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Hydrological and nitrate modelling for the River Ic in Brittany (France) - Simulation results and pre-liminary scenario analysis

Project acronym: AQUISAFE 1 Extension

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Title

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Abstract

The Aquisafe project aims at mitigation of diffuse pollution from agricultural sources to protect surface water resources. The first project phase (2007-2009) focused on the review of available information and preliminary tests regarding

(i) most relevant contaminants,

(ii) system-analytical tools to assess sources and pathways of diffuse agricultural pollution,

(iii) the potential of mitigation zones, such as wetlands or riparian buffers, to reduce diffuse agricultural pollution of surface waters and

(iv) experimental setups to simulate mitigation zones under controlled conditions.

The present report deals with (ii), testing the biogeochemical model Soil and Water Assessment Tool (SWAT) on the watershed of the Ic in Brittany, France, to evaluate scenarios for reduction of nitrate in the stream water. The model has been calibrated in several steps, each including additional information on the watershed. For the last calibration the hydrologic model predictions showed fair results with a Nash-Sutcliffe Efficiency of 0.53 at the watershed outlet.

The scenarios cover fertilizer reduction and the introduction of wetlands. Decrease of nitrogen input was applied on a) selected subbasins, b) on drained fields, c) all agricultural fields; wetlands were placed at three model subbasins. Three most effective measures according to scenario analysis were a) 50% fertilizer reduction in selected subbasins resulting in a 6.2% reduction of nitrate loads, b) wetlands draining 30% of the subbasin area with a 5.4% reduction of nitrate loads, c) 10% fertilizer reduction for all agricultural fields with 4.6% reduction of nitrate loads.

The management goal for the watershed is the meeting of drinking water threshold at the watershed outlet. The analysis of observed data revealed that nitrate loads would have to be reduced by 17% on average to reach that goal. Consequently, none of the tested measures achieves a sufficient reduction. Combined measures such as enhanced fertilizer management and concurrent introduction of wetlands seem to be the most promising way to approach the drinking water threshold.

Acknowledgements

We would like to acknowledge the “Syndicat Mixte Environnement du Goëlo et de l'Argoat“ that supplied most of the data used in this work, as well as Adrien Morel-Fatio who literally dug up some soil profiles for the Ic catchment.

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Chapter 1

Background of the project

The Ic river basin is a watershed dominated by agricultural land use. Agricultural practise is affecting water quality of streams by the use of organic and inorganic fertilizers, which contain nutrients like phosphorous and nitrogen. These nutrients reach the river system mainly through diffuse pathways. The EU-raw water directive (EU, 1975) defined maximum concentrations of some contaminants in surface water, which is used for drinking water production; the threshold for nitrate-N is 11.3 mg/l. Studies (Goël'eaux, 2007) in the Ic-Catchment showed that concerning nitrate this threshold is exceeded (see also Figure 1). For a site downstream of the waterworks on the Ic the mean measured concentration of nitrate-N for the period 2001-2005 was 16.39 mg/l. Due to this excess of the EU raw water threshold the waterworks was closed in December 2008 and can only be reopened if concentrations drop below 11.3 mg/l.

The aim of this project was to use the model SWAT to simulate the water and nutrient balance of the Ic watershed in order to (i) identify hotspots of diffuse pollution and (ii) develop and test mitigation strategies to reduce the nitrate pollution of the streams.

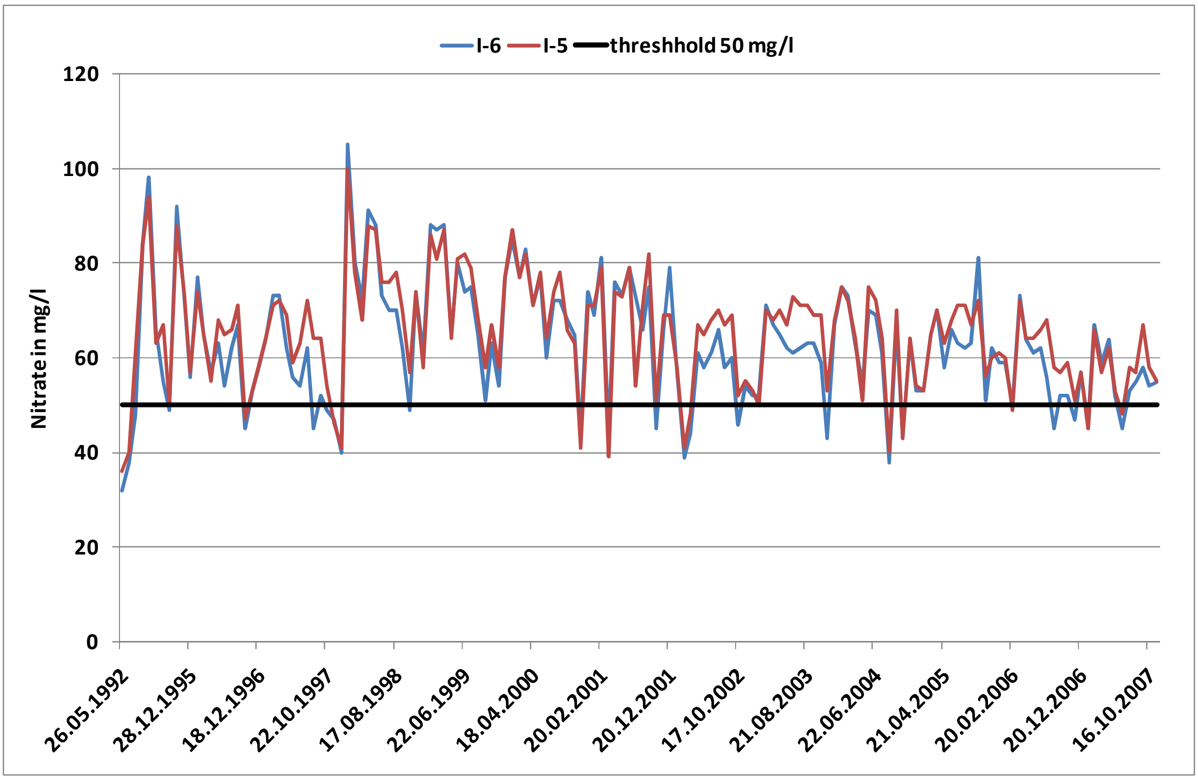

Figure 1: Measured time series of nitrate concentrations in the Ic at sites upstream (red line) and downstream (blue line) of the waterworks; black line is representing threshold for maximum nitrate concentration (50 mg/l Nitrate or 11.3 mg/l Nitrate-N)

Chapter 2
The SWAT - Model

Hydrological and nutrient fluxes were simulated with the hydro-biogeochemical model Soil and Water Assessment Tool (SWAT, Neitsch et al. 2005). In SWAT, the watershed and stream-network delineation is based on a digital elevation model (DEM) and the catchment is divided into subcatchments. The subcatchments are in turn divided into HRUs (hydrological response units) based on the overlay of spatial land use and soil data. HRUs are the smallest computation units and are not spatially located. At the HRU level elements of the hydrologic and nutrient cycle are calculated and updated at a daily time step.

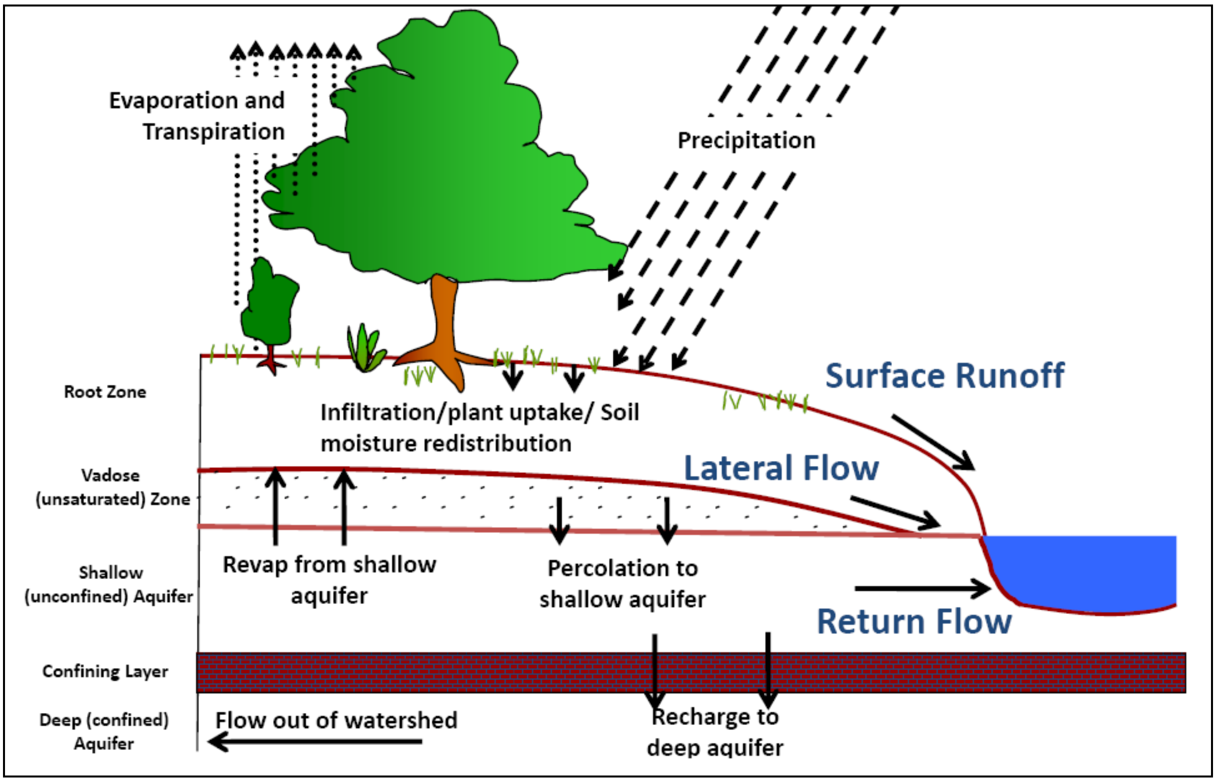

Figure 2: Water cycle in SWAT

In Figure 2 the hydrologic cycle in SWAT is depicted. Surface runoff is calculated with the SCS-Curve Number approach, which takes into account precipitation input and soil cover. Water, which is not subject to surface runoff infiltrates into the soil. In the soil, water moves between the horizons following a kinematic storage approach; which means if one soil layer is filled with water, the excessive water percolates to the underlying soil horizon. Water in the soil can leave the HRU either as lateral flow or groundwater flow. Evaporation can be calculated either using the Penman-Monteith, Priestley-Taylor or Hargreaves method. Plant growth is simulated following a growing concept based on degree days (time × temperature) and can be limited by water or nutrient stress (N and P). Nutrients (N and P) can enter the system by the use of fertilizers (organic and inorganic) or through the decomposition of organic material (plant biomass). Plant decomposition and nutrient fluxes into the soil are driven by the soil water content and soil temperature. The multiple nutrient pools and nutrient fluxes are updated on a daily time step. Water or nutrient components leaving the HRU via surface, lateral or groundwater flow are accumulated to the subbasin outlet at every time step and then routed through the river network towards the watershed outlet as simulated discharge or nutrient loading. As routing method could either be used the muskingum approach or the variable storage method (see Neitsch et al., 2005 for details).

Chapter 3
Materials and Methods

3.1 Study area

For the modelling of the Ic watershed (90 km^2) with SWAT different types of data were provided by KWB and Goël'eaux. The catchment has an undulating character with elevations ranging from 4 m asl (in the north-eastern part) to 206 m asl (in the southern part). According to the land use data (provided by Goël'eaux, Figure 3), crop agriculture is dominant in the Ic watershed. It accounts for around 65% of the basin area, of which 3.5% are drained (2.3% of total catchment area). Pasture and grasslands are the second major landuse type in the watershed with 20% of the basin area. Forest (11%) and urban residential area (4%) cover smaller parts of the catchment.

According to the data provided by Goël'eaux (2007) the soils in the watershed are mainly rich in silt with varying contents of sand and clay. Soils are divided in two classes according to soil depth, one with depth until 60 cm and one with depth greater than 60 cm. Both classes occur in equal shares in the watershed. The soils are mainly followed by bedrock of different geologic formations (Goël'eaux, 2007). Due to this combination surface runoff and lateral subsurface flow are expected to be dominating, whereas groundwater flow is probably of minor importance in this catchment.

Due to the lack of detailed spatially distributed soil data, a soil map had to be interpolated. The interpolation was done based on GIS-data of soil depth, soil texture (provided by Goël'eaux) and several soil profiles (provided by the local authorities). As a result 5 synthetic soil types have been formed (representing variety of soil depth and texture, see also Goel'Eaux, 2007) and included in the model to estimate all soil input parameters necessary for the SWAT model.

3.2 Model forcing data

Climate data (rainfall, temperature, wind speed, rel. humidity and radiation) were available for the period 01.01.1996 – 13.10.2007 for the station Aeroport Trémuson-Saint-Brieuc, supplied via the US National Climatic Data Center (station Nr. 77380) and Goël'eaux. For an additional calibration step artificial precipitation stations were included in the model set up. The data for those stations were interpolated based on a map of long term mean annual precipitation for eastern Brittany (provided by Goël'eaux). From this map we calculated the relative difference of mean annual rainfall of each artificial precipitation station from the mean annual rainfall of the meteorological observation station at the Aeroport Trémuson-Saint-Brieuc. This relative difference was then used to calculate time series for the artificial precipitation stations based on daily data of the available meteorological station.

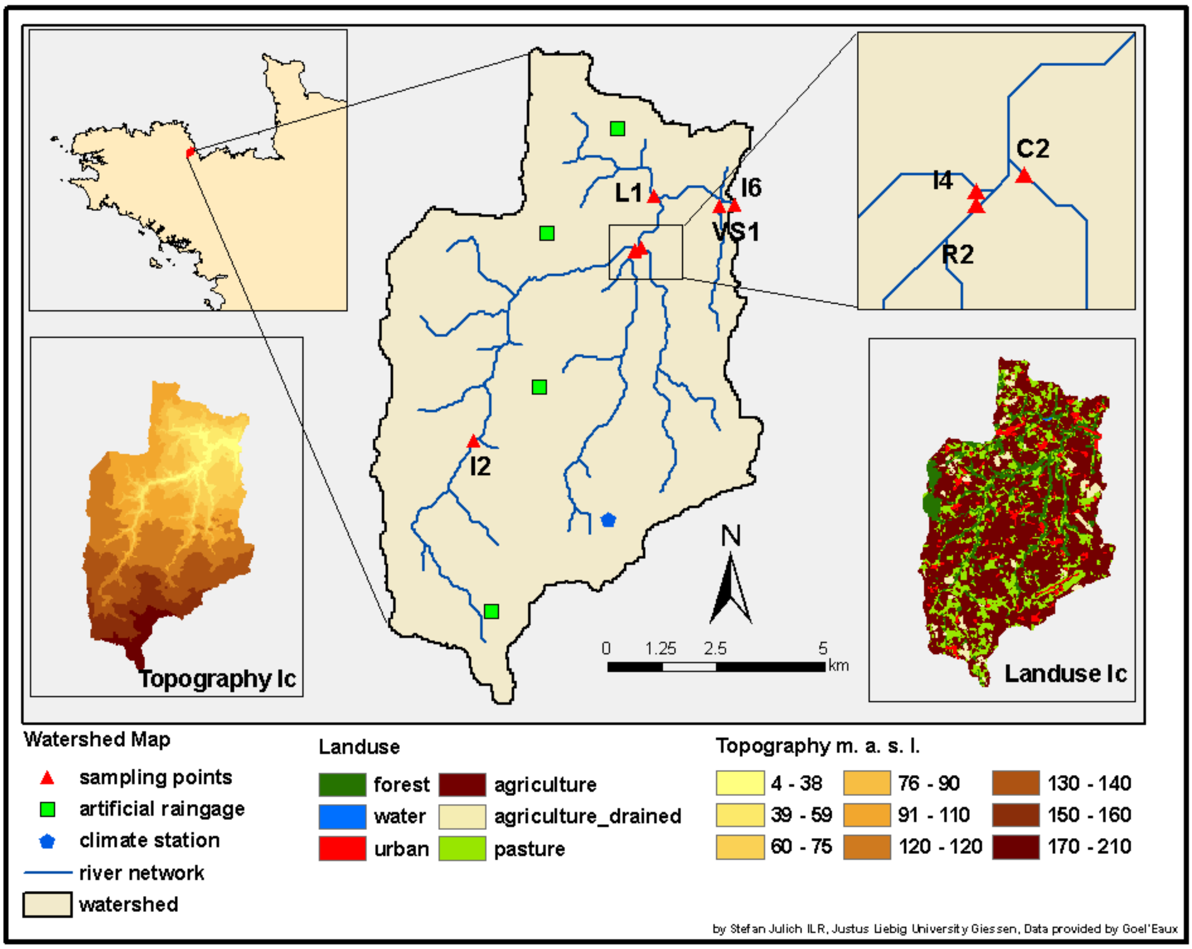

Figure 3**:** Overview of the Ic-Watershed

Measured water quality data (nitrate concentrations) and measured flows for 7 sites in the watershed (red triangles in Figure 3) were provided for the period 20.03.1996 to 22.11.2007, in a temporal resolution of one measurement per month. In addition, daily discharge data were provided for the gauge I6, situated at the outlet of the watershed. The rating curve of this point is not correct due to turbulences at the measurement site, and seems to underestimate the flows by around 20% (personal communication P. Durand, INRA); for that reason this time series was not used for model calibration.

3.3 Model set up and calibration:

Hydrological fluxes in SWAT were calibrated for three different approaches, since during the project new information became available from partners:

1. In the first calibration step, the watershed was split into 47 subbasins and 422 HRUs. Simulation period was 1996-2000 with year 1996 as start up period.
2. In the second calibration step, the watershed was divided into 52 subbasins and 538 HRUs. Simulation Period was 2001-2005 with year 2001 as start up. The land use map was extended by the class “drained agricultural fields”.

3. In the third calibration step the watershed was divided into 32 subbasins and 390 HRUs. Simulation Period was 2001-2004 with 2001 as start up year. Additional 4 artificial precipitation stations have been included in the model, to include information on the east-west precipitation gradient (see description above).

Table 1: Upper and lower bounds of the parameter sets used in the Monte Carlo calibration framework

SWAT model parameter	lower bound	upper bound
Surface runoff lag time (SURLAG) (d)	1	8
Manning's n value for main channel (CH_N) (-)	0.01	0.3
Baseflow alpha factor (ALPHA_BF) (d^{-1})	0.01	1
Groundwater delay (GW_DELAY) (d)	1	25
Groundwater „revap" coefficient (GW_REVAP) (-)	0.02	0.2
Lateral flow travel time (LAT_TIME) (d)	1	8
Soil Bulk Density (SOL_BD) (g/cm^3)	1	1.4
Available water content shallow soil (SOL_AWC) (mm/mm)	0.1	0.5
Saturated hydraulic conductivity shallow soil (SOL_K) (mm/h)	10	300
Curve Number – forest (-)	40	60
Curve Number – pasture (-)	40	60
Curve Number – urban (-)	65	90

Calibration was done by using a Monte Carlo Framework to estimate values for twelve selected model parameters concerning soil properties, groundwater and routing (Table 1). In a Monte Carlo Calibration Framework a large number of simulations are performed, each using a different set of the estimated parameters, which are randomly chosen within their respective range. Among the simulations the best runs can then be selected. In the case of the Ic, approximately 5000 model runs were performed for each of the three calibration steps above. After each model run simulated flows were compared to the measured flows at every site where observed data was available, by calculating the model efficiency after Nash and Sutcliffe (1970) (NSE):

$$NSE = 1 - \frac{\sum (qobs - qsim)^2}{\sum (qobs - \overline{qobs})^2} \quad (1)$$

where qobs is observed discharge, qsim is simulated discharge and $\overline{qobs}$ is the mean observed discharge. According to the definition NSE ranges from 1 (= perfect fit) to -∞.

Instead of selecting one best parameter set we decided to include 10 parameterization sets to account for input parameter uncertainty (Beven and Binley, 1992). The selection criteria for the consideration of parameter sets were the average of the model efficiencies for discharge at the seven monitoring stations in Figure 1. These parameter sets were also used for the scenario analyses in chapter 4.

For agricultural management a two year crop rotation scheme was chosen, with corn in the first year (fertilizer input 203 kg N ha^{-1} yr^{-1}) and winter wheat in the second year (173 kg N ha^{-1} yr^{-1}). Pasture has been fertilized with 180 kg N ha^{-1} yr^{-1}. The crop rotation and the fertilizer rates were developed based on data from Goël'eaux (2007). Consequently, no calibration step was performed for nutrient loading.

3.4 Hot spot analysis:

Based on the model output from calibration step 3 the NO_3-N load was calculated in kg ha^{-1} yr^{-1} for each of the 32 subbasins. Subbasins with NO_3^--N loadings of 70 kg ha^{-1} yr^{-1} or higher were considered as hot spots for further scenario analysis.

3.5 Scenario definition:

The major aim of this project was to investigate possible effects of improved N management in the Ic watershed. Overall, seven scenarios have been defined to investigate the effects of reduced N fertilizer applications and constructing wetlands to act as N buffer zones. In detail, the following scenarios were simulated:

Fertilizer reduction scenarios 1-4

To evaluate the effects of fertilizer input reduction on nitrate-N loads in the river, four fertilizer reduction scenarios have been defined. For scenarios 1 and 2 subcatchments with high potential of nitrate-N load contribution were selected based on the hot spot analysis. In these selected subcatchments N-Input was reduced by 25% and 50% for scenario 1 and 2, respectively. A third scenario has been defined by decreasing fertilizer inputs by 10% in all agricultural areas. In scenario 4 a reduction of fertilizer input by 25% has been assumed for the drained agricultural areas in the watershed only (for a summary of the scenarios see table 2).

Wetland scenarios 5-7

To assess the effects of constructed wetlands on the nitrate-N loads, wetlands were implemented in the model in 3 hotspot subbasins. Wetlands were parameterized as follows: The maximum wetland area was defined to be 1% of the agricultural area in the respective subbasin. The maximum volume of the wetlands is defined as the maximum area times 1 m storage depth. To evaluate the effectiveness of the wetlands in the SWAT model, the drainage area of the wetlands has been defined in 3 steps. In the current SWAT version nutrients are removed in wetlands by settling. That means the mass of the removed nutrient depends on the settling velocity, the area of the wetland and the initial nutrient concentration in the water. These wetlands are able to take up 10, 20 and 30% of the water and nutrients of the respective subbasin area. (for summary see Table 2)

Table 2: Overview of developed scenarios

Scenario	Provided measures
Scenario 1	25 % fertilizer input reduction on selected subbasins
Scenario 2	50 % fertilizer input reduction on selected subbasins
Scenario 3	10 % fertilizer input reduction for all agricultural areas
Scenario 4	25 % fertilizer reduction on drained fields
Scenario 5	Wetlands in selected subbasins with 10 % of respective subbasin area draining to wetland
Scenario 6	Wetlands in selected subbasins with 20 % of respective subbasin area draining to wetland
Scenario 7	Wetlands in selected subbasins with 30 % of respective subbasin area draining to wetland

Chapter 4
Results

4.1 Hydrological fluxes and nutrient loads – current land use

In the framework of this study, three steps considering different sets of model input data were performed to calibrate the model (see section 3.3). Table 3 gives an overview of the quality of the simulated results for each calibration step based on the Nash-Sutcliffe-Efficiency (equ. 1).

Table 3: NSE for simulated discharge for the three calibration steps (section 3.3, for gauges see Figure 3)

Gauge	Step 1	Step 2	Step 3
I2	0.21	0.24	0.32
I4	0.40	0.55	0.56
I6	0.43	0.51	0.53
R2	0.42	0.57	0.58
C2	0.34	0.57	0.55
L1	0.39	0.58	0.59
VS1	-224	0.43	0.46

In general Table 3 shows that the inclusion of additional information in the model from step 1 to step 3 led to an improvement of simulation results, as indicated by an increase in NSE. Already the first calibration showed fair results except for the subbasin of Ville Serho (VS1). One reason for the unacceptable performance of the model in this subcatchment was attributed to the relatively high portion of drained fields (around 15%), which was not considered in step 1. Thus we included GIS-based data of drained fields in the land use map and incorporated this information in the SWAT set up. Due to the inclusion of this land use category an additional calibration step 2 was necessary. The results in Table 2 indicate that the neglected drainage was indeed the reason for the suboptimal model performance in Ville Serho; the inclusion of drainage also led to an improvement at the other sites. Since information on tile drainage is expected to be incomplete (pers. comm. Goël'eaux) for all subcatchments, this lack of knowledge may be one reason for model deviations. Information on long term distributed rainfall was considered in step 3 by using 4 artificial rain gauge data sets. However, the NSE only slightly improved, most obviously for gauge I2. Nevertheless, for further analysis it was decided to utilize the parameter sets obtained in calibration step 3.

Figure 4 shows simulated and observed discharge as well as nitrate-N loads for the best 10 parameter sets of calibration step 3. The overall dynamics of the runoff system is captured.

However, uncertainty remains for high flow simulations since there is a lack of observed data. In general, the simulated nitrate-N curve follows the observed curve. Predicted and observed nitrate-N loads are closely linked to discharge. However, predicted nitrate-N loads during the period of day 350-450 were substantially higher than observed data, which may indicate an overestimation of nitrate loss during rain events. Generally, similar as for simulated discharge the simulated nitrate-N curve could not be evaluated for higher loads as monitoring data is not available for peak flows.

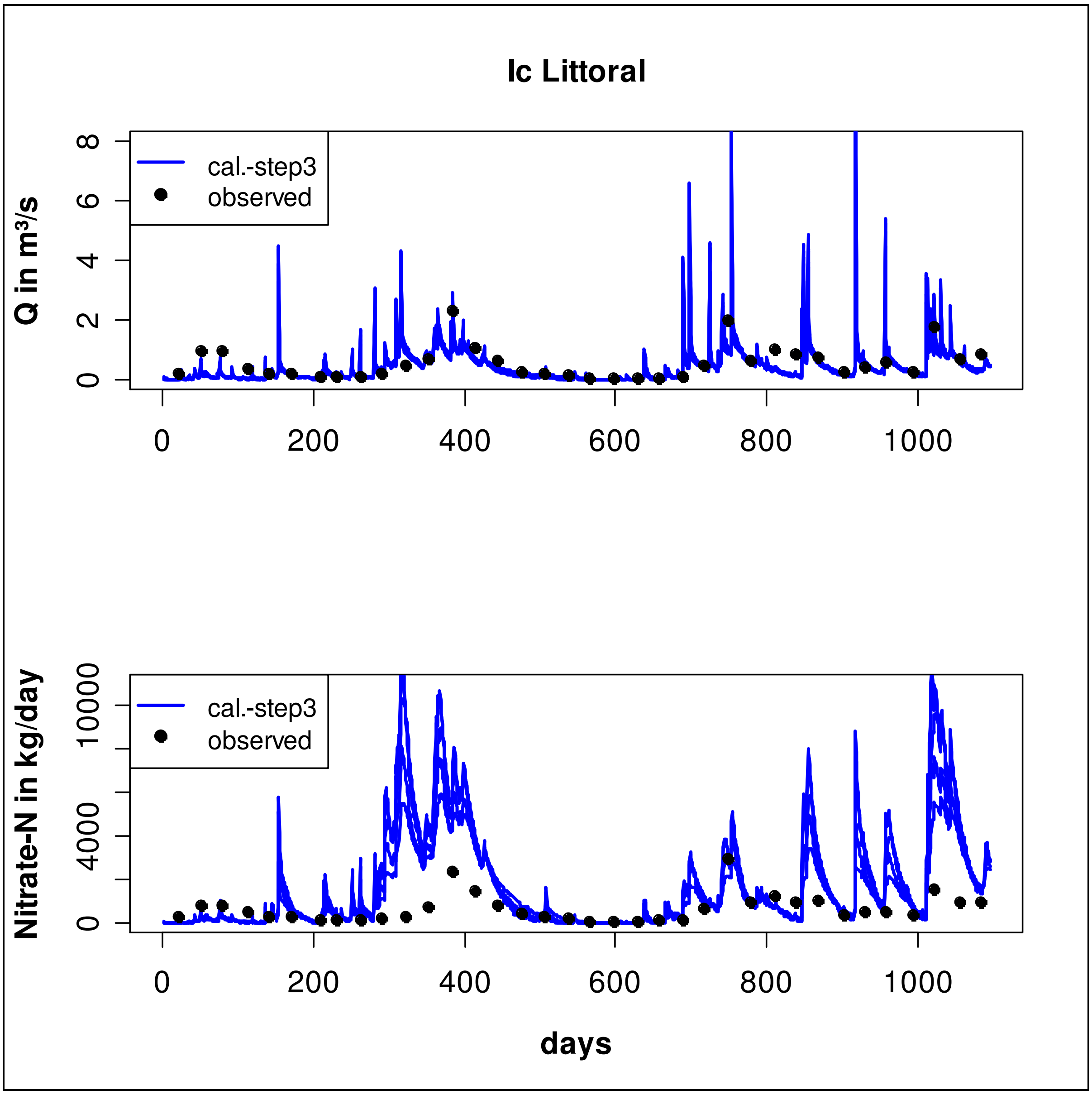

Figure 4: Observed and simulated flows and observed and simulated Nitrat-N loads of calibration step 3 for site I6 (Ic-Littoral) years 2002 -2004

4.2 Hot spots of nitrogen load

A spatial analysis was performed to locate sites of high nitrate-N loads. Predicted SWAT loads of each subcatchment were calculated and are shown in Figure 5. Highest loads of up to 80 to 96 kg NO_3-N ha^{-1} yr^{-1} are predicted for those subcatchments with mainly shallow soils as Ic Amont in the South or Rodo in the North. In addition the subcatchment of Ville Serho shows high contribution to the nitrate loads due to its high portion of drained fields with shallow soils. Subcatchments with lower nitrate-N loads of 40 to 70 kg NO_3-N ha^{-1} yr^{-1} are characterized by higher portions of forest or urban area where the N-Input is lower than from agricultural areas.

A nitrate balance based on the monthly measurements also indicated highest areal contributions from Ic Amont in the South, but did not show high loads for the Eastern part of the watershed. Thus the simulations allow an estimation of contributions in the absence of intense monitoring programs. Moreover the simulation allows the splitting of the watersheds into smaller sub-catchments than the monitoring data.

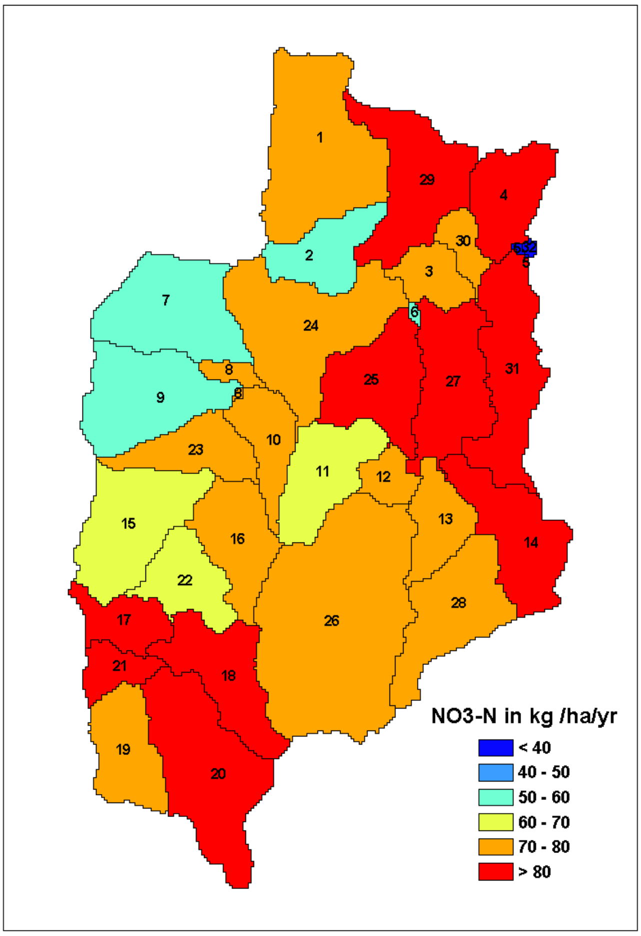

Figure 5 Map of nitrate-N hot spots predicted using the SWAT model.

4.3 Land management scenarios

Based on the delineation of hot spots several N management and wetland scenarios were developed to investigate the reduction potential of different measures regarding the total nitrate-N load in the respective hot spot subcatchments and the overall Ic catchment. It is unlikely that N-fertilizer inputs can be reduced by 25 or 50% in all hot spot areas. As a result, we randomly selected a number of subcatchments with NO_3-N-loads > 70 kg/ha/yr (3, 14, 16, 17, 20, 21, 22, 27, 31, see Figures 5 and 6), where reduced N-fertilizer input was assumed in the model.

Constructed wetlands were implemented in subcatchments 20, 29 (both headwater catchments) and 31 (subcatchment with largest contribution of drained agricultural area).

To evaluate the modelling results of the scenarios some considerations based on measured data were made. At point I6 (the modelled watershed outlet) the mean measured concentration of nitrate-N was 13.6 mg/l, the mean measured flow was 662 l/s and the mean (calculated) load was 776.5 kg/day for the period 2001-2006. Thus, to meet the threshold of 11.3 mg/l nitrate-N (or 646 kg/day), the loads have to be reduced by at least 17 % to reach the EU threshold.

Different fertilizer reduction scenarios have been set up that focus on reducing the nitrate-N loads in the Ic catchment (see Table 2). Results of the scenarios on the loads at each subbasin are shown in Figure 6. Table 4 shows the effect of the scenarios on the total nitrate-N load of the Ic-Watershed.

Table 4: Total NO_3-N loads for the Ic-watershed for all scenarios compared to baseline condition. Scenario 1-4 = Fertilizer reduction, Scenarios 5-7 = Constructed wetlands, for further details of scenarios see Table 2.

	Total of NO_3-N load [kg ha^{-1} yr^{-1}]	Reduction from baseline [kg ha^{-1} yr^{-1}]	Reduction [%]
Baseline	76.6		
Scenario 1	74.0	2.6	3.5
Scenario 2	71.9	4.7	6.2
Scenario 3	73.0	3.6	4.6
Scenario 4	76.2	0.4	0.5
Scenario 5	75.2	1.4	1.9
Scenario 6	73.8	2.8	3.7
Scenario 7	72.4	4.2	5.4

For scenario 1 a 25% reduction of fertilizer application in selected subbasins has been assumed. As anticipated the highest decrease in nitrate-N loads occurs in these subbasins (Figure 6). Nevertheless, the effect can also be seen in the subbasins downstream. The decrease in the selected subbasins is around 10-15% with respect to the baseline scenario, clearly below the fertilizer reduction. The further downstream the subbasin is located, the smaller is the amount of reduction. The reduction of nitrate-N loads for the entire catchment is predicted to be 2.6 kg NO_3-N ha^{-1} yr^{-1} which corresponds to a reduction by 3.5 % (Table 4).

The set up for scenario 2 is similar to the scenario 1 set up but a reduction of 50% N fertilizer application in the hot spot subcatchments was assumed. The results show similar behaviour as in scenario 1 but the decrease is higher. The overall reduction in nitrate-N loads is 4.7 kg N ha^{-1} yr^{-1} or 6.2 % and thus higher than in scenario 1.

A reduction of fertilizer input of 10% at all agricultural sites in the whole watershed in scenario 3 leads to a decrease of nitrate-N loads of around 3.6 kg N ha^{-1} yr^{-1} or 4.65% in the whole watershed.

In scenario 4 the amount of fertilizer is reduced by 25% for all drained areas in the watershed. Only in subbasins with a high portion of drained fields a rate of reduction of 3-4% is achieved. In subbasins with only low or no portions of drained fields the reduction rate is very low. The total nitrate-N reduction for the Ic catchment is negligible with only 0.4 kg N ha^{-1} yr^{-1} or 0.5% (Table 3).

The results of the case study on the impacts of constructed wetlands on the nitrate loads are shown in Figure 6. All 3 scenarios indicate that the highest rates of nitrate-N reduction is at the sites were the wetlands have been introduced. Subbasins situated downstream of the wetlands show also significant decreases in nutrient loads with the amount of decrease being proportional to the wetland sizes. Table 4 summarizes the results of the wetland scenarios in comparison to the N fertilizer management strategies. The effectiveness of wetlands is very much depending on their set up and local conditions, as for example the wetland size and the area draining to the wetland. We therefore considered different contributing areas of the respective wetlands. This contributing area threshold reflects how much of the drainage area of the wetland is really processed within the wetland. As can be shown, the proportional increase of the contributing area shows a non-linear effect in the nitrate-N load reduction potential. It is obvious that the current representation of wetlands in SWAT is a rather rough approach with a simple relationship between drained area and the amount of removed nutrients. So the results can only be seen as an estimation of the effectiveness of wetlands concerning nutrient removal. However, the modular structure allows an easy revision of the (wetland) submodule with more detailed information in order to obtain a more sophisticated process representation.

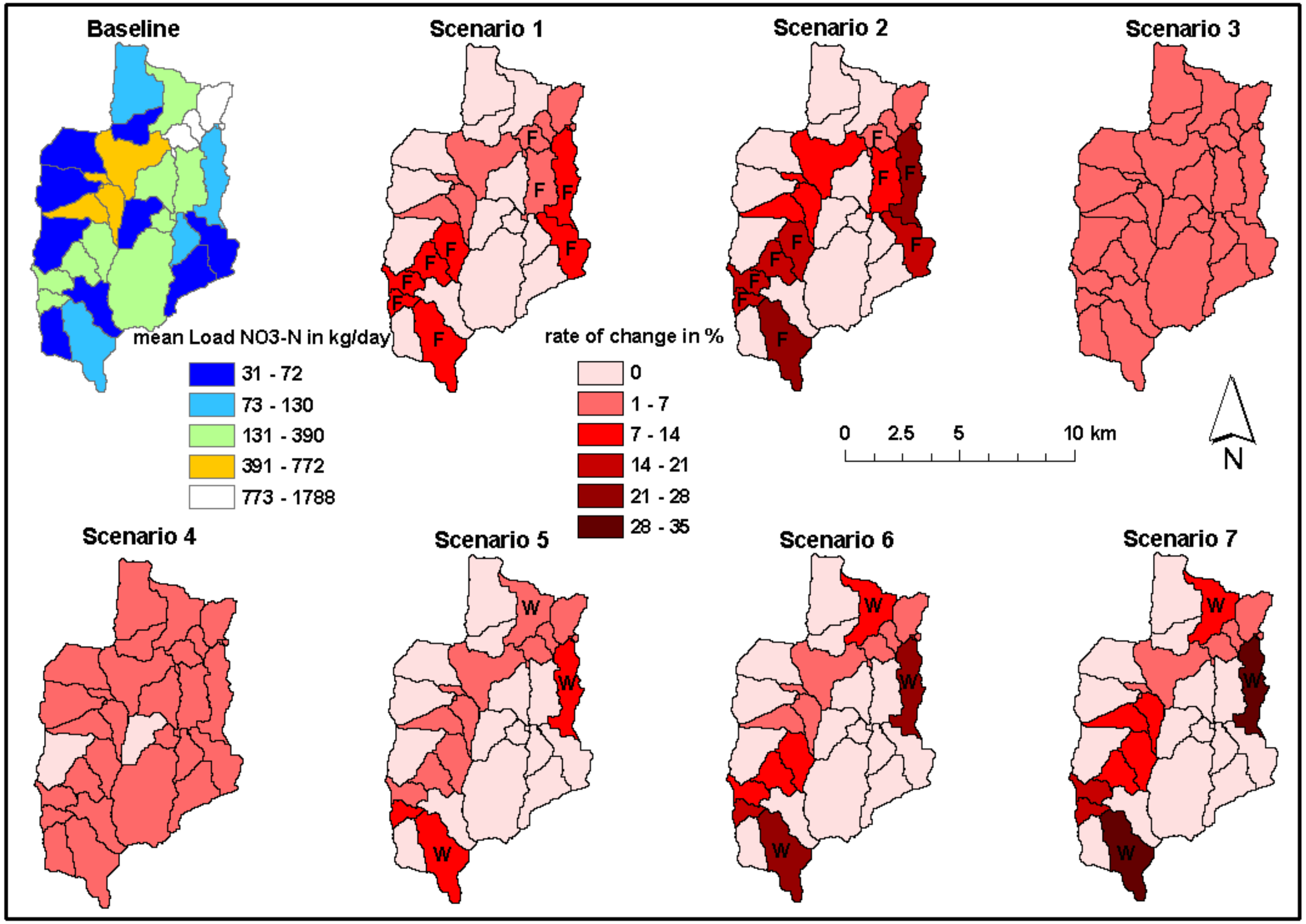

Figure 6: Results of scenario analysis; F represents subbasins with fertilizer reduction; W indicates subbasins with constructed wetlands

Chapter 5

Conclusions

The most effective scenario was scenario 2 (50% reduction of N-input on selected subbasins) (Tables, 2;4). However, the required reduction of 17% in total nitrate-N loads for the Ic catchments can hardly be achieved by single measures such as wetland construction or reduced N-fertilizer application alone. These results are in agreement with other model studies by INRA and BRGM (INRA, 2008; Mougin et al. 2008; INRA/BRGM 2008), which indicate that simple fertilizer reduction scenarios are not sufficient to reduce nitrate loads at a shorter time scale.

Based on the results obtained in this case study we suggest to combine a general N-fertilizer reduction strategy for the entire catchment (such as indicated in scenarios 3 or 4 with the construction of wetlands distributed in the hot spot areas of the watershed such as presented in scenarios 5-7. When wetlands are constructed it is important to make them most effective with respect to realizing a large drainage area, and water should be filtered over the entire length and width of the wetland.

Despite the fair results the study also revealed some short comings of the model. The most obvious is the performance of predicting nitrate loads in the river. Compared to measured loads (Figure 4) the model seems to overestimate the observed loads significantly, although the dynamics of predicted loads is similar. There could be several causes for the model performance like errors in model structure or uncertainties in input data. An important reason might be the lack of observed data. Measured data was only available in a rough temporal resolution (monthly measurements) which is only representative for low flow conditions of the Ic. Consequentially the model performance regarding hydrologic flows and especially for nutrient loadings could not be judged for medium and high flow conditions.

An example for uncertainty in model structure is the wetland module currently implemented in SWAT, which represents only a simple approach depending on wetland size and stored water volume. Hence the results could only be seen as rough estimation but still give valuable information about potential effects of wetlands in the Ic watershed.

The most promising measures to overcome the above mentioned uncertainties are the reduction of the lack of data. Daily hydrologic flow data and water quality data is helpful to enhance the process understanding in the catchment as well as improve, respectively judge the performance of the applied SWAT model. This is also true for more detailed information on soil properties. Detailed information on effectiveness and processes of nitrogen removal in wetlands could also be used to revise and thus improve the performance of the SWAT-wetland module. This information could be obtained via experiments underlain by information of a literature review.

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