HYDROLOGIC AND HYDRAULIC ANALYSIS OF LESS STUDIED WATERSHEDS

Diana Šustić[1], Zdenko Tadić[2], Lidija Tadić[3], Tomislav Kržak[1]
[1]Hidroing LTD. Osijek
Zagreb, Croatia
[2]Hidroing LTD. Osijek
Osijek, Croatia
[3]Civil engineering faculty, University of Osijek
Osijek, Croatia
dianas@hidroing-os.hr, zdenkot@hidroing-os.hr, ltadic@gfos.hr, tomislavk@hidroing-os.hr

Abstract

Increasing flooding frequencies of settlements, roads, agricultural lands, and other areas, which often result in high economic losses and threaten human lives, require modelling of high water level hydrographs for less studied watersheds. Accuracy and reliability of the results is dependent on: precipitation data, physical, geographic and other characteristics of the watershed, geometry of river valleys and waterways, and selected method for analysis of precipitation to drainage relation, in other words on defining of overall hydrograph. Processing of physical and geographic characteristics of watershed and preparation of spatial data related to geometry of river valleys and waterways are simplified by using digital elevation models and GIS tools. Calculation of hydrographs is performed using mathematical modelling software HEC-HMS 3.1.0. (Hydrologic Engineering Center - Hydrologic Modelling System). After hydrographs are defined, the next step is to calculate water quantities and levels in waterways based on the calculated inflow from the watershed area. Calculation of water flow in natural streams in modelled as unsteady flow using mathematical modelling software HEC-RAS 4.0 (Hydrologic Engineering Center's River Analysis System) produced by US Army Corps of Engineers – Hydrologic Engineering Centar. Calculations were processed for different values of roughness coefficient for surface runoff and roughness coefficient of waterbed and inundation area until satisfactory values are reached, including approximate flood lines and water level for 5-year recurrence interval on existing water gauge station. Obtained coefficients were used for calculations of water levels for higher order of recurrences.

Keywords: *watershed, drainage, hydrograph, mathematical models.*

1 INTRODUCTION

The river Bednja, on the right confluent of river Drava, is long 106 km. Due to her characteristics it is divided in to lowland and mountain sections. The river Bednja has the shape of a fan watershed in the upper part with runoff from the hills Ivančica, Ravna gora and Kalnik mountains that forms flash floods causing frequent flooding and erosion of river bed. The area of mountain part watershed is 378 km^2. The only available data on the watershed is recorded flood levels one limnigraph station Bednja-Željeznica, which have acceptable sets of measurements.

2 HYDROLOGIC MODEL

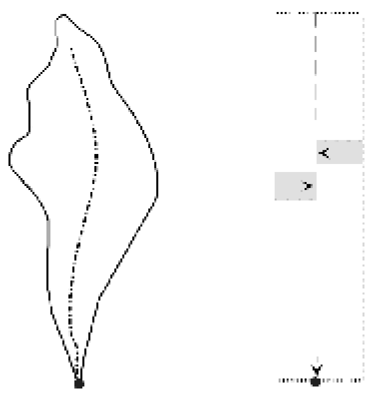
The hydrologic analysis was made with the mathematical modeling software HEC HMS 3.1.0. (Hydrologic Engineering Center - Hydrologic Modeling System) which describes runoff characteristic through the following hydrological input data: meteorological model, basin model, control specifications

The chosen methods of calculation are:

- Transformation of surface runoff using kinematic-wave method
- Infiltration losses using SCS (Soil Conservation Service) curve number loss model

2.1 Kinematic-wave model

This model represents a watershed as an open channel (a very wide, open channel), with inflow to the channel equal to the excess precipitation. Then it solves the equations that simulate unsteady shallow water flow in an open channel to compute the watershed runoff hydrograph.
Figure 1. (a) shows a simple watershed for which runoff is to be computed for design, planning, or regulating. For kinematic wave routing, the watershed and its channels are conceptualized as shown in Figure 1. (b). This represents the watershed as two plane surfaces over which water runs until it reaches the channel. The water then flows down the channel to the outlet.



(a) (b)

Figure 1.: Simple watershed with kinematic-wave model representation

At the heart of the overland model are the fundamental equations of open channel flow: the momentum equation and the continuity equation. Flow over the plane surfaces is primarily one-dimensional flow. In one dimension, the momentum equation is:

$$S_f = S_0 - \frac{\partial y}{\partial x} - \frac{V}{g}\frac{\partial y}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t}$$

S_f energy gradient
S_0 bottom slope
V velocity
y hydraulic depth;

x distance along the flow path
t time
g acceleration due to gravity;

This equation, these terms, and the basic concepts are described in detail in Chow (1959), Chaudhry (1993), and many other texts.

The energy gradient can be estimated with Manning's equation, which can be written as :

$$Q = \frac{CR^{2/3}S_f^{1/2}}{N}A$$

Q flow
R hydraulic radius
A cross-sectional area,
N a resistance factor that depends on the cover of the planes (note that this is not Manning's n).

For shallow flow, bottom slope and the energy gradient are approximately equal and acceleration effects are negligible, so the momentum equation simplifies to:

$$Q = \alpha A^m$$

Where α and m are parameters related to flow geometry and surface roughness.

The second critical equation, the one-dimensional representation of the continuity equation, is:

$$A\frac{\partial V}{\partial x} + VB\frac{\partial y}{\partial x} - B\frac{\partial y}{\partial t} = q$$

B water surface width
q lateral inflow per unit length of channel;

Again, the equation, the terms, and the basic concepts are described in detail in Chow(1959), Chaudhry (1993), and other texts.

With simplification appropriate for shallow flow over a plane, the continuity equation reduces to:

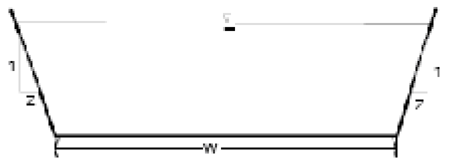
$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q$$

Combining the continuity and the momentum equation as a rusult folov the equation:

$$\frac{\partial A}{\partial t} + \alpha m A^{(m-1)}\frac{\partial A}{\partial x} = q$$

This equation is a kinematic-wave approximation of the equations of motion. HEC-HMS represents the overland flow element as a wide rectangular channel of unit width; α=1.486 $S_{1/2}$/N and m=5/3. N is not Manning's n, but rather an overland flow roughness factor.

For certain classes of channel flow, conditions are such that the momentum equation can be simplified. In those cases, the kinematic-wave approximation of of early mentioned equation is an appropriate model of channel flow. Values for α and m for diferent types of section channel shapes used in HECHMS could be defined. The Kinematick wave equaton for the trapezoidal section is given below:



$$Q = \frac{1.49}{n} S^{1/2} A^{5/3} \left(\frac{1}{W + 2Y\sqrt{1+Z^2}} \right)^{2/3}$$

The kinematic-wave approximation is solved in the same manner for either overland or channel flow:

- The partial differential equation is approximated with a finite-difference scheme;
- Initial and boundary conditions are assigned
- The resulting algebraic equations are solved to find unknown hydrograph ordinates.

In the early mentioned equation, A is the only dependent variable, as α and m are constants, so solution requires only finding values of A at different times and locations. To do so, the partial difference scheme approximates with finite difference scheme using a scheme proposed by Leclerc and Schaake (1973). The resulting algebraic equation is:

$$\frac{A_i^j - A_i^{j-1}}{\Delta t} + \alpha m \left[\frac{A_i^{j-1} + A_{i-1}^{j-1}}{2} \right]^{m-1} \left[\frac{A_i^{j-1} - A_{i-1}^{j-1}}{\Delta x} \right] = \frac{q_i^j + q_i^{j-1}}{2}$$

To estimate runoff with the kinematic-wave model, the watershed is described as a set of elements that include:

Overland flow planes	**Main channel**
• Typical length L (km) • Representative slope S (‰) • Overland-flow roughness coefficient • Area represented by plane • Loss model parameters	• Channel length • Channel slope • Representative Manning's roughness coefficient • Principle dimensions of channel cross section)

2.2 Basin model

The runoff model scheme is defined by a grid of runoff elements and it analyzes each of them by their dimensions and hydrological parameters
The Mountain part of the river Bednja watershed is divided into main confluent and from it divided into smaller sub watersheds. For each sub watershed there are defined physical characteristics based on topographic maps, ortophoto maps and site visits

$\mathbf{L} = \sqrt{\frac{\mathbf{F(2-K)}}{\mathbf{K}}}$ typical lenght, lenght of the fictive rectangle in km

F wathershed area in (km2)

K watershed concentration coefficient $\mathbf{K} = \frac{\mathbf{2F}}{\mathbf{OU}}$

U distance from barycenter (km)

O watershed perimeter (km)

$\mathbf{S} = \frac{\mathbf{2\Delta A}}{\mathbf{L}}$ representative slope of the watershed (‰)

where is: $\Delta A = A_{sr} - A_{min}$

A_{sr} - average altitude of the watershed

A_{min}- altitude of the watershed on the outlet

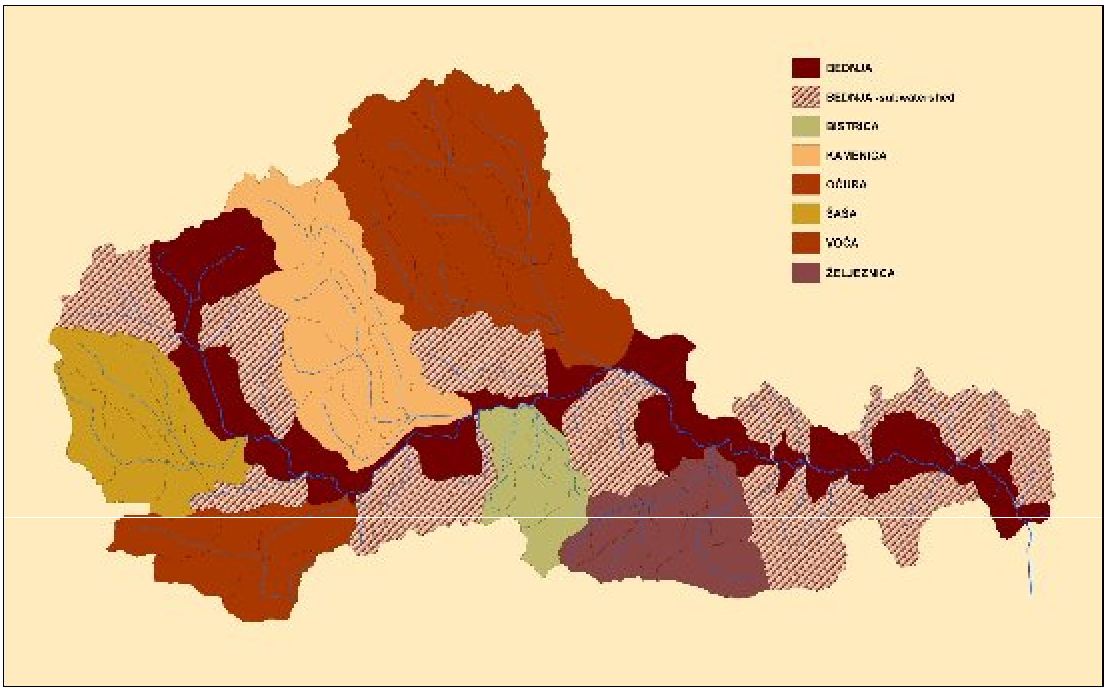


Figure 2.: Map of the mountain part of the river Bednja watershed

2.3 Meteorological model

Meteorological model – the rain model, which defines precipitation events with basic meteorological data: precipitation – definition of applicable rain event on each observed runoff element, evapotranspiration, snow.

For the use of the regulation of the mountain watershed part there was an ombrograf record that was analyzed, from main meteorological station Varaždin for the period 1955-2005. Evaluation of maximum expected precipitation volumes were defined with help of Jenkinsons general distribution of extreme values. By the calculated parameters of distribution of extremes, considering relationship between variant y and return period Tr (years), one can calculate evaluation of extreme values for the selected return period therefore values for which is certain that will be overcome once in the Tr period. In this way maximum values of precipitation were estimated which could be expected to occur in return period of 5, 10, 25, 50, 100, 1000 years. On the other hand there should be mentioned that estimated maximum values of precipitation for return period 1000 years have small reliability taking into account the smaller record data available.

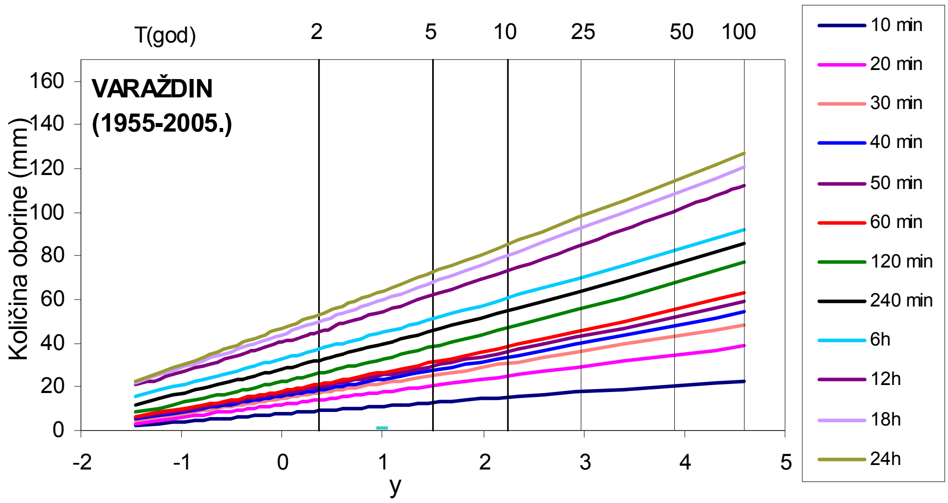


Figure 3.: Estimated maximum precipitation value per year for the time period from 10 min – 24 hour (meteorological station Varaždin 1955-2005).

Control specifications – these are one of the main components in the model. Their principle purpose is to control when simulations start and stop, and what time interval is used in the simulation.

3 HYDRAULIC MODEL

The next step in the analysis of the mountain part of the river Bednja watershed is to calculate water levels and flow rates for the Bednja river based on output hydrographs from the hydrologic model above.

While carrying out unsteady processes in the main channel and inundation, mathematical model HEC-RAS (Hydrologic Engineering Center's River Analysis System) version 3.1.3 developed in the US Army Corps of Engineers – Hydrologic Engineering Center has been used. HEC-RAS supports one-dimensional steady and unsteady flow water surface profile calculations, as well as rapidly varied unsteady flow in open channel.

One-dimensional equations of open channel flow are based on continuity equation and momentum equation, known as Saint-Venant equations. These equations could be solved if initial and boundary conditions are known.

Preparation of records and furthermore analysis of output results has been done with help HEC-GeoRas. HEC-GeoRAS is a set of ArcGIS tools specifically designed to process geospatial data for use with the HEC-RAS.

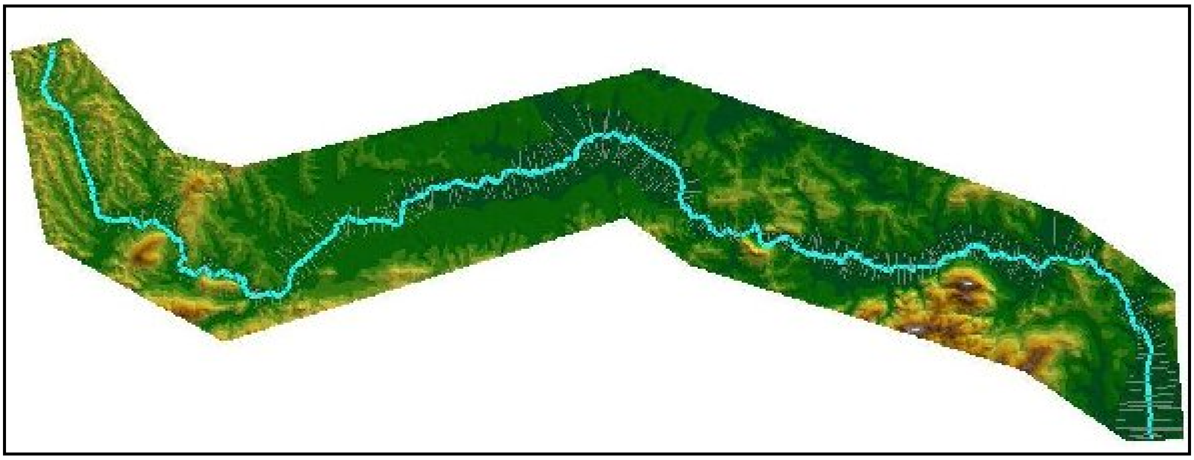


Figure 4.: Digital model of Bednja river valley

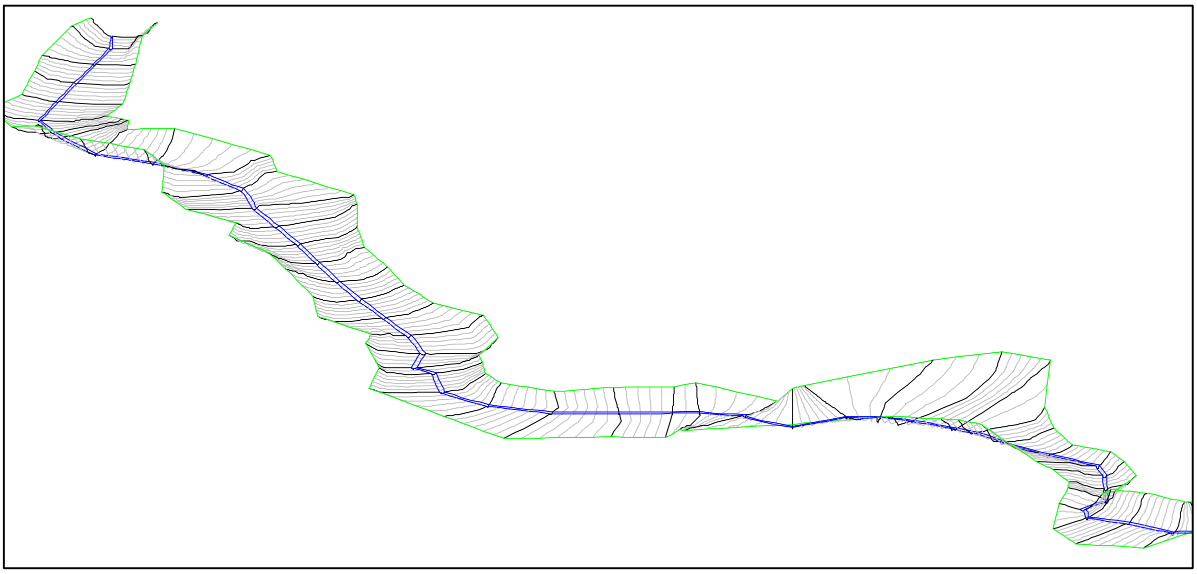


Figure 5.: Geometry of river-bed

Boundary conditions were set and initial roughness coefficient were defined on river bed geometry and flow rates of the sub watersheds for each returned period were established.

3.1 Model calibrating

Calibration was performed on the model based on the recorded high frequency of floods in the mountain part of the river Bednja watershed. Records were taken from limnigraph station Bednja-Željeznica for a returned period of 5 year.
The Calculation is repeated for different values of roughness coefficient until the results approximated to the 5 year return period from earlier mentioned limnigraph station.

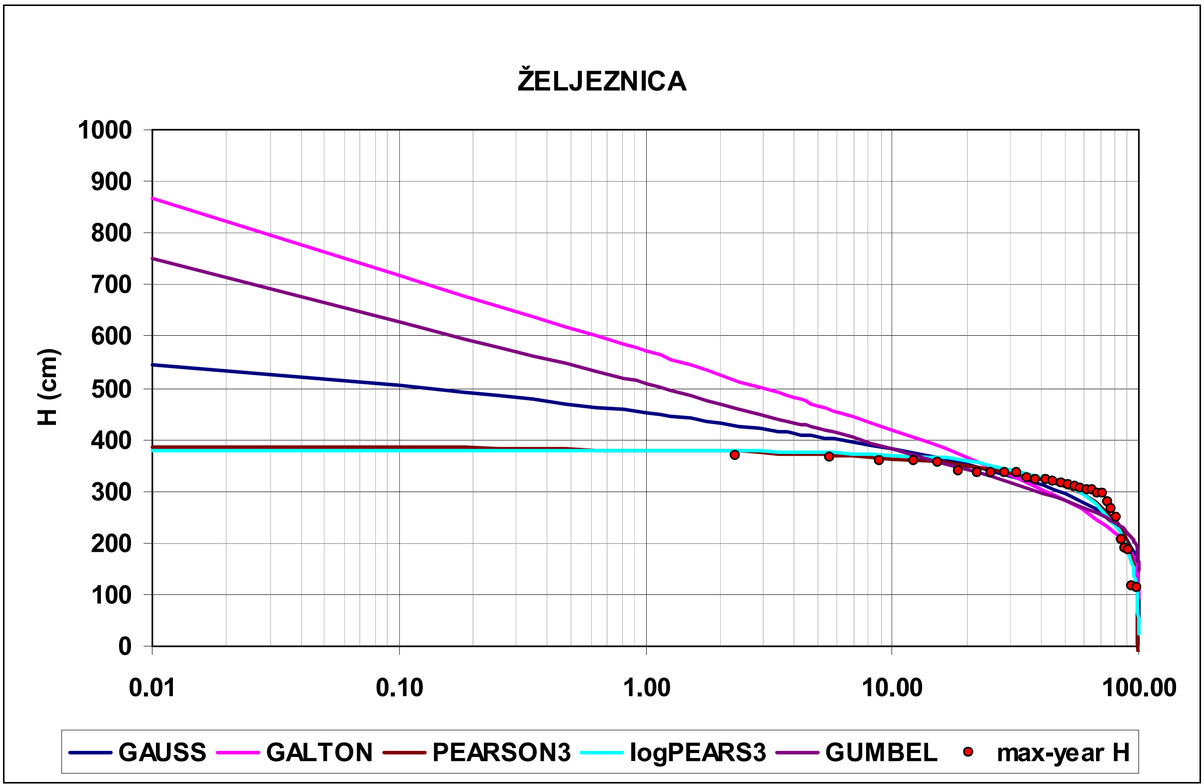


Figure 6.: Maximum water levels probability curve analyze

3.2 The modeling results

	water gauge station	model
H (cm) / H (m.a.s)	**350 cm / 200.33 m.a.s**	**350 cm / 200.33 m.a.s**
Q (m^3/s)	**64,86 m^3/s**	**67,07 m^3/s**

Table 1. The modeling results for return period of 5 years

The results have been obtained for the values of the overland-flow roughness coefficient (N) and for Manning´s roughness coefficients of river bed and inundation.

Overland-flow roughness coefficient:

plough-fields N=0.06
woods N=0.40
meadows N=0.15
vineyards N=0.08

Manning's roughness coefficient of the river bed (n) 0,036 – 0,071
Manning's roughness coefficient of the inundation (n) 0,042 – 0,083

The Obtained coefficients were used for calculating water levels of 25, 50, 100 years repetition period.

4 CONCLUSION

The hydrologic and hydraulic analyses were made with mathematical modeling software HEC HMS and HEC-RAS base on known records of precipitation data, watersheds, land usage, topographic maps (scale 1:5000), ortophoto maps (scale 1:5000), site visits, contacts with local inhabitants, geological maps, present buildings and infrastructure as a result, maximum water levels and waters waves along water courses for the different return periods were computed.

This kind of analysis is the first step towards the watershed planning. Based on earlier mentioned analysis there could be defined on site measurement points for future detailed analyses of relationship among precipitation and runoff, with which existing model could be upgraded.

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