Regional hydrochemical modeling by delineating Chemical Hydrological Response Units (CHRU's) within a GIS - An approach of observing man-made impacts in the mesoscale Broel-catchment (Germany)

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ABSTRACT

Characterizing and modeling hydrochemical catchment dynamics is dealing with the challenges of upscaling point measurements to a regional, spatial distribution and with the regional spatial dynamics of nonpoint sources and their relation to catchment management. These two challenges can be met by applying the concept of "Chemical Response Units (CHRU's)" and using GIS-analysis to delineate their spatial distribution. CHRU's can be defined as areas having similar hydrochemical dynamics dependent on their landuse management. This concept was applied to the 216 km^2 mesoscale catchment of the Broel River Basin in the middle mountain range of the Rheinische Schiefergebirge in Germany. It has been mapped for landuse pattern and digitized for GIS-analysis. The catchment has been intensively instrumented including continuous water sampling for dissolved solids, logging electric conductivity (mS/m) at two river gauging station and atmosheric deposition as bulk samples. the database includes additional fertilizer application data and catchment characteristics. Data from neighbouring forested test catchspheric deposition. The annual chemical balances of the Broel catchment were calculated using the CHRU's and results compared with the measured output at the two gauging stations. Results showed deviations associated with undetected point sources but also good fits during periods with unique hydrological conditions. In summary the concept of CHRU's proved to be a practical method for the evaluation of the chemical dynamics within watersheds and therefor observing man-made influence on them. Future research is directed to combine the CHRU-concept with a hydrologicalchemical models like MMS/PRMS, APEX or AgNPS, and thereby interfacing the hydrochemical and the hydrological dynamics, on a basin-scale.

1. INTRODUCTION

Rivers and lakes with a free surface to the atmosphere are open systems each coupled with the water cycle of their catchments. Hence they are directly influenced by its components precipitation, surface runoff, infiltration, interflow, and groundwater seepage. Here they could be directly connected to man's system showing up as spatial distribution of the atmospheric and anthropogeneous chemical input (Flügel, 1991). Whereas the point source like outflow from seewage plants could be easily detected along the river stretch (Kern & Stednick, 1993), diffuse sources such as nutrients from fertilized fields or atmospheric deposition are difficult to identify and quantify (Novotny & Olem, 1994). The solute transport dynamics of the dissloved solids occur in various processes such as chemical reactions, adsorption and desorption of the soil matrix, fertilizer consumption of plants and their storage and decompositions of harvest residues (Nolte & Werner, 1991; Beegle & Lanyon 1994).

These different processes are strongly related to the variability of time (seasonal change of plant growth and climate conditions), and are also highly dependent on the various physiographic factors like precipitation, topography, soils, geology (Flügel & Lüllwitz 1993) and land use management. Each of this process is spatially distributed within the catchment composing it's three-dimensional heterogeneity (Flügel, 1993). Using the capabilities of spatial analysis provided by a GIS (Geographic Information System) this heterogeneity can be represented by various two-dimensional coverage layers, and by overlay analysis unit areas of similar hydrochemical and hydrological dynamics can be delineated (Kovar & Nachtnebel 1993, Engel 1993). They were introduced by Kern & Stednick (1993) as Chemical Hydrological Response Units (CHRU's). If these CHRU's are linked with solute balance models as described by Bach (1987) and Wendland et al. (1993) the hydrochemical dynamics of a river catchment can be characterized and modeled according to its spatially distributed physiographic heterogeneity. They are proved to be a proper method to observe long-term influences on rivers according to the landuse management. The method has been successfully applied for the Bröl-mesoscale catchment in Germany.

2. STUDY AREA

The 216 km² River Bröl catchment is located on the nothern bound of the middle mountain range of the Rheinische Schiefergebirge, Germany, about 50 km east of Bonn. The River Broel drains into the Sieg which is a tributary of the River Rhine. It faces on the weather side of the industrial zone of Cologne whereas heavy emissions are expected.

The climate is oceanic with mean annual temperature of 8°C and having annual precepitation ranging from 950 mm to 1100 mm. During the winter season the precipitation is driven by advective rainfall due to atlantic disturbances (zyclones), locally modified by topography. Most of the rainfall occurs in summer as convective thunderstorms. Evapotranspiration adds up to about 50% of the annual precipitation and the runoff is clearly dominated by the interflow dynamics appearing as lateral flow along the hillslopes.

The river basin is underlayn by impermeable devonian shale. Therefore losses of water due to deep percolation are negligible. Native soil-series are brown soils and soils lessivé on the hillslope (partially eroded) as well as on the upper peneplain. Gleysols are found on plaines and fluvisols within the valley floor. They are all consisting to over 90 % of homogeneous material such as silty loam.

Based on the natural conditions the predominant landuse besides settlements and forests (45%) is covered with pastures and meadows (52%) used for grazing and haying. Agricultural land (corn, wintergrain) accounts for fodder purposes only (3%).

3. METHOLOGY

The purpose of this pilot study was twofolded. For observing input-output relation a linkage between the water quality dynamics observed at the downstream gaging stations in the River Broel, and the landuse management in the catchment was established. To preserve its three-dimensional heterogeneity for distributed transport modelling, the CHRU's as dynamic modeling units, were delineated by using the physiographic properties of the catchment and GIS-analysis (Fig. 1). The ojectives of modeling approach were: (i) Implementation of data sampling routines to collect continuous input and output data as well as water samples for lab analysis, (ii) development of a project database including meteorological, hydrological, hydrochemical and landscape data, (iii) calculation of water and nutrients balances to evaluate nutrient gains and losses, (iv) application of GIS-technoloy for catchment classification to identify 'Chemical Hydrological Response Units' due to potential nutrient losses.

For model-application the Quadtree structured GIS SPANS was used to perform the project database for the Broel catchment and are described as follows: (i) development of a landscape element database by (a) building up a DEM with a solution of 50 * 50 m and deriving slope and aspect, (b) field mapping of landuse in addition to remote sensing data and (c) digitizing maps of soils and geology; (ii) development of the meterological database according to the (a) measured point precipitation and its regionalisation to spatially distributed data by using Thiessen-Polygons, (b) calculatition of evapotranspiration as a function of regulating the hydrological cycle; (iii) development of a hydrochemical database with (a) measured point wet and dry atmospheric deposition and their translation within space and time and the (b) establish crop specific nutrient input according to farmers questionary (c) linkage of continuous measured data from gauging station in respect to calculated catchment-output. For the water year 1992 and 1993 the two-weeks interval samples have been taken for anorganic analysis and additionally related to the 5 min logged electrical conductivity data .

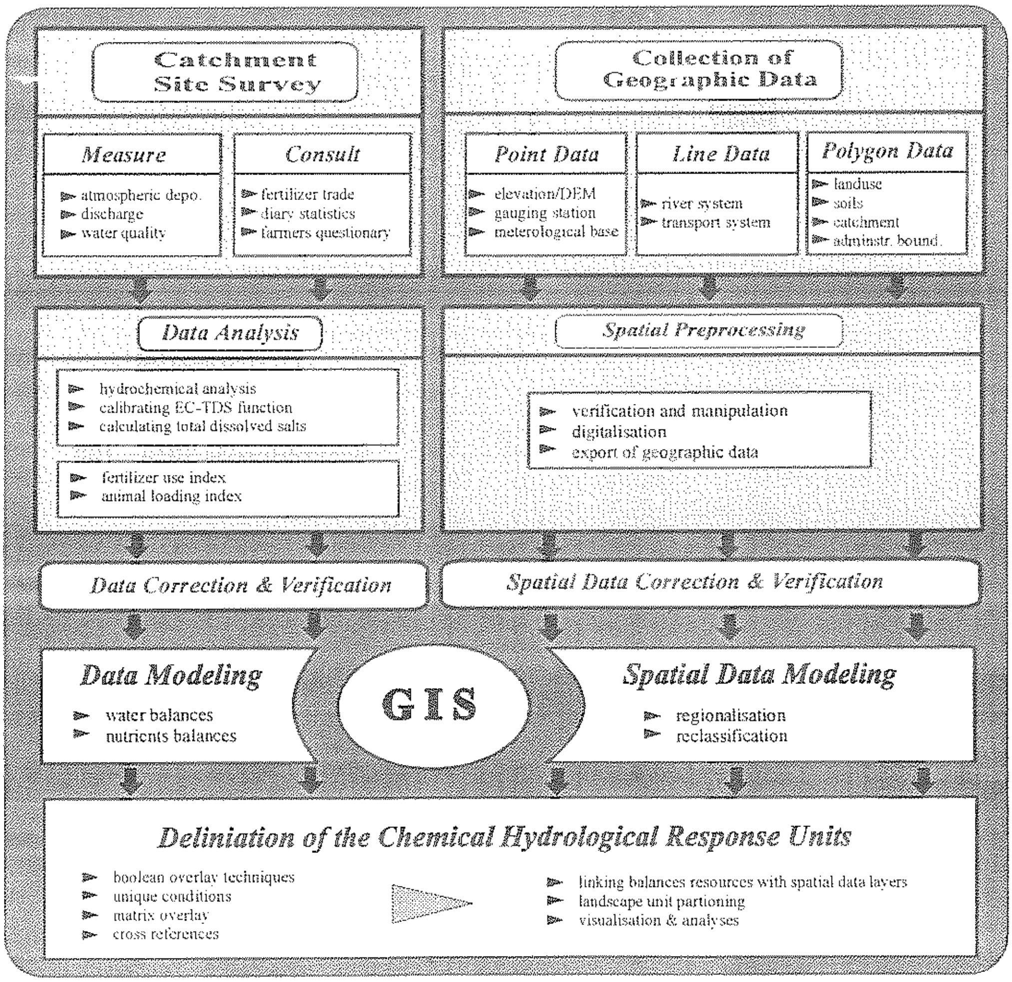

Fig. 1: Schematically presentation of the development of the project database and the linkage between GIS and the process of regionalisation

4. MODEL-APPLICATION AND RESULTS

Nutrient Balance

A nutrient balance calculation model was applied for the Broel basin related to the local landuse management system. Fertilizer and manure application were determinedby questioning farmers. A goal was to quantify the crop specific nutrient cycle during the growing season when gains and losses will be recognizable. The method is based on summing the nutrient input for each crop unit according to applied typ of fertilzer and the amount of atmospheric deposition within the catchment, both reduced by the plantspecific nutrient removal in relation to a crop harvest factor and nurtrients losses depending on the adaption of manure and fertilizer techniques. For nitrate the amount of symbiosis fixation was addionally considered on meadows and pasture land as well as degas losses caused by denitrification and ammoniafication processes.

As a result three major classes of potential nutrient losses were derived. In case of nitrogen the classes are low (0-10 kg $ha^{-1}year^{-1}$), medium (>10-35kg $ha^{-1}year^{-1}$) and high (>35-50kg $ha^{-1}year^{-1}$) losses. The analysis showed that the high fertilized tillage system is not necessarily correlated with a high surplus. The classified output components were than refered to their specific landuse units and transfered within the GIS into potential nutrient loss units.

Delineation of Chemical Hydrological Response Units using GIS-Application

To regionalize 3-dimensional spatial data, a CHRU is assumed to have homogeneous hydrochemical dynamics and processes relativ to adjacent units. This method allows a combination of various scales within space and time depending on the need of application.

Deriving the CHRU's for the Broel catchment was realized by using GIS capabilities of boolean overlay-techniques. Aggregation procedures such as unique conditions and cross reference operations, were used to outline the best fitting parameters for deliniating the CHRU's.

For this purpose the landscape elements such as landuse, soils and topography have been digitized, slope and aspect were obtained from the DEM and than transformed and stored into digital vector and raster layers within the GIS. The delineation process can be described as follows: landuse-units (LU's) as already mentioned were transfered into units describing their crop specific nutrient surplus (CNSU's) whereas settlements as impervious areas were related to point sources as outflows of sewage treatment plants and forested areas are counting for the natural driven load. On the base of soil texture, depth, field capacity and their dominant hydrological transport system (lateral flow, vertical flow) as well as depending on terrestric and semi-terrestric dynamics soil units (SU's) were aggregated. In addition to slope, aspect and through the combination of Topography units (TU's) were build along valley floors, slopes and high plains. Termed as CHRU's the typical unit layers were recombined together. As a result 16 CHRU's (Tab. 1) have been delinetated, each reflecting the local unique conditions of hydrochemical relevant combination of parameters. The CHRU's 1-3 and 16 are differenciated according to the landuse specific nutrient surplus whereas other parameter are set equally. This covers impervious areas as well as forests and agricultural areas with low area coverages. The highest amount of area coverages (40%) is charaterized by brown soils and soils lessivé (CHRU's 4,7,10 and 13). Owing to their location on 10-20 % slopes they are related to the interflow dynamic and are showing a high Thethe meterological database specific conditions for nutrient cycle (e.g. soil moisture and temperature as a function of precipitation and incoming radiation) could be derived.dependence on topography and exposition. Most of the meadows and pastures with a medium and high amount of nutrient surplus are here distinguished. The influence of groundwater and vertical water flow are the most important factor in case of CHRU 8,9 14 and 15 which are exhibited to medium and high nutrient surplus. They are located in the valley floors and show a high potential towards nitrogen reduction processes such as denitrification.

CHRU No.	Area (km²)	Area (%)	Topography	Slope (%)	Soil	Landuse/ Nutrient Surplus	Exposition N,O,S,W
1	25,04	11.62	all	all	all	Impervious	all
2	1.72	0,80	all	all	all	Wintergrain - low -	all
3	6,42	2,98	all	all	all	Corn - medium -	all
4	11,66	5,41	Slope	10 - 20	Brown soil/ Soils lessivé	Meadow - medium -	NE
5	16,53	7,67	Slope	10 - 20	Brown soil/ Soils lessivé	Meadow - medium -	SE
6	12,54	5,82	Slope	10 - 20	Brown soil/ Soils lessivé	Meadow - medium -	SW
7	11.53	5,35	Slope	10 - 20	Brown soil/ Soils lessivé	Meadow - medium -	NW
8	3,99	1,85	Valleys	0 - 10	Fluvisols	Meadow - medium -	alle
9	8,96	4,16	Plains	0 - 10	Gleysols	Meadow - medium -	all
10	7,52	3,49	Slope	10 - 20	Brown soil/ Soils lessivé	Pasture - high -	NE
11	10,86	5.04	Slope	10 - 20	Brown soil/ Soils lessivé	Pasture - high -	SE
12	8,32	3,86	Slope	10 - 20	Brown soil/ Soils lessivé	Pasture - high -	SW
13	7,82	3,63	Slope	10 - 20	Brown soil/ Soils lessivé	Pasture - high -	NW
14	2,95	1,37	Valley	0 - 10	Fluvisols	Pasture - high -	all
15	7,54	3,50	Plains	0 - 10	Gleysols	Pasture - high -	all
16	72.06	33,45	all	all	all	Forest	all

Notation: Nurient Surplus: low = 0-10 kg/ha, medium =10-35 kg/ha, high =35- 60 kg/ha;

Tab. 1: Properties of the Chemical Response Unit's in the Broel catchment regarding the nitrogen dynamic

5. CONCLUSIONS AND FUTURE RESEARCH

Delineation of the CHRU's in regarding to their hydrochemical dynamic based on the water and the nutrient balances is a powerful tool to establish the linkage between the observed water quality dynamics and the catchment landuse management. According to this method man-made impacts and landuse management changes can also be observed. Calculation of all quantified catchment input parameters such as point and non-point sources as described in the project database show that in case of nitrogen most of the catchments input (64% = 462t) is related to the surplus of agricultural land, meadows and pasture (Fig. 2).

peaks caused by heavy precepitation and snowmelt events. Regarding the fact that the amount of nitrogen input (720 t) exceeds the measured output (618 t) it indicates the catchments potential of hydrochemical reactions ecpecially for dentrification processes and ammonia-fixation (nitrogen immobilisation). Denitrification conditions (field capacity and temperatures up to 5° C) are spatially related to CHRU 8,9,14 and 15 mostly during spring and autumn seasons whereas ammonia-fixation is more depending on NH_4^+-concentration of the soilwater solution and therefore

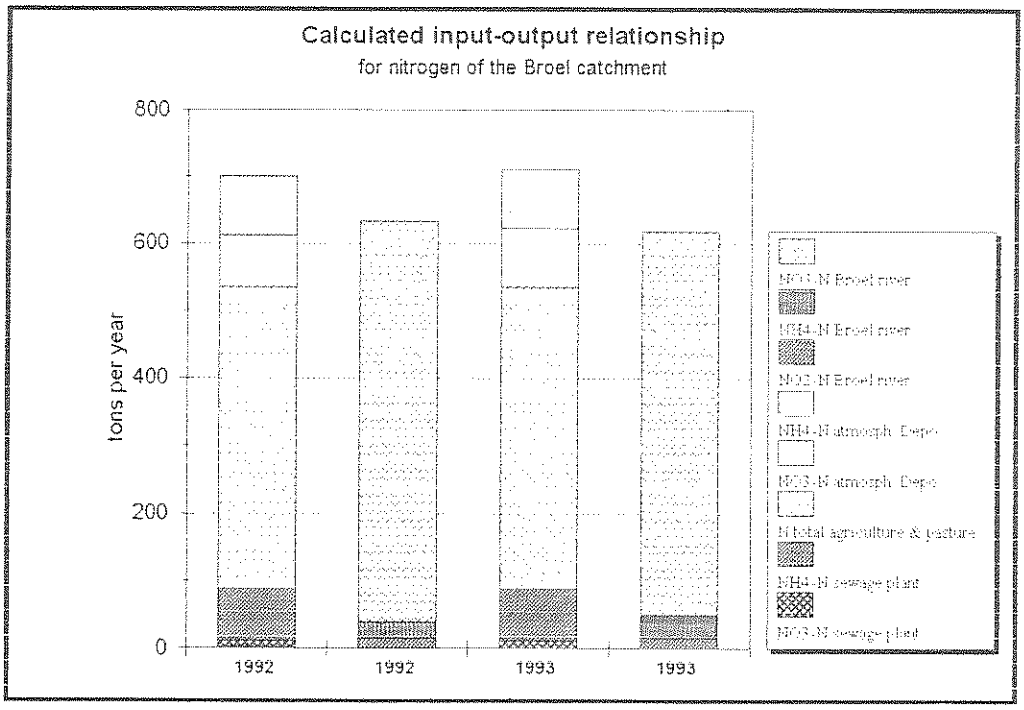

Fig. 2: Calculated input-output relationship for nitrogen within the Bröl catchment (wateryear 1992 and 1993)

The amount of the atmospheric deposition input accounts 25% (=178t) and detected by nitrate and ammonia. Their impact is strongly depending on the seasonal climatic conditions. Detected point sources such as sewage treatment plants are responsible for a continuous impact of 11% (=80t) as ammonia and less of nitrates.

The output is made up for about 93 % by nitrate and is showing a slow catchment response. Therfore concentration effects are found during summer period as a result of baseflow and diluting processes which are coupled to river

not exclusivly related to a specific CHRU. Additionally, nitrification (nitrogen mobilisation) and wash-out effects are responsible for nitrate-dynamics. The evidence of the approach of nutrient balance calculation is successly applied by the use of the CHRU-application, but the nutrient cycle is to complex to be fully quantified and qualified by that method. For better understanding of hydrochemical modeling future research is likely linking the CHRU's with hydrochemical models such as APEX, AgNPS or SWRRBWQ within a GIS (Kern & Stdnick 1993, Tim *et al.* 1992, Vieux 1991).

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