An adapted modelling approach for the nitrogen load management on a catchment scale

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ABSRACT

This paper presents a model which aim is to study the effects of land use and human activities on the nitrogen loads produced at the outlet of a catchment, during a rain event. The POL model is based on a simple conceptual approach and involved a reduced number of parameters. A spatial segmentation of the catchment is determined according to topography, land use and human activities. The catchment is subdivided into subcatchments and associated reaches. Land use, determined by remote sensing, and point source pollution are integrated on GIS tool ARC-INFO® to characterise each model unit (subcatchment or river reach). Two main processes are taken into account : nitrogen production on the subcatchment surfaces and transport along the river reaches. A flexible modelling environment is used to conceptualise, simulate and optimise the POL model (VENSIM® software).

This modelling approach is conducted on the Salaison catchment, (53 km²), located in the South of France.

Keywords : Catchment, Nitrogen loads, Water quality modelling

1. INTRODUCTION

Since more than 20 years, many water quality models have been developed helping to analyse the relationships between human activities and water quality. These models classically integrate geographical information (land uses, topography, …) and hydro-chemical modelling in a database management system such as a Geographic Information System (GIS) [1]. The operational use of these water quality models is limited because of the great amount of data needed to their application at a catchment scale. For example, in the SWAT model [2], more than hundred different data files are required to apply the model. In the GIBSI system, many input data files must be collected to use the different models (HYDROTEL, SWAT, EPIC, QUAL2E) [3]. Moreover a huge number of parameters are involved in these models. The model development must be guided by the principles of reduced number of parameters and modesty [4]. Very few model approaches take into account these principles to avoid manipulation of many parameters [5, 6].

We propose, here, a model based on 2 parameters, that is able to simulate the nitrogen loads during a rain event at the outlet of a catchment. We present an application of this model on the Salaison catchment (Hérault, France). The results are compared to the monitoring data obtained at the outlet of this catchment (1998-2000).

2. MODEL DESCRIPTION

The POL model calculates at a catchment scale the total nitrogen loads for a given rainfall event. The catchment is divided into subactchments and river reaches. This delineation allows the distinction between nitrogen production function on subcatchment surfaces and nitrogen transport along the river reaches.

POL model database is integrated in a GIS-environment (ARC-INFO®) used to extract and characterise the subcatchment production units (in terms of area, land use, …) and the reach transport units (in terms of length, slope, …).

POL model production and transport functions are implemented into a dynamic simulation environment (VENSIM®).

The POL model architecture is illustrated in the figure 1. Each part of this structure is developed in this paragraph.

2.1. Hypothesis

The model conception is based on four strong hypothesis :

- Rainfall triggers the nitrogen production and transport processes. It is the only meteorological forcing variable taken into account in the model.
- Land use information, point source and agricultural nitrogen input data are sufficient to characterise the human activities.
- The output variables of the model are the total nitrogen load produced during the rain event and the flood event duration.
- Nitrogen mass is conservative during river transport. This hypothesis is acceptable if the river length does not exceed a few kilometres.

The nitrogen processes involved in the POL model are illustrated in Figure 2.

2.2. POL model database

A database management system has been built for the POL model, using the Geographic Information System ARC/INFO® software. This software was chosen because of its capacity to define and model a great number of objects : lines, polygons and points. Moreover specific hydrological routines may be implemented using the Arc Macro Language (AML).

The database requires four data coverages : a Digital Elevation Model (DEM), hydrographic network, pollution point source locations and land use (determined by satellite imagery).

The subcatchment delineation is based on the river network and involves three steps. (1), we choose the hydrologic network (perennial stream) as structure reference. (2), we define junctions and sources (river sources or pollution point sources) as nodes on the reference structure. (3), for each node, we calculate the “contributing area” (subcatchment). So the catchment is divided into subcatchments (the production units) and river reaches (the transport units), as illustrated in the Figure 3. The required spatial characteristics (i.e. area, length, land use) are calculated [7].

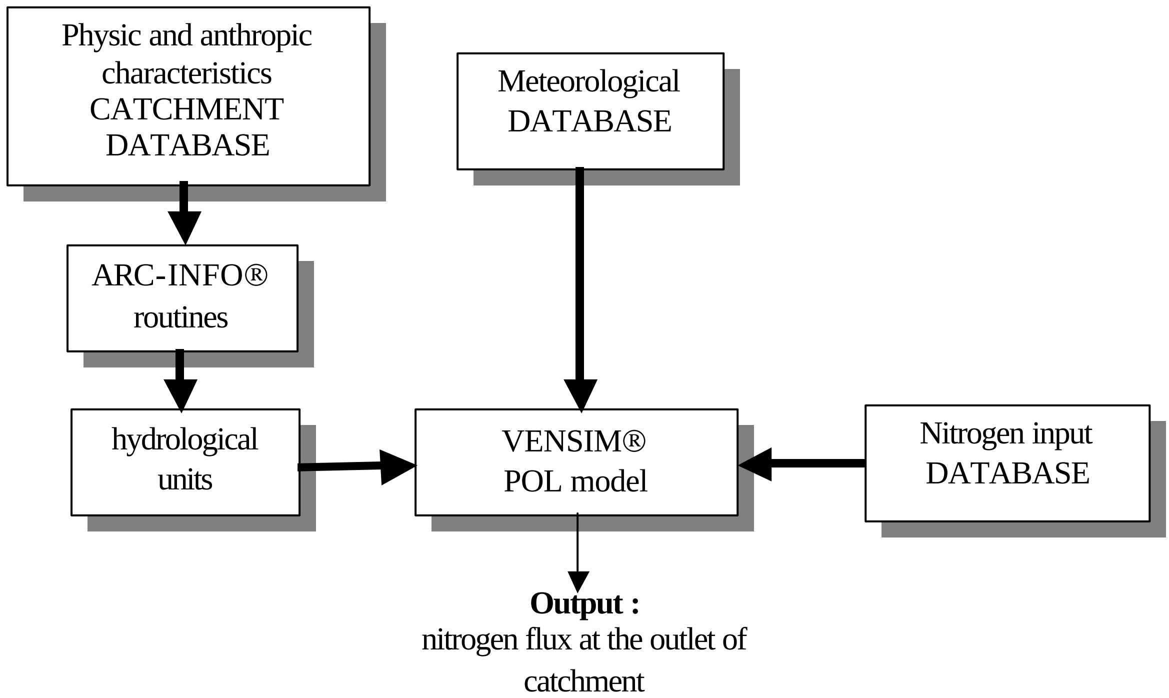


Figure 1. Nitrogen load model structure

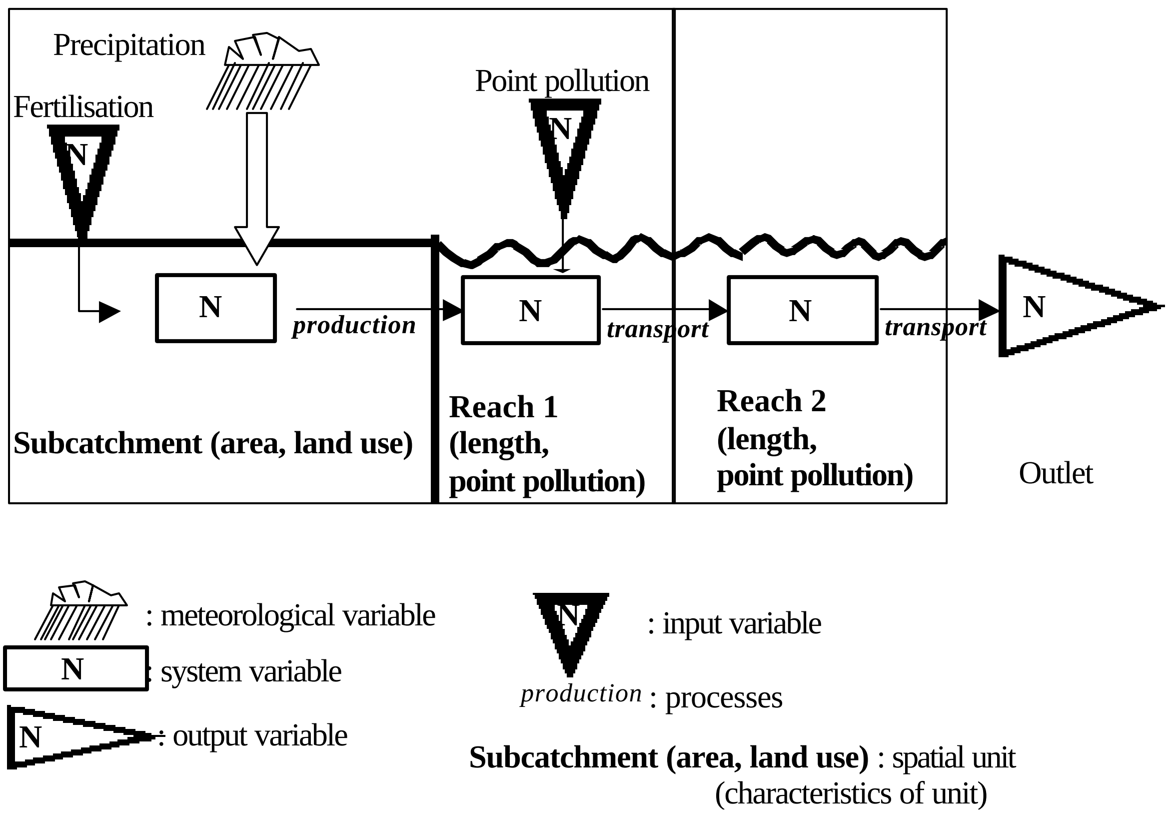


Figure 2. Schematisation of nitrogen processes in the POL model

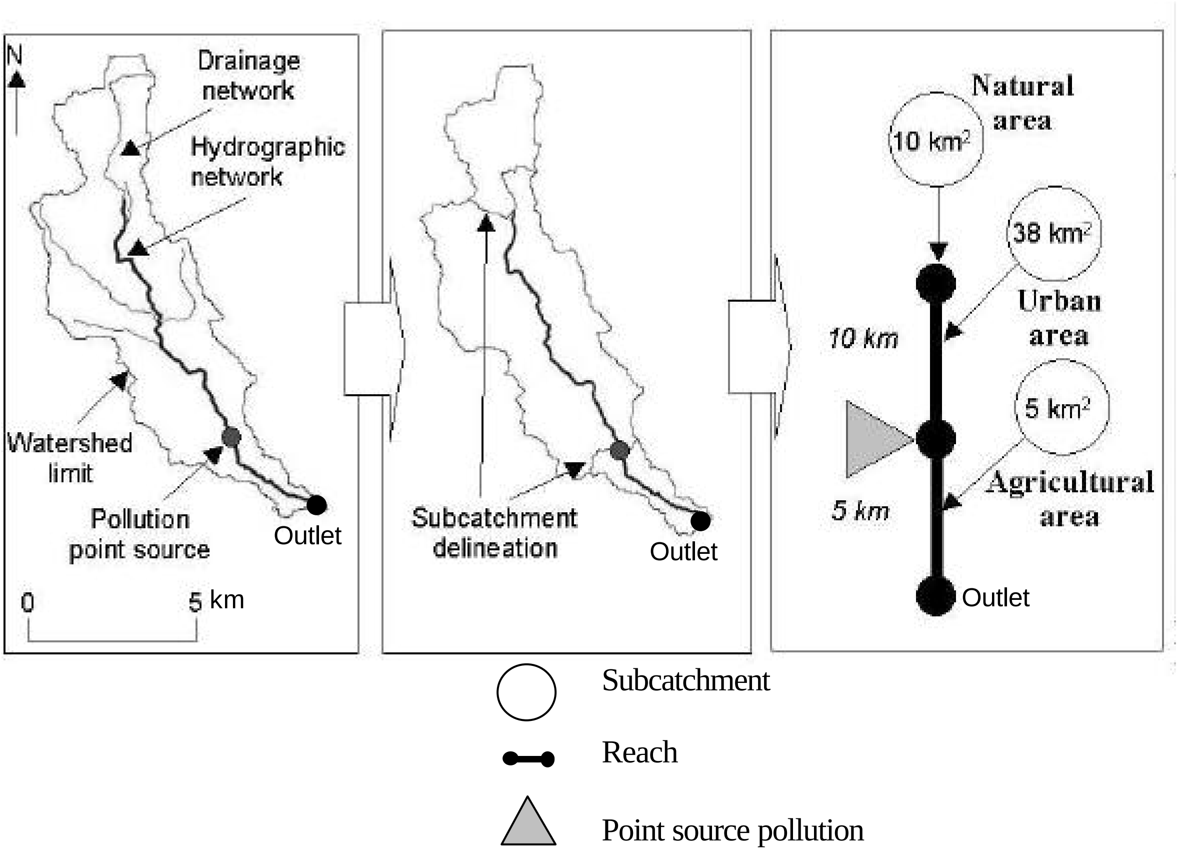


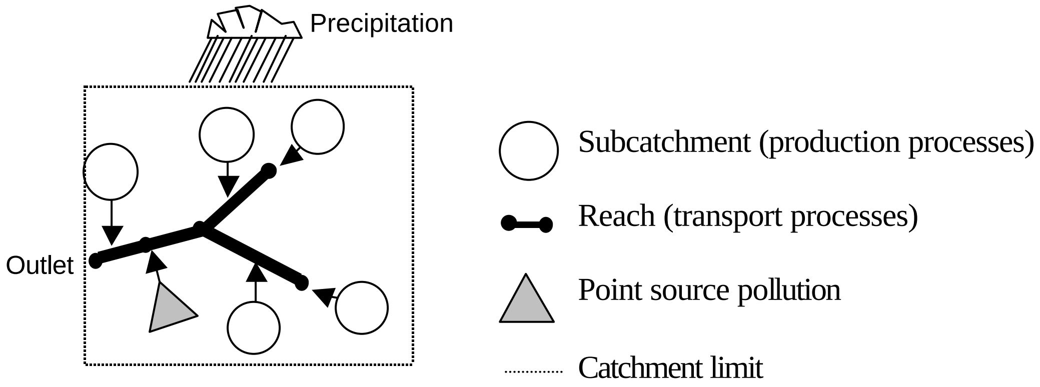
Figure 3 : Subcatchments and reaches extraction (example for the Salaison catchment).

2.3. POL model routines

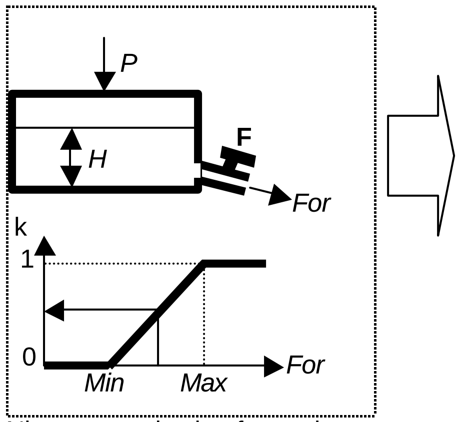
The development of POL model requires an adapted programming language. We chose VENSIM®, an object oriented dynamic simulation software well adapted to model complex system [8]. Two main processes are integrated in the POL model.

Nitrogen production processes affect the different subcatchments during the rain event. Each subcatchment is seen as a reservoir (Figure 4). The reservoir storage represented the nitrogen mass on the sub-basin and the storage coefficient is a function of the rain event. We consider a homogeneous effect of rainfall on nitrogen production for the whole catchment (Figure 4). The nitrogen storage for each subcatchment is theoretically function of land use and agricultural inputs. For this model development step, we have to obtain it by numerical optimisation.

The nitrogen loads produced on each subcatchment are routed to the outlet of catchment through the river reaches. Each river reach is seen as a series of reservoirs whose number is directly function of the reach length. Nitrogen point sources (industrial and domestic wastewaters) are considered as a nitrogen input in the river reach.



Precipitation impact for the whole catchment



Mass conservation :

$$DH/dt = P - For$$

H : precipitation reservoir storage (mm)
P : precipitation (mm/h)
For : precipitation impact (mm/h).

Linear reservoir :

$$For = \mathbf{F} \times H$$

F : storage coefficient (h^{-1}).

Rainfall impact function :

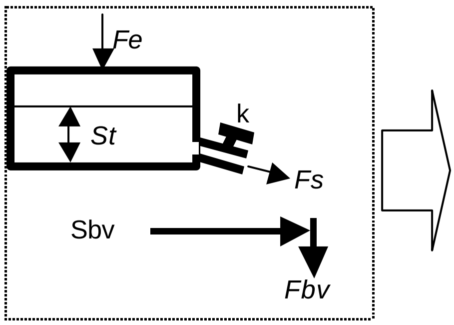
$$k = 1 \text{ if } For >= Max$$

$$k = 0 \text{ if } For <= Min$$

$$k = (For - Min) / (Min\text{-}Max) \text{ if } Min < For < Max$$

k : subcatchment storage coefficient (h^{-1})
Min : minimum value of rainfall impact (mm/h)
Max : maximum value of rainfall impact (mm/h)

Nitrogen production for each Subcatchment



Mass conservation :

$$DSt/dt = Fe - Fs$$

St : Nitrogen storage in reservoir “subcatchment” (kg/ha)
Fs : nitrogen flux output (kg/ha/h)
Fe : nitrogen flux input (kg/ha/h).

Mass conservation:

$$Fs = k \times St$$

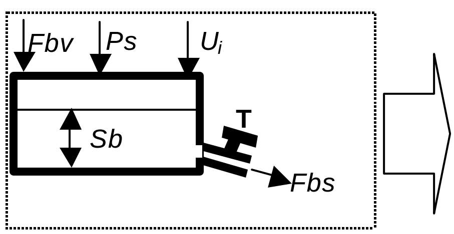
k : storage coefficient (h^{-1}) with k = f(*For*)

Total nitrogen flux produced on the subcatchment :

$$Fbv = Sbv \times Fs$$

Sbv : subcatchment surface (ha).

Nitrogen transport for each river reach



Mass conservation :

$$DVb/dt = (Fbv + Ps + U_i) - Fbs$$

Vb : Nitrogen storage in reservoir “reach” (kg)
Fbv : nitrogen flux input produced on the associated subcatchment (kg/h)
Ps : Point source input (kg/h)
Fbs : nitrogen flux output (kg/h).
U_i : upstream reach nitrogen input (kg/h)

Mass conservation :

$$Fbs = \mathbf{T} \times Vb$$

T : storage coefficient (h^{-1}).

Figure 4. Nitrogen load model structure

3. APPLICATION

3.1. The study area : Salaison Catchment

The POL model is applied on the Salaison catchment (53 km^2) located in the South of France. The length of the Salaison hydrographic network is 15 km. This catchment is characterise by 30 % of agricultural area, 45 % of natural area (scrub and forests) and 25 % of urban area. The Salaison river receives the municipal wastewaters of 23000 inhabitants.

The database created for this study includes the digital elevation model (DEM) with a horizontal resolution of 50 m, the hydrographic network (at 1:50,000 scale), the point source database (at 1:50,000 scale) and the land use coverage classified from three SPOT images with a resolution of 20 m. The nitrogen input data is issued from local authority databases. The rainfall data is collected at Montpellier-Fréjorgues raingauge located near the Salaison catchment outlet.

3.2. Model calibration and validation

The model calibration requires observed nitrogen load data. We use data collected at the outlet of Salaison from September 1998 to September 2000. Samples were taken during seven flood events (characterised in Table 1). Each sample was analysed to determine total nitrogen concentrations. The flow discharge was continuously monitored [9].

The quality of model parameter calibration is evaluated with a criteria based on a comparison between simulated and observed values of the total nitrogen load produced during the flood event and the duration of the flood event (illustrated by Equation 1) :

$$\text{Criteria} = 1 - (\text{abs}(M_{Sim} - M_{Obs}) / M_{Obs} - \text{abs}(D_{Sim} - D_{Obs}) / D_{Obs}) \quad (1)$$

with M_{Sim} : Simulated total load, M_{Obs} : Observed total load, D_{Sim} : Simulated event duration and D_{Obs} : Observed event duration.

When the number *n* of observed events is not enough large to constitute a calibration and validation data set, Bertoni [10] proposes to calibrate the model on *n* - 1 events, and to validate the model on the extreme event. Following this method, the POL model has been calibrated on the events 1 to 5 and 7 and validated on the event 6 corresponding to the higher nitrogen load.

Table 1
Event characteristics

Event	Date	Precipitation (mm)	Volume (m^3)	Duration (h)	Nitrogen load (kg)
1	25/03/99	21	23984	22	335
2	26/04/99	39	33317	19	337
3	03/05/99	85	230649	48	733
4	06/09/99	50	41886	7	542
5	20/10/99	48	233575	33	656
6	12/11/99	130	1066415	142	3674
7	16/04/00	34	66540	33	502

3.3. Results

For each of the 6 calibrated events, the simulated nitrogen loads show a good agreement with the observed values. The simulated flood event duration are underestimated for the event 5 and well reproduced for the events 1, 2, 3, 4 and 7. The validation on event 6 shows an important underestimation of the event duration but, taking into account the uncertainties, the nitrogen load is quite well reproduced. This result demonstrates the importance of calibration and validation data sets. By using the events characterised by the lower nitrogen loads for calibration, the model is unable to simulate a very high nitrogen load event. Moreover, we have considered in this calibration step a unique value of the initial nitrogen storage for all the events. The results show that this hypothesis is not adapted to reproduce the nitrogen load dynamic on the catchment.

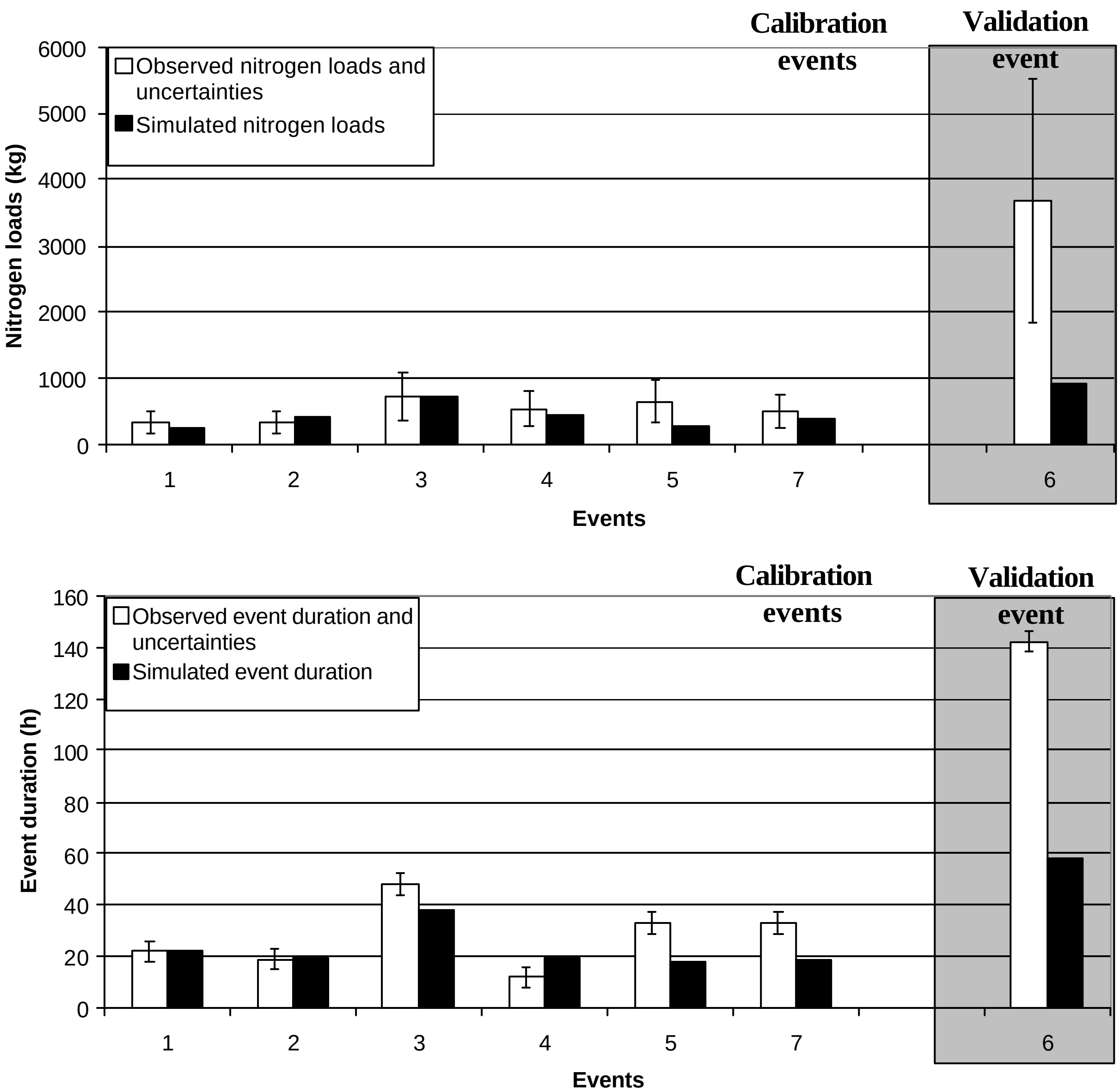


Figure 5. Results of parameters calibration and validation

4. CONCLUSION

To avoid the imbalance between model complexity and data availability, we propose in this paper a nitrogen load model based on a small number of parameters.

The POL model integrates the physic and anthropic characteristics of the catchment to delineate nitrogen production and transfer units. The model shows a good agreement with monitored flood events. However, the model is unable to reproduce the more higher nitrogen load event.

These results demonstrate the importance of the duration of monitoring study to improve a water quality model. Indeed, the available observed data just represent two hydrological years, while Meybeck [11] estimates that 10 years is the necessary duration of water quality monitoring study to understand and model a catchment behaviour for nitrogen production. Moreover, to calculate the initial nitrogen storage for each event, the next step of model development requires the integration of the nitrogen balance between the events.

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