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# A conceptual river model to support real-time flood control (Demer River, Belgium)

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ABSTRACT: Model-supported real-time flood control requires the development of effective and efficient hydraulic models. Because of the large number of iterations required in optimization procedures, the hydraulic model needs to be fast. But at the same time, it should produce results with high accuracy. With view to achieving this target, a simplified but accurate conceptual model was established in this research. An identification and calibration procedure has been developed such that the conceptual model can be built and calibrated to a more detailed full hydrodynamic model. While doing so, also the robustness and stability of the conceptual model has been considered.The procedure has been tested for real-time flood control applications along the river Demer basin in Belgium. A detailed full hydrodynamic model, implemented in the InfoWorks-RS (IWRS) software was available for this case. Conceptual model building and calibration has been done based on two severe historical flood events in the years 1998 and 2002. Model testing was conducted based on the data for 2 other events.The model simplification is reached by lumping the processes in space. Water levels and discharges are simulated, not every 50 meters as the full hydrodynamic model does, but only at the relevant locations. These are the locations up- and downstream of the hydraulic regulation structures, to be considered by the real-time controller, as well as the locations along the river network where potential flooding is induced. Advanced conceptual modelling procedures have been considered based on separation of static and dynamic storage along river reaches.

*Keywords: Flood Control, Conceptual River Model*

## 1 INTRODUCTION

Flood is one of the natural disasters. It frequently causes costly economic losses and numbers of lives come to harm. Due to these severe injuries, how to perform an effective flood control is always a huge challenge for governments and water authorities.

In this study we applied a full hydrodynamic model "InfoWorks RS" to do detailed simulations and analyses and in support of the calibration of a simplified conceptual model. The conceptual model equations (based on a reservoir type approach) were identified and calibrated based on the results of this detailed model.

Concerning the study area, in the Flanders region of Belgium, there are eleven river basins (Figure 1). The Demer basin is one of these basins, located in the eastern part of Belgium, and has an area of 2,267 km$^2$. The river Demer has a total length of 85 km; the most important towns along the river (starting from the source) are Bilzen, Hasselt, Diest and Aarschot. The topography of the Demer basin is presented in Figure 2.

The river Demer has been a definite case for discussing flood problems. In the past, this river could not prevent flooding from occurring during several periods of heavy rainfall events. Table 1 provides a damage report for five major historical flood events in the Demer basin. From the table it can be realized that flooding brought about huge economical losses in the Demer basin, especially in September 1998. In order to alleviate flood disasters the local water administration, the Flemish Environment Agency (Vlaamse Milieumaatschappij, VMM), installed hydraulic facilities (e.g. movable gated weirs) in this river system. Besides, several flood-control reservoirs provide storage for the excess volume of water. Two of the largest ones are called Schulensmeer and Webbekom (Figure 3). Structures control the flows towards or out of the available reservoirs; they are regulated by the operating rules formulated by the VMM water authority. The operations of these facilities are based on monitored water levels at critical locations along the main rivers; they are influencing the magnitude of stream discharge released from individual gates.

The reservoirs start to be filled when one of monitored water levels reaches the “warning level.” The reservoir filling continues till a first storage level is reached. Subsequently, the river level(s) increase till the “alarm level”. When the alarm level is reached in any of the critical locations, the reservoir filling will increase until a second storage level. Through the implementation of the two reservoirs and hydraulic structures, the water authority has dominated or reduced the majority of flooding caused by non-extremely heavy rainfall events.

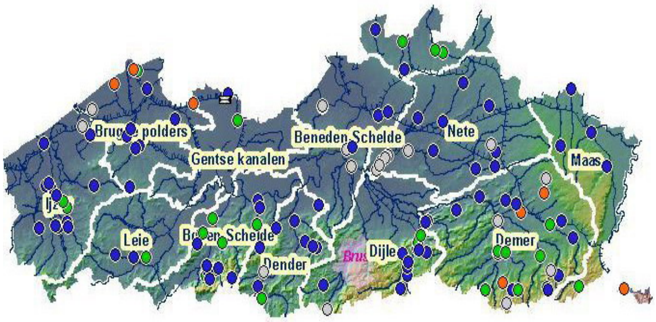

Figure 1. Eleven river basins in the Flanders area of Belgium [HYDRONET, 2007]

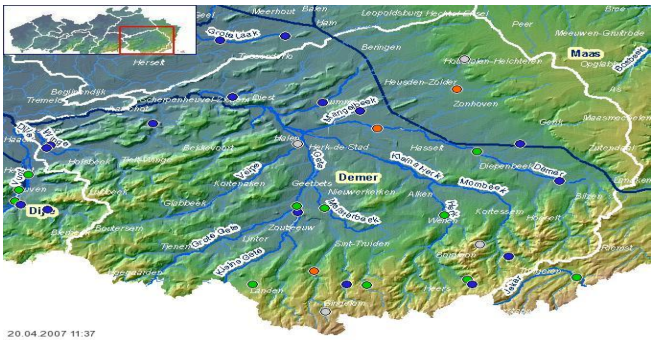

Figure 2. The basin of the river Demer [HYDRONET, 2007]

Table 1. Flood area and damage costs for five major historical flood events in the Demer Basin [HIC, 2003]

| Period | Estimated flood area (km$^2$) | Cost in Euros |
|---|---|---|
| Dec 1993– Jan 1994 | 23.5 | 47,000 |
| Jan 1995 – Feb 1995 | 22.9 | 11,000 |
| Sep 1998 | 32.6 | 16,169,000 |
| Feb 2002 | 15.7 | Still unknown |
| Dec 2002 – Jan 2003 | 18.0 | Still unknown |

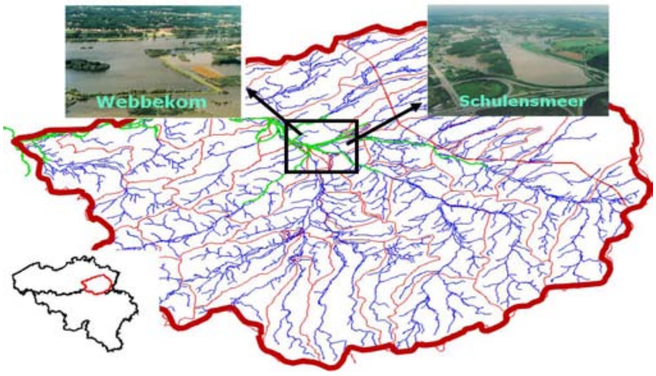

Figure 3. Two flood-control reservoirs “Schulensmeer” and “Webbekom” along the river Demer at the confluence of Mangelbeek, Herk, Gete, Velpe, Zwartebeek, Zwarte Water & Begijnenbeek tributaries

## 2 METHODS

In this study, a conceptual river model was built in order to reduce the calculation time compared with a detailed hydrodynamic model. Its structure was identified and calibrated based on simulation results with the detailed model. The following sub-sections will introduce the simulation models and calibration methods applied in this approach.

### 2.1 *Systematized description of the study area*

Figure 4 plots the scheme of the hydraulic components for the study area around the two flood-control reservoirs “Schulensmeer” and “Webbekom” in the Demer basin. The river reaches in this scheme are represented by lines with positive flow in the direction of the arrows, the hydraulic regulating structures by rectangles, and the water storage volumes by nodes. The symbols are described below: “q” for discharge, “h” for water level, “v” for water storage volume, and “k” for gate crest level. The rainfall-runoff inflows are indicated by discharges entering the river system through tributaries of the river Demer, namely Mangelbeek, Herk, Gete, Velpe, Zwartebeek, Zwarte Water and Begijnenbeek. Related information of each tributary is provided in Table 2.

Table 2. The tributaries of the Demer [AMINAL, 2004]

| Water course | Length (km) | Inflow variable in model |
|---|---|---|
| Mangelbeek | 18 | $q_{man}$ |
| Herk | 40 | $q_{hopw}$ |
| Gete | 11 | $q_{gopw}$ |
| Grote Gete | 48 | |
| Kleine Gete | 35 | |
| Melsterbeek | 35 | |
| Velpe | 34 | $q_{vopw}$ |
| Zwartebeek | 37 | $q_{zbopw}$ |
| Zwarte Water | 3.8 | $q_{zwopw}$ |
| Begijnenbeek | 16 | $q_{bgopw}$ |

## 2.2 *Hydrodynamic model of the river system*

The operational efforts of the two main flood control reservoirs in the study area (Schulensmeer and Webbekom) affect the downstream cities; Diest and Aarschot. In September 1998, the Diest city underwent severe flooding. For the sake of analyzing and better controlling such flood events, the VMM water authority developed a full hydrodynamic model implemented in the InfoWorks-RS (River System) software developed by Wallingford Software & Halcrow in the UK (InfoWorks-RS, 2006). This detailed physically-based hydrodynamic model solves the full hydrodynamic equations, the De St. Venant momentum and continuity equations (Chow & Maidment, 1998), which are solved by the computation of finite differences (implicit computational scheme). The InfoWorks-RS model is based on cross-sectional data and roughness information of the river bed along approximately every 50 meters of the modeled rivers, geometric data on all hydraulic structures (e.g. weirs, culverts, flow and water level control structures), and bridges along the course of all these rivers (AMINAL, 2004). This model was used to perform detailed simulations for this study area.

## 2.3 *Conceptual model of the river system*

With a view to reducing the model calculation time and computational complexity, a more simplified conceptual river model was evolved. The simplification of the hydrodynamic river flow processes is achieved by lumping the processes in space, and by limiting the study area to the region affected by the flood control. Lumping of the processes in space is done by simulation of the water levels, not every 50 meters as the full hydrodynamic model does, but only at the relevant locations. The locations are required to be selected such as up- and downstream of each hydraulic regulation structure and at the places along the river Demer where potential flooding is induced. Depending on these locations, the river was subdivided in reaches, in which water continuity is modeled (in a spatially lumped way per reach).

A reservoir model simply assumes water continuity (increase in volume per time step equals inflow minus outflow). The inflow in each reservoir (sub-model representing a river reach) is the discharge from the more upstream river reach (result of the more upstream sub-model). The outflow depends on the water storage in the reach or is assumed equal to the sum of the upstream discharge and the other inflows along the reach (e.g. from catchment rainfall-runoff or from the tributary rivers). The volume-variation of every river reach can be obtained so that the water level of that can sequentially be derived as well.

For long regular river reaches, they can be modeled by two diverse methods: in method 1, the reach is to be schematized by a serial connection of reservoirs; method 2 makes use of the water surface profile concept. Through these two methods, the relation between water levels and discharges can be acquired. The derivational processes of the two methods depend on the simulation results with the full hydrodynamic model.

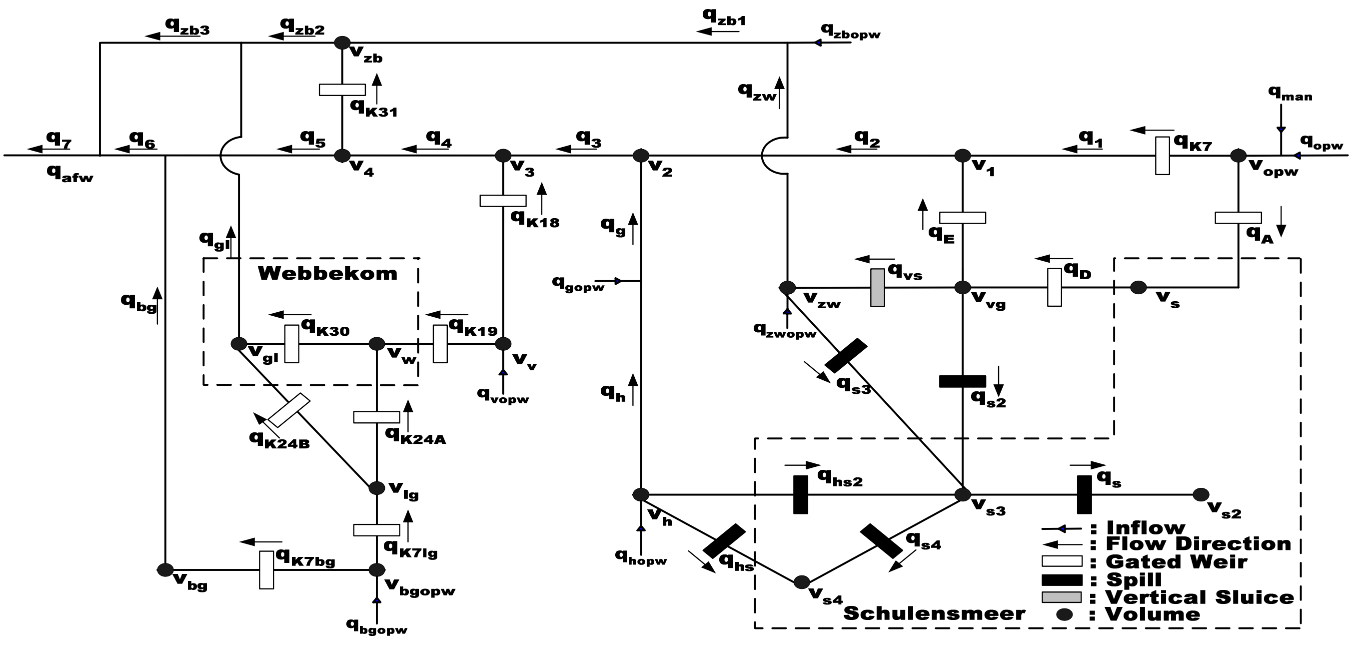


Figure 4. Schematic overview of the conceptual model structure for the study area

### 2.3.1 *Calibration for water levels and discharges ~ method 1*

Method 1 makes use of (serially connected) reservoirs, where the storage volume ($v$) of each reservoir is modeled based on the water continuity equation:

$$\frac{dv(t)}{dt} = q_{up}(t) - q(t) \tag{1}$$

where $q$ is the outflow from the storage reservoir considered (flow to downstream) and $q_{up}$ the inflow from (one or more) upstream storages nodes. The outflow is based on an additional relation between outflow, storage and inflow:

$$q(t) = f(v(t), q_{up}(t)) \quad \text{or} \quad q(t) = f(v(t)) \tag{2}$$

The latter relation depends on the type of reservoir model considered. In the linear reservoir model case, (2) becomes:

$$q(t) = \frac{v(t)}{k(t)} \tag{3}$$

where $k$ is the reservoir constant.

The variation of storage volume ($v$) will give rise to the water level ($h$) change. Therefore, this method takes a $v$-$h$ rating curve into account. The curve is calibrated to the simultaneous $v$ and $h$ results derived from the detailed model simulations. An example of such calibration result is shown in Figure 5 for the storage node $v_w$.

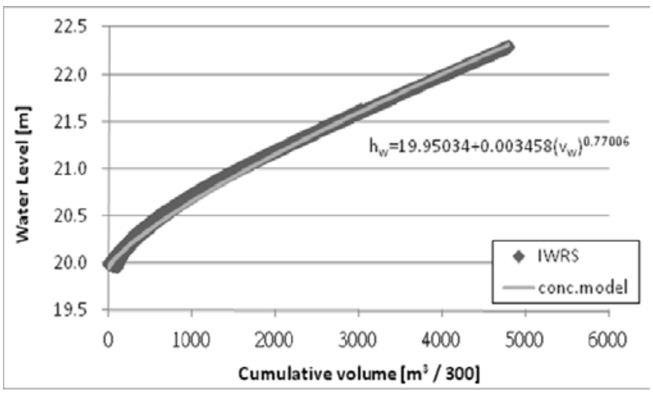


Figure 5. Calibration result for the storage volume-water level relation of the storage node $v_w$

### 2.3.2 *Calibration for water levels and discharges ~ method 2*

In method 2, the water level $h$ of storage node is based on the water level $h_{up}$ in the more upstream storage node. The water level differences along the reach considered ($h_{up}$ - $h$) are modeled proportional to the ratio of the squared discharge ($q$) in the reach and the squared downstream water depth ($h$- $h_0$, where $h_0$ is the river bed level):

$$h_{up}(t) - h(t) \sim \frac{q(t)^2}{\left(h(t) - h_0(t)\right)^2} \tag{4}$$

Equation (4) is expected for most river reaches after the equation of Manning (Chow & Maidment, 1998). The precise relation, for instance a power relation, as described in Equation (5), is calibrated based on the simulation results for a few historical flow events (including flood events) with the detailed InfoWorks-RS model:

$$h_{up}(t) = h(t) + a\left(\frac{q(t)^2}{\left(h(t) - h_0(t)\right)^2}\right)^b \tag{5}$$

where $a$ and $b$ are coefficients. An example of such calibration result is shown in Figure 6 for the Demer reach corresponding to the water level differences ($h_2$ - $h_3$) between nodes $v_2$ and $v_3$ (see Figure 4).

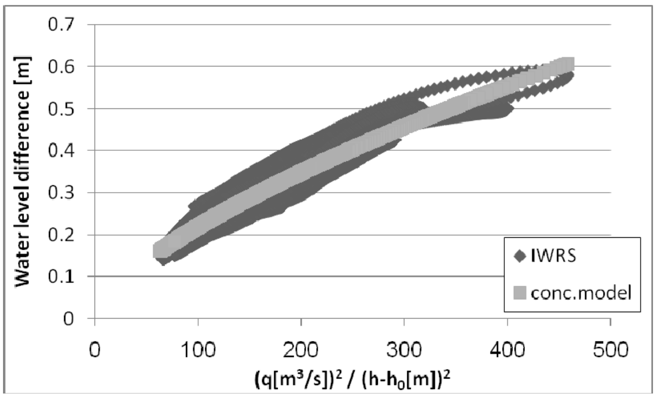


Figure 6. Calibration result for the storage node $v_2$ (and related water level $h_2$) along the Demer based on the downstream water level $h_3$ following method 2

### 2.3.3 *Calibration for storages*

However, some relations cannot be directly derived based on the two methods mentioned above, whereas they reveal 'hysteresis effects'. In these cases, they need to be considered by a more complicated calibration method whereby the total storage in the river reach is divided into two parts: static storage and dynamic storage (Figure 7). The static storage is identified as the lowest storage for a given outflow discharge and the dynamic storage dominates the variation between the total storage and the static storage (based on the inflow discharge). This static storage and dynamic storage respectively symbolize the decreasing and increasing flanks of the flow in the hysteresis loops.

The calibration process then involves analysis of the relationship between the static storage $v_{stat}$ and the outflow discharge $q$, and between the dynamic storage $v_{dyn}$ and the inflow upstream discharge $q_{up}$, so that suitable functions or equations can be fitted to these relations:

$$q(t) = f(v_{stat}(t)) \quad (6)$$

$$v_{dyn}(t) = f(q_{up}(t)) \quad (7)$$

$$v(t) = v_{stat}(t) + v_{dyn}(t) \quad (8)$$

An example of such calibration result is shown in Figure 8 regarding the storage node $v_{lg}$. The figure shows the hysteresis effect in the total storage volume - water level relation, modeled after combining sub-models for the static and dynamic storages, separated from the total storage.

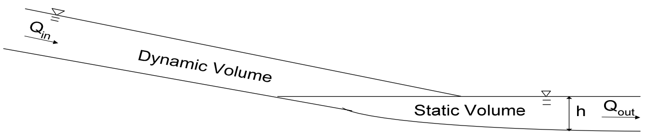


Figure 7. The total storage in a river reach is separated by dynamic storage and static storage

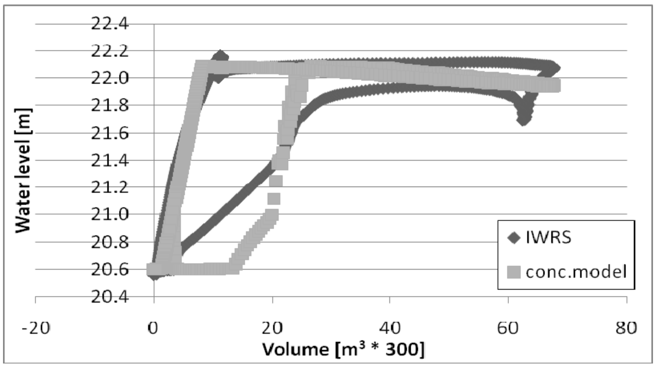


Figure 8. Hysteresis in the relation between total storage volume and water level for storage node $v_{lg}$, and conceptual model result after separation of the total storage in static and dynamic storage and the calibration of separate relations for both storage parts

## 2.4 *Hydraulic structure operations*

Next to the river reaches, schematized by means of storage nodes and flow units, several types of hydraulic structures were present in the detailed models: gated weirs, vertical sluices, orifices and spills. For these structures, some equations have been implemented as for the detailed model to describe over- or through-flows based on up- and downstream water levels.

The gated weirs of the river system have to adhere to their physical limitations, upper and lower bounds, as the gates cannot violate them in reality. In addition, the speed restriction of the gate movement also was obeyed. The operations of all hydraulic structures follow the operating rules formulated by the VMM water authority.

# 3 RESULTS

We applied data from two flood events (years 1998 and 2002) for calibration and another two flood events (years 1995 and 1999) for validation. The model used 5-minute simulation time step, but model results were aggregated to a 1 hour time step. Table 3 provides a description of the 4 events including their individual year, duration and amount of hourly data. It is worth mentioning that the 1998 flooding was clearly the highest of all; this catastrophic flood event is well known in the memory of the people in Flanders.

Table 3. The description of the four flood events simulated

| Year | Duration | Data Amount (Number of hours) |
|---|---|---|
| 1995 | 18/01/09h00 ~ 16/02/12h00 | 700 |
| 1998 | 02/09/09h00 ~ 01/10/12h00 | 700 |
| 1999 | 14/12/09h00 ~ 12/01/12h00* | 700 |
| 2002 | 15/01/09h00 ~ 14/02/23h00 | 735 |

*Year 2000

Figures 10 ~ 14 reveal the model calibration and validation results, comparing the results of water levels, discharges (for main river reaches, spills and hydraulic structures) at selected nodes simulated by the conceptual model (Conc) with those calculated by the InfoWorks-RS model (IW). Concerning the comparisons with the InfoWorks model for historical flood events, the conceptual river model has been investigated whether it can perform well for all conditions (hydraulic structure regulations and gate crest levels) during the historical flood events. Besides, the model also has been checked for discontinuities and stability.

In Figure 10, variables $h_1$ and $h_4$ demonstrate 2 water levels located at the specific junctions of the river Demer and its tributaries. Taking $h_1$ for example, it receives flow from two sources: $q_1$ (the Demer upstream) and $q_e$ (flow through gate E). Through computing the storage volume at this junction and applying one of the methods described in the sub-sections 2.3.1 ~2.3.3, water level at this node is obtained. From this figure we found that the peaks of the water levels $h_1$ and $h_4$

were closely matched except some small underestimations during some lower peak flow periods.

Figure 10 also shows another 2 water levels ($h_s$, and $h_w$) at the selected nodes. Also for these levels, results of the conceptual model match those of the InfoWorks model. It is important to be noted that the water level $h_s$, which is the water level in the flood control reservoir Schulensmeer and thus the downstream water level of the gate that controls the flow $q_A$ (see Figure 4), cooperates with $h_{opw}$ (the upstream water level of the gate) to determine when the reservoir Schulensmeer starts to be filled. The accuracy of this water level will affect the operation of the reservoir.

In Figure 11, variables $q_2$ and $q_5$ are two discharges at specific locations of the river Demer indicating the magnitude of the flows passing just downstream the junctions of the river Demer and its tributaries. This figure shows that the results of $q_2$ and $q_5$ simulated by the conceptual model well match those calculated by the InfoWorks model. It means that the water continuity at these reaches computed by these two models achieved similar simulation results.

Figure 12 and 13 respectively show spill discharges in selected reaches and discharges through selected hydraulic structures. The spill computation involves the magnitude of the discharge flowing over the river bank or flowing into the river. The difficulty in calculating the spill discharge is how to sum up all segments of this discharge along every cross-section of the river reach. As shown in Figure 12, the results simulated by the conceptual model match those run by the InfoWorks model. Moreover, the figure also demonstrates that there was a severe flooding especially in the flood event 1998 because all spills had non-zero spill discharges (flowing over the river banks / flowing into the river). Figure 13 presents the discharges for selected hydraulic structures. The discrimination between good and bad for a hydraulic structure simulation is decided by its up- and downstream water levels, because these two water levels will influence its operating rules. This figure reveals that the results of the selected structures are similar to those of the InfoWorks model. Figure 14 finally shows the comparison between the simulation results of the InfoWorks and conceptual models and the measurement data for two selected water levels ($h_4$ and $h_{zb}$). The differences between the InfoWorks and conceptual model results were found smaller than between the models' results and the measurement values.

Given that the professed goal of the simplified conceptual lumped model is reduction of the computational (CPU) time, Table 4 gives an overview of the CPU times of both the detailed hydrodynamic and the conceptual models.

Table 4. CPU times of the InfoWorks (IW) and conceptual models for the four flood events simulated (output time step: 5 min)

| Year | CPU time IW | CPU time Conc. model |
|---|---|---|
| 1995 | 31 min. | 9.098 sec. |
| 1998 | 120 min | 9.145 sec. |
| 1999 | 30 min. | 9.061 sec. |
| 2002 | 151 min. | 9.546 sec. |

## 4 CONCLUSIONS

This paper has demonstrated that a simplified conceptual river model can simulate river hydrodynamic states and flow processes in an accurate and fast way. Simulation results were obtained that are similar to the full hydrodynamic InfoWorks-RS model results for the Demer basin.

The most important advantage of the conceptual model is its reduced calculation time so that this simplified model will enable integration in a real-time flood control operation scheme. Such operation requires optimization based on a huge number of iterations; thus requiring limited model computational times. Physically-based methods have been successfully developed and applied to construct, calibrate and validate lumped conceptual model structures based on a limited number of flood event simulations in the detailed InfoWorks model.

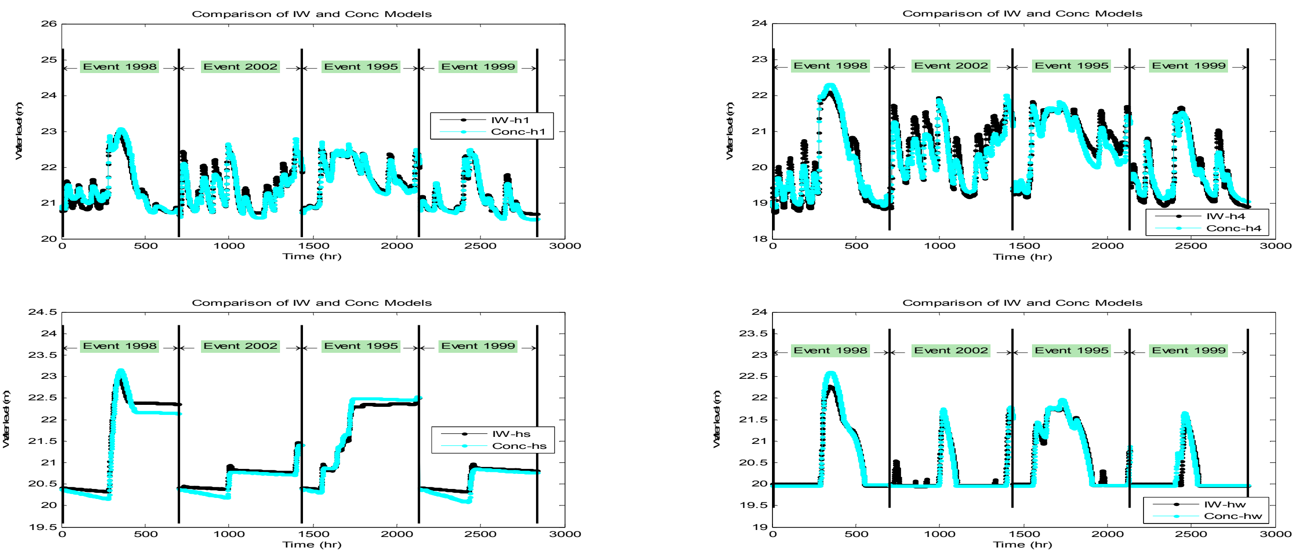


Figure 10. Comparison of the InfoWorks (IW) and Conceptual model (Conc) simulation results for water levels at selected nodes

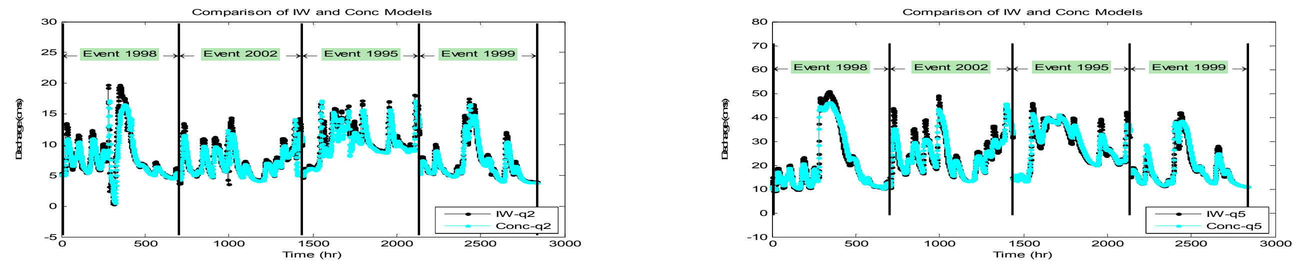


Figure 11. Comparison of the InfoWorks (IW) and Conceptual model (Conc) simulation results for discharges in selected reaches

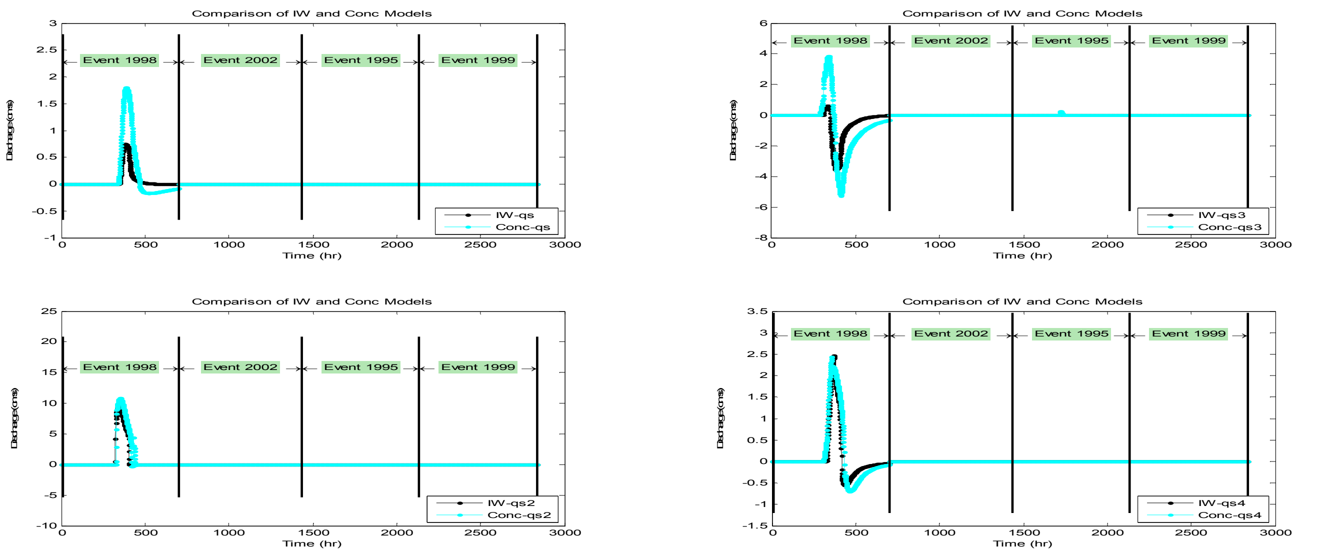


Figure 12. Comparison of the InfoWorks (IW) and Conceptual model (Conc) simulation results for spill discharges in selected reaches

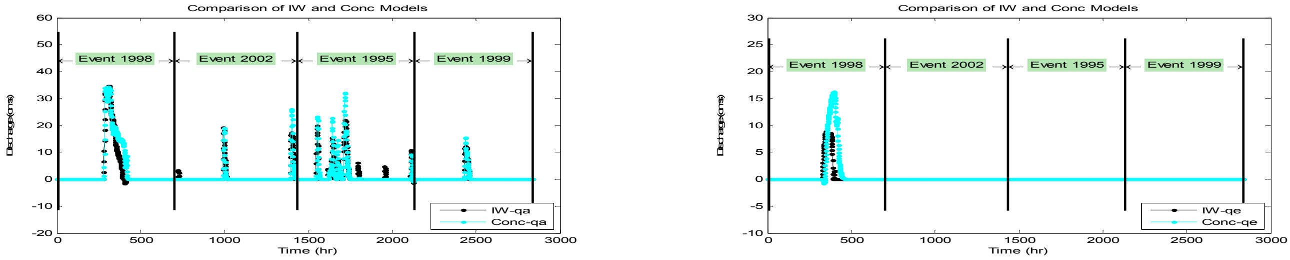


Figure 13. Comparison of the InfoWorks (IW) and Conceptual model (Conc) simulation results for discharges through selected hydraulic structures

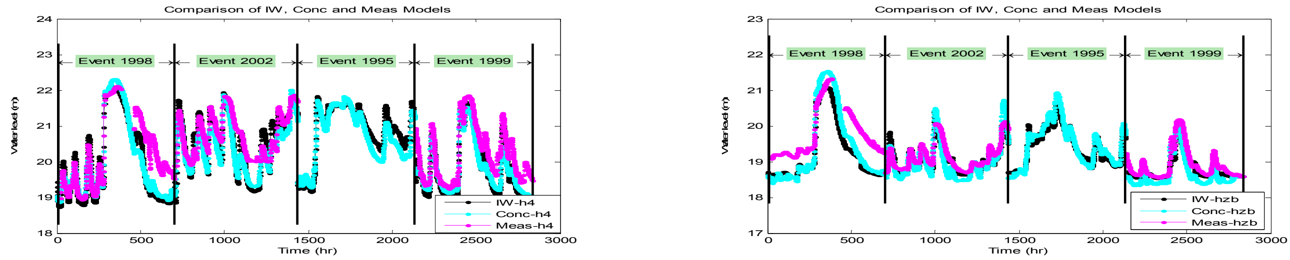


Figure 14. Comparison of the InfoWorks (IW), Conceptual model (Conc) simulation results and measurements (Meas) for water levels at selected nodes

## 5 FUTURE RESEARCH

Future research will combine spatial rainfall and rainfall-runoff models with the conceptual river model. In order to achieve model-based real-time flood control, real-time rainfall predictions will be simulated, the model state variables updated in real-time, based on river flow and water level observations, and combined with flood control optimization schemes. So far, the model has been integrated in Model Predictive Control (MPC) applications, as described by Barjas Blanco et al. (2008, 2010) and Willems et al. (2008).


## ACKNOWLEDGEMENTS

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