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Quantifying structural uncertainty due to discretisation resolution and dimensionality in a hydrodynamic polder model

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ABSTRACT

In flood modelling, the structure of conceptual models may have a large influence on the simulation results. Hence, the focus of this paper is on the structural uncertainty in hydrodynamic flood modelling systems. Three different conceptual models with an increasing order of complexity of the spatial discretisation of the flow through a polder system were compared in order to investigate the effect of spatial resolution and dimensionality on flood modelling. The hydrodynamic 1D model DYNHYD was used as a basis for the simulations. The model was extended to incorporate a quasi-2D approach and a Monte Carlo analysis was used to show the effect of structural uncertainty on the resulting flow characteristics of the diverted flood waters. Two flood events of the River Elbe were used to calibrate and test the model. The results of the velocity fields indicate that the simplest 1D model revealed more predictive uncertainty than the other two more complex models. The differences in model structure does not cause large differences in the capping of the peak discharges, but may substantially influence the results of subsequent modelling of sediment and contaminant transport.

Key words | hydrodynamic modelling, model structure, polder system, structural uncertainty

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INTRODUCTION

Polders are efficient measures for reducing flood risk and capping the flood peak discharge. After the flood event along the River Elbe in 2002, which caused huge damage in hazardous areas of the Elbe catchment, it was recognised that flood and flood risk management schemes for the Elbe basin and other German river basins needed to be updated (Petrow *et al.* 2006). For this reason an impetus for large research activities in Germany was given. RIMAX, founded by the Germany Ministry of Education and Research, is a consortium of projects to develop methodologies for risk management of extreme flood events (http://www.rimax-hochwasser.de). Three of the about 40 projects incorporate polders as a measure for flood management strategies. Polder control, too, is an interest in the EU-financed project FLOODsite (http://www.floodsite.net) on integrated flood risk analysis and management methodologies. A research team of the Center for Disaster Management and Risk Reduction Technology (CEDIM), founded by the University of Karlsruhe (TH) and the Geoforschungszentrum Potsdam (GFZ), is developing a modelling system to quantify the risk of extreme flooding in large river basins (http://www.cedim.de/902.php). The project also considers polder control of peak discharge capping as a possible means of flood mitigation.

Computer models are important tools to test the design and efficacy of an existing or planned polder system for flood discharge capping and to predict the best control strategy for the flood hydrograph during operational flood management (Förster *et al.* 2005). Predicting the amount of solutes retained in such flood water retention systems is gaining in importance (Baborowski *et al.* 1999; Engelhardt *et al.* 1999). Quantifying the impact on the environment is

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also an important requirement for flood management plans in the proposed European Union Floods Directive (Commission of the European Communities 2006).

An inherent feature of computer models, as is the case for any modelling abstraction, is that they do not completely depict all the processes and conditions of the physical system. Hence, error in the simulation outcome occurs. An additional feature is that certain processes or conditions in the modelling formulation react more sensitively to model outcome than others. This may emphasize or dampen certain behaviours that may or may not occur in the actual natural state. Both error and sensitivity contribute to the uncertainty in the model (Snowling & Kramer 2001).

Uncertainty must be considered when dealing with models with errors in parameter estimations, sampled data and model structure. There are three main sources of uncertainty in models:

- Parameter uncertainty is the uncertainty in the values and usable range of values for the settings of uncertain model parameters. It is used to gauge the outcome of the model.
- Input data uncertainty is the uncertainty in the data used as initial and boundary conditions for the model, and/or the model's external forcing.
- Structural uncertainty is the uncertainty due to the model structure which involves the equations and algorithms used for the model simulations.

In this paper the focus is on the last source of uncertainty–the structural uncertainty of modelling systems. Structural uncertainty is currently more abstract and harder to quantify than the other uncertainty sources; hence only a few examples currently exist in the literature. Radwan *et al.* (2004) points out the importance and research need for studying uncertainty due to model structure in river water quality modelling. Reichert & Omlin (1997) show that ignoring the uncertainty in model structures in classical system identifications leads to underestimations of the uncertainty in model prognosis. Engeland *et al.* (2005) calculated total and parameter uncertainty in a hydrological model and observed that the uncertainties in the simulated streamflow due to parameter uncertainty are less important than uncertainties occurring from other sources. An indication was made to model structure as one of the main sources of uncertainty but its effect was not quantified.

A good example of the importance of the structure of conceptual models is given by Refsgaard *et al.* (2006). The county of Copenhagen asked five different consultants to conduct studies on an aquifer's vulnerability towards pollution. The five consultants had a different idea about the causes of groundwater pollution and used models with different processes, so they all had different results for the part of the particular area that is most vulnerable to pollution. Butts *et al.* (2004) give another example in which ten model structures using different processes and spatial distributions were compared and tested on calibration and validation periods. All the models produced different simulation results and performance statistics. These two examples show how much influence model structure has on the predictive outcome. Another approach to characterise structural uncertainty suggested by Wagener *et al.* (2003) and Gupta *et al.* (2005) is to track temporal parameter variations. In general, parameters are constants applied throughout the simulation and, if they need to be varied substantially throughout the simulation, the structure of the process description may not be adequate to fully capture the flow behaviour in the system.

In this study, three different conceptual models of the flow through a polder system along the River Elbe are compared in order to investigate the effect of model structure on simulation results. All of these models contain the same river model, which has the same temporal resolution, initial and boundary conditions. The models are ordered in increasing order of complexity of the spatial discretisation in polders:

- PS_1D: in which each polder is represented by a simple discrete element arranged in series.
- PS_1Dplus: the discretisation is still in series but each polder is represented by several smaller discretisation elements.
- PS_2D: the discretisation is spatially distributed in both the lateral and longitudinal directions within the polders.

Hence, this study is focused on the dimensionality and spatial representation constituting the model structure, and less on the temporal resolution, initial and boundary conditions or process descriptions.

METHODS

Hydrodynamic model DYNHYD

The hydrodynamic model DYNHYD, which is part of the WASP5 (Water Quality Analysis Simulation Program) package developed by the US Environmental Protection Agency (Ambrose *et al.* 1993), was implemented to simulate peak discharge capping of floods using polder systems. It is a 1D model but can be discretised in both the lateral and longitudinal dimensions to allow 2D representations of flow. The following description has been drawn from Lindenschmidt (2008).

DYNHYD solves the 1D equation of continuity and momentum for a branching link–node computational network. Hence, a water body is discretised using a 'channel–junction' scheme (see Figure 1). In the model the transport of water is computed according to 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 in the channel, $\partial U/\partial t$ 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. At the junctions the storage of water is computed through the continuity equation

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

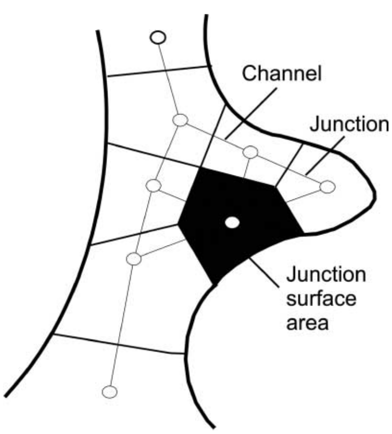

Figure 1 | 1D hydrodynamic channel–junction (link–node) network allowing a 2D spatial representation of overbank inundated areas (source: Ambrose *et al.* 1993).

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 river morphology and bottom roughness using Manning's equation:

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

where A is the cross-sectional area of the water flow, n is the roughness coefficient of the river bed, r_H is the hydraulic radius and $\partial H/\partial x$ is the slope of the river bed in the longitudinal direction x. Discharge over a weir is calculated by the weir equation:

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

where α is the weir coefficient, b is the weir breadth and h is the depth between the upstream water level and the weir crest. Backwater effects are computed by throttling the weir discharge when the water level on the flow-receiving side of the weir rises above the weir crest (Chow 1973).

Adaptations of DYNYHD for modelling flow through polders

Even though the equations of motion and continuity are computed in the model using a 1D framework, the channel–junction methodology permits the channels to be linked to several junctions, enabling a 2D spatial configuration of the discretisation network. An extension to the model was implemented to capture the flooding and emptying of the polder during a flood simulation. In this algorithm the inlet and outlet discharges of a polder are controlled by a 'virtual' weir. As a consequence of the condition of water stability and continuity requirements, water levels in the discretisation elements cannot fall dry. During low flow, when the polder system is not in use, a small amount of water is allowed to leak through the weir from the river into the polder. It can prevent the discretised elements representing the polder from becoming dry. This volume is very small compared to the water volume in the polder, so that the contributions to total error in the simulations are negligible. The opening and closing of the polder gates is simulated by lowering and raising the weir crest, respectively. The opening can be done gradually to allow better control of polder filling and emptying, which leads to a more effective capping of the peak discharge. The weir algorithm has already been integrated effectively for dyke breach areas (see Huang *et al.* 2007*b*) and floodplains (see Lindenschmidt *et al.* 2006).

STUDY SITE AND MODEL SET-UP

The location of this study is at the middle course of the River Elbe in Germany, between the gauges at Torgau (Elbe 154.2 km) and Wittenberg (Elbe 214.1 km). This section of the River Elbe has been heavily modified with dykes on both sides for almost the entire flow distance.

Polder systems

The construction of polders along this section has been suggested by IWK (2004). Two of them, the south polder (P1) and the north polder (P3), are the targets of this paper (see Figure 2). Characteristics of these two polders are listed in Table 1. Polders P1 and P3 form a polder system, which has a maximum capacity of 3.3 m filling depth, and are mutually connected by a gate between them. For the modelling exercise only the section between the points Elbe 176 km and Elbe 192 km, as upper and lower boundaries in the modelling, was considered.

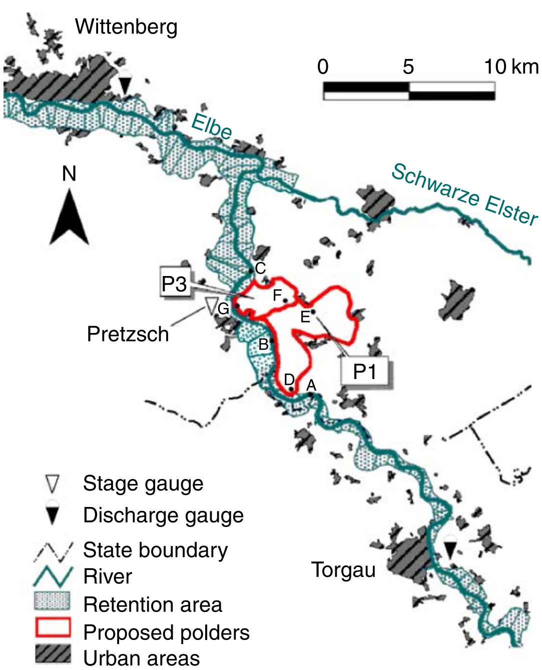

Figure 2 | Researched river section and polders along the middle reach of the River Elbe in Germany between Torgau and Wittenberg (source: IWK 2004). Points A–G are the researched locations in the river and polders.

Input data

The model of the river section was formed on the basis of cross-sectional profiles available every 500 m along the river. From these profiles initial hydraulic radii and segment water volumes were deduced. The time window of the modelled flood event is 13–22 August, 2002. Characteristics of the discharges logged at the gauges at Torgau and Wittenberg are provided in Table 2. The discharge recordings from the gauge at Torgau were used for the boundary conditions for the hydrodynamic model. The discharges do not differ significantly at the time that the flood wave reaches the polder area. No major tributaries are flowing into the studied section of the River Elbe. The simulating time step is 10 s.

Discretisation

The discretisations of the channels and junctions with inlet and outlet weirs for the three models of polders P1 and P3 are shown in Figure 3. The least complex model is named PS_1D, which is a 1D model with only one channel and two junctions (one large plus one small junction) for each of the polders P1 and P3. The model PS_1Dplus is a 1D model, too, but polder P1 consists of seven junctions and polder P3 of three junctions in series. The large polder junctions of PS_1D are divided into several smaller junctions with the same volume. These small volumes together are equal to the volumes of the large junction in PS_1D. In the 2D model PS_2D the polders are constructed of several junctions connected with channels in a 2D network, which is differentiated in the lateral and longitudinal directions.

Table 1 | Characteristics of the studied polders; source: IWK (2004)

Polder	Surface area (km^2)	Volume (10^6 m^3)	Head (m.a.s.l.)	Depth (m)
P1	24.5	85	77.5	3.3
P3	8.2	20	75.3	2.3

Table 2 | Discharge statistics for the gauges at Torgau and Lutherstadt Wittenberg (MQ—mean discharge, MHQ—mean maximum annual flood, HQ—highest recorded flood event). Source: Gewässerkündliches Jahrbuch, Elbegebiet Teil 1 (2003)

			Discharge (m^3/s)		
Gauge	**Elbe-km**	**Series**	**MQ**	**MHQ**	**HQ (date)**
Torgau	154.2	1936–2003	344	1,420	4,420 (18.08.2002)
L. Wittenberg	214.1	1961–2003	369	1,420	4,120 (18.08.2002)

The structure of the polders P1 and P3 is the only difference in these three discretisations. The main channel and the three weirs are unaltered.

Polder control

In these discretisations (Figure 3) three weirs represent the inlet and outlet water flow in the polder system. In Figure 4 the optimum control strategy for polder flooding and emptying to cap the peak discharge is shown. At the beginning of the simulation all gates are closed. During day 4 the gate G1 is opened first to start capping of the peak discharge in the river. Shortly afterwards, the gate at location G2, which connects polders P1 and P3, is opened at day 5. It is also the first gate which closes again during day 6, because the volume capacity of P3 is smaller and fills quicker than P1. During day 7 the inlet gate G1 of polder P1 is closed. On day 9 emptying of polders P1 and P3 starts by opening gates G2 and G3.

Monte Carlo analysis

To investigate the largest source of uncertainty in the resulting water flow in the polders and the river channel a Monte Carlo analysis (MOCA) was performed. DYNHYD was embedded in the simulation platform High Level Architecture (HLA) (Kuhl *et al.* 1999) to aid the MOCA computations. For the MOCA, the modeling system was run 1,000 times using different sets of values for the parameters, which were generated randomly from normal probability distributions. This was performed for all three models with

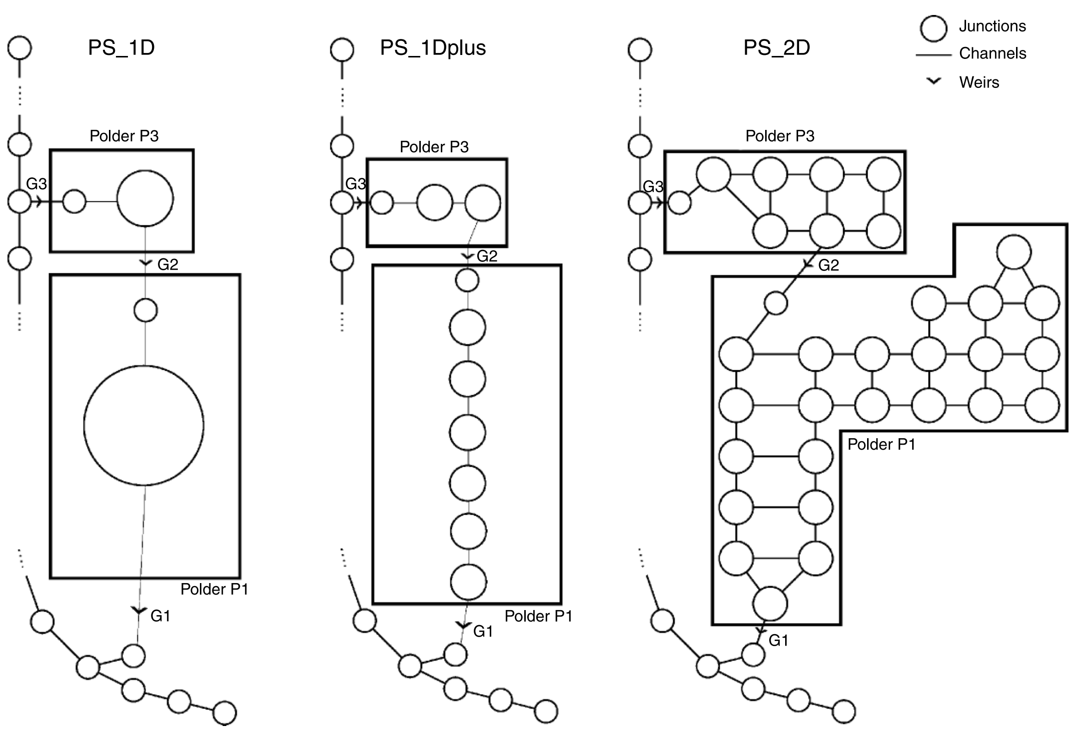

Figure 3 | Discretisations by junctions and channels for the three conceptual models of the studied area and polders.

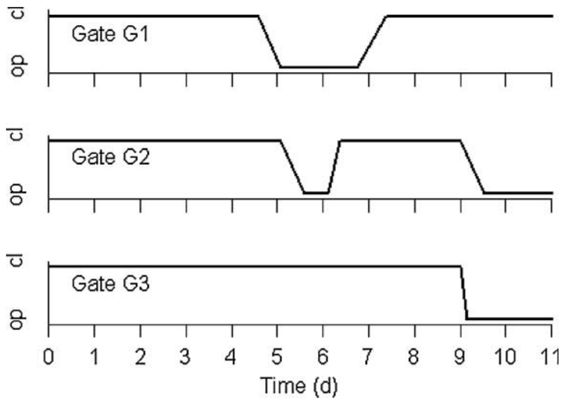

Figure 4 | Control strategy for polder flooding and emptying to cap the peak discharge in the river, optimised for the August 2002 flood event.

different parameter settings each time. The parameters in a MOCA include:

- the Weir coefficient α from the weir discharge equation. A factor percentage deviations in α may also represent a factor percentage deviation in weir breadth b, because the α and b are multiplicative components in the weir equation. Only one of these parameters can be used in a simulation run due to the compensatory effect of α and b on output variables (e.g. a 10% increase in α can be compensated by a 10% decrease in b).
- Roughness coefficient n of the channel bed from Manning's equation.
- Percentage deviations in the discharge boundary condition q at the gauge at Torgau.

In the settings used the parameters α (reference value 1.3) and n (reference value 0.04) were increased or decreased with a $\pm$ 10% deviation range. The values were selected from a normal distribution within the ranges 1.17–1.43 for α and 0.036–0.044 for n (the variation of roughness coefficients in the hinterland was calculated for different land-use types; see Vorogushyn *et al.* 2007). Also the variation in the boundary conditions q was from a normal distribution with the mean value of 0.0, a standard deviation of 0.05 and a range from -0.1 to $+0.1$ (typical error range for discharge measurements; see Herschy 1995), which is adequate for the distribution having about 90% of the values lying within the range.

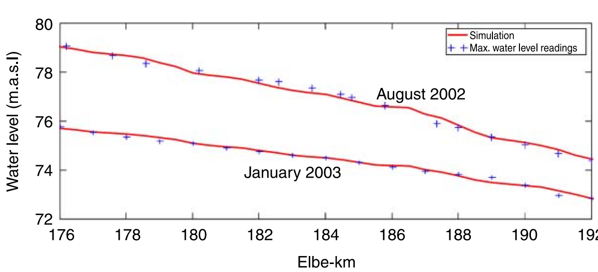

Figure 5 | Longitudinal profiles of the simulated and recorded values of the highest water levels attained along Elbe 176–192 km during the August 2002 flood event (validation) and the January 2003 flood event (calibration).

RESULTS AND DISCUSSION

River model calibration

As a first step, the river model without water diversion to polders was calibrated on the basis of the January 2003 flood event, in order to obtain an initialisation of the parameter setting for more extreme flood events. A longitudinal profile of maximum water levels measured during this flood event was used for the calibration of the hydrodynamic model. Figure 5 compares the measured and the simulated values of this flood event for the entire model section and shows a very good fit of the predictions of the calibrated model and measurements. The best fit of the simulations to the data is provided using a roughness coefficient (Manning's coefficient) between 0.030 to $0.035\,\mathrm{s/m^2}$. The water levels measured at the gauge at

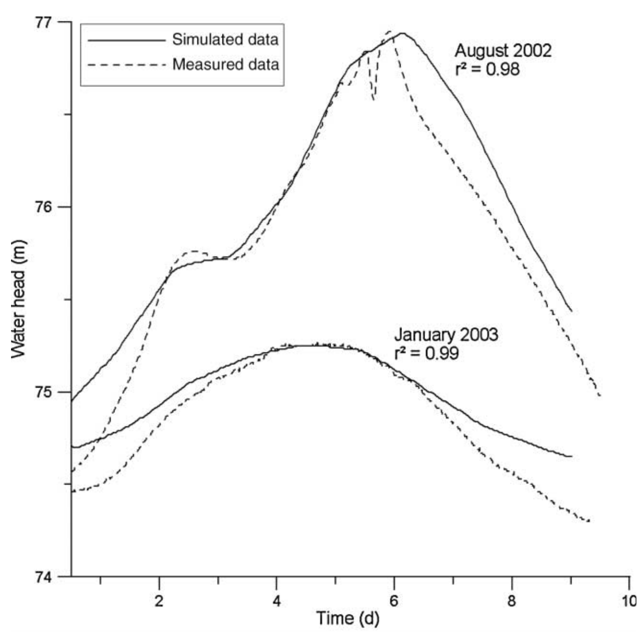

Figure 6 | Simulated and gage recordings of the water level at Pretzsch during the August 2002 flood event (validation) and the January 2003 flood event (calibration).

Pretzsch provided temporal data for a comparison of measurements and simulation results, as shown in Figure 6.

River model testing

The data from the August 2002 flood event was used to test the calibrated model. This is the most severe event for which data was available. We refer to model testing instead of validation because a true model validation of this hydrodynamic model is not possible, and 'fine-tuning' of the roughness coefficient is required for the most accurate simulation of each flood. This is due to the fact that different flood characteristics, such as water depth and inundation extent, have different mean bottom roughness values within the river–floodplain system. Hence, we refer to model testing, in which the calibrated model is transferred to the August 2002 situation, and the roughness coefficient is 'fine-tuned' to depict the discharge behaviour of the flood.

In Figure 5 the simulated water levels match the maximum measured water levels very well, using a roughness coefficient between 0.038–0.040 s/m^2. After the second day the simulated hydrographs agree well with the recordings of the gauge at Pretzsch (see Figure 6). There is a 30–40 cm overestimation for the first two days at the beginning of the curve. The smaller the water discharge is, the greater the error becomes, which has been observed in

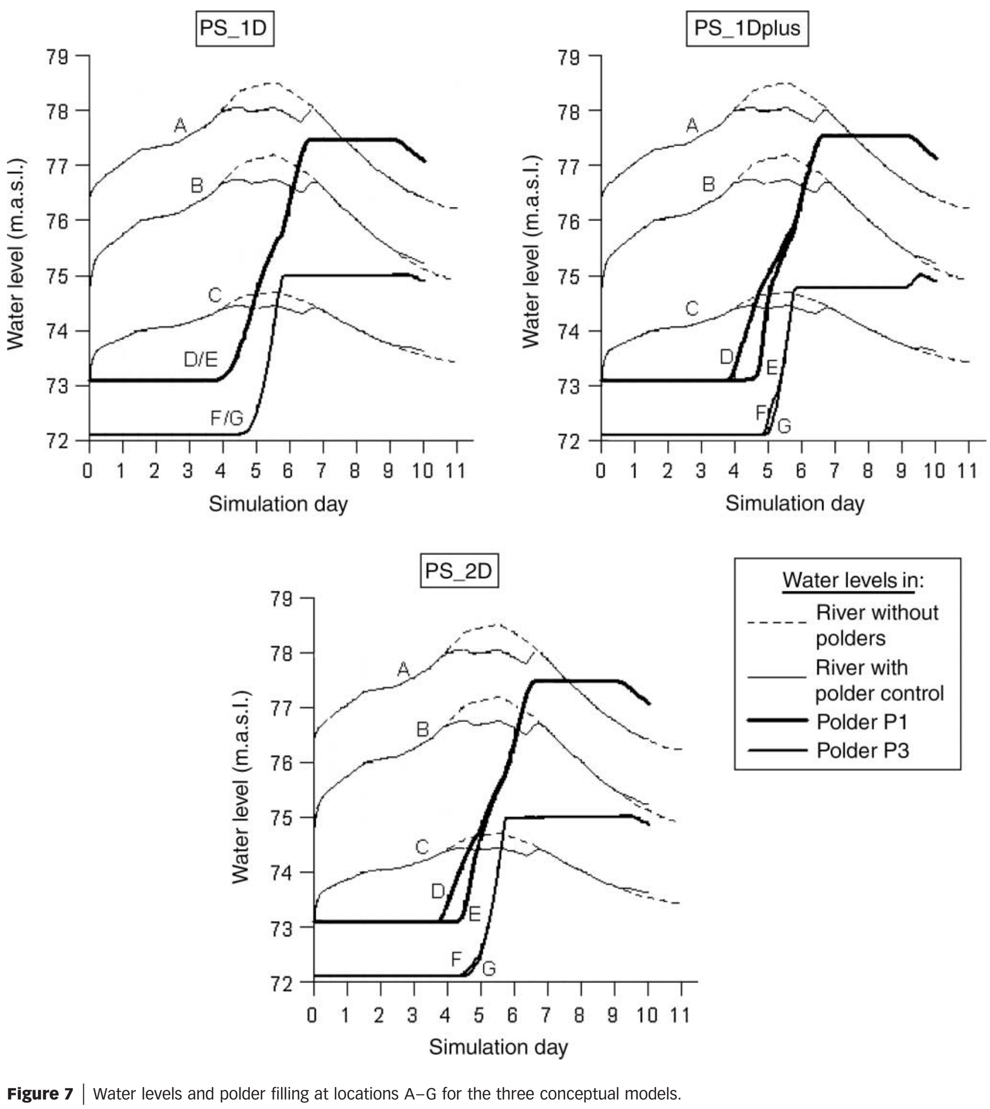

Figure 7 | Water levels and polder filling at locations A–G for the three conceptual models.

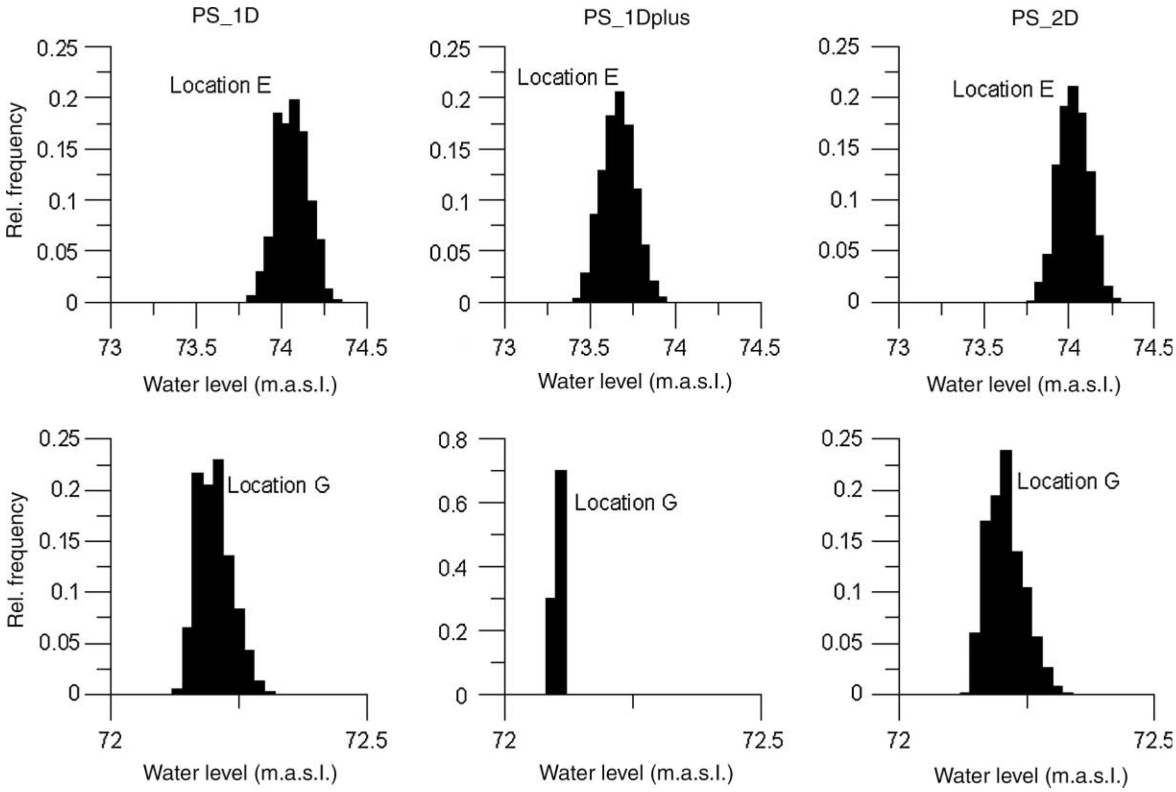

Figure 8 | Water level histograms of gates G2 and G3 for the three conceptual models at interval 4.5–5.

other modelling studies of the same river section (see Huang *et al.* 2007*a*; Vorogushyn *et al.* 2007). This is probably due to the model being calibrated to fit the peak discharge. Varying the roughness coefficients during the flood to reflect the dependence of bottom roughness with flood water depth and extent may alleviate this discrepancy and is a subject of future work.

Peak discharge capping by polders and Monte Carlo analysis

Under the same weir control strategy and reference parameter settings for polders, the capping effects during the 2002 flood were then simulated for different spatial discretisations of the polders. All the conceptual models show a good effectiveness of polders in capping the peak discharges (see Figure 7), and the water level behaviours are also well simulated in polders. The Monte Carlo analysis provides the distributions of water levels and channel velocities in the polders for the three conceptual models (see Figures 8 and 9). The variation of channel velocity versus time steps is also shown in Figure 10. Furthermore, the coefficient of variation *Cv* is calculated to measure the predictive uncertainty. It is defined as the ratio of the standard deviation σ to the average μ:

$$C_v = \frac{\sigma}{\mu}$$

In Table 3 the coefficient of variation of the channel velocity of different locations in the system is provided. The comparisons of the different model structures, which are based on these results, are carried out considering both discretisation resolution and dimentionality aspects.

Effect of discretisation resolution

For the aspect of the spatial discretisation resolution the results of the MOCAs of the models PS_1D and PS_1Dplus were compared. There is only a slight variation in heads, flows and velocities in the main channel at locations A, B and C (see Figure 7). The polder filling of PS_1Dplus shows a different

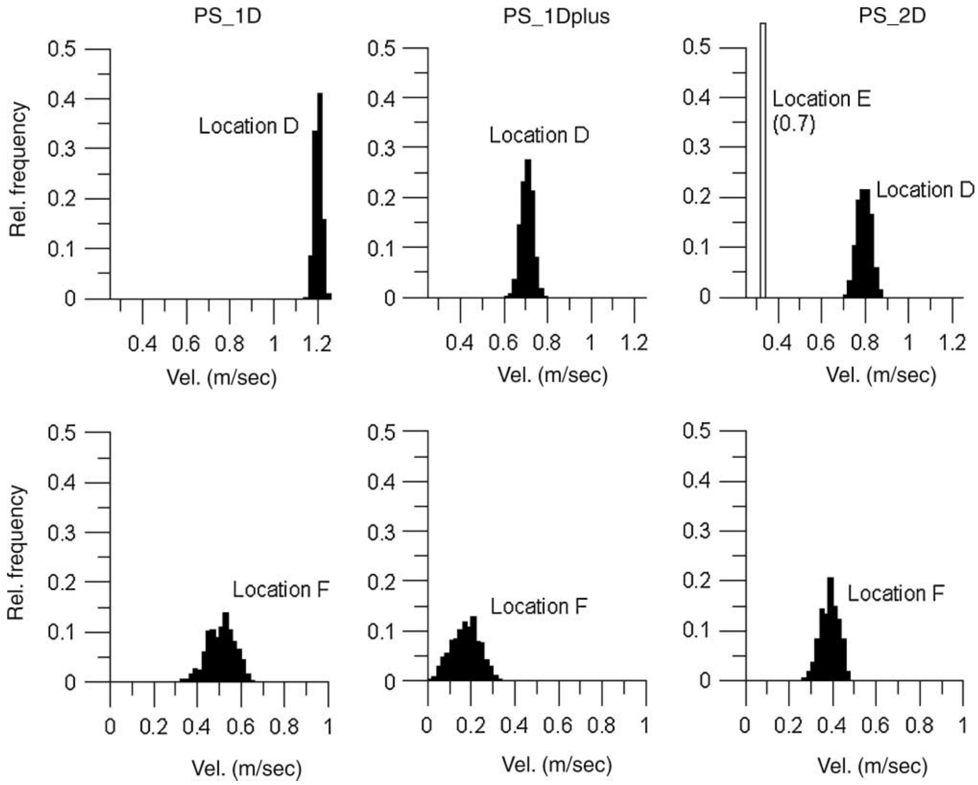

Figure 9 | Channel velocity histograms of gates G1 and G2 for the three conceptual models at interval 4.5–5.

water head than in PS_1D or PS_2D, and the water level in P3 is some mm higher (see also Figure 8). The channel flow does not show a large variation, but the channel velocities vary between the two less complex models. The mean of the velocity distribution for polder P1 of PS_1D in interval 4.5 – 5 is approximately 70% higher than for PS_1Dplus. For polder P3 there is even a 150% difference in the mean of the velocity distributions attained from the two models. The lower discretised model PS_1D has much higher velocities (see Figure 9). This is an important consideration if subsequent sediment and pollutant transport is to be modelled in such a system.

Figure 10 shows the channel velocity versus time steps (from day 4 to 6.5) for 50% and 90% bounds of the most frequent values at the inlet weirs of polders P1 and P3. The largest variation in velocity is at the onset of polder filling. The variation is greatest for PS_1D for both polders. The initial velocity values are also the largest for the least complex model. Once the polders are full, the variations decrease and there is little difference in the velocity values between the models.

This large variation in velocity is due to the intensity of the roughness coefficient affecting the flow in the system. In PS_1Dplus the roughness coefficient has a higher effect, since the polders consist of more junctions and channels. Hence, the greater number of channels results in more friction in the system. Another reason is that the polder junctions in PS_1Dplus, which are connected in series, may act as a buffer and cause an impoundment of the water, so that the water cannot flow unaffected through the polders.

Effect of dimensionality

For the aspect of dimensionality the results of the MOCAs of models PS_1D and PS_2D were compared. The heads, flows and velocities in the main channel at locations A, B and C are similar (see Figure 7). For PS_2D the time for polder filling can be determined by the time lag between an upstream and a downstream point in the polder, here taken as locations D and E in polder P1, and locations F and G in polder P3. This differentiation is not possible for the 1D structure of PS_1D; hence only one filling curve for each polder is displayed. The

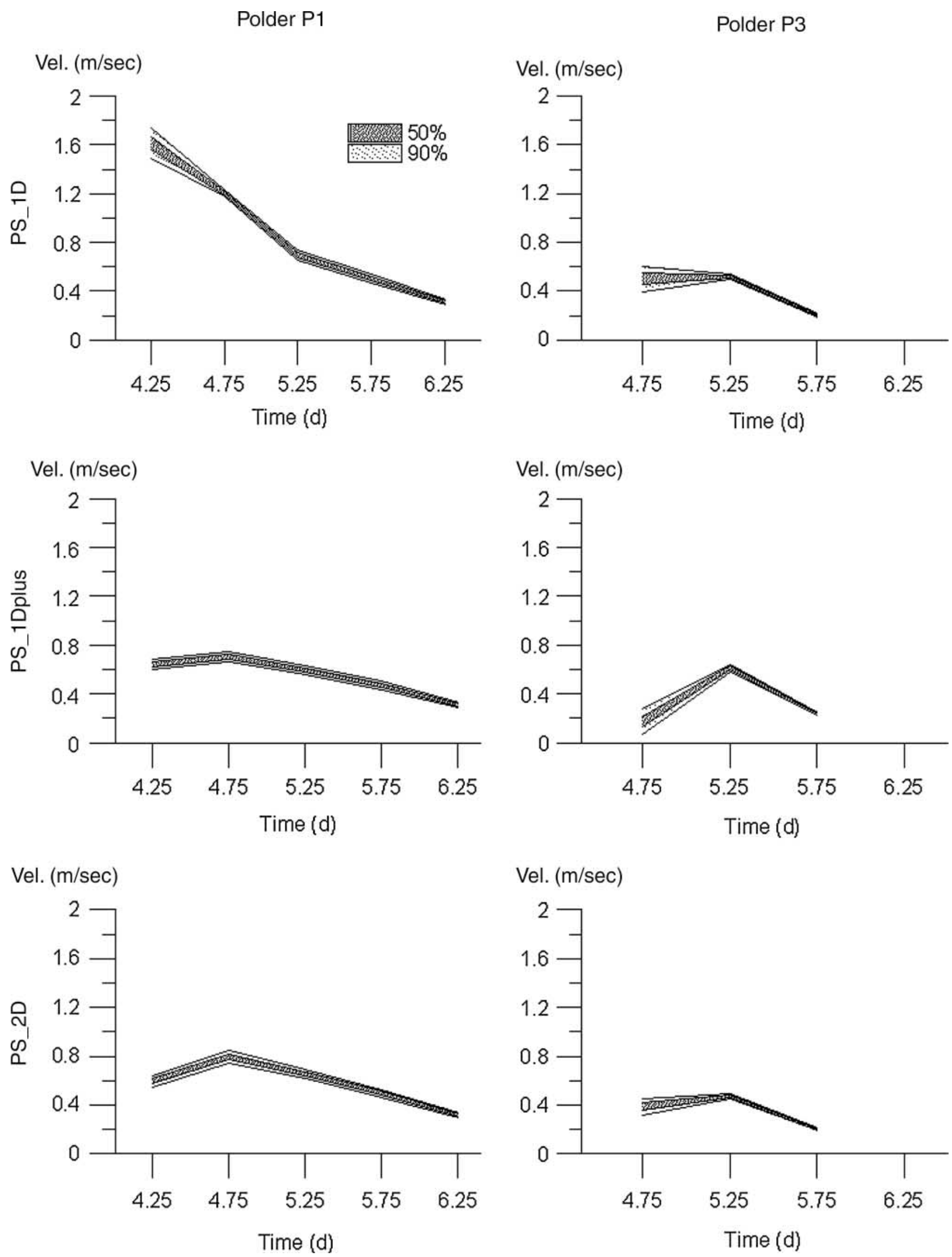

Figure 10 | Channel velocity versus time steps for 50% and 95% of the most frequent values at the inlet weirs of polders P1 and P3.

water levels simulated by PS_1D during filling of the two polders represent a mean of the heads simulated by PS_2D. For the remaining time frame the heads of the two simulations coincide (see also the histograms in Figure 8).

The comparison of the channel flows shows that they are nearly identical in both models. Only the channel velocity shows a mismatch, which is, however, not so large as the difference for PS_1D and PS_1Dplus. In both polders of the 1D model PS_1D the velocity is higher than in PS_2D (50% for polder P1 and 25% for polder P3) and the distribution of the values varies (see Figure 9).

In Figure 10 the difference in channel velocity in these two models is more pronounced. In polder P1 of PS_2D the velocity increases first till a maximum is obtained at the

Table 3 | Coefficient of variation of the channel velocity of different locations in the system. G1, G2 and G3 are the gates shown in Figure 3

Location	PS_1D	PS_1Dplus	PS_2D
P1 inlet (G1)	0.040	0.038	0.038
P3 inlet (G2)	0.028	0.031	0.022
P3 outlet (G3)	0.124	0.703	0.127
River upstream	0.040	0.037	0.040
River downstream	0.040	0.037	0.040

second time step 4.75, and then the velocity decreases again. In polder P1 of PS_1D the highest values are already reached at the first time step 4.25 and the values decrease onwards. From time step 5.25 the values in both models behave nearly identically again.

The difference in velocity is, as in the comparison of PS_1D and PS_1Dplus too, due to the intensity of the

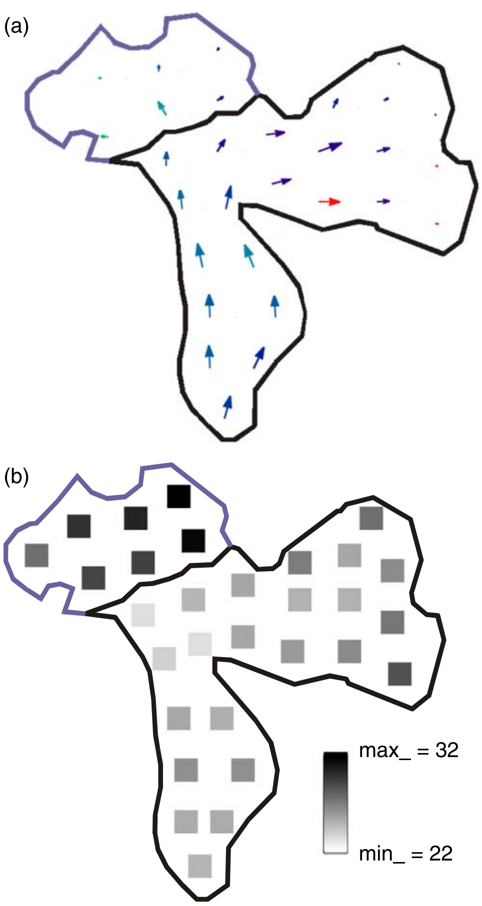

Figure 11 | (a) Vectors of flow velocities during filling of the polder system on day 4.5; the longest vector corresponds to a magnitude ca. 1.2 m/s. (b) Reduction in particulate zinc concentrations (μg/L) during flood water retention on day 8.5.

roughness coefficient affecting the system. It again has the same influence with a larger number of channels resulting in more friction. Another reason is that the flow in PS_1D is more concentrated while in PS_2D it is more spatially distributed. Hence, the water flows quicker in PS_1D and more directly from one polder to the next.

Förster *et al.* (2006) also made a comparison between a 1D and a full 2D modelling exercise of the same polder system and found that the computations of the capping effect of the peak discharge did not differ between the two model structures. The model structure may, however, have an impact on the predictive uncertainty of sediment transport and deposition within the polder system.

Figure 11(a) shows the 2D spatial distribution of the flow field with the largest velocity magnitude corresponding to 1.2 m/s. The flow field has a significant effect on a subsequent simulation of substance transport, as can been seen in Figure 11(b) for the heavy metal zinc, which is a potential contaminant of inundated land surfaces in this catchment area (Lindenschmidt *et al.* 2008).

CONCLUSIONS

- The structure of a hydrodynamic model system affects the results of a simulation. A simple 1D model shows significant variations in velocity in comparison to a complex 2D model. A 1D model with junctions in series shows additionally variations in channel flows and water levels. These structural differences may have an influence on the modelling of sediment and contaminant fate and transport, which is a subject for future work.
- Discretisation resolution has a larger influence on predictive uncertainty than dimensionality. Differences in uncertainties due to structural differences between the simplest 1D model and the 2D model are minimal.
- For investigating the degree of peak discharge capping or polder filling times the simplest model representation of the polder is adequate. For subsequent sediment transport simulations, a more complex model is recommended due to the spatial differences in flow velocities.
- Model structure is an important source of uncertainty and should be taken into consideration when modelling hydrodynamic systems. The modelling example presented here shows that structural uncertainty can be of the same

order of magnitude or more as parameter uncertainty. However, structural uncertainty is difficult to quantify and can add considerable additional effort to the modelling exercise. We have provided one approach in which discretisation schemes of varying dimensionality and resolution are used, which may be simple enough to be adapted in other hydrodynamic modelling applications.

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