Simulation of Dissolved Oxygen and Dissolved Substrate for Hasel River

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Abstract—**Hasel is considered a moderately polluted river in Germany. This study investigated its water quality, examining Dissolved Oxygen (DO) and dissolved substrate (COD) with the use of AQUASIM. The calibration procedure used observed data from various locations along the river. The model's calibration was used to study the response of Hasel River to the effluents of wastewater treatment plants and sewer overflow emissions. Results revealed that high emissions from sewerage systems may reduce the oxygen concentration to low levels. Furthermore, joined sewer overflows may disrupt the oxygen levels for a long period. In addition, oxygen was over saturation in some periods of the calibration period. The proposed model can be utilized in future analyses, improving the functional understanding of ecological processes in rivers and the identification of ecological effective management strategies.**

Keywords-water quality models; rivers; dissolved oxygen; eutrophication; impact assessment

I. Introduction

Most water quality models are flexible to several environments and subjected to proper definitions of boundary conditions, dimensional variation, and factor characterization. The basic goal of River Water Quality Models (RWQMs) is to simulate the spatial-temporal effect of organic pollution on oxygen level, because of its significance for aquatic life. The Streeter-Phelps model, which describes the balance between deoxygenation and reaeration, was presented in [1]. Another important example of RWQM is the simulation of toxic substances, such as organic chemicals or heavy metals, via the WASP model package [2]. The Aquatic Simulation (AQUASIM) program [3] was designed for creating standardized and consistent river water quality models. Besides the fundamentals of biochemical conversion processes, the structure of compartments of flowing water ecosystems was examined in [4], including the longitudinal, vertical, and lateral zonation patterns. This aspect has not gained much attention in river water quality modeling so far [5], while it should be examined in order to attain an ecologically convenient choice of model compartments and state variables [6, 7]. Streaming waters are linked elements within the hydrological continuum [8-10]. As a result, the hydrological interactions between water compartments are important, as they influence the transport and storage of water, chemical compounds, and nutrients [11-13]. Quantifying the prominence of the exchange processes is complex, due to high spatial and temporal variations of the hydrological system based on a set of factors such as river morphology and hydraulic gradients [14-17]. Furthermore, rivers' dynamics are shaped by a complicated temporal style, due to daily and seasonal changes in trophic and respiration activities [18-22]. This complexity may be narrowed by analyzing the relevance of temporal dynamics of water constituents in a eutrophic shallow river [5]. This case study considered the Hasel River in Germany. Its main goal was to analyze the oxygen concentrations as one of the water quality parameters using an AQUASIM model [23], and discuss the future river water quality management.

II. Materials and Methods

A. Study Site

Hasel River is a right-sided tributary in the middle reach of Werra River, located in Thuringia, Germany between 10°28′ and 10°47′E longitude and 50°32′ and 50°38′N latitude. Its total length is 25Km, and it is divided into four reaches coming from four catchment areas of 321Km^2, having an average gradient of 2‰. The first reach has a length of 6.0Km and an average discharge of 1.54m^3/s. The second reach has a length of 9.25Km, and the catchment area discharges 0.02m^3/s in average. The third reach has 2.75Km length, and its catchment area brings an average discharge of 3.01m^3/s. The fourth reach has 7Km length, and its catchment area has an average discharge of 0.01m^3/s. This study selected five trapezoidal cross-sections in the boundaries of the four reaches, with surface width ranging from 0.70m at the spring to 11.00m at the mouth. Hasel River is affected by the influx of the wastewater treatment plants at Suhl and Rohr, located at 19.3Km and 6.1Km upstream (US) its mouth, respectively. The Suhl plant, serving 48,000 inhabitants, discharges directly US the first reach terminal, while the Rohr plant, serving 300 inhabitants, discharges downstream (DS) the third reach terminal [24]. The temporal and spatial dynamics of flow and physico-chemical parameters were measured during 1990-2001 by *Thüringen Landesamstadt für Umwelt und Geologie,* TLUG (National Thuringia Town of Environment and Geology, Germany). The surface water body was measured nearly every month in monitoring stations at Ellinghausen, Diezhausen, and Simon (2.99, 14.6, 17.9Km upstream the mouth respectively) for pH, Oxygen, COD, BOD, ON, NH_4, NO_2, NO_3, OP, OPO_4. Temperature and light intensity were measured daily in 2001.

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B. Modeling Approach

One-dimensional river hydraulics can be described by a set of two partial differential equations representing mass and momentum balance. The two most important approximations to these equations, the kinematic and diffusive wave [25], are implemented in AQUASIM to describe river hydraulics. The equations for river hydraulics are coupled with advection-diffusion equations to describe the transport of dissolved or suspended substances in the water, leading to the following set of differential equations. The first equation describes the water flow through the compartment as:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \quad (1)$$

The temporal change in the immersed cross-sectional area A, is determined by the spatial gradient of the discharge Q and the lateral inflow q. The behavior of the substances transported with the water flow is described by:

$$\frac{\partial AC}{\partial t} = -\frac{\partial}{\partial x}(QC) + \frac{\partial}{\partial x}\left(AE\frac{\partial C}{\partial x}\right) + r + S_{qn} \quad (2)$$

The concentration is affected by four terms: advection with the water flow, longitudinal dispersion, transformation processes, and lateral inflow or outflow. In order to combine the above system of differential equations, one boundary condition is necessary for (1), and two boundary conditions are required for (2). The boundary condition for (1) that describes the discharge through river's sections at the start point x_s is:

$$Q(x_s) = Q_{in} \quad (3)$$

The boundary conditions for (2) are given by the continuity of the substance mass flows entering the river section and a transmission boundary condition [26] at the compartment end:

$$Q(x_s)C - AE\frac{\partial C}{\partial x} = I_{in,C} \quad (4)$$

$$\frac{\partial^2 C}{\partial x^2} = 0 \quad (5)$$

where $I_{in,C}$ is the total mass input of substances, described by the concentration C per unit of time. Equation (5) is omitted for dispersion-free transport. The longitudinal dispersion coefficient in (2) is estimated according to [27], as:

$$E = c_f \frac{w^2 v^2}{u^* d} \quad (6)$$

where c_f is a non-dimensional dispersion coefficient, w is the surface width of the river, d is the mean river depth, and $u^* = \sqrt{gdS_f}$ is the friction velocity. The empirical expression (7) is used to calculate the friction slope:

$$S_f = \frac{1}{K_{St}^2}\frac{1}{R^{4/3}}v^2 \quad (7)$$

where K_{St} is the friction coefficient according to Strickler, R is the hydraulic radius of the river, and v is the average cross-sectional flow velocity.

C. Modeling of Oxygen Series

The oxygen balance of Hasel River is characterized by high daily and seasonal temporal dynamics triggered from radiation and intense production-respiration processes. According to (2), it can be modeled with a simple version of AQUASIM using:

$$r = K_2(C_{sat} - C_{O2}) + \frac{PI}{d} - \frac{R}{d} - K_{deg}\frac{C_{O2}}{K_{O2}+C_{O2}}COD \quad (8)$$

where r is the net oxygen production rate, K_2 is the reaeration rate constant, C_{sat} is the oxygen saturation concentration, C_{O2} is the oxygen concentration, I is the light intensity, d is the mean river depth, P and R are production and respiration parameters respectively, K_{deg} is the degradation rate constant, K_{O2} is the half saturation concentration with respect to oxygen, and COD is the concentration of substrates.

III. RESULTS AND DISCUSSION

A. Verification of Hydraulic Model

The study of Hasel River was modeled using cross-section profiles throughout river's length, a constant slope, and an effective coefficient through every reach. All simulations were performed using an extended version of AQUASIM [3, 28-30]. The calibration of the effective Strickler friction coefficient in the four reaches of Hasel River ($K_{St,I}$, $K_{St,II}$, $K_{St,III}$, and $K_{St,IV}$) was performed according to the TLUG estimated values. The non-dimensional dispersion coefficient c_f had a constant value based on the tracer transients in a water column [5]. The estimated parameters are given in Table I. Figure 1 shows the water level profile of Hasel River. Hydraulic height gradients through the four reaches and the calculated longitudinal water surface profile were in acceptable agreement.

TABLE I. HYDRAULIC PARAMETERS ESTIMATES

Parameter	Unit	Value
$K_{St,I}$	$m^{1/3}s^{-1}$	40.0
$K_{St,II}$	$m^{1/3}s^{-1}$	35.0
$K_{St,III}$	$m^{1/3}s^{-1}$	30.0
$K_{St,IV}$	$m^{1/3}s^{-1}$	32.5
c_f		0.006

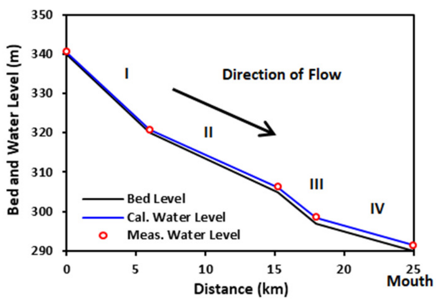

Fig. 1. Profile of water levels of Hasel River.

B. Verification of Dissolved Oxygen Model

Estimates for physical reaeration were based on empirical assessments [31, 32], considering the given flow velocities and water depths for the investigated time periods. Empirical formulas resulted in K_2-values ranging between 17.0 and $29.0d^{-1}$. A value of $K_2=20d^{-1}$ was selected for model calculations. The oxygen saturation concentration formula is given in [33]. Based on these boundary conditions, production and respiration rate parameters were estimated from continuously measured oxygen time series (Table II). In [34], an approximate value of K_{deg} was reported ranging between 0.5 and $3.0d^{-1}$.

TABLE II. PARAMETER ESTIMATES FROM OXYGEN TIME SERIES

Parameter	Unit	Value	Std. dev.
P	g/(Wd)	0.10097	0.0006
R	g/(m^{2}d)	11.27	0.06

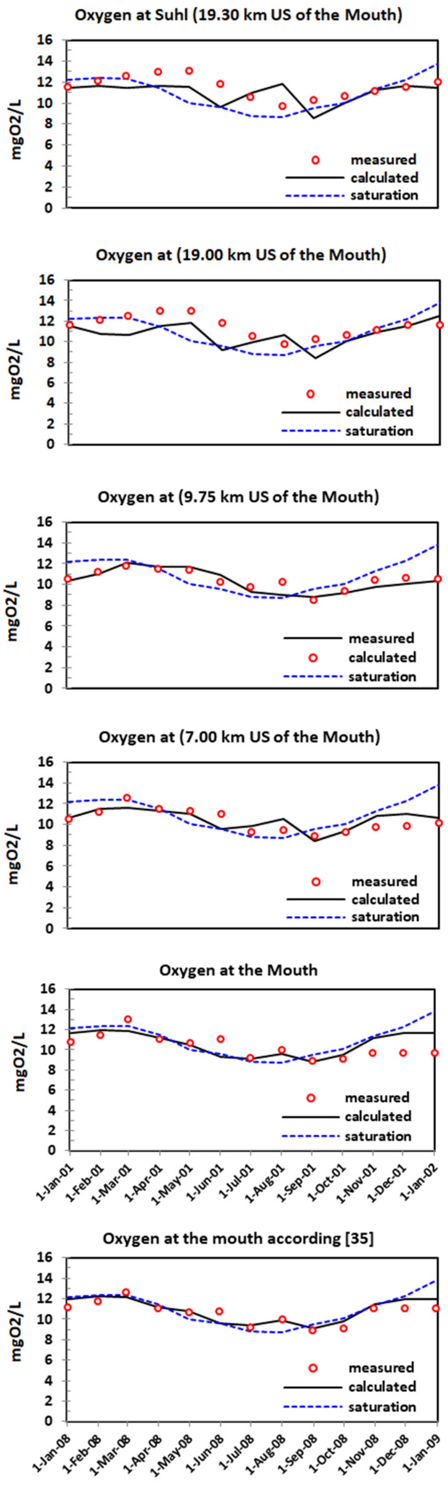

Fig. 2. Oxygen time series for Hasel River.

The effect of the effluents on oxygen concentration in the river is based on a degradation rate coefficient of 1.0d^{-1}. Figure 2 shows the concentration of oxygen at five sections of Hasel River at the boundaries of the river reaches. This method achieved a meaningful agreement between measured and calculated oxygen concentrations. Despite the enhanced gas exchange with the atmosphere, due to low depth and turbulent flow, daily oxygen amplitudes highly exceeded saturation up to 6mg/l in May-August 2001, while oxygen deficits were almost equal pronounced. These patterns were still existent in the remaining period of 2001, but in a more narrow range of oxygen concentrations. In addition, the concentrations of oxygen were validated for the mouth with data from [35].

When considering the oxygen balance in shallow eutrophic rivers, one important concern is the over-saturation which leads to gas-blisters in fishes. According to the European Classification of Water Quality in water bodies, Table III shows the trophic state of Hasel River [36-38]. As it is evident, Hasel River is moderately polluted except some locations such as near the waste water treatment plant at Suhl.

TABLE III. TROPHIC STATUS FOR HASEL RIVER

Cross-sectional locations*	O_2-saturation %	Trophic state
19.30Km (Suhl)	132.53	Eutrophic
19.00Km	120.37	Mesotrophic
9.75Km	116.74	Mesotrophic
7.00Km	119.08	Mesotrophic
0.00Km (mouth)	107.92	Mesotrophic

* The locations are measured US of the mouth.

C. *System Response to Inputs of Organic Matter*

The sewage treatment plant at Suhl is at x=19300m, having a mean dry weather discharge of 0.07m^3/s and a mean COD of 77.3mg/l. The sewage treatment plant at Rohr is at x=6100m, having a mean dry weather discharge of 0.004m^3/s and a mean COD of 50mg/l. In addition, there is a sewer overflow at x=20600m with a mean COD of 125mg/l. In order to examine the pollution load impact, oxygen concentrations were calculated at x=19200m, 100m DS the sewage treatment plant effluent at Suhl, under the assumption of constant COD concentrations of 90mg/l (upper legislation limit) combined with a sewer overflow duration of 2.4h, a discharge of 2m^3/s, and COD concentration of 125 mg/l (about the yearly average). Figure 3 shows the actual and hypothetical load cases. The comparison shows that during a dry period COD effluent concentration leads to a slight decrease in DO concentrations, with no significant differences between the actual and hypothetical loads of COD. The decrease is between 0.3 and 0.5mg/l while daily fluctuations do not change significantly.

The effect of a sewer overflow in August 26, 2001 is shown in Figure 3(b). The simulation is in agreement with the documented effects of immediate and delayed oxygen depletion in the surface flow of running waters [39]. Figure 4 shows the time series for COD and oxygen at 100m DS Suhl. The joined sewer overflow increased COD concentrations for more than 4 hours. Meanwhile, the oxygen concentrations decreased below 4mg/l for several hours, followed by a slow recovery. Therefore it is concluded that joined sewer overflows have the potential to disrupt oxygen balances for extended time periods. Those single events suggest a real endangerment for populations of macro-organisms and fishes [5].

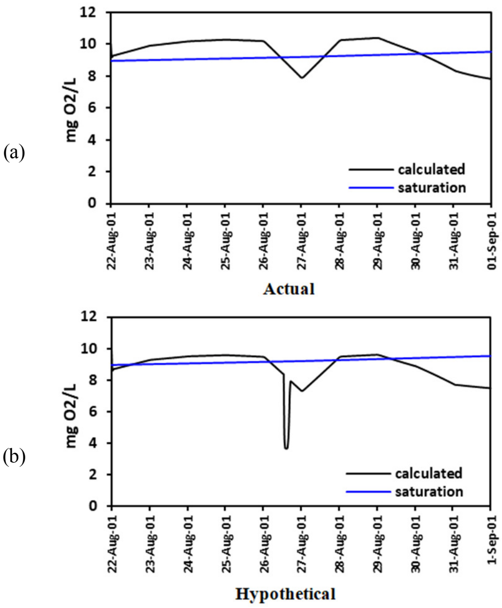

Fig. 3. Oxygen time series at 100m DS Suhl of Hasel River: (a) actual, b) hypothetical.

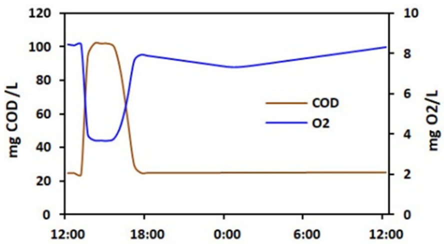

Fig. 4. Hypothetical time series for COD and oxygen at 100m DS Suhl.

IV. CONCLUSION

The proposed AQUASIM model was used to quantify the oxygen balance of a highly eutrophic shallow river, using a systematic procedure of river compartmentalization including identification of flows and a simplified description of biochemical conversion processes in Hasel River. The modeling approach quantified the temporal dynamic of oxygen in surface flow for spatially averaged scales, with consideration of distinct patterns at the boundaries of the river reaches, using physico-chemical data of 2001. The proposed model opens new perspectives in the study of ecological system responses to anthropogenic impact. The model's potential is demonstrated by simulations showing the effect of emissions from wastewater treatment plants operating according to emissions standards, which may disrupt oxygen concentrations. Moreover, combined sewer overflows may cause severe oxygen depletion for extended time periods, endangering macro-invertebrate and fish populations. Further research is needed in ecologically meaningful river water quality modeling. In these efforts, this AQUASIM model could be utilized during system analysis at several levels of intricacy and human impact, improving the functional understanding of ecological processes in rivers and the identification of ecological effective management strategies.

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