Modelling time and spatial variable nutrients impacts and flow dynamics on agricultural systems by delineation of 'response units'

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Abstract Modelling hydrochemical contaminant catchment dynamics in agricultural basins is dealing with the detection and the quantification of spatial distributed and time variable impacts - known as nonpoint sources and the knowledge of their transformation and translocation into the catchments output. Coupling the concept of response units (RUs) through GIS analysis and the physical based solute model WASMOD were used to monitor the magnitude of export rates and dynamics of nutrients into the catchment outlet on different time and spacial scales. Thereby RUs are defined as areas having unique or similar hydrochemical dynamics related to the physiographic catchment characteristics and to the landuse strategies. Furthermore the delineation process accounts for the dominant occuring hydrological pathways, the solute source and its determinant transformation process. The concept was applied to the 216 km² Broel River basin, Germany. The catchment has been intensivly mapped and digitized for GIS analysis. Data collection included water samples for dissolved solids, fertilizer application and catchment characteristics. Hydrological and chemical balances were modelled for different time series and the results were compared with the measured output at the gaging station. Modelling results showed a good fit during unique hydrological conditions whereas RUs were adapted to. Therefore the approach is validated to monitor and control landuse changes and its effects on the magnitude of nutrients losses on a basin-scale. Future research is dedicate to transfer the RUs as modelling entities on the macroscale Sieg catchment.

1. INTRODUCTION

Known as ´environmental change´ it has become obvious in the last decades that man is drastically interfering the natural cycles of water and elements such as carbon and nitrogen (Sharpley et al., 1988; Goudie & Viles, 1997). In case of nutrients the decreasing availability of non contaminant surface and groundwater is one problem among several other and is often related to the intensive use of agricultural lands. Facing towards the next millennum the problem of contaminant impact on rivers known as point and non-point sources needs to be solved. Whereas the first source is easily to be detected along the river stretch, the latter is difficult to quantify as fertilizer transport lag application (Novotny & Olem, 1994). Various processes occur including hydrochemical reactions, ad- and desorption at the surface of the soil matrix, nutrients plant uptake and decomposition of harvest residues. The importance of these spatially distributed processes is therefore highly dependent on the physiographic catchment factors such as precipitation, soil, geology, topography and landuse. In hydrological and hydrochemical studies the GIS-based concept of 'respone units' is often used to preserve such catchments heterogeneity (Vieux, 1991; Flügel, 1995, 1996, Kern & Stednick, 1993, Bende, 1997). They are defined as areas having a unique hydrochemical process dynamics according to their landuse and the underlaying geo-pedo-topo sequence. Coupling RUs with the physical based model WASMOD (Reiche, 1991) the nitrogen dynamics of the mesoscale Broel river catchment were modelled interdependently on the spatially distributed heterogenous catchment characteristics.

2. OBJECTIVES

The purpose of this study focused on two main topics. First for input-output evaluation a linkage between the water quality dynamics observed at a downstream gaging station in the river Broel and the landuse management in the catchment was established. Second for the model application the RUs were delineated and linked to the hydrochemical model WASMOD. According to these main issues the following objectives can be outlined:

(i) Implementation of data sampling routines to collect continuous input and output data as well as water samples for lab analysis during a period of five hydrological years (1992 to 1996),

(ii) Development of a catchment-information-system including hydrometeorological, hydrochemical and landscape data,

(iii) Using GIS-overlayanalysis to proceed a unique-condition modelling entity layer as inputset for running the model WASMOD,

(iv) Identification and determination of dominant hydrologic and solute processes for delineation of response units (RUs) according to the main water and nitrogen turnoverrate dynamics.

3. MATERIALS AND METHODS

3.1 Study area

The mesoscale catchment of the River Broel (216 km²) is located on the northern bound of the middle mountain range of the Rhenish Slate Mountains, Germany. It drains into the River Sieg which is a tributary of the River Rhine. The basin faces on the weather side the industrial zone of Cologne whereas heavy emission is expected. The climate is oceanic with an annual mean temperature of 8°C.

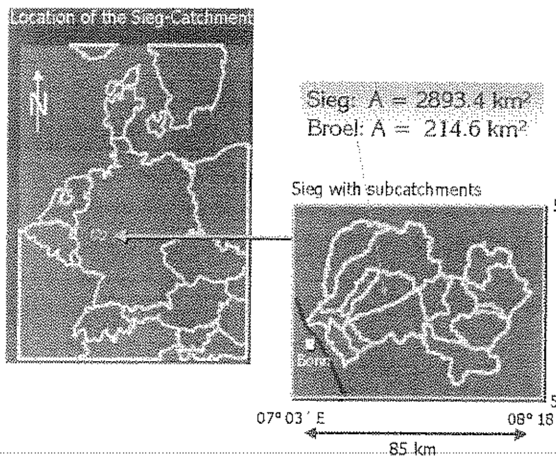


Fig. 1: Map showing the location of the study area

Additionally it can be characterized by annual precipitation ranging from 950mm to 1100mm. During the winter season the precipitation is driven by advective rainfall due to mesoscale atlantic disturbances (zyclones) locally modified by topography whereas the majority of rainfall is taking place in summer related to convective thunderstorms. Evapotranspiration adds up to about 60% of the annual precipitation and the runoff is clearly dominated by the interflow dynamics appearing as lateral flow along the hillslopes. The catchment is underlain by impermeable devonian shale. Therefore losses of water due to deep percolation are negligible. Native soil-series are developed with brown soils and soils lessivé on the hillslope (partially eroded) as well as on the upper peneplain. Gley soils are found on plains and fluvisols within the valley floor. The soils are all largely comprised (up to 90%) of homogeneous silty loams. Given the natural conditions, the predominant landuse besides settlements and forests is grassland (~50%). It is used as pasture, mown grass and hay meadows. Here the annual mean fertilizer application accounts for ~190 kg N/ha. Arable production (corn, winter grain) is for fodder purposes only, and so the arable area is small (4%).

3.2 Database and Catchment-Information-system

To perform the catchment-informationsystem the database management system ORACLE was used to store:

(i) The hydrometerological data including climate data such as precipitation, temperature, solar radiation and discharge during the water years 1970 - 1996 and

(ii) the hydrochemical data during water years 1992-1996 for (a) bulk samples such as point measured wet and dry atmospheric deposition and (b) the two weeks intervaled samples at the gaging station which were taken for anorganic analysis of major anions and cations and additionally related to the 5 min logged electrical conductivity data.

The GIS ARC/INFO was used to perform the GIS database for the Broel catchment by

(i) Implementation of a 50*50m DEM for terrain analysis,

(ii) Field mapping of landuse in addition to remote sensing data,

(iii) Digitizing maps like soils, landuse and geology and

(iv) Integration of point measured precipitation and its regionalisation to spatially distribution by using Thiessen-Polygons.

Both systems were interlinked through SQL-query.

3.3 Modell Description

The process orientied model WASMOD (water and substance model) was selected to calculate water and nutrients flow dynamics on the mesoscale Broel River

Heat and water transfer

The heat mass transfer in the soil is following the numerical solution of the general heat flux equation according to the thermal conductivity and heat capacity (de Vries, 1963). Thereby the modell accounts for the convective type of heat transport and the dependence on the soil water content and the soil composition. Soil water movement and flux is modelled with the potential concept, by solution of the Richards equation. In addition the model accounts for bypass flow along macropores and drainages (Reiche, 1991). Boundary conditions are taking soil-evaporation, transpiration and interception as well as groundwater recharge into account.

C and N transformation and solute transport

Three pools of organic matter based on specific decay rates are used to describe the heterophic and autotrophic activity of microbial biomass and their sequential reduction of organic matter and anorganic contents as O_2, NO_3- and N_2O during C-oxidation (Jenkinson et al., 1987). The mineralisation-immobilisation turnover as well as the nitrification and denitrification processes were driven according to the growth and decay rates of the decomposition and transfer rate between the pools (Reiche, 1994). They follow first order kinetics according to abiotic factors such as soil water content, temperature, soil acidity and clay content and additionally oxygen content for denitrification processes. Ammoniac-votalisation is calculated as sink according to the type of fertilizer application, the LAI and potential evaporation (Hoffmann, 1995). De- and adsorption of ammonia is described by linear adsorption isotherm in relation to immobile and mobile soil water contents. The nitrogen dynamics are furthermore coupled to the general convection-dispersion equation for solute transport simulation. Nitrogen uptake by plants is simulated by a cropspecific plant uptake function following the Michaelis-Menten type.

Modelling preprocessing and modell output

Preprocessing routines of WASMOD included coupling the unique condition modelling entity layer with field datas to build up a set of input parameters. Further each modelling entity was routed according single cell algorithmen towards the river stretch. Simulation output included calculated water and nutrient balances for each entity (in terms of microscale) and water and nitrogen dynamics (in terms of mesoscale). The model was run for 1990 to 1996 and modell validation was carried out for hydrological year 1994 showing a good correlation fit between observed and simulated discharge and nitrogen-concentration.

4. RESULTS

4.1 Modelling results

As shown for the hydrological year 1995 during the period of advective winterly rainfall occuring in december to february WASMOD did not reach the dynamics of the peak discharge. The retarded drop of the recession curve may be caused by the single cell routing mechanismen of the modelling entities.

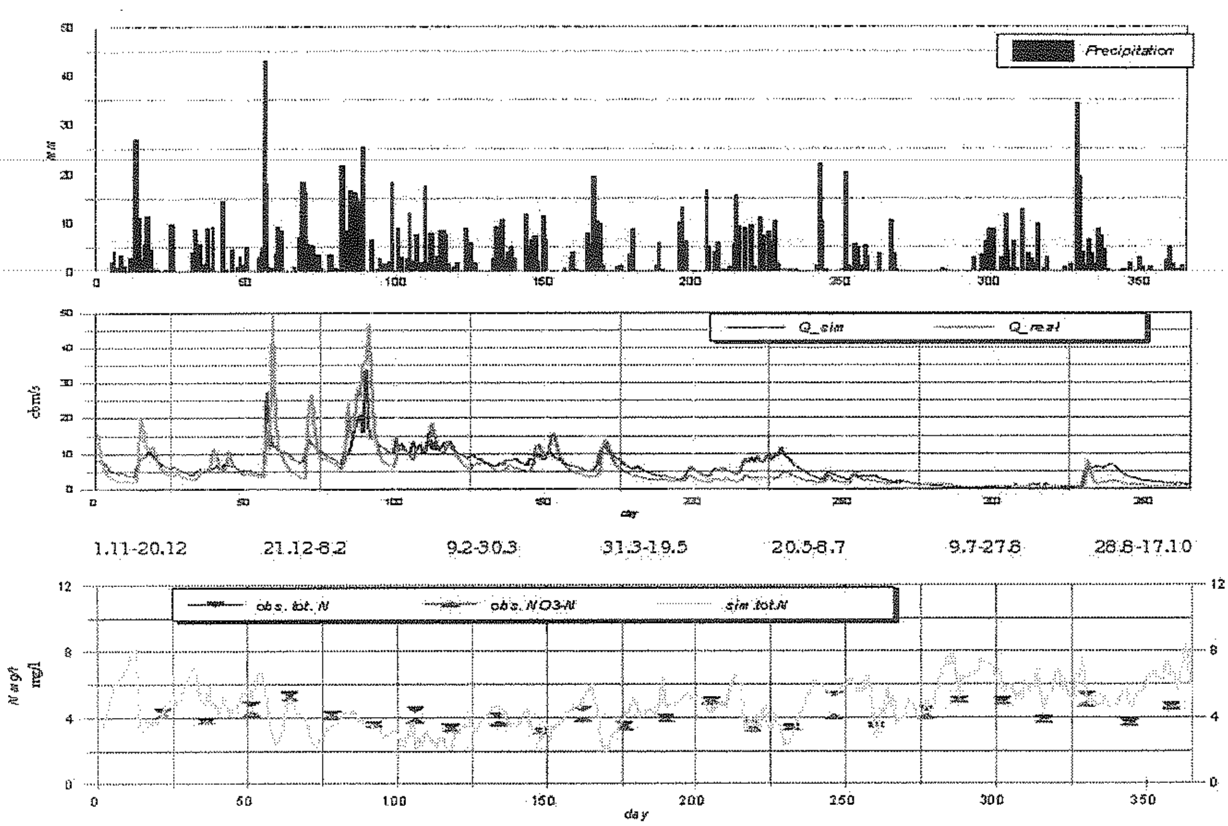


Fig. 2: Simulation results for water&nitrogen dynamics (HY95)

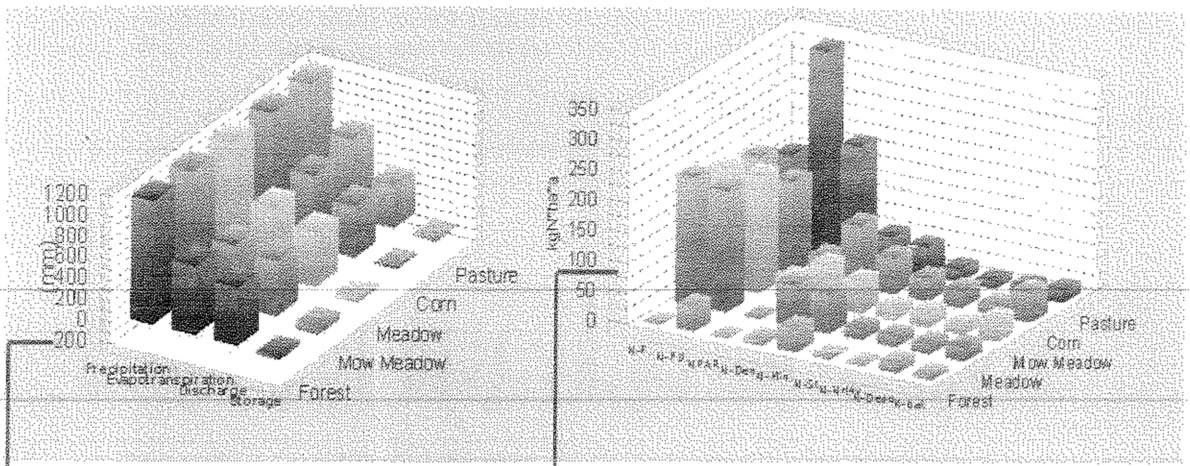
Here the roll of linear elements is not correcty understood (e.g. streets channels, small ditches acting as quick transfer). Additionally especially in january where sudden snow melt processes producing surface runoff on frozen top soils are not covered by the model. Overestimation is found in the beginning of the summer low flow period. This may be caused by underestimation of the evapotranspiration rate due to not adopted crop-factors (empirical Haude-evapotranspiration). Low flow dynamics are show a good fit between observed and simulated discharge.

Regarding nitrogen output concentration it is shown that the simulation showed undersimulation during oversimulation periods resulting in diluting processes of the discharge and contrariwise. A good correlation fit is shown during the summerly low flow period. In most cases the amount of the total observed nitrogen output is given by the nitrate component which indicates mineralisation and nitrification as main nitrogen turnover process.

However in some cases during and after peak flows, here occuring in september, the total nitrogen output is based also on other nitrogen components like ammonia. This can be interpreted as impact from quick response of surface runoff as well as macroporeflow. In some cases however mainly occuring in late summer it can also be caused by direct impact of cows along the river stretch.

4.2 Determination of Response Units (RUs)

On the base of the annual water and nitrogen budgets RUs were determined. Accounting for the catchments heteorogeneity the delineation process is thereby based according to the unique water and nitrogen turnover dynamics whereby (i) first the roll of the landuse was intevestigated resulting in 5 main types of landuse units (Fig. 3) and (ii) additionally topography, aspect and soils conditions were considered resulting in 17 classes of RUs (Tab. 1).



	Precipi-tation	Storage	Evapotrans-piration	Discharge
Forest	1168,53	-24,00	742,00	402,53
Mow Meadow	1168,53	-10,00	674,00	484,53
Meadow	1168,53	-27,00	647,00	523,10
Corn	1168,53	-24,20	570,80	563,00
Pasture	1168,53	-34,00	653,00	549,53

	N-Fertil.	N-PlantU.	N-Pl-AnR.	N-Denitr.	N-Miner.	N-Stor.	N-NH4v.	N-Depo.	N-balance
Pasture	150,00	335,00	188,00	50,70	44,47	20,00	12,50	15,88	20,15
Corn	180,00	160,00	37,00	80,50	58,81	36,00	38,40	15,88	48,79
Mow Meadow	193,00	191,30	34,00	66,10	52,38	20,90	23,80	15,88	34,96
Meadow	210,00	200,00	0,00	66,90	63,22	17,50	16,90	15,88	22,8
Forrest	0,00	41,2	0,00	8,20	38,62	3,00	0,60	15,88	7,5

Annotation:

- N-Fertil: (+) Fertilizer&Manure application
- N-PlantU.: (-)Plant Uptake
- N-PL_AnR: (+)Plant & Animal Residues
- N-Denitr.: (-) Denitrification
- N- Miner.: (+) Mineralisation
- Stor.: (+) Storge
- NH4v: (-) Ammoniavotalisation
- N-Depo.: (+) Atm. Deposition

Fig. 3 Water & Nitrogen budget (HY95) for the Broel basin

(i) Due to different evapotranspiration rates all classes react in a different way. It can be seen that forests producing a lower amount of discharge on the base of higher transpiration rates followed by mow meadows, pasture, meadows and corn. Additionally the duration of vegetation period is shorter. Concerning the nirogen budget a high amount of nitrogen export rates is found on corn fields followed by mow meadows, meadows, pastures and forests – although farmers are concerned to fertilizer in an adopted way. Here the amount of applicated fertilizer corresponds or is even lesser than the amount of estimated losses by plant uptake demands (e.g. corn, pasture). This rests upon other impact sources, such as atmospheric deposition and mineralisation processes. These processes are varying according to climatic conditions throughout the year and in general can not be adopted and calculated for the actual nitrogen need of plants during the vegetation period. Regarding nitrogen loss components different amounts of ammonia-votalisation rates can be seen. On corn fields highest rates are found due to mostly manure application in the middle of april (rising temperatures); lowest votalisation rates are found on pasture where lesser and the mineral type of fertilizer is used in the beginning of march occuring low temperatures. Denitrification rates varying also and here they are functioned by topography and soils conditions as arable land is located on even plains and valley floors which have saturated conditions especially in hydrologic winter years.

(ii) Considering topography, slope, aspect and soils the variablity of spatial related nitrogen export becomes more complex (Tab. 1).

RU No.	Area (km²)	Area (%)	Landuse Units	Landuse Management & N-fertilizer& export	Soil types & depth	Topography& Curvature	Slope (%) & Aspect
1	25,0	11,6	Impervious	No fertilizer	all	all	All
2	1,7	0,80	Wintergrain	- 130 kg N/ha[*a] S: 10 kg N/ha[*a]	all	all	All
3	6,4	2,98	Corn	- 180 kg N/ha[*a] S: 48 kg N/ha[*a]	all	all	All
4	10,0	4,95	Pasture	- 150 kg N/ha[*a] S: 20,1 g N/ha[*a]	all	all	All
5	10,2	4,75	Mow Meadow	- 193,0 kg N/ha[*a] S: 37,9 kg N/ha[*a]	Brown soil 220cm	Slope - convex	>10-20% N, NE, NW
6	12,5	5,81	Mow Meadow	- 193,0 kg N/ha[*a] S: 34,2 kg N/ha[*a]	Brown soil 160cm	Slope - concave	>10-20% N, NE, NW
7	11,0	5,12	Mow Meadow	- 193,0 kg N/ha[*a] S: 31,7 kg N/ha[*a]	Brown soil 220cm	Slope - convex	>10-20% W – E
8	10,0	4,65	Mow Meadow	- 193,0 kg N/ha[*a] S: 28,4 kg N/ha[*a]	Brown soil 160cm	Slope - concav	>10-20% W - E
9	3,1	1,43	Mow Meadow	- 193,0 kg N/ha[*a] S: 26,9 kg N/ha[*a]	Fluvisoil 250cm	Valleys - even	0-10% all
10	7,7	3,59	Mow Meadow	- 193,0 kg N/ha[*a] S: 32,9 kg N/ha[*a]	Gleysol 60cm	Plains - even	0-10% all
11	7,5	3,58	Meadow	- 210,0 kg N/ha[*a] S: 24,8 kg N/ha[*a]	Brown soil 220cm	Slope - convex	>10-20% N, NE, NW
12	10,9	5,04	Meadow	- 210,0 kg N/ha[*a] S: 22,4 kg N/ha[*a]	Brown soil 160cm	Slope - concave	>10-20% N, NE, NW
13	8,3	3,86	Meadow	- 210,0 kg N/ha[*a] S: 21,7 kg N/ha[*a]	Brown soil 220cm	Slope -convex	>10-20% W – E
14	7,8	3,63	Meadow	- 210,0 kg N/ha[*a] S: 19,3 kg N/ha[*a]	Brown soil 160cm	Slope -concave	>10-20% W - E
15	2,9	1,37	Meadow	- 210,0 kg N/ha[*a] S: 18,6 kg N/ha[*a]	Fluvisoil 250cm	Valleys - even	0-10% all
16	7,54	3,50	Meadow	- 210,0 kg N/ha[*a] S: 20,7 kg N/ha[*a]	Gleysol 60cm	Plains - even	0-10% all
17	72.0	33,45	Forest	No fertilizer S: 7,5 kg N/ha[*a]	all	all	all

Tab.1: Properties of the RUs for the Broel basin   Annotation: S= nitrogen surplus – export rate

As result 17 different RUs have been determined each reflecting local unique conditions of hydrochemical relevant parameters. The RUs Nos. 1-4 and 17 are differentiated according to their landuse specific nitrogen export rate whereas other parameters are set equally. This covers impervious areas as well as forests and agricultural lands. One third of area coverage obtains brown soils and soils lessivé (RUs 5-8; 11-14). Due to their locations on slopes (>10-20%) they are related to interflow dynamics and further the influence of aspect and soil depth becomes here apparent. Higher temperature gradient is liable for higher mineralisation rate and higher plant uptake demand (comparing RU5-7;6-8; 11-13; 12-14). Therefore lower export rates are found on west-east exposed slopes are found. Further the soil depth regulates the duration of nitrogen turnover rates. For RUs 5,7,11,13 although receiving addition impact from adjacent slopes the nitrogen output is reduced by higher denitrification rates due to higher water contents (if comparing to RUs 6,8,12,14). Additionally denitrification conditions are especially found on valley floors (RUs 9, 15; receiving percolation water from the slopes obtaining a groundwater zone along the river stretch) and temporary on peneplains (RUs 10, 16; building up wetting zones in the shallow soils along the bedrock) where vertical flow dynamics and higher nitrogen impacts are found.

5. CONCLUSION

The concept of coupling model entities with the solute model WASMOD was prooved to be a powerful tool to monitor catchments nutrients impacts and responses on agricultural in case of nitrogen. As a result 17 major classes have been delineated whereby the roll of the catchments heterogeneity such as landuse specific fertilizer impact, topography influencing slope, aspect, soils properties can be concluded as dominant factors for nitrogen transformation and translocation processes. Therefore it could be pointed out that high fertilizer application does not necessarily mean high nitrogen export rates. Furthermore the aggregating of unique condition modelling entities to RUs allows combining the micro-scale and meso-scale. Future studies will transfer the approach to the basinwide macro-scale Sieg catchment (a= 2893km²). Hereby parameter optimizing will be improved as well as multiple flowdirection cell routing routines of the modelling entities. Additional snow melt routines have to be included for better winterly season simulation.

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