upland areas (e.g. maize and cassava) in combination with permanent paddy fields at the lower slopes and valley bottoms. Over the last decades the duration of the fallow periods has been reduced and composite swidden agriculture has been replaced by permanent annual cropping systems which resulted in accelerated land degradation through erosion and nutrient losses (Dung et al. 2008; Pansak et al. 2008; Vezina et al. 2006; Ziegler et al. 2009), and changes in catchment hydrological behavior due to landscape fragmentation (Ziegler 2007).

Sediment and associated nutrient transport depend on soil and land use type, slope and landscape fragmentation (Valentin et al. 2008; Van De et al. 2008; Ziegler et al. 2007), and can cause negative on- (e.g. soil fertility reduction and crop productivity decline) and off-site (e.g. stream pollution and reservoir siltation) impacts at catchment level (Berka et al. 2001; Havens et al. 2001; Lu and Higgitt 2001; Pansak et al. 2008; Wezel et al. 2002). Van Oost et al. (2007) estimated that globally 1 Pg year^{-1} of organic carbon (C) is lost by erosion from agricultural land and found ranges of organic C losses between 30 and 300 kg ha^{-1} year^{-1} depending on land use, cultivation practices and watershed characteristics. Lal (2003) reported considerably higher rates of organic C redistributed worldwide by water erosion ranging between 4 and 6 Pg year^{-1} of which 2.8–4.2 Pg year^{-1} was transferred to lowland areas.

Climate change studies have pointed out that extreme rainfall events and an increase in drought periods will continue to occur (Bates et al. 2008; Cruz et al. 2007). Water demand for agricultural and non-agricultural use will continue to increase although water availability will be challenged in the future (Xiong et al. 2010). Cruz et al. (2007) stated that due to water scarcity, rice yields will drop at the end of the twentyfirst century by 3.8% in Asia. As rice is the main staple food in southeast Asia, seasonal water shortage will call for expansion and improvement of irrigation systems as well as water management in order to meet the increasing food demand (Hatcho et al. 2010; Kirby and Mainuddin 2009; Turral et al. 2010). Besides surface water induced erosion and sedimentation patterns in the landscape, the presence of irrigation systems can contribute additionally to the redistribution of nutrients within irrigated lowlands. The contribution of irrigation water in terms of nutrient and sediment deposition is highly influenced by irrigation channel gradient (Mingzhou et al. 2007) and irrigation scheme (King et al. 2009; Poch et al. 2006). In Sacramento valley (USA), furrow irrigation in an intensively cultivated watershed resulted in a net input of 2 Mg sediment ha^{-1} year^{-1} (Poch et al. 2006) and 0.03 total C Mg ha^{-1} year^{-1} from which the majority was delivered during rainfall events. Furthermore the study showed a net loss of 0.005 total N Mg ha^{-1} year^{-1} due to runoff created during irrigation after fertilization (King et al. 2009). In China, Tang et al. (2008) reported an averaged input of 0.02 Mg total N ha^{-1} year^{-1} in paddy fields from irrigation water in an intensively cultivated watershed. While small and moderate nutrient-rich sediment deposition on downstream located farmland such as paddy fields might be beneficial, large nutrient-poor sediment delivery could decrease the original soil fertility (Cassel et al. 2000; Mingzhou et al. 2007; Schmitter et al. 2010).

The purpose of this study was to assess the redistribution of C and N through irrigation water in intensively cultivated mountainous regions of northwest Vietnam and to evaluate the contribution of rainfall induced runoff from upland areas on additional irrigated C and N loads. The specific aims were (i) to separate the measured discharge in the irrigation channels into the different flow components and their role in redistributing C and N loads (e.g. overland flow, direct rainfall, inlet, outlet and irrigation discharge), (ii) to evaluate the role of an irrigation system with regards to sink and sources of C and N into the lowland, and (iii) to estimate the vulnerability of irrigated lowlands during the rainy season with regards to nutrient fluxes.

Materials and methods

Experimental site and hydrological characterization

The assessment of carbon and nitrogen loads in the irrigation water was carried out from May till September 2008, during the rainfall season in the Chieng Khoi commune, Yen Chau district, Son La province, northwest Vietnam. As the area is located in the tropical monsoon belt, the rainy season starts in April and can last till September–October. Especially at the end of the rainy season the occurrence of typhoons is not uncommon where daily rainfall amounts can rise to 200 mm.

In the south of the Chieng Khoi catchment, a stream originating from Karst mountains was dammed in 1962, resulting in a lake with a capacity of 1×10^6 m^3, which currently serves as an irrigation reservoir (Fig. 1). The contributing area of intensively cultivated uplands to the reservoir is approximately 490 ha. The maximum water level of the reservoir is 12.25 m and the fluctuations strongly depend on rainfall and irrigation requirements. Construction of open-channel irrigation systems made intensification of rice production in the area possible by providing enough water for surface irrigation in the dry season to allow a spring (February/March–June/July) besides a summer rice season (July–October/November). The reservoir is feeding a main irrigation channel which splits after 200 m in two irrigation channels supplying irrigation water to 60 ha of paddy rice. The streambed of the open-channel irrigation system under study was made out of concrete. Additionally, the spillover of the reservoir feeds the dammed stream during July–September when the reservoir fills up completely. Outside of this period, runoff, interflow and baseflow mainly originating from the irrigated rice fields are the only contributing processes influencing the river discharge.

The present study focused on a subwatershed within the Chieng Khoi catchment which consisted out of 17.1 ha of upland area draining toward the irrigation channel and 6.5 ha of irrigated paddy area fed by the channel. The irrigation water used in this area is supplied by one of the two irrigation channels originating from the reservoir (Fig. 1). In the subwatershed, the upland area is characterized by steep upland hills (i.e. slopes up to 86%) which are intensively cropped with maize (*Zea mays* L.) and cassava (*Manihot esculenta* Crantz) from March until December. The parent material is often silt-fine sandstone and limestone and the two major occurring soil types in the upland area are alisols and luvisols (Deckers et al. 1998). In the lowland, the soils are classified as anthraquic anthrosols on which paddy rice (*Oryza sativa* L.) is the major cultivated crop, in some areas for up to 200 years.

Total organic carbon and total nitrogen fluxes in irrigation water

Rainfall was monitored every 2 min and summarized every 10 min by a weather station (Campbell Scientific, UK) which included a tipping bucket rain gauge with a precision of 0.1 mm. In 2008, the total rainfall amounted to 1,054 mm of which 720 mm fell within the measured period (May till September 2008). As the irrigation channel was of concrete, the baseflow and interflow of the upland area could be neglected as extra input sources as well as percolation losses from the bed with regards to outflow components. Within the channel, two automatic water samplers were installed: (i) at the inlet of the concrete irrigation channel (upper gage) after the split of the main irrigation channel and (ii) at 1.1 km downstream from the inlet, leaving the delineated studied subwatershed (lower gage) (Fig. 1). This set up assisted in differentiating the amount and quality of the water coming from the reservoir (upper gage) and the water from the surrounding uplands along the irrigation

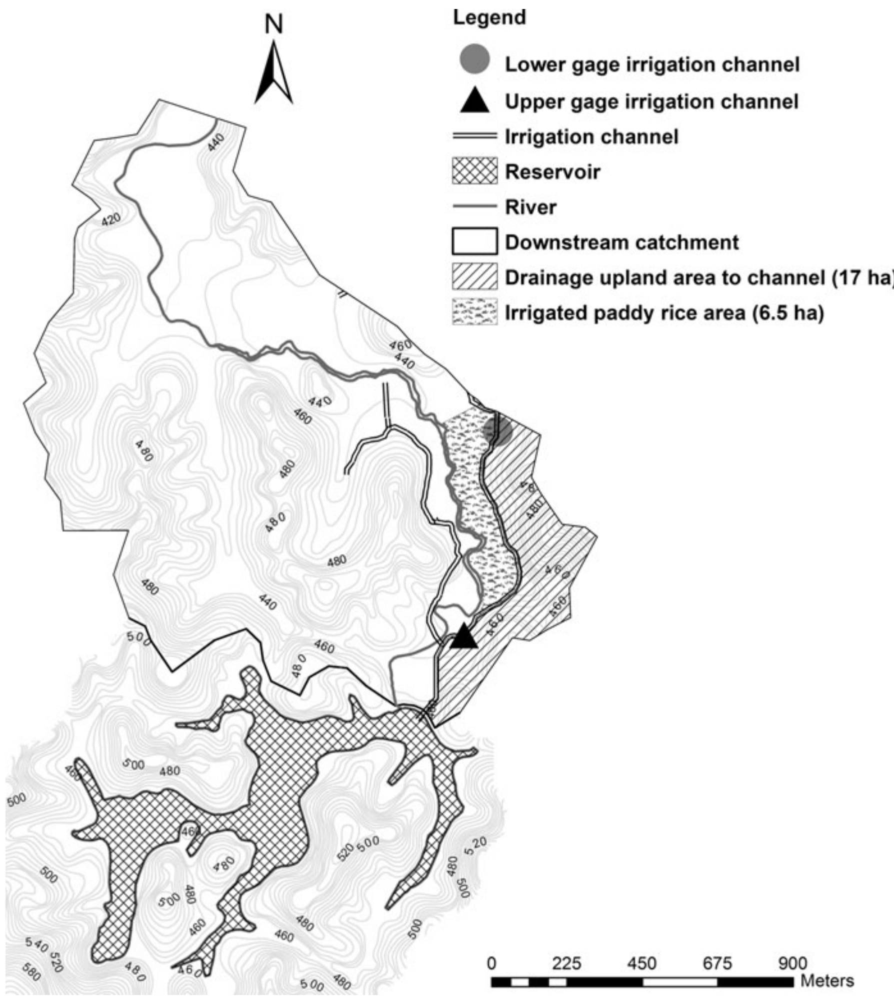

Fig. 1 Overview of the position of both automatic water samplers (upper gage and lower gage, *black triangle* and *grey circle*, respectively) along one of the irrigation channels within the Chieng Khoi watershed (Son La province). The marked area above the irrigation channel delineates the upland drainage area towards the channel while the area between the irrigation channel and the river marks the paddy area that is irrigated between both measurement stations

channel. In total 25 events, covering various average rainfall intensities ranging between 0.1 and 11 mm h^{-1} and different rainfall amounts, fluctuating between 0.1 and 30 mm were sampled at both sampling stations. During each rainfall event, sampling was carried out flow proportionally at both measurement stations (Fig. 1) using automatic water samplers (Maxx Mess-und Probennahmetechnik GmbH, Germany) which were connected with ultrasonic sensors (Nivus GmbH, Germany) for water level measurements. Water levels were automatically converted to discharge using a calibrated stage-discharge curve. Five flow proportional samples each of 50 ml were combined into one flask creating a composite flow proportional sample. The amount of composite samples taken during rainfall events depended on rainfall duration and discharge in the channel (Table 1). Each monitored event started with a baseline sample before rainfall started and ended when the baseline was reached after a rainfall event. Furthermore, baseline samples were taken in a biweekly interval throughout the measurement period May–September 2008. In total 419 composite samples were taken, frozen to avoid C and N losses, and analyzed for total N, inorganic and organic C by combustion using a LiquitocII C and N analyzer (Elementar Analysensysteme GmbH, Germany). Inorganic C was measured at 32°C after acidification with HCl while total organic C and total N was measured by combustion until 800°C.

Table 1 Event mean concentration (EMC; mg l^{-1}) for organic C and total N, total rainfall (mm), average rainfall intensity (mm h^{-1}), rainfall duration (min), rainfall amount of the event preceding the measured event (pre-rainfall, mm), time between the rainfall event studied and the previous rainfall event (time pre-rainfall, h) and total amount released from the reservoir into the irrigation channel (discharge reservoir, m^3) for all measured events at the two measurement stations (upper and lower gage)

Event (No.)	Date	No.[a]	R[b] (mm)	Average RI[b] (mm h^{-1})	Duration R[b](min)	Discharge reservoir (m^3)	Time pre-R[b] (h)	Pre-R[b] (mm)	EMC organic C (mg l^{-1})		EMC Total N (mg l^{-1})	
									Upper[c]	Lower[c]	Upper[c]	Lower[c]
1	04/05	7/5	1.2	0.5	160	1016	70.5	3.7	5.1	6.2	2.1	2.5
2	05/05	10/12	20.7	11.6	110	3313	17.0	1.2	3.7	115.7	2.1	15.5
3	06/05	5/5	0.7	1.1	40	966	28.8	17.4	4.3	7.4	2.1	2.4
4	07/05	10/16	0.9	0.5	120	2679	20.0	0.7	3.6	5.1	2.2	2.6
5	09/05	10/12	12.0	10.3	70	1832	18.5	0.3	3.7	33.9	1.7	5.9
6	30/05	9/11	12.2	2.2	340	2749	92.0	0.2	4.2	9.3	1.8	2.9
7	31/05	5/6	0.2	0.3	40	1152	3.0	12.2	2.7	3.4	1.4	1.2
8	05/06	3/4	3.2	9.6	20	1119	8.2	6.4	4.1	6.6	1.8	2.3
9	05/06	5/7	18.8	5.6	200	1713	2.5	3.2	12.7	64.6	3.7	12.3
10	08/06	3/4	0.8	1.6	30	864	17.5	2.4	4.0	4.5	1.8	1.9
11	08/06	3/12	0.7	0.7	60	780	6.3	0.8	4.6	5.1	2.1	2.0
12	11/06	7/12	22.3	7.9	170	2173	42.5	0.6	29.3	117.7	4.4	17.5
13	11/06	5/6	0.2	0.3	40	965	2.5	22.3	4.9	8.4	1.6	3.2
14	12/06	4/6	1.1	0.7	100	623	7.3	0.2	4.9	3.8	3.0	1.9
15	12/06	3/5	0.4	0.8	30	488	1.2	1.1	2.5	4.7	2.0	2.5
16	14/06	12/16	30.7	8.0	230	3680	6.3	3.2	17.5	68.6	4.6	10.3
17	15/06	5/5	1.3	0.8	100	1167	9.3	0.2	4.8	6.5	3.0	3.4
18	18/06	3/4	0.2	0.6	20	267	7.7	0.8	3.7	7.2	4.2	4.6
19	25/06	5/9	12.5	5.1	180	1657	37.2	4.0	3.6	14.0	5.3	6.3
20	27/06	3/6	1.8	3.6	30	244	36.3	0.5	3.3	4.6	4.8	5.1
21	27/06	3/5	0.7	0.5	90	303	1.0	1.8	3.3	4.4	4.7	4.6
22	03/07	9/6	1.7	1.8	120	2932	13.8	2.1	3.2	3.9	4.8	4.6
23	07/07	6/7	12.0	5.5	130	1478	15.5	28.1	5.9	34.4	5.1	8.8
24	30/08	4/4	23.1	8.2	170	9593	30.3	2.1	4.5	6.5	5.1	5.8
25	03/09	5/5	10.4	3.5	360	15311	80.5	23.1	4.7	4.4	5.1	5.2

[a] Number of samples taken per event at the upper gage and lower gage, respectively

[b] R and RI referring to rainfall and rainfall intensity, respectively

[c] Upper and lower referring to the upper and lower measurement stations along the irrigation channel, respectively

Data analysis

The data analysis was designed to carry out a flow component separation (overland flow, direct rainfall, inlet, outlet and irrigation discharge). This allowed (i) characterizing and classifying rainfall events based on the different flow components and their effect on mean inorganic and organic C and total N concentrations for each event (i.e. event mean concentration, EMC), (ii) calculating the loads of total N, inorganic and organic C associated to these components, and (iii) evaluating the nutrient loads irrigated to the paddy fields and leaving the watershed at the outlet.

Event definition

Cross correlation analysis was used to quantify the temporal lag between peaks in rainfall time series and discharge time series at the outlet. According to Biron et al. (1999) stationary event time series were established out of the original precipitation and flow time series through least-squares regression with time as predictor variable by adding the model residuals to the mean values of the respective time series. The calculated lag times were interpreted as reaction time of the hydrologic system under study. Rainfall events were consecutively defined to last from start to finish of periods of continuous precipitation and appending the calculated lag times to the end of these periods. Periods of continuous precipitation were defined as not being intermitted by periods of no precipitation longer than 30 min.

Flow component calculation

As the irrigation channel monitored in this study was constructed out of concrete, baseflow and interflow were excluded from the calculation of the flow components. With this precondition the hydrological system can be described as follows:

$$Q_{pp} + Q_{in} + Q_{of} = Q_{irr} + Q_{out} \tag{1}$$

where Q_{pp} (m^3) is the direct precipitation into the stream channel, Q_{in} (m^3) the gaged outflow from the reservoir (upper gage), Q_{of} (m^3) the overland flow discharging into the stream channel from adjacent slopes between the two gages, Q_{irr} (m^3) the amount of water used for irrigation of the paddy fields situated between the upper and lower gage and Q_{out} (m^3) the measured outflow at the lower gage. Q_{pp} (m^3) was calculated multiplying the channel surface area by precipitation. For all further analyses Q_{in} was shifted two time steps forward (10 min per time step) according to an observed overall lag time of 20 min between Q_{in} and Q_{out}. During dry periods, i.e. in absence of Q_{pp} and Q_{of}, Q_{irr} was calculated at time step i by subtracting outflow at the lower gage from outflow from the reservoir:

$$Q_{irr,i} = Q_{in,i} - Q_{out,i} \tag{2}$$

During rainfall events, where Eq. 1 has two unknowns (i.e. Q_{irr}, Q_{of}), Q_{irr} was assumed the product of pre-event irrigation rates and the relative change in reservoir release (Q_{in}) due to irrigation management since the onset of the event:

$$Q_{irr,i} = (Q_{in,pre} - Q_{out,pre}) \times \left(1 + \left((Q_{in,i} - Q_{in,pre})Q_{in,pre}^{-1}\right)\right) \tag{3}$$

with subscript pre denoting the last time step preceding the event. The partitioning of inputs from Q_{in} into contributions to Q_{out} and Q_{irr} was thus kept constant during the event and Q_{of} subsequently calculated recalling Eq. 1.

Event characteristics

For exploratory data analysis and the subsequent mixed effects model, all events were characterized by hydrological and hydrochemical parameters. The former comprised average precipitation intensity, cumulative precipitation amount and duration, cumulative flow component discharges and preceding rainfall conditions (i.e. time to the preceding event and cumulative rainfall of the preceding rainfall event). The latter included total N, inorganic and organic C minimum and maximum concentrations of the two gages, flow component loads and *EMC*, which allowed cross event intercomparison, calculated according to:

$$EMC = \left(\sum Q_j \times C_j\right) / \left(\sum Q_j\right) \tag{4}$$

with Q_j the discharge (m^3) for a composite sample j during an event and C_j the corresponding concentration (mg l^{-1}) of a water parameter (e.g. inorganic C, organic C and or total N).

Within each event, for each composite sample, the load for all water parameters was calculated for each measurement station according to:

$$L_j = (C_j \times Q_j)/1000 \tag{5}$$

where L represents the total N, inorganic C or organic C load (kg) for a composite sample j. These calculations were done for both water sampling stations. The use of subscript i in Eqs. 2–3 denote the equidistant discharge measurements (10 min) and the time period for the composite sample respectively while j varies in accordance with flow proportional sampling. The load for the irrigation component was estimated with the assumption that the concentration of irrigation water equals the concentration of outflow, implying that all input sources mix fully at the uppermost point of the stream segment between the two gages. This approach was based on the observation that loads from overland flow in the lower part of the stream segment contributed much less to irrigation water due to absence of favouring landscape features (e.g. roads). Overall, the initial assumption holds, if the irrigation load is interpreted as maximum possible load. With the same degree of uncertainty, the load of overland flow was calculated by subtracting the loads of rain and reservoir outflow from the sum of the loads of irrigation discharge and lower gage outflow. Event loads for each flow component where calculated by summarizing all composite sample loads within the event.

Using the average baseline concentration of organic C and total N in the irrigation water measured before each rainfall event, the contribution of a rainfall event to the overall load at the point of interest (e.g. upper gage, lower gage and irrigation water) can be calculated according to:

$$L_{irr,R0} = \left(C_{irr,R0} \times Q_{irr}\right)/1000 \quad (6)$$

$$D_L = L_{irr} - L_{irr,R0} \quad (7)$$

$L_{irr,R0}$ represents the cumulative baseline load irrigated during an event assuming baseline (pre-event) concentrations $C_{in,R0}$ and event cumulated Q_{irr}. D_L, the difference between L_{irr} (Eq. 5) and $L_{irr,R0}$ reveals the irrigation load, which can be attributed to flow processes connected to the rainfall event, which can also be expressed as an event load factor [%], when normalized by L_{irr}.

Mixed effects model

A general description of the different flow components and associated variation of total N, inorganic and organic C concentrations and loads for all 25 events was obtained by using the procedure Univariate in SAS v9.2 (Liu et al. 2004). The Spearman rank correlations between the discharge of the different flow components, water level at the reservoir and the total N, inorganic and organic C loads were calculated by running the procedure CORR in SAS v9.2. The results were used to exclude correlated variables when developing the mixed effect model.

In order to extrapolate the contribution of the 25 sampled events on the irrigation water diverted to the paddy fields between upper and lower gage and the load leaving the lower gage, over the entire monitored season (May till September), a mixed effects model was built for total N, inorganic and organic C using the procedure MIXED in SAS v9.2. Previous studies have pointed out the linkage between load estimation and discharge components in natural rivers using multiple linear regression or generalized linear models (Cox et al. 2008; Haggard et al. 2003; Stenback et al. 2011). Filling time of a composite sample influences the load calculation due to the effect of cumulative discharge fluctuations as the samples are taken flow proportionally. Therefore the MIXED procedure was chosen in this study where filling time for each composite sample was taken as a random effect. Within the model, reservoir level, average rainfall intensity, cumulative irrigation discharge to the paddy fields, overland flow discharge and discharge at the lower gage, were taken as fixed effects. As samples were taken flow proportionally, there is a time dependency between the samples of one event. Therefore, all samples taken within the event were treated as a repetition. The calculated loads for each water parameter and discharge data were log normal transformed in order to obtain homogeneity of variance and normal distribution among the residuals. The model used was:

$$\ln(y) = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5 + e \quad (8)$$

where y is the total N, inorganic or organic C load (kg event^{-1}) of the irrigation water or passing through the lower gage, respectively; α is the intercept; β_1, β_2, β_3, β_4 and β_5 the regression coefficients; x_1 the average rainfall intensity (mm h^{-1}) during bottle filling; x_2 the log normal transformation of the cumulative discharge irrigated to the paddy fields between the upper and lower gage (m^3); x_3 the log normal transformed cumulative overland flow; x_4 the log normal transformation of cumulative discharge passing through the lower gage and x_5 the water level in the reservoir during the event (m). In order to evaluate the impact of rainfall events on load contribution, the factor describing the average rainfall intensity (x_1) and overland flow (x_3) equalled zero. Therefore the percent change can be estimated using:

$$R = [\exp(\alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_5 x_5)/ \exp(\alpha + 0 + \beta_2 x_2 + 0 + \beta_4 x_4 + \beta_5 x_5)] \quad (9)$$

$$C_R = (R - 1) \times 100 \quad (10)$$

with R the ratio between the prediction of the model using the average of each covariate (x_1, x_2, x_3, x_4 and x_5) with ($x_1 > 0$ and $x_3 > 0$) and without rainfall ($x_1 = 0$ and $x_3 = 0$) for the same time period, α the intercept, β_1, β_2, β_3, β_4 and β_5 the regression coefficients and e the error and C_R the contribution of rain.

The confidence interval (CI) of 95% for the covariance parameter estimate (x_1 and x_3) was computed using the CL (confidence limit) statement in the mixed procedure. The calculation of C_R and respective CI computation was using the average of each covariate over the 25 rainfall events in order to analyse the impact of the 25 events on the loads irrigated toward the paddy fields and the loads passing through the lower gage. The functions from the mixed effects model were used for estimating the loads for the entire period May till September using the overall dataset containing rainfall, discharge and lake level.

Results

Hydrological characterization of the subwatershed

Depending on the reservoir management, the discharge passing the upper gage varied between 0.01 and 0.34 $m^3\ s^{-1}$, while the irrigation discharge to the paddy fields and at the lower gage fluctuated between 0 and 0.26, and 0 and 0.30 $m^3\ s^{-1}$, respectively. For the measured events, rainfall ranged between 0.2 and 30.7 mm with average intensities varying from 0.3 to 11.6 mm h^{-1} (Table 1) and maximum intensities between 0.6 and 74 mm h^{-1} (data not shown). Depending on the rainfall duration and intensity of the 25 rainfall events, the contribution of overland flow to total discharge in the irrigation channel varied between 0 and 46% with an average of 12% (Fig. 2). The contribution of direct rainfall captured by the surface of the irrigation channel was found to be negligible (Fig. 2). Events 3, 4, 7, 8, 11, 13, 15, 17, 18, 20 and 21 showed negligible overland flow discharge compared to the other events.

Hydrochemical characterization of reservoir and irrigation water along the channel

Throughout the entire measurement period and in absence of rainfall, the average baseline concentrations found in the reservoir were 29.0 ± 4.4, 4.7 ± 1.2 and 3.8 ± 1.6 mg l^{-1} for inorganic C, organic C and total N. Rainfall had an average concentration of 4.0 ± 1.6 mg l^{-1} inorganic C, 2.6 ± 0.1 mg l^{-1} organic C, and 1.1 ± 0.1 mg l^{-1} total N. A quick response was observed of increased inorganic and organic C and total N concentrations at the lower gage depending on rainfall intensity (organic C shown in Fig. 3). During rainfall events the quality of the water at the upper gage (inlet), coming from the reservoir, fluctuated between 14.9–52.2 mg l^{-1} inorganic C, 1.6–118.8 mg l^{-1} organic C, and 1.2–23.0 mg l^{-1} total N (Fig. 4). At the lower gage (outlet) the water quality ranged between 12.0 and 84.4 mg l^{-1} inorganic C, 2.1 and 311.4 mg l^{-1} organic C, and between 1.1 and 52.6 mg l^{-1} total N. Fluctuation of inorganic C between the various samples taken within one rainfall event was found to be limited for both gages as well as between gages. Additionally, organic C and total N

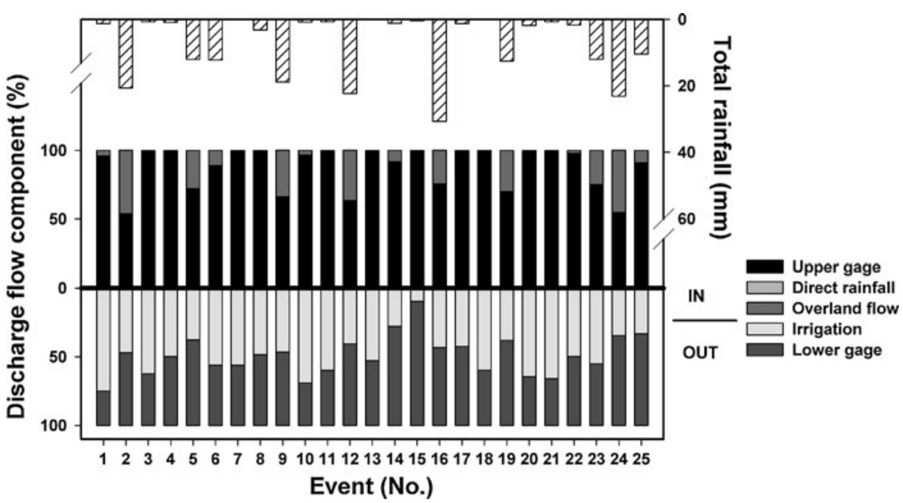

Fig. 2 Overview of the different flow components (%) entering (i.e. direct rainfall, upper gage, overland flow) and leaving the irrigation channel (i.e. irrigation between upper and lower gage, non-irrigated discharge passing through the lower gage) during a rainfall event. *Vertical bars* at the top represent the total rainfall (mm) for each event

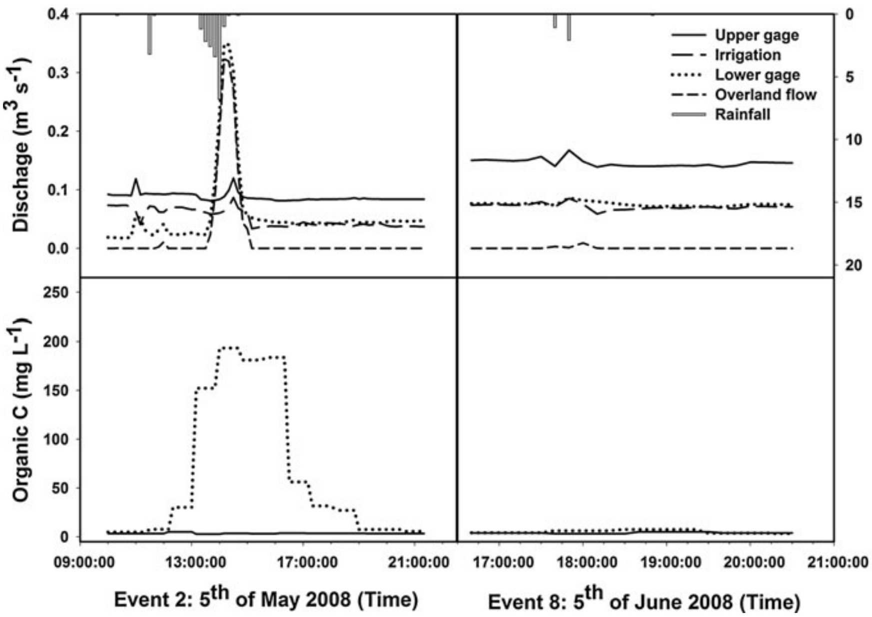

Fig. 3 Changes in flow components ($m^3\ s^{-1}$) (*top*) and corresponding organic C concentrations ($mg\ l^{-1}$) (*bottom*) for a high (Event 2) and low (Event 8) intensity rainfall event

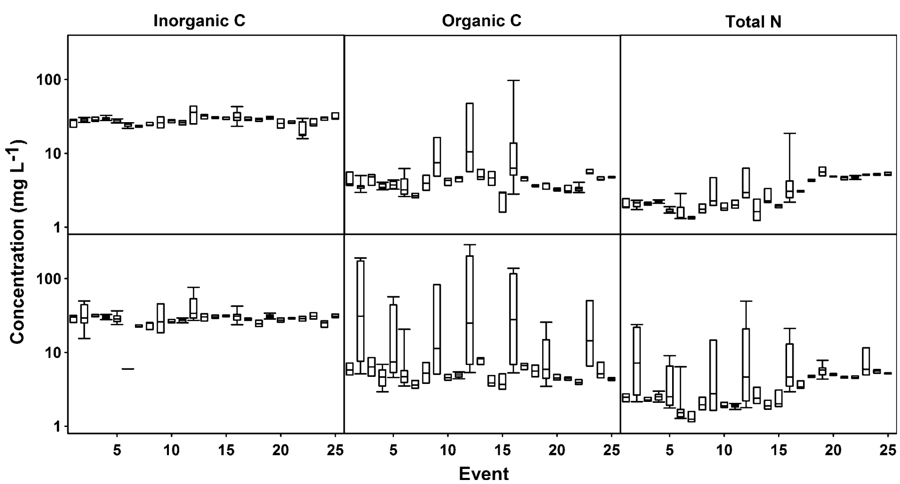

Fig. 4 *Box plots* of inorganic C, organic C and total N concentrations ($mg\ l^{-1}$) for all 25 events monitored at the upper gage (*top*) and lower gage (*bottom*) with *crossbars*, *boxes* and *whiskers* giving the median, quartile range and range, respectively

concentrations among the different samples, taken within a rainfall event, showed a limited fluctuation at the upper gage compared to the lower gage (Fig. 4).

For organic C, the EMC at the inlet (upper gage) ranged between 2.5 (event 15) and 29.3 $mg\ l^{-1}$ (event 12), while for total N values between 1.6 (event 13) and 5.3 $mg\ l^{-1}$ (event 19) were obtained (Table 1). At the lower gage, EMC ranged between 3.4 (event 7) and 117.7 $mg\ l^{-1}$ (event 12) organic C, and between 1.2 (event 7) and 17.5 $mg\ l^{-1}$ (event 12) total N. In general EMC concentrations at the upper gage were found to be lower than EMC measured at the lower gage within the same event.

Flow components and their contribution to organic C and total N loads

The calculated loads strongly depended on the duration of the rainfall event and the amount of water released from the reservoir and therefore passing through the upper gage. The events with the highest average rainfall intensity also showed the highest load for organic C and total N in the overland flow (e.g. Events 2, 5, 12 and 16) with the exception of event 8 (Table 1; Fig. 5). Estimated overland flow loads for organic C, derived from the load balance, varied between 0 and 386 kg and for total N between 0 and 48 kg per event (data not shown). When summarizing the estimated overland flow loads, for the 25 rainfall events, coming from the surrounding 17 ha of upland area which drained towards the irrigation channel between the upper and lower gage, a total of 188 kg of inorganic C, 1074 kg of organic C and 145 kg of total N was found. Based on the calculated organic C and total N load of the overland flow component for each event, the average organic C/total N ratio was calculated. On average the water released from the reservoir had an organic C/total N ratio of 2 with a slight decreasing trend along the season. The range of the organic C/total N ratio in the overland flow varied strongly among the 25 events especially for the rainfall events with higher rainfall intensity (events 2, 5, 9, 12, 16 and 23) where values up to 6.8 were found (event 16). A significant linear relationship was found ($R^2 = 0.82$, $P < 0.001$) between the organic C/total N ratio of the overland flow and the amount of rainfall (Fig. 6). Rainfall characteristics and overland flow were strongly correlated among each other ($r = 0.82$–0.99, $P < 0.001$) (Table 2). Irrigated inorganic carbon was found to be weakly correlated with the discharge at the upper gage ($r = 0.26$, $P < 0.001$) and irrigated total N loads were stronger correlated to the lake level ($r = 0.43$, $P < 0.001$).

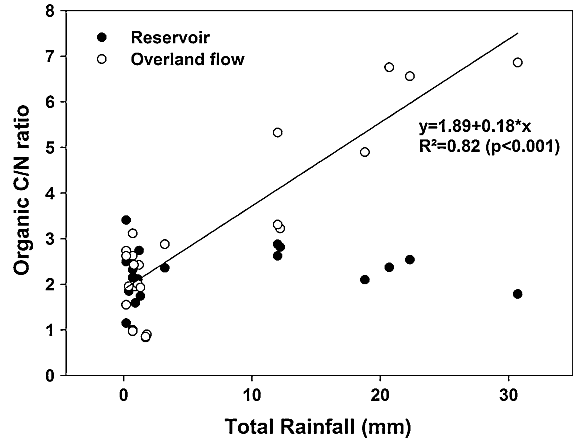

Fig. 6 Relationship between the estimated organic C/total N ratio of the overland flow and the amount of rainfall (mm) compared to the organic C/total N ratio of the reservoir

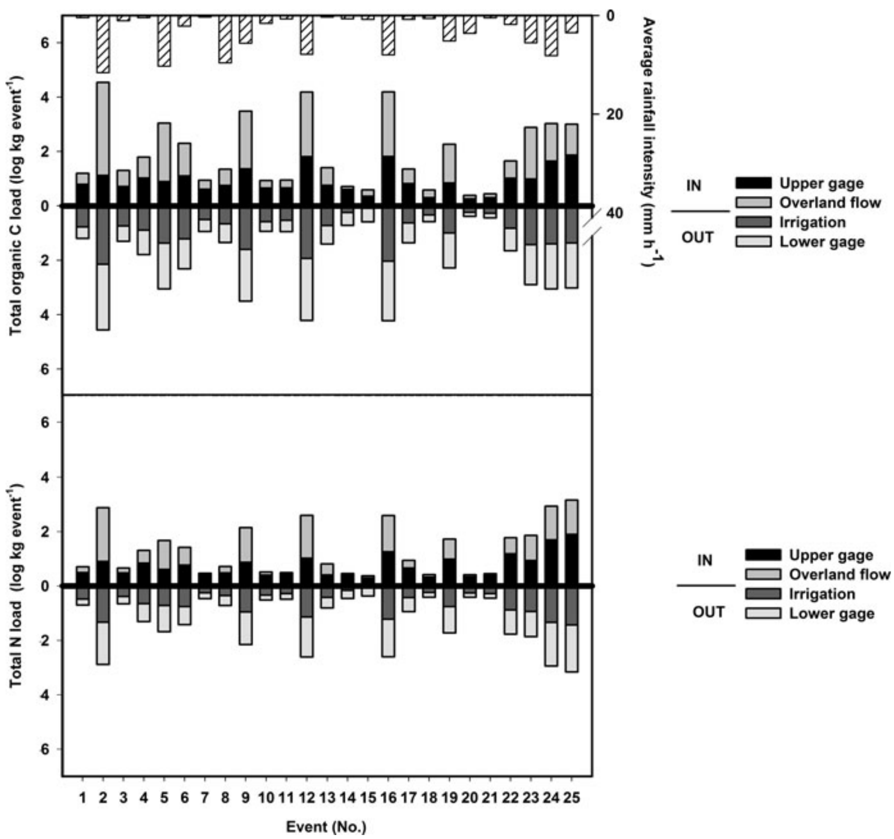

Fig. 5 Separation of the total load in organic C (*top*) and total N (*bottom*) (kg event^{-1}) for each event into the contribution of the different in- and out-flow components. The data are $\log_{10}$ transformed. *Vertical bars* at the top represent the average rainfall intensity (mm h^{-1}) for each event. Loads from direct rainfall were negligible and hence not presented

Table 2 Spearman correlation coefficients (*r*) between julian day (day), rainfall characteristics (average intensity (mm h^{-1}), rainfall amount (mm) and rainfall duration (min)), volume of each flow component (m^3) (overland flow, irrigation, direct precipitation, upper gage and lower gage), water level in the lake (lake level) (m) and loads irrigated (inorganic C, organic C and total N) (kg $sample^{-1}$)

Parameter	*No*[a]	Julian day	Average rainfall intensity	Rainfall amount	Rainfall duration	Overland flow	Irrigation	Direct precipitation	Upper gage discharge	Lower gage discharge	Lake level	Load inorganic C irrigated	Load organic C irrigated
Julian days	419	1.00											
Average rainfall intensity	419	0.02	1.00										
Rainfall amount	419	0.02	0.99[b]	1.00									
Rainfall duration	419	0.02	0.97[b]	0.98[b]	1.00								
Overland flow	410	−0.02	0.84[b]	0.85[b]	0.82[b]	1.00							
Irrigation	410	0.17[c]	−0.10	−0.09	−0.06	−0.06	1.00						
Direct precipitation	410	0.00	0.96[b]	0.97[b]	0.95[b]	0.87[b]	−0.06	1.00					
Upper gage discharge	334	−0.01	−0.11	−0.11	−0.09	−0.10	0.32[b]	−0.12[d]	1.00				
Lower gage discharge	410	0.25[b]	0.03	0.03	0.03	0.08	0.69[b]	0.04	0.38[b]	1.00			
Lake level	419	0.68[b]	0.01	0.02	0.03	−0.01	0.19[b]	0.00	−0.08	0.10	1.00		
Load inorganic C irrigated	414	0.23[b]	−0.08	−0.06	−0.04	−0.03	0.92[b]	−0.04	0.26[b]	0.65[b]	0.17[c]	1.00	
Load organic C irrigated	414	0.23[b]	0.24[b]	0.24[b]	0.21[b]	0.31[b]	0.65[b]	0.25[b]	0.18[c]	0.60[b]	0.20[b]	0.73[b]	1.00
Load total N irrigated	414	0.46[b]	0.10[d]	0.11[d]	0.10[d]	0.17[c]	0.71[b]	0.12[d]	0.16[c]	0.59[b]	0.43[b]	0.81[b]	0.87[b]

[a] Number of observations

[b,c,d] Correlation is significant at the $P < 0.001$, 0.01 level and <0.05 level (two-tailed), respectively

The additional load irrigated to the paddy fields during rainfall events (D_{load}) calculated using Eq. 7 (Fig. 7) showed that from all 25 monitored events, events 2, 9, 12 and 16 contributed most to additional irrigated organic C and/or total N loads to the paddy fields. The highest values were found for event 2 which showed an increase of 18 kg inorganic C, 130 kg organic C and 16 kg total N. During the rainfall events between 9 and 74% of organic C and total N loads found in the channel (an overall average of 47%) were transported through irrigation water into the paddy fields. At the lower gage between 26 and 91% of organic C and total N loads (an average of 53%) left the subwatershed monitored in this study (data not shown).

The mixed effects model for the calculation of the irrigated loads for all three water parameters showed

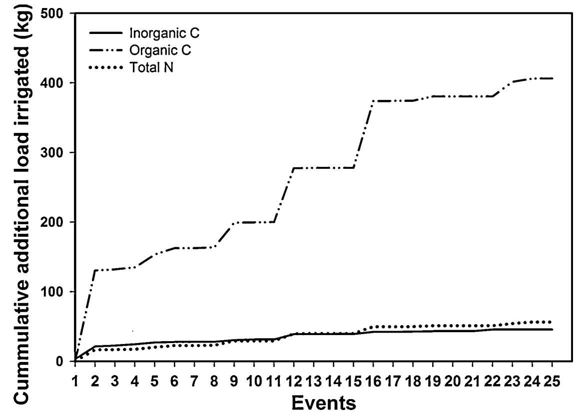

Fig. 7 Cumulative additional (to baseline) load (kg) of inorganic and organic C and total N irrigated to the paddy fields during the 25 rainfall events

Table 3 Mixed effects model including flow components (irrigation, overland and lower gage volume), rainfall characteristics and lake level for estimating inorganic C, organic C and total N loads (ln kg event^{-1}) irrigated to the paddy fields between the upper and lower gage (irrigation) and leaving the subwatershed (lower gage)

Model	Irrigation				Lower gage			
	Parameter estimate	df	*F*-value	Pr > F	Parameter estimate	df	*F*-value	Pr > F
Load inorganic C (kg event^{-1})[a]								
Model intercept	−3.460				−3.477			
Rainfall intensity (mm h^{-1})	0.008	159.0	17.5	<0.0001	0.008	159.0	17.12	<0.0001
Irrigation volume (m^3)[b]	0.906	15.7	821.9	<0.0001	−0.108	13.4	11.79	0.0043
Lower gage volume (m^3)[b]	0.071	93.8	5.7	0.0190	1.09	93.3	1308.74	<0.0001
Load organic C (kg event^{-1})[a]								
Model intercept	−4.662				−4.685			
Rainfall intensity (mm h^{-1})	0.022	150.0	28.9	<0.0001	0.022	150.0	28.9	<0.0001
Irrigation volume (m^3)[b]	0.566	32.8	28.3	<0.0001	−0.448	28.7	17.9	0.0002
Overland flow volume (m^3)[b]	0.151	170.0	33.2	<0.0001	0.150	169.0	32.7	<0.0001
Lower gage volume (m^3)[b]	0.335	164.0	9.4	0.0026	1.350	164.0	152.6	<0.0001
Load total N (kg event^{-1})[a]								
Model intercept	−6.190				−6.218			
Rainfall intensity (mm h^{-1})	0.017	144.0	23.5	<0.0001	0.017	144.0	23.35	<0.0001
Irrigation volume (m^3)[b]	0.656	171.0	71.6	<0.0001	−0.354	171.0	20.80	<0.0001
Overland flow volume (m^3)[b]	0.077	171.0	13.6	0.0003	0.077	177.0	13.29	0.0003
Lower gage volume (m^3)[b]	0.250	134.0	9.6	0.0024	1.267	134.0	244.91	<0.0001
Lake level (m)	0.129	40.9	24.6	<0.0001	0.128	40.9	24.38	<0.0001

df Degrees of freedom

[a] Transformation according to ln(x)

[b] Transformation according to ln(x+1)

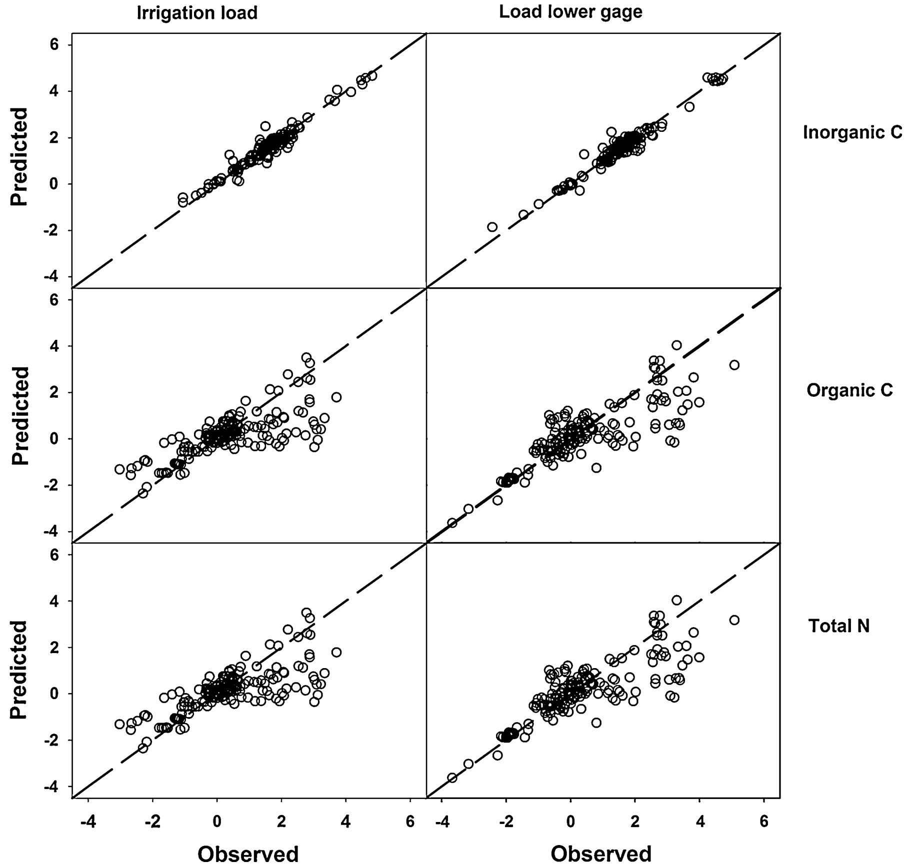

Fig. 8 Predicted versus observed loads of inorganic C, organic C and total N (ln kg event^{-1}) irrigated to the paddy fields (*left*) and passing through the lower gage (*right*) for all composite samples taken within the 25 rainfall events

a significant response to irrigation discharge into paddy fields between upper and lower gage and rainfall intensity (Table 3). Overland flow had additionally an impact on organic C and total N loads while the level of the lake was only of significant influence for total N. Similar results were shown by the mixed effects model on the loads passing through the lower gage of the studied subwatershed. For the irrigated as well as for the loads passing through the lower gage, good predictions were found for each water quality parameter (Fig. 8). However, a small trend was noticeable for higher loads pointing towards difficulty of the model in predicting high loads of organic C and total N.

Considering all 25 events, the estimated contribution of runoff processes induced by rainfall on total load was minor compared to the overall loads irrigated during dry weather periods (Table 4). For inorganic C, the contribution of rainfall on total loads was estimated to be 0.04 (irrigated to the paddy fields) and 0.04% (lower gage), for organic C 6.7 (irrigated to the paddy fields) and 6.6% (lower gage), and for total N 1.8 (irrigated to the paddy fields) and 1.8% (lower gage). Estimating the loads over the entire period May till September 2008 resulted in an estimated irrigated load of 25.4 Mg inorganic C, 5.5 Mg organic C and 4.6 Mg total N (Table 4).

Discussion

Effect of a surface water reservoir on C and N redistribution

The results of the mixed effects model showed that the majority of nutrients redistributed via the irrigation channel to the lowland were mainly coming from the reservoir. Only for rainfall events with maximum rainfall intensities higher than 15 mm h^{-1}, significant additional organic C and total N loads were irrigated compared to the baseline loads. Thus, the rainfall induced overland flow draining towards the irrigation

Table 4 The contribution of rainfall events to the increase of inorganic C, organic C and total N loads (%) irrigated to the paddy fields (irrigation) and at the outlet of the subwatershed (lower gage) for the 25 events and the total estimated loads (Mg) irrigated and passing through the lower gage in the overall period (May–September)

	Contribution of rainfall events (%)		Estimated total loads May–September[a]	
	Irrigation[b]	Lower gage[b]	Irrigation (Mg)[c]	Lower gage (Mg)
Load inorganic C	0.04 (0.02–0.05)	0.04 (0.02–0.05)	25.4 (3.9)	23.8
Load organic C	6.7 (4.4–9.1)	6.6 (4.3–9.1)	5.5 (0.8)	5.7
Load total N	1.8 (0.9–2.8)	1.8 (0.8–2.8)	4.6 (0.7)	4.7

[a] Loads are estimated applying the functions obtained by the mixed effects model (Table 3) on the entire dataset May till September

[b] The CI (95%) of the contribution is given in parenthesis

[c] The estimated irrigated load per ha of paddy in parenthesis (Mg ha^{-1})

channel seemed to have a minor impact compared to the loads released from the reservoir (Table 4). These results suggest that the surface water reservoir acted as a major sink for inorganic and organic C, and for N transported from the surrounding 490 ha during erosive rainfall events to the reservoir. The contribution of rainfall events to the irrigated nutrient loads will thus strongly depend on the management of crop fields surrounding the reservoir thereby affecting the water quality and quantity of the reservoir. Therefore, the reservoir played a dominant role in overall nutrient loads in irrigation water as it contributed >99, 93 and 98% of the irrigated inorganic C, organic C and total N loads. This also points towards the importance of irrigation management as it will influence the fraction and timing of these nutrients distributed to the lowland during irrigation practices throughout the year.

The baseline concentration of organic C in the irrigation water, found in this study, corresponded with concentrations found by King et al. (2009) and Poch et al. (2006) who reported dissolved organic C values ranging from 2 to 5 mg l^{-1} and dissolved organic N values of 2 mg l^{-1} in a with surface water irrigated sunflower field in Sacramento valley (California, USA). Similar values for total N (1.2 mg l^{-1}) were found in the irrigation water studied in China by Tang et al. (2008). In contrast, inorganic C was found to be much higher in this study compared to the results of King et al. (2009) who found that inorganic C was negligible due to the absence of carbonate-rich soils. The high values of inorganic C found in the irrigation water in our study were due to the fact that the reservoir of the studied watershed was surrounded by Karst mountains.

During rainfall events good model predictions were found for the irrigated loads as well as the loads passing through the lower gage (Fig. 8). The derived model parameters showed high similarities with other multiple linear regression or generalized linear based models used for load estimations (Cox et al. 2008; Haggard et al. 2003; Stenback et al. 2011). However, in this study, the incorporation of lake level used for nitrogen load estimations was an important addition in the model as the reservoir played a significant role in the redistribution of N. Furthermore, when using composite sampling, the model showed that using the filling time as a random effect improved predictions significantly. The established models were found to be somewhat less accurate for high loads of organic C and total N in the irrigation water as well as those in the water passing through the lower gage. In general, load estimations are highly depending on monitoring period, sampling strategy and the load estimation method used (Johnes 2007; Stenback et al. 2011). Overland flow discharge, as well as irrigated discharge, was estimated using Eqs. 1–3. As overland flow was absent in the model for the prediction of inorganic C, it might suggest that the error in predicting overland flow could have had an influence on the performance of the model towards organic C and total N load estimations. An additional factor which could have played a role is the influence of the filling time in combination with the available dataset which constituted out of a larger number of small compared to high intensity rainfalls. Regarding the estimations of the irrigated nutrient loads, the assumption of maximum concentrations (using Eq. 5) could contribute towards an overestimation of the simulated predicted loads. However, as the trend was visible within the predicted versus observed loads passing through the lower gage, it is believed that this error contribution was minor. The assumption of maximum concentrations used in the irrigated loads calculations will play a more important role when quantifying the overall irrigated load compared to the individual model predictions.

Contribution of overland flow on the redistribution of C and N

Although the majority of the irrigated loads within the overall measurement period originated from the reservoir, strong rainfall events did significantly contribute additional quantities of organic C and total N to the irrigation water due to draining overland flow (Fig. 7). An estimation of the total overland flow from the 25 events can be made when using the drainage area of 17 ha, showing that the total organic C transported, via overland flow, into the investigated irrigation channel segment was approximately 63 kg ha^{-1}. Overland flow accumulation is highly dependent on rainfall characteristics, soil type, topology, land use fragmentation, and the size of the draining catchment (López-Tarazón et al. 2010; Pansak et al. 2010; Römkens et al. 2002; Valentin et al. 2008; Ziegler et al. 2004b). The effect of drainage area and soil type and its effect on different non-point sediment sources draining as overland flow to the irrigation water was demonstrated by the changes in organic C/total N ratio among the various events. Overall, the estimated organic C/total N ratios of the overland flow were found to be higher than the organic C/total N ratio of the water in the reservoir. Low ratios as observed in the reservoir (±2) are likely to depend mainly on in situ production of C and N during decomposition in the reservoir as aquatic plants are much poorer in C as compared to terrestrial plants (Beusen et al. 2005), leading also to accumulation of mineral N, such as NH_4^+. An increase of the organic C/total N ratio up to 7 was found for the overland flow during higher rainfall intensity events (events 2, 5, 9, 12 and 16) which denoted towards the drainage of non-point sediment sources from upland areas into the irrigation channel. This suggests that particularly the contribution of organic C during erosion events increases (probably particulate organic matter) leading to higher organic C/total N ratios. Similarly, Beusen et al. (2005) found that organic C/N ratios in rivers were lower for less turbid waters (often lower than 8) and higher in more turbid waters (>10) pointing to the drainage of soil erosion and terrestrial vegetation pools. However, the total amount of overland flow and the associated nutrient transport from the upland area feeding the reservoir in this study area will be higher than the estimated portion of nutrients draining to the irrigation channel due to the larger contributing area (490 vs. 17 ha). Although linear segments in the landscape (e.g. unpaved roads), due to their lower hydraulic conductivity, significantly contribute to convey runoff (Valentin et al. 2008; Ziegler et al. 2004a), a significant amount of sediments and accompanying nutrients will be deposited before reaching the irrigation channel or reservoir.

Comparison of the EMC between upper and lower gage for organic C and total N showed a clear response to rainfall intensity confirming that rainfall induced overland flow can convey significant amounts of C and N from intensively cultivated upland fields into the irrigation water. Although the effect of overland flow on EMC of organic C and total N was highly influenced by rainfall characteristics, the relative increase in EMC between the upper and lower gages was found in some cases to be additionally depending on the amount of irrigation water released from the reservoir (e.g. events 2 vs. 24). The amount of irrigation water released from the reservoir was higher during event 2 compared to event 24, which caused dilution of organic C and N loads deposited by overland flow although the rainfall condition was comparable. Therefore caution is needed when assessing the impact of overland flow on redistribution of nutrient loads as irrigation management (i.e. release of water from the reservoir) plays an additional role in irrigated watersheds besides the known effect of climate, drainage area, topography, soil and land use characteristics.

Contribution of irrigation water to C and N transport to paddy fields

Taking into account the irrigated paddy area, the amount of inorganic C load entering paddies with the irrigation water between May and September was estimated at 3.9 Mg ha^{-1}, while the irrigated organic C load only amounted up to 0.8 Mg ha^{-1} and the total N load up to 0.7 Mg ha^{-1}. These values are higher than the ones reported by King et al. (2009) and Poch et al. (2006) who found 0.03 and

0.02 Mg ha^{-1} $year^{-1}$ of organic C, respectively and 0.07 Mg ha^{-1} $year^{-1}$ of total N. Their lower values partly could be due to the fact that their furrow irrigated fields were not continuously irrigated throughout the cropping season and the values estimated in their study reflected the total contribution of only four irrigation events. Secondly, as in this study maximum concentrations for overland flow were used when estimating the irrigated loads, the resulting load values have to be considered as the maximum limit that one could expect to be irrigated. Nevertheless, as less than 10% of the loads were derived from the overland flow draining towards the channel it will have had only a minor impact on the overall load estimation. As often two rice crops are established per year within the subwatershed and rainfall events were found to play a minor role in overall estimated nutrient budgets within this specific watershed for 2008, the total N, inorganic and organic C load irrigated in the watershed will be approximately double of the amounts found in this study. When looking at sediment deposition in rice paddies, a clear enrichment of organic C and total N was found along irrigated rice cascades creating a spatial pattern with a positive effect on rice productivity (Schmitter et al. 2011; Yan et al. 2010). However, as runoff from paddy fields were not within the framework of this study, the question remains whether the entire irrigated C and N loads found in this study are deposited within the paddy fields and can be seen as a net gain or are partly lost by other pathways such as runoff, leaching or gaseous losses. Additionally, as irrigation management—and associated wetting and drying cycles—causes an increase of dissolved organic carbon content due to the stimulation of soil microbial activity (King et al. 2009), labile C can be reallocated with the runoff water from paddy fields (Ruark et al. 2010), or CO_2 and CH_4 production can be enhanced (Kimura et al. 2004). Indeed, results of Dung et al. (2009) indicated that a proportion of nutrients entering paddy fields with the irrigation water might be lost into the downstream river system.

Often fertilizer recommendations are made for larger areas covering district or commune level rather than catchment level. This study showed that the associated nutrient redistribution through irrigation in intensively cultivated mountainous areas needs to be taken into account as it could influence the indigenous nutrient supply of irrigated rice paddy fields and therefore would contribute to the need of site specific fertilizer recommendation (Dobermann et al. 2003; King et al. 2009).

Conclusion

The present study indicated that significant amounts of total N, inorganic and organic C were reallocated to the lowland by irrigation water which was mainly influenced by the water quality of the reservoir and the overland flow draining directly to the reservoir. Although, the additional contribution of overland flow along the channel on irrigated C and N loads was temporally significant during intensive rainfall events it did not act as a major source of nutrients for paddy fields. Thus, over the entire measurement period the reservoir contributed between >99, 93 and 98% of the irrigated inorganic C, organic C and total N loads to the lowland. As overland flow is highly depending on rainfall intensity, probable higher extreme rainfall periods in the future due to climate change, could induce even higher C and N flows draining into the reservoir. However, the continuous soil degradation of intensively cultivated upland slopes in tropical mountainous areas raises the question whether the quality and quantity of organic C and total N contributions will decrease in the long term and become less favorable for the lowlands. Whether the water nutrient contents will decrease or not in the future, this study shows that the redistribution of C and N through irrigation water is highly influenced by management practices and about half of the total nutrient load entered the paddy fields. This should be taken into consideration when optimizing rice productivity in the lowland and developing site specific fertilizer recommendations. Further research, however, is needed to estimate the final deposition of C and N within the lowlands as the amount of C and N transported from the rice fields by runoff especially during land preparation and heavy rainfall events or lost through volatilization was beyond the scope of this study.

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