The significance of hydrological criteria for the assessment of the ecological quality in river basins

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Abstract With the implementation of the European Water Framework Directive (WFD) the achievement of a good ecological status of surface waters and a good quantitative and qualitative status of groundwater has become obligatory. The ecological status is defined by biological, chemical and physical criteria. In the River Basin Management Plans required by the WFD, all human impacts on the aquatic environment shall be quantified and evaluated. For this purpose catchment related assessment methods which describe the physical and chemical predictors of the ecological status in surface waters and the status of groundwater are needed. They will have to be combined with monitoring programs and assessments of the water bodies themselves.

To complete the existing biological, chemical and morphological assessment methods a spatially orientated assessment procedure for the hydrological quality of meso-scale river basins was developed. In this procedure human impacts on hydrology, river morphology and water quality are quantified and assessed. The procedure is divided into the three assessment units “catchment properties”, “runoff dynamics” and “nutrient budget, water quality and solute dynamics”. It was applied to 22 meso-scale river basins in South-West Germany. The assessment results enable a quantification of the level of human impact on the aquatic environment.

1 Introduction

In the European Water Framework Directive (EU-WFD) the achievement or maintenance of a good ecological status of surface waters and a good chemical and quantitative status of groundwater is requested. The ecological status of surface waters is defined by biological, chemical, morphological and hydrological criteria. To assess the ecological status of surface waters according to the EU-WFD the existing biological assessment methods have to be improved regarding the biotic indicators and the reference status. The reference status will have to be defined according to different ecological regions regarding climatic and physiographic criteria (EU 2000).

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In these ecological regions the natural status of the aquatic biota will be different due to a different hydrological and geochemical behaviour, defining flow conditions, river morphology and chemistry of surface waters. Approaches to identify a specific biological reference status for the ecological regions have been introduced by several authors (e.g. Bostelmann, 1998, Moog et al. 2001):

A central instrument of the EU-WFD is the river basin management plan, in which all human impacts on the aquatic environment shall be quantified and evaluated (EU 2000). Although management plans are requested only for large river basins, human impact as well as management options have to be investigated on a meso-scale level. While the ecological status of surface waters can be assessed by monitoring programs, human impact on river ecology and on groundwater status have to be assessed considering different non biotic factors (Fuhrmann 2000). Water quality of surface- and groundwater is affected by emissions of nutrients and pollutants from agriculture, urban areas and industries (Walther 1999). As human activities are also influencing the water balance as well as runoff generation and concentration they lead to alterations in stream flow quantities and variability as well as in groundwater recharge. In rivers with a good status of water quality other non biotic factors are becoming more important for the ecological quality. For example factors of stream flow variability have been described as predictors for the biological status in rivers (Richter et al. 1996, Clausen & Biggs 2000). In many industrialized countries improving the morphological status of rivers will be the key factor for a restoration of natural river ecosystems.

To link the assessment of surface water and groundwater status with its non biotic influences a spatially orientated hydrological assessment procedure is required. For this reason an assessment procedure for the hydrological quality of meso-scale catchments was developed. The chosen parameters of the hydrological quality describe the different aspects of catchment properties, hydrology and hydrochemistry. An assessment is achieved by quantifying human impacts on the chosen parameters. This paper describes the methodology of the procedure and presents results of its application.

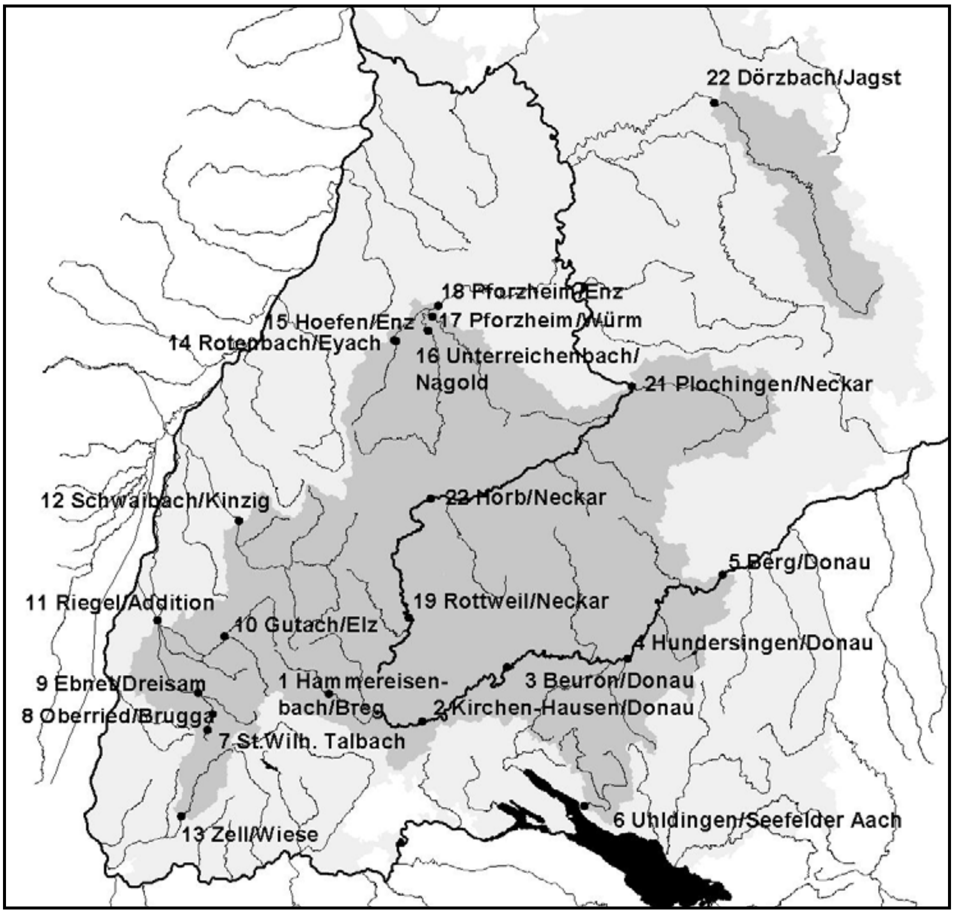

Fig.1 Overview on the investigated catchments (No. /gauging station / river).

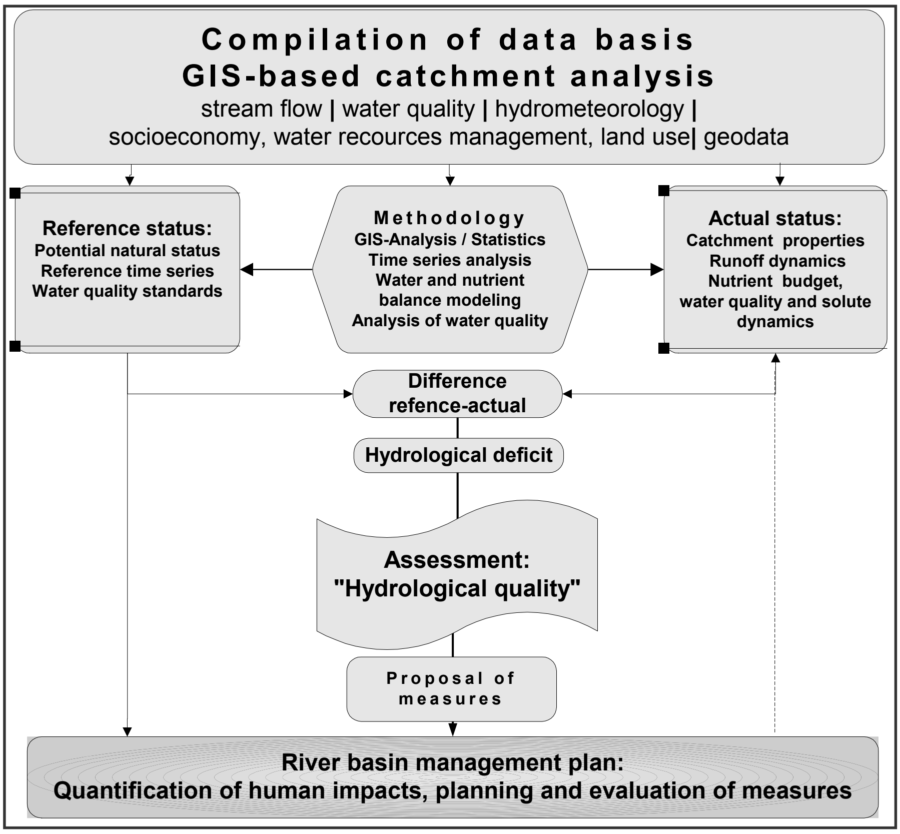

Fig. 2 Concept of the assessment procedure

2 Study Area

The assessment procedure was developed and tested in 22 meso-scale river basins in South-West Germany (Figure 1). For the investigation sub-catchments in the large river basins of the Upper Rhine, Lake Constance, Danube and Neckar were chosen. The investigated catchments ranging from 15 to 4.000 km² in size are characterized by a different morphology, geology and land use structure. In the mountainous "Black Forest" catchments of the upper Rhine tributaries and the western parts of the Neckar and Danube basins (river basins 1; 7 - 16) forestry is the dominant form of land use. All other catchments are more dominated by agricultural land use and have a smaller percentage of forestry (river basins 2-6 and 17-22). In the Neckar basin significant proportions of the catchment area are urban areas (catchments 17-21).

3 Material and methods

The procedure is divided in the assessment units "catchment properties", "runoff dynamics" and "nutrient budgets, water quality and solute dynamics". In a first step a detailed database is compiled for the investigated catchments using GIS-techniques. For each assessment unit a set of parameters is quantified for the actual status based on different methods of data analysis and modeling procedures. The assessment of the *hydrologic quality* is carried out by quantifying a hydrological deficit for each parameter using the range between actual status and a reference status. To quantify the hydrologic deficit 7 classes of hydrological quality are defined, referring to the system of 7 classes which is used in the assessment procedures for biological, morphological and chemical quality established in Germany (LfU 1998, LfU 2001, DVWK 1998).

Table 1 Parameters and classifications used in the assessment unit "catchment properties"

Parameter	**Methodology**	**Reference / Classification**
Group 1: Degree of natural status		
Land use structure	Ranking of land use classes and calculation of mean ranking value	Forest, Water, Riparian zones: 1; Grassland: 2; Agriculture 3; Wine, Plantations: 4; Urban areas 7
Population density	Number of inhabitants divided by catchment area (km²)	< 50 = 1; 50 to 100 = 2; 100 to 250 = 3; 250 to 500 = 4, 500 to 750 = 5; 750 to 1000 = 6 ; > 1000 = 7
Group 2: Human impact on water balance		
Consumed water	Balance of abstracted water, consumed water and water which is transferred from outside the catchment.	% of low flow classification: < 5 = 1; 5 to 10 = 2; 10 to 20 = 3; 20 to 40 = 4; 40 to 80 = 5; 80 to 160 = 6; > 160 = 7
Storage of water	Balance of abstracted water, consumed water and water which is transferred from outside the catchment.	% of mean annual discharge volume: < 0,5 = 1; 0,5 to 1 = 2; 1 to 2 = 3; 2 to 4 = 4; 4 to 8 = 5; 8 to 16 = 6; > 16 = 7
Group 3: River morphology		
Result of morphology survey	Mean of classification per river segment	Classification: natural = 1; small alteration = 2; slight alteration = 3; distinct alteration = 4; heavy alteration = 5; very heavy alteration = 6; complete alteration = 7

Table 2 Classification of hydrological quality in the assessment units "runoff dynamics" and "nutrient budget, water quality and solute dynamics"

RVA-value (positive or negative)	0 - 0,33	0,33 - 0,41	0,41 - 0,47	0,47 - 0,54	0,57 - 0,61	0,61 - 0,67	0,67 - 1
Deficit N-Budget	0 - 25	> 25 - 50	> 50 - 100	> 100 -200	> 200 - 400	> 400 - 800	> 800
Deficit P-Budget	0 - 5000	> 5000 - 1000	> 10000 - 20000	> 20000 - 50000	> 50000 - 100000	> 100000 - 150000	> 150000
Water quality N (90-percentile, mg/l)	< 1	< 1,5	< 3	< 6	< 12	< 24	> 24
Water quality PO_4-P (90-percentile, mg/l)	< 0,02	< 0,04	< 0,1	< 0,2	< 0,4	< 0,8	> 0,8
Classification of quality	1 very high	2 high	3 good	4 moderate	5 poor	6 bad	6 very bad

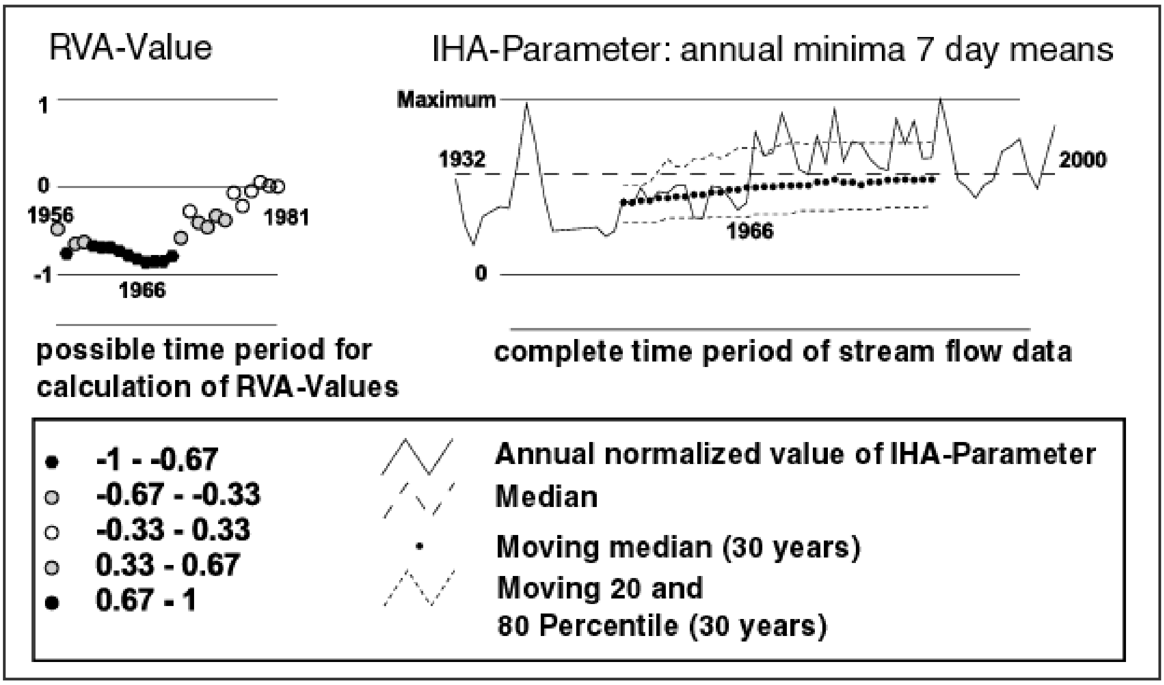

Fig. 3 Alteration of runoff dynamics: IHA-Parameter: "annual minima 7-day-means" at catchment 17 (River Würm at Pforzheim).

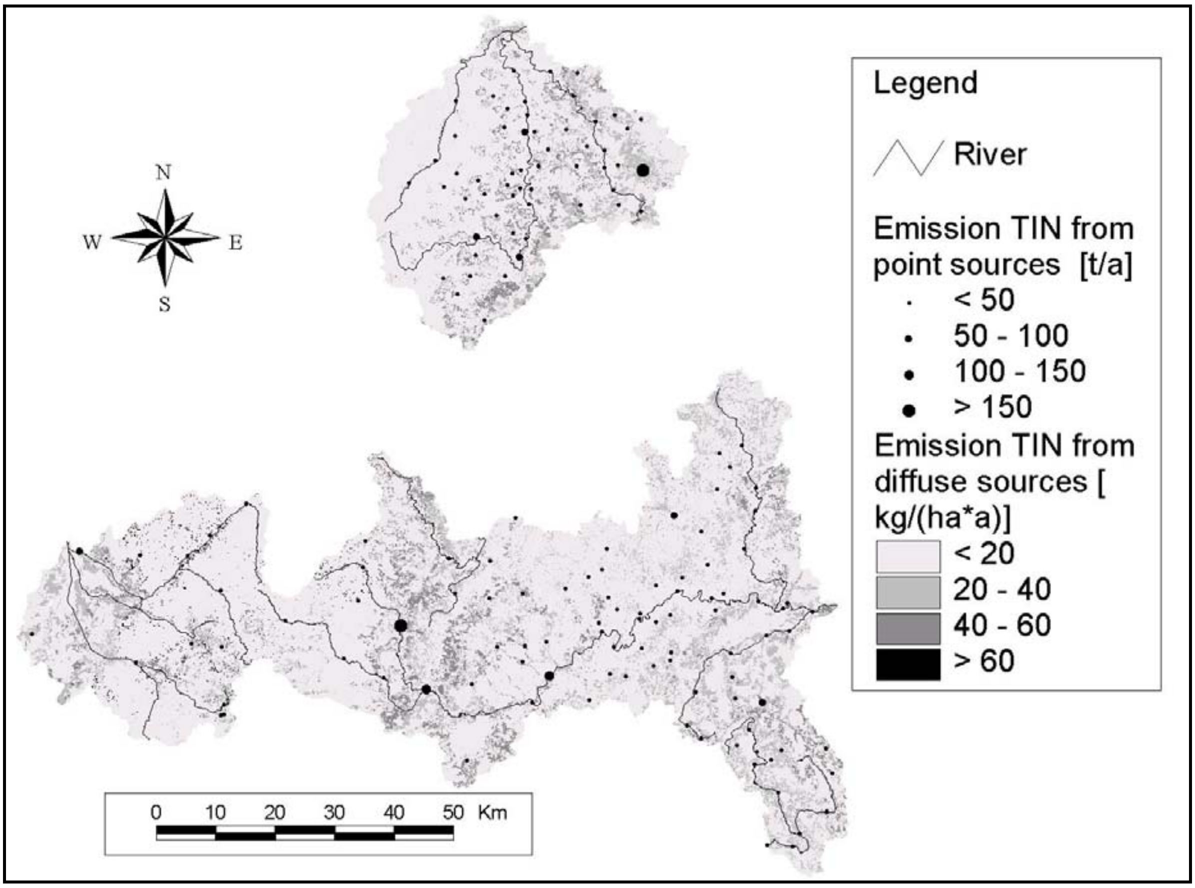

Fig. 4 Emissions of Total Inorganic Nitrogen (TIN) from diffuse and point sources in the investigated catchments.

The individual parameters are then assembled in parameter groups, in which the parameter with the highest deficit defines the assessment result. Finally a general assessment for each unit is derived from the mean of all parameter groups. A visualization of the assessment concept is given by Figure 2.

The assessment unit *catchment properties* focuses on the quantification and assessment of catchment related parameters, which describe potential human impacts on surface and groundwater. For this purpose the parameters land use structure, population density, human impacts on the water balance, number and size of dams and reservoirs and a parameter group for river morphology are used. The values for the last parameter group are derived from the results of a river morphology survey (LfU 2001). In Table 1 an overview on the parameters of the assessment unit *catchment properties* and the related methodology is given.

In the assessment unit *runoff dynamics* the alteration of the hydrologic behavior due to human impacts on the water balance and runoff generation in the catchment is described. The assessment is based on the so called Indicators of Hydrological Alteration (IHA) (Richter et al. 1996) which were selected due to their importance regarding biological habitats. The parameters which are calculated from long time series of stream flow can be divided into five groups:

- Regime parameters (Monthly means, regime indices, base flow index)
- Extremes (Values of high and low flow exceeding certain limits)
- Seasonality (appearance time of extremes as well as of maximal and minimal monthly means)
- Frequency and duration of extremes
- Rise and fall rates

The assessment is carried out based on the older parts of the time series in which the probability of human impacts is smaller (reference periods). The hydrological alteration is quantified by comparing medians and measures of variability for the reference and evaluation periods using the Range of Variability Approach (RVA) (Richter et al. 1997):

$$RVA = \frac{\left(nE_{(inTarget)} / nE_{(all)}\right) - \left(nR_{(inTarget)} / nR_{(all)}\right)}{nR_{(inTarget)} / nR_{(all)}}$$

$nE_{(inTarget)}$ Number of years of evaluation period with IHA-Values within the target (Range between 20- und 80-Percentile of the reference period)

$nE_{(all)}$ Number of all years of evaluation period

$nR_{(inTarget)}$ Number of years of the reference period with IHA-Values within the target (Range between 20- und 80-Percentile of the reference period)

$nR_{(all)}$ Number of all years of reference period

RVA-Values are quantified for all possible years of separation, dividing the complete time series into reference and evaluation periods. To insure a sufficient number of data in each part of the time series the minimal length of both reference and evaluation period is 20 years. Using the resulting time series of the RVA-values possible hydrological alterations can be visualized. Figure 3 shows an example of a significant hydrological alteration. The RVA-values ranging from –1 to 1 indicate decrease of variability (positive values), no alteration (values close to zero) and increase of variability or trends (negative values). The temporal behaviour of the RVA time series indicates whether alterations are occurring promptly (significant increase or decrease within few years), over longer time periods (trends for several decades) or in a cyclic way. To identify long term changes a trend analysis is carried out. Cyclic behaviour of the RVA-values indicate the effect of temporal changes in climatic conditions. Possible climatic effects on the identified hydrologic alteration are investigated using time series of precipitation and temperature. If no climatic effect is identified, the alteration is likely to be induced by human impacts in the catchment. To identify the character and amount of the human impact a research procedure using the catchment data base and additional investigations is carried out. The strong increase of the RVA-values calculated for IHA-Parameter "annual minima 7-day-means" shown as an example in Figure 3 indicates a hydrological alteration in the low flow behaviour of the river Würm (catchment 17). In the assessment of *catchment properties* a high human impact on the water balance, caused by a continuous water transfer into the catchment, was identified. This water transfer, which - according to the data base and previous studies (LfU 1985) - can be quantified to a mean increase of 0,25 to 0,3 m^3/s in stream flow leads to a significant alteration during low flow periods. The identified hydrological alterations are assessed using the observed RVA-values, which are then classified (Table 2) and aggregated for the different parameter groups. Within the groups the assessment is defined by the highest RVA-value. An overall assessment of *runoff dynamics* is derived by the mean value of all parameter groups.

In the assessment unit *nutrient budget, water quality and solute dynamics* the human impact on water quality in surface and groundwater is quantified. *Emissions* of the nutrients nitrogen and phosphorus due to diffuse and point sources are quantified on the basis of a spatially distributed water and nutrient balance and evaluated referring to a scenario simulation of the "potentially natural status" of the catchment. The nutrient input is derived from the nutrient surplus which is calculated for all permeable land surfaces based on the land use classification and agricultural statistics using the calculation methods and values described in literature (Wendland et al. 1993, Bach et al. 1998, Behrendt et al. 1999, Kolbe 2000).

In the distributed water balance interpolated data of mean annual precipitation (DWD 1999) and the results of a simulation of the actual evapotranspiration in South-West Germany (Armbruster et al. 2001) are used. The resulting spatially distributed mean annual discharge is further divided into the runoff components "fast runoff", "delayed runoff", and "base flow". The component "fast runoff" is an estimation of surface runoff, macropore flow and drainage runoff. It is quantified using empirical functions (US SCS 1972) and spatially distributed data of topography, soil characteristics and land use (Uhlenbrook et al. 2000). Proportions of base flow are derived using results from base flow separations in sample catchments and a regionalization of the base flow proportion (Demuth 1993, Armbruster et al. 2001). The mobilization of nutrients is estimated using the described runoff components, soil characteristics (field capacity) and a coefficient describing the chemical behaviour. To quantify the transport of sediment associated phosphorus a simplified sediment delivery calculation is executed based on data of topography and land use. Nutrient retention and denitrification in the vadose zone and groundwater aquifer is estimated based on the ratio between calculated soil water concentrations and measured concentrations in groundwater and springs. The nutrient delivery from point sources is quantified based on statistical data for sewage plants and urban canalization as well as data for precipitation and the area of impermeable surfaces using the methods described in Behrendt et al. (1999). Nutrient retention and denitrification in the river system is quantified with an empirical model based on the hydraulic impact (annual volume of streamflow divided by the surface area of the water bodies, Behrendt et al. 1999). To achieve a validation of the nutrient budget the resulting concentrations in surface water are compared to long term means of measured concentrations.

For the simulation of the "potential natural status" of nutrient emissions all land use classes are parameterized using the nutrient input and water balance terms for forest vegetation. Finally the nitrogen and phosphorus budgets are assessed by comparing the actual and potential natural status. The deficit is calculated by subtracting the emissions of actual and potential status and dividing them by the emissions of the potential status.

The *water quality* in the river system is quantified based on measured or simulated concentrations of nitrogen and phosphorus and assessed using chemical water quality standards (Rocker 1999). For catchments with long term measurements the temporal variability is taken into account by an assessment of *solute dynamics*. For this purpose monthly nutrient loads are calculated and assessed using monthly reference loads. The reference loads are derived by combining monthly values of stream flow and the concentration given in the water quality standard.

The classifications for the parameter groups "nutrient budget and "*water quality and solute dynamics*" are given in Table 2.

4 Results

As a result of the assessment procedure in the test catchments classes of hydrological quality are quantified for the three assessment units. Table 3 shows the results of the parameter groups as well as the related human impacts responsible for the hydrological deficits.

Table 3 Assessment results of the parameter groups in the investigated catchments

C	Deg. natu-ral status	Human impact on WB	River morpho-logy	Runoff regime	Extre-mes	Sai-sona-lity	Freq. & duration of extremes	Rise and fall rates	Nutrient budget	Water quality / solute dynamics	Reasons for hydrological deficits >4
1	2	1	3	1	7	1	1	1	3	3	M RG
2	3	3	4	1	3	1	1	3	5	4	M RG E_{NP}
3	3	2	5	5	7	1	1	2	4	5	M RG E_{NP}
4	3	2	5	1	2	1	1	1	5	4	M E_{NP}
5	3	2	5	1	1	1	1	1			M
6	3	2	5	1	1	1	1	1	5	4	M E_N
7	1	1	2	1	1	1	1	1	1	2	
8	2	1	2	1	1	1	1	1	1	2	
9	3	2	3	1	1	1	1	3	3	3	
10	2	1	3	1	1	1	1	1	2	3	
11	4	3	4	1	1	1	1	1	4	4	U, M, E_N
12	3	3	4	1	1	1	1	1			M
13	2	1	3	1	3	1	1	1			
14	1	2	2	6	2	1	1	6	1	3	T-
15	2	2	2	3	5	1	1	2	1	3	T-
16	3	3	3	1	1	1	1	1	4	5	E_P
17	5	5	5	1	7	1	7	1	5	5	M T RG E_{NP}
18	4	4	3	1	1	1	5	1	4	5	M T RG E_{NP}
19	4	3	4	1	1	1	1	1	5	5	M E_{NP}
20	3	3	4	1	1	1	1	1			M
21	4	4	4	4	1	1	2	1			M T
22	3	5	6	1	2	1	3	3			M T D

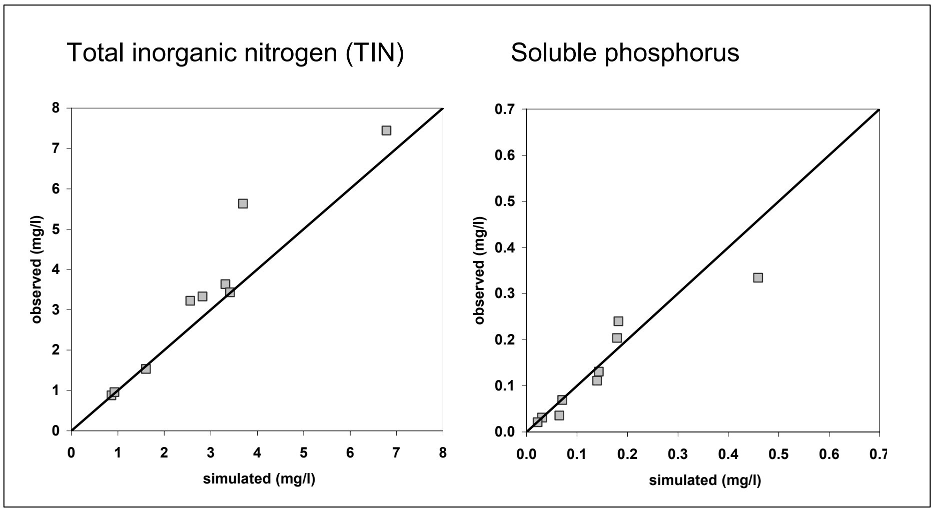

Fig. 5 Simulated and observed concentration means of Total Inorganic Nitrogen (TIN) and Soluble Phosphorus.

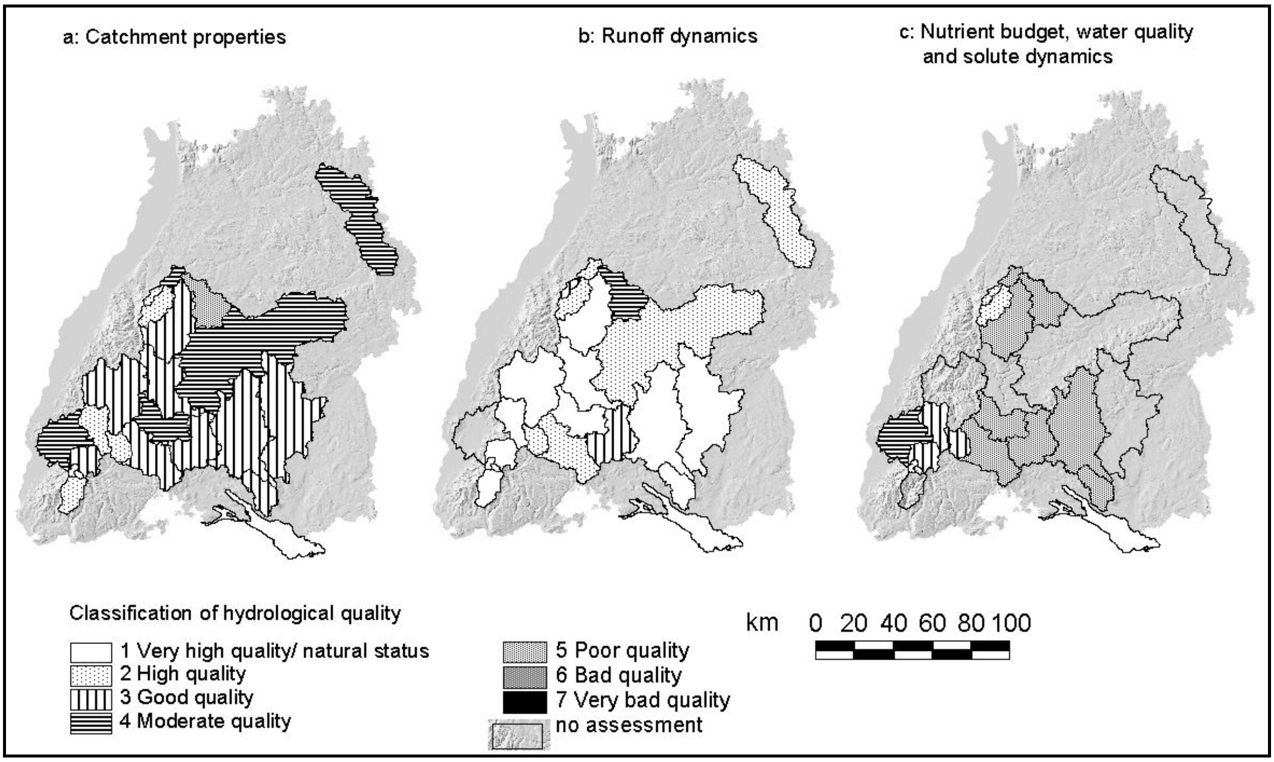

Fig. 5 Classification of status in the assessement units “catchment properties”, “runoff dynamics” and “nutrient budget, water quality and solute dynamics”

In Figure 6 the overall results of the three assessment units are mapped for the investigated river basins. In the assessment unit *catchment properties* most catchments show a very good or good quality of hydrological catchment properties. River basins in the more urbanized areas are classified into the quality classes 4 and 5 (moderate quality) due to intensive water use and water transfer across catchment borders, heavily modified morphological structures or high number of dams. The parameter group river morphology shows a moderate to poor status in the majority of the investigated river basins.

In the assessment unit *runoff dynamics* human impacts were found to be small or negligible in most investigated river basins. A smaller number of river basins show moderate or high alterations resulting from water transfers, land use change (urbanization and intensification of agriculture) or the building of dams and reservoirs. In river basin 17, showing an overall quality class of 4, alterations of low flow conditions and an increase of flood events were detected (Figure 3, Table 3). These alterations are a consequence of water transfers from outside and an increased urbanization in the last decades.

The investigations revealed significant climatic impacts on the runoff regimes of most of the river basins. These impacts are caused by alterations in precipitation, which have been identified in some other studies as well (LfU 1997, Sanchez Penzo et al. 1998). As these climatic impacts are not assessed in the procedure, they are not presented in this paper.

To illustrate the assessment of the nutrient budget results from the simulation of nitrogen emissions into the river system are given (Figure 4). The nutrient loads are a reflection of the land use structure in the catchment, the nutrient surplus on the farm lands and the number and size of sewage systems. From the resulting concentrations in the different runoff components the impact on the chemical quality of groundwater and surface water can be estimated. The validation of the surface water concentrations using the means of long term measurements (Figure 5) showed good results for nitrogen ($r^2 = 0.94$) and soluble phosphorus ($r^2 = 0,88$). The assessment of water quality and solute dynamics (Table 3) demonstrates, that in most catchments showing high emissions of nutrients a good chemical quality of surface waters is not achieved. In the river basins of Danube and Neckar (catchments 2, 3, 4, 16, 17, 18, 19) the low water quality values are a consequence of high nutrient emissions from both diffuse and point sources. Due to a low specific discharge and therefore small dilution potential the impact of phosphorus and nitrogen emissions on water quality is on a critical level in many rivers in the Neckar and Danube basins.

4 Conclusion

The application in different river basins demonstrates, that the proposed methodology is capable to establish a spatially orientated assessment of the hydrological quality of meso-scale catchments. As a result of the procedure human impacts on water and nutrient balance, runoff dynamics and water quality are identified, quantified and assessed. In the assessment unit *catchment properties* a realistic estimation of human impacts that might be relevant to the aquatic ecosystems is performed. With the assessment of human impacts on the *runoff dynamics*, an aspect of river ecology which was neglected up to now is investigated. The described methodology enables the identification of both human and climatic effects on the water balance and runoff dynamics.

Using the methodology of the assessment unit *nutrient budget, water quality and solute dynamics* a spatially differentiated quantification and assessment of the emission of nutrients as well as an evaluation of water quality and its temporal variability is possible. The assessment results confirm the key role of agriculture for the restoration of water quality which is already known from various studies (e.g. Heathwaite et al 1989, DVWK 1998, Quinn et al. 1999, Kolbe 2000). By combining the quantification of the emissions with an assessment of water quality the "combined approach for point and diffuse sources", required by the EU-WFD (EU 2000), is addressed.

The ecological status of surface waters includes biological, chemical morphological and hydrological criteria. An assessment including all these criteria can be performed by the application of biologically based ecological assessment procedures and hydrological procedures as described in this paper. In river basin management plans according to the EU-WFD the assessment of human impacts on the aquatic ecosystems within the river basin will have a key function. The hydrological assessment procedure can be used as a helpful tool in the implementation of the directive. Together with morphological and biological assessment procedures the proposed methodology enables a holistic approach regarding water protection, in which the catchment and its water bodies are treated as a hydrological unit.

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