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RIVER FLOOD LINES PREDICTION WITH 1D OPEN CHANNEL FLOW MODEL

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1. Introduction

Numerical modelling is becoming standard practice for river flood lines prediction among other procedures in flood mitigation planning. 1D open channel flow model has shown to be optimal for large-scale natural watercourses modelling thus it was used for determining river flood lines in the entire Croatian region of Gorski kotar where total length of all modelled watercourses amounted to 108 km.

Software package *Stripp12* used for river flow and flooding simulation was employed for unsteady water wave propagation simulations, as opposed to classic steady-state simulations of peak discharge flow regime. The simulations based on all available hydrological information were performed for each of the major watercourses of the region. Out of unsteady flood wave propagation simulation results, the maximum water levels along the watercourse were extracted and used for flood lines construction.

The most important outcome of the research presented in the paper was the fact that the created flood lines geo-informational (GIS) layer was included in the official hydrological GIS database.

2. Mathematical model

For the unsteady water wave propagation modelling 1D open channel flow model was used with first-order upwind Q-Scheme as implemented in the software package *Stripp12*.

2.1 One-dimensional open channel flow model

The flow through rivers and surrounding flood areas was modelled with 1D St. Venant equations:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}+gI_1\right)=gI_2+gA\left(S_0-S_f\right) \tag{2}$$

where term

$$I_1=\int_0^h(h-\varsigma)B(x,\varsigma)d\varsigma \tag{3}$$

models the hydrostatic pressure forces, term

$$I_2=\int_0^h(h-\varsigma)\frac{\partial B}{\partial x}(x,\varsigma)d\varsigma \tag{4}$$

represents the forces related to changes of the channel width, term

$$S_0 = -\frac{dz}{dx} \tag{5}$$

is the channel bed slope, and term

$$S_f = \frac{n^2 Q|Q|}{A^2 R^{4/3}} \tag{6}$$

models the friction forces through the channel. In the above equations x denotes the longitudinal space coordinate, t is time, $A=A(x,t)$ is the wetted cross section area, and $Q=Q(x,t)$ is the discharge. Furthermore, $h=h(x,t)$ is water depth, $z=z(x,t)$ is the bed level, $B=B(x,\varsigma)$ is channel width, q is lateral inflow, n is Manning friction factor, $R=R(x,A)$ hydraulic radius, and g is the gravitational constant.

In the defined equations no constraints are proposed to the geometrical properties of the considered channel, which enabled the inclusion of the flood areas surrounding the rivers in the channel geometry.

In order to solve the equations, initial conditions need to be defined, meaning initial water levels and discharges in rivers: $H(x,0)=H_0(x)$ and $Q(x,0)=Q_0(x)$, respectively. Here water level $H(x,t)$ is defined as $H=h+z$. Additionally, inlet discharge hydrographs $Q(t)$ (as defined by the hydrological analysis) were defined at the upstream boundary of each modelled river.

So as to model natural river flow realistically, lateral inflows were defined in specified channel points and segments. When applying lateral inflow to a channel segment, the inflow is equally distributed along the segment defined with two channel cross-sections.

At the downstream end of the channels, water level hydrographs $H(t)$ were applied as a boundary conditions.

2.2 First-order balanced upwind Q-Scheme

Previous research and practical projects ([1], [2], [3]) demonstrated the first-order balanced upwind Q-Scheme as stable and reliable, especially for difficult channel geometries.

The considered numerical scheme includes the numerical approximations of the spatially dependent flux function and of the geometrical source term by using the upwinding technique. The discretization of both terms is made in a similar manner such that the balancing between the flux gradient and the source term can be achieved.

The formulation of the balanced Q-Scheme for the open channel flow equations (1)-(2) can be written as:

$$\mathbf{u}_i^{n+1} = \mathbf{u}_i^n - \frac{\Delta t^n}{\Delta x_i}\left(\mathbf{f}_{i+1/2}^n - \mathbf{f}_{i-1/2}^n\right) + \Delta t^n\left(\mathbf{g}_{i+1/2}^{n,L} + \mathbf{g}_{i-1/2}^{n,R}\right) \tag{7}$$

$$\mathbf{f}_{i+1/2}^n = \frac{1}{2}\left(\mathbf{f}_i^n + \mathbf{f}_{i+1}^n\right) - \frac{1}{2}\left|\mathbf{Q}_{i+1/2}^n\right|\left(\mathbf{u}_{i+1}^n - \mathbf{u}_i^n\right) - \frac{1}{2}\left|\mathbf{Q}_{i+1/2}^n\right|\mathbf{Q}_{i+1/2}^{n\ -1}\mathbf{V}_{i+1/2}^n \Delta x \tag{8}$$

$$\mathbf{g}_{i+1/2}^{n,L} = \frac{1}{2}\left(\mathbf{I} - \left|\mathbf{Q}_{i+1/2}^n\right|\mathbf{Q}_{i+1/2}^{n\ -1}\right)\tilde{\mathbf{g}}_{i+1/2}^n \tag{9}$$

$$\mathbf{g}_{i+1/2}^{n,R} = \frac{1}{2}\left(\mathbf{I} + \left|\mathbf{Q}_{i+1/2}^n\right|\mathbf{Q}_{i+1/2}^{n\ -1}\right)\tilde{\mathbf{g}}_{i+1/2}^n \tag{10}$$

Here

$$\mathbf{u} = \begin{pmatrix} A \\ Q \end{pmatrix} \tag{11}$$

represents the solution vector,

$$\mathbf{f} = \begin{pmatrix} Q \\ \dfrac{Q^2}{A} + gI_1 \end{pmatrix} \tag{12}$$

is the numerical flux, and

$$\mathbf{g} = \begin{pmatrix} 0 \\ gI_2 + gA\left(S_0 - S_f\right) \end{pmatrix} \tag{13}$$

is the source term. Furthermore, the superscript indices mark the temporal discretization (i.e. number of time step) while the subscript indices represent the spatial discretization (i.e. number of cell); thus Δt^n denotes the nth time step and Δx_i denotes the size of the ith cell.

The matrix $\mathbf{Q}^n_{i+1/2}$ in the equations (8)-(10) represents the numerical approximation of the Jacobian matrix

$$\mathbf{A} = \frac{\partial \mathbf{f}}{\partial \mathbf{u}} = \begin{pmatrix} 0 & 1 \\ c^2 - v^2 & 2v \end{pmatrix} \tag{14}$$

where the term $\widetilde{\mathbf{u}}^n_{i+1/2}$ represents the extended Roe average state satisfying the relation:

$$\mathbf{A}\left(\widetilde{\mathbf{u}}^n_{i+1/2}\right)\cdot\left(\mathbf{u}^n_{i+1} - \mathbf{u}^n_i\right) + \frac{\partial \mathbf{f}}{\partial x}\left(\widetilde{\mathbf{u}}^n_{i+1/2}\right)\Delta x_i = \mathbf{f}\left(\mathbf{u}^n_{i+1}\right) - \mathbf{f}\left(\mathbf{u}^n_i\right) \tag{15}$$

The equation (14) uses flow velocity $v=Q/A$ and wave celerity:

$$c = \sqrt{g\frac{A}{B}} \tag{16}$$

The vector $\mathbf{v}^n_{i+1/2}$ in (8) represents the numerical approximation of

$$\mathbf{v} = \frac{\partial \mathbf{f}}{\partial x} = \begin{pmatrix} 0 \\ g\left(I_2 - \frac{A}{B}D\right) \end{pmatrix} \tag{17}$$

while vector $\widetilde{\mathbf{g}}^n_{i+1/2}$ in (9) and (10) designates the numerical approximation of the source term (13), also in the average state (15). More precisely, for the friction part it is sufficient to evaluate it pointwise in the ith cell, while for the other part, in order to satisfy the exact conservation property i.e. quiescent flow test ([4]), terms $\mathbf{v}^n_{i+1/2}$ and $\widetilde{\mathbf{g}}^n_{i+1/2}$ need to be decomposed and evaluated at the cell boundaries as follows:

$$\mathbf{v}^n_{i+1/2} = \begin{pmatrix} 0 \\ g\left(I^n_{2,i+1/2} - \frac{A^n_{i+1/2}}{B^n_{i+1/2}} D^n_{i+1/2}\right) \end{pmatrix} \tag{18}$$

$$\widetilde{\mathbf{g}}^n_{i+1/2} = \begin{pmatrix} 0 \\ \left(gI^n_{2,i+1/2} - gA^n_{i+1/2}\frac{z_{i+1} - z_i}{\Delta x}\right) \end{pmatrix} \tag{19}$$

where

$$I^n_{2,i+1/2} = \frac{I^n_{1,i+1} - I^n_{1,i}}{\Delta x} - A^n_{i+1/2}\frac{h^n_{i+1} - h^n_i}{\Delta x} \tag{20}$$

$$D^n_{i+1/2} = \frac{A^n_{i+1} - A^n_i}{\Delta x} - B^n_{i+1/2}\frac{h^n_{i+1} - h^n_i}{\Delta x} \tag{21}$$

3. Flood wave propagation simulations

Before the simulations of the flood wave propagation could be performed, the model input data was collected and prepared, meaning that:

- all available topographic data (maps, drawings, etc.) was collected and digitalized,
- hydrologic analysis of each of the watercourses was conducted, yielding triangle-shaped hydrographs of the 5, 10, 20, 50, 100 and 1000 year return periods (Fig. 1), and
- watercourse cross-sections were extracted out of available geodesic data such as geodesic

surveys, previous projects documentation, etc.; the obtained watercourse cross-sections spacing ranged between 50 and 200 m, depending on the watercourse length and complexity and the quality and quantity of the available geodesic information.

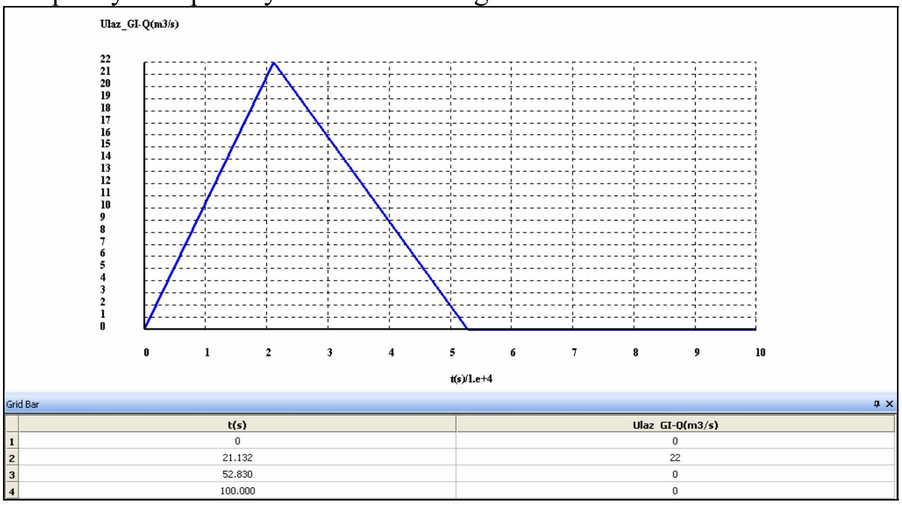

Figure 1. Inlet discharge hydrograph as shown in *Stripp12*

Essentially, the procedure of the flood wave propagation simulations was the same for each of the analysed watercourses and went as follows:

1. Prepared channel cross-sections were input to *Stripp12*, which together with inlet and outlet boundary conditions defined the numerical model of the watercourse.
2. All other numerical parameters for the model were defined, such as cell size (5-25 m for the analyzed watercourses), CFL condition, etc.
3. Test simulations were performed for the 1000-year return period discharge hydrographs in order to determine the locations at which the water levels reach the top of the river banks. These locations were identified in the available drawings and maps and the watercourse cross-sections in these areas were extended so to include the flood areas (Fig. 2). In this manner broadened 1D watercourse model thus included all potential flood areas.
4. Lateral inflows were adjusted through a series of test simulations to facilitate the agreement of the computed discharge values and the hydrological analysis results in the control cross-sections.
5. Flood wave propagation simulations were performed on the developed numerical models of the analyzed watercourses, for each of the return periods.

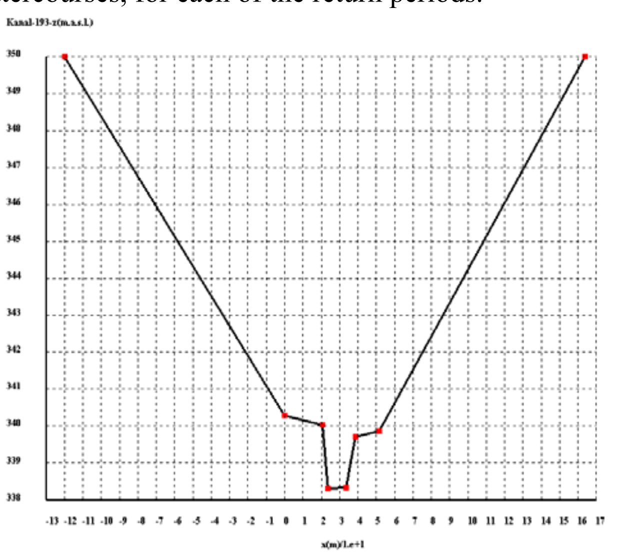

Figure 2. Broadened cross-section of a canyon river

4. Flood lines construction

On the basis of the flood wave propagation numerical simulations results, flood lines were constructed, i.e. flood risk maps were produced.

The results of the unsteady flood wave propagation simulations were filtered in a way that only the maximum water level values at each of the domain cells were preserved. Thus the longitudinal maximum water level cross-sections were obtained for all analyzed watercourses for each of the different return period scenarios.

Computed maximum water level values were then transferred into GIS. Based on the available geodesic information and maximum water level values at a specific watercourse reach, left and right water perimeter points were determined for the corresponding river cross-section (Fig. 3). This procedure was performed along the entire watercourse length, yielding flood lines. The outcome of the process were the flood lines for all analyzed watercourses for each of the different return period scenarios.

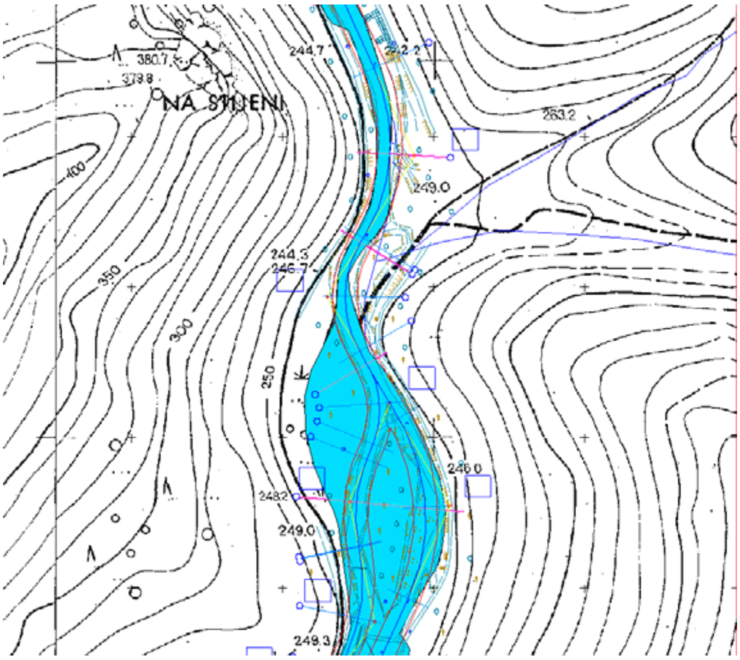

Figure 3. Flood lines construction in GIS

Finally, the flood lines were output as separate GIS layers in the form of ArcView Shapefile format. Standard maps of the analyzed region overlapped with the flood lines were used as flood risk maps (Fig. 4). Maps of this kind were afterwards overlapped with spatial planning maps, which made possible the implementation of flood damage analysis, cost-benefit analysis of the flood prevention measures, etc.

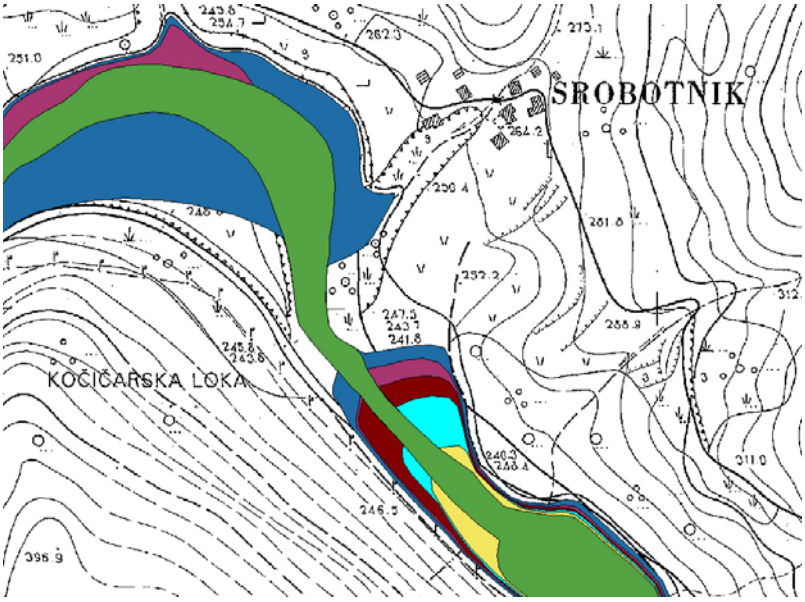

Figure 4. Segment of river Kupa flood lines for different return periods

5. Conclusion

The 1D open channel flow model was successfully applied for the purpose of flood lines prediction for very long watercourses (the total length of all modelled watercourses was about 108 km). First-order balanced upwind Q-Scheme has shown to be robust and reliable. It enables unsteady modelling of steep, irregular and discontinuous channel geometries. Therefore it was especially useful for the modelling of the watercourses such as the mostly canyon rivers of the Gorski kotar region.

Unlike previously practiced steady-state simulations of maximum discharge for the purpose of flood lines prediction, the procedure described here was based on unsteady simulations of the flood wave propagation in its whole time period. This makes the simulations far more realistic and usually results in smaller flood areas, since steady-state simulations systematically overestimate the size of the flood areas.

In order to further improve the explained methodology of the flood risk maps production, it is advised to maximize the quantity and quality of the geodesic and hydrological input data. Moreover, in the areas of potentially greatest flood-induced damage, it would be necessary to employ 2D modelling. However, 2D modelling is much more demanding in terms of required geodesic survey.

References

[1] Sopta, L., Crnjaric-Zic, N., Vukovic, S., Holjevic, D., Skific, J., Druzeta, S., "Numerical Simulations of Water Wave Propagation and Flooding", Proceedings of the Conference on Applied Mathematics and Scientific Computing, ed. Drmac, Marusic, Tutek, Springer, Dordrecht, 2005, pp. 293-304

[2] Sopta, L., Holjević, D., Vuković, S., Črnjarić-Žic, N., Družeta, S., Škifić, J., "Analiza propagacije poplavnih valova rijekom Rječinom upotrebom matematičkog modela", Zbornik radova 3. Hrvatske konferencije o vodama, Osijek, 2003, pp. 917-925

[3] Sopta, L., Družeta, S., Škifić, J., Crnković, B., Ožanić, N., "Studija rizika od poplava na rijekama Čabranki i Kupi (od izvora do lokacije Zdihovo) te vodotocima zatvorenih planinskih polja Gorskog kotara", Tehnički i Građevinski fakultet Sveučilišta u Rijeci, Rijeka, 2005

[4] Vukovic, S., Sopta, L., "Upwind Schemes with Exact Conservation Property for One-Dimensional Open Channel Flow Equations", SIAM Journal of Scientific Computing, 24(5), 2003

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