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HYDRAULIC MODELING FOR RISK MAPS AND IDENTIFICATION OF CRITICAL INFRASTRUCTURES IN WATER SECTOR

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Rezumat. *Procesul de identificare a infrastructurilor critice a demarat, drept pentru care în domeniul apelor se fac pași repezi în definirea și stabilirea acestora. Identificarea infrastructurilor critice în domeniul apelor se poate face având la bază hărțile de risc pe bazine hidrografice. Acest deziderat are la bază realizarea unor modele hidraulice uni- și bi-dimensionale care să genereze parametri necesari calculului pagubelor procentuale ce intră în ecuația evaluării riscului asociat unor evenimente naturale în domeniul apelor. În cuprinsul articolului este prezentată modalitatea de realizare a calculelor hidraulice din ambele perspective dimensionale. Rezultatele acestor calcule constituie datele de bază pentru etapa următoare a procesului de obținere a hărților de risc – evaluarea pagubelor.*

Abstract. *The Critical Infrastructure identification process started therefore rapid steps are made to define and set them up. Identification of critical infrastructures in water sector can be done based on risk maps for hydrographical basins. This goal has at its lowest level the achievement of some uni and two-dimensional hydraulic models that generate the required parameters necessary to calculate the damage percentage that enters in the equation of risk assessment, associated to natural events in water sector. This Article presents the way to achieve hydraulic calculations from both one- and two-dimensional perspectives. The results of these calculations are a database used for the next stage of risk maps obtaining process – damage assessment.*

Keywords: risk maps, two-dimensional flow, natural floods, hydrodynamic modeling, digital terrain model

1. Introduction

The term critical infrastructure has started to be used since 1996 when the US president Bill Clinton issued ”The Executive Order on Critical Infrastructure Protection” due to the need of combat against possible attacks on critical information structures. In accordance with the Preamble of this order, ”Certain national infrastructures are so vital that their incapacity or destruction would have a debilitating impact on the defense or economic security of the United States”.

The family of critical infrastructures includes: telecommunications, electrical power systems, gas and oil storage and transportation, banking and finance, transportation, water supply systems, emergency services (including medical, police, fire and rescue) and continuity of government.

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The Europe Council Directive 2008/114/CE issued on the 8th of December 2008 states the responsibility of Member States regarding the identification of critical infrastructures within national frontiers and for establishing and managing protective measures, regarding the declared goal of contributing to personal security.

The existing Directive represents a first step toward an approximation in the direction of identifying and establishing a European Programme for Critical Infrastructure and the need to improve assessment of the degree of protection. Basic and final responsibility for this program are assumed by Member States and, respectively, by the owners / operators of these infrastructures.

European Commission suggests three essential criteria for identifying critical infrastructure:

- expansion and surface area;
- level of severity. Types of severity can be: economical impact, the incidence of the general public, environmental incidence, addiction, political incidence;
- long-term effect on the period after the consequences occurred, which may be significant or severe. This criterion indicates when the degradation of infrastructure could lead to a major incident or a severe consequence (immediately after 24 - 48 hours, after a week or after a longer period of time).

2. Water within the Critical Infrastructure

A naturally occurring element that can be compared with the vulnerability of critical infrastructure is water.

This forms an earth coating and by its movement and status depends the physical and mechanical process that occurs at the surface. From the preliminary data we can easily observe that water is one of the elements that can form the basis for any of the three criteria for identifying critical infrastructure.

Moreover, the European Community has urged the risk maps of natural events such as earthquakes, floods, landslides, etc.

Because its author is specialized on hydraulics, the subject will be treated only for natural or accidental flooding. These maps will form the basis for making structural decisions in developing the communities situated on floodplain of watercourses.

For this article the presentation will be limited to how the flow is formed on the surface of the earth and variations on how to calculate the hydraulic parameters that have major impact on a building.

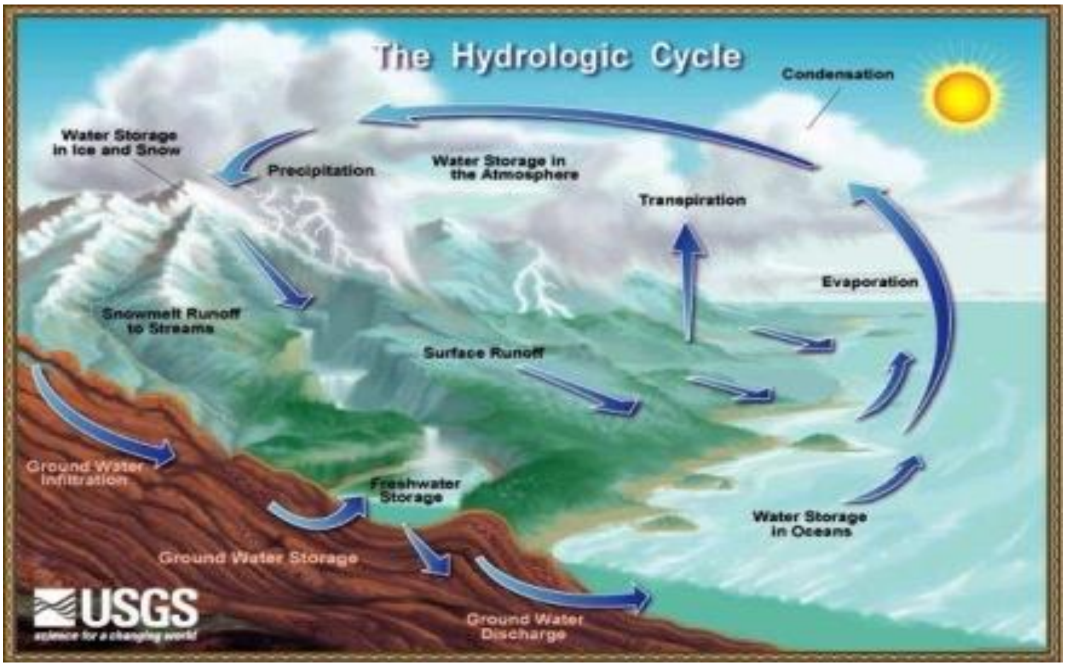

Fig. 1. The hydrologic cycle..

Figure 1 shows the general nature of the water cycle from evaporation and transpiration, then passing through the stage of condensation, transport through the atmosphere, returning to earth via precipitation and draining to the oceans by surface runoff, superficial flow and the underground flow. Among the possibilities for discharging water to the envoy, surface runoff has the greatest impact on the socio-economic objectives it meets in its path.

Rainfall is the only appreciable contribution to the volume of water available. At the same time, their nature is irregular, uneven and random. This characteristic leads in some cases to natural flood waves or accidental flooding due to failing water retention structures built upon water necessity.

Whatever their nature, floods are accompanied by spatial hydraulic phenomena (three dimensional). Although the main flow direction is along the river course, there are important cross current flow exchanges and flow velocities between the riverbed and overbanks. Currently there are three-dimensional computer programs of the flow but they are extremely expensive, demanding and require a lot of data entry and long processing calculation time, therefore are not effective. This is why, generally, the flood wave transit is a one-dimensional calculation (if the river is relatively straight and the main direction of propagation is the alignment of the river) or two-dimensional calculation (if the river sector is meandered or opposes resistance to flow and the wave attenuation normal to the river bed is important).

Flood waves (as the name says) are flow curves whose parameters vary in time and falls in the category of nonpermanent flow where the discharge varies with time. All subsequent references will be made for such conditions of the flow regime, permanent regime not being met in reality for such problems.

3. One-dimensional modeling

One-dimensional calculations of the flow is recommended for river sectors with relatively high slopes, stable and well defined beds and reduced widths, where flow in normal direction to the river bed is negligible and depression areas where water accumulates volumes are insignificant.

Also, such calculations are recommended in areas with relatively flat overbanks but irrelevant in terms of economic development, due to its low socio-economic level.

There are many computer programs but the most used in Romania are:

- MIPE – one-dimensional computer program of permanent movements in rivers (Amaftiesei R.);
- UNDA – one-dimensional computer program of nonpermanent movements in rivers (Amaftiesei R.);
- HEC-RAS – one-dimensional computer program of permanent and nonpermanent movements in rivers (U.S. Army Corps of Engineers);
- SWMM (Storm Water Management Model) – computer program for flow propagation in hydrographical basins (U.S. Environmental Protection Agency);

Further on, the equations that form the basis of HEC-RAS program and how to view and interpret the results will be presented.

3.1. The main principles for one-dimensional modeling

Transiting a water volume between two sections in one-dimensional problem is expressed by solving the equations governing the phenomenon which are: the principle of conservation of mass (continuity) and the principle of conservation of momentum (moment flux). Mathematically, these laws are expressed in the partial differential equations which applied to a finite field can be expressed in finite differences.

The Principle of Conservation of Mass (continuity):

Let's consider an elementary control volume element (see fig. 2). Main flow direction is the x direction. In the middle the total flow volume control is denoted $Q(x, t)$. The flow is produced through total area A.

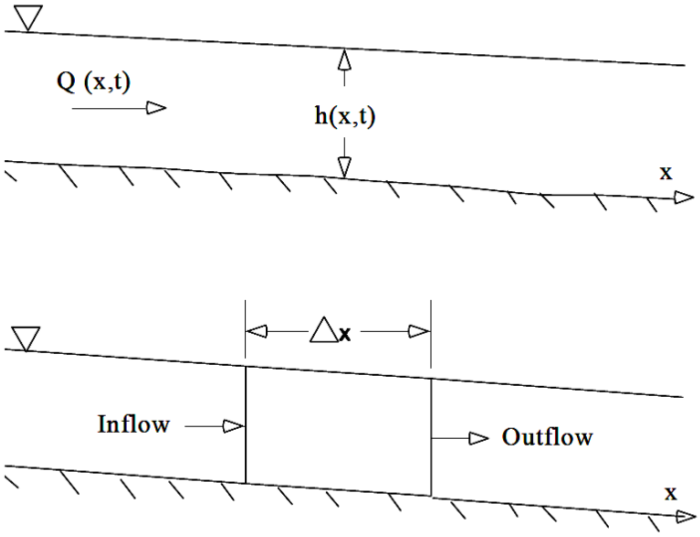

Fig. 2. Schematization of the Principle.

Conserving the mass implies that the flow entering the elementary volume is equal to the flow inside the volume control which was changed. Inflow can be written as:

$$Q - \frac{\partial Q}{\partial x} * \frac{\Delta x}{2}, \tag{1}$$

outflow as:

$$Q + \frac{\partial Q}{\partial x} * \frac{\Delta x}{2} \tag{2}$$

and the flow rate inside the control volume:

$$\frac{\partial A_T}{\partial t} * \Delta x \tag{3}$$

Assuming that Δx is low, the mass exchange within the volume element is:

$$\rho * \frac{\partial A_T}{\partial t} * \Delta x = \rho * \left[\left(Q - \frac{\partial Q}{\partial x} * \frac{\Delta x}{2}\right) - \left(Q + \frac{\partial Q}{\partial x} * \frac{\Delta x}{2}\right) + Q_i\right], \tag{4}$$

where Q_i is the discharge entering in the control volume and ρ is fluid density. Simplifying and dividing by $p * \Delta x$ the final form of continuity equation arises:

$$\frac{\partial A_T}{\partial t} + \frac{\partial Q}{\partial x} - q_i = 0, \tag{5}$$

where q_i is the unitary discharge entering the volume element.

The Principle of Conservation of Moment (moment flux):

Momentum conservation is expressed in Newton's second law.

$$\sum F_x = \frac{d\vec{M}}{dt}, \tag{6}$$

Conservation of momentum means that the rate of momentum entering the volume element (flow time) plus the sum of all external forces acting on volume element to be equal to the rate of accumulated moment. It’s a vector equation applied in the direction x of the water flow. Moment flux (MV) is the mass multiplied by the fluid velocity vector in the direction of flow. Three forces are considered: (1) pressure, (2) the force of gravity and (3) friction.

(1) Pressure:

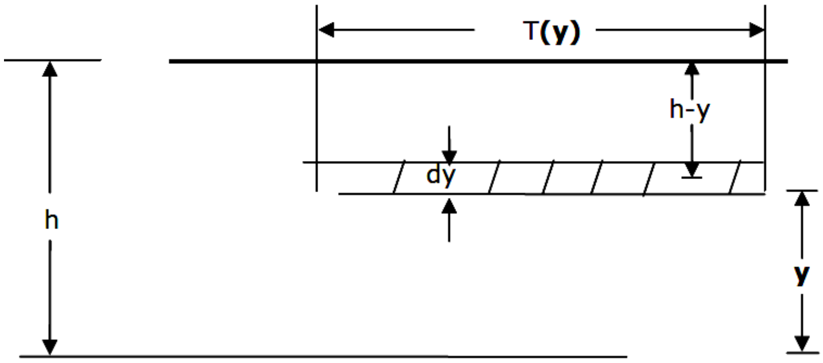

Fig. 3. Schematization of the pressure force.

Figure 3 shows the general case of an irregular cross-sections. Pressure distribution is considered linear (hydrostatic) and the total pressure force is the integral of the pressure-area product over the cross section. The pressure force at any point can be written as:

$$F_P = \int_0^h \rho * g * (h - y) * T(y) * dy, \tag{7}$$

with *h* depth, *y* distance above the channel invert and *T*(*y*) a function that relates the cross section width and the distance above the channel invert.

If F_P is the pressure force in *x* direction at the middle of the element, the upstream end force can be written as:

$$F_P - \frac{\partial F_P}{\partial x} * \frac{\Delta x}{2}, \tag{8}$$

and at the downstream end:

$$F_P + \frac{\partial F_P}{\partial x} * \frac{\Delta x}{2} \tag{9}$$

The sum of pressure force for the volume element becomes:

$$F_{Pn} = \left|F_P - \frac{\partial F_P}{\partial x} * \frac{\Delta x}{2}\right| - \left|F_P + \frac{\partial F_P}{\partial x} * \frac{\Delta x}{2}\right| + F_B, \tag{10}$$

were:

$$F_{Pn} = -\frac{\partial F_P}{\partial x} * \Delta x + F_B \tag{11}$$

Differentiating equation (7) through Leibnitz method and replacing in relation (11) result:

$$F_{Pn} = -\rho g \Delta x \left[\frac{\partial h}{\partial x}\int_0^h T(y) * dy + \int_0^h (h-y) * \frac{\partial T(y)}{\partial x} * dy\right] + F_B \tag{12}$$

The first integral from relation (12) is the cross sectional area A. The second integral (multiplied by $-\rho g \Delta x$) is the pressure force exerted by the fluid on the banks, which is equal in magnitude but opposite with F_B. While the net pressure force can be written as:

$$F_{Pn} = -\rho g * A \frac{\partial h}{\partial x} \Delta x, \tag{13}$$

(2) The force of gravity in x direction is:

$$F_g = \rho g * A * sin\theta * \Delta x, \tag{14}$$

where θ is the angle made by the bed slope with the horizontal. For natural rivers the angle θ is small and $sin\theta \approx tan\theta = -\frac{\partial Z_0}{\partial x}$ where Z_0 is the bed elevation. Therefore, the gravity force can be written as:

$$F_g = -\rho g * A \frac{\partial Z_0}{\partial x} \Delta x \tag{15}$$

This force will be positive for negative river slopes.

(3) The Friction force between the fluid and the bed is:

$$F_f = -\tau_0 * P\Delta x, \tag{16}$$

where τ_0 is the medium tangential shear stress (force / surface) which take action at the fluid contact limits and P is the wetted perimeter. The ”–” sign indicates that when flow is in the ”+” sense of x direction the force is acting in the ”–” sense of *x* direction. From the dimensional analysis, τ_0 can be expressed as a drag coefficient C_D:

$$\tau_0 = \rho C_D V^2 * P\Delta x \tag{17}$$

The drag coefficient is related with Chezy coefficient through:

$$C_D = \frac{g}{C^2} \tag{18}$$

Furthermore, Chezy equation can also be written as:

$$V = C\sqrt{R * S_f} \tag{19}$$

Replacing the equations (17), (18) and (19) and simplifying we find the next friction force expression:

$$F_f = -\rho g * A * S_f \Delta x, \tag{20}$$

where S_f is the friction slope. The friction slope is correlated with the flow and the time step. Given the widespread use of the Manning and Chezy coefficients, further on they will be used with priority. Manning equation is:

$$S_f = \frac{Q * |Q| * n^2}{2{,}208 * R^{4/3} * A^2}, \tag{21}$$

with *R* – hydraulic radius and n – Manning roughness coefficient.

The three forces explained, remains to be expressed only the moment flux. Flow entering the control volume can be written as:

$$\rho * \left[QV - \frac{\partial QV}{\partial x} * \frac{\Delta x}{2}\right], \tag{22}$$

and outgoing flow as:

$$\rho * \left[QV + \frac{\partial QV}{\partial x} * \frac{\Delta x}{2}\right] \tag{23}$$

Therefore, the net rate of moment flux which enters the control volume element is:

$$-\rho * \frac{\partial QV}{\partial x} \Delta x \tag{24}$$

Because fluid moment in the control volume is $\rho * Q * \Delta x$, accumulated flow rate can be written as:

$$\frac{\partial}{\partial t}(\rho * Q * \Delta x) = \rho * \Delta x * \frac{\partial Q}{\partial t} \tag{25}$$

Then, according to the definition of conservation of momentum: The net rate of momentum entering the volume (24) plus the sum of all external forces acting on the volume (13)+(15)+(20) is equal to the rate of accumulation of momentum (25):

$$\rho * \Delta x * \frac{\partial Q}{\partial t} = -\rho * \frac{\partial QV}{\partial x} \Delta x - \rho g * A \frac{\partial h}{\partial x} \Delta x - \rho g * A \frac{\partial z_0}{\partial x} \Delta x - \rho g * A * S_f \Delta x \tag{26}$$

Water surface elevation, z, is equal to $z_0 + h$. Therefore:

$$\frac{\partial z}{\partial x} = \frac{\partial h}{\partial x} + \frac{\partial z_0}{\partial x}, \tag{27}$$

where $\frac{\partial z}{\partial x}$ is water surface slope. Replacing (27) in (26), dividing to $\rho * \Delta x$ and translating all terms to the left, the final form of momentum equation results as:

$$\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0 \tag{28}$$

3.2. Interpretation of results

We have seen how the one-dimensional flow phenomena are expressed mathematically in natural river beds. In reality, on the water course are a series of structures (e.g. bridges, spillways, gates, etc.), bringing a resistance to the flowing process. These buildings, according to their type, have an influence that can be expressed in the form of mathematical formulas and will not be detailed below. Existing computer programs were developed in this industry to bring into account the effects of structures if they are defined in the model. What is interesting is the way the results are expressed and their utility in flood risk maps.

Viewing the results is simple today. It can be accomplished through the main programs or post-processing, GIS, etc.

These programs can create the water surface at a given time and thus results depth of water at any point or water level from a reference plane. Another important parameter for the risk maps is the water velocity at any point of the model. These two parameters (water depth and velocity) are the pillars of calculations for the economic loss. In the figure below we can observe the presentation of HEC-RAS results.

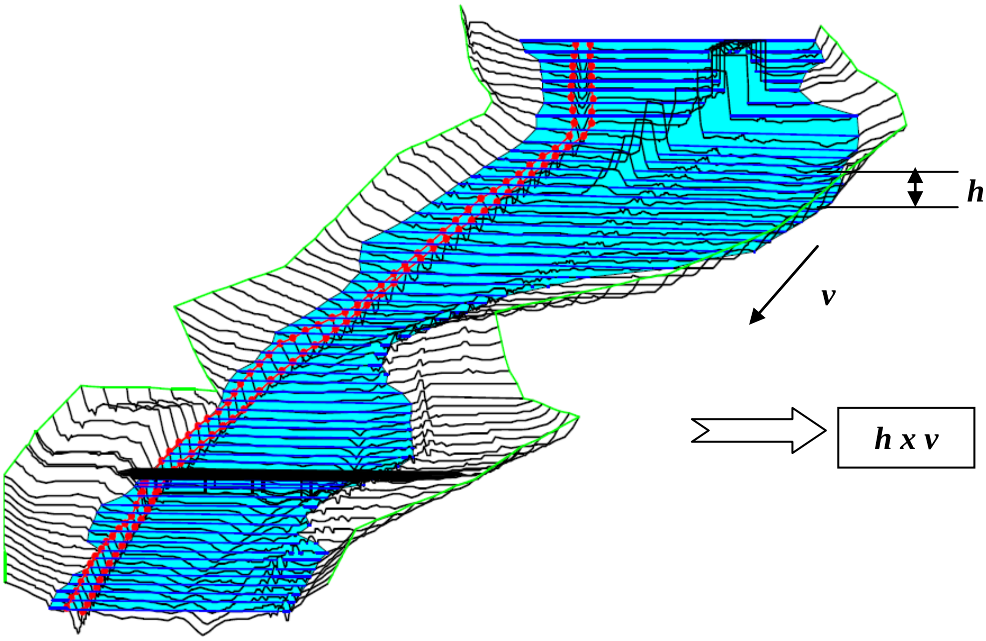

Fig. 4. Visualising results in HEC-RAS.

Basically, through these models water depth and water velocity can be read by the operator around the objectives and after that those informations can be in a database that is then processed to obtain a percentage of the loss of those objectives.

But as I said above, this type of calculation is used with satisfactory performance on bad sectors of the river with certain features and is not recommended for heavily populated areas or important flow component normal to the main direction of river flow. For such problems it is recommended to achieve a two-dimensional model calculation.

4. Two-dimensional modeling

Compared with one-dimensional modeling, the two-dimensional one has the advantage that it uses for calculations a numerical model of terrain (NTM) which simulates a three-dimensional relief very close to the natural landscape. Thus, the calculation uses almost all existing land discontinuities and land parcels as in reality (of course, digital terrain model accuracy depends crucially on the quality of topographic surveys).

The second advantage is the effective way of calculation. The method of calculation is based on Navier-Stokes equations that define how the speed, pressure, temperature and density of a fluid in motion interrelate. For effective calculation, Saint-Venant shallow water equations are used for fluid flow applied to the finite element or volume scheme.

There is in this case a series of computer programs developed by different companies or individuals. For example:

- ISIS – computer program for two-dimensional modeling made by HALCROW;
- MIKE FLOOD – computer program for two-dimensional modeling made by DHI Grup;
- RiverCAD – set of computer programs for calculations and vizualisation with CAD, and modeling with HEC-2 (BOSS International);
- SMS/HYDRO_AS-2D – set of computer programs made by BOSS International and Dr. Marinko Nujic.

To give you an example I will present the underlying equations of the two-dimensional modeling programs SMS/HYDRO_AS-2D and how to view and interpret the results of calculation.

4.1. Main equations for two-dimensional modeling

Modeling with this set of programs consists of going through three stages: pre-processing, the effective calculation and post-processing. Pre-and post-processing is done with SMS whilst HYDRO_AS-2D is for effective calculation. The physical phenomenon of the two-dimensional flow is similar to that enunciated before but applied to the two-way flow using the main direction x and the second direction normal to the main, *y*.

Given the assumptions on the incompressibility of the fluid and constant density, its momentum conservation law in the direction of *y*-*z* is:

$$p * dy * dz + \left(p + \frac{\partial p}{\partial x} * dx\right) * dy * dz + X * dm - dm * \frac{dv_x}{dt} = 0 , \tag{1}$$

where $p * dy * dz + \left(p + \frac{\partial p}{\partial x} * dx\right) * dy * dz$ is the pressure force, $X * dm$ is the force from moving volume mass and $dm * \frac{dv_x}{dt}$ is the inertial force.

Dividing the three equations of equilibrium with dm results the Euler equations for fluid forms:

$$\frac{dv_x}{dt} = x - \frac{1}{\rho} * \frac{\partial p}{\partial x}, \quad \frac{dv_y}{dt} = y - \frac{1}{\rho} * \frac{\partial p}{\partial y} \text{ și } \frac{dv_z}{dt} = z - \frac{1}{\rho} * \frac{\partial p}{\partial z} \tag{2}$$

But as Euler equations do not take into account the fluid viscosity and heat exchange therefore do not apply to real fluids.

Before applying them, the hydraulic losses should be placed inside the fluid.

For *y-z* direction, they can be expressed as a function of normal and tangential efforts:

$$F_{F(yz)} = \frac{1}{\rho} * \left(\frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z}\right) \tag{3}$$

Since the shear stress is equal to force/surface after Newton, it can be written as:

$$\tau = \frac{F}{A} = \eta + \frac{dv}{dn}, \tag{4}$$

where η is the dynamic viscosity and $\upsilon = \nu/\rho$ the kinematic viscosity.

Introducing the friction in the Euler equations, Navier-Stokes equations results for each component:

$$\begin{aligned}
\frac{dv_x}{dt} &= x - \frac{1}{\rho} * \frac{\partial p}{\partial x} + \upsilon * \left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2}\right), \\
\frac{dv_y}{dt} &= y - \frac{1}{\rho} * \frac{\partial p}{\partial y} + \upsilon * \left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2}\right), \\
\frac{dv_z}{dt} &= z - \frac{1}{\rho} * \frac{\partial p}{\partial z} + \upsilon * \left(\frac{\partial^2 v_x}{\partial x^2} + \frac{\partial^2 v_y}{\partial y^2} + \frac{\partial^2 v_z}{\partial z^2}\right)
\end{aligned} \tag{5}$$

Dr. Nujic, elaborator of the calculation program (1999), expressed two-dimensional flow equations in a compact form for easy use by the program as:

$$\frac{\partial w}{\partial t} + \frac{\partial f}{\partial x} + \frac{\partial g}{\partial y} + s = 0, \tag{6}$$

with:

$$w = \begin{bmatrix} H \\ uh \\ vh \end{bmatrix} \qquad f = \begin{bmatrix} uh \\ u^2 h + 0{,}5 * g * h^2 - v * h * \frac{\partial u}{\partial x} \\ uvh - v * h * \frac{\partial v}{\partial x} \end{bmatrix}$$

$$S = \begin{bmatrix} 0 \\ g * h * (I_{Fx} - I_{Sx}) \\ g * h * \left(I_{Fy} - I_{Sy}\right) \end{bmatrix} \qquad g = \begin{bmatrix} vh \\ uvh - v * h * \frac{\partial u}{\partial y} \\ v^2 h + 0{,}5 * g * h^2 - v * h * \frac{\partial v}{\partial y} \end{bmatrix} \tag{7}$$

where:

$H = h + z$ is the water level above z elevation,

u and v are velocity components in x and y directions,

the friction slope and river bed slope are contained in term S

through I_{Fx}, I_{Fy} and I_{Sx}, I_{Sy} coefficients.

Roughness is taken into account through Darcy-Weisbach formula:

$$I_F = \frac{\lambda * v * |v|}{2 * g * D}, \tag{8}$$

where the friction factor λ is done by Manning – Strickler coefficient (Strickler = 1/Manning):

$$\lambda = 6{,}34 * \frac{2 * g * n^2}{D^{1/3}}, \tag{9}$$

with

n - Manning coefficient

$D = 4r$ – the hydraulic diameter.

These relations applied to the finite volume elements give the most real and stable two-dimensional modeling results.

Pre-processing stages involves inserting a field data and create a network of points and elements that defines the terrain model in SMS program.

Such data can be entered through the riverbed cross sections, digital terrain model, etc. (Fig. 5).

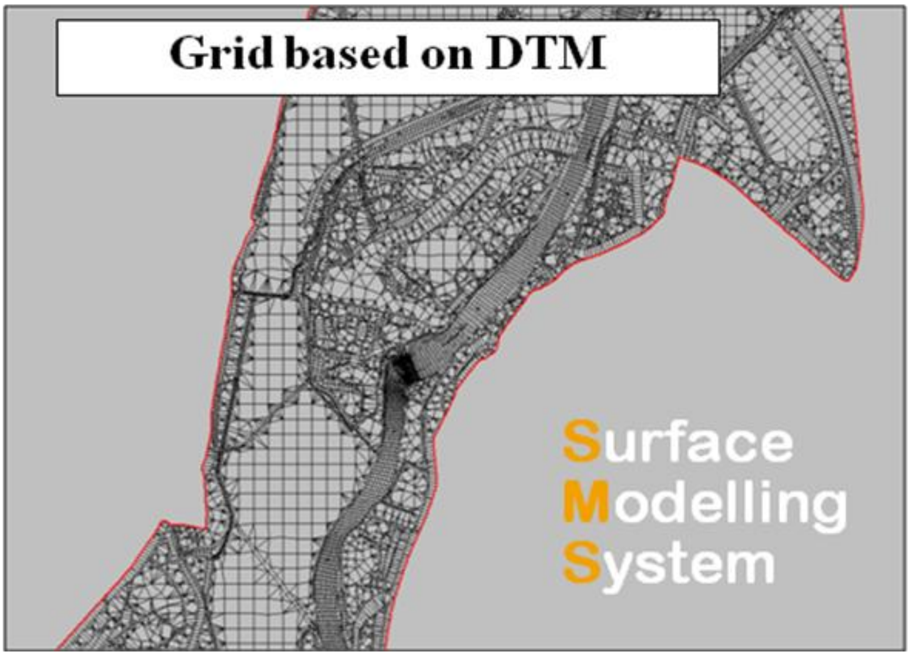

Fig. 5. Points and network elements of the digital terrain model.

The next step is used for verifying if the digital model created corresponds to the topography of the land (Fig. 6).

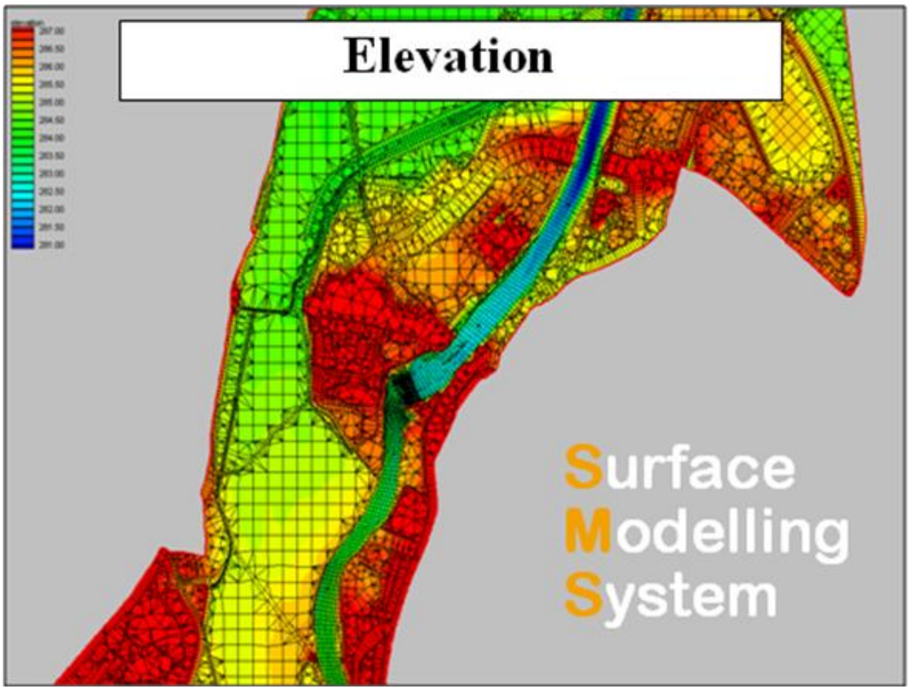

Fig. 6. Digital terrain model relief.

Land use is then inserted in correspondence with a Manning roughness coefficient (Fig. 7).

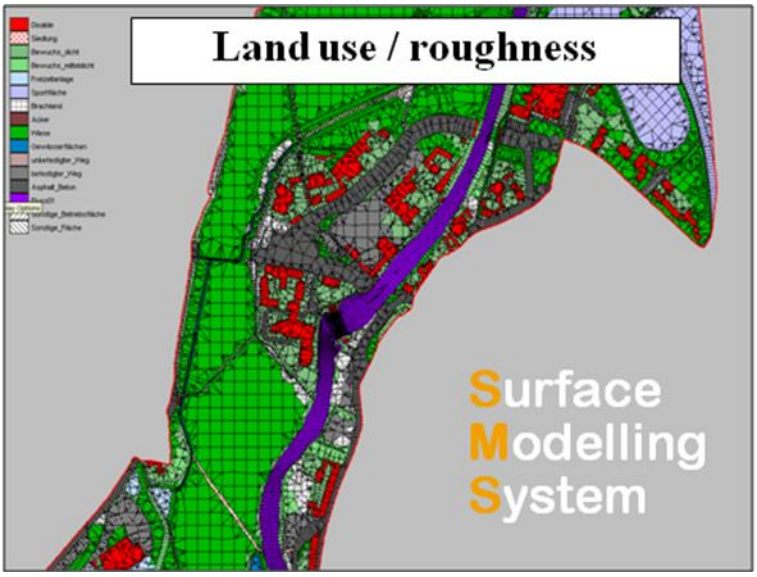

Fig. 7. Digital terrain model roughnesses.

Successive steps of creating a digital terrain model are presented below: based on aerial photographs NTM's profiles and cross sections were introduced, then the areas were defined with different land uses and during the final step the model structures were labeled (houses, bridges, spillways, etc.) (Fig. 8).

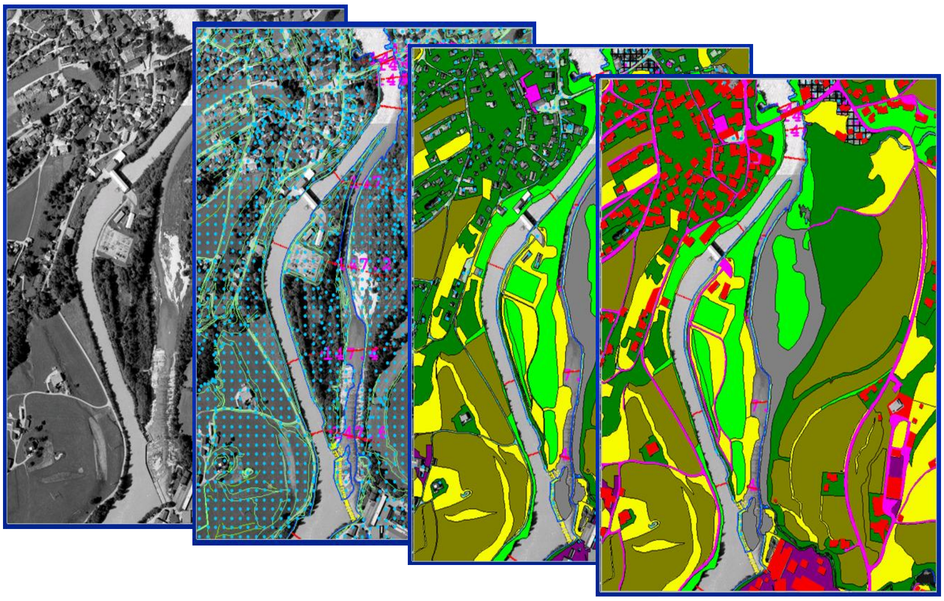

Fig. 8. Successive steps to achieve the digital terrain model.

After entering the correct data defining the digital terrain model we can start the effective calculation that involves inserting the initial and boundary conditions (input hydrograph, specific conditions at the model output, the flow conditions inside the model, etc.) and run the HYDRO_AS-2D computer program.

The resulting files are in a data format file and contain information on water level, discharge and velocity at any point of the model and at any time step.

Post-processing (using SMS) results lies in viewing, editing and analyzing the flow resulting from the calculation parameters (water level, flow speed) and processing them to find other parameters of interest (shear force, Froude number, etc.) (Fig. 9).

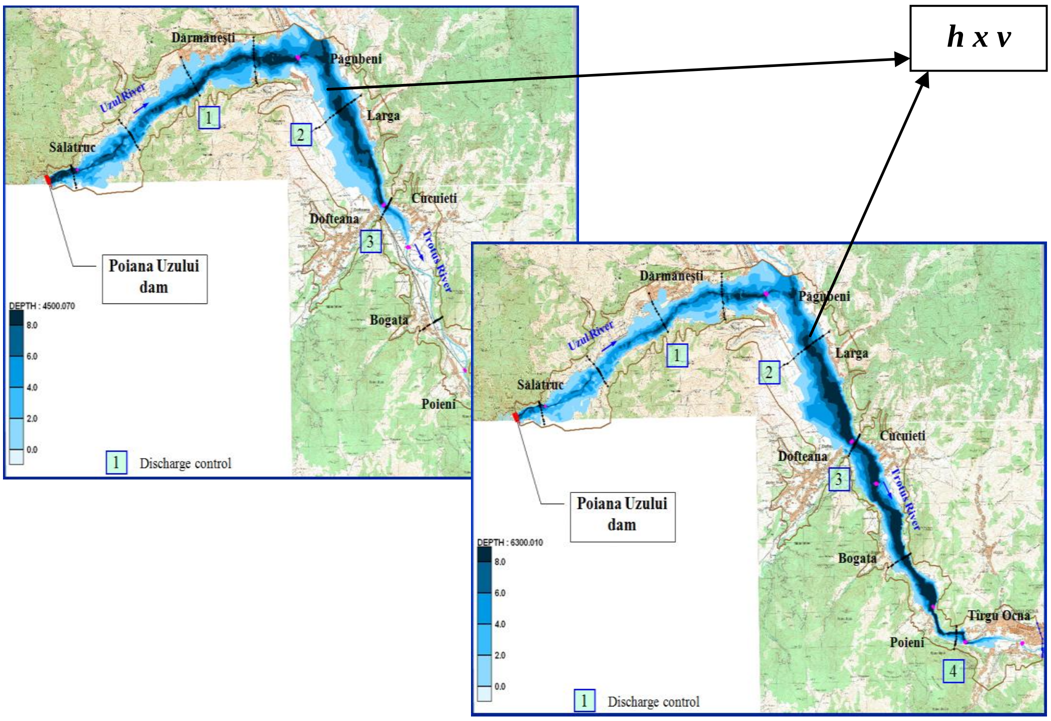

Fig. 9. Viewing, analyzing and editing results calculated as the product *h x v*.

Compared with one-dimensional modeling, the two-dimensional program also has the advantage that pre- and post-processing can be used as an interface for the program which calculates damage assessments.

To achieve risk maps, h x v product can be automatically exported and run under the assess the damages program.

This way more precisely estimates in risk analysis can be done, risk being given by the probability of an event to take place multiplied by the amount of damage recorded when the event happens.

Conclusions

The above leads to a clear conclusion that in order to identify critical infrastructure in the water sector is necessary for the first phase to create flood risk maps with two purposes: to establish related critical infrastructure mapping and watershed management plans.

This article's goal is based on the development of uni- and bi-dimensional hydraulic calculations that generate parameters needed for percentage damage calculation used with the associated risk assessment evaluation related to natural events.

The article presents how to do hydraulic calculations from both dimensional perspectives. The result of these calculations constitutes the database for the next stage of the process to obtain risk maps.

Next step in developing a risk map is to identify and evaluate the percentage damages which, associated to economic value (financial) of the objective, provide the value of damage linked to the occurrence event.

The procedure to create risk maps is a very laborious one, in their assessment being used a series of natural factors hard to describe in a mathematical way. Modern computing and the improvement of existing and future applications in order to increase processing speed and data capacity in the near future will lead to the ability to simulate real scenarios, assumptions for the production of natural disasters and damage assessment in real time related. Thereby the wisest decisions for the development of both rural communities and urban areas can be made.

REFERENCES

[1] Stoenescu L.C., *Contributions to evaluation of damages resulted from flooding caused by dam failure* (PhD Thesis, U.T.C.B, Bucharest, Romania, 2009).

[2] Badea A., Chiuta I., Valciu A., Sima M., *Critical Infrastructure Management of Electro-Energetic Systems* (Annals of the Academy of Romanian Scientists, **2**, 135, 2010).

[3] Mateescu C., *Hydraulics* (Didactic and Pedagogic Ed. II, Bucharest, Romania, 1963).

[4] Ying X., Khan A., Wang S.S.Y., *Modeling flood inundation due to dam and levee breach* (US-CHINA Workshop on advanced computational modeling in Hydro – Science & Engineering, Oxford, Mississippi, SUA, 2005).

[5] *HEC-RAS Hydraulic Reference Manual v. 4.1* (US Army Corps of Engineers, SUA, 2010).

[6] *Surface Water Modeling System, SMS* (BOSS International, SUA, 2006).