EFFECT OF THE ACCURACY OF STREAM PARAMETER ESTIMATION ON SIMULATED WATER QUALITY FOR THE GERMAN WETLAND REGION SPREEWALD

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Abstract: For the water quality management of the Spree River a long-term river basin water quality model was developed. This model integrates a self-contained module for the wetland region Spreewald. The development of the wetland module was based on the Dutch water quality model system DUFLOW. As a physical deterministic and distributed model DUFLOW considers the interaction between the running water system and the adjacent areas as well as the interaction between the sediment and the water column like, among others, matter transformation processes.

The module concept is described. Sulphate concentrations were simulated with the aim to estimate the rates of the different processes of time-variable load reduction and load increase within the wetland and to estimate the calculation error under conditions of a scarce hydrogeometric data base. The sensitivity of cross sectional and sediment parameters on nitrogen, phosphorus, and phytoplankton is tested and discussed with respect to data collection accuracy and –acquisition.

INTRODUCTION

For the Spree river basin – from its spring in the Lusatian mountains in Saxony to its mouth near the capital of Germany, Berlin - a prediction model was developed to forecast the water quality up to the year 2035. In the future the model shall act as a decision support instrument for long-term water management. The background of this task is given by changing conditions in the Lusatian brown coal mining development in the region of the middle course of the Spree River. Effects on the Spree River water quality, especially high sulphate and iron concentrations as well as low pH-values, are expected in conjunction with a rising groundwater table during the post mining period. The newly developed river basin water quality

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model ArcGRM Spree/Water Quality (Schlaeger, 2002) is based on the existing long-term water management model ArcGRM Spree/Schwarze Elster (Kaden et al., 1998). This water management model uses a stochastic approach for simulating the actual water inflow and simulates 100 times possible system conditions. By dynamic links water quality modules are coupled with the basic model. The Spree basin was divided into seven zonal types according to the different water quality behaviour, e.g. natural and post mining lakes, running water sections, wetlands, areas of groundwater table rise, non-point and point sources from the catchment, for which self-contained quality modules were developed. Because of a better suitability for the users like environmental authorities and agencies, a short simulation time for each water quality module is demanded. The simulation time step is 1 month.

The Spreewald wetland region is the transfer area between the upper Spree River section influenced by coal mining and the downstream situated section near Berlin, where the Spree water is of importance for drinking water abstraction. The wetland with a high water consumption during the summer time and a water storage during the winter time acts as a sink for dissolved matter. In times of a hydrological turnover mainly groundwater is drained by channels and ditches. The concentration of some hydrochemical parameters increases, e.g. dissolved organic carbon, or decreases because of mixing processes with groundwater of lower concentration, e.g. sulphate. In case of high concentrations from the upstream just this effect of the wetland is of importance for the water quality management in the Spree river basin.

Another future problem is a decreasing water inflow into the Spreewald wetland region caused by decreased coal mining activities since 1990. In consequence the cone of water table depression decreases and consequently the surplus water volume for the wetland from brown coal mines, which has stabilised the wetland water balance in former time. A declining groundwater table leads to matter transformation processes in the peaty, organic soils due to peat degradation. Eutrophication processes in surface water could be the consequence.

For future time, the European Water Framework Directive demands the compliance with a good ecological status, further on the preservation of the wetland character. Socio-economic conditions in the region are directed towards tourism, agriculture and forestry. The main problem is the water distribution within the region. New water management concepts have been developed. Just these conditions had to be considered in the development of the water quality module for the wetland region Spreewald.

This paper briefly describes the developed wetland water quality module. With respect to the topic of the 1. Wethydro-workshop “Measurement techniques and data assessment in wetland hydrology”, tests were performed on the basis of this module to investigate the impact of the accuracy of hydromorphological parameters on several modelled water quality parameters. The results are discussed with regard to data collection and -acquisition.

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MODULE CONCEPTION

The demand for a short simulation time excludes the direct link of extended water quality models to the basic long-term water balancing model. Therefore, at first the suitability of a black box approach was tested by a 10-years data base with monthly input and output data for deriving transfer functions. For a monthly forecast the results were statistically dissatisfying. Therefore, a process-orientated approach was used. It serves as an instrument to calculate the in future expected matter concentration for deriving a reduced module based on transfer functions. In this chapter the modelled region and the main wetland water quality processes are described, the basic model is exemplified for the Spreewald region with respect to some stream parameters. More details about the model structure are reported in Balla et al. (2004).

Model region

Downstream of its middle reach, the Spree River flows through the wetland region Spreewald with an extension of 320 km^2. Besides the Spree River the Spreewald region has 6 tributaries: Malxe, Greifenhainer Fließ, Vetschauer Mühlenfließ, Dobra, Wudritz and Berste (Fig. 1).

The wetland region is characterised by:

- a dense network of channels and ditches with a total lengths of about 1600 km, which were canalised and equipped with about 500 weirs and other hydraulic structures;
- shallow groundwater tables, ca. 30% peat soils (fens) at different degree of degradation. Due to low precipitation and high evapotranspiration rates during the summer time the wetland acts as a water consumption area with a negative water balance;
- water management with an intensive groundwater table control. It differs between summer and winter time. During the winter time the groundwater table is kept higher. Some parts of the Spreewald region are flooded for water and solid matter storage and for fish breeding. This water table control regime lasts from October/November to March. In this time the wetland is partly inundated.

The water distribution within the wetland is performed by 13 cascade belts (see Fig. 1). The rules for water distribution are fixed in regional water management framework concepts (LUA, 1996; 2002).

Since 1990 the Spreewald region is designated as UNESCO`s Biosphere reserve.

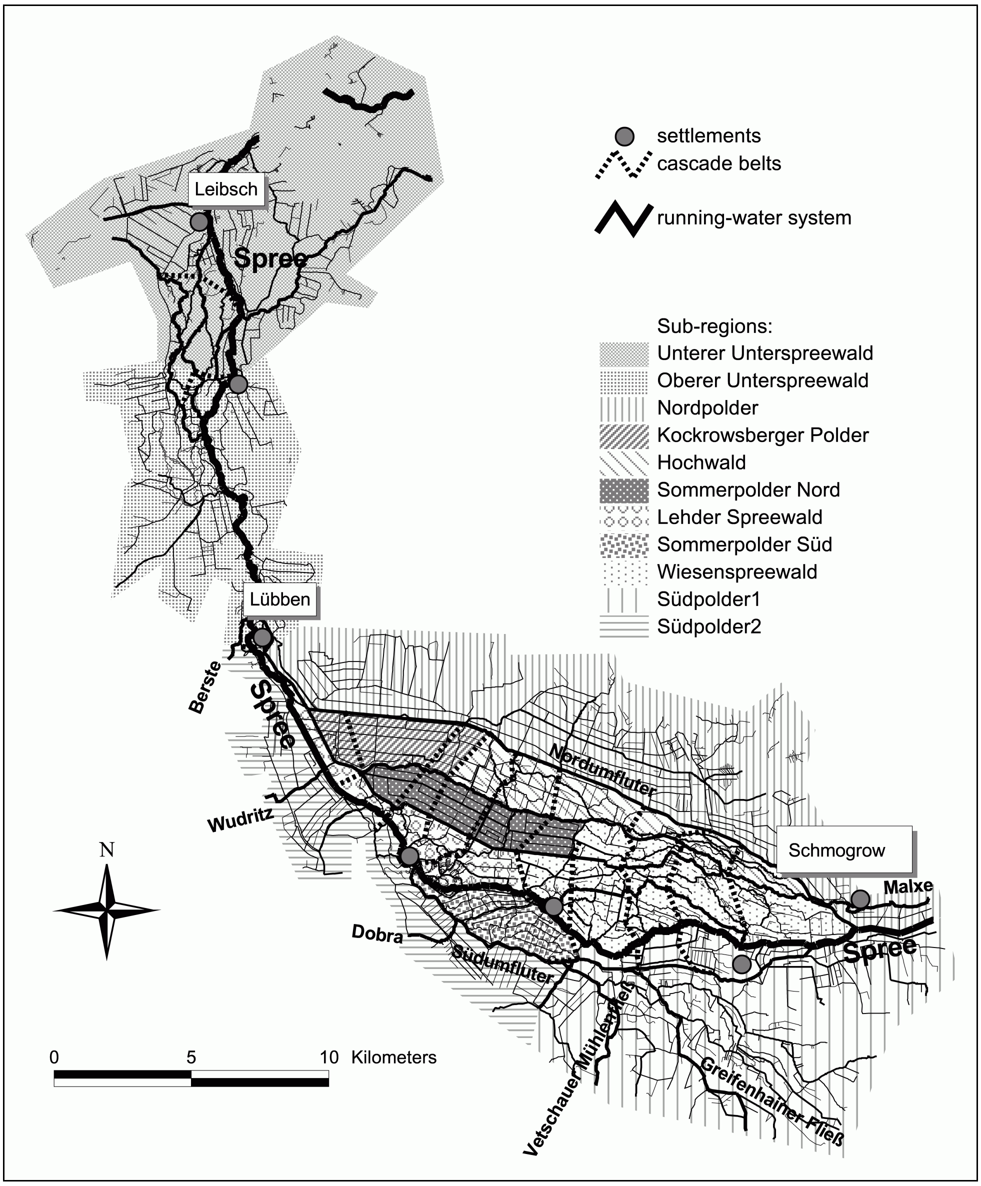

Figure 1. Wetland region Spreewald with running water system, cascade belts and classification in sub-regions with respect to groundwater quality

The Spreewald is devided into two parts – the Upper Spreewald, which reaches from Schmogrow to Lübben, and the Lower Spreewald from Lübben to Leibsch (see Fig. 1). These parts are not only different in their geomorphological properties but in the flow net density and flow velocity. In consequence muddy sediments with an high organic content predominate in the Upper Spreewald region and more sandy sediments in the lower part.

Main processes

Both, the inflow discharges from the different tributaries to the Spreewald as well as the water table control within the Spreewald influence the solute concentration by mixing processes. Furthermore, the flow velocities are diminished due to the water table control. The average value for the Upper Spreewald region is approximately 0.01 m s^{-1} for a mean water situation (MQ), and – up to 0.1 m s^{-1} for the less branched lower part. This results in a longer travel time for the Upper Spreewald, supporting transformation processes and matter exchanges betweenthe sediment and the water column.

Furthermore, the water table control of the ditches affects the groundwater table in the surrounding wetland areas. An alternating water exchange between groundwater and surface water takes place: surface water infiltrates into the wetland areas in periods of high evapotranspiration rates during summer time resp. during the flooding period in winter time (sink function) and, reversibly, a groundwater exfiltration into the surface water occurs in times of water surplus, mainly at the beginning of the summer water table control regime (source function). These controlling processes are abstracted in Fig. 2.

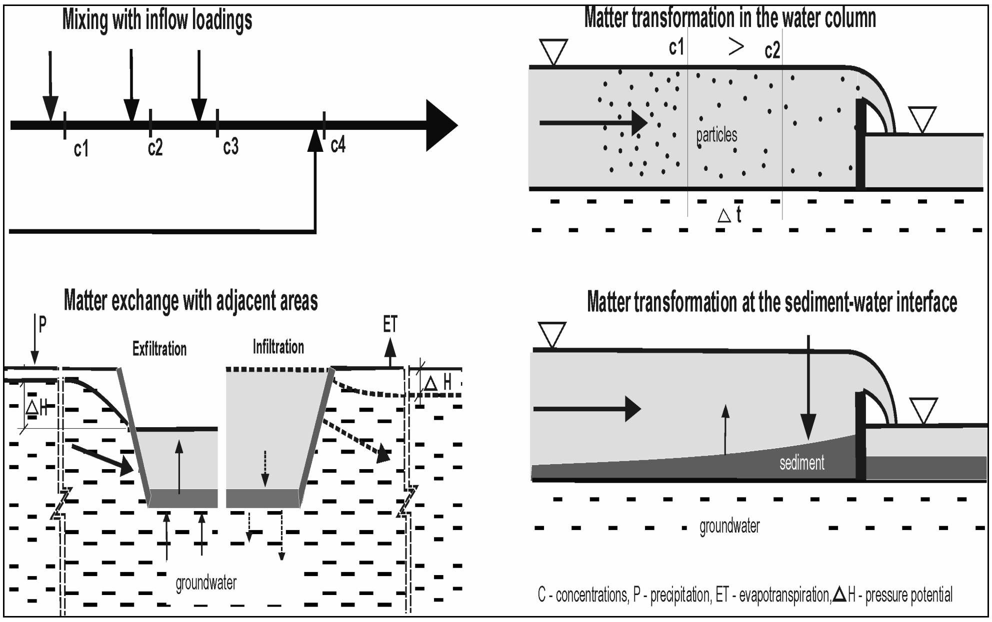

Figure 2: Main water quality processes

Model description

For the water quality modelling the Dutch modelling system DUFLOW (version 3.5 and 3.6) was used (Stowa, 2000). This software is suitable for subcritical flow (Froude<1) and for alternating flow directions, just like wetlands. The model package integrates a hydraulic flow module based on the unsteady 1-D-flow equation, a water quality module, and a module for groundwater exchange. For the Spreewald water quality modelling, the hydraulic module and the water quality module were used.

Besides transformation processes, the water quality module has to consider the alternately exchanging area loads (sources and sinks). The model package DUFLOW allows the calculation of losses by a Precipitation Runoff Module (RAM). To consider the sinks as well, the Spreewald model uses results of a specific approach for balancing the water volume for sub-areas which includes the water distribution within the wetland for wetland protection (Dietrich et al., 2003). The wetland area was subdivided into sub-areas. The exchanging loads from these sub-areas to the river section are considered as a point source or sink. The principal module conception and the link to the river basin model is shown in Fig. 3.

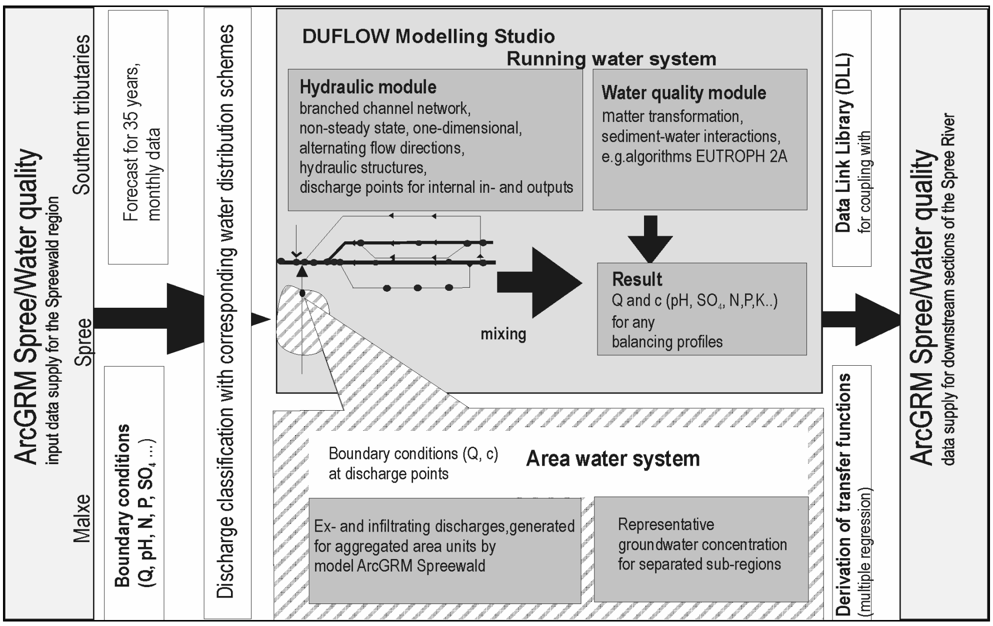

Figure 3: Conceptual module for water quality modelling of the Spreewald wetland region with linking to the river basin model ArcGRM Spree/Water quality

Flow network

The modelled running water system was built up on a GIS-based flow network (LAGS, 1999). The flow network had to be simplified because of its extremely high density of about 4 km km^{-2}. With respect to water quality modelling the following water ways were included:

- main longitudinal water courses for water and matter transit regarding the influence of travel time, matter transformation and decay;
- transversal water courses which connect the longitudinal channels regarding the influence of mixing processes;
- water ways with structures and connections for area loads and point loads.

Thus, the computed flow lengths of all running water sections was reduced to about 220 km.
In Fig. 4 is shown a part of the flow network after the selection of the main water ways used as basis for further calculations.

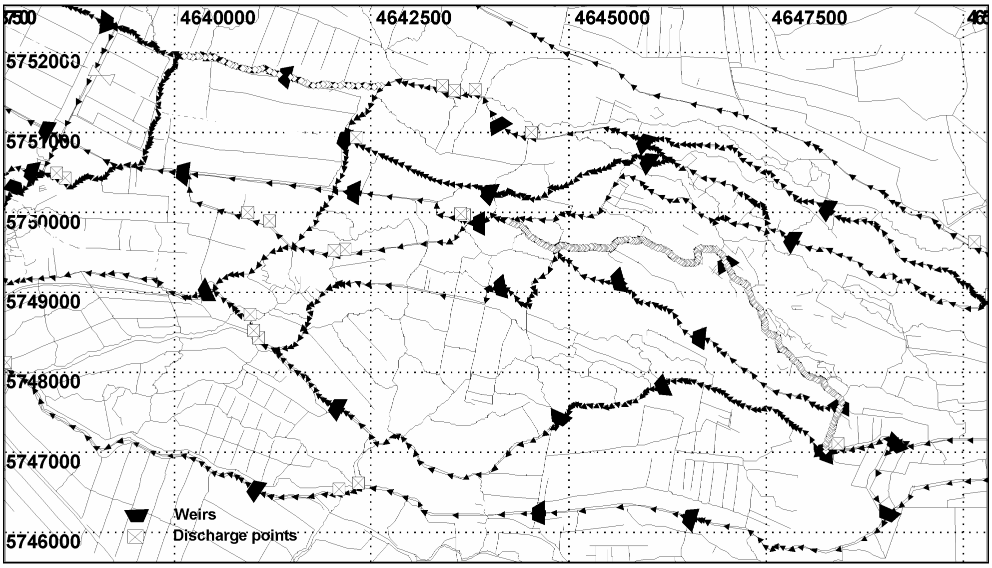

Figure 4. Sector of the modelled flow network of the Spreewald wetland with weirs and discharge points, based on a separate GIS-file

Profiles and hydraulic structures

For longitudinal and cross-sectional profiles, an actual data base was scarce. Existing profiles, which had been taken in most cases during the 50^{th}, have changed due to reconstruction works or sedimentation processes. A first approximation was undertaken on the basis of the topographic map 1:10,000 (TK10), where some data exist for water depths and flow widths. During monitoring campaigns some profiles were determined. The bottom levels were checked by water levels, measured by staff gauges in the headwater and bottom water at each weir, combined with measurements of the actual water depths.
The geometric parameters of the hydraulic structures were taken from technical documentations or determined by additional measurements.

Hydraulic and hydrochemical boundary conditions

The hydraulic calculation and quality simulation require necessarily the time-dependent surface water boundary discharges, water levels, and concentrations for all tributaries. Furthermore, the actual sill level for weirs have to be included in the model to allow for the consideration of the water distribution within the Spreewald region by weirs in dependence on the available water supply. This is, in fact, a difficulty. The water level management and the weir control are intensively performed by territorial water and soil associations using expert knowledge. Detailed documentations do not exist, which could be included in the model as a trigger function. For the water distribution the headwater and bottom water levels were used, which are taken for each structure for at least weekly by the associations. Therefore, with regard to dependencies of water distribution on discharge, the model was simplified. The input discharge was divided into 7 classes (Tab. 1). For each class the water distribution scheme as well as the weir sill levels were assumed as constant. That means the quality calculations were performed for 7 classes of discharge, changing the boundary concentrations of the chemical substances. For each discharge class a model adjustment was done. For all river sections between weirs (about 50) the roughness coefficient and the sill level have been calibrated by means of measured water levels in the back and bottom waters for a comparable discharge situation in the past for each discharge class. The partition in summer time and winter time considers the different water management and distribution schemes during the hydrological summer and winter period with respect to flooding of sub-areas for water storage.

Table 1. Inflow discharge classification for the Spreewald region in accordance with typical schemes of water distribution

Inflow Q in $m^3 s^{-1}$ (sum Q_Spree and Q_Malxe)							
Variants	SH6	SH10	WH10	SH17	WH17	SH45	WH45
Hydrological winter half-year (WH)			6 - 10		10 - 17		>17
Hydrological summer half-year (SH)	<6	6 - 10		10 - 17		>17	

The next simplification was performed with respect to the area – surface water exchange:
For the same discharge classes the water balances for each sub-division were calculated by the separate water balancing model (Dietrich et al., 2003) according to the measured data sets for discharges and connected as discharge points (see Fig. 3). With respect to the modelled time step of 1 month the exfiltrating water is considered as groundwater. Possible run off could be neglected. Representative groundwater concentration, measured in shallow groundwater for sub-areas were assumed as concentrations at the considered discharge points. According to the different soil and geomorphological properties as well as land reclamation and land use strategies (e.g. embanked areas, forests, extensive land use) the Spreewald area was subdivided into 11 sections of typical groundwater concentrations (see Fig. 1).

For calibration and validation of the quality algorithms data sets for the input parameters (1991-2003) were used which had been collected by the Environmental agency of the State of Brandenburg/Germany and by own additional surface water and groundwater monitoring. Calibration and validation were more complicated because of data lacks regarding the completeness of the hydraulic **and** hydrochemical boundary parameters for all tributaries as well as groundwater concentration.

MODEL ANALYSES AND DISCUSSION

By the following examples it was tried to quantify the percentages of the different processes (see Fig. 2) on the sink and source function of the wetland – mixing, area water exchange and matter transformation as well as to test the sensitivity of stream parameters on the matter transformation within the channel network. For quantifying the sink and source function 5 discharge situations were compared whereas for the evaluation of transformation processes the discharge situation SH10 was assumed.

Time-dependent sink and source function of the wetland with respect to sulphate

Tab. 2 shows the load reduction by the running water system and the area water system. A critical high sulphate concentration for the Spree River was assumed as boundary condition which could endanger the running water system in case of water overflowing from the careers in the upstream (Maul, 2002). The sulphate concentration SO_4 of the other tributaries are assumed as the 10-years summer and winter means.

Table 2: Load reduction by the Spreewald wetland and percentages of the different processes in the sulphate load reduction in dependence on the assumed discharge situations (see Tab. 1)

Discharge variations		**SH6**	**SH10**	**SH17**	**WH10**	**WH45**
SO_4 input to the Spreewald (Spree river)	mg l^{-1}l	1000	1000	1000	1000	1000
SO_4 output (Spree river)	mg l^{-1}	208	451	525	381	587
SO_4 input as load M_{in}	kg s^{-1}	2.6	8.5	15	11	64
SO_4 output as load M_{out}	kg s^{-1}	1.7	6.9	13.3	8.8	58
Percentage of load reduction by matter transformation processes	% of M_{in}	21	18	12	21	10
Load reduction by area water uptake (sink)	% of M_{in}	15	2	2	0	0
Load increase by area water surplus (source)	% of M_{out}	0	0.1	3	4.5	0

The load reduction of the running water system ranges between 10 and 21% while the impact of area water on the load changes ranges from a reduction of 15% during summer time and low discharges to an increase of 4.5% during winter time and exfiltration situations. In most cases the decrease of loads and concentration results from mixing processes with the less concentrated tributaries.

Influence of hydraulic stream parameters on the sulphate concentration

The inorganic sulphate concentration is predicted as a first-order model (Chapra, 1997):

$$c = c_0 \cdot e^{-kt} \tag{1}$$

where	c	concentration at the outflow profile [mg l^{-1}]
	c_0	concentration at the inflow profile [mg l^{-1}]
	t	travel time [d]
	k	decay rate [d^{-1}]

If the temperature-dependent decay rate k is constant, the modelled concentration depends on the flow velocity respectively the travel time only, which are influenced by hydraulic stream parameters.

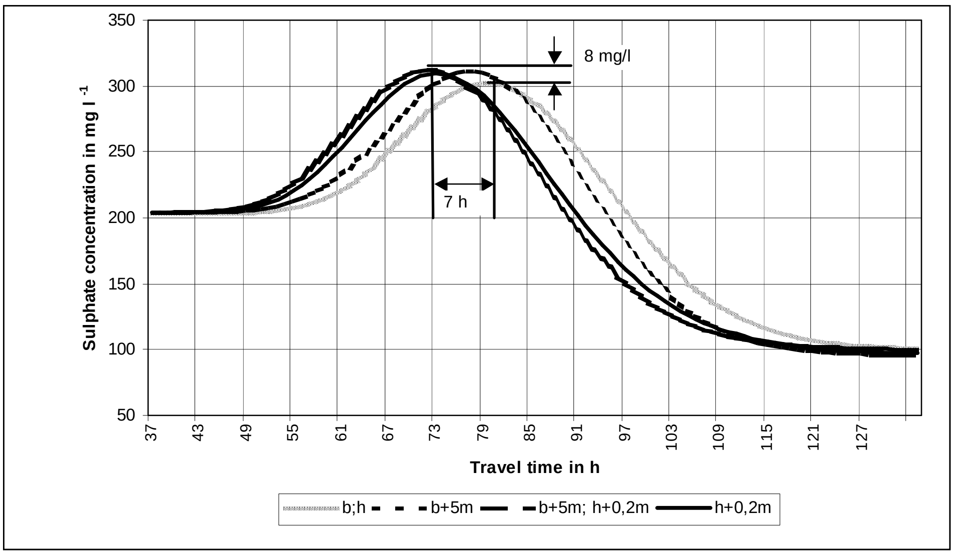

Figure 5. Travel time and concentrations at the Spreewald outflow profile Leibsch for the discharge situation SH10 (see Tab. 1) and varying geometric stream parameters – flow width b and water depths h

For the Spreewald wetland example the flow width of all channels was altered by an amount of 5 m (b + 5m) and all water depths were decreased by 0.2 m. This changes caused an increase of a specific cross section by 35% resp. an decrease of the flow depths of 20%. A sulphate input of 1000 mg l^{-1} was induced like a tracer at the first day. The simulated time period amounts 1 month, the decay rate $k = 0.03\ d^{-1}$. Dependence of concentration on travel time for different parameters at the Spreewald output profile Leibsch is shown in Fig. 5.

In comparison with the reference variant with b and h (etalon) the strongest decrease in travel time and concentration is achieved in the third variant. But the error, related to the etalon, amounts only 3%.
That means, that in the case of a matter transformation with the assumed decay rate k, errors in cross-section geometries (of up to 35%) are not sensitive.

Influence of hydraulic stream parameters on biotically-relevant parameters

While sulphate can be considered as a tracer-like parameter the biotically-relevant parameters nitrogen, phosphorus, and chlorophyll-a vary with changing environmental conditions.
The matter transformation processes are modelled by the algorithm EUTROPH 2a (Aalderink, 2000).
This algorithm considers the mass balance in the water column and in the sediment - water interface, e.g. the diffusion between the sediment and the water column, the sedimentation, resuspension of particles, and the burial of particles in the sediment.
The algal growth is considered to be limited by nutrients, light, and temperature. The nutrient transformation in the water column, like nitrification and denitrification, described as a first-order reaction, depends on the travel time and, therefore, on the cross-sectional area. The light limitation is a function of the water depths. There exists a dependence of the transformation and exchange processes on the hydraulic parameters, especially on water depths.

Table 3. Variation of parameters ammonia-nitrogen NH_4-N, nitrate-nitrogen NO_3-N, phosphorus as soluble reactive phosphorus (SRP) and phytoplankton as chlorophyll a (chl-a) by variation of cross-sectional parameters (B – flow width in m, h – water depth in m)

Variants	**NH_4-N [mg l^{-1}]**	**% deviation**	**NO_3-N [mg l^{-1}]**	**% deviation**	**SRP [mg l^{-1}]**	**% deviation**	**chl-a [µg l^{-1}]**	**% deviation**
B; h	2.67		6.12		0.077		35.76	
B+5;h	2.69	0.99	6.14	0.26	0.078	1.38	34.96	-2.14
B+5;h-0.2	2.68	0.70	6.11	-0.11	0.079	2.15	36.72	2.13
B; h-0.2	2.68	0.58	6.12	0.00	0.079	1.49	36.26	1.41

In Tab. 3 the differences in the concentrations at the Spreewald output profile Leibsch are presented for the inorganic nitrogen and phosphorus fractions and for

the algal growth. All input parameter are constant in time and within the variants. The modelled time period is 1 month.
The concentrations vary in a range of $\pm 2{,}15\%$. Comparable to sulphate concentrations the parameters for N, SRP, and chl-a are not sensitive to changes of the cross sectional parameters.

Influence of the sediment and suspended solids on biotically-relevant parameters

The sediment and the suspended solids influence the diffusion and resuspension processes.
In general the diffusion flux is described as

$$F_{XD} = \frac{E_Z}{0{,}5 \cdot DZ}(D_{XB} - D_{XW}) \qquad (2)$$

where F_{XD} diffusion flux [g m^{-2} d^{-1}]
E_Z diffusion coefficient at the sediment - water interface [m^2 d^{-1}]
DZ thickness of the bottom sediment layer [m]
D_{XB} pore water concentration [g m^{-3}]
D_{XW} concentration of soluble in the water column [g m^{-3}]

Equation 2 shows the dependence of the diffusion process on the sediment pore water concentration and the concentration in the water column. The pore water concentration varies in dependence on organic material. Thus, for the Spreewald sediments an inorganic phosphorus concentration of 1.54 mg l^{-1} and 6 mg l^{-1} of organic nitrogen were determined for mud sediments, whereas sandy sediments contents 0.4 mg l^{-1} and 3 mg l^{-1}, respectively.
The influence of a different sediment distribution on the biotically-relevant parameters is shown in Tab. 4. It was assumed that in variant 2 all sediments are mud and in variant 3 all sediments are sand. The reference variant 1 consists of muds for the Upper Spreewald channels and of sands for the lower part, according to the topographic map TK10 and own measurements.

Table 4. Variation of calculated concentrations for ammonia-nitrogen NH_4-N, nitrate-nitrogen NO_3-N, phosphorus as SRP and phytoplankton as chlorophyll a (chl-a) with respect to varying sediment parameters (variant 1 - assumed sediment distribution according to TK10, variant 2 – all sediments are sandy, variant 3 - all sediments are muddy)

Variants	NH_4-N [mg l^{-1}]	% deviation	NO_3-N [mg l^{-1}]	% deviation	SRP [mg l^{-1}]	% deviation	chl-a [µg l^{-1}]	% deviation
Variant 1	2.67	0	6.12	0	0.077	0	35.76	0
Variant 2	2.62	-1.09	6.12	-0.013	0.077	-0.93	35.73	-0.068
Variant 3	2.70	1.19	6.12	0.008	0.077	0.60	36.77	0.028

The percentages of differences of the variants 2 and 3 to the variant 1 is highest for NH_4-N, but in a small range of about 1%. The SRP concentration shows a similar variation. It could be assumed that under the considered conditions and parameters the diffusive flux is not sensitive to uncertainties in pore water concentration estimations.

The sedimentation flux of the matter X is directly coupled to the sedimentation of suspended solids SS:

$$F_{XPS} = F_{Sed} \cdot P_{XW} + V_S \cdot POR \cdot D_{XW}) \qquad (3)$$

where	F_{XPS}	sedimentation flux [gX m^{-2} d^{-1}]
	F_{Sed}	sedimentation flux of suspended particles [gSS m^{-2} d^{-1}]
	P_{XW}	bound matter content at suspended solids [gX gSS^{-1}]
	V_S	sedimentation velocity [m d^{-1}]
	POR	porosity of the sediment [-]
	D_{XW}	diluted matter in the water column [gX m^{-3}]

The first term of equation 3 describes the particulately-bound matter, which deposes, the second term matter, which is captured in the sediment. Here the first term was regarded. It depends on the sedimentation flux F_{sed}

$$F_{Sed} = V_{SS} \cdot SS_W \qquad (4)$$

where	V_{SS}	settling velocity [m d^{-1}]
	SS_W	suspended solids [gSS m^{-3}]

The settling velocity for different particles, cited in literature, ranges from 0.08–30 m d^{-1} (Chapra, 1997). For 60–80% of the particles estimated in the Spree River settling velocities of less than 0.3 m d^{-1} were measured (Prochnow et al., 2000).
Tab. 5 shows the results if the parameter V_{ss} varies in a range from 0.02 to 2 m d^{-1}.

Table 5. Changes in concentrations of NH_4-N, NO_3-N, SRP and chl-a for varying settling velocities, absolutely and percentages related to the etalon

V_{SS} [m d^{-1}]	**NH_4-N [mg l^{-1}]**	**% deviation**	**NO_3-N mg l^{-1}**	**% deviation**	**SRP [mg l^{-1}]**	**% deviation**	**chl-a [µg l^{-1}]**	**% deviation**
2	2.67		6.12		0.077		35.76	
0.2	2.77	4.02	6.12	0.01	0.094	21.2	27.84	-22.9
0.02	2.83	4.87	6.12	0.01	0.117	29.2	25.85	-27.9

A decrease of the parameter V_{ss} has a remarkable influence on the SRP concentration and chl-a. The range of differences amounts about $\pm 30\%$.

The resuspension flux depends, in analogy to the sedimentation flux, on the resuspended particles P_{XW}:

$$F_{XPR} = F_{res} \cdot P_{XW} + V_r \cdot POR \cdot D_{XB} \quad (5)$$

where F_{res} resuspension flux of the particulate phase [gX m^{-2} d^{-1}]
V_r resuspension velocity of the sediment [gX gSS^{-1}]
D_{XB} diluted matter in the sediment [gX m^{-3}]

The impact of resuspension is considered for the first term of equation 5, the particulately-bound matter, varying the resuspension flux in a range of 0.00001 and 1 (Tab. 6).

The strongest impact on varying parameter F_{res} is to be seen with the SRP concentration and its deviation of about 13% in comparison with the etalon.
Comparing the diffusion, sedimentation, and resuspension fluxes, the sedimentation flux shows the highest sensivity to all biotically-relevant parameters.

Table 6. Variations of concentrations by varying the particulate component of resuspension flux

F_{res}	NH_4-N [mg l^{-1}]	% deviation	NO_3-N [mg l^{-1}]	% deviation	SRP [mg l^{-1}]	% deviation	chl-a [µg l^{-1}]	% deviation
0.00001	2.67		6.12		0.077		35.76	
0.001	2.66	-0.13	6.12	0.00	0.077	0.00	35.76	0.00
1	2.66	-0.15	6.12	0.00	0.087	12.65	35.76	0.00

CONCLUSIONS

For the derivation of a computing-time limited water quality module for the Spreewald wetland region a process-orientated water quality model, based on the DUFLOW software package, was developed. This model enables the quantification of the internal load retention and loss dynamic as well as the estimation of essential factors influencing the matter transformation within the surface water system.
Basis for the water quality model is the identification of the surface water flow network. In the case of the Spreewald this network was to be schematised taking into consideration the water distribution and water quality impacts. For including water distribution aspects it was necessary to classify discharge situations in which the hydraulic structure control does not change.

With respect to water quality the influence of cross-section accuracy does not play the dominant role. It is sufficient to approximate the profile parameters.
More accurateness is needed to determine the parameters influencing particle-driven processes as sedimentation and resuspension.
For model calibration and validation an exact, synchronised data base for all boundary conditions, i.e. hydraulic and hydrochemical parameters is needed.
As shown in the Spreewald example the groundwater exfiltration and the load emission into the surface water bodies is significant. Although in the case of the sulphate a load increase of about 4% is only expected during winter time, for other elements which do not underlie transformation processes in the groundwater zone due to anoxic environment in the waterlogged zone, the emission takes a higher part. There is a need for a more exact data base for groundwater references.

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