A FIRST ANALYSIS OF THE FLOOD EVENTS OF AUGUST 2002 IN LOWER AUSTRIA BY USING A HYDRODYNAMIC MODEL

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ABSTRACT

Getting an overview of the general situation is very often the first step in an engineering approach towards the analysis of a flood event. If little is known a priori about the terrain, the flow directions and flow conditions, a detailed analysis can only be performed by investing large amounts of money and time to gather the required data in a first step. However, for the investigation of a larger area of interest, this detail is often not necessary and delays the delivery of results to the contracting authority.

The paper shows that exactness of the digital terrain model and detailed surface roughness information is not always required in the hydrodynamic modelling of a larger area, by analysing the August 2002 flooding at the rivers Danube and Kamp in Lower Austria. Simulation is performed with a two-dimensional finite element model based on the shallow water equations. The results are compared to aerial views that were made at the peak of the flood event and show a good conformity with reality in large parts of the area of interest. Even some of the local effects of the combined flooding of two rivers are precisely predicted by the coarse analysis model.

KEYWORDS

Danube, flooding, hydrodynamic model, shallow water equations, parameter sensitivity

INTRODUCTION

In August 2002, a catastrophic flood event following several days of heavy rainfall struck large parts of Central and Eastern Europe. Among the most affected places were villages and towns at the Black Sea, as well as alongside the rivers of Vltava in the Czech Republic, the Elbe in Germany, but also the Danube and many of its tributaries throughout the northern regions of Austria.

The city of Vienna, Austria’s capital, is protected by a flood protection system that was mainly built during the years of 1975 through 1985, featuring a second river bed which is normally used for recreational purposes but fulfils the purpose of increasing the cross section of the river in case of a passing flood wave (Freisitzer and Maurer, 1985). Vienna's flood protection is dimensioned for a discharge of 14,000 m³/s, however due to inundation and retention effects upstream of the city, the peak of the wave in August 2002 was estimated to have reached roughly 10,000 m³/s, therefore the event did not cause damage to the capital city.

Figure 1: Broken road embankment and pipes for district heating, near Stratzdorf

But many regions upstream of Vienna were highly affected by the flooding, especially the very flat region where the river Kamp meets the Danube in Lower Austria (see figure 3 for an overview); figure 1 gives an impression of the damage that occurred in vast parts of that area. Just a week after the flood wave had passed Vienna, it was decided to do a first hydrodynamic analysis of the event in the region of interest. The main goals were to compare the results of the numerical computation to information gathered from the inundation area, and – if these results were satisfactory – perform several case studies to find out which part of the area was flooded by each of the two rivers. Furthermore, such an investigation would show which of the effects that occurred in real world are represented by the coarse hydrodynamic model, enabling the user to decide whether an in-depth investigation would be needed in certain parts of the region.

In order to perform this analysis, the following information had to be gathered: Aerial views of the flood event – taken at the point of time when the peak of the flood wave passed the area of interest in the afternoon of August 14, 2002 – were gathered and evaluated to draw inundation lines for comparison with those from the model to be constructed later. For the hydrodynamic simulation itself, it was necessary to use a digital terrain model. It was decided to use a terrain model with a squared grid size of 250 meters, for two reasons: first, the computation area is larger than 200km², and a larger grid size greatly reduces cost; secondly, from an engineering point of view it is important to know whether a very detailed model is needed at all to reproduce the effects seen in reality. Cross sections and information about bed elevations of Kamp and Danube were used to augment the digital terrain model with river information. Finally, the exact flow and stage hydrographs measured during the flood event were collected and used as boundary conditions to the hydrodynamic model.

THE FLOOD EVENT

During the first days of August 2002, several low-pressure systems moved from the British Isles to Central Europe, causing humid air to be transferred to Austria. Especially in the Kamp catchment, heavy rainfalls over a period of several days caused an extraordinary catastrophic event that was estimated with an annuality of 2,000 to 10,000 years (Gutknecht et al., 2002). As a consequence in Stiefern, just north of the investigation area, the water level of the river Kamp reached almost seven meters, that's about five meters above the mean water level, in the early morning hours of August 8, 2002 (see figure 2a). But just six days later, a second flood wave – caused by another series of severe rainfalls – again hit the Kamp valley with a maximum water level of almost six meters.

At the same time, the river Danube was also at high watermarks following the propagation of two flood waves. In the city of Krems, the western boundary of the computational domain, the water level rose to almost 10 meters on August 14, 2002 (figure 2b) – a mere five meters above mean level. Here, the second flood wave was by far the dominant one, causing severe inundations east of Krems.

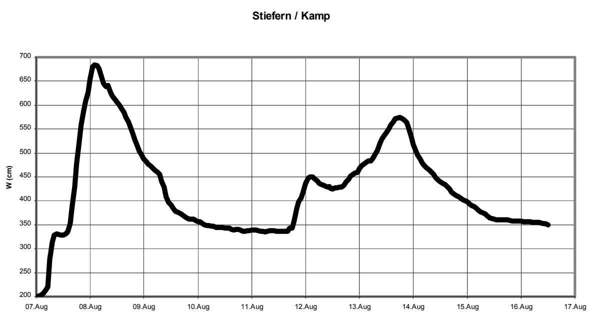

Figure 2a: Stage hydrograph at Stiefern/Kamp

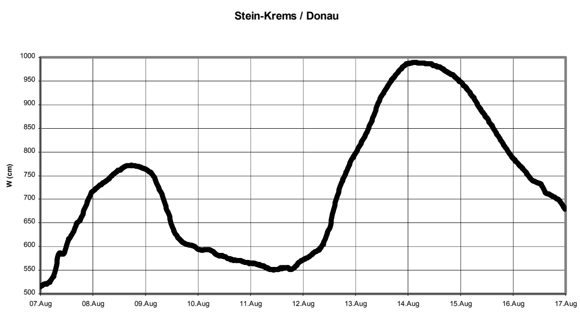

Figure 2b: Stage hydrograph at Krems/Danube

HYDRODYNAMIC MODEL

Digital terrain and river model

In terms of information concerning a river course, ordinary digital terrain models normally just reflect its water surface; information about bed levels and cross sections is not contained therein. Therefore, in a first step, known cross section data of both rivers were used to create an approximated river model in the computer. A sufficient number of geographic coordinates of the river courses were taken out of a map, and interpolated cross sections were computed for these coordinates. Because a linear interpolation of the river courses between those coordinates would have led to discontinuities with intersecting cross sections, the approximated river bed was computed by using natural cubic splines to connect the geographic points by preserving the first and second derivatives of the resulting curve. Natural cubic splines have the disadvantage that they are not locally controlled, thus a change in one point's coordinates in turn changes all curve segments, not only the curve segment to the next point. However, as long as all points are chosen in a decent distance to each other, such a curve gives a good representation of the river course.

The cross section data being used was augmented with height information of the embankment crest. However, all other dams and man-made structures in the flooded areas are not represented specifically in the digital terrain model. There are two main reasons for this: first the analysis of the aerial views has shown that most dams in the region of interest were useless because either the water was overflowing or the structures simply broke. Second, the exact heights of these structures are unknown and it would have taken a lot of field measurements to gather the required data. The computational result confirms that such a procedure still gives acceptable results in the area of interest.

The combined digital terrain and river model is accompanied by a digital roughness model. Two different cases have been investigated, in a first variant for both terrain and rivers a Strickler coefficient of 40 is used, in a second variant this parameter is modified to 20 for all terrain elements except the rivers which gives a more realistic modelling of the situation. Further detailing of the roughness model did not yield any visible improvement of the results.

Hydrodynamic Model

The instantaneous water levels and flows are obtained from the solution of the vertically integrated equations of continuity and conservation of momentum in two horizontal dimensions:

$$
\begin{aligned}
\frac{\partial U_x}{\partial t} &= -U_x \frac{\partial U_x}{\partial x} - U_y \frac{\partial U_x}{\partial y} - g\frac{\partial \eta}{\partial x} + U_y \cdot 2\Omega \sin\varphi + \frac{1}{\rho(\eta+h)}\left(T_x + T_x^B + T_x^W\right) \\
\frac{\partial U_y}{\partial t} &= -U_x \frac{\partial U_y}{\partial x} - U_y \frac{\partial U_y}{\partial y} - g\frac{\partial \eta}{\partial x} + U_x \cdot 2\Omega \sin\varphi + \frac{1}{\rho(\eta+h)}\left(T_y + T_y^B + T_y^W\right) \\
\frac{\partial \eta}{\partial t} &= -\frac{\partial U_x(\eta+h)}{\partial x} - \frac{\partial U_y(\eta+h)}{\partial y}
\end{aligned}
\tag{1}
$$

η is the instantaneous water surface above datum, U_x and U_y representing the velocities in x- and y-direction, h is the mean water depth, Ω the angular velocity of the earth's rotation, and φ the latitude of the area of interest. The wind shear parameter T^W is set to zero in this investigation, but the parameters for turbulent exchange T and friction T^B have to be taken into account. Turbulence is modelled by the eddy-viscosity approach named by Smagorinsky:

$$
\begin{aligned}
\frac{1}{\rho(\eta+h)} T_x &= \varepsilon_x \frac{\partial^2 U_x}{\partial x^2} + \varepsilon_y \frac{\partial^2 U_x}{\partial y^2} \\
\frac{1}{\rho(\eta+h)} T_y &= \varepsilon_x \frac{\partial^2 U_y}{\partial x^2} + \varepsilon_y \frac{\partial^2 U_y}{\partial y^2}
\end{aligned}
\tag{2}
$$

The coefficient ε_i is computed by

$$
\varepsilon_i := (c_s \cdot \Delta)^2 \left[2\left(\frac{\partial U_x}{\partial x}\right)^2 + \left(\frac{\partial U_x}{\partial y} + \frac{\partial U_y}{\partial x}\right)^2 + 2\left(\frac{\partial U_y}{\partial y}\right)^2 \right]
\tag{3}
$$

where c_s is a constant and Δ is the characteristic length of the grid.
Bottom friction enters the computation by using Strickler's law:

$$
\begin{aligned}
\frac{1}{\rho(\eta+h)} T_x^B &= \frac{g}{(\eta+h)^{\frac{4}{3}} k_{Str}^2} U_x \cdot \left\|\vec{U}\right\| \cdot \left\|\nabla B\right\| \\
\frac{1}{\rho(\eta+h)} T_y^B &= \frac{g}{(\eta+h)^{\frac{4}{3}} k_{Str}^2} U_y \cdot \left\|\vec{U}\right\| \cdot \left\|\nabla B\right\|
\end{aligned}
\tag{4}
$$

k_{Str} is the abbreviation for the Strickler friction coefficient described in the previous section and ∇B describes the bottom slope in both coordinate directions.

The shallow water equations are solved with stabilized finite elements on a triangular mesh (Milbradt, 1995). Discretisation in time is performed by an explicit Euler technique, thus the maximum time step is limited by the Courant condition. For the computation of the time step only those elements are being used which are not completely dry.

The numerical treatment of wetting and drying is implemented in the following way: A minimal limit of the water depth is set forth for all elements in the computational domain. As soon as the water depth is less than this limit at one node, the element is considered partially dry, resulting in only a standard Galerkin approximation being performed. Within the element, a horizontal water surface is assumed and its level is approximated by the water levels of the surrounding elements (Milbradt, 2002).

<u>Boundary conditions</u>
The numerical model employs two areas of inflow and one where outflow takes place. Inflow is modelled by applying known water levels and discharge data at the two gauge stations of Krems (western domain boundary) for the river Danube and Stiefern (just north of the computational domain) for the river Kamp. The outflow region is much larger, consisting of the river Danube with known discharge at the hydroelectric station of Altenwörth plus the flooded area north of it where little is known about discharges or water levels. At the location of the hydroelectric station, the known discharge condition is applied. Due to the slope in the Danube valley, a gradient of the water surface is all that is known about the other parts of the outflow region. Due to the fact that the computational model does not contain an option to set the surface gradient to a known value, this was vicariously modelled by setting all boundary nodes to a depth slightly less than their neighbour nodes. With this modelling approach, water can only leave but not enter the computational domain at the flooded region.

<u>Simulation</u>
A fully unsteady simulation of the computational domain was performed using stage and discharge data of ten days between August 7 and August 17 (see figure 2). The unknown Strickler coefficient for the flooded areas was varied to find the best fitting results. Furthermore, three variants of the flood event were considered to find the influence of every river to the complete event: Alternating flood stages at both Danube and Kamp with the other river at mean water levels and both rivers at flood level in a third variant.

RESULTS

The limits of the flooded regions are plotted alongside with the water depth (coloured in magenta tones in figure 3) and compared to the actual boundaries of the flooded area (green line in figure 3) at the point of time the aerial views were made. Figure 3 shows the computation of both rivers at flood level with Strickler's friction coefficient of 40 for the rivers and 20 for all other areas.

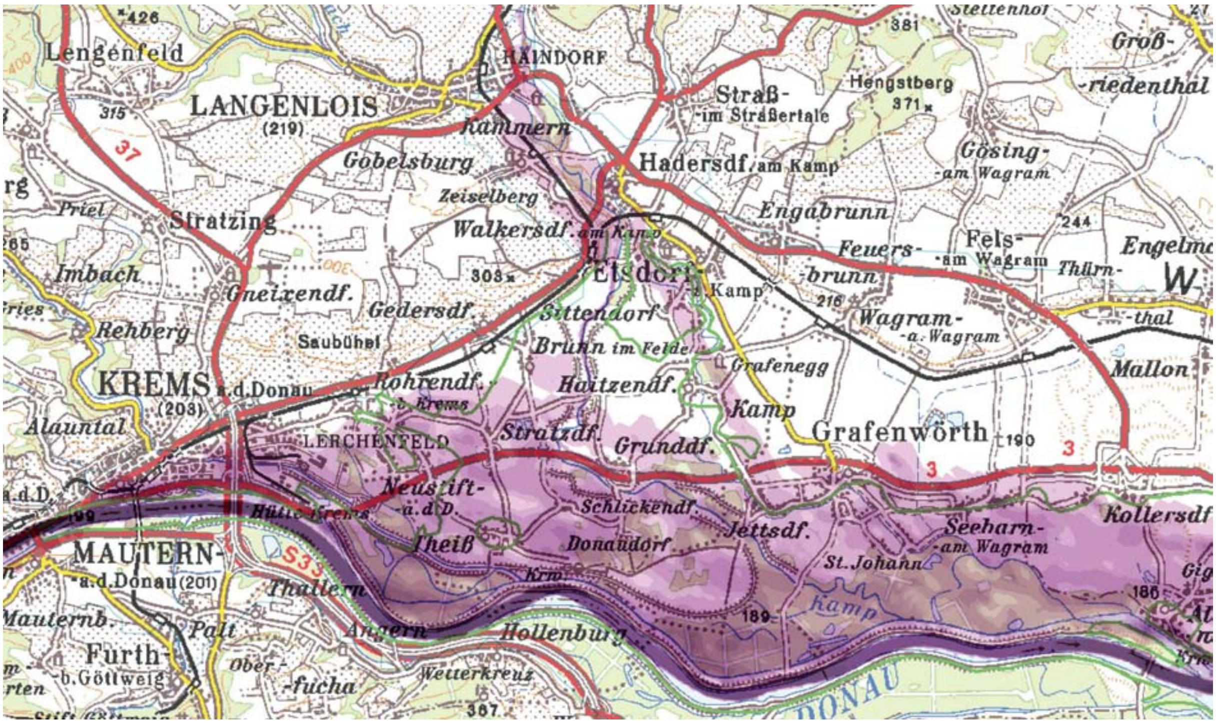

Figure 3: Comparison between real and computed boundary of the flooded area (August 14, 4 pm.)

It is visible that the flooded area is almost correctly predicted in the east of the river Kamp's confluence with the Danube. An error near the town of Grafenwörth is explicable due to the national road (visible in red) acting as dam in the real flood event. The river Kamp splits into two streams near the town of Hadersdorf; only the main river was modelled but the second stream is reflected by surface heights in the digital terrain model, thus an overland flow can be seen at this area.

Apparently, the information about the embankment crest of the river Kamp was not precise enough in all regions. Furthermore, the city of Krems was saved from flooding due to the city's mobile flood protection system which could not be included in the computations. That's the reason for the incorrect result in and near Krems. Finally, the village of Theiß apparently employed another means of flood protection with success, most probably sandbags were used. The fact that no inundations occurred south of the Danube is correctly represented by the numerical model. In reality, flooding occurred also in that region, but not due to the river Danube but some tributaries that enter the river at a later point of time.

Even though the computational results do not fit the information from the aerial views in every detail, a good conformity can be seen. A more detailed digital terrain model along with including dams and man-made structures may give better results but at the same time at a much higher project cost. However, for an engineer's consideration of a flood event, a less cost-intensive study like the one presented here, may be enough for many situations.

As a main result of the study, it is found that the friction coefficient in the land region does not significantly influence the overall size and shape of the flooded area. A significance can of course be seen when flow velocities and directions are examined. For an investigation of that kind, the application of exact roughness data is crucial, but for drawing the inundation line of the flooded regions it need not necessarily be modelled in detail, as the example shows.

In figure 4, a detailed plot of the flow situation in a bend of the river Kamp, not far from the location where figure 1 was taken, is depicted. The picture features a colour filled contour plot of the flow velocities and vectors, indicating the flow direction. In addition, isolines are being used to indicate the terrain height and make the river bed more clearly visible.

The main flow direction is from left to right, resulting from the Danube inundation. In the vicinity of the river Kamp, the water is drawn-in and thus changes its main direction. After the bend, the water escapes from the river bed again and reaches maximum velocities of around 3 m/s when crossing the embankment in a weir-like way. Even though the phenomenon in reality contains turbulent and highly three-dimensional effects, its two-dimensional representation is correctly predicted in the model's computational results.

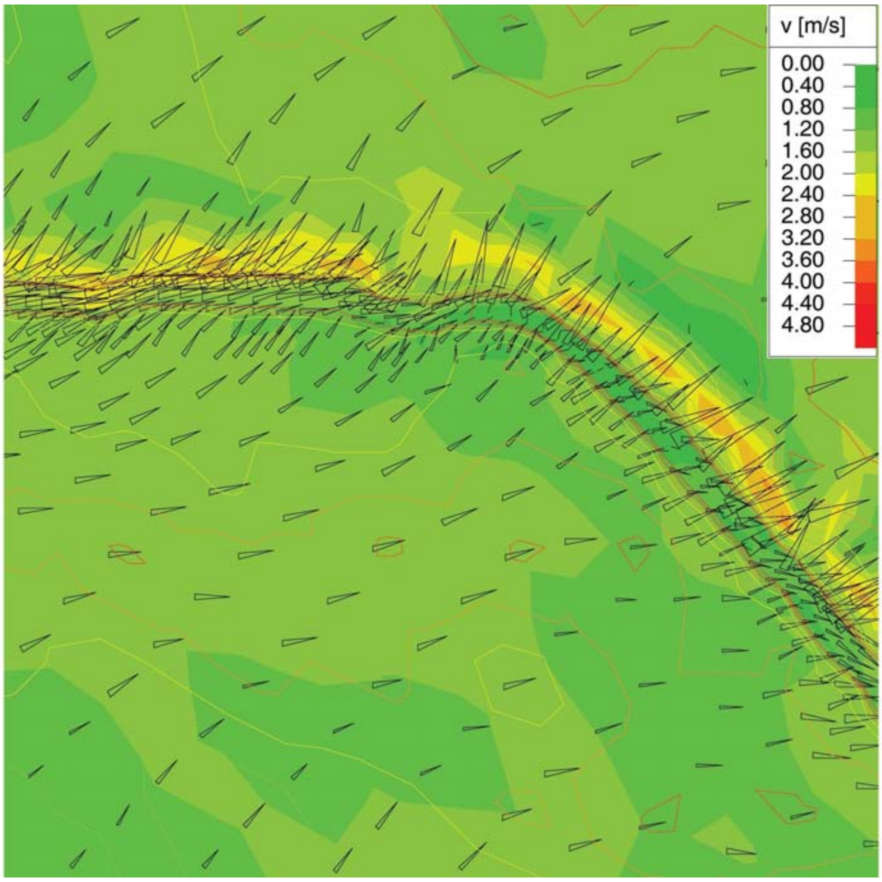

Figure 4: Flow situation in a bend of river Kamp, superimposed by water from the Danube

CONCLUSIONS

A study of the August 2002 flood event in Lower Austria using a technique of abstraction to reduce modelling costs has been presented. The resulting flood map is in good agreement with the information gathered from aerial views, even though the data is not correct in some places, mostly due to the result of human actions. Detailed information about terrain roughness is not required as long as the engineer is mainly interested in water levels of the flooded terrain. Also, the contribution of each river to the entire flood event can be studied very well on the presented model. Finally, some important local effects are reproduced by the hydrodynamic model, which overall leads to a qualitative good result at a comparatively low modelling cost.

For future research, a more detailed investigation will be required if the focus lies on the analysis of morphodynamic processes in the flooded terrain, flood forecasts for evacuation and rescue plans or the dispersion of pollutants by extension of the one-dimensional case (Tritthart, 2002). A survey of that kind would have to be based on a digital terrain model with a higher resolution, containing most of the visible structures that were abstracted for the sake of savings in time and costs in the study presented here.

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