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Using GIS to delineate Chemical Hydrological Response Units (CHRUs) for hydrochemical modeling in a mesoscale catchment in Germany

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Abstract For catchment management, modeling hydrochemical dynamics involves up-scaling point measurements to a spatial distribution and regional dynamics of non-point sources. The concept of "Chemical Response Units" (CHRUs) and GIS analysis are used here to delineate spatial distribution. CHRUs are areas of similar hydrochemical dynamics. This concept was applied to the Broel River Basin, Germany, which was mapped for land use and digitized for GIS analysis. Data collection included water sampling for dissolved solids, fertilizer application and catchment characteristics. Chemical balances of the Broel River catchment were calculated using CHRUs and results were compared with measured output at gages. Results showed deviations associated with undetected point sources but agreement during periods with unique hydrological conditions. CHRUs proved useful and practical to evaluate chemical dynamics of the Broel River catchment. Future research will combine the CHRU concept with a hydrological model like MMS/PRMS, and thereby interface dynamics on a basin scale.

INTRODUCTION

Rivers and lakes with a free surface to the atmosphere are open systems coupled with the water cycle of the catchment. Hence, they are directly influenced by precipitation, runoff, interflow and groundwater seepage. The dynamics of solute transport in a catchment are driven by water balance, and are dependent on spatial distributions of atmospheric and anthropogenic chemical inputs (Flügel *et al.*, 1991).

Chemical inputs to a river system include point sources like outflow from sewage treatment plants or diffuse sources like seepage of nutrients from fertilized fields (Novotny & Olem, 1994). The first input source can be detected easily along the river stretch (Kern & Stednick, 1993). The latter, however, is difficult to quantify as fertilizer transport lags application. Various processes occur including chemical reactions, adsorption and desorption at the surface of the soil matrix, fertilizer consumption, storage in the plant material, and decomposition of harvest residues in the soil (Nolte & Werner, 1991; Beegle & Lanyon, 1994).

The importance of these processes varies in time (seasonal change of plant growth and climate), and is highly dependent on various physiographic factors such as precipitation, topography, soils and geology (Flügel & Lüllwitz, 1993), and land use; each process is spatially distributed within the catchment composing its three-dimensional heterogeneity (Flügel, 1993). Using the spatial analysis of a Geographic Information System (GIS), 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). The unit areas were introduced by Kern & Stednick (1993) as Chemical Hydrological Response Units (CHRUs). If CHRUs 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 spatially distributed physiographic heterogeneity.

OBJECTIVES

The purpose of this study was twofold. For input-output evaluation, a linkage between water quality dynamics at a downstream gage on the River Broel and land use management in the catchment was established. To preserve 3-dimensional heterogeneity for distributed transport modelling, CHRUs, as dynamic modeling units, were delineated by using physiographic properties of the catchment and GIS-analysis (Fig. 1). According to these main issues, objectives were:

(a) implementation of data-sampling routines to collect continuous input and output data, as well as water samples for laboratory analyses;
(b) development of a project database including meteorological, hydrological, hydrochemical and landscape data;
(c) calculation of water and nutrient balances to evaluate nutrient gains and losses; and
(d) application of GIS technology for catchment classification to identify "Chemical Hydrological Response Units" due to potential nutrient losses.

STUDY AREA

The 216 km^2 River Broel catchment is on the northern bound of the middle mountain range of the Rheinische Schiefergebirge, Germany, about 50 km east of Bonn. The River Broel drains into the Sieg River, which is tributary to the River Rhine. The River Broel faces the weather side of Cologne, an industrial zone of heavy emissions.

The climate is oceanic with annual mean temperature of 8°C and annual precipitation of 950 to 1100 mm. During winter precipitation is driven by advective rainfall of mesoscale Atlantic disturbances (cyclones), locally modified by topography. Most rainfall, however, occurs as convective summer thunderstorms. Evapotranspiration is about 50% of annual precipitation, and runoff is dominated by interflow dynamics appearing as lateral flow along hill slopes.

The River Broel catchment is underlain by impermeable Devonian shale. Water losses due to deep percolation, therefore, are negligible. Native soil series are brown soils and soils lessivé on the hill slope (partially eroded), as well as on an upper pene-

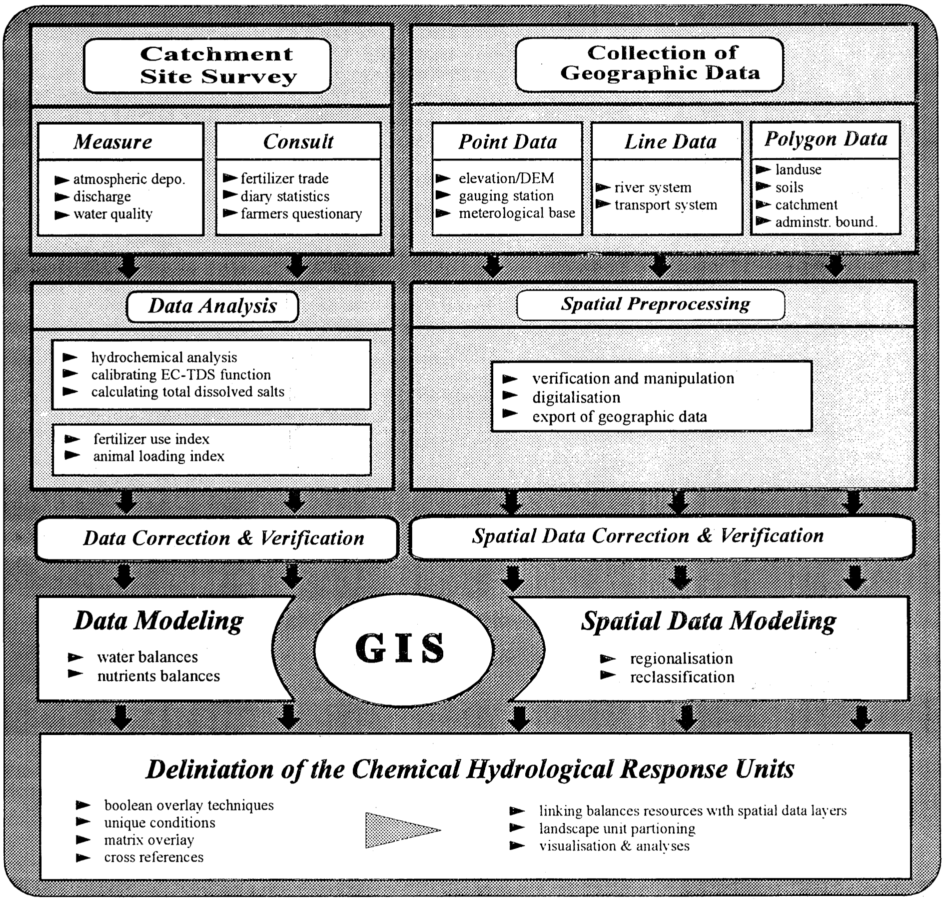

Fig. 1 Schematic presentation of the development of a project data base and the linkage between a GIS and regionalization.

plain. Gleysols are on plains and fluvisols are on the valley floor. All soils are silty loams of 90% homogeneous material. Based on natural conditions, predominant land uses, besides settlements and forests, are pastures and meadows of grazing and haying. Agricultural land (corn, winter grain) accounts only for fodder.

DATA BASE AND METHODS

The Quadtree structured GIS "SPANS" was used to generate the project data base for the River Broel catchment. This (a) develops a landscape-element database by (i) building a DEM with a resolution of 50 × 50 m and deriving slope and aspect, (ii) field mapping of land use and use of remote sensing data, and (iii) digitizing maps of soils and geology; (b) develops a meterological database according to (i) measured point precipitation and regionalization to spatially distributed data by using Thiessen polygons, and (ii) calculation of evapotranspiration as a function of regulating the hydrological cycle; and

(c) develops a hydrochemical database with (i) measured point wet and dry atmospheric deposition and its translation within space and time, and (ii) linkage of continuous measurements from gaging stations in respect to calculated catchment output. For water years 1992 and 1993, samples were taken at 2 week intervals for inorganic analyses that were related to 5-min logged electrical conductivity data.

RESULTS

Nutrient balance

A nutrient balance calculation model was applied to cultivation practices of the River Broel catchment. Fertilizer practices were determined by questioning farmers. A goal was to quantify the land use nutrient cycle during the growing season, when gains and losses are recognizable. The method sums nutrient inputs for each cultivation unit according to the fertilizer applied and the amount of atmospheric deposition within the catchment, both reduced by the plant-specific nutrient removal relative to a crop factor and nutrients loss dependent on techniques of manure and fertilizer application. For nitrate, the amount of symbiosis fixation was considered, as well as the de-gas losses caused by denitrification and ammonia-fixation processes.

Three major classes of potential nutrient losses were derived. For nitrogen, the classes are low (0-10 kg ha^{-1} $year^{-1}$), medium (10-35 kg ha^{-1} $year^{-1}$) and high (35-50 kg ha^{-1} $year^{-1}$) loss. The analysis showed that a highly fertilized tillage system is not necessarily correlated with a high nitrogen surplus. The classified output components were referred to the specific land use units and were transferred within the GIS into potential nutrient loss units.

Delineation of CHRUs using GIS application

To regionalize 3-dimensional spatial data, a CHRU is assumed to have homogeneous hydrochemical dynamics relative to adjacent units. This method allows a combination of various space and time scales depending on the need of application. Deriving CHRUs for the River 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 delineating the CHRUs. For this purpose, elements such as land use, soils and topography were digitized, slope and aspect were obtained from the DEM, and then the elements were transformed and stored in digital vector and raster layers within the GIS.

The delineation process involved the transfer of land use units (LUs), as already mentioned, into cultivation-specific nutrient surplus units (CNSUs). Settlements in impervious areas were related to point sources of nutrients as outflow from sewage treatment plants, whereas forested areas contributed to the natural load. Soil units (SUs) were aggregated on the bases of soil texture, depth, field capacity, dominant hydrologic transport system (lateral flow, vertical flow), and terrestrial and semi-terrestrial dynamics. From slope and aspect, combined with the meterological database, specific conditions for nutrient cycle (e.g. soil moisture and temperature as functions of precipitation and incoming radiation) were derived. Topography units (TUs) were delineated on valley floors, slopes, and high plains. Termed as CHRUs, the typical unit layers were recombined.

Sixteen CHRUs were delineated (Table 1), each reflecting unique conditions of hydrochemical parameters. CHRUs 1, 2, 3 and 16 were differentiated according to the specific land use nutrient surplus, whereas other parameters were set equal. Impervious areas were covered as well as forests and agricultural areas with low area coverages. The highest amount of area coverage (40%) is of brown soils and soils lessivé (CHRUs 4-7 and 10-13). Owing to 10-20% slopes, these CHRUs were related to interflow dynamics and showed a high dependence on topography and exposition. Most meadows and pastures with medium to high amounts of nutrient surplus were distinguished. The influence of groundwater and infiltration were the most important factors for CHRUs

Table 1 Properties of the Chemical Hydrological Response Units in the River Broel catchment regarding the movement of nitrogen.

CHRU no.	Area (km^2)	Area (%)	Topography	Slope (%)	Soil	Land use/nutrient surplus	Position N,E,S,W
1	25.04	11.62	all	all	all	Impervious	all
2	1.72	0.80	all	all	all	Winter grain/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	all
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: nutrient surplus: low = 0-10 kg ha^{-1}, medium > 10-35 kg ha^{-1}, high > 35- 60 kg ha^{-1}.

8, 9, 14 and 15, which also exhibited medium and high nutrient surpluses. These CHRUs are on valley floors and showed high potential for nitrogen reduction processes.

CONCLUSIONS AND FUTURE RESEARCH

Delineation of the CHRUs relative to hydrochemical dynamics of water and nutrient balances is a powerful tool to establish linkages between observed water quality dynamics and land use management. Calculation of catchment input parameters, such as point and non-point sources as described in the project data base, shows that for nitrogen, most of the catchment inputs (64% or 462 t) are related to surpluses of agricultural land, meadows and pasture. Inputs by atmospheric deposition account for 25% (178 t) and are detected by nitrate and ammonia. Impacts are strongly dependent on seasonal climatic conditions. Point sources of nitrogen, such as sewage treatment plants, contribute a continuous impact of 11% (80 t) as ammonia and nitrates (Fig. 2).

Nitrogen output is about 93% nitrate and shows slow catchment response. Concentration effects, therefore, occur in summer as a result of baseflow and diluting processes that are coupled to peak discharges from heavy precipitation and snowmelt. Because nitrogen input (720 t) exceeds measured output (618 t), a strong catchment potential for hydrochemical reactions, especially for dentrification processes and ammonia fixation (nitrogen immobilization), is indicated. Denitrification conditions (field capacity and temperatures up to 5°C) are spatially related to CHRUs 8, 9, 14 and 15, mostly during spring and autumn, whereas ammonia fixation is more dependent on NH_4^+ concentration of soil water and therefore is not exclusively related to a specific CHRU. Nitrification (nitrogen mobilization) and wash-out effects are also responsible for nitrate dynamics. The nutrient balance calculation approach is successfully applied by use of CHRUs, but

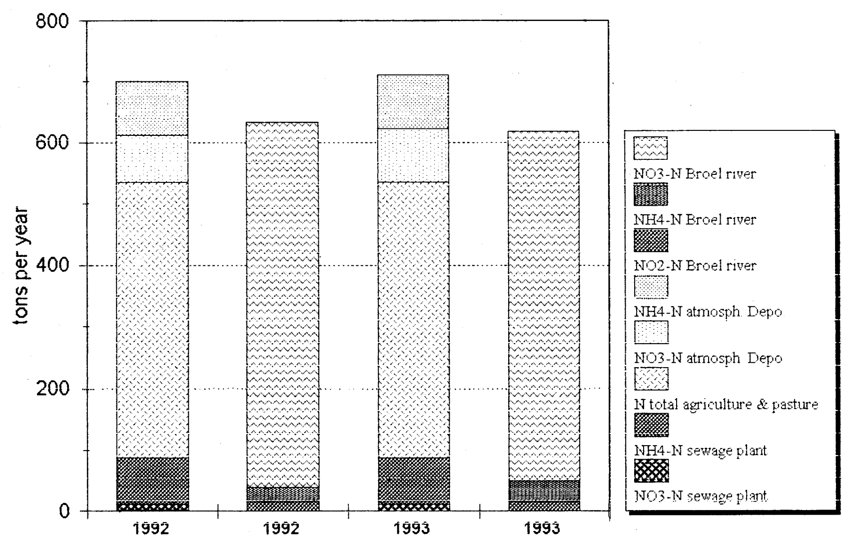

Fig. 2 Calculated input–output relation for nitrogen in the River Broel catchment (water years 1992 and 1993).

the nutrient cycle is too complex to be qualified fully by the method. For future hydrochemical modeling, research is likely to link CHRUs with hydrochemical models such as CHRIS, AgNPS, or SWRRBWQ in a GIS (Kern & Stednick, 1993; Tim *et al.*, 1992; Vieux, 1991).

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