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Hydrological and Hydraulic Modelling

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University of Nis

HYDRAULIC MODELING OF FREE SURFACE FLOWS FOR THE PURPOSES OF FLOOD HAZARD MAPPING

Introduction

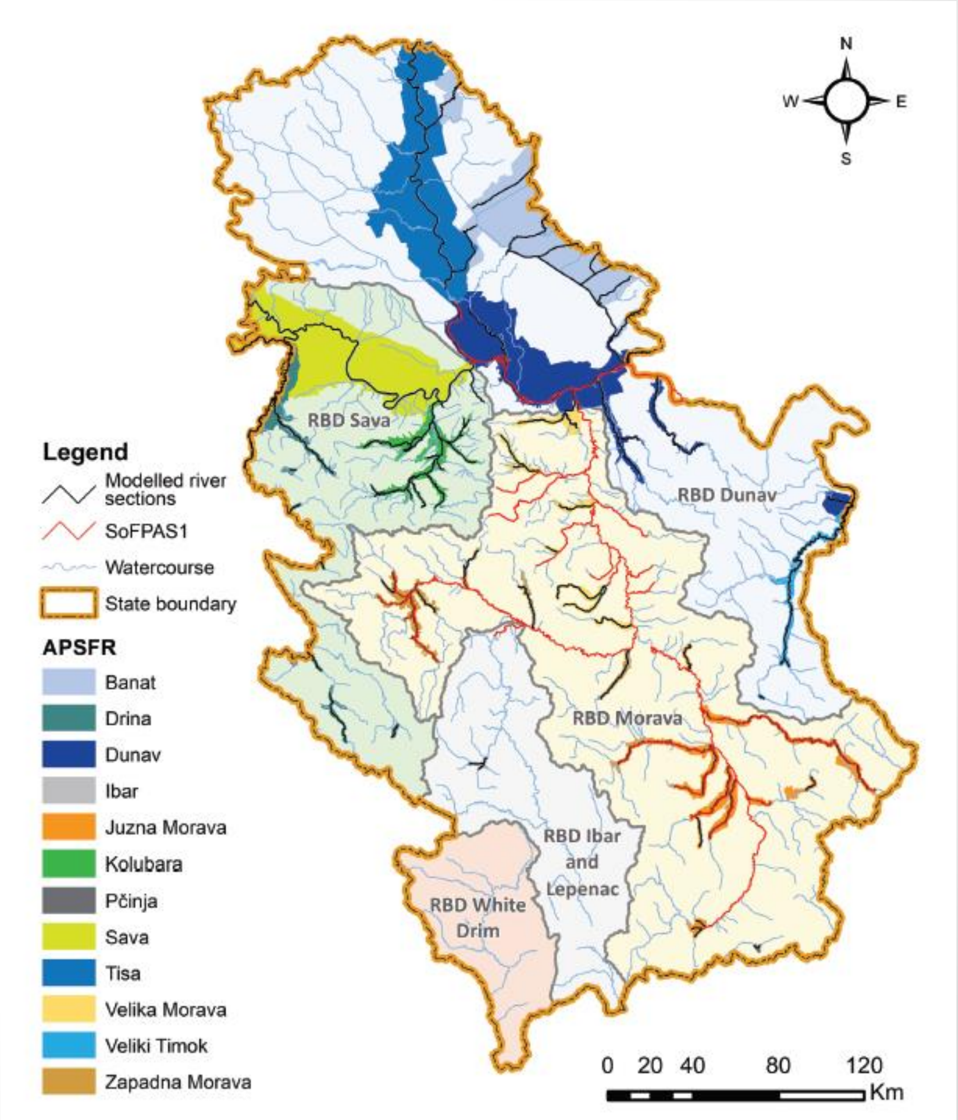
- According to CEA data the flood induced damage costc in the time period 1986 – 2006 exceed **100 B. €**
- Directive 2007/60/EC on the assessment and management of flood risks
    - Flood risk management plans (FRMPs)
    - First cycle – 2016 – 2021
    - Second cycle – 2022 – 2027
        - Preliminary flood risk assessment (PFRA) + Areas of Potentially Significant Flood Risk (APSFR)
        - Flood hazard and flood risk mapping (FHRM)
        - Development of Flood risk management plan (FRMP) with Programme of Measures (PoM)

Introduction

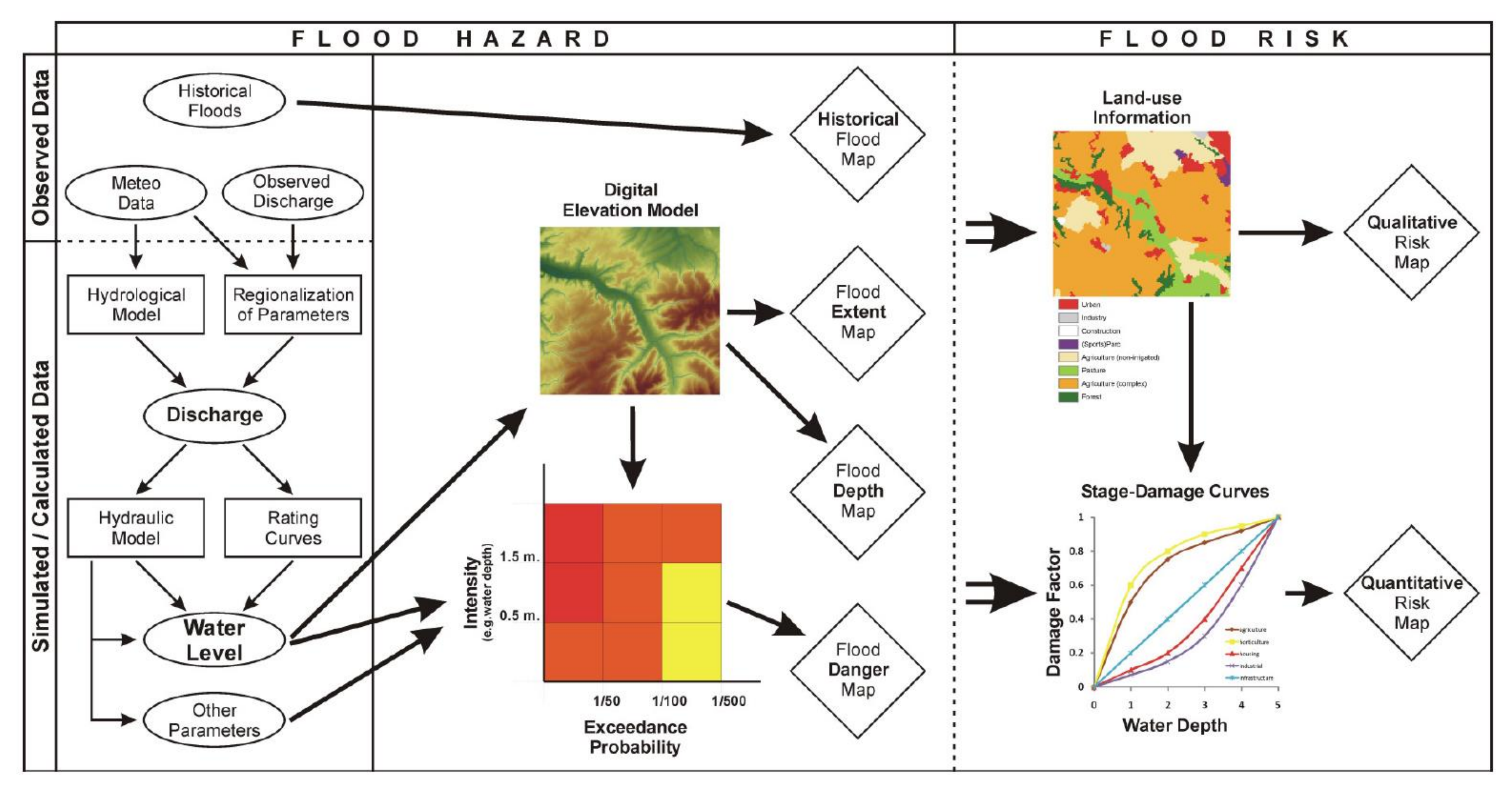
- Following the 2014 floods, the Serbian Government approved a National Disaster Risk Management Program to develop a long-term risk management system, including the generation of flood risk information.
- Republic of Serbia is aligning its water legislation with the EU
  - the EU Floods Directive is almost fully transposed into the Water Law in Serbia

Introduction

- 75 Areas of Potentially Significant Flood Risk (APSFR)
  - 16% of the territory



1. Flood hazard and flood risk mapping



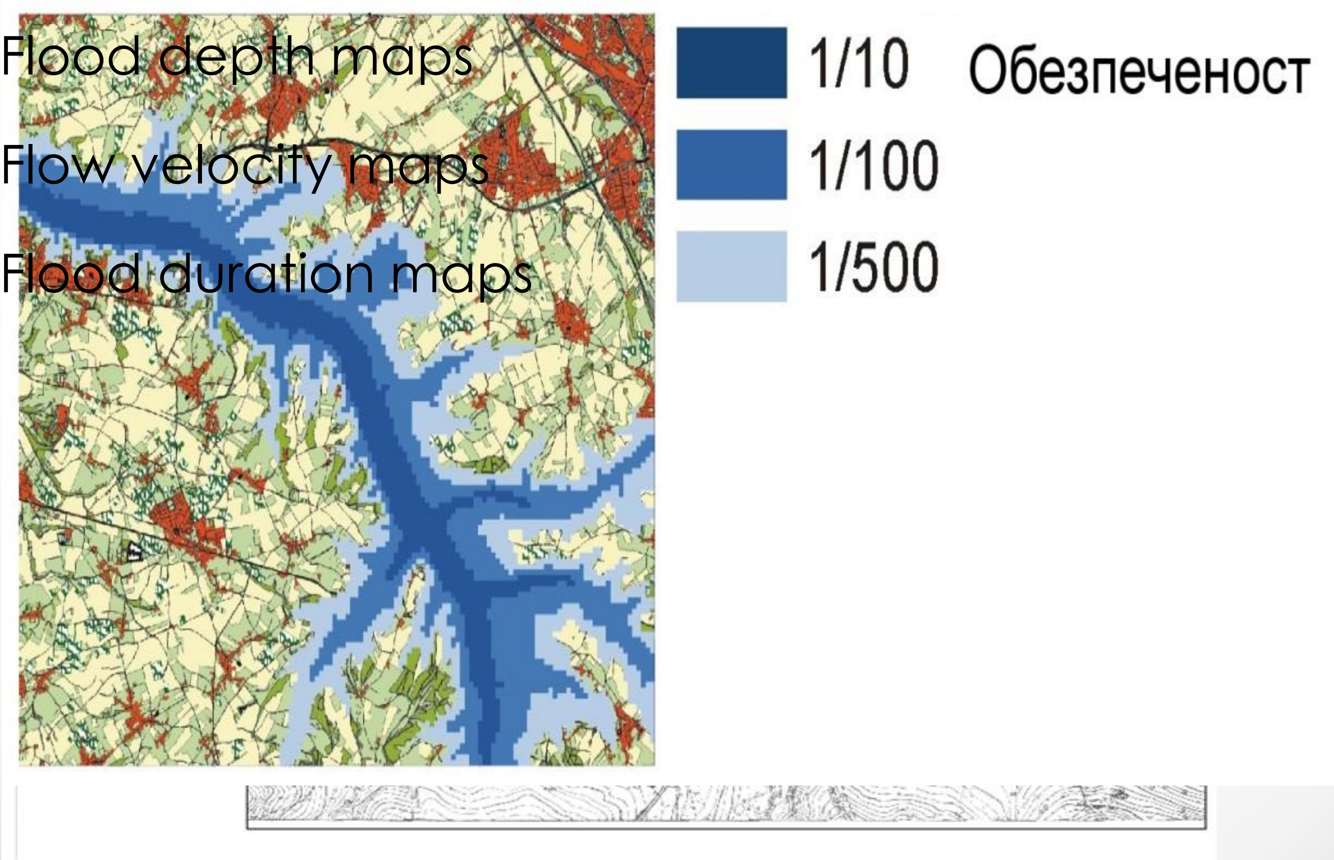
(de Moel, van Alphen and Aerts 2009)

1. Flood hazard and flood risk mapping

- *1.1* Assessment and mapping of flood hazard
    - Estimation of flood discharges with characteristic probabilities of exceedance
    - **Estimation of flood water levels for the characteristic discharges**
    - Estimation of flood extents and flood depths for the obtained water levels

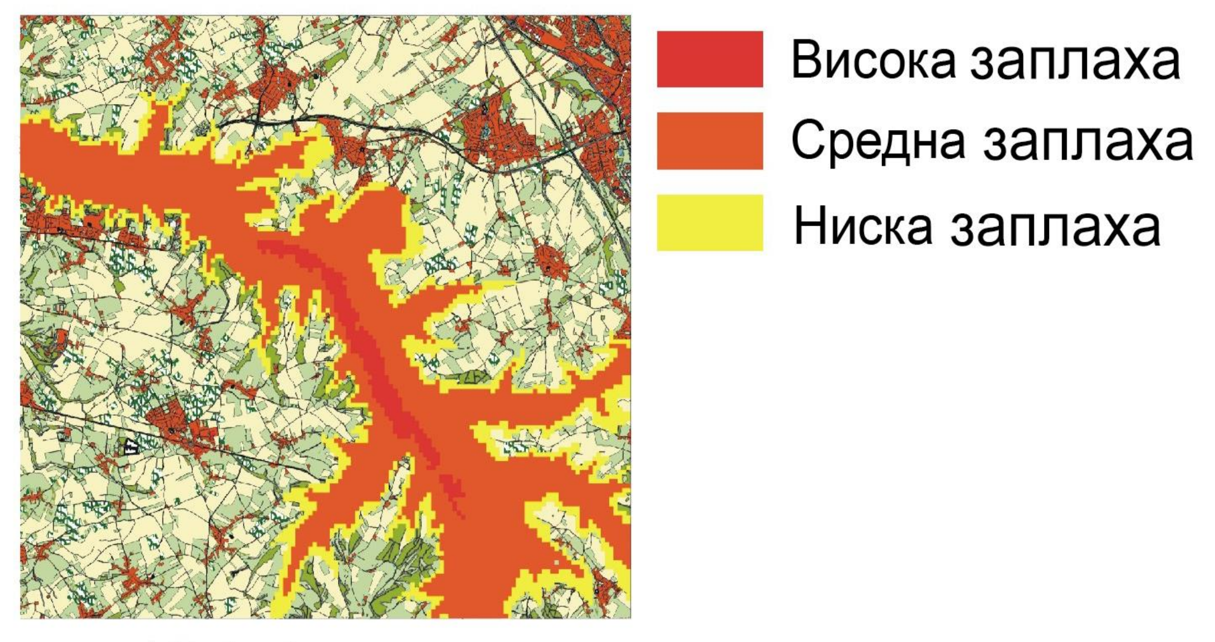
1. Flood hazard and flood risk mapping

- *1.2* Map types
  - Flood extent maps
  - Flood depth maps
  - Flow velocity maps
  - Flood duration maps



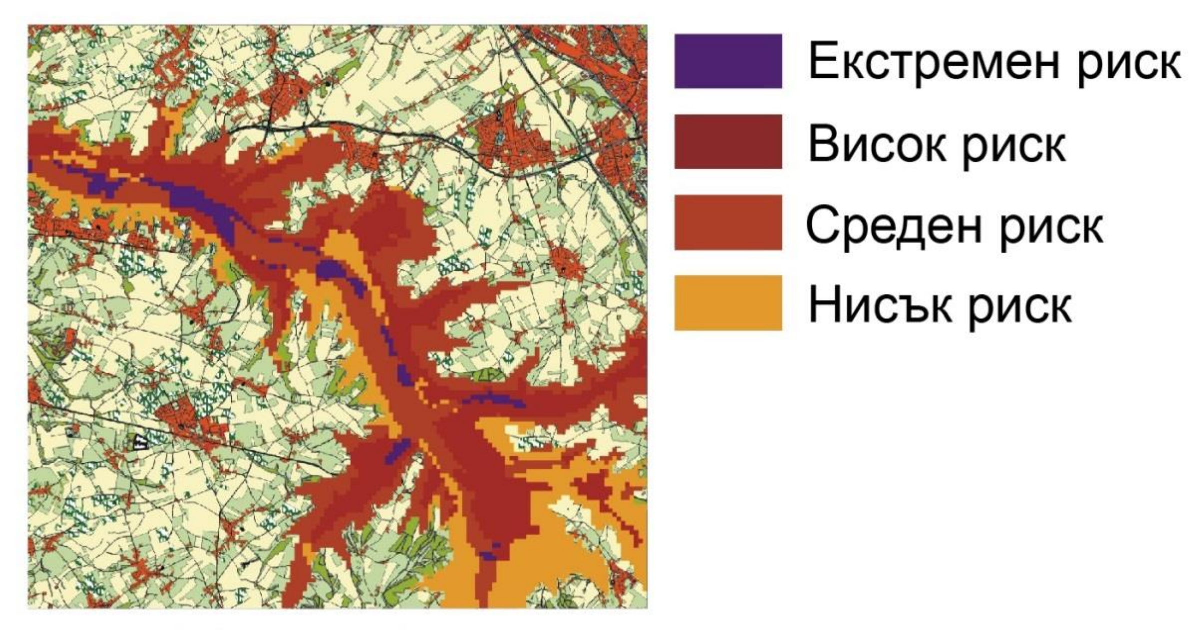
1. Flood hazard and flood risk mapping

- *1.2* Map types
  - Flood danger maps



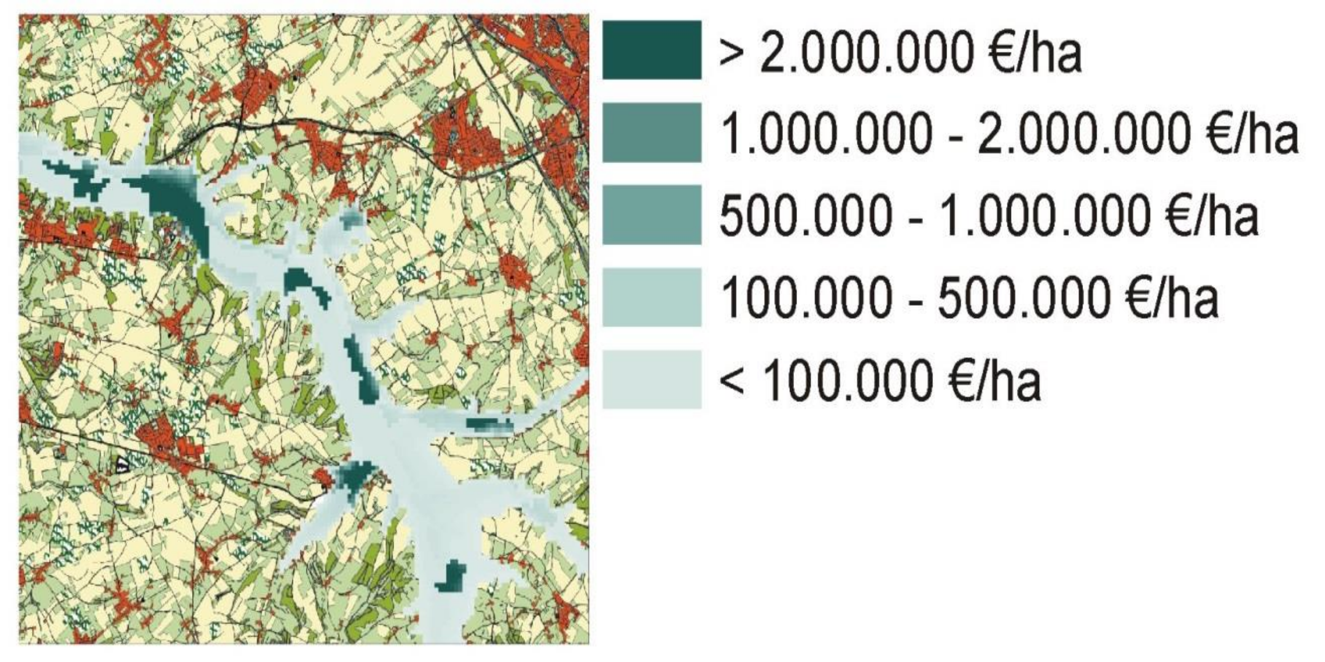
1. Flood hazard and flood risk mapping

- *1.2* Map types
  - Flood risk maps
    - Qualitative risk map



1. Flood hazard and flood risk mapping

- *1.2* Map types
  - Flood risk maps
    - Quantitative risk map



1. Flood hazard and flood risk mapping

- Mandatory maps according Directive 2007/60/EC
  - **Flood extent maps** for probabilities of exceedance 0.1% and 1%, and if/where needed - 5%
  - **Quantitative risk maps**, which show the number of potentially affected citizens, type of affected economic activity, affected protected areas and potential contamination sources
- The member states are encouraged to prepare additional **flow depth and flow velocity maps**

1. Flood hazard and flood risk mapping

- Responsible institutions:
  - Governments
  - Transboundary Basin Directorates
  - Insurance companies

1. Flood hazard and flood risk mapping

- Measures for flood risk reduction:
  - Extremely reach European experience
  - Bulgarian experience, resp. Serbian experience
  - Classification of measures
    - Non-structural measures for sustainable prevention, protection and mitigation of the negative impact of floods
    - Structural measures for flood protection

1. Flood hazard and flood risk mapping

- Measures for flood risk reduction:
  - Catalogue of measures
    - According to aspects
    - According type
    - According extent
    - According impact type on the flood risk components

2. Numerical hydraulic modeling

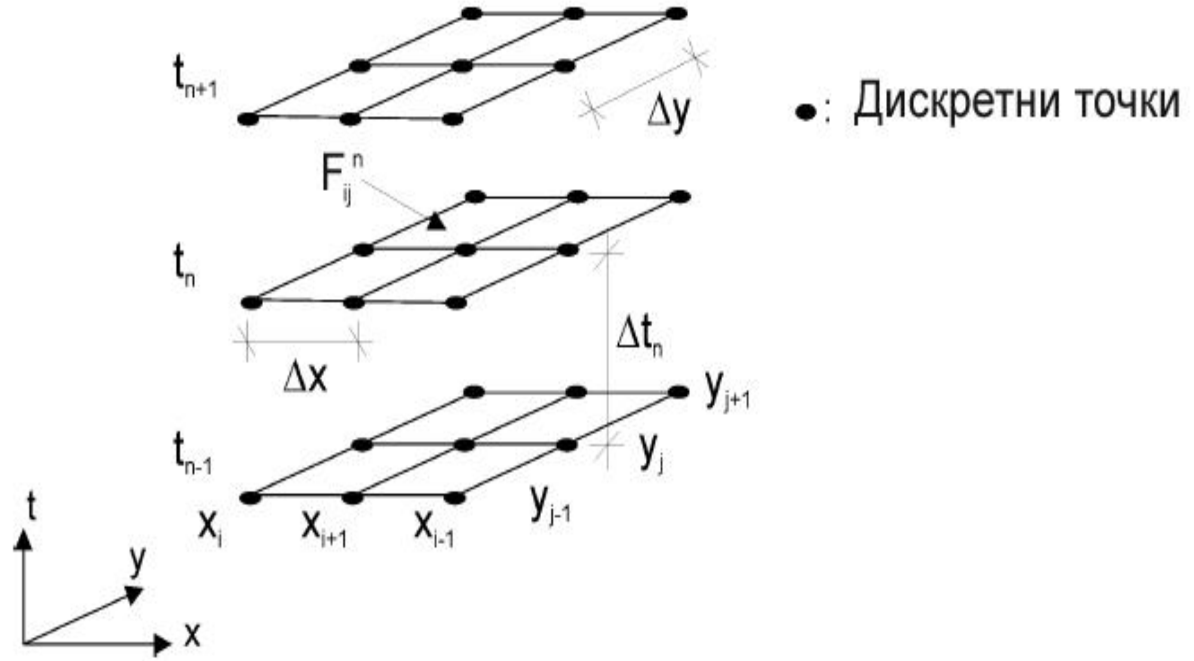
- 2.1 Numerical methods for solving the differential equations of fluid movement
    - 2.1.1 Temporal discretization
    - 2.1.2 Spatial discretization
- 2.2 Numerical problems. Analysis of the numerical schemes
- 2.3 Comparison of spatial discretization methods

2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
    - *3.4.1 One – dimensional (1D)*
    - *3.4.2 Two – dimensional (2D)*
    - *3.4.1 Three – dimensional (3D)*
    - *3.4.1* Conceptual
- *2.5 Specifics of modeling of turbulent flows*
- *2.6 Choice of appropriate model*
- *2.7* Needed input data
- *2.8 Calibration, sensitivity analysis and validation*
- *2.9 Impact of different factors on model accuracy*

2. Numerical hydraulic modeling

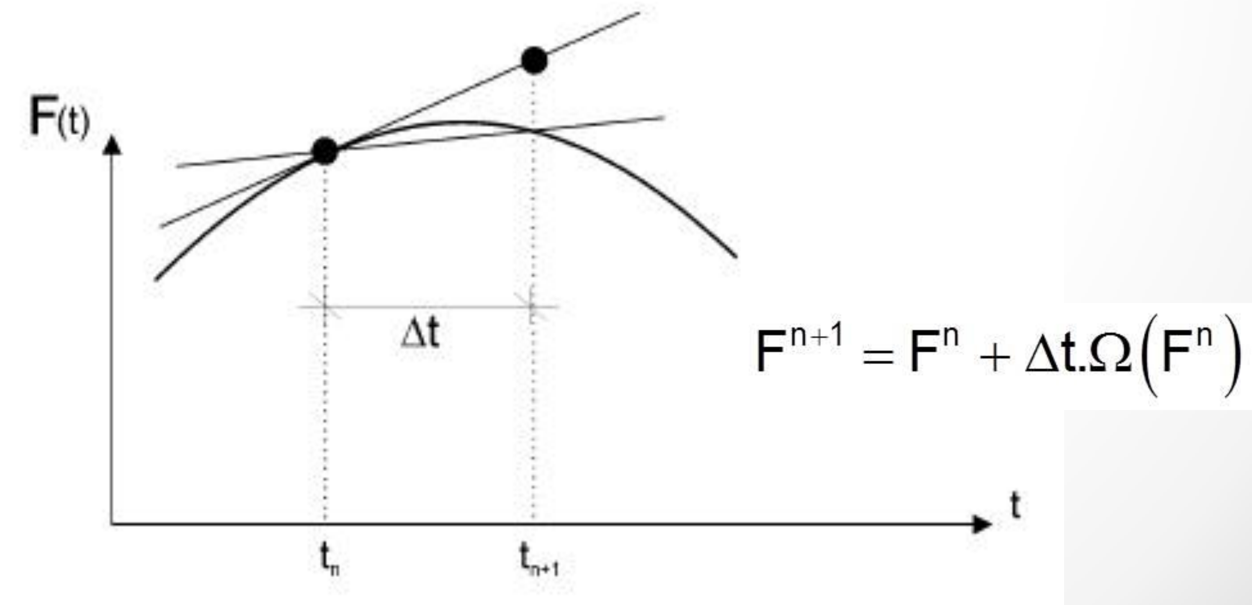
- *2.1* Numerical methods for solving the differential equations of fluid movement



2. Numerical hydraulic modeling

- *2.1* Numerical methods for solving the differential equations of fluid movement
    - *2.1.1* Temporal discretization
        - *2.1.1.1* Explicit one-step methods

Explicit Euler method

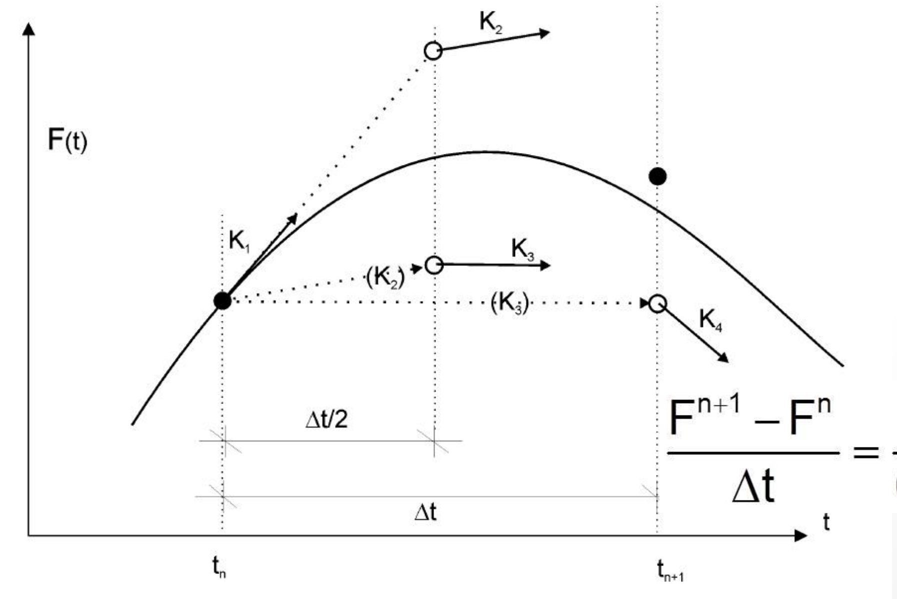


$$F^{n+1} = F^{n} + \Delta t.\Omega\left(F^{n}\right)$$

2. Numerical hydraulic modeling

- *2.1* Numerical methods for solving the differential equations of fluid movement
  - *2.1.1* Temporal discretization
    - *2.1.1.1* Explicit one-step methods

Runge – Kutta methods

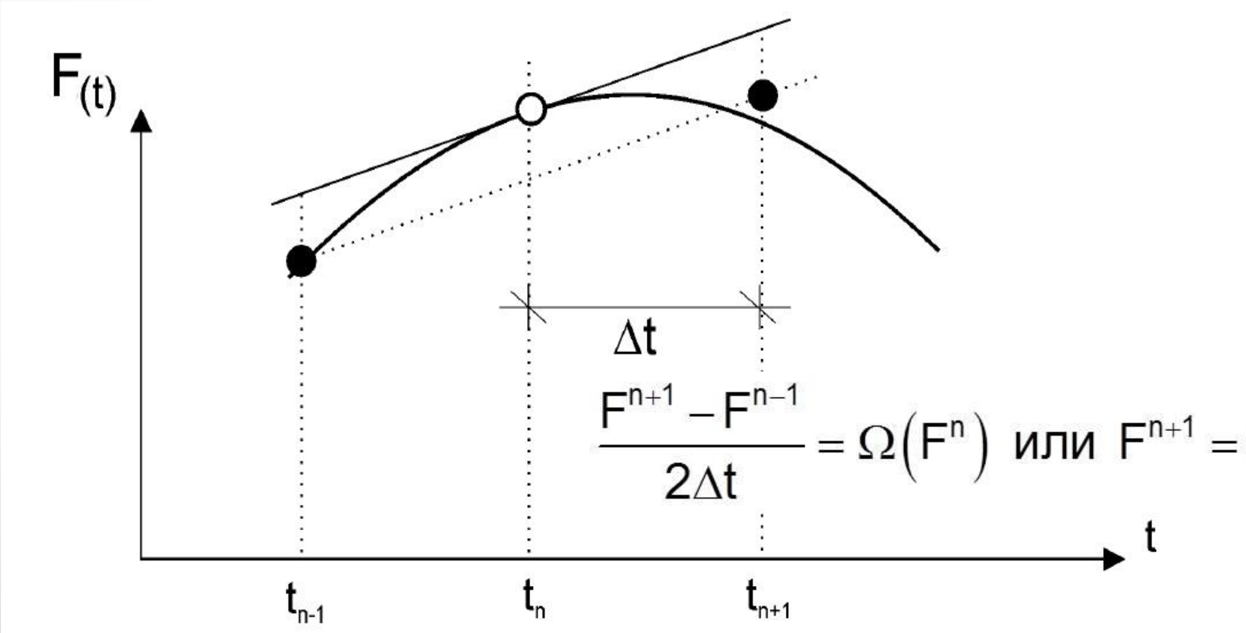


$$\frac{F^{n+1}-F^{n}}{\Delta t}=\frac{1}{6}\left(k_1+2k_2+2k_3+k_4\right)$$

2. Numerical hydraulic modeling

- *2.1* Numerical methods for solving the differential equations of fluid movement
    - *2.1.1* Temporal discretization
        - *2.1.1.2* Explicit multi-step methods

Leap – Frog method

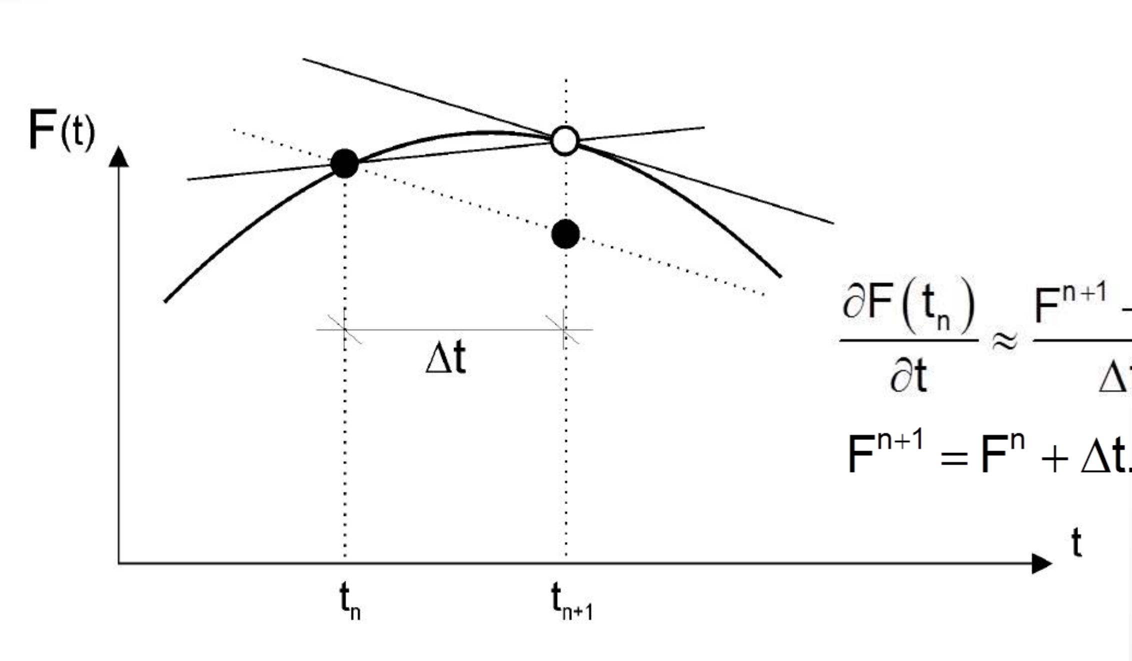


$$\frac{F^{n+1}-F^{n-1}}{2\Delta t}=\Omega\left(F^{n}\right) \text{ или } F^{n+1}=2.\Delta t.\Omega\left(F^{n}\right)+F^{n-1}$$

2. Numerical hydraulic modeling

- *2.1* Numerical methods for solving the differential equations of fluid movement
  - o *2.1.1* Temporal discretization
    - *2.1.1.3* Implicit one-step methods

Implicit Euler method



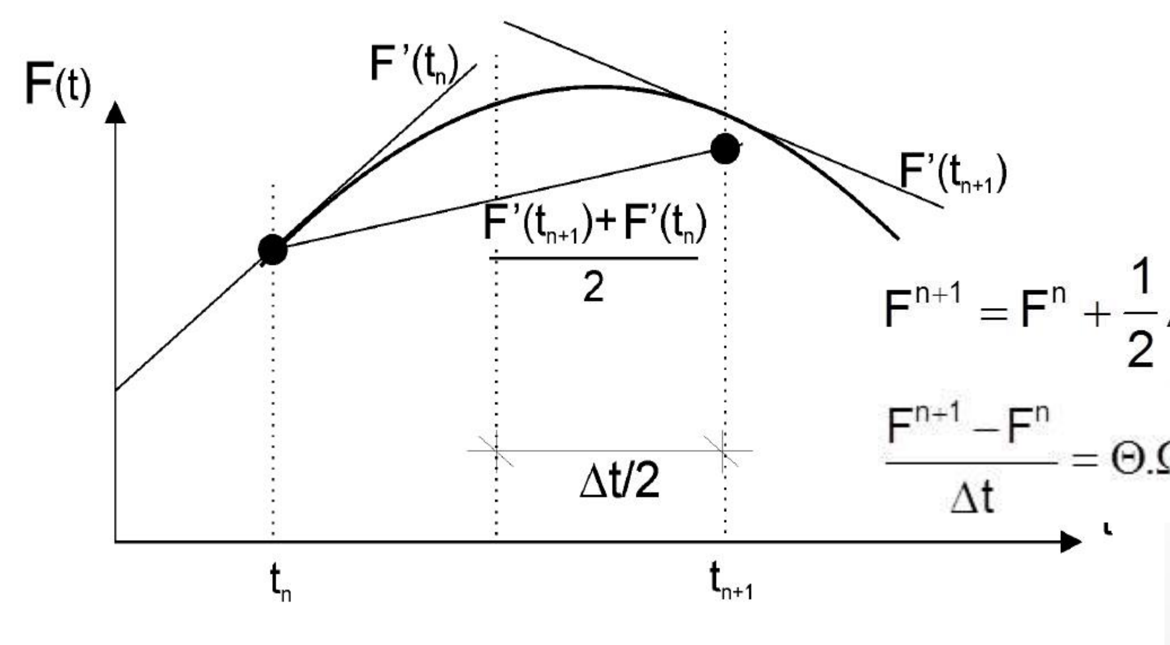
$$\frac{\partial F(t_n)}{\partial t} \approx \frac{F^{n+1} - F^n}{\Delta t} = \Omega\left(F^{n+1}\right)$$

$$F^{n+1} = F^n + \Delta t.\Omega\left(F^{n+1}\right)$$

2. Numerical hydraulic modeling

- *2.1* Numerical methods for solving the differential equations of fluid movement
    - *2.1.1* Temporal discretization
        - *2.1.1.3* Implicit one-step methods

Crank – Nicolson method



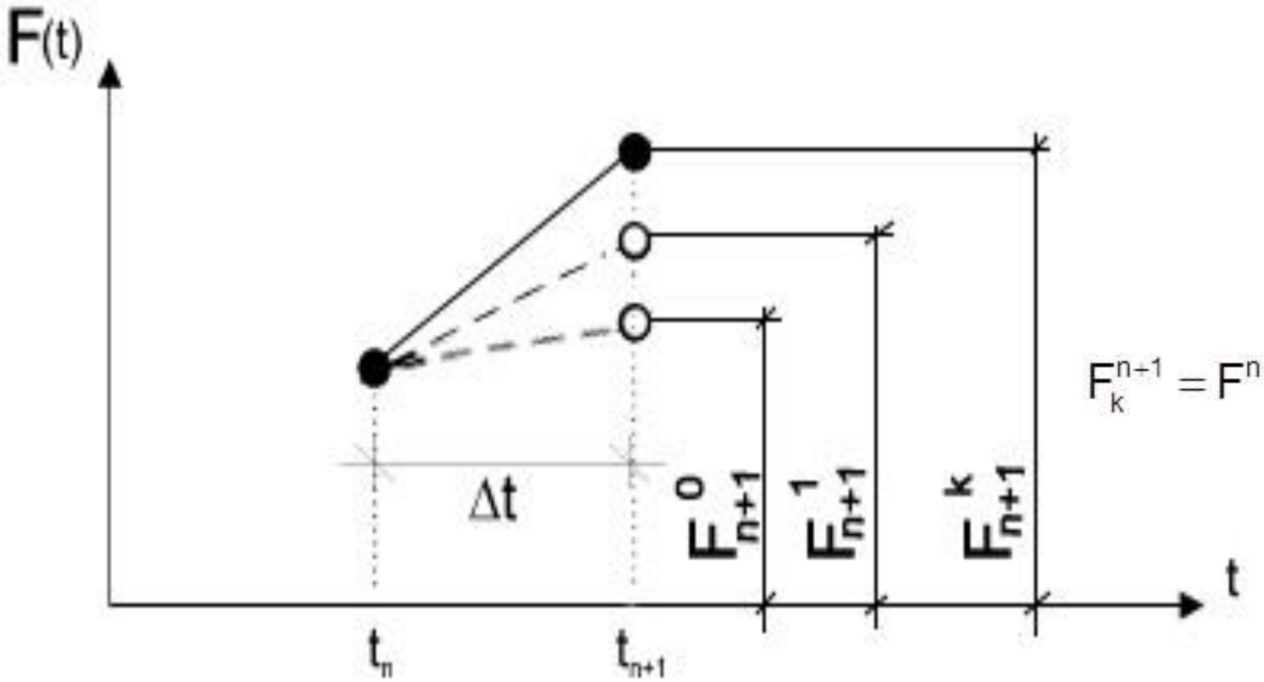
$$F^{n+1} = F^{n} + \frac{1}{2}\Delta t\left[\Omega\left(F^{n+1}\right) + \Omega\left(F^{n}\right)\right]$$

$$\frac{F^{n+1} - F^{n}}{\Delta t} = \Theta.\Omega\left(F^{n+1}\right) + \left(1-\Theta\right)\Omega\left(F^{n}\right)$$

2. Numerical hydraulic modeling

- *2.1* Numerical methods for solving the differential equations of fluid movement
  - *2.1.1* Temporal discretization
    - *2.1.1.3* Implicit multi-step methods

Euler – Cauchy method



$$F_k^{n+1} = F^n + \frac{1}{2}\left[\Omega\left(F^n\right) + \Omega\left(F^{n+1}\right)_{(k-1)}\right]$$

2. Numerical hydraulic modeling

- *2.1* Numerical methods for solving the differential equations of fluid movement
    - *2.1.1* Temporal discretization
    - *2.1.2* Spatial discretization

2. Numerical hydraulic modeling

- *2.1.2* Spatial discretization
    - **Finite difference method**
    - **Finite volume method**
    - **Finite element method**

2. Numerical hydraulic modeling

- *2.1.2* Spatial discretization
  - **Finite difference method**
    - The solution of the differential equation is in discrete form
    - Discretization in grid:
      - In one-dimensional case – arranged along an axis
      - In one-dimensional case – usually in orthogonal grid
    - Very fast calculations
    - It is not suitable for areas with complex geometry

2. Numerical hydraulic modeling

- *2.1.2* Spatial discretization
  - **Finite volume method**
    - The differential equations are not approximated directly, but integrated in control volumes, built around the discrete points
    - „conservative discretization“
    - Huge advantage over FDM if irregular element mesh or curvilinear coordinates should be used
    - Structured and unstructured meshes – very flexible

2. Numerical hydraulic modeling

- *2.1.2* Spatial discretization
  - **Finite element method**
    - In contrast to previous methods, instead of solution in the neighboring points, an approximation function which approximates all the unknown values in the whole domain is looked for
    - Discretization with finite element meshes
      - Most common – irregular triangles or quadrangels

2. Numerical hydraulic modeling

- *2.1.2* Spatial discretization
  - **Finite element method**
    - The differential equations are replaced with their integral (weak) form
    - Usually the solution is performed using the **method of weighted residuals**

$$F^{\delta}(x,t)=\sum_{i=1}^{M}F_i(t).N_i(x)$$

    - Galerkin Method

2. Numerical hydraulic modeling

- 2.2 Numerical problems. Analysis of the numerical schemes
  - Consistency
  - Stability
  - Convergence

2. Numerical hydraulic modeling

- 2.2 Numerical problems. Analysis of the numerical schemes
  - **Consistency**
    - If $\varphi(t_n, \Delta t) \rightarrow 0$ when $\Delta t \rightarrow 0$, then the chosen numerical method is **consistent**
    - It can be used as a mechanism for error evaluation and evaluation of the impact of time step size on the precision of a chosen discretization method
    - The consistency is one of the most important necessary but not sufficient conditions for convergence and stability of the finite numerical schemes

2. Numerical hydraulic modeling

- 2.2 Numerical problems. Analysis of the numerical schemes
  - **Stability**
    - the difference between the calculated and the precise solution of the differential equation to be limited when $n \rightarrow \infty$ for given Δx
    - **Courant, Friedrich и Lewy condition** :
      - **необходимото** условие да бъде една явна диренчна схема, решаваща параболични проблеми, стабилна, трябва за всяка точка от мрежата зоната на зависимост на диференчната схема да съдържа зоната на зависимост на частното диференциално уравнение
    - Анализ на устойчивостта по Von Neumann (или Fourier)

2. Numerical hydraulic modeling

- 2.2 Numerical problems. Analysis of the numerical schemes
  - **Convergence**
    - A scheme is convergent if the difference between the calculated and exact solution disappears when the cell size decreases

$$\lim_{\Delta x,\, \Delta t \to 0} \left| E_i^n \right| = 0$$

    - **Lax theorem**:
      - *The stability is a necessary and sufficient condition for convergence of* ***consistent*** *linear approximation in finite differences for* ***correctly set*** *linear initial condition problem*

2. Numerical hydraulic modeling

- 2.3 Comparison of spatial discretization methods

Критерий за сравнение	Метод на крайните разлики	Метод на крайните обеми	Метод на крайните елементи
Форма, в която се извършват изчисленията	Диференциална форма на частните диференциални уравнения	Интегрална форма	Слаба интегрална форма
Зависимост на решението от изчислителната форма	Колкото по-висок е редът на производната на търсената величина, толкова по-точно е решението ⇒ висока точност	Задължително запазване на масата, количеството движение и енергията ⇒ висока точност Балансиране, независимо от формата на елемента ⇒ гъвкавост	Чрез използването на метода на претеглените остатъци пресмятането се извършва върху цялата изследвана област ⇒ по-точен при едно и също изчислително време

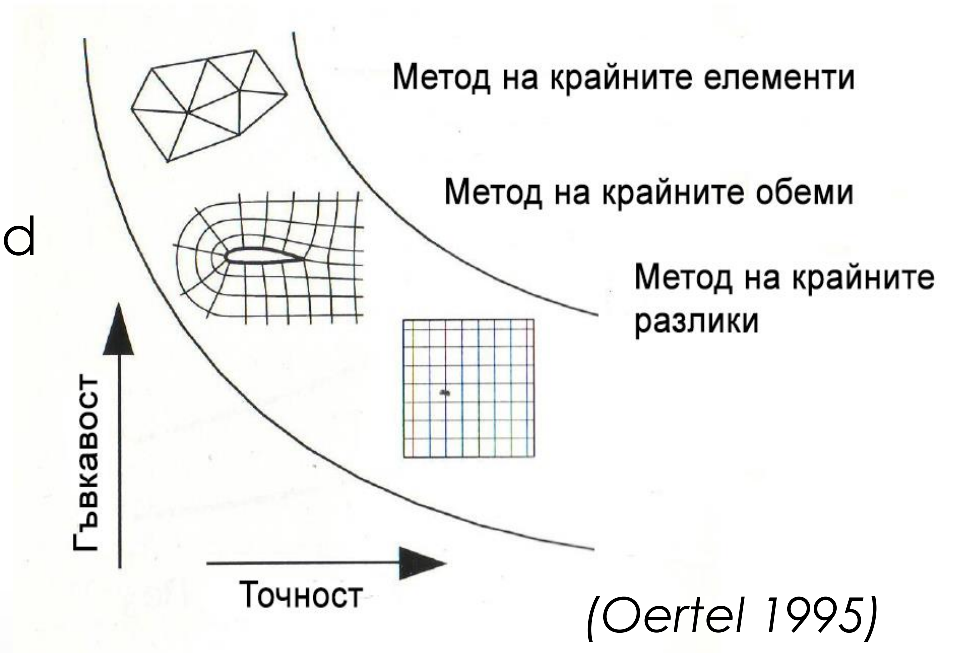
(Opalchenski 2012, Oertel 1995, ÖWAV 2009)

2. Numerical hydraulic modeling

- 2.3 Comparison of spatial discretization methods
  - It can’t be specified which of the three methods has advantage over the other two or is the most appropriate
  - Each method has different advantages and disadvantages. **Knowing them** is essential for choice of the most appropriate one for each particular problem

2. Numerical hydraulic modeling

- 2.3 Comparison of spatial discretization methods
  - **FDM** – appropriate for tasks with relative simple geometry, where a precise solution is achieved with minimal computational time
  - **FVM** and **FEM** are suitable for complex geometries, but the domain should be properly discretized in order to minimize the computational error



(Oertel 1995)

2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
  - **Conceptual models** – a concept is applied, which represents a natural process, i.e. linear reservoir
  - **Deterministic models** – mathematical solution of differential equations, which describe a natural process (hydrodynamic equations, continuity equations etc.)
  - **Stochastic models** – based on simulation of natural processes with statistical methods

2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
  - *One – dimensional (1D) hydraulic models*
  - *Two – dimensional (2D) hydraulic models*
  - *Three – dimensional (3D) hydraulic models*
  - Conceptual *hydraulic models*

2. Numerical hydraulic modeling

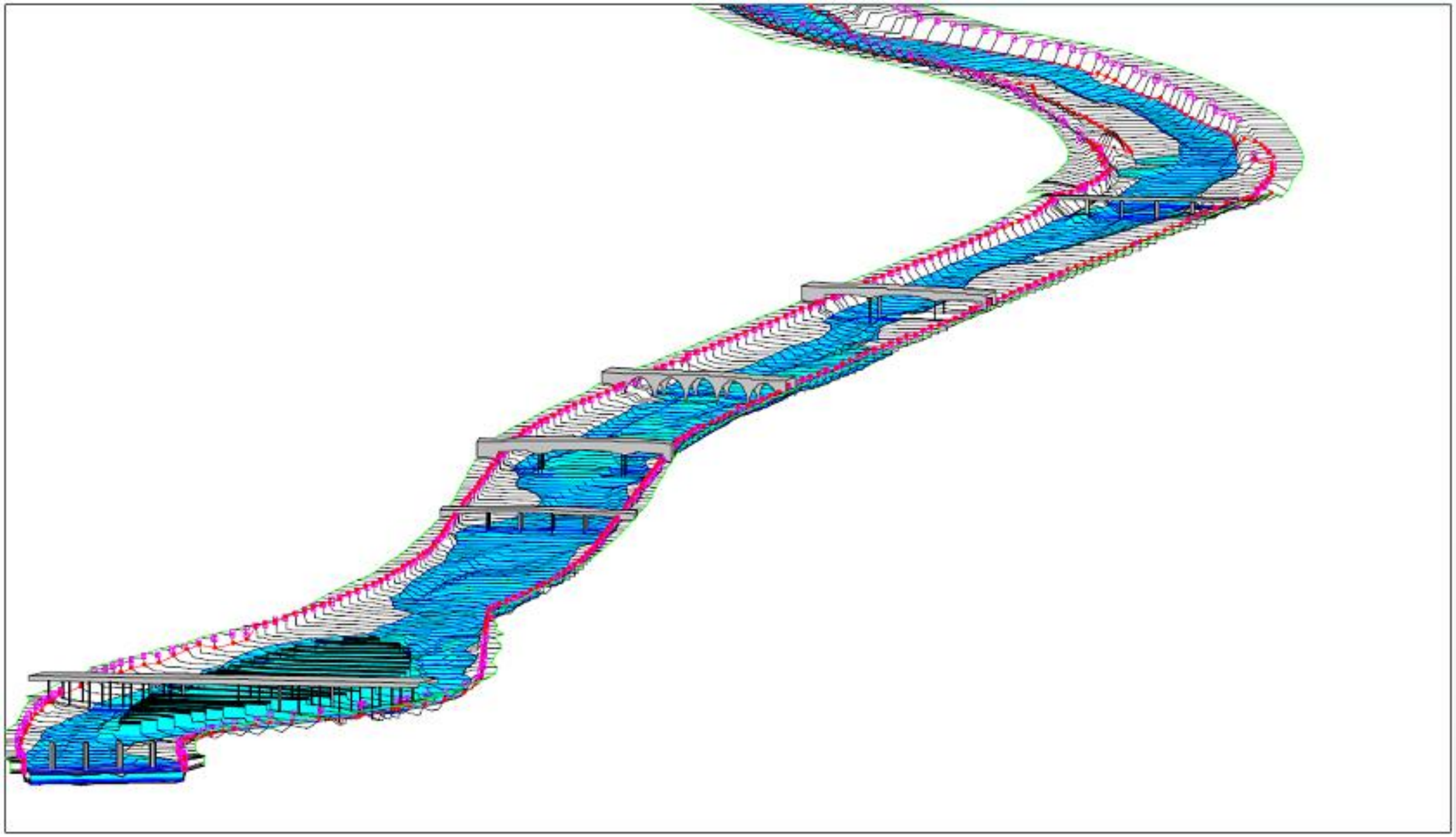
- *2.4 Brief description of the hydraulic models*
  - One – dimensional hydraulic models
    - St. Venant equations

$$\left|\begin{aligned}&\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{\omega}\right)+g\omega\frac{\partial h}{\partial x}-g\omega\left(i_0-i_f\right)=0\\&B\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=0\end{aligned}\right.$$

    - Considers the flow in only one spatial direction and represents the water level as a broken line along the flow
    - The geometry is represented as a sequence of cross sections with their geometric properties

2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
  - One-dimensional hydraulic models



2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
  - One-dimensional hydraulic models
    - Usually the flow velocity is obtained as a **constant value for the whole cross section**
    - The most available models function under the condition for **gradually varied flow**
    - They can simulate the flow through different hydraulic structures – inline structures (weirs), lateral structures, gates, bridges, culverts etc.

2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
    - One-dimensional hydraulic models
    - **Advantages**
        - Simple, can be easily automated, reasonably priced;
        - Appropriate for river topographies which are mainly one-dimensional;
        - Used at large river systems;
        - Short computational times (1D:2D 1:100 up to 1:500);
        - Appropriate for long river reaches or channels.
        - Convenient for flow modeling through hydraulic structures.

2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
  - One-dimensional hydraulic models
  - **Disadvantages**
    - Can be used only if the flowpath is known in advance;
    - Inability to represent some flow specifics – horizontal or vertical flow velocity distribution in the cross section, secondary flows in curves or bends, resp. sloped water surface in cross sectional direction;

2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
  - Two-dimensional hydraulic models
    - Depth-averaged Reynolds' equations

$$\frac{\partial h}{\partial t}+\frac{\partial(hU)}{\partial x}+\frac{\partial(hV)}{\partial y}=0$$

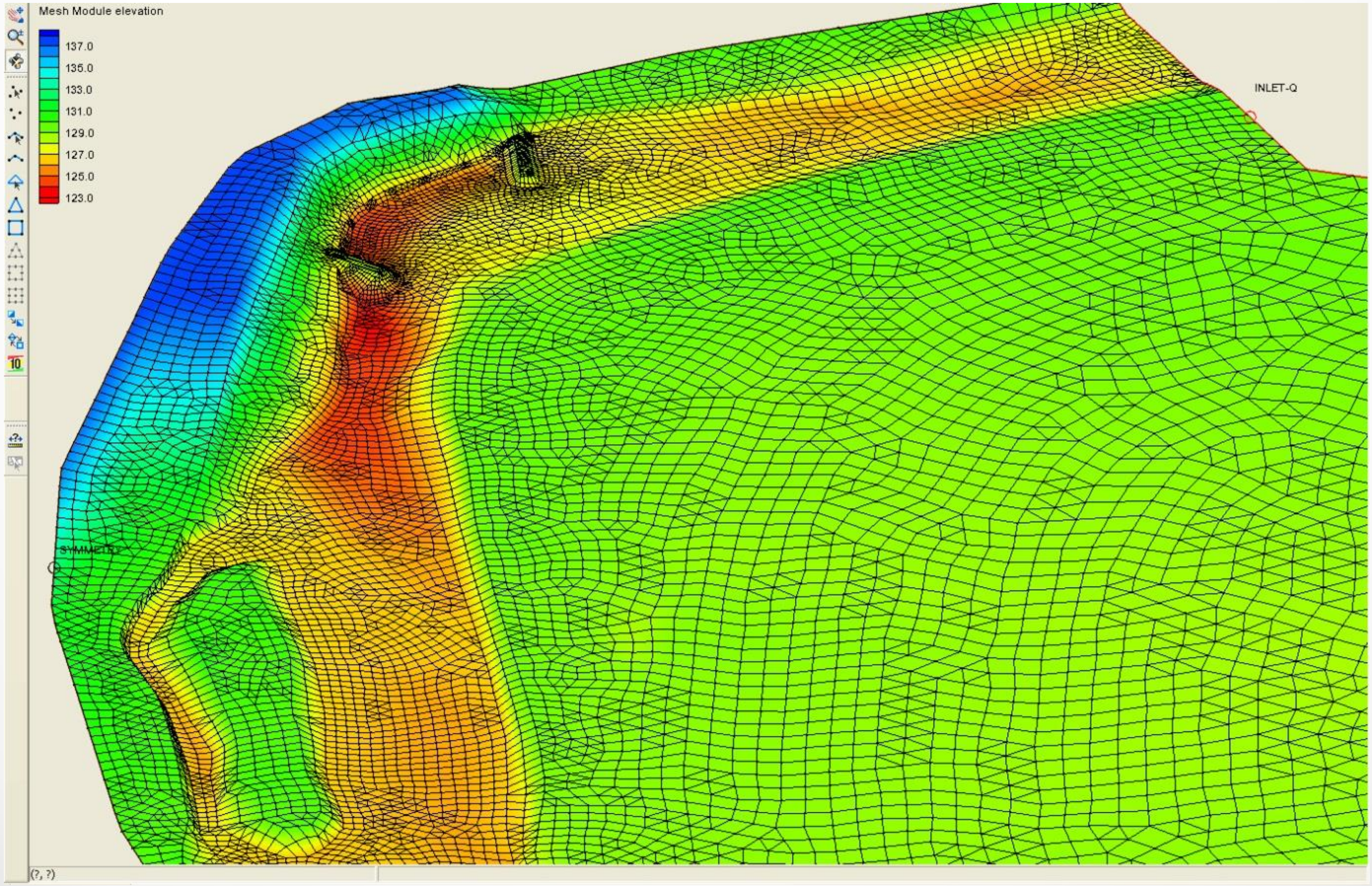
$$\frac{\partial(hU)}{\partial t}+\frac{\partial(hUU)}{\partial x}+\frac{\partial(VU)}{\partial y}=\frac{\partial(hT_{xx})}{\partial x}+\frac{\partial(hT_{xy})}{\partial y}-gh\frac{\partial z}{\partial x}-\frac{\tau_{bx}}{\rho}$$

$$\frac{\partial(hV)}{\partial t}+\frac{\partial(hUV)}{\partial x}+\frac{\partial(VV)}{\partial y}=\frac{\partial(hT_{xy})}{\partial x}+\frac{\partial(hT_{yy})}{\partial y}-gh\frac{\partial z}{\partial y}-\frac{\tau_{by}}{\rho}$$

    - More complex spatial discretization compared to cross section discretization used by 1D models

2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
  - Two-dimensional hydraulic models



2. Numerical hydraulic modeling

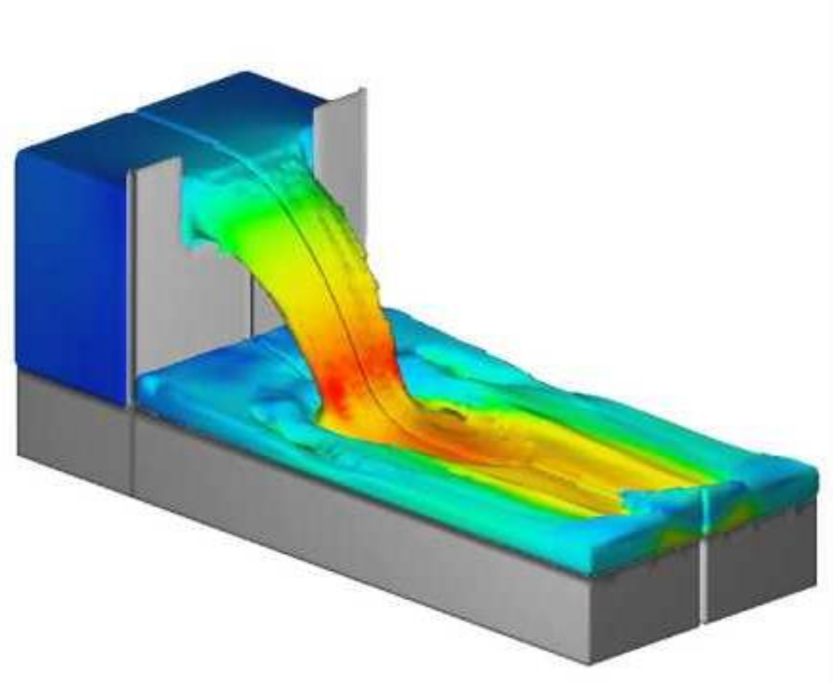
- *2.4 Brief description of the hydraulic models*
  - Two-dimensional hydraulic models
  - **Advantages**
    - Very effective if sufficient high quality input data is available;
    - Velocity components in two plane direction; water level and water depth at each point of the computational mesh;
    - Good representation of the changes in flow parameters in cross section;
    - Suitable for river sections with irregular distribution of flow parameters;
    - Suitable for complex geometries;
    - Huge potential for visualization and presentation of the obtained results.

2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
  - Two-dimensional hydraulic models
  - **Disadvantages**
    - Long computational times (1D:2D 1:100 up to 1:500);
    - Precise DTM (Digital Terrain Model) is needed;
    - Detailed data for the vegetation and the spatial variaton of roughness coefficient is needed;
    - Inability to represent some flow specifics – vertical velocity distribution.
    - Expensive – highly qualified and educated professionals are required.

2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
    - Three-dimensional hydraulic models
        - Consider the flow in all three spatial dimensions – study of local problems with high complexity and limited spatial extent



2. Numerical hydraulic modeling

- *2.4 Brief description of the hydraulic models*
  - Three-dimensional hydraulic models
    - **Advantages:**
      - Still the only option for solving complex three-dimensional problems.
    - **Disadvantages:**
      - Don’t bring additional value when solving two-dimensional problems, at the expense of huge computational resource

2. Numerical hydraulic modeling

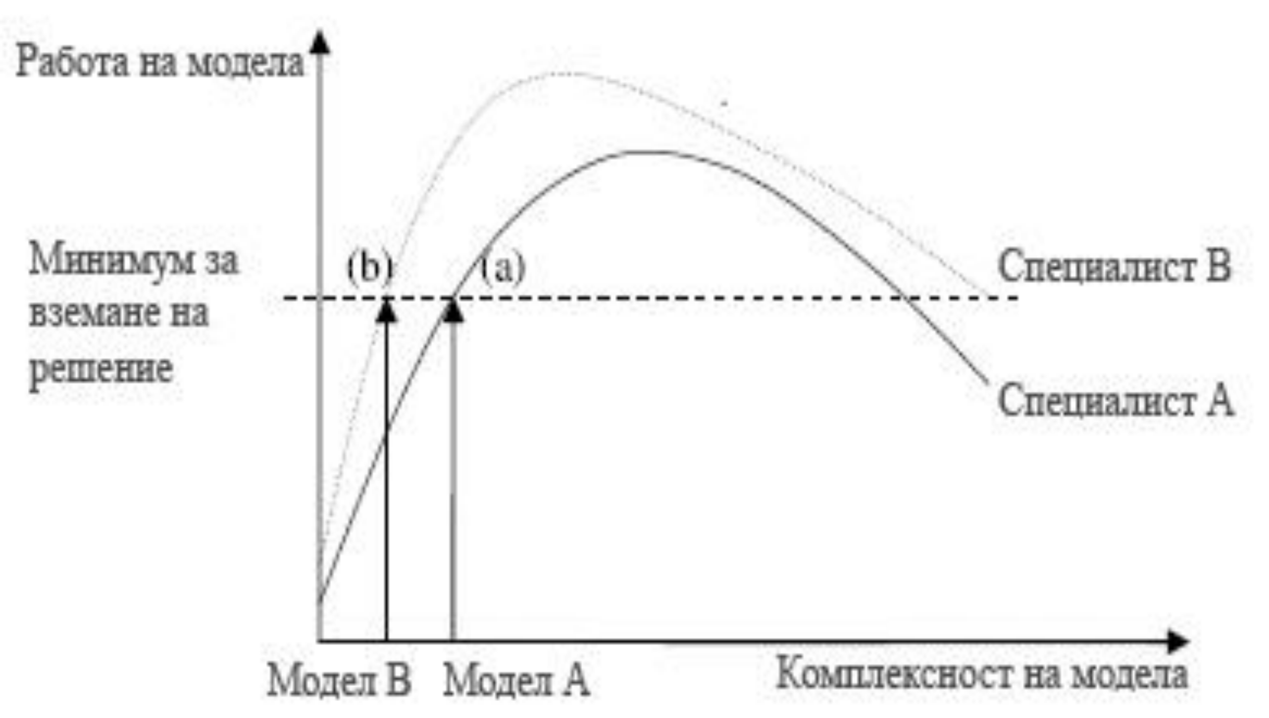
- *2.4 Brief description of the hydraulic models*
  - Conceptual hydraulic models
    - Don’t have practical application in the hydraulic modeling, but are widely used in the hydrological modeling
    - They use simplified representation of the flow through some simple process, which corresponds to the studied phenomenon – linear reservoir
    - **Advantages:**
      - Fast and stable
    - **Disadvantages:**
      - Inability to obtain water levels
      - The influence of changes in the system can be reflected very difficult

2. Numerical hydraulic modeling

- *2.5 Specifics of modeling of turbulent flows*
  - „Linear scales“
    - The ratio between macroscale and microscale is proportional to $Re^{3/4}$
    - For flows with $Re = 10^4$, in order to take into account the effect of the small vertices 10^3 control volumes for each spatial direction are needed
    - Eddy viscosity coefficient
    - Additional equations are needed in order to close the systems
      - $k-\varepsilon$ model
      - $k-\omega$ model

2. Numerical hydraulic modeling

- *2.6 Choice of appropriate model*



2. Numerical hydraulic modeling

- *2.6 Choice of appropriate model*
  - Comparison of needed resource for development of 2D model compared to the needed resource for development of 1D model (Environment Agency - DEFRA 2009)

Дейност	Необходим ресурс в сравнение с 1D моделирането
Събиране на данни	По-малък
Създаване на модела	По-малък
Справяне с проблеми във входните данни	По-малък
Калибриране на модела	По-голям
Валидиране на модела	Съпоставим
Настройки за пускане на симулация	Съпоставим
Извършване на симулация	По-голям
Докладване на резултати	По-малък
Обучение на персонала	По-голям
Справяне с проблеми на софтуера	Съпоставим

2. Numerical hydraulic modeling

- *2.6 Choice of appropriate model*
    - No universal rules for choice of most appropriate hydraulic model
    - Detailed knowledge of the specifics of the problem and detailed knowledge about the instruments for its solving are needed
    - Complete clarity about the way a model operates and about it specifics
    - Only this way the choice of appropriate instrument can be solid and adequate!

2. Numerical hydraulic modeling

- 2.7 Needed input data
  - Hydrological data
  - Terrain data
    - Raster
    - Vector
    - Interpolation method
  - Roughness coefficient data
  - Other important data
    - i.e. sediment data

2. Numerical hydraulic modeling

- *2.8 Calibration, sensitivity analysis and validation*
  - Calibration
    - „trial – error“ method
    - reverse modelling
  - *Sensitivity analysis*
  - Validation

2. Numerical hydraulic modeling

- *2.9 Impact of different factors on model accuracy*
  2.9.1 Неточности в модела
  - 2.9.2 Неточности във входните данни

2. Numerical hydraulic modeling

- *2.9 Impact of different factors on model accuracy*

  2.9.1 Inaccuracies in the model
    - Impact of the roughness coefficient
    - Impact of the spatial and temporal discreditation
        - at 1D models
        - at 2D models

2. Numerical hydraulic modeling

- 2.9 Влияние на различни фактори върху точността на моделите
- 2.9.2 Inaccuracies in the data
    - Impact of the topographic data and the resolution of DTM
    - Impact of the roughness coefficient

Mizia flood study

Mizia flood study

Mizia flood study

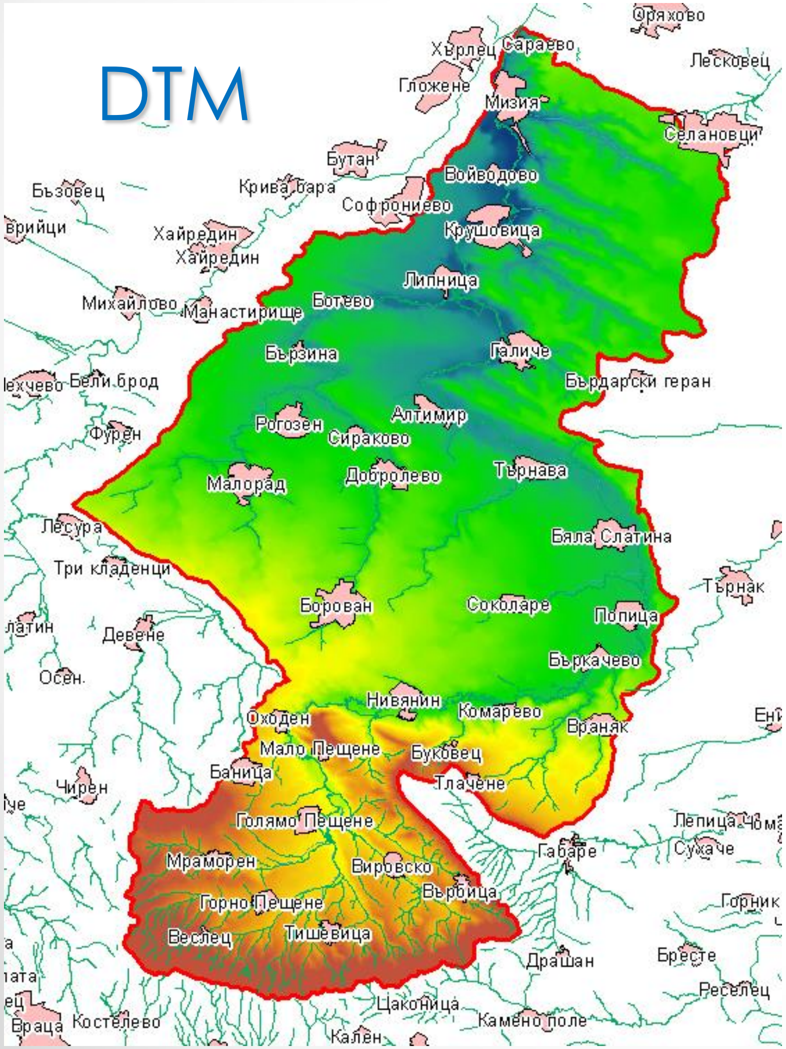
- The whole city was flooded in August 2014
- The reasons were unclear
  - Dams?
  - 2 broken dams
- **Discharge?**

Mizia flood study

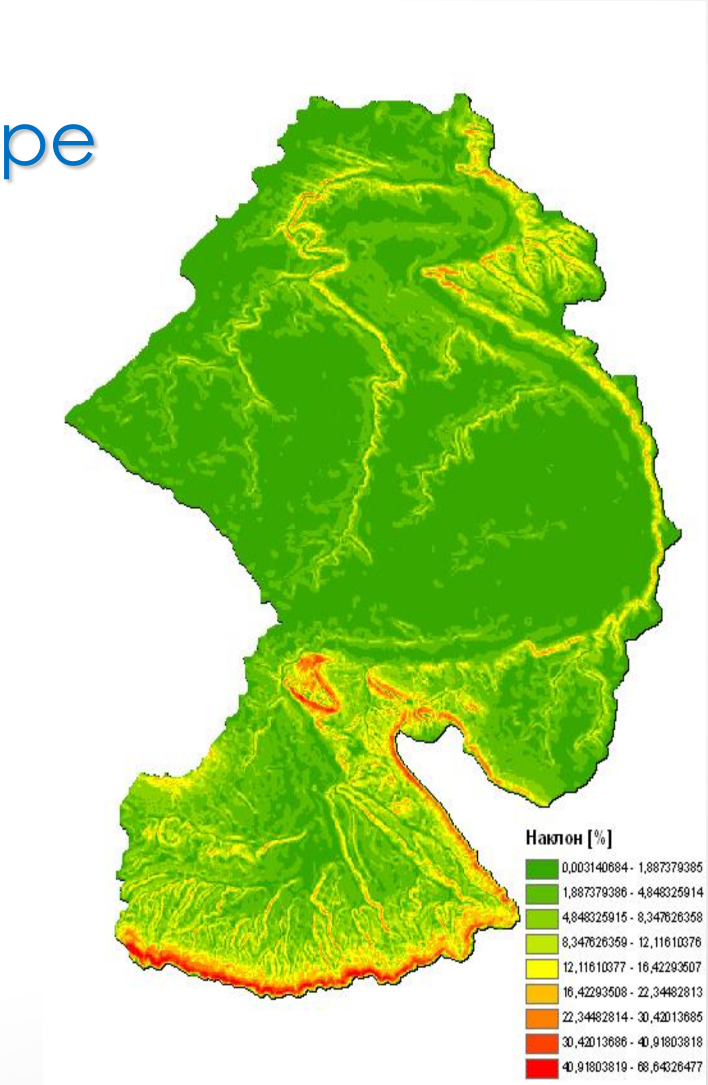
- Hydrological + Hydraulic model study
  - Lack of calibration data for both models
- Hydrological model
  - Rainfall – Runoff model
  - HEC - HMS

Mizia flood study

DTM

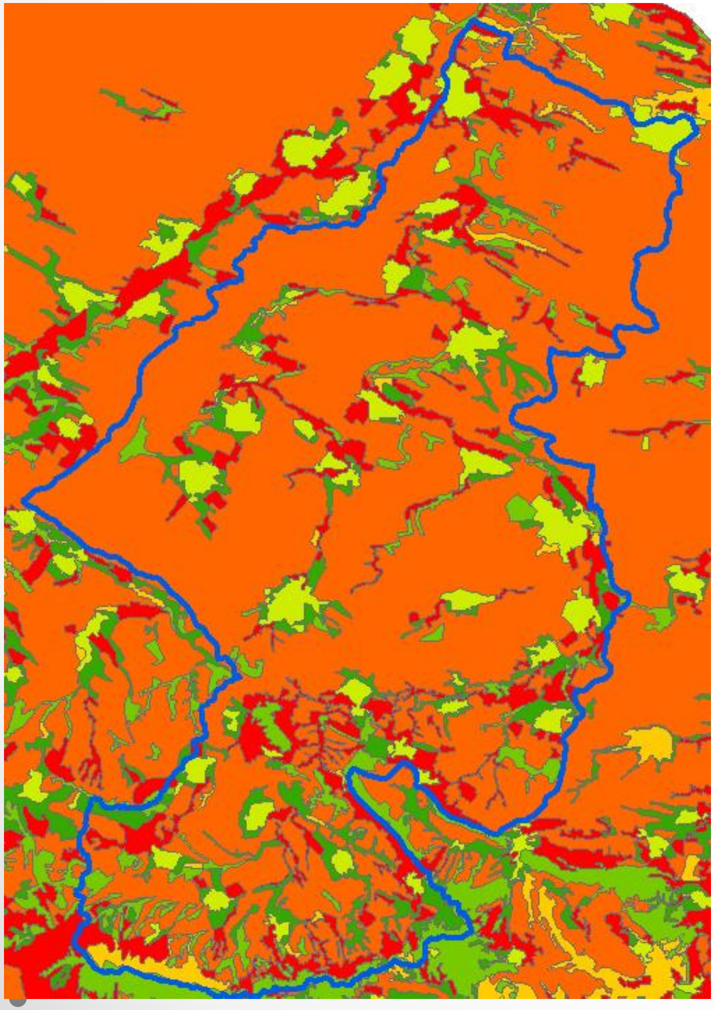


Slope

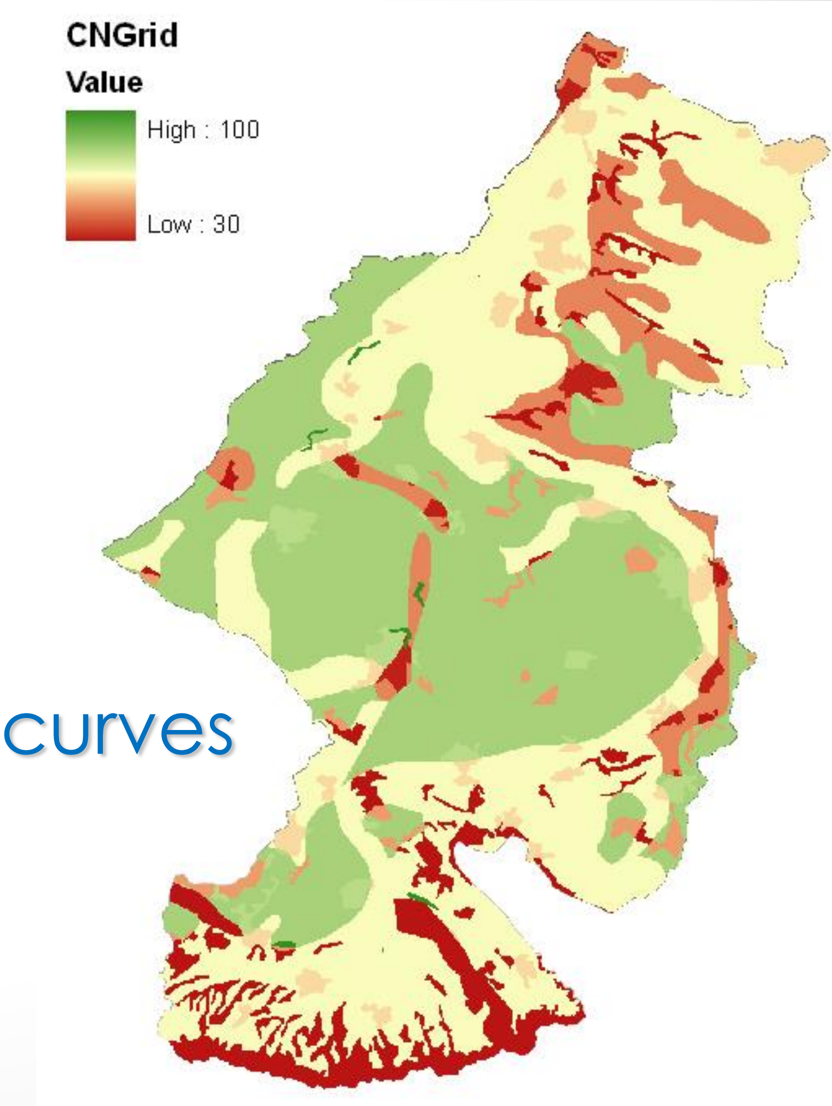


Mizia flood study

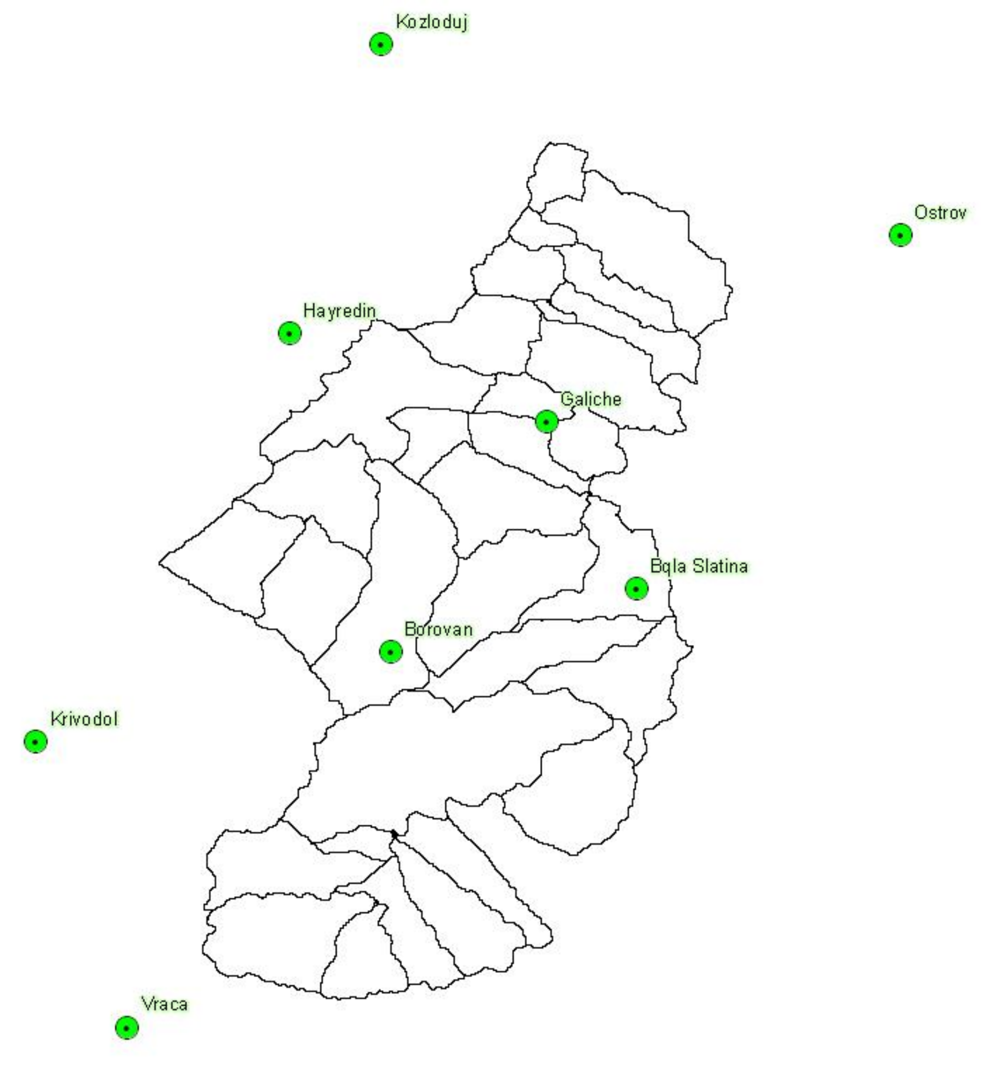
Land cover



CN curves



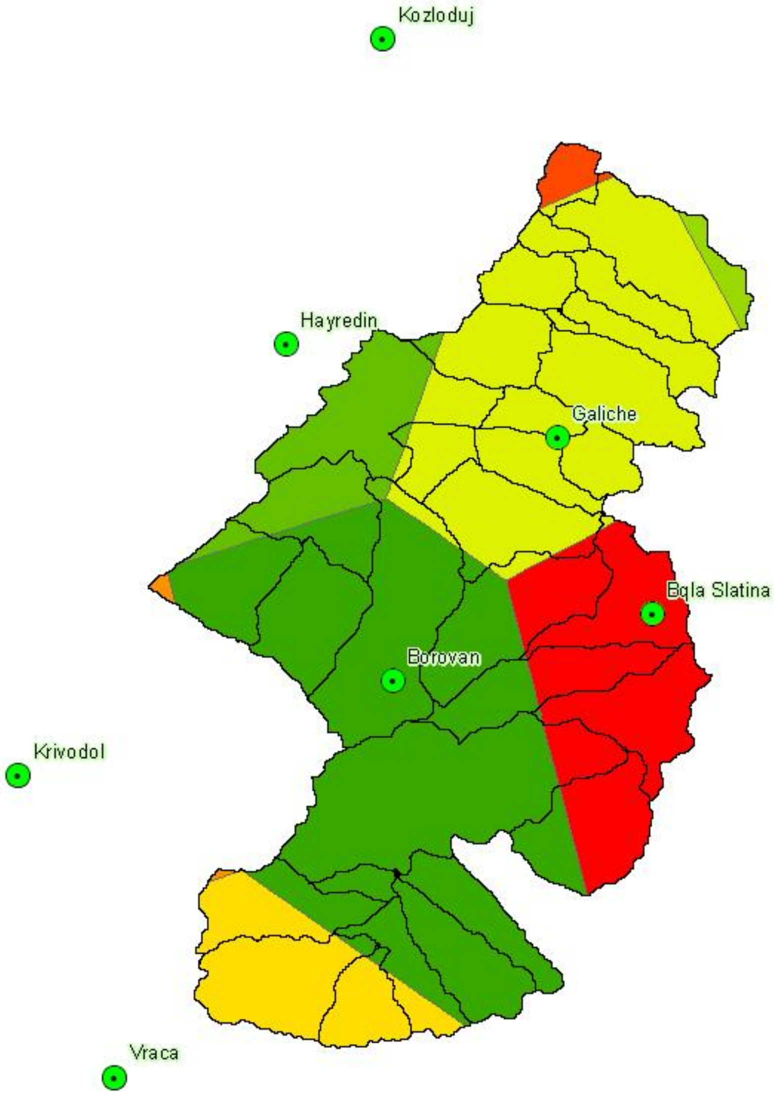
Mizia flood study



Rainfall data:

- 8 measurement points
  - 3 points iside the watershed

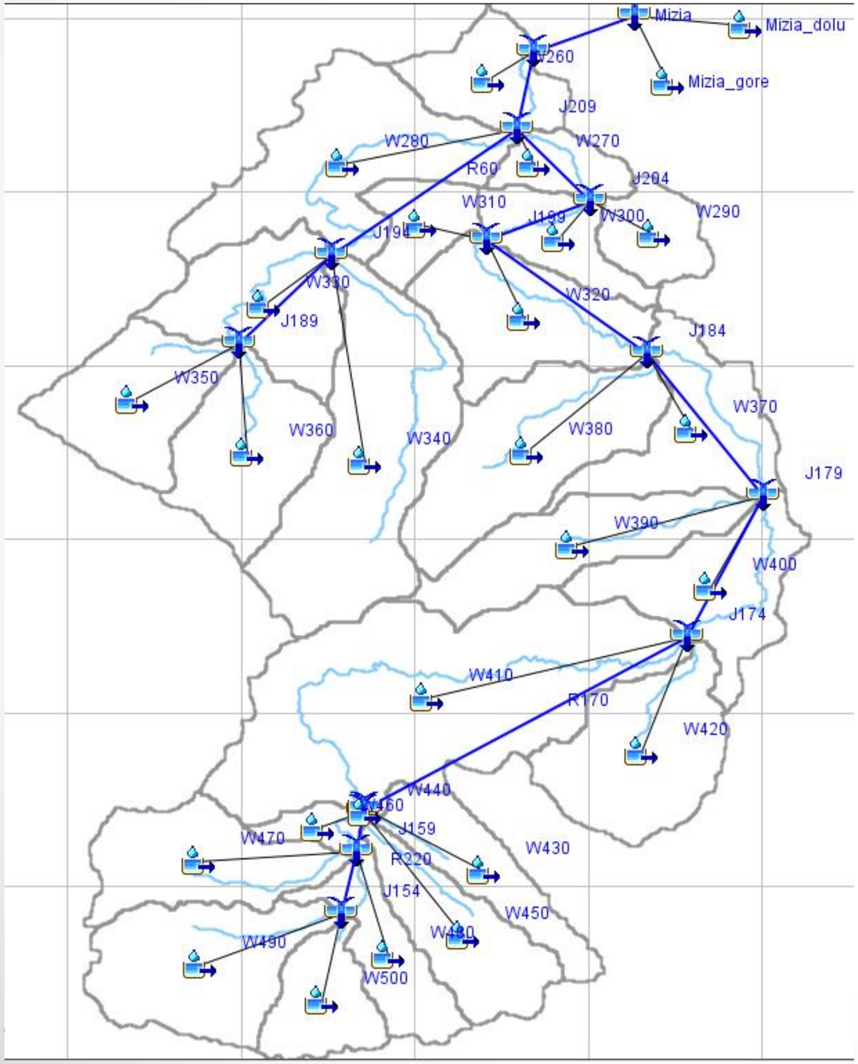
Mizia flood study



Rainfall data:

- 8 measurement points
  - 3 points iside the watershed
- Thiessen polygons

Mizia flood study



Hydrological model:

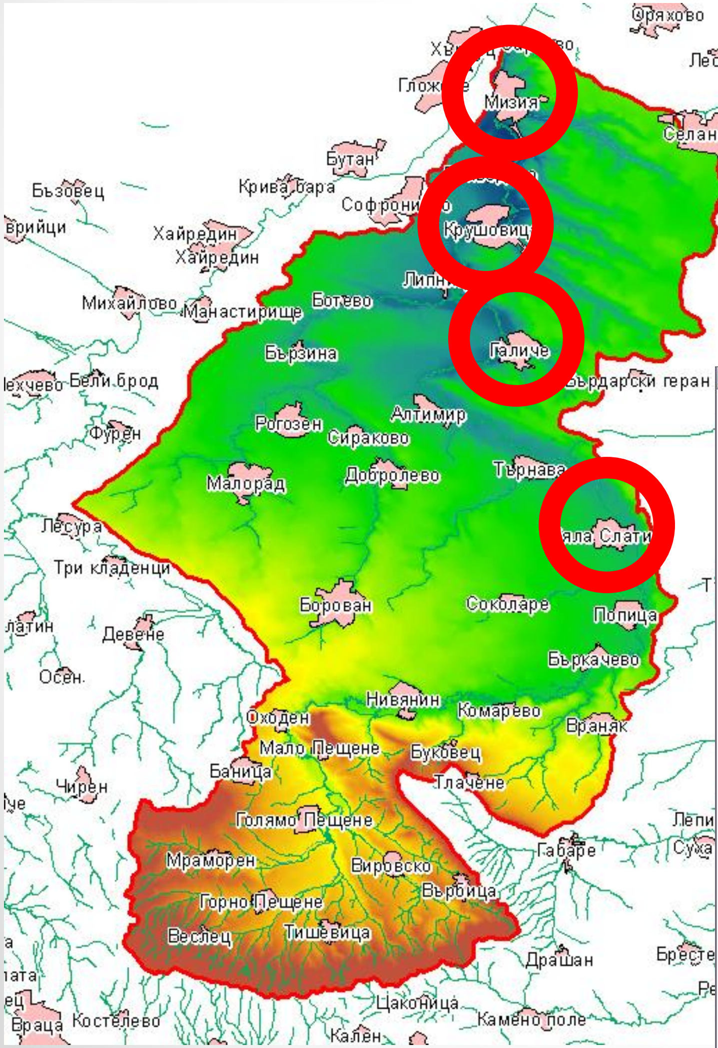
- 23 watersheds
- 1 month simulation period

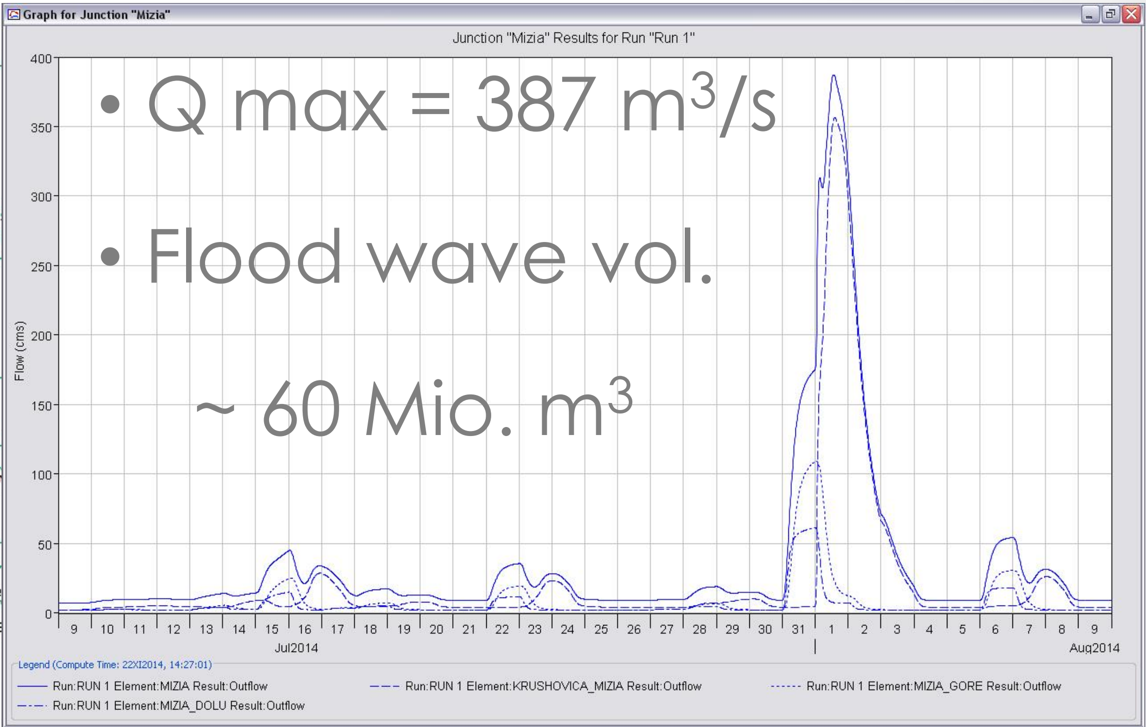
Mizia flood study

Results:

- 4 points
- Flow hydrographs
- Q max = 387 m^3/s
- Flood wave vol.

  ~ 60 Mio. m^3





Junction "Mizia" Results for Run "Run 1"

Legend (Compute Time: 22XI2014, 14:27:01)

- Run:RUN 1 Element:MIZIA Result:Outflow
- Run:RUN 1 Element:KRUSHOVICA_MIZIA Result:Outflow
- Run:RUN 1 Element:MIZIA_GORE Result:Outflow
- Run:RUN 1 Element:MIZIA_DOLU Result:Outflow

Mizia flood study – Hydraulic model

- Main task:
  - To use the available calibration data (water level marks) and to check if they can be reached with the obtained in the hydrological model hydrographs.
  - Hydraulic models, involving all 4 output points of the rainfall – runoff model.

Mizia flood study – Hydraulic model

- Methodology of the study
  - two hydraulic models
    - 1D – HEC-RAS v.4.1
    - 2D – SRH – 2D
  - The whole reach was modelled with 1D model
  - Additional 2D models were developed for the urban areas

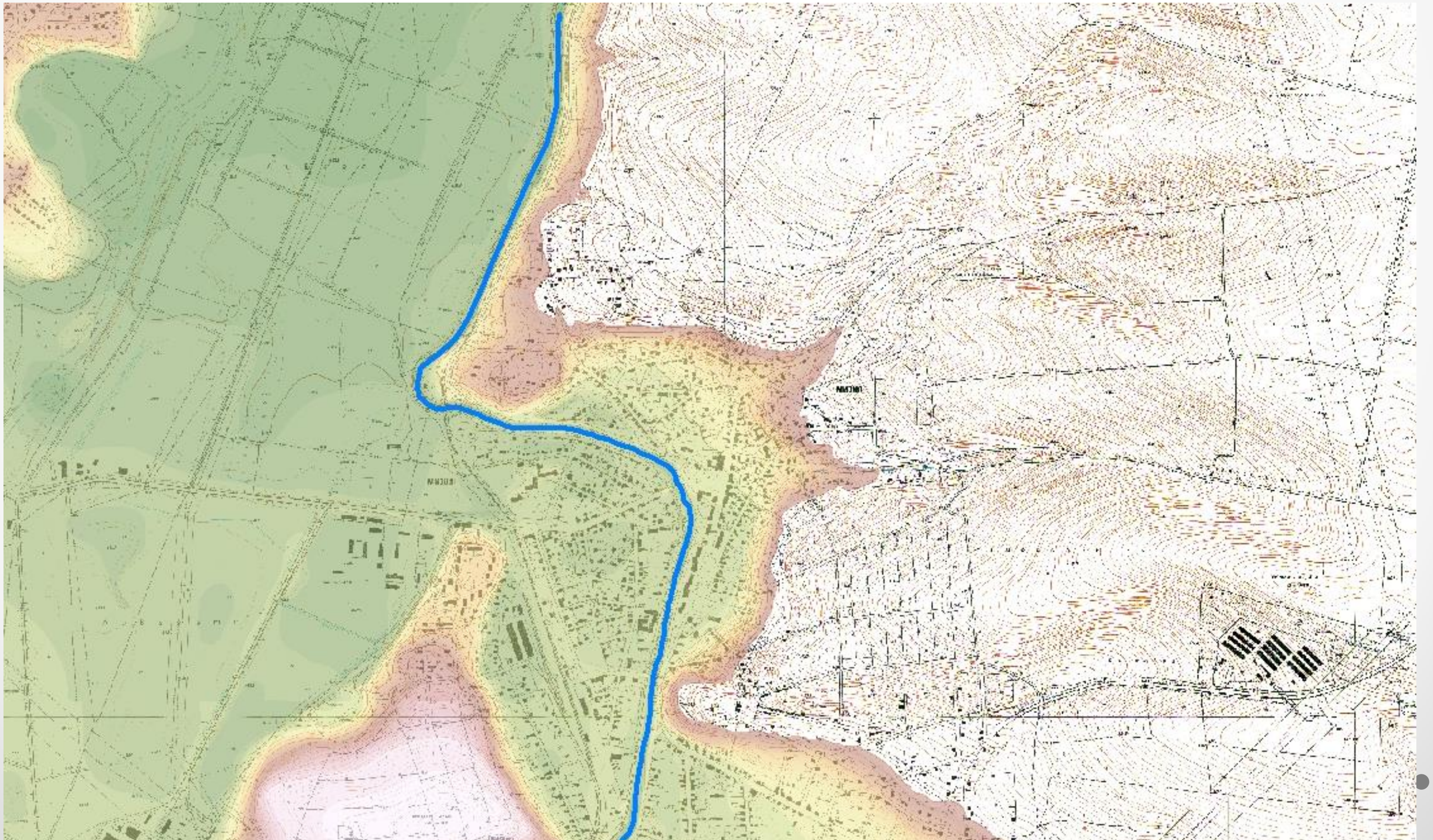
Mizia flood study – Hydraulic model

Additional analysis of the Terrain models

- *2 Digital Terrain Models*
  - by aerial orthophotogrammetry
  - by combining of precise geodetic survey of the river bed with digitized topographic maps (1:5000)
- Main task:
  - To analyze the results of the hydraulic model and to assess if these two fast and cheap methods for DTM generation can be used in praxis

Mizia flood study – Hydraulic model

- *Short description of the studied area*



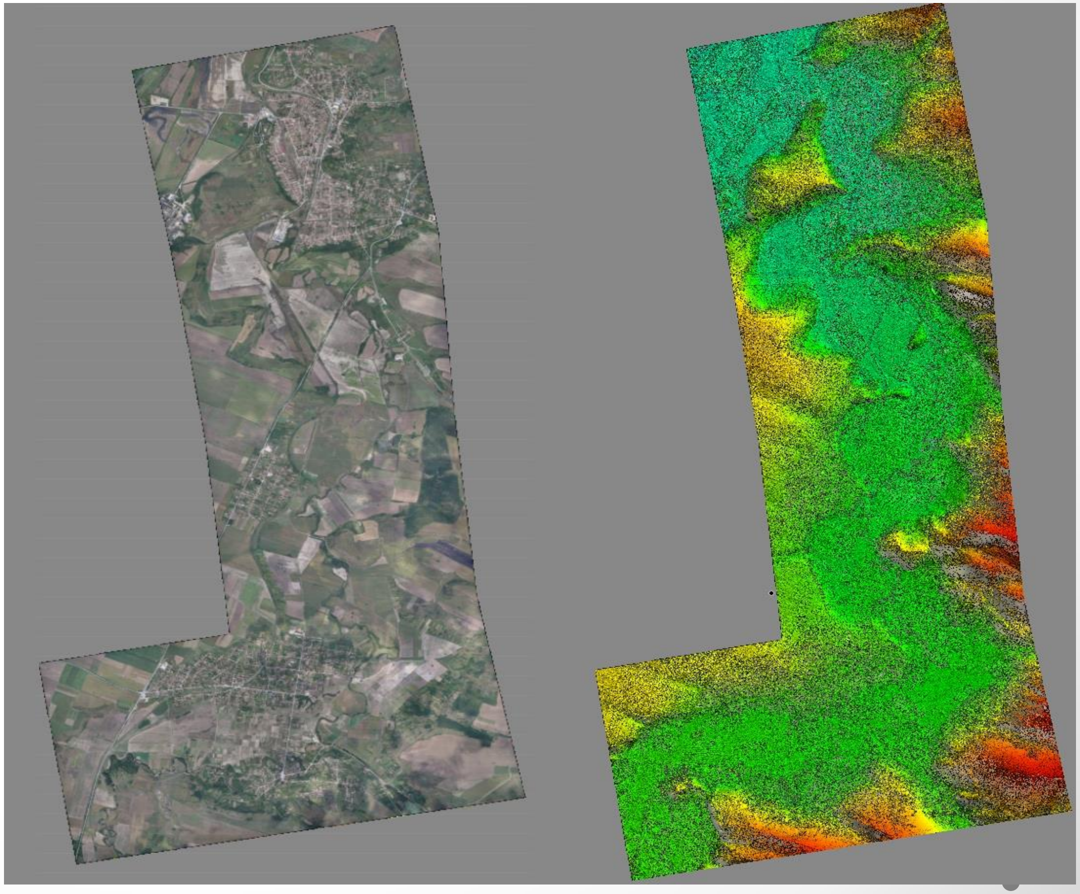
Mizia flood study – Hydraulic model

- Short description of digital terrain models
  - Aerial imagery

Mizia flood study – Hydraulic model

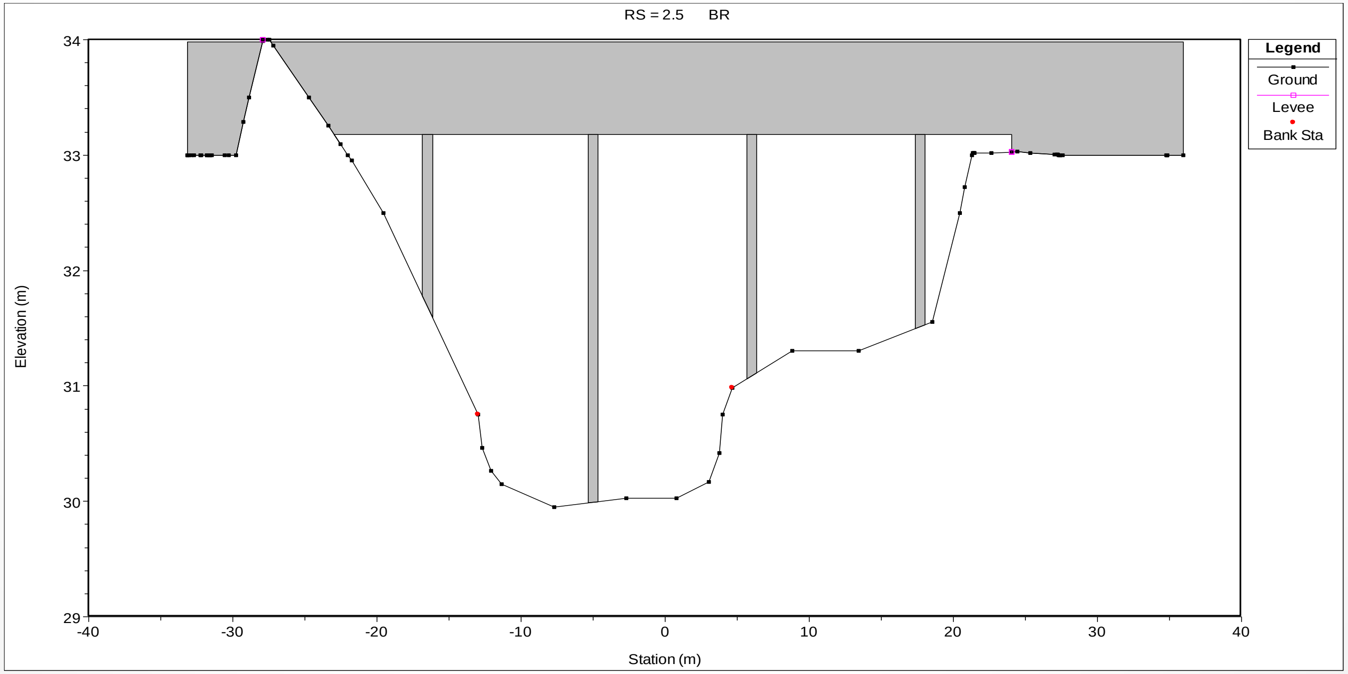
- Short description of digital terrain models
  - Aerial imagery
  - DSM with resolution

    0.917 x 0.917 m

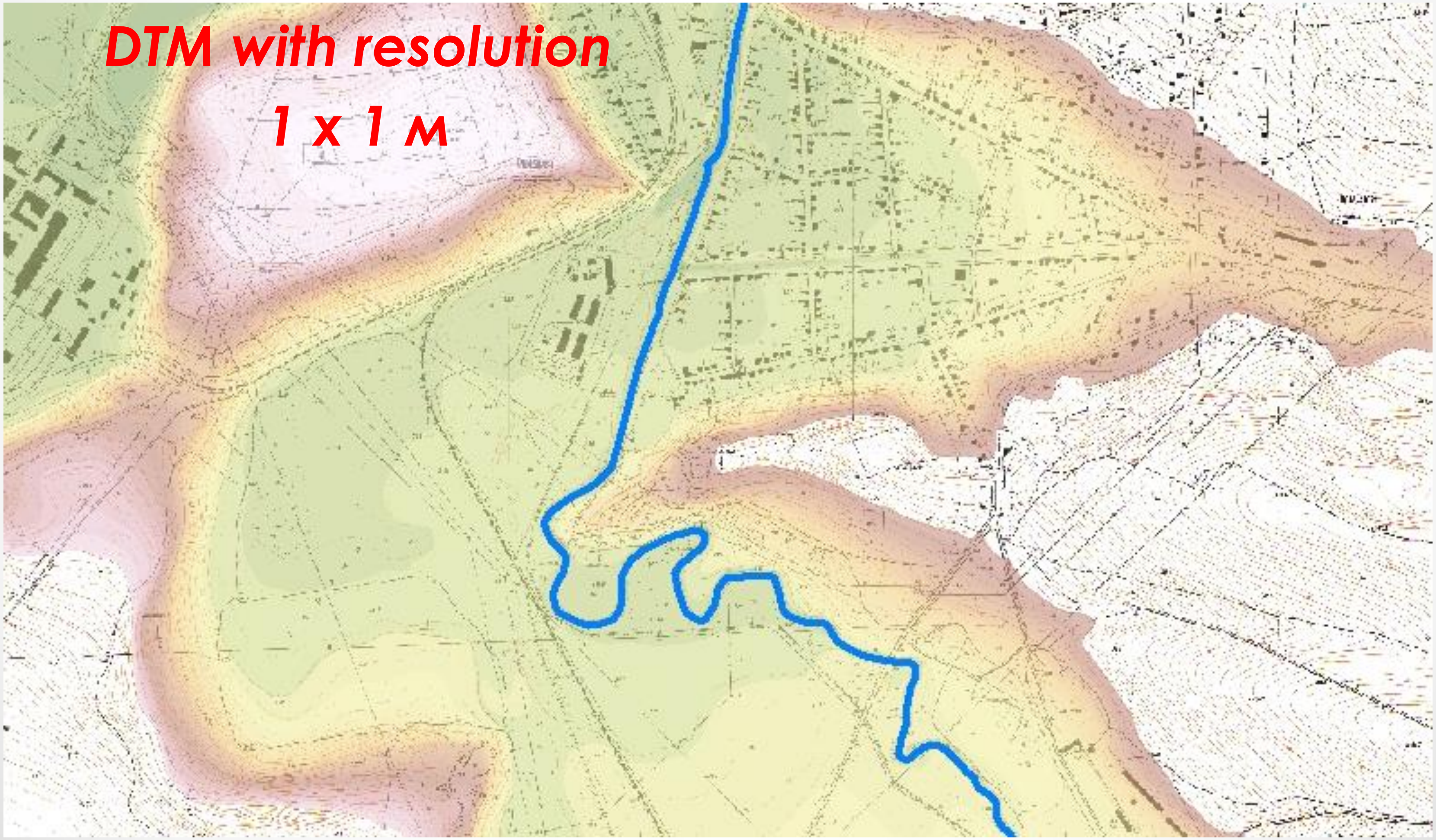


Mizia flood study – Hydraulic model

- Short description of digital terrain models
    - Detailed geodetic survey + digitized topomaps



Mizia flood study – Hydraulic model



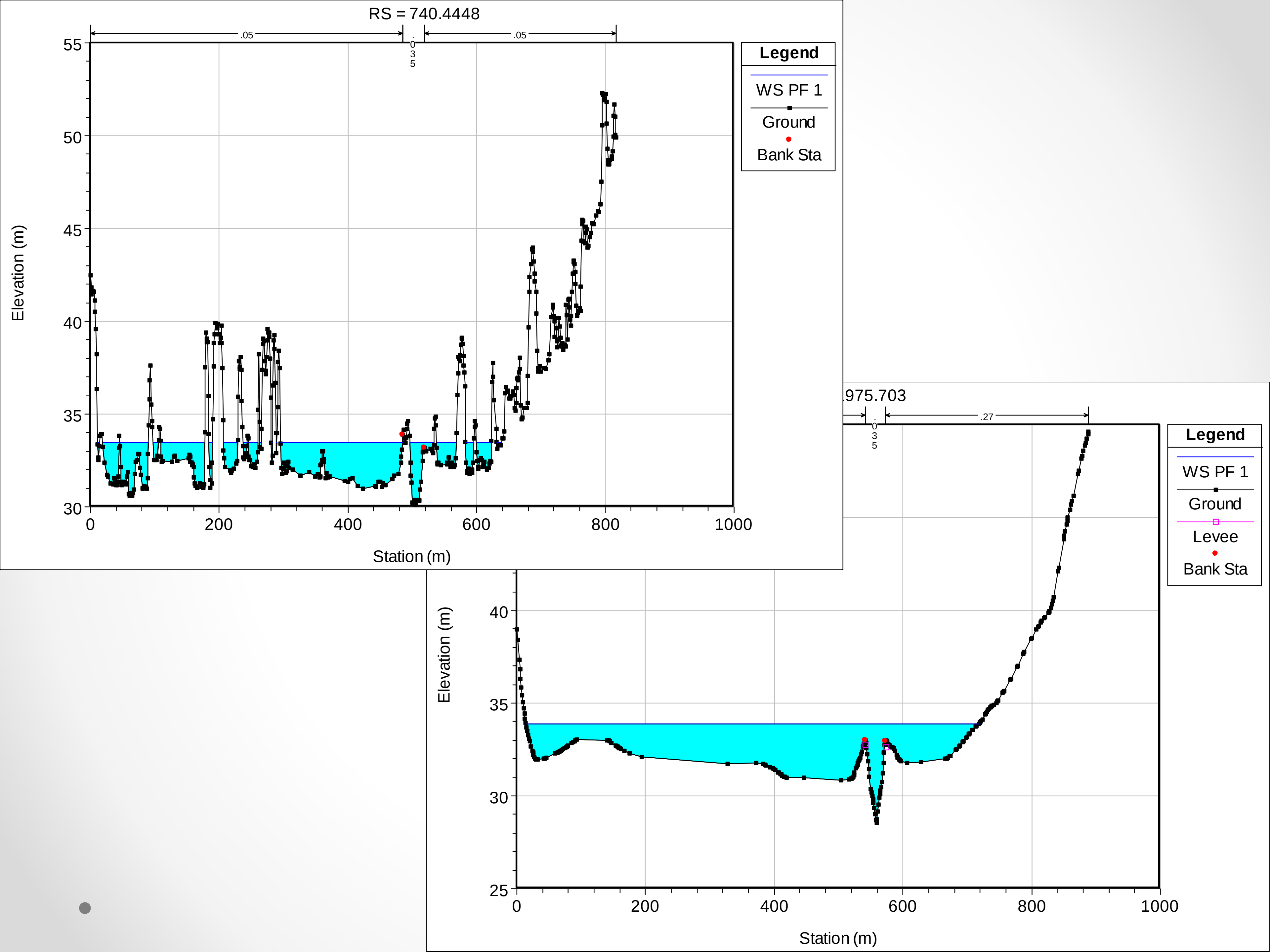
DTM with resolution
1 x 1 м

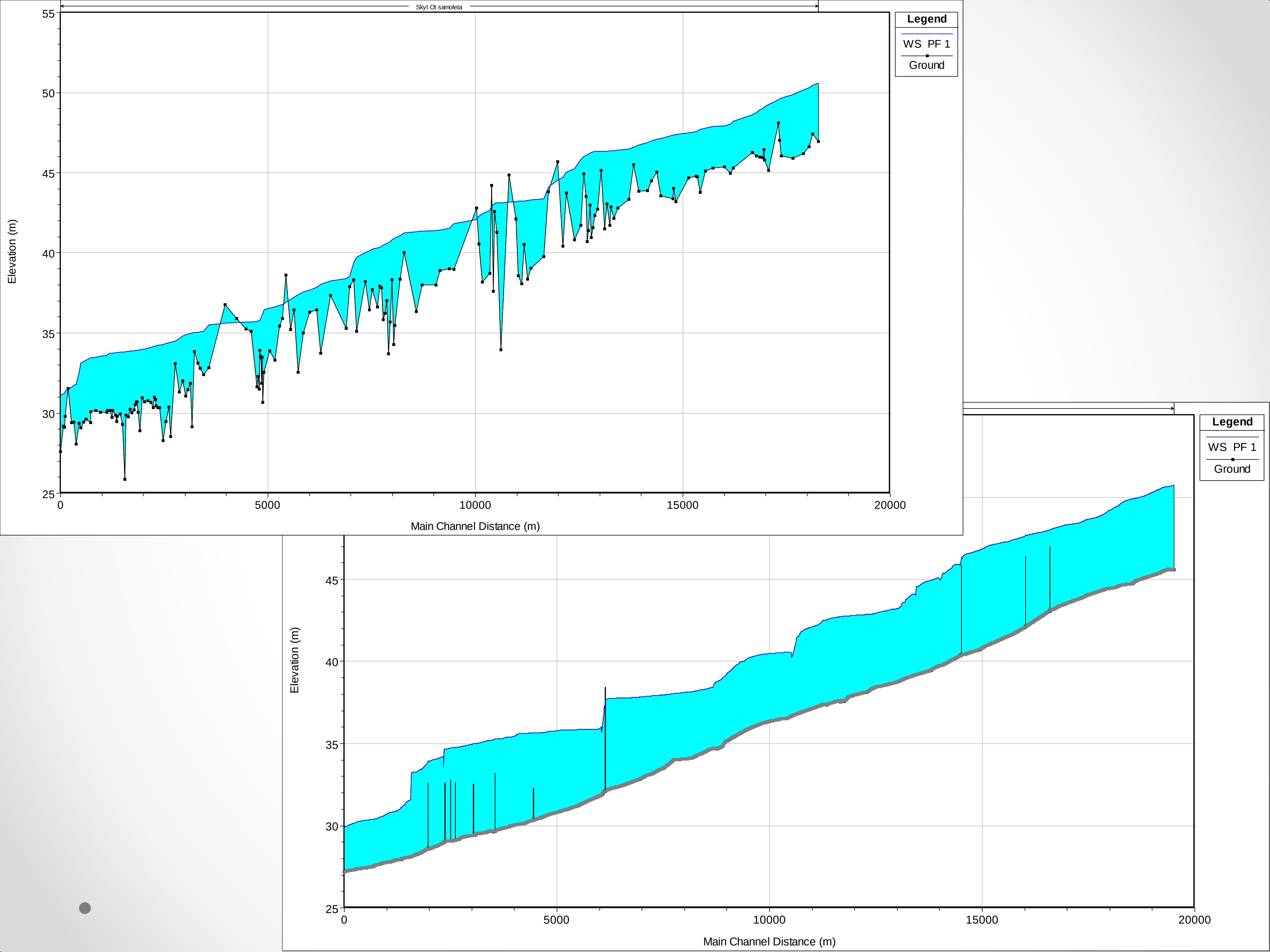
Mizia flood study – Hydraulic model

- Comparison between both DTMs

4. Изследване влиянието на точността на модела на терена при моделиране на висока вълна с различни математически модели

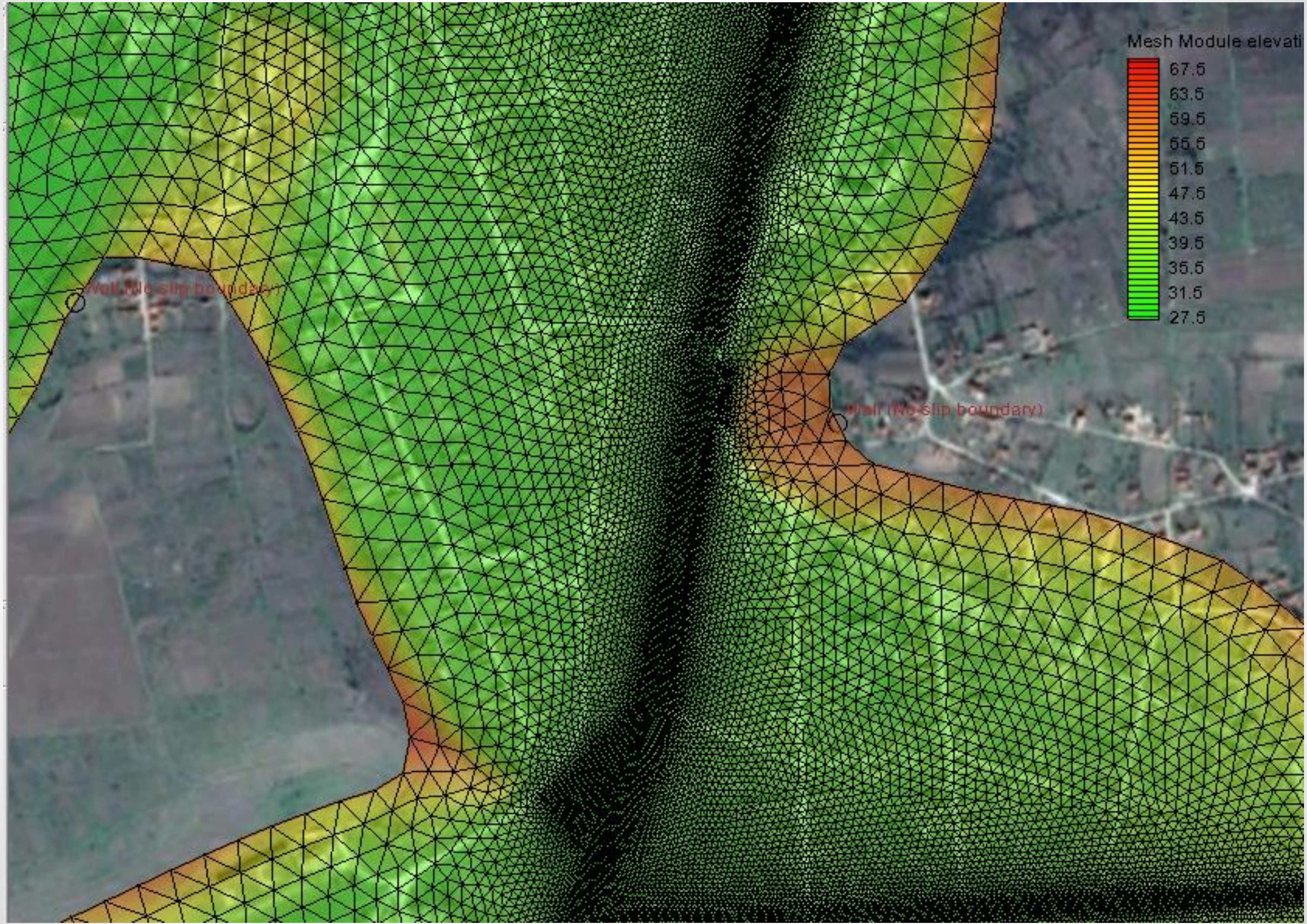
- *Building of the hydraulic models*
  - 1D hydraulic model
    - 231 detailed cross sections
    - M a and
      co
  - Boun

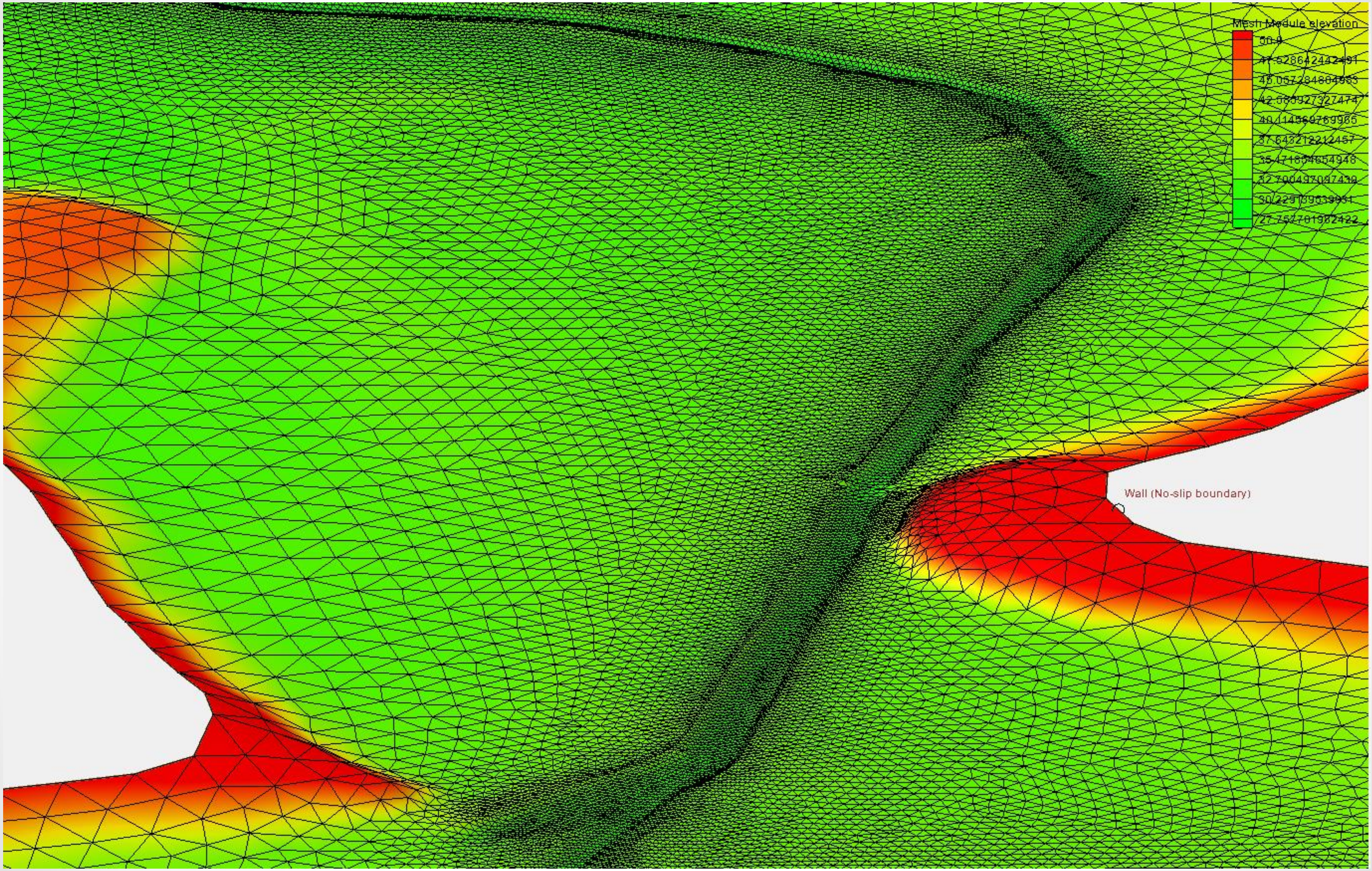

RS = 740.4448
.05
.035
.05
Elevation (m)
Station (m)
55
50
45
40
35
30
0
200
400
600
800
1000
Legend
WS PF 1
Ground
Bank Sta
.975.703
.035
.27
Elevation (m)
Station (m)
40
35
30
25
0
200
400
600
800
1000
Legend
WS PF 1
Ground
Levee
Bank Sta

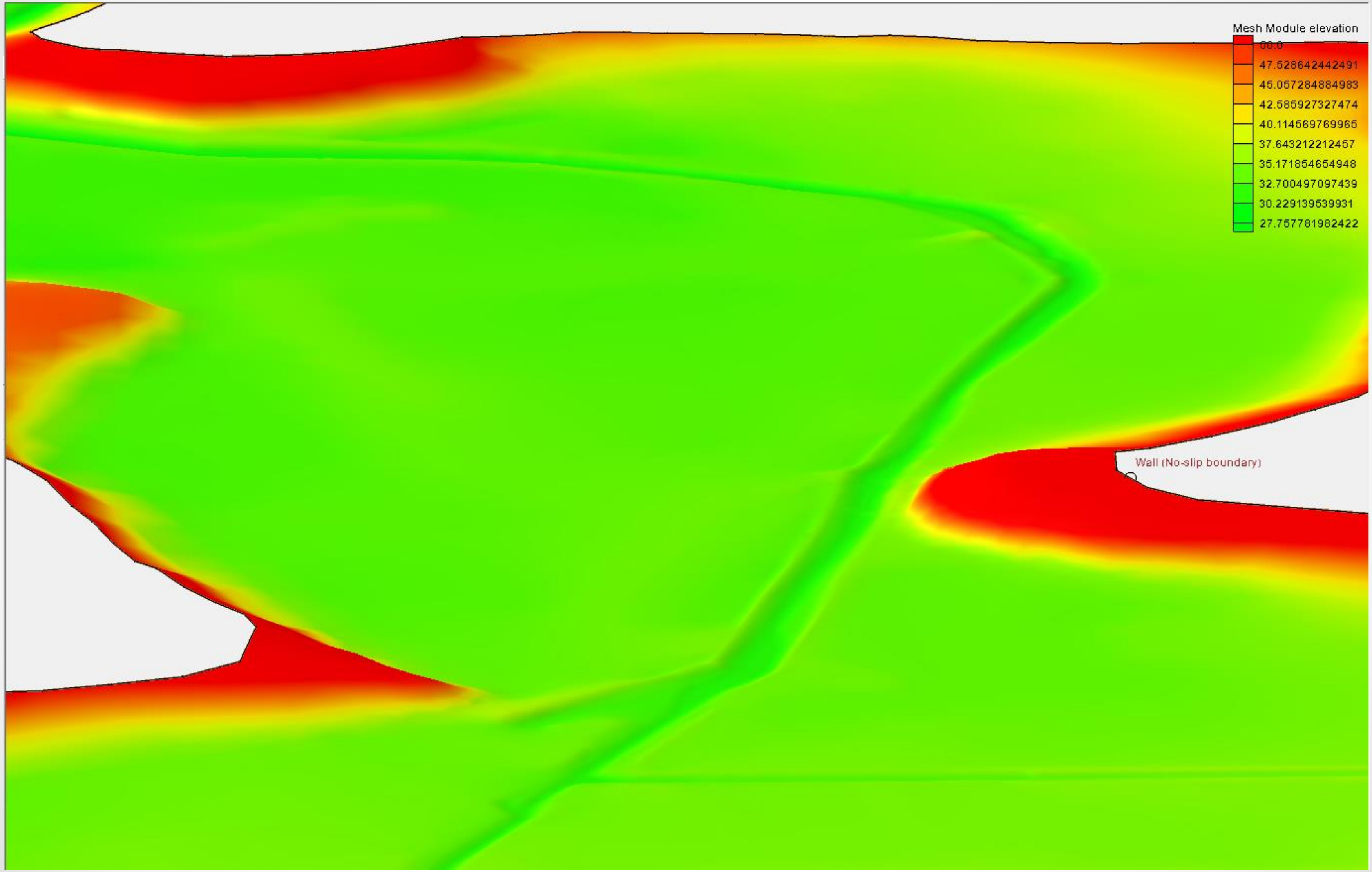

Skyt Ot samoleta
Legend
WS PF 1
Ground
Elevation (m)
Main Channel Distance (m)
55
50
45
40
35
30
25
0
5000
10000
15000
20000
Legend
WS PF 1
Ground
Elevation (m)
Main Channel Distance (m)
45
40
35
30
25
0
5000
10000
15000
20000

Mizia flood study – Hydraulic model

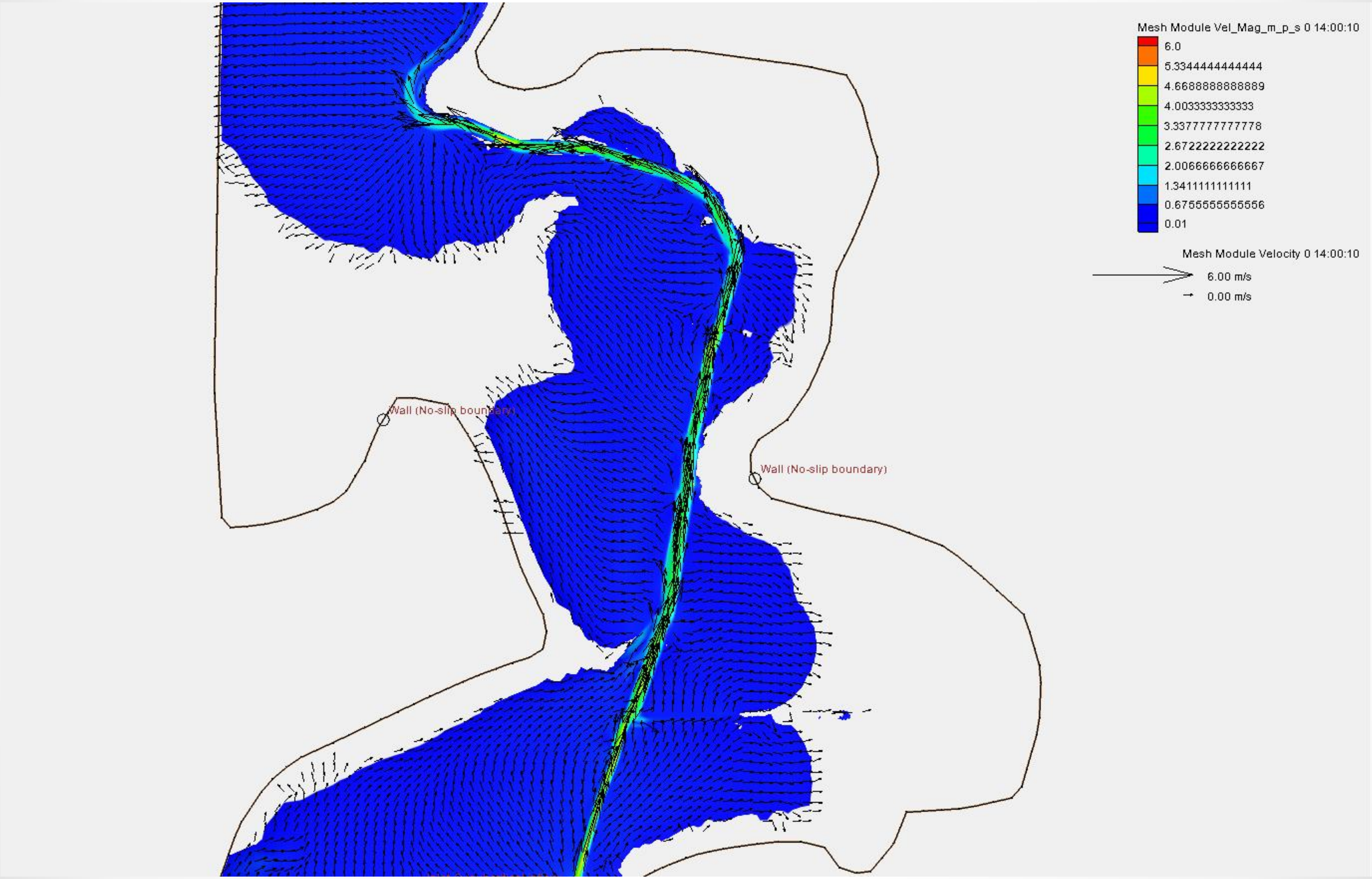
- *Building of the hydraulic models*
    - 2D hydraulic model
        - only in the urban areas
        - only with DTM, obtained with survey data + topomaps
        - Variable size flexible mesh

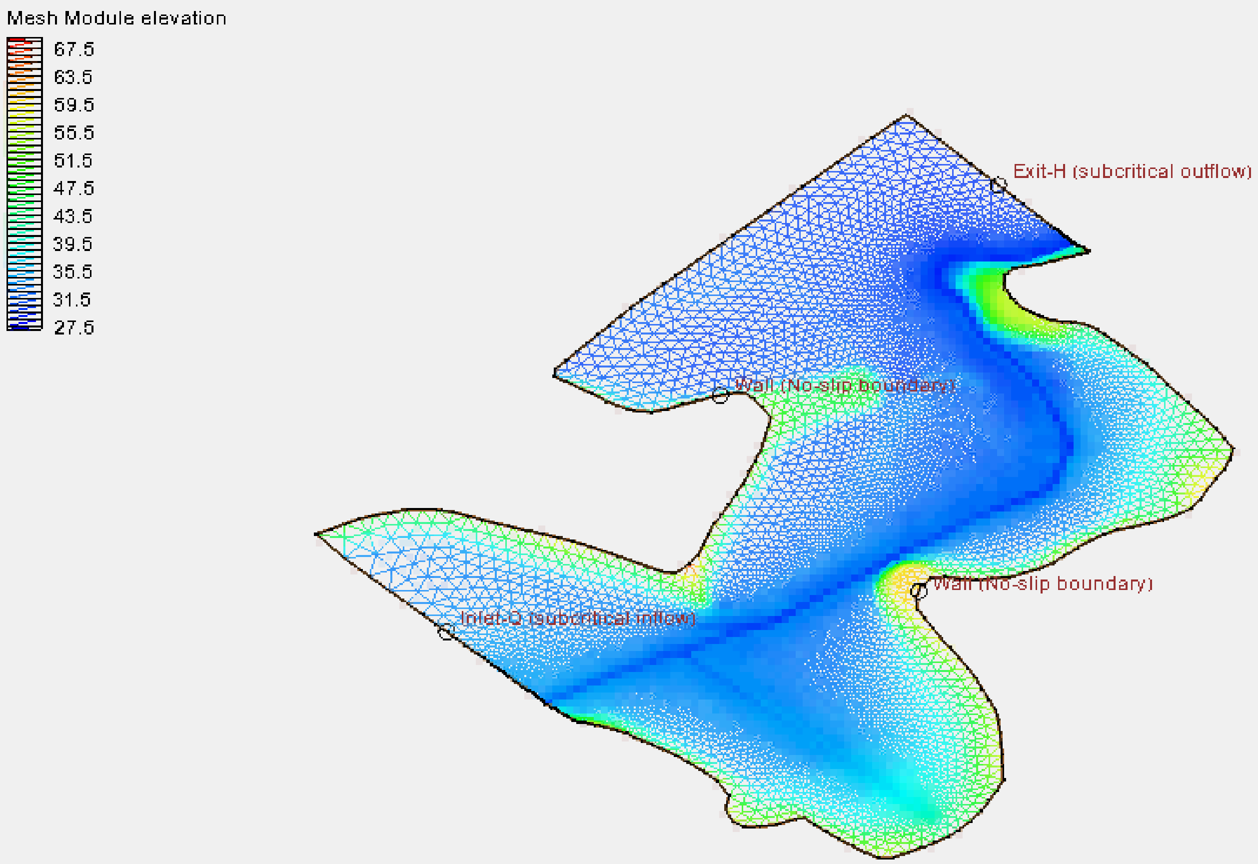

Mesh Module elevati
67.5
63.5
59.5
55.5
51.5
47.5
43.5
39.5
35.5
31.5
27.5
Wall (No slip boundary)
Wall (No slip boundary)

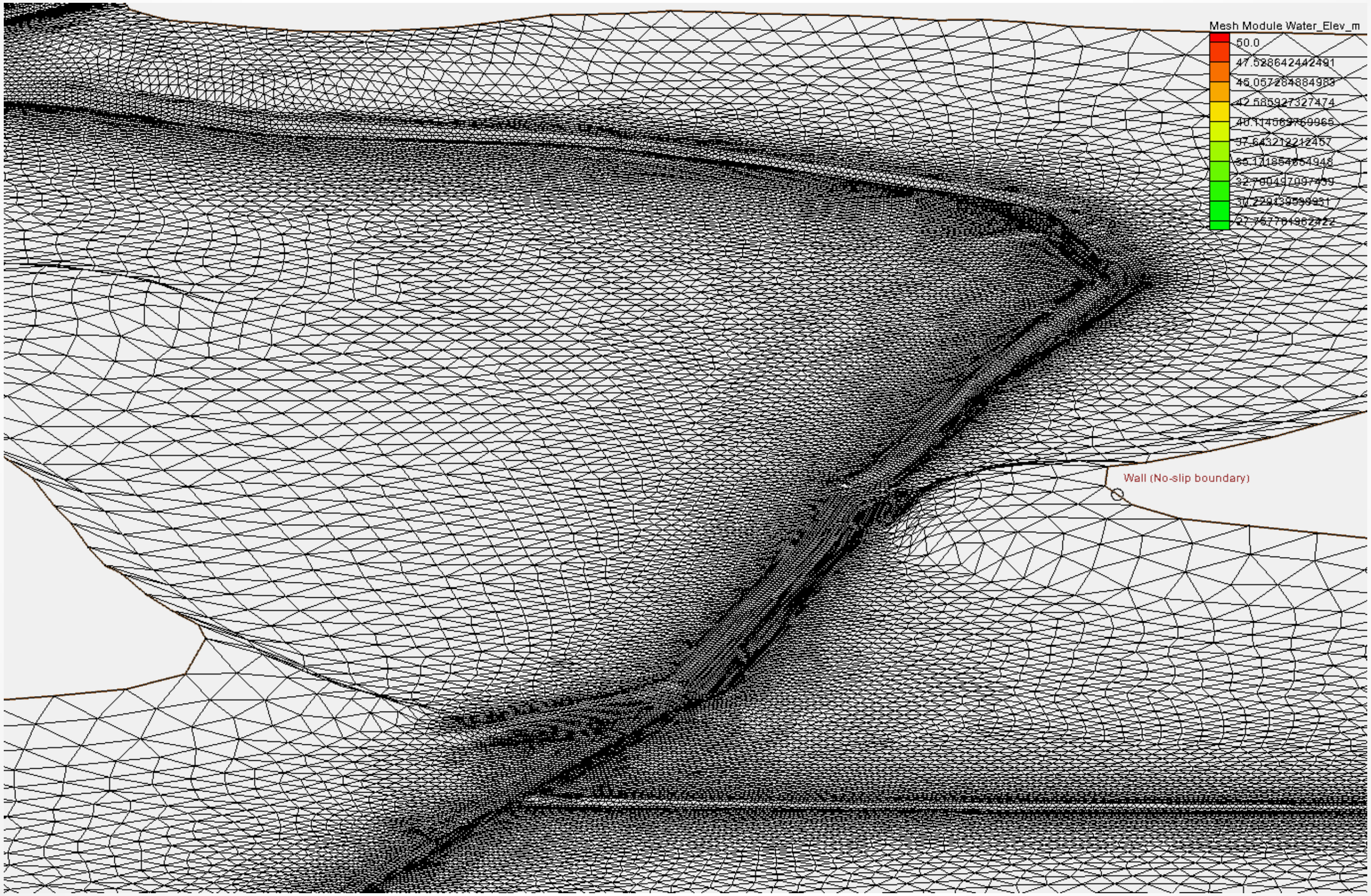

Mesh Module elevation
50.0
47.528642442491
45.057284884983
42.585927327474
40.114569769965
37.643212212457
35.171854654948
32.700497097439
30.229139539931
27.757781982422
Wall (No-slip boundary)


Mesh Module elevation
00.0
47.528642442491
45.057284884983
42.585927327474
40.114569769965
37.643212212457
35.171854654948
32.700497097439
30.229139539931
27.757781982422
Wall (No-slip boundary)


Wall (No-slip boundary)
Wall (No-slip boundary)
Mesh Module Water_Depth_m 0 14:00:10
6.0
5.3344444444444
4.6688888888889
4.0033333333333
3.3377777777778
2.6722222222222
2.0066666666667
1.3411111111111
0.6755555555556
0.01


Mesh Module Vel_Mag_m_p_s 0 14:00:10
6.0
5.3344444444444
4.6688888888889
4.0033333333333
3.3377777777778
2.6722222222222
2.0066666666667
1.3411111111111
0.6755555555556
0.01
Mesh Module Velocity 0 14:00:10
6.00 m/s
0.00 m/s
Wall (No-slip boundary)
Wall (No-slip boundary)


Mesh Module elevation
67.5
63.5
59.5
55.5
51.5
47.5
43.5
39.5
35.5
31.5
27.5
Exit-H (subcritical outflow)
Wall (No-slip boundary)
Wall (No-slip boundary)
Inlet-Q (subcritical inflow)


Mesh Module Water_Elev_m
50.0
47.528642442491
45.057284884983
42.585927327474
40.114569769965
37.643212212457
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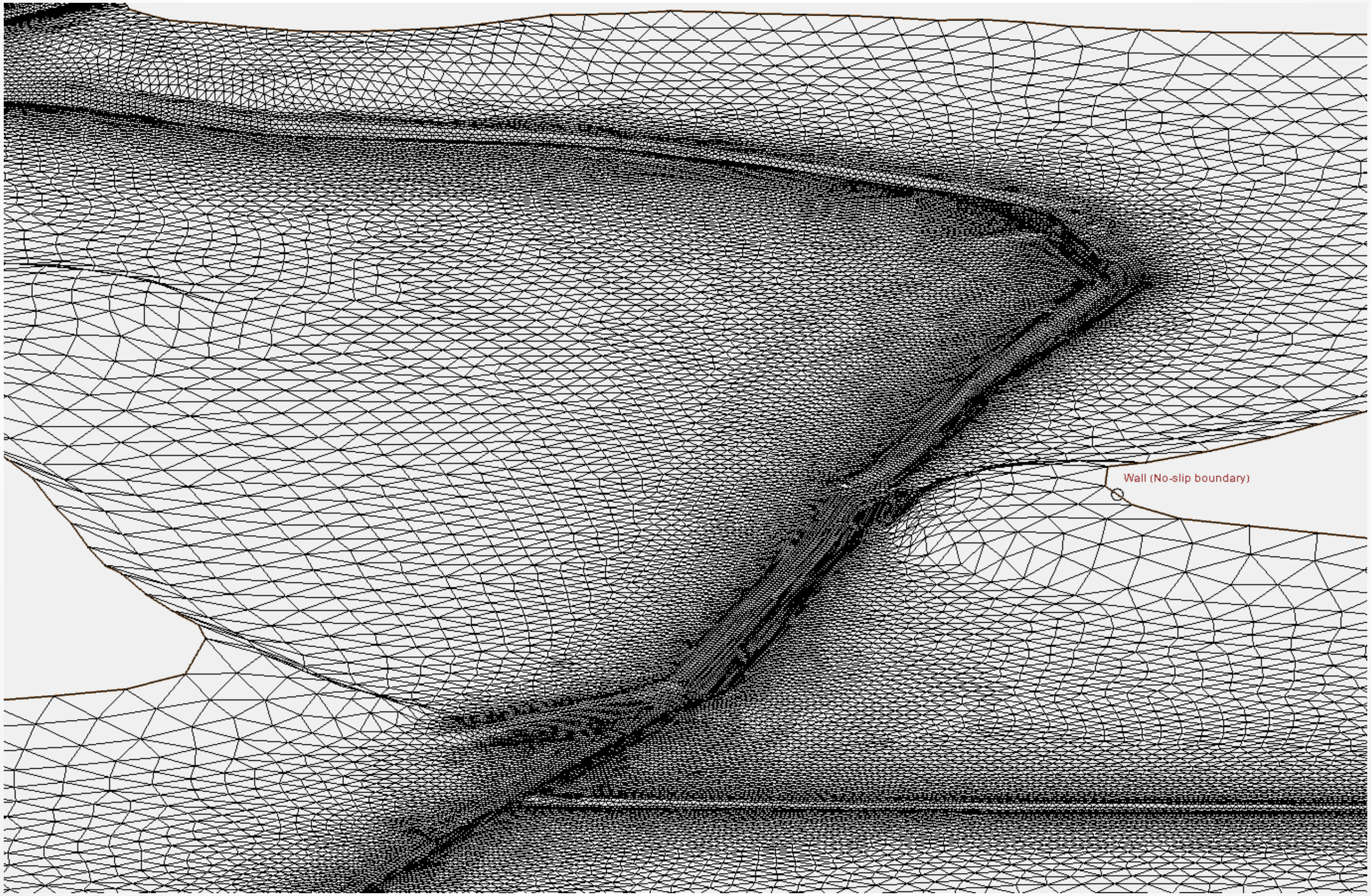
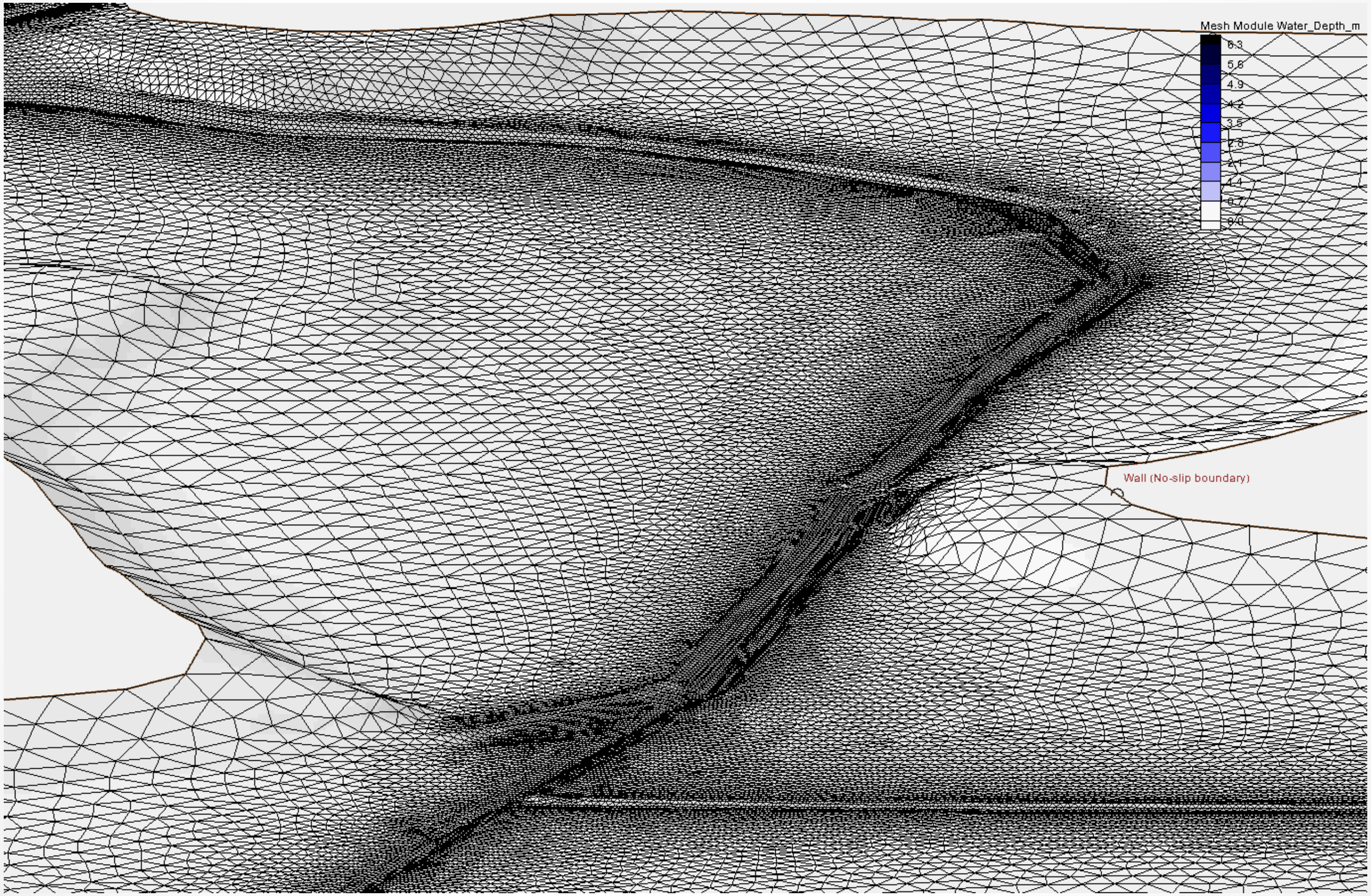
32.700497097439
30.229139539931
27.757781982422
Wall (No-slip boundary)


Wall (No-slip boundary)


Mesh Module Water_Depth_m
6.3
5.6
4.9
4.2
3.5
2.8
2.1
1.4
0.7
0.0
Wall (No-slip boundary)

Mizia flood study – Conclusions

- *The calculated hydrograph is realistic*
    - The calculated flood is very close to the observed

- The maximum discharge is approx. 380 m^3/s (vs. **1000** m^3/s – officially reported)

- The volume of the flood wave is approx. 60 Mio. m^3
  (The volume of all reservoirs in the watershed is approx. 250 000 m^3)