Quasi-2D approach in modelling the transport of contaminated sediments in floodplains during river flooding - model coupling and uncertainty analysis

K.-E. Lindenschmidt[a] **and J. Rauberg**[a]

[a] *GeoForschungsZentrum Potsdam, Section 5.4 – Engineering Hydrology, Telegrafenberg, 14473 Potsdam, Germany, kel@gfz-potsdam.de*

Abstract: In flood modelling, many one-dimensional (1D) hydrodynamic and water-quality models are too restricted in capturing the spatial differentiation of processes within the floodplain and two-dimensional (2D) models are too demanding in data requirements and computational resources. The latter is an important consideration when uncertainty analyses using the Monte Carlo technique are to complement the modelling exercises. Hence, we have developed a quasi-2D modelling approach which still calculates the dynamic wave in 1D but the discretisation of the computational units is in 2D, allowing a better spatial representation of the flow and substance transport processes in the floodplain without a large additional expenditure on data pre-processing and simulation processing. The models DYNHYD (1D hydrodynamics) and TOXI (sediment and micro-pollutant transport) from the WASP5 modelling package were used as a basis for the simulations. The models were extended to incorporate the quasi-2D approach and a Monte-Carlo Analysis was used to investigate the contribution of uncertainty from parameters and boundary conditions to the resulting substance concentrations. A flood event on the River Saale, Germany, was used as a test case. The results show a more realistic differentiation of suspended sediment within the floodplain and between the floodplain and the main channel. The results also show that for flood simulations, uncertainties in boundary conditions are higher and should be given more attention than uncertainties in model parameters.

Keywords: DYNHYD; Floodplain; Hydrodynamics; Quasi-2D Modelling; Sediment transport; TOXI

1. INTRODUCTION

Hydrodynamic and water quality models are important tools for the simulation and prediction of the transport of micro-pollutants in floodplains during flood events. An array of models of varying complexity levels may be used. A categorisation in the number of spatial dimensions that are simulated is useful. As an example for hydrodynamic models, one-dimensional (1D) models are often based on the St.Venant full dynamic wave equations solving the momentum and mass continuity equations of water transport through a meshed system. Two-dimensional (2D) models are often based on shallow water equations, which are hyperbolic partial differential equations describing water motion. A combination of both 1D and 2D approaches have also been used in which the flow in the main river channel is solved in 1D and the overbank inundated areas are solved in 2D (diffusive wave equation). 2D models are generally computationally more extensive and have more requirements on input data and pre-processing than 1D models. Horritt and Bates (2002) compared the utilisation and results of a flood simulation with three different models: the 1D model HEC-RAS (HEC 2002), the 1D/2D combination model LISFLOOD-FD (Bates and De Roo, 2000) and the 2D model TELEMAC-2D (Galland et al., 1991). Horritt and Bates (2002) illustrate that both the 1D and 2D models deliver comparable results regardless if the models are calibrating using data from gage hydrographs or inundation extent. Calibrating the 1D/2D model with only hydrographs did not suffice in giving good flood predictions and additional data on inundation extent is required for the calibration.

Water quality models require a good description of the water movement in order to accurately simulate the transport of substances in the river-floodplain system. Generally, 2D models require more computation and data resources than 1D models.

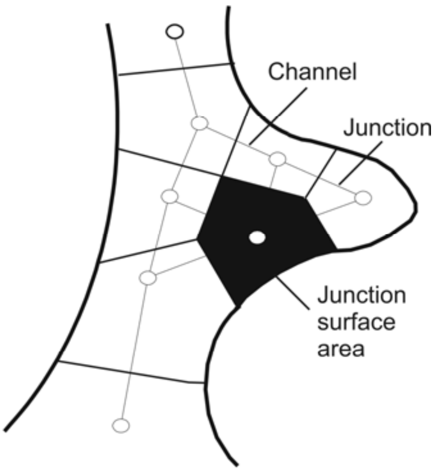

Figure 1. Discretisation in DYNHYD using channels and junctions (Ambrose et al., 1993).

In order to keep computational times at a minimum for Monte-Carlo uncertainty analyses and since less complex models do deliver reasonably accurate results, a quasi-2D approach using the hydrodynamic model DYNHYD coupled with the water quality model TOXI was chosen for the application presented here. Both models were developed by the U.S. EPA and belong to the WASP5 modelling package (Ambrose et al, 1993). DYNHYD is a 1D hydrodynamic model but allows its discretisation to be extended into the floodplain giving a 2D representation of the inundation area (see Figure 1). Due to the conditions of water continuity and stability requirements water levels in the discretisation elements cannot fall dry, hence an extension to the model needed to be carried out to capture the flooding and drying of floodplains during a flood simulation. A weir representation of the floodplain inflow and outflow with leakage through the weir prevents floodplain elements from becoming totally dry. The discretisation elements in TOXI correspond one-to-one to those in DYNHYD.

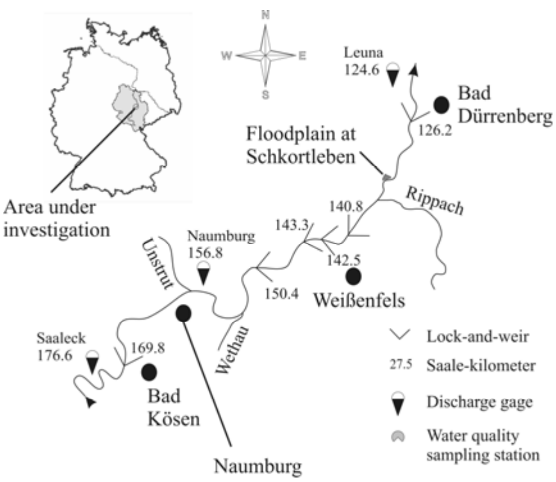

Figure 2. Middle reach of the river Saale.

2. STUDY SITE

The study site is a stretch 43.6 km along the middle reach of the Saale river, Germany between the lock-and-weir systems at Bad Kösen and Bad Dürrenberg (see Figure 2). The river is heavily modified and regulated and has many dykes for flood protection. The gages at Saaleck and Leuna respectively serve as the upper and lower boundaries of the model control volume. The gage at Naumburg is used for calibration and validation. Some discharge characteristics are given in Table 1 for all three gages. Dyke shifting has been proposed in some areas to increase water retentiveness of the river during floods (Uhlmann, 2001). One of such retention locations is at Schkortleben with a floodplain area of 171 150 km^2 and a retention volume of 120 000 m^3 at the mean annual maximum discharge.

Table 1. Discharge statistics for the three discharge gages: Saaleck, Naumburg and Leuna. *MQ* – mean discharge; *MHQ* - mean annual max. discharge; *HQ* – highest recorded discharge.

		Discharge (m^3/s)		
Gage	Series	MQ	MHQ	HQ (Date)
Saaleck	1965 - 1998	41.5	176	558 (14.04.94)
Naumburg	1934 - 2001	67.6	245	695 (15.04.94)
Leuna	1995 - 1998	71.5	270	377 (02.02.95)

3. HYDRODYNAMIC MODEL DYNHYD

This description of the model DYNHYD has been drawn from Lindenschmidt et al. (2005) but a short excerpt is warranted here. In DYNHYD a river is discretised using a “channel-junction” scheme (see Figure 1). The channel calculates the transport of water described by the equations of motion:

$$\frac{\partial U}{\partial t} = -U\frac{\partial U}{\partial x} + a_g + a_f$$

where a_f is the frictional acceleration, a_g is the gravitational acceleration along the longitudinal axis x, U is the mean velocity, $\partial U / \partial t$ is the local inertia term, or the velocity rate of change with respect to time t and $U\ \partial U / \partial x$ is the convective inertia term, or the rate of momentum change by mass transfer. The junctions calculate the storage of water described by the continuity equation:

$$\frac{\partial H}{\partial t} = \frac{1}{B} \cdot \frac{\partial Q}{\partial x}$$

where B is the channel width, H is the water surface elevation (head), $\partial H / \partial t$ is the rate of water surface elevation change with respect to time *t*, and $\partial Q / \partial x$ is the rate of water volume change with respect to distance *x*. The discharge *Q* is additionally related to the two parameters *n* and α by Manning's equation:

$$Q = \frac{r^{2/3} \cdot A}{n} \sqrt{\frac{\partial H}{\partial x}}$$

and discharge over a weir:

$$Q = \alpha \cdot b \cdot h^{1.5}$$

where *A* is the cross-sectional area of the water flow, *b* is the weir breadth, *h* is the depth between weir crest and upper water level and *r* is the hydraulic radius. The calculated flows *Q*, volumes *V* and water column depths *d* of each discretized unit were determined and, together with the mean velocities *U*, stored in a file for subsequent simulations with the model TOXI.

4. QUASI-2D ADAPTATION OF DYNHYD

In this algorithm the inlet and outlet discharge of the floodplain are controlled by a "virtual" weir. During low flow a minute amount of water is allowed to leak through the weir from the river into the floodplain to prevent the discretised elements depicting the floodplain from becoming dry and causing a numerical instability in the model simulations. During flooding the river water can overtop the weir crest into and out of the floodplain. The height of the weir crest corresponds to the height of the bottom surface of the floodplain. The discretisation of the additional channels and junctions with inlet and outlet weirs is shown in Figure 3.

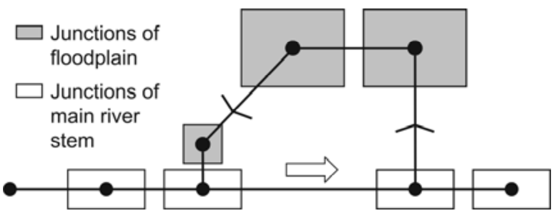

Figure 3. Floodplain discretisation.

Another study by von Saleski et al. (2004) presents the calibration and validation of DYNHYD for the lower Saale reach between km 90 and km 0 (confluence) using a three year time series of the mean daily discharges. Most of the simulation values agree well with gage reading within a ± 5 cm deviation range. The deviation increases with increased discharges which can reach up to a 15 cm difference for flood peaks. This is due to the fact that floodplains were not considered for the high flows, which was not a strict requirement since the Saale in this area is bounded by an extensive dyke system and the discharges were not so extreme as to cause overtopping or breaching of the dykes.

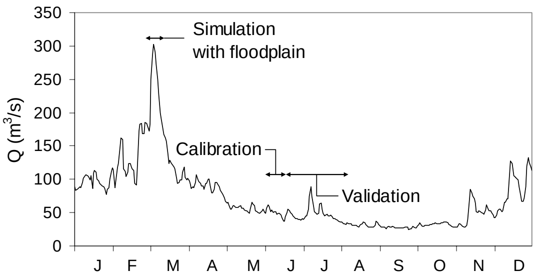

Figure 4. Mean daily discharges at Naumburg in 1999 (from Lindenschmidt and Rauberg, 2005).

Figure 4 shows the daily mean discharges at Naumburg for the year 1999. The transferred model required some additional calibration and validation to adapt the roughness coefficients in the model for this middle reach using water level readings at all the weirs. Figure 5 shows this exemplarily for the gage at Naumburg.

The flood event from 1. to 7. March 1999 was used for the development and testing of the DYNHYD extension algorithm. Unfortunately, gage data were not available at the floodplain area itself; hence only conclusions on the plausibility of the models applicability can be drawn.

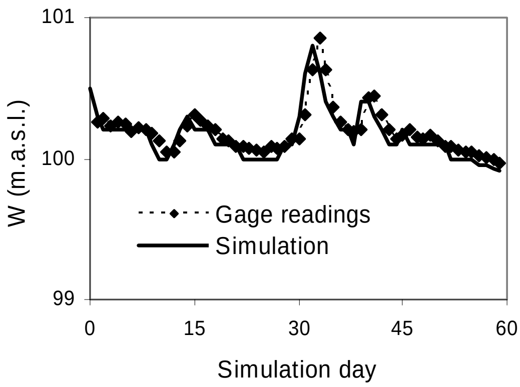

Figure 5. Validation time period (see Figure 4) (from Lindenschmidt and Rauberg, 2005).

5. WATER QUALITY MODEL TOXI

In TOXI, a mass balance equation is used accounting for all material entering and leaving the system by direct and diffuse loading, advective and dispersive transport and physical, chemical and biological transformations:

$$\frac{\partial C}{\partial t} = -\frac{\partial}{\partial x}(U_x C) - \frac{\partial}{\partial y}(U_y C) - \frac{\partial}{\partial z}(U_z C) + \frac{\partial}{\partial x}(E_x \frac{\partial C}{\partial x}) + \frac{\partial}{\partial y}(E_y \frac{\partial C}{\partial y}) + \frac{\partial}{\partial z}(E_z \frac{\partial C}{\partial z}) + S_B + S_K + S_L$$

where C is the substance concentration with $\partial C / \partial t$ representing its change with respect to time *t*, E_x , E_y and E_z are the longitudinal, lateral and vertical diffusion coefficients (only the first was implemented here), S_B, S_K and S_L are the rates for boundary loading, kinetic transformations and loading from point and non-point sources, respectively, and U_x , U_y and U_z are the longitudinal, lateral and vertical advective velocities (only the first is required for our one-dimensional case). The substances transported were any combinations of three dissolved and three particulate substances. The transformations include ionization, equilibrium sorption, volatilization, hydrolysis, photolysis, oxidation, biodegradation and an extra second-order reaction. The only sink considered was sedimentation of the particulate phases of the substances. Point and non-point loadings, resuspension of particulate matter from the bottom sediments and diffusion of dissolved substances from the sediment pore water comprise possible sources to the system.

Table 2. Distribution type and range of values for the TOXI parameters used for the Monte-Carlo Analysis.

Parameter	Distribution	Range	
		River	*Floodplain*
Sedimentation rate (1/d)	Uniform	0.01 - 0.1	0.4 - 1.0
Resuspension rate (1/d)	Uniform	10^{-5} - 10^{-4}	10^{-6} - 10^{-5}

A Monte-Carlo Analysis (MOCA) was carried out to investigate the largest source of uncertainty on the resulting substance concentrations in the floodplain and the adjacent portion of the main river channel. For the MOCA, TOXI was run 500 times for which a new set of values for the parameters and the boundary conditions were generated randomly from probability distributions each time. The parameters include the sedimentation and resuspension rates, which differed between the main channel and the floodplain. Table 2 gives a summary of the type and range of the probability distributions used from which parameter values were drawn for each MOCA run. Additionally, the suspended sediment and chloride concentrations of the two most upstream boundary conditions were regarded. An analysis of historical data shows that values of the suspended sediment concentrations are gamma distributed and those for the chloride concentrations are normally distributed. Only the samples from the winter months (November – April) for the years 1994 – 2002 were used to construct the distributions. The samples were generally taken every two weeks. Those of the summer months were omitted to exclude the affect of phytoplankton growth from the analysis. The gamma distribution was fitted to the suspended sediment data using a shape and a scaling factor as shown in Figure 6 for the boundary at Bad Kösen. The mean and standard deviations were used to fit the normal distributions to the chloride data. Table 3 gives the ranges in which 90% of the values lie.

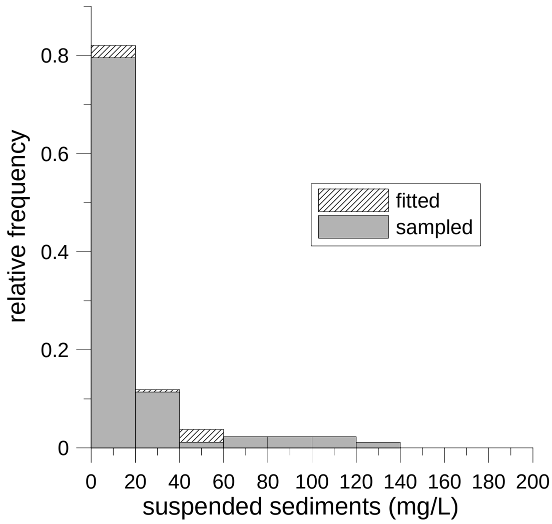

Figure 6. Histogram of sampled suspended sediment concentrations at Bad Kösen fitted with a gamma probability distribution.

Table 3. Distribution type and range which contains 90% of the substance concentration values at the upper most boundary conditions.

Substance	Distribution	Range for 90% of values	
		Bad Kösen	*Unstrut*
Suspended sediments (mg/L)	gamma	5 - 40	5 - 80
Chloride (mg/L)	normal	28 - 67	110 - 458

6. RESULTS AND DISCUSSION

Figure 7 shows the hydrographs in the floodplain and the adjacent main river channel using the quasi-2D approach. The bank overtops on the second simulation day and is completely empty on the seventh simulation day. During this time, water diversion reaches approximately 50 m^3/s from the main channel through the floodplain, which caps the discharge peak in the main channel by approximately 20%. The most sensitive value for flow diversion from the river channel into the floodplain was the height of the weir crest. The roughness coefficient had little effect on the hydrographs.

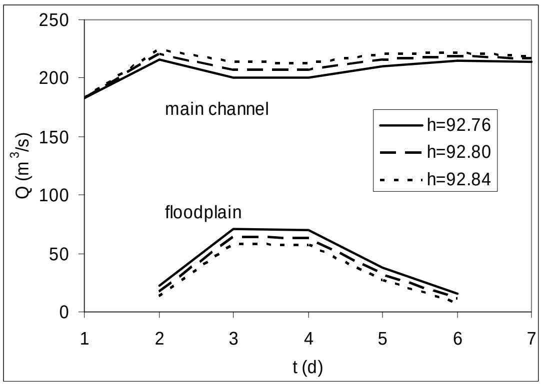

Figure 7. Hydrographs of the discharge through the floodplain and the adjacent lying river channel for different weir crest heights *h* (m.a.s.l.).

Figure 8 shows the resulting distributions of the substances in the floodplain for two MOCAs. In the first one only the suspended matter and chloride concentrations of the boundary conditions were varied and in the second MOCA only the parameters were varied. For this flood event the boundaries have a larger effect on the resulting distributions than does the uncertainty in the parameter values. The suspended sediment results are approximately normally distributed but skewed due to the gamma distributed boundary condition values. The chloride results are more evenly distributed but with two peaks due to the superposition of the two distributions of the upper boundaries.

Figure 9 shows the correlation between the concentrations in the floodplain and in the adjacent channel of the river flowing parallel to the floodplain. The chloride concentrations correlate almost one-to-one as is to be expected for a conservative material. The suspended sediment concentrations in the floodplain are larger due to the large sedimentation rates.

7. CONCLUSIONS AND OUTLOOK

A quasi-2D modelling approach in which the river channel and the floodplain can be represented in 2D using a 1D hydrodynamic model was successfully implemented to capture the flood dynamics in a river-floodplain system. The algorithm implements "virtual" weirs to divert water from the river through the floodplain.

The quasi-2D approach developed here offers a possibility to model a river-floodplain system for a flood event in 1D. The representation of the bank peripheral areas using weir systems is easy to implement, provides stable simulations and is computationally faster than other 2D approaches. The discretisation using weirs also allows a flexible means of extending the floodplain area and providing a mechanism to simulate other flood processes such as dyke breaching and flood water diversion using polders.

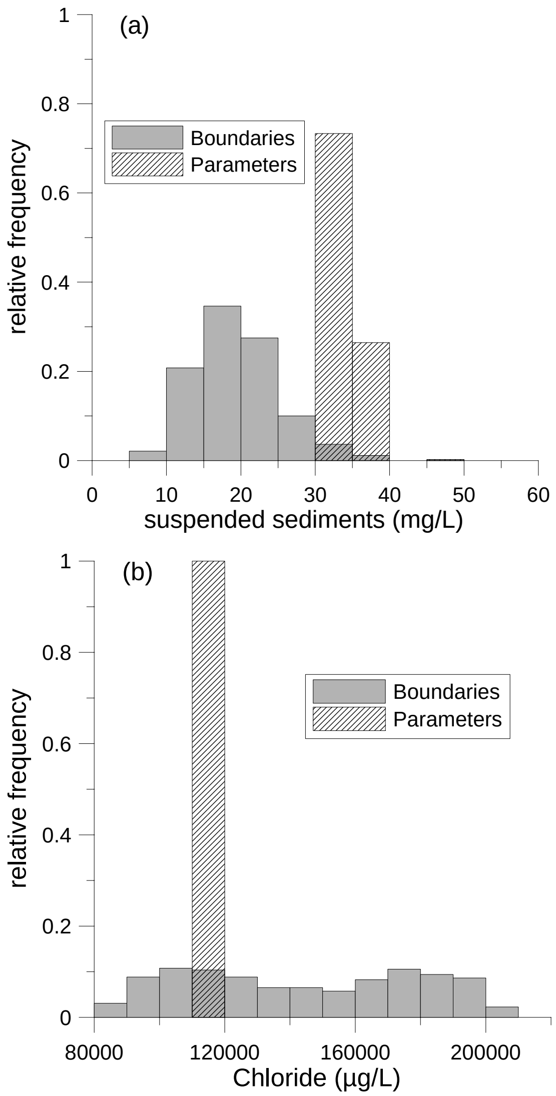

Figure 8. Resulting histograms of (a) suspended sediments and (b) chloride in the floodplain for Monte-Carlo simulations using varying TOXI parameters or substance boundary conditions.

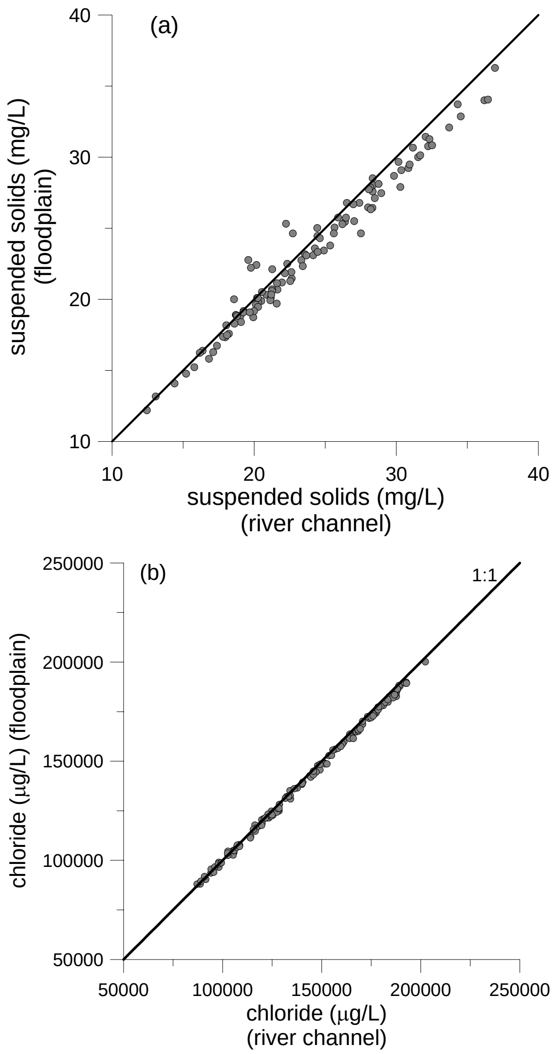

Figure 9. Correlation between substances in the floodplain and the adjacent river channel for (a) suspended sediments and (b) chloride.

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