

Identifying human induced pressures and their impact on water resources—the assessment of hydrological quality in river basins

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Abstract The assessment procedure presented in this paper is a combination of tools, by which identification and quantification of human impacts on the quantity and quality of water resources within a catchment can be carried out. The application of the procedure is demonstrated in a meso-scale catchment. Quantitative pressures on water resources are identified using criteria of land-use structure, river morphology, water consumption, water abstraction and transfer, and the storage volume of dams and reservoirs. Additionally, human induced alterations of runoff dynamics are evaluated using statistical methods, taking into account climatic effects. Pressures on water quality are characterized using criteria for land use, agricultural intensity, population density, sewage system and urban runoff, as well as a detailed water and nutrient balance. To examine the human impact on water quality, different scenarios are calculated and compared to the actual status. The potential range of error in the predictions is estimated based on a sensitivity analysis.

Key words assessment; pressures; runoff dynamics; water quality

INTRODUCTION

The central management instruments of the EU Water Framework Directive are River-Basin Management Plans, in which all significant human impacts on surface water and groundwater, as well as management strategies to improve the deficits in the quality of water resources, have to be documented. Following these obligations an integrated perspective of the quality status of the resources (surface waters and groundwater) and its predictors present in the catchment is required (EU, 2000). To establish a sustainable use of water resources the identification of human induced pressures on the hydrological system has to be combined with an assessment of its vulnerability. However, in the field of river protection there is a lack of well-established assessment procedures that combine these features and integrate all relevant hydrological criteria on the catchment scale.

For this purpose, a new assessment procedure, “Hydrological Quality”, which can be applied to meso-scale catchments using the readily available data sets, was developed. The procedure is a combination of tools by which an identification and quantification of human pressures on quantity and quality of water resources is carried out. This paper describes the methodology used in the procedure and demonstrates its application by presenting exemplary results derived for the meso-scale catchment of the River Wülm.

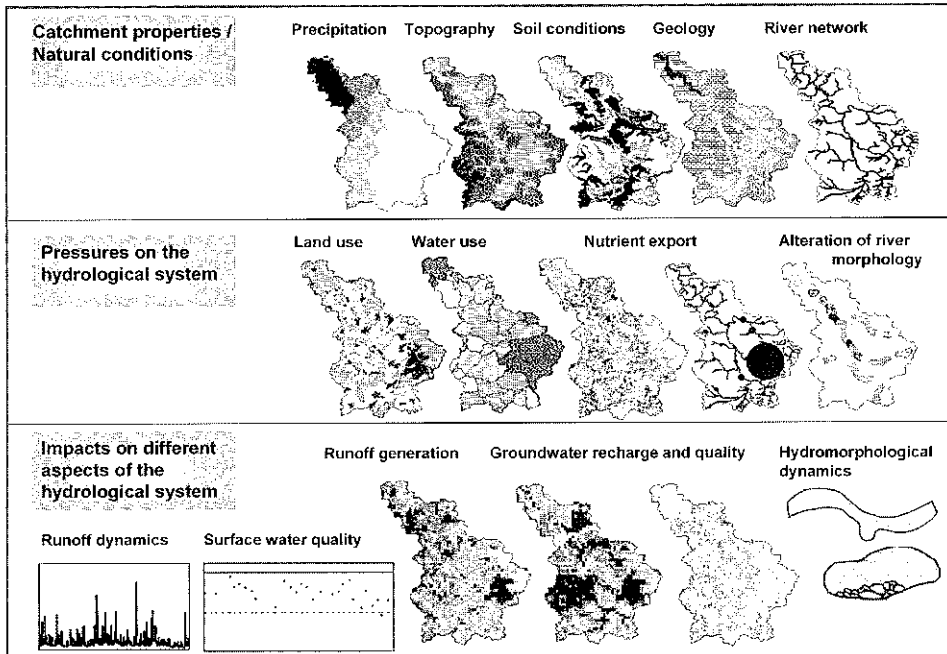


Fig. 1 Data basis for the quantification of pressures and impacts used in the assessment procedure.

MATERIALS AND METHODS

The meso-scale Würm catchment (417 km²) is situated in the Neckar River basin in southwest Germany. Its land use is dominated by agriculture (43.5%) and forestry (34.9%) as well as significant proportions of urban areas (13%).

Pressures and impacts in the catchment are quantified using different parameters which are combined in parameter groups. To identify pressures on the hydrological system and the resulting impacts, different catchment related criteria, which are derived from commonly available data sets, are used. The assessment of pressures is carried out by comparing the actual status to the “potential natural status” (reference status), which is defined as the status for the scenario of no human influence and the related natural vegetation. Impacts are assessed using different references (status previous to impact or quality standards). The hydrological quality is quantified by comparing the actual and the reference status and a classification of the deviance (deficit) using seven classes. In Fig. 1 the data used in the procedure and the quantification of pressures and impacts are illustrated.

A priori estimation of human pressures is derived in the parameter group “degree of natural status” using the parameters “land use structure” and “population density”. To describe physical pressures on the ecological habitats in the river system, criteria which describe morphological alterations in the river systems and its surrounding area and their impact on the hydro-morphological dynamics, are assessed (LfU, 2001). The evaluation system leads to an aggregated value of the “morphological quality”, which can be seen as a description of the habitat quality in the river. “Pressures on the water

balance” are quantified using the volumes of water abstraction, water use and transfer, as well as the storage volume of major impounded areas for each catchment. The vulnerability of the hydrological system towards these quantitative pressures is represented using a spatially differentiated estimation of groundwater recharge, the mean annual runoff volume and the low flow parameter NM30Q (mean annual minima 30-day means).

Using the assessment of “runoff dynamics”, the alteration of the hydrological behaviour due to human induced impacts on the water balance and runoff generation in the catchment, are identified. The assessment is based on the “Indicators of Hydrological Alteration” (*IHA*) (Richter *et al.*, 1997) which were selected due to their importance regarding biological habitats. The parameters, which are calculated from long time series of daily values, describe different aspects of the temporal behaviour of stream flow (monthly means, regime, quantity, frequency and duration of extremes, aspects of seasonality, and rise and fall rates). Potential hydrological alterations are identified based on the comparison of the older periods of the time series (reference periods), in which the human pressure is assumed to be less pronounced, with the younger parts of the time series (evaluation period). Alterations are quantified using the Range of Variability Approach (*RVA*; Richter *et al.*, 1997):

$$RVA = \frac{(nR_{(inT\ arg\ et)} / nR_{(all)}) - (nE_{(inT\ arg\ et)} / nE_{(all)})}{nR_{(inT\ arg\ et)} / nR_{(all)}} \quad (1)$$

where $nR_{(inT\ arg\ et)}$ is the number of years of the reference period with *IHA* values within the target (range between 20th and 80th percentiles of the reference period), $nR_{(all)}$ the total number of years in the reference period, $nE_{(inT\ arg\ et)}$ the number of years of the evaluation period with *IHA* values within the target (range between 20th and 80th percentile of the reference period), and $nE_{(all)}$ the total number of years in the evaluation period.

RVA values are quantified for all possible years of separation, dividing the complete time series into reference and evaluation periods of different length. To ensure a sufficient number of data in each part of the time series, the minimal length of both the reference and evaluation periods is 20 years. Using the resulting time series of the *RVA* values, possible hydrological alterations can be visualized. The *RVA* values ranging from -1 to 1 indicate a 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 intermittently over longer time periods, or are cyclical. In addition, a trend analysis is carried out to identify long-term changes. Possible climatic effects on the identified hydrological alteration are investigated using a time series of precipitation and temperature. If no climatic effect is identified, the alteration is expected to be induced by human pressures in the catchment. To identify the character and amount of human pressures, a research procedure using the catchment database and optionally, additional investigations, are carried out.

“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”. The nutrient input is quantified based on the land-use classification and agricultural

statistics using the calculation methods and values described in literature (Behrendt *et al.*, 1999; Kolbe, 2000). In the distributed water balance, interpolated data of mean annual precipitation and the results of a simulation of the actual evapotranspiration in southwest 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 “baseflow” (Eisele, 2002). The mobilization of nutrients is estimated using the runoff components, soil characteristics (field capacity) and a coefficient describing the mobility of the nutrient species. Nutrient retention on land surfaces, in the vadose zone and in the groundwater aquifers is estimated based on measured values of groundwater, baseflow concentrations and sediment loads. The nutrient delivery from point sources as well as the nutrient retention in the river system are quantified based on statistical and hydrological data using the methods described in Behrendt *et al.* (1999). The nutrient balance is validated based on long-term measurement concentrations in surface waters. For the simulation of the reference status (“potential natural status”) of nutrient export, all land-use classes are parameterized using the nutrient input and water balance terms for forest vegetation. The “water quality” in the river system is assessed based on measured or simulated concentrations of nitrogen and phosphorus, and assessed using the official water quality standards for surface water and groundwater.

To examine the potential for the improvement of water quality, different scenarios (land-use change, urban water management) are calculated and compared to the actual status. The potential range of error in the predictions resulting from the calibration of parameter values is estimated based on a sensitivity analysis.

RESULTS

As a result of the assessment, procedure classes of hydrological quality are quantified for the different parameter groups. In Table 1 the parameter values and assessment results are listed for the Würm River basin. The results for the parameter group “degree of natural status” indicate a high potential for pressures on the hydrological system. Comparably high proportions of settlement and agricultural areas lead to pressures on water balance, water quality and the morphological quality of the river system. Because the specific streamflow and groundwater recharge are relatively low (compared to other catchments in the region) these pressures affect the water bodies significantly regarding the quantitative, qualitative and ecological aspects.

Because of the limited water resources, most of the water supply of the region is provided via a water transfer from a distance of 120 km (Lake Constance). The described pressures on the hydrological system are leading to alterations in streamflow which are indicated by the parameter group runoff dynamics. In the analysis of the time series of *IHA* and *RVA* values a positive trend and a decrease of variability of low flow parameters (e.g. Fig 2(a)) and an increase of flood events was identified. To check possible climatic influences the mean values of monthly streamflow and precipitation in the periods 1922–1966 and 1966–1997 were analysed. In the low flow period ranging from June to October, no increase or even a decrease of precipitation, but significant alterations of monthly values were identified.

Table 1 Parameter values and assessment results for the Würm catchment.

Parameter	Unit	Parameter value:		Assessment result
		Actual status	Reference status	
Mean annual stream flow	mm	245.9		
Mean annual low flow (30 days)	mm	97.0		
mean annual groundwater recharge	mm	161.1		
annual minima 30 day means (NM30Q)	mm	97.0		
Parameter group “degree of natural status”				
Land use index	–	2.7	1	3
Population density	no./km ²	533.7	0	5
Degree of natural status				5
Parameter group “morphological quality” (mean values of river system)				
River bed dynamics	–	4.0	1	4
Dynamics in riparian zone	–	3.6	1	4
Morphological/Habitat quality				4
Parameter group “Pressures on water balance”				
Groundwater abstraction (Proportion of recharge)	%	7.0	0	2
Water consumption (Proportion of MN30Q)	%	33.5	0	4
Water transfer (Proportion of MN30Q)	%	24.5	0	5
Volume of impoundments	m ³	1 434 000		
Impoundment index	–	0.69	0	2
Pressures on water balance				5
Parameter group “runoff dynamics”				
Alterations of runoff regime	<i>RVA</i>	0.58	$-0.33 < RVA < 0.33$	5
Alterations of extremes (low flow)	<i>RVA</i>	-0.86	$-0.33 < RVA < 0.33$	7
Alteration of frequency and duration of extremes	<i>RVA</i>	-0.82	$-0.33 < RVA < 0.33$	7
Alterations of rise and fall rates	<i>RVA</i>	$-0.33 < RVA < 0.33$	$-0.33 < RVA < 0.33$	1
Alterations of runoff dynamics				5
Parameter group “nutrient emissions”				
Nitrogen export from diffuse sources	kg ha ⁻¹ y ⁻¹	14.6		
Nitrogen export from point sources	kg ha ⁻¹ y ⁻¹	11.9		
Nitrogen export	kg ha ⁻¹ y ⁻¹	26.5	7.9	5
Phosphorus export from diffuse sources	kg ha ⁻¹ y ⁻¹	0.3		
Phosphorus export from point sources	kg ha ⁻¹ y ⁻¹	0.9		
Phosphorus export	kg ha ⁻¹ y ⁻¹	1.2	0.0	5
Nutrient export				5
Parameter group “water quality”				
Nitrogen in surface water (90 percentile)	mg l ⁻¹	9.1	<1.0	5
PO ₄ -P in surface water (90 percentile)	mg l ⁻¹	0.36	<0.02	5
Surface water quality / solute dynamics				5
Groundwater quality (mean value)	mg-N l ⁻¹	4.5	<0.5	5
Water quality				5

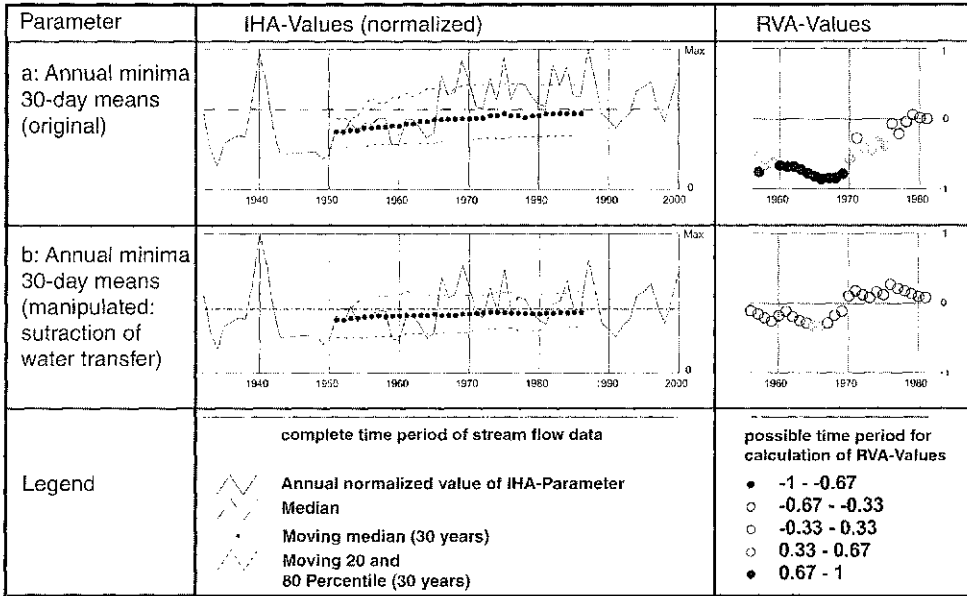


Fig. 2 IHA/RVA-analysis of the low flow parameter “annual minima 30-day means” based on the original time series and a manipulated time series (with subtracted water transfer).

To quantify the impact of the water transfer, the average daily water input into the river was calculated from the transfer rate. For the period after 1965 this value (~0.3 m³ s⁻¹) was subtracted from the streamflow values. The comparison of the calculated *RVA* values of the original time series and the manipulated time series (Fig. 2(b)) for the low flow parameter “annual minima 30-day means” shows that the positive trend of the latter is much smaller, resulting in lower *RVA* values. Although the identified changes in low flow do not fit exactly to the water volumes calculated for the transfer, it is obvious that a high proportion of the alteration of the low flow behaviour is caused by human pressures. The alterations in the frequency and duration of floods can be traced back to the increase of impermeable surfaces and the alterations of the channel morphology in the last five decades. However, a quantification of these impacts can only be performed using detailed rainfall–runoff model applications.

From the calculation of nutrient export from diffuse and point sources it can be demonstrated that both agricultural and settlement areas lead to pressures on water quality (Table 1). Due to the low specific groundwater recharge and streamflow, the dilution capacity in both groundwater and surface water is very low. The calculated loads of nitrogen leached from the agricultural soils into the groundwater, ranging from 9 to 67 kg ha⁻¹ year⁻¹ are not extremely high compared to leaching rates known from other experimental and modelling studies (Behrendt *et al.*, 1999; Kolbe, 2000; Parkinson *et al.*, 2000). However, the resulting nitrogen concentrations in groundwater are quite high because of the low specific groundwater recharge. In some areas the concentrations of nitrate in groundwater already exceed the official limits for drinking water.

In the surface waters an essential part of the nutrient input is originated in point sources. According to the simulations the proportion of point sources is 45% for nitrogen and 76% for phosphorus. Due to the low specific discharge and the resulting small dilution capacity, the surface water quality is poor. The nutrient balance model relates a significant part (N: 6.5%; P: 14.4%) of the nutrient exports from point sources to sewage overflows during rainfall events. To examine the potential for the improvement of water quality in groundwater and surface water, different scenarios of nutrient export scenarios were calculated:

Scenario 1 Land-use change: reduction arable land 26%, change to meadows.

Scenario 2 Improvement of sewage system: 50% higher retardation capacity of the sewage system.

In the sensitivity analysis the coefficients describing the mobility of diffuse nitrogen and phosphorus were altered within plausible ranges (lower limit: -20%; upper limit: +20% for nitrogen, +11% (maximum of possible values) for phosphorus). Due to the variation in nutrient mobilization, the parameter values for the nutrient retention, which are calibrated based on groundwater concentration levels and sediment loads, have to be changed as well. The nutrient emissions are then calculated with the resulting parameter sets. In the scenario simulations the parameter sets derived for the upper limit, the lower limit and the mean of the simulation results were used. Figure 3 illustrates the results for the actual status as well as scenarios 1 and 2. It can be shown that the deviation resulting from the variation of the parameters for diffuse mobilization is higher for nitrogen, corresponding to its higher proportion of diffuse emissions. The scenario results for the phosphorus emissions indicate a smaller reduction potential compared to nitrogen.

The relatively small potential of prediction error (about ±5%) indicated by the illustrated ranges in Fig. 3 might increase due to errors in the input data of the water and nutrient balance. Nevertheless the potential concentrations of nitrogen and phosphorus resulting from the scenario calculations show that only a combination of measures concerning land use and urban water management can lead to a significant improvement of the overall water quality in the catchment.

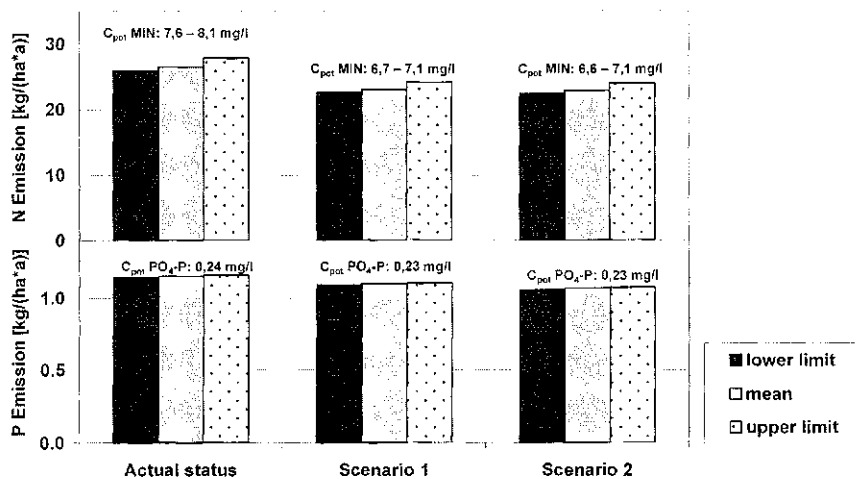


Fig. 3 Scenario results of the nutrient balance simulation using different parameter sets.

CONCLUSIONS

The presented application results demonstrate that the proposed methodology is capable of establishing a spatially orientated assessment of human pressures and their impacts on the hydrological system in a catchment. To ensure general applicability in meso-scale catchments the methodology uses simple conceptual approaches. As a consequence the quantification of the cause-effect relations of pressures and impacts can only be given within an uncertainty range. Nevertheless the potential of different management measures for the improvement of the quality status of surface water and groundwater can be estimated based on the methodology presented.

To illustrate the methodology the catchment of the River Würm, which faces a relatively high degree of human pressures, was chosen as an example for this paper. Thus the impacts detected are much more severe in this catchment compared to assessment results, which were derived in other catchments with lower degrees of human pressures (Eisele *et al.*, 2003).

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