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MINISTRY OF ENVIRONMENT WATER AND FORESTRY

Romania-Ukraine-Republic of Moldova
CROSS BORDER COOPERATION

EAST AVERT Project

TECHNICAL REPORT

OPERATION CONCEPT GUIDELINE FOR FORECASTING MODELLING AND DATA INPUTS

2017

TECHNICAL REPORT

OPERATION CONCEPT GUIDELINE FOR FORECASTING MODELLING AND DATA INPUTS

Coordinated by

Partner 4: National Institute of Hydrology and Water Management, Romania

Partner 7: Chernivtsi Regional Centre on Hydrometeorology, Ukraine

With the contribution of:

Lead Partner:	*Ministry of Environment, Romania*
Partner 2:	*Prut-Barlad Water Basin Administration, Romania*
Partner 3:	*Siret Water Basin Administration, Romania*
Partner 5:	*"Apele Moldovei" Agency, Republic of Moldova*
Partner 6:	*Dnister-Prut Basin Department of water resources, Ukraine*
Partner 8:	*State Scientific and Technical Centre for inter-sectorial&regional problems of the Environenental Safety and Resources Conservation "EcoResources", Ukraine*

Ref: The trilateral project "The prevention and protection against floods in the upper Siret and Prut River Basins, through the implementation of a modern monitoring system with automatic stations EAST AVERT",

cod 966, funded by the Joint Operational Programme Romania - Ukraine - Republic of Moldova, European Neighbourhood and Partnership Instrument (ENPI)

1. Introduction

In order to satisfy the specific needs for improving the real time forecasting and warning system capabilities in Prut and Siret transboundary River Basins, the following hydrological and meteorological forecasting components have been implemented by the project partners:

• A detailed spatial and temporal scale hydrological model for the upper part of the Siret and Prut River basins, in Ukraine, in order to provide short term detailed rainfall-runoff, and flood routing capabilities.

• A high resolution local numerical weather prediction model is used to provide adequate, improved quantitative precipitation forecasts.

• For the same area, for the routing and the flood inundation mapping needs, a hydraulic model was implemented.

• A second type of model, a conceptual hydrological rainfall-runoff model was implemented, in order to satisfy the needs of medium term forecasts and scenarios analysis for the Siret and Prut river basins at the entrance in Romania.

• These forecasts will be used both by the partners from Romania and Moldova, in order to optimize the operation of Stânca-Costeşti reservoir for flood defense in Prut river basin, and by Romanian partners for optimize the operation of reservoirs on Siret river.

• For the Prut River, downstream the entrance in Romania, a hydraulic model was implemented by the Romanian and Moldavian partners, based on HEC-RAS hydraulic model, including the Stânca Costeşti reservoir. This hydraulic model was used for the flood hazard maps generation on Prut River, and will also be used for more accurate real-time forecasts during extreme flood events.

2. Meteorological Forecasting System based on the Numerical Weather Prediction Model WRF

Weather Research and Forecasting (WRF) Model is a contemporary mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting needs by several USA agencies and universities. The input data for the regional implementation of WRF can be download from the servers NOMADS of the USA agency http://nomads.ncep.noaa.gov/

Within the EAST AVERT the software system was developed and installed in the server on Chernovtsy (in DPDWM) for the four times per 24 hours automatic computing of the detailed weather forecast in the areas of the Prut and Siret basin in

Ukraine up to 7 days on the basis of the automatic retrievals of the global model results from the NOMADS servers/

The simulations are performed on a sequence of 3 nested domains (Fig. 1) with the outer (first) domain having resolution of 27 km, second domain having resolution of 9 km and the inner (third domain) having resolution 3 km (Fig. 1, 2).

The model parameters were calibrated on the weather obseravtuon data to increase the predictive power of WRF for this specific mountain region (Fig. 3)

The results of WRF simulation are transferring from DPDWM to ChHMC for the further use as the input information for the operational Rainfall- Runoff model.

Fig. 1 Three nested domains of the WRF model customized for the basins of the Prut and Siter rivers in Ukraine

Fig. 2 Internal domain of WRF- PRUT - UA model, with the grid 3*3 km

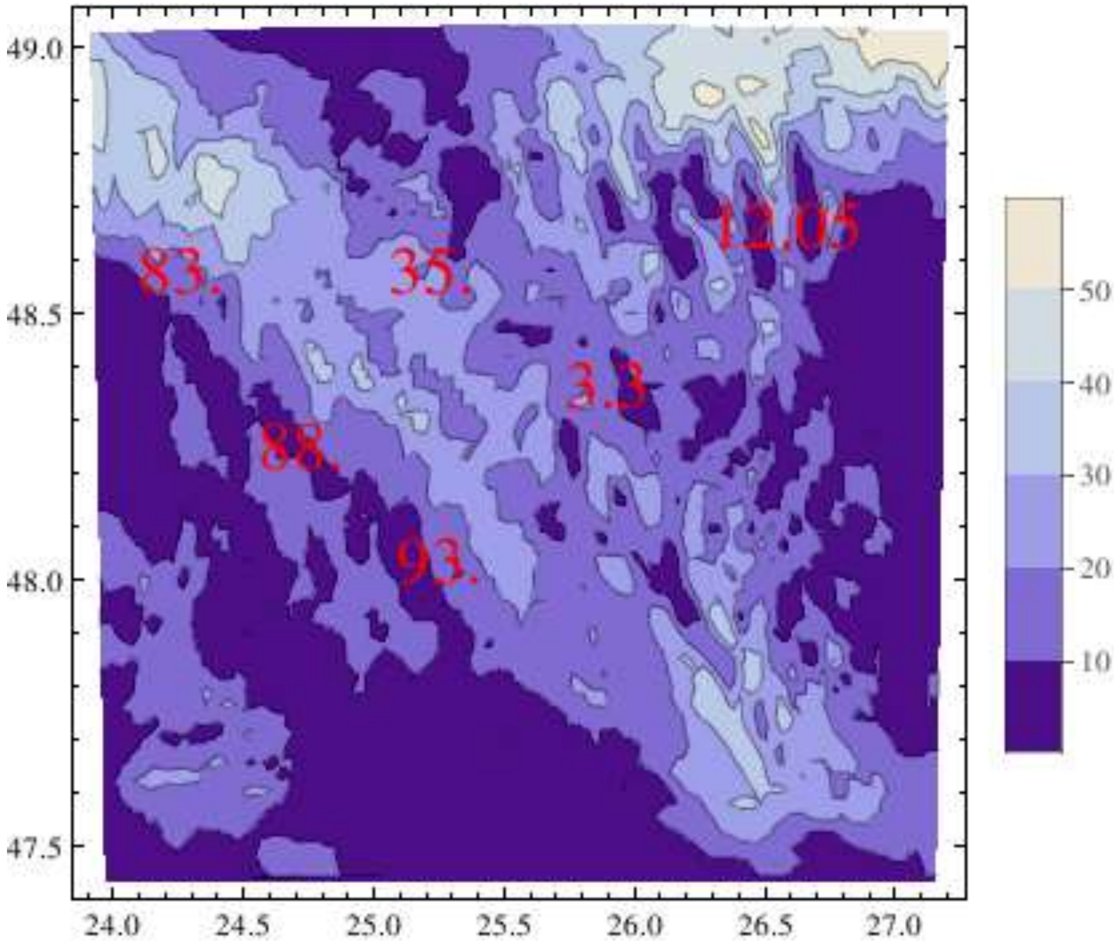


Fig. 3 The distribution of the day sum of the precipitation simulated by WRF in the period of the extrem flood 25.07.2008 and observed precipitation at several monitoring stations

3. Hydrological Rainfall-Runoff Model TOPKAPI-UKRAINE

TOPKAPI model is fully distributed rainfall-runoff model based on combining GIS data and kinematic wave approach. Due to its distributed nature model in easy way can assimilate the results of numerical weather prediction systems (in our case regional WRF model).

Original TOPKAPI model was developed at the University of Bologna. Many research groups around the world have been developed own implementations of TOPKAPI models that were used for hydrological studies and flood forecasting systems. Ukrainian Center of Environmental and Water Projects (UCEWP) developed own code of TOPKAPI model (TOPKAPI-U) and successfully used it before for hydrological studies of Ukrainian rivers of Transcarpathian region. TOPKAPI-U comprises modules that describe interception, evapotranspiration, snow accumulation and snow melting, subsurface flow, overland flow, channel flow processes.

Model is used for flow calculation from upper subwatersheds of Prut and Siret basins and for lateral inflow calculation to river networks for further routing.

Collected historical hydrometeorological data models setup

There are 16 manual hydrological gauging stations and 5 meteostations within Ukrainian part of Prut and Siret river basins. Hydrological stations carry out twice observations per day during normal situations (at 8:00 and 20:00 local time) and every 4 hour during floods. Meteostations perform observations in terms established by World Meteorological Organization: precipitation is measured every 6 hours and air temperature every 3 hours.

The list of stations are shown on table 1 and fig. 4.

Table 1 – Hydrometeostations in Prut and Siret basins. H – water level, Q – water discharge (calculated from stage-flow relationship curves), P – precipitation, T – air temperature, PR – air pressure, HU – air humidity, U – wind direction and speed, SH – sun hours.

Hydrologocal Station	River	Measurements
Tatariv	Prut	H, Q, P, T
Yaremche	Prut	H, Q, T
Kolomyia	Prut	H, T
Vorokhta	Prut	H, Q, P, T
Chernivtsi	Prut	H, Q, T
Yaremche	Zhonka	H, Q, T
Dora	Kamyanka	H, Q, P, T
Lyubkivtsi	Chornyava	H, Q, P, T
Usteriky	Cheremosh	H, Q, P, T
Kuty	Cheremosh	H, P, T
Yablunytsya	White Cheremosh	H, Q, P, T
Verkvovyna	Black Cheremosh	H, Q, P, T
Putyla	Putyla	H, Q, P, T
Storozhynets	Siret	H, Q, P, T
Verhny_Yaseniv	Veretyn	H, Q, P, T
Iltsi	Iltsya	H, Q, P,T
Meteorological stations	**Basin**	**Measurements**
Pozhezhevska	Prut	P, T, PR, HU, SH, U
Yaremche	Prut	P, T, PR, HU, U
Kolomyia	Prut	P, T, PR, HU, U
Selyatyn	Siret and Suchava	P, T, PR, HU, U
Chernivtsi	Prut	P, T, PR, RH, HU, U

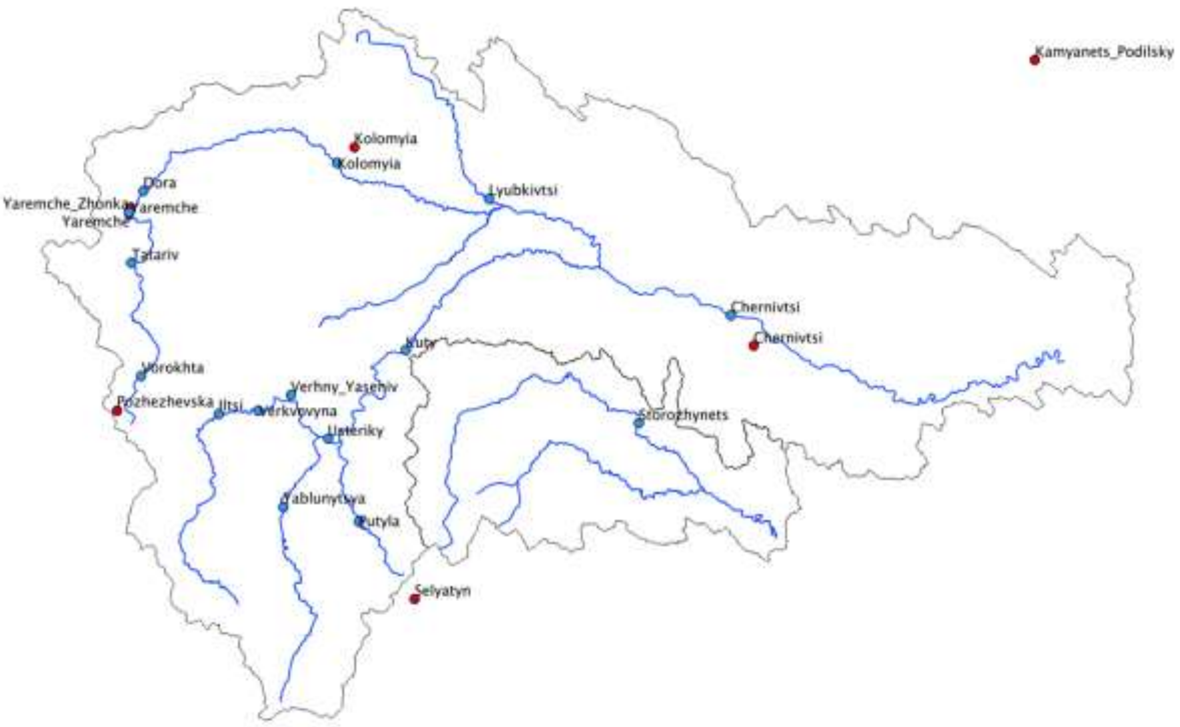


Fig. 4 Sites of hydrological stations (blue points) and meteorological stations (red points)

For calibration and verification of rainfall-runoff model TOPKAPI-U it was collected hydrometeorological data for period of 01.01.2003 – 31.12.2010. Collected data include water levels, discharges, precipitation, air temperature measured by hydrological stations and precipitation, minimal and maximal daily air temperature, daily wind speed, daile relative humidity and daily sun hours for meteorological stations. Also it was collected daily flow and precipitation data for the same time period for Romanian hydrological stations Oroftiana (only precipitation) Radauti-Prut and Siret-Siret.

Input GIS maps for hydrological model setup

Rainfall-runoff model TOPKAPI-U utilizes following GIS data that cover watershed's area: Digital Elevation Model (DEM); Flow directions and Slopes maps which are typically derived from DEM; Soils map; Landcover map; Monthly Leaf Area Index maps (LAI). Following datasets were used for hydrological model of Prut and Siret rivers basins:

- Digital Elevation model SRTM DEM (http://srtm.csi.cgiar.org) with spatial resolution 1km (fig. 5). Flow directions and Slopes were derived from DEM using corresponding GIS algrorithms (fig. 6 – 7).

- Harmonized World Soil Database v.1.2 (fig. 8) with spatial resoultion 1 km (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/);
- World Landcover dataset - GlobCover v.2.3 dataset (fig. 9) with spatial resolution 300 m (http://due.esrin.esa.int/page_globcover.php);
- World Leaf Area Index dataset GLASS LAI (fig. 10) with spatial resolution (http://glcf.umd.edu/data/lai/description.shtml) with spatial resolution 1 km.

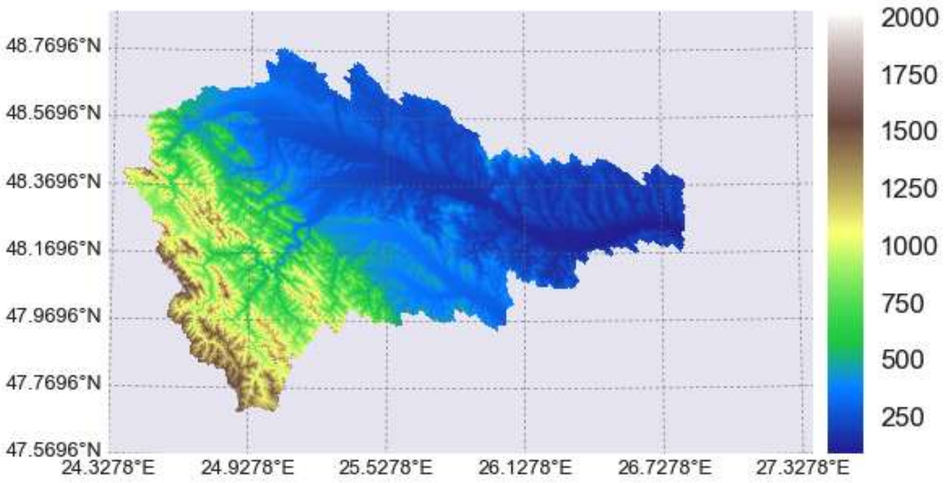


Fig. 5 Digital Elevation Model

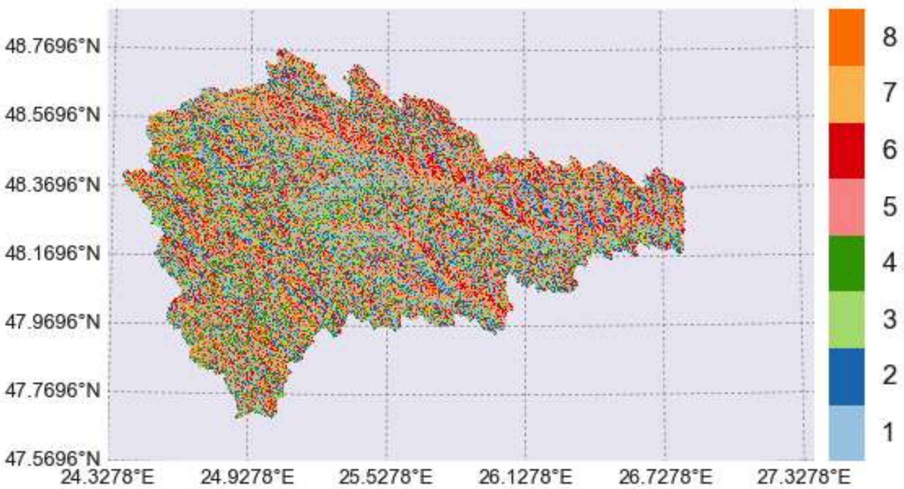


Fig. 6 Flow directions map

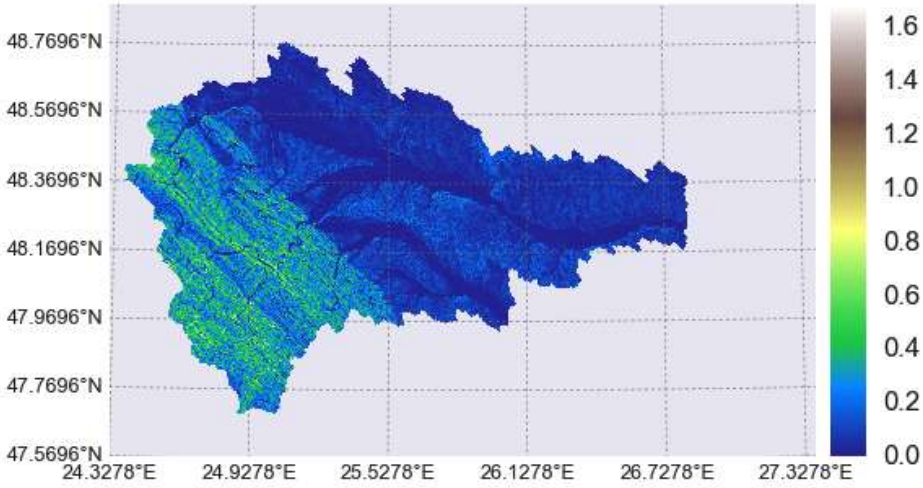


Fig. 7 Slopes map

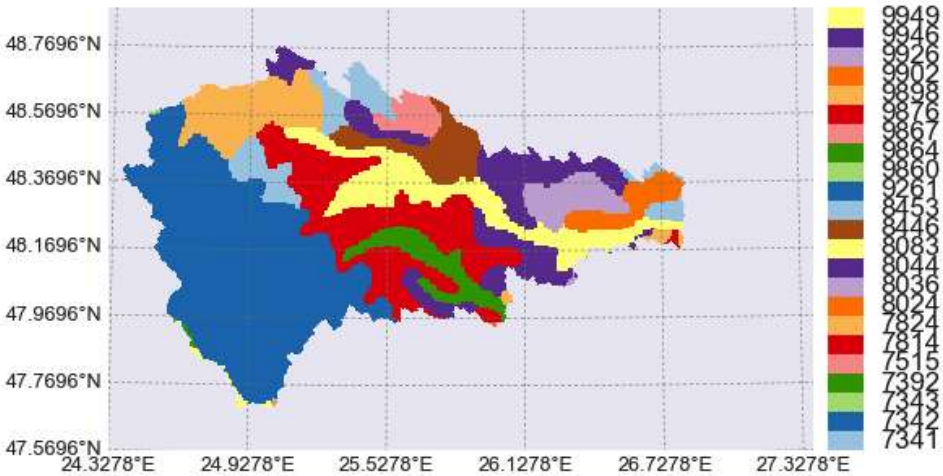


Fig. 8 Soils map

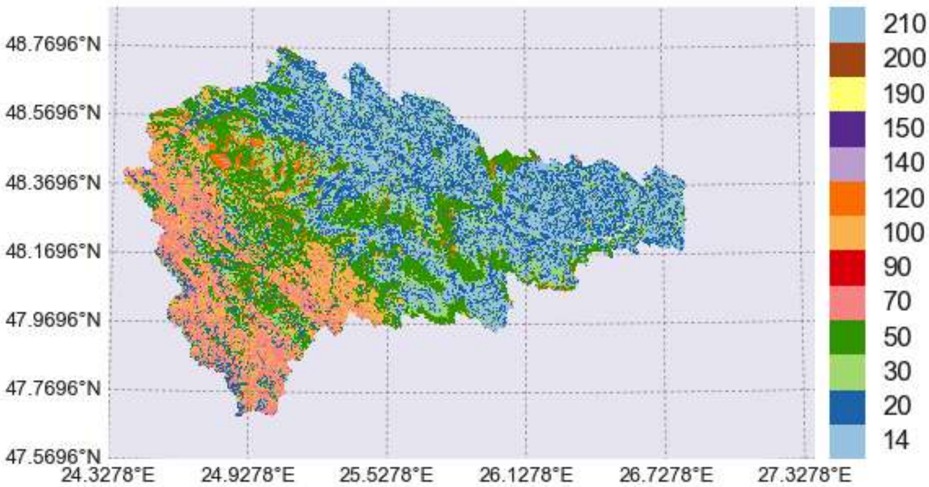
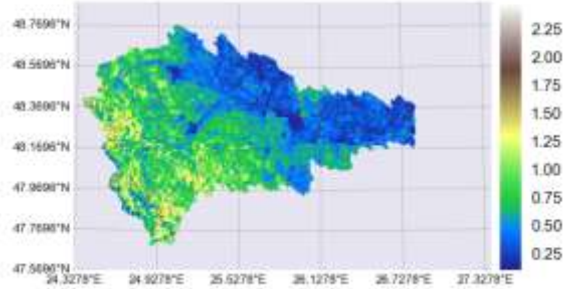
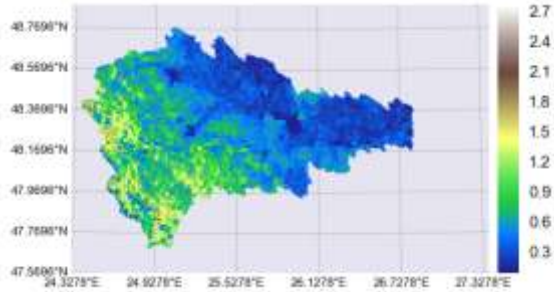


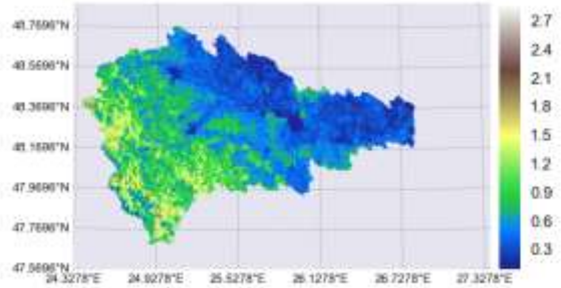
Fig. 9 Landcover map



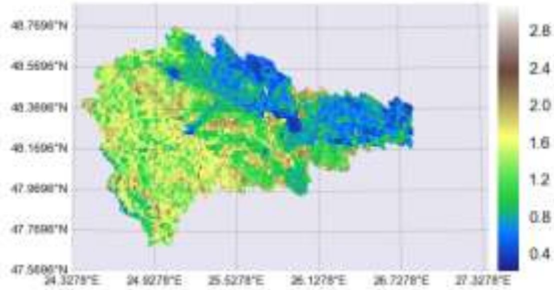
a) January



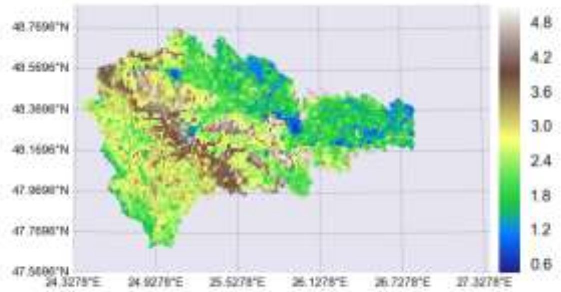
b) February



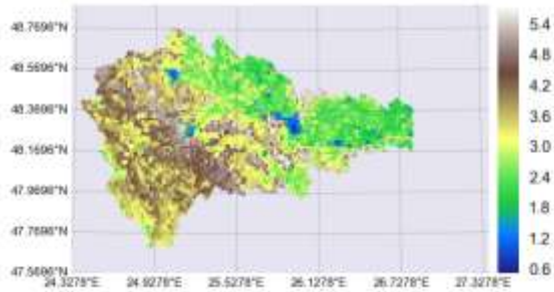
c) March



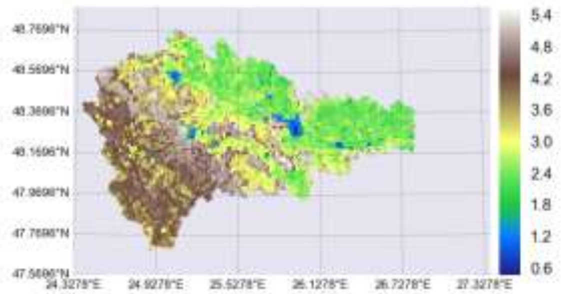
d) April



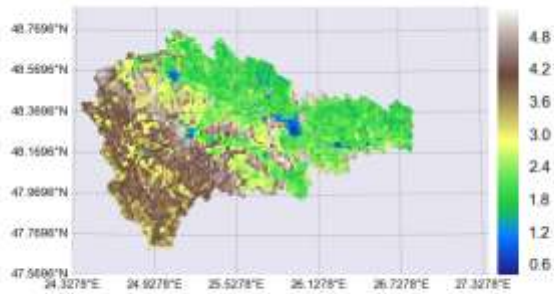
e) May



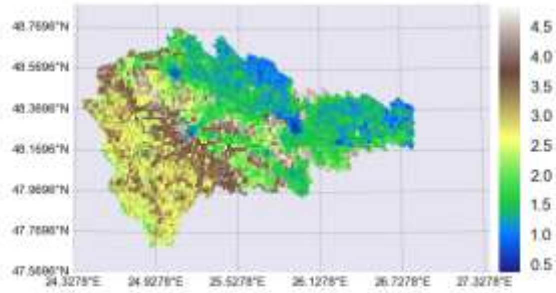
f) June



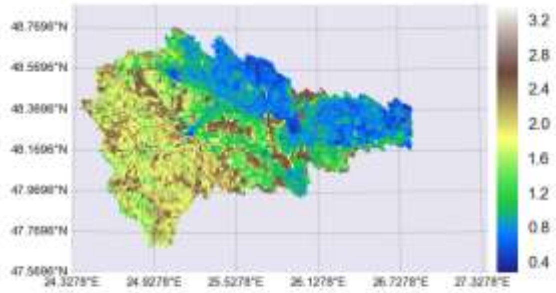
g) July



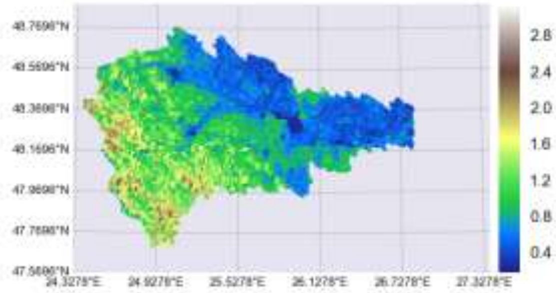
h) August



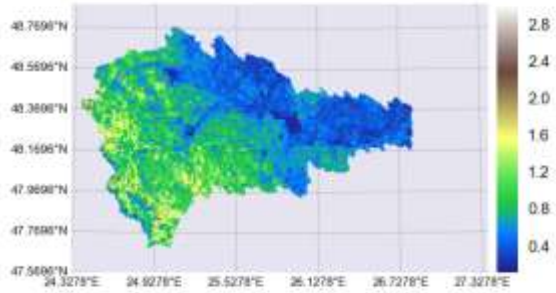
i) September



j) October



k) November



l) December

Fig. 10 Seasonal Leaf Area Index (LAI) values for Prut and Siret rivers basins

Measured crossections of Prut and Siret river

It was measured 208 crossections of Prut, Cheremosh and Siret rivers (fig. 11). Crossections are used to setup hydrodynamic model RIVTOX for flow routing.

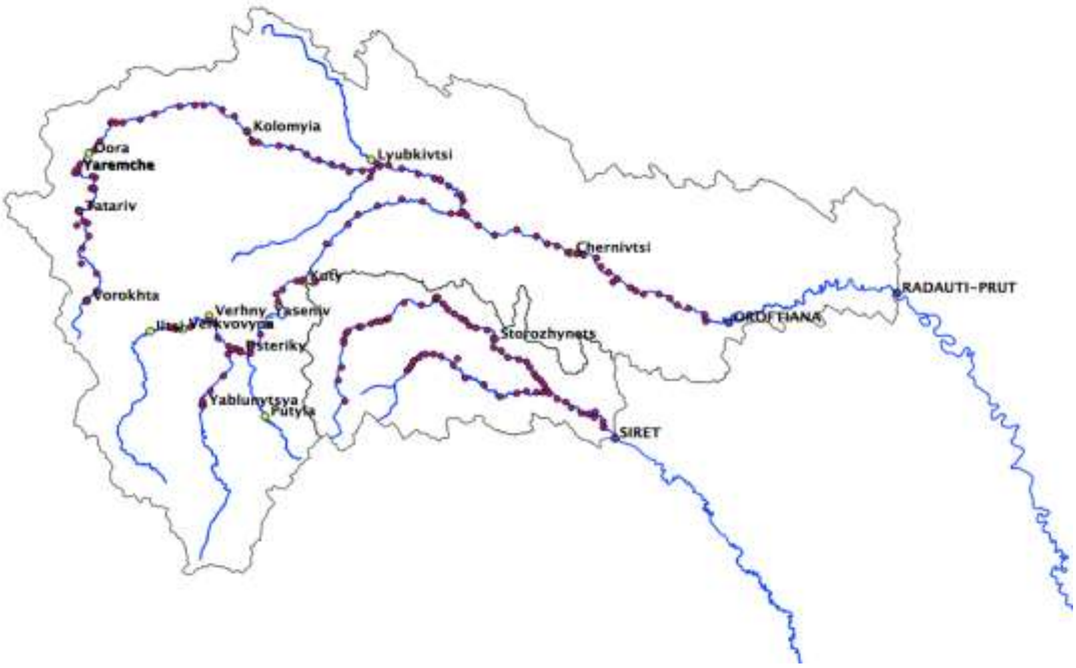


Fig. 11   Sites of crossections surveys (red dots)

SIMULATIONS OF CATASTROPHIC FLOOD OF 2008

Chapter presents results of implementation of TOPKAPI-U model for simulations of historical flow during catastrophic summer flood of 2008 for Prut river. Following figures shows the comparison of measured (red color) and simulated flow (blue color).

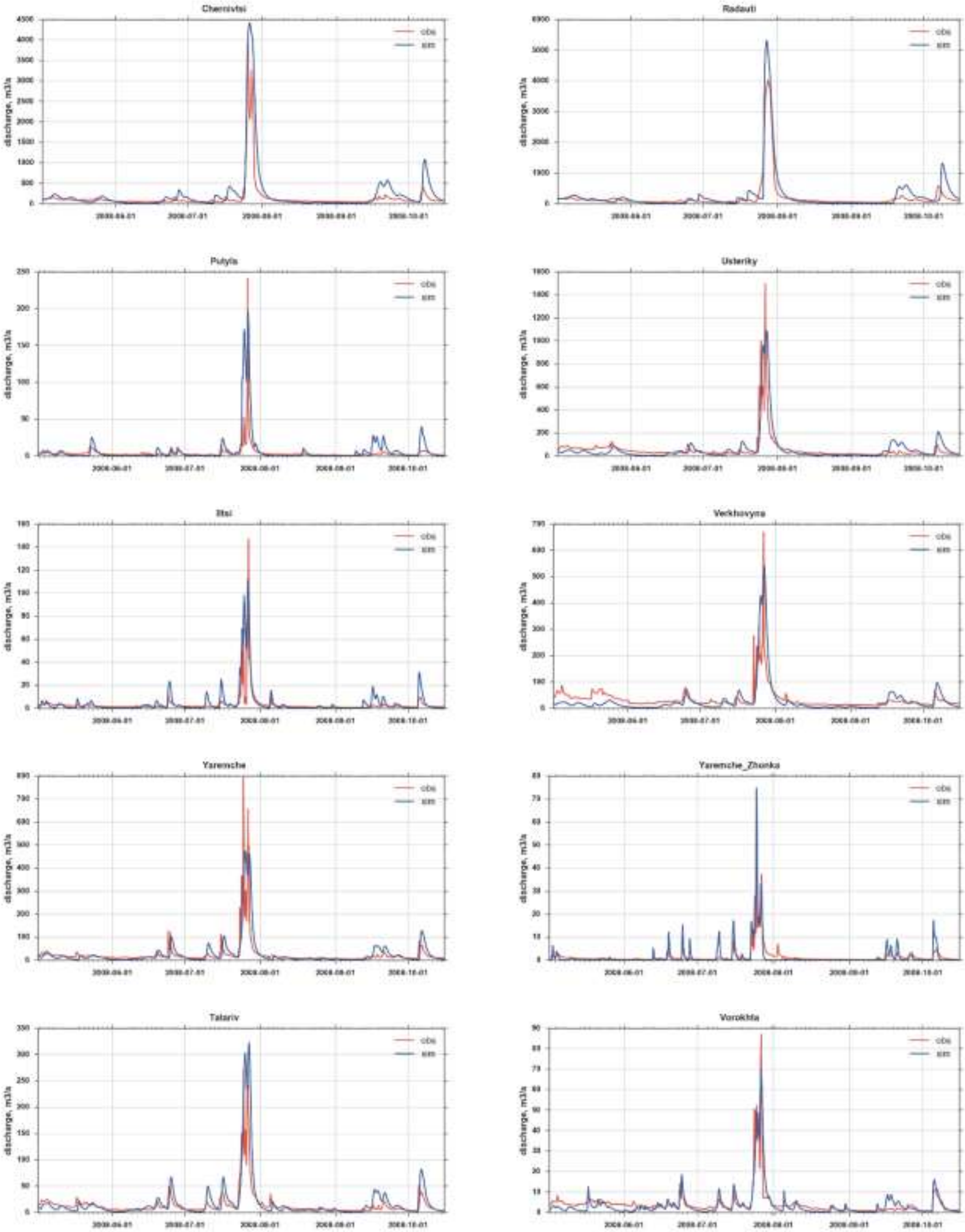


Fig. 12 Observed and simulated flow for principal hydrological gauging stations

4. Description of forecasting system workflow

System comprises two servers, namely: Computational server of Numerical Weather Prediction model WRF which is situated in Chernivtsi, Water Resources Directorate of Prut and Dnister rivers basins (BUVR); Computational server of hydrological and hydrodynamic models TOPKAPI-U and RIVTOX (server "HYDROS") which is situated in Chernitvtsi Hydrometeorological Center (ChGMC). Also system has connection via FTP with main database of Ukrainian Hydrometeorological Center (UkrGMC) for retrieving data of previous manual observations.

Principal scheme of data flow between servers is shown on fig. 13.

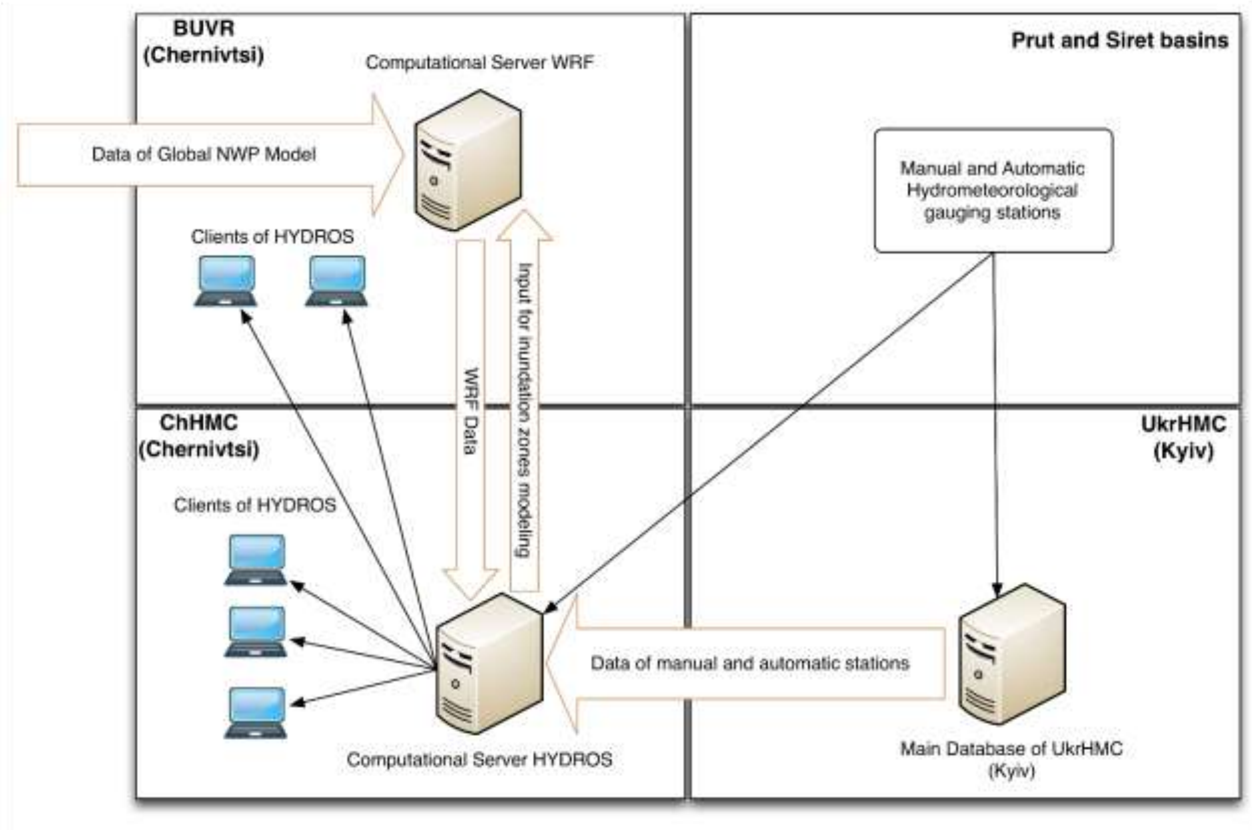


Fig. 13 Principal scheme of data exchange within the System

Every six hours numerical weather prediction model WRF calculates meteorological forecast with 96 hours lead time and time step 1 hour. WRF model produces NetCDF file that contains spatial fields of precipitation, air temperature, wind speed, relative humidity and incoming solar radiation with resolution 3x3 km (fig. 14).

NetCDF file is processed by script which by means of bilinear or nearest neighbour interpolation recalculates WRF spatial fields on computational grid of rainfall-runoff model TOPKAPI-U. Interpolated grids are stored in corresponding HDF5 format file which is meteorological forcing file for model TOPKAPI-U. Before start of the hydrological forecasting, system retrieves last 15 days observation data of precipitation, water level, air temperature from the main server of UkrHMC. Accordingly to that data TOPKAPI-U and RIVTOX model update current watershed state for beginning time point of forecasts. On the next step hydrological and hydrodynamic models calculate forecast of water flow and levels with lead time 96 hours for corresponding outlets – sites of 16 hydrological stations in Ukraine and 3 stations in Romania, namely Radauti-Prut, Oroftiana-Prut and Siret-Siret.

Final results are stored in database of forecasting system and may be viewed in user interface of "HYDROS" system.

Scheme of described workflow is shown in fig. 15.

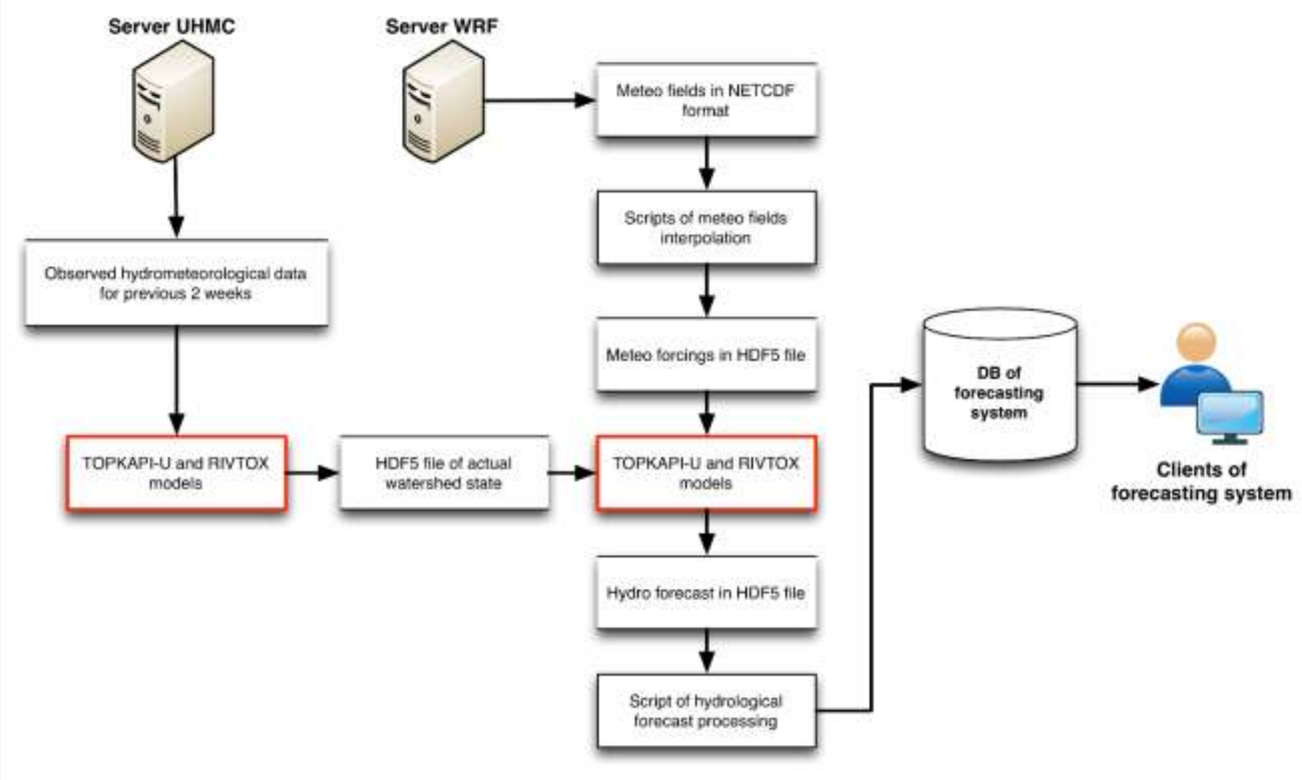


Fig. 15 Workflow of hydrological forecasting for PRUT and Siret in UA

5. HYDROS – the software system integrating the modelling modules of the forecasting system and providing the user interfaces

The “Hydros” system has a client-server architecture, where the server is located in “DP BUVR” and clients can be located in both ChGMC and on other workstations.

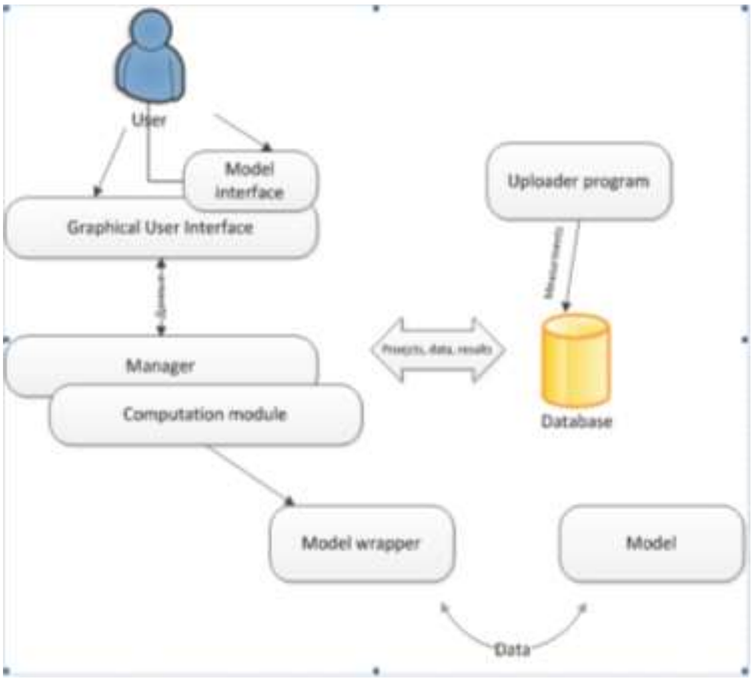


Fig. 16 “Hydros” system client-server architecture

Computational module is responsible for initializing, launching models for performance and getting results. It stores information of tasks and each project you are working with at the moment. This component of the team with the manager runs the execution calculation engine model turns information from a unified data type in the format required for each model, collects and stores the results of calculations.

Horizontal scaling is maintained at a calculator, that is, to increase productivity is possible to add new nodes, servers, processors.

The user enters data through a graphical user interface. This data is transmitted via the Manager and Computation module in a unified data type format where the data are converted into a format of model, and sent to the calculation engine model. After finishing the simulation data is loaded into the shell model, wherein they are converted into system data types and are sent to the system kernel. Results may be stored in a database or displayed in a graphic user interface.

The graphical user interface allows the operator of the system to provide convenient system management, input the necessary input data and visualization of calculation results and measurement data coming into the system.

Main window containing map with Prut (outlet in Radauti) and Siret (outlet in Siret) river basins including water gages and meteo stations.

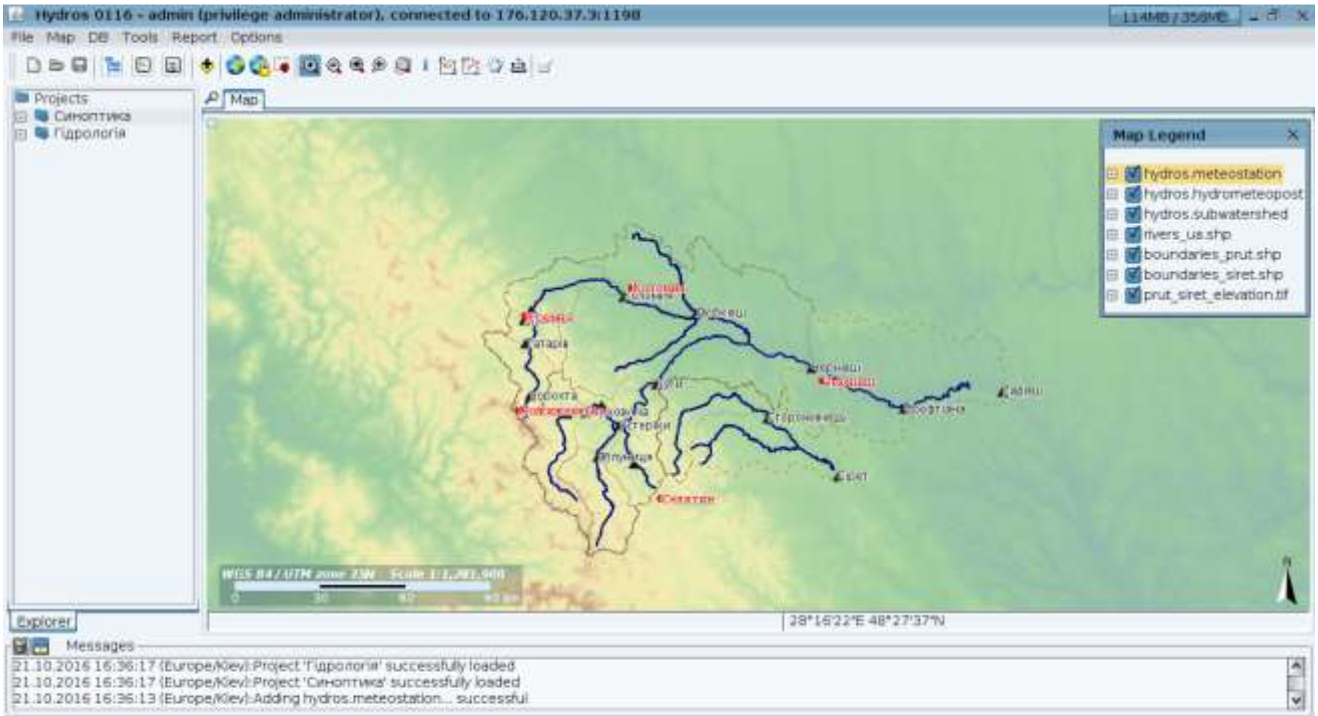


Fig. 17 "Hydros" graphical user interface

The client part of the system is a user-oriented component, its' main task is the displaying information to the user and sending data and requests to the Manager. The client provides a graphical interface, which consists of such modules: main module, models' interface module, GIS module, reporting and visualization modules.

The main module controls the other modules and is designed to provide the user with the appropriate functional and display the loaded projects. The main actions performed by the user is to create, copy, delete projects; up, the allocation of tasks within a project, the user interface for call patterns, call visualizer, display information from a database; group tasks, which is sent to the manager: initialization, startup performance problems and getting results.

Module interface displays models of computational models and interfaces designed to collect parameters from the user, check the settings. Communication occurs through "dataitems" tree, which interface module receives from the main module.

An important part of the data is georeferenced data, for which there is a geoinformation module. Geoinformation module is designed to display the spatio-temporal and thematic data, which consist of digital terrain models (levels of heights, land-use categories, soil, rivers and lakes, settlements, boundaries of administrative areas, etc..), The results of calculations and information from the database (Weather forecast maps, measurements of different characteristics).

The HYDROS software system displays the results of the numerical weather forecasting model WRF:

- Fields of precipitation
- Field temperature
- Wind field

- Humidity field

Project Navigator has a tree structure:

- Cards
    - precipitation
    - air temperature
    - wind
    - air humidity
- Accumulated precipitation
    - for 6 hours
    - for 12 hours
    - 24 hours
- Charts and tables
    - precipitation
    - air temperature
    - wind
    - air humidity

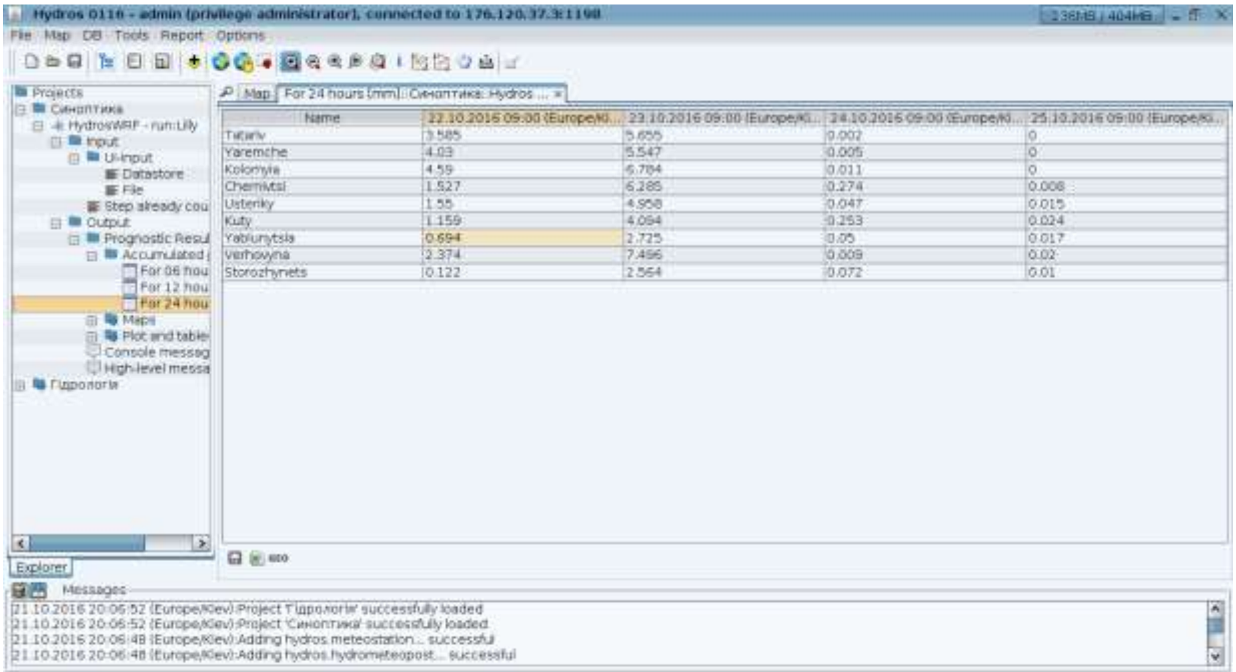


Fig. 18 Table view of accumulated precipitation per subwatershed for 24 hour period

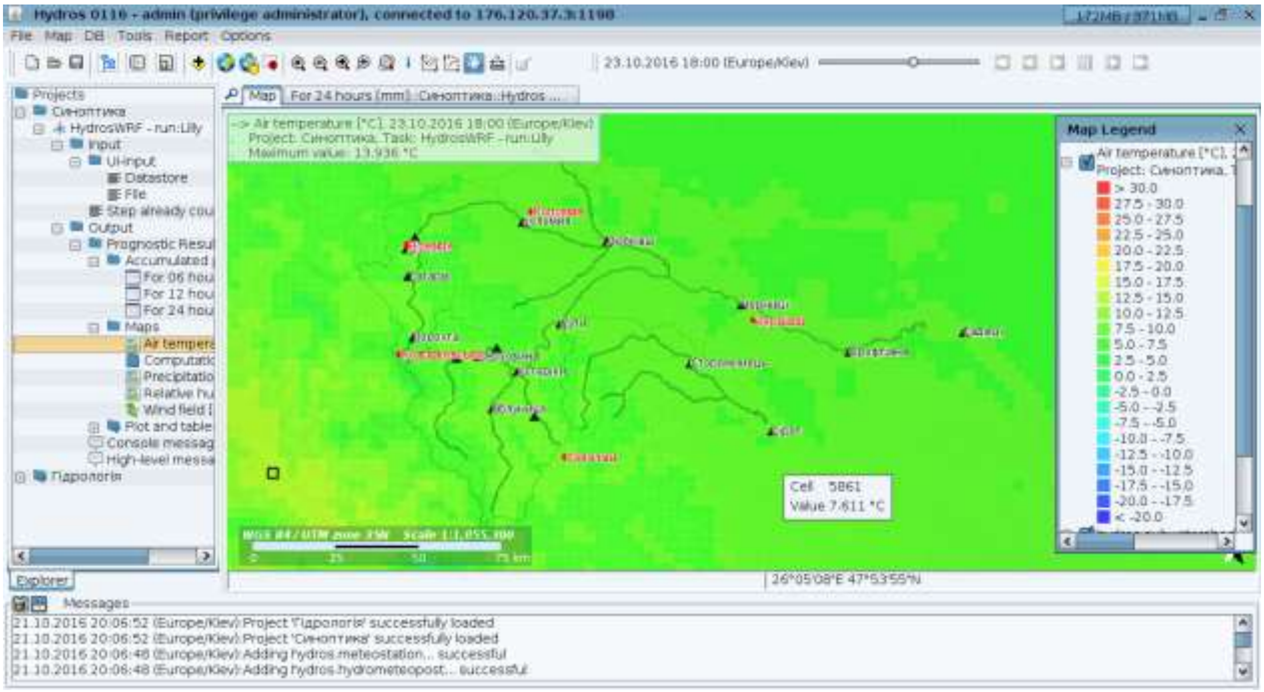


Fig. 19 Map view. Air temperature field.

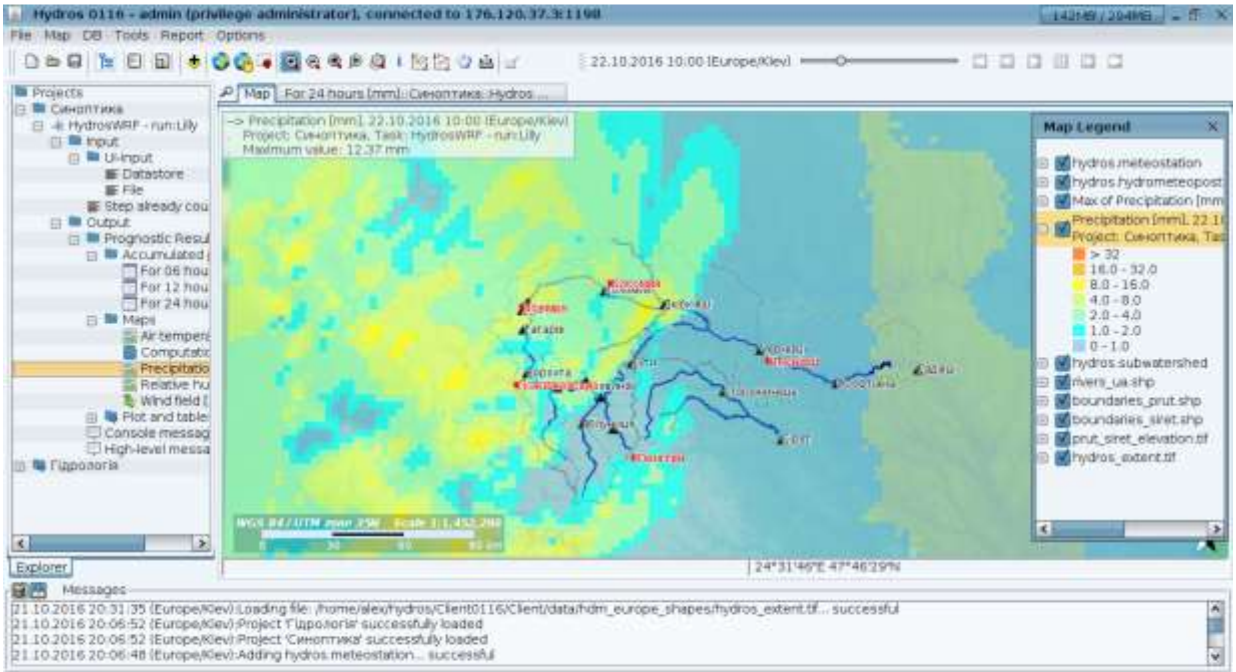


Fig. 20 Computational grid of WRF model

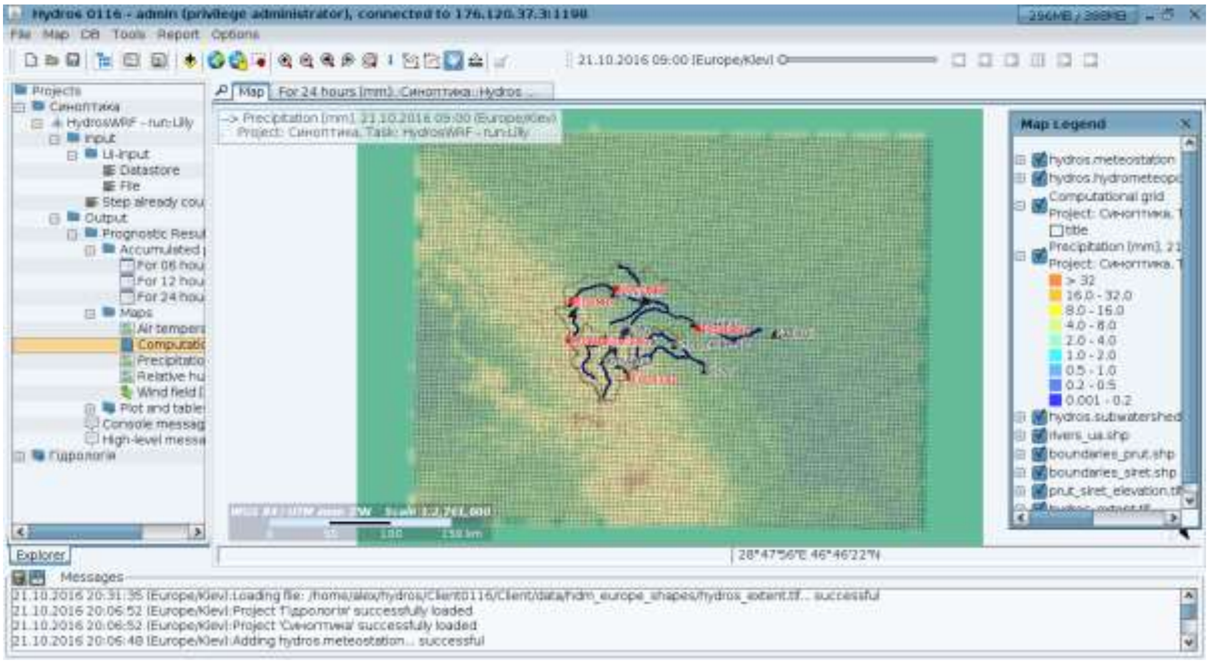


Fig. 21 Precipitation map

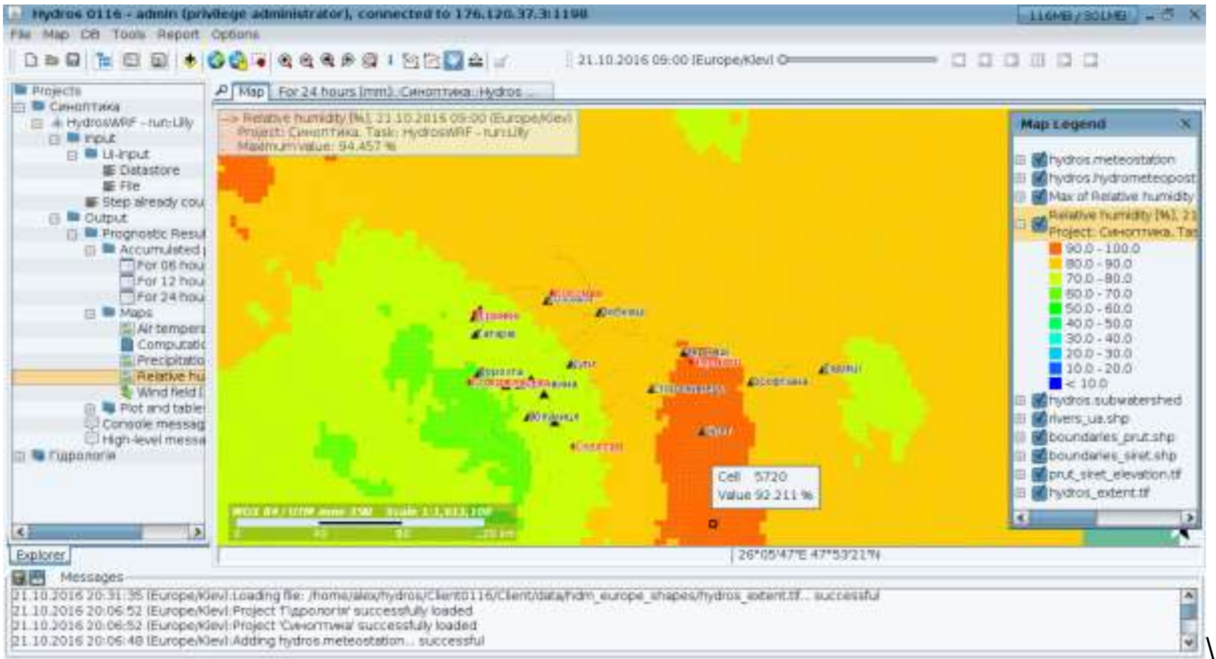


Fig. 22 Relative humidity map

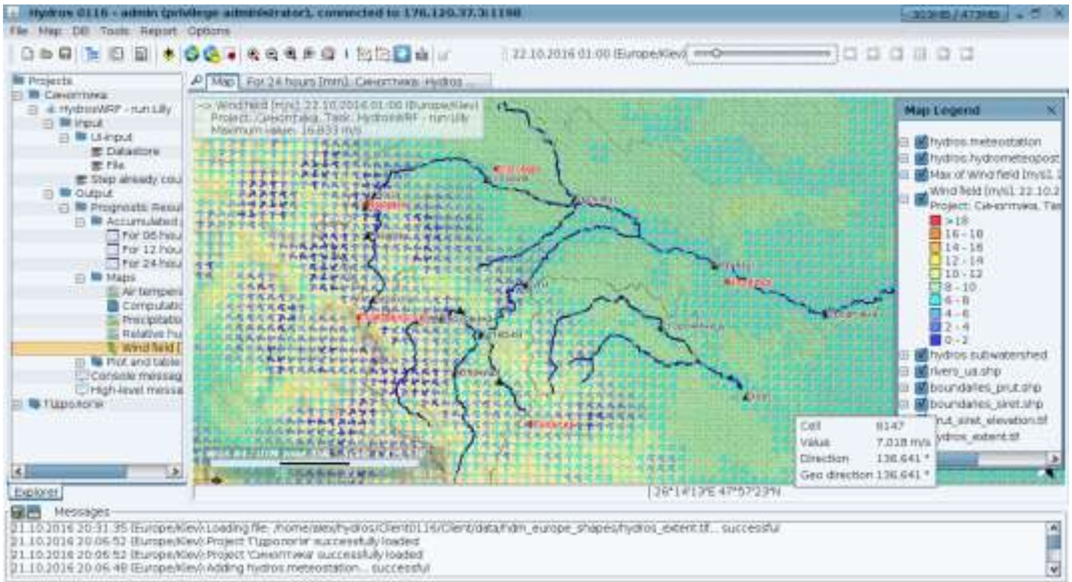


Fig. 23 Wind field of WRF model

Maps can be animated. Near the slider, that controls the animation, there is a list of all the forecast date to jump to the desired step forecast.

Vertical - subwatersheds, horizontally - the forecast of steps (6, 12, 24 hours). Graphs and tables for each parameter are displayed in the central panel tab. These all weather stations and gauging stations are displayed one hectare plot and in the same table. To schedule the X-axis - forecast steps on the Y-axis - value. For horizontal table - forecasting steps, vertical weather station name or gauging.

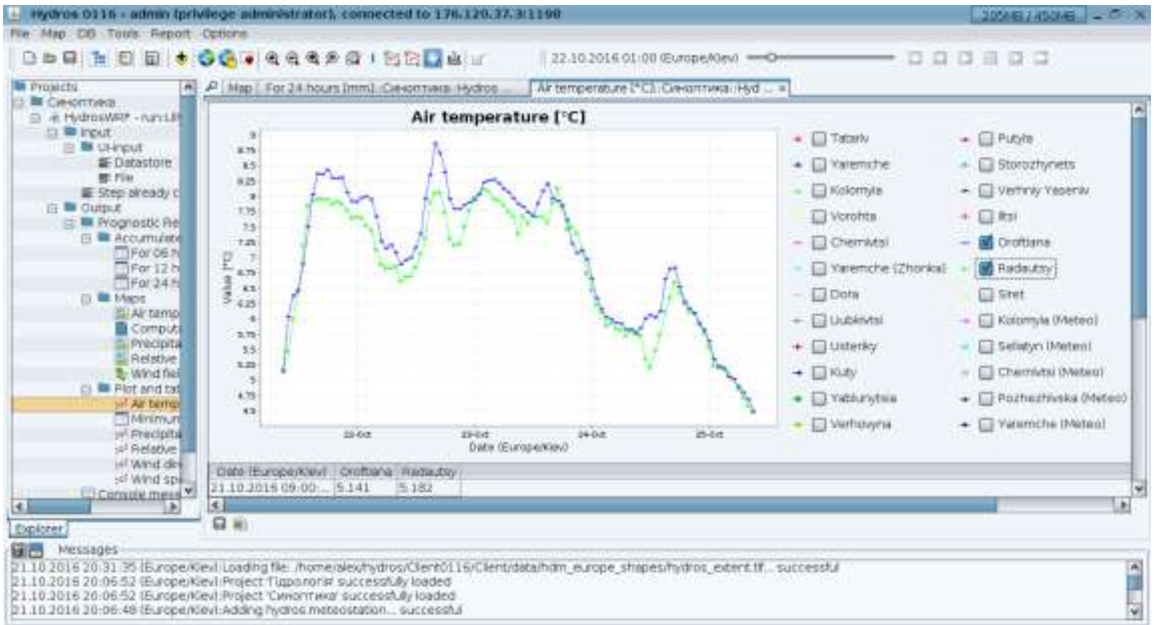


Fig. 24 Plot view of air temperature on Oroftiana and Radăuţi

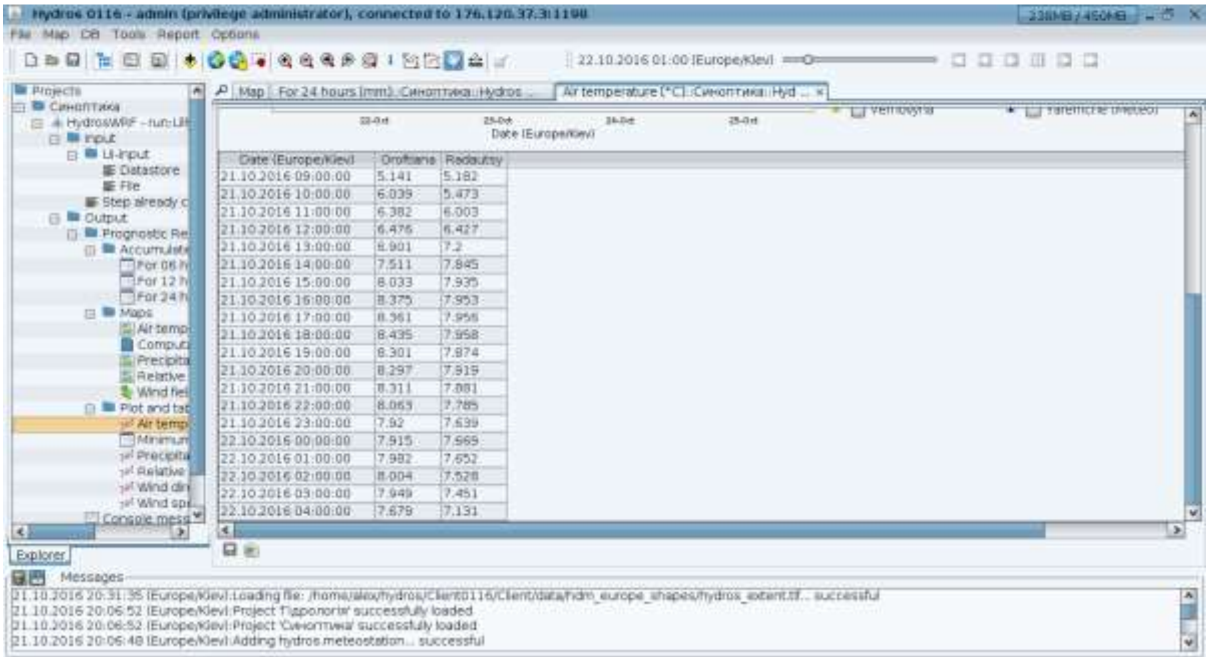


Fig. 25 Table view of air temperature on Oroftiana and Radăuţi

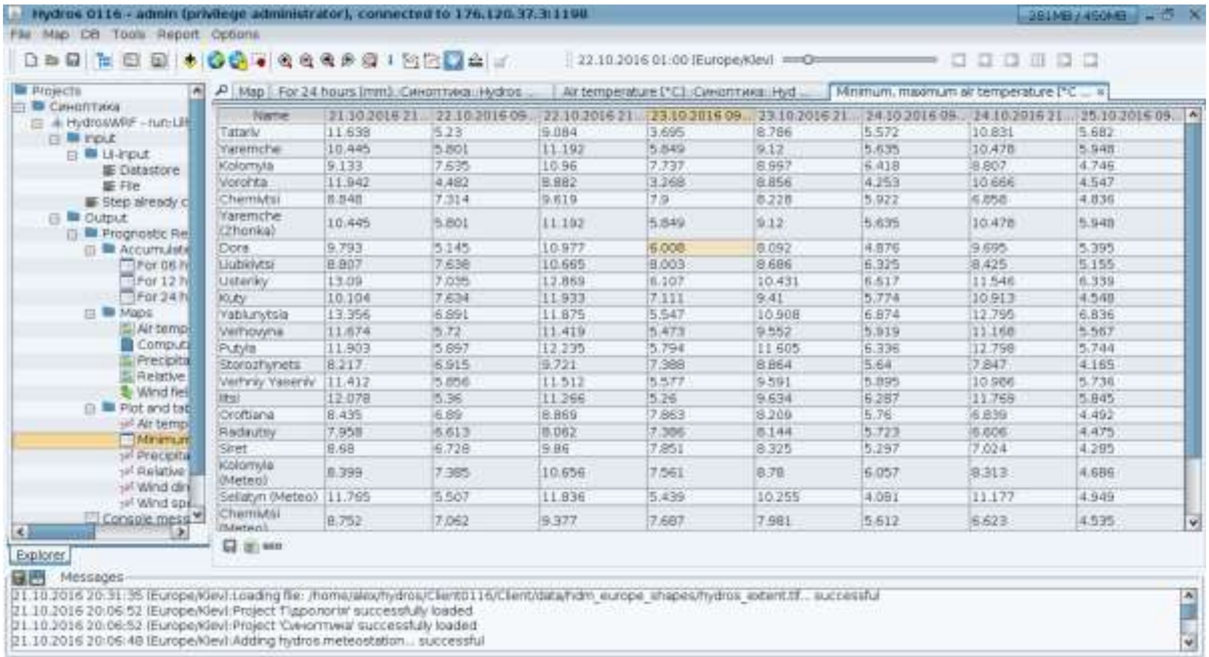


Fig. 26 Table view of minimum and maximum temperature

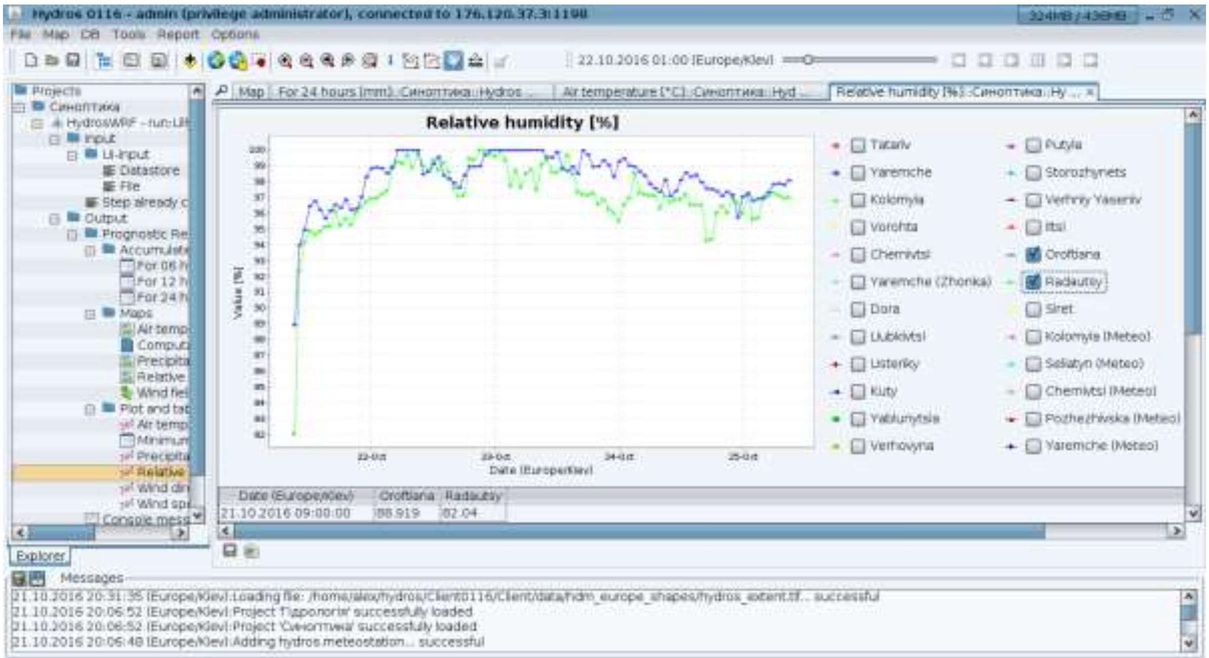


Fig. 27 Relative humidity plot view on Oroftiana and Radăuţi

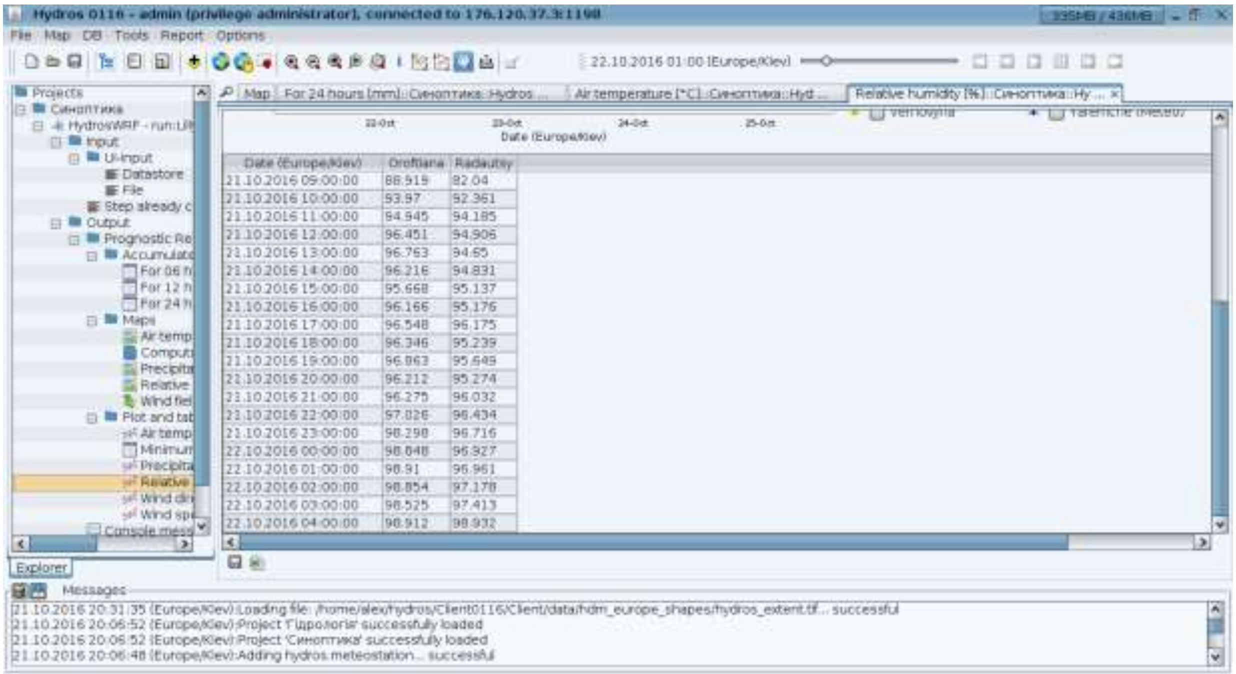


Fig. 28 Relative humidity table view on Oroftiana and Radăuţi

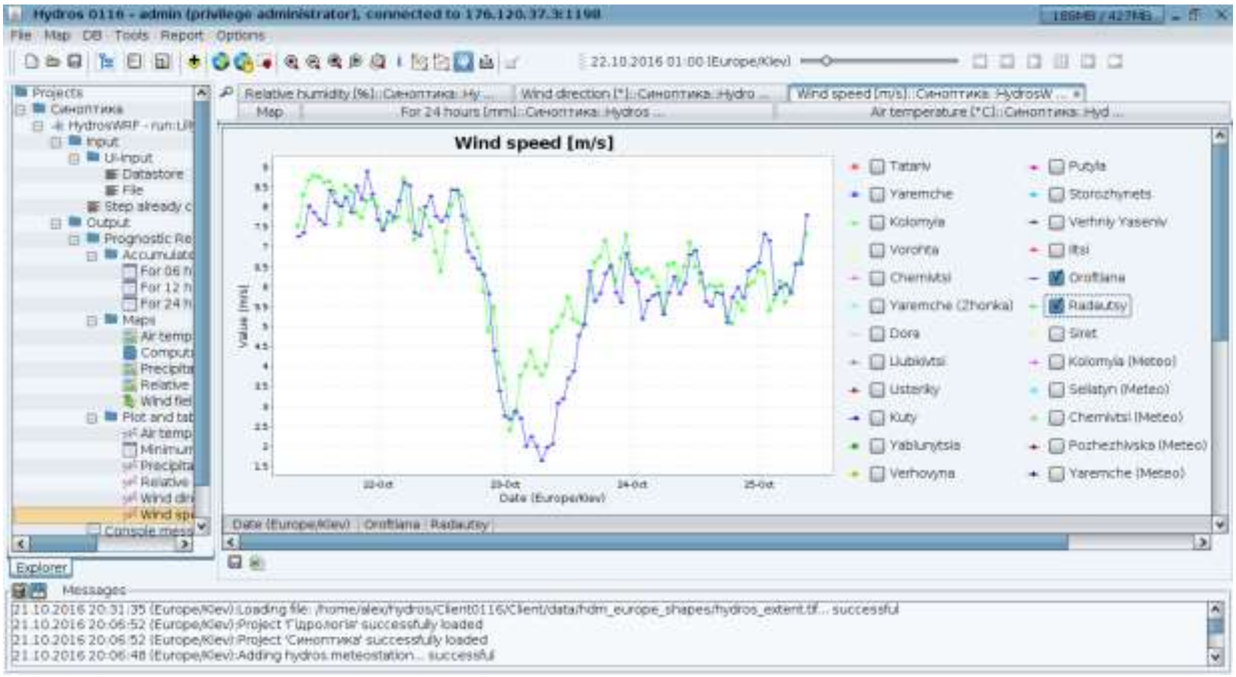


Fig. 29 Wind speed plot view on Oroftiana and Radăuţi

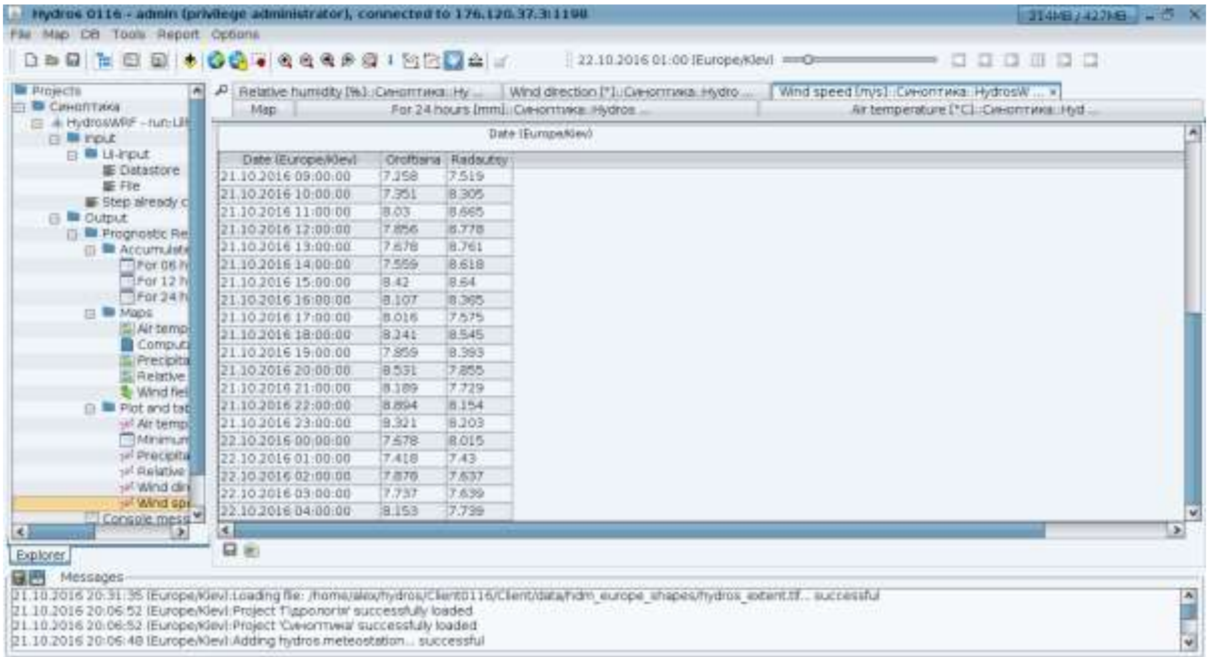


Fig. 30 Table view of wind speed on Oroftiana and Radăuţi

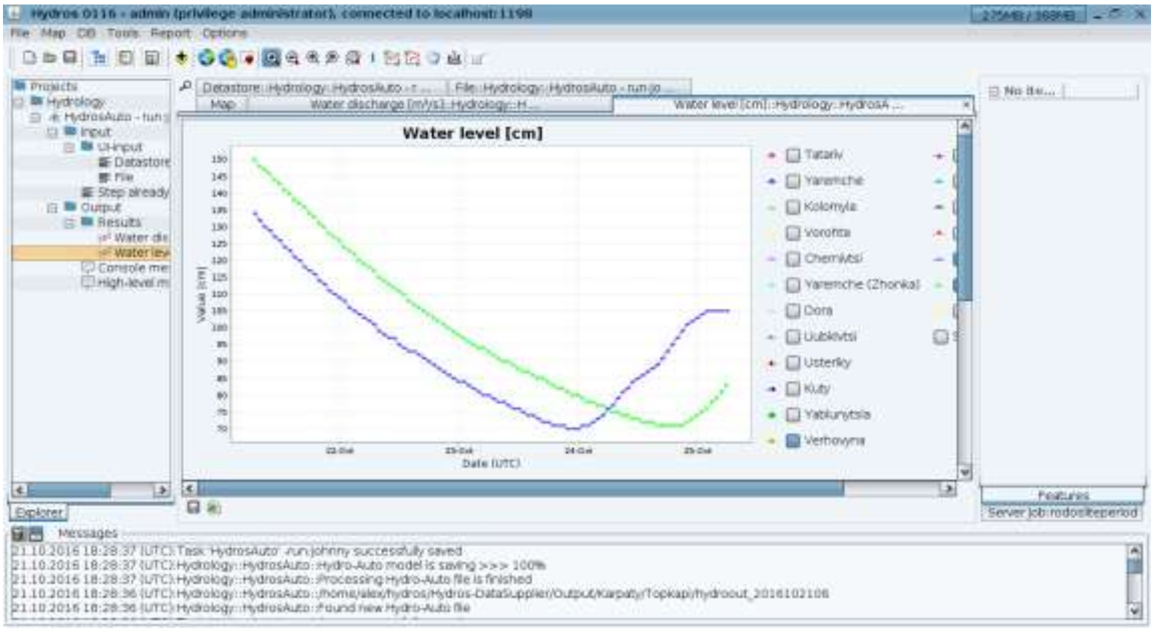


Fig. 31 Plot view. Water levels on stations Oroftiana and Radăuţi

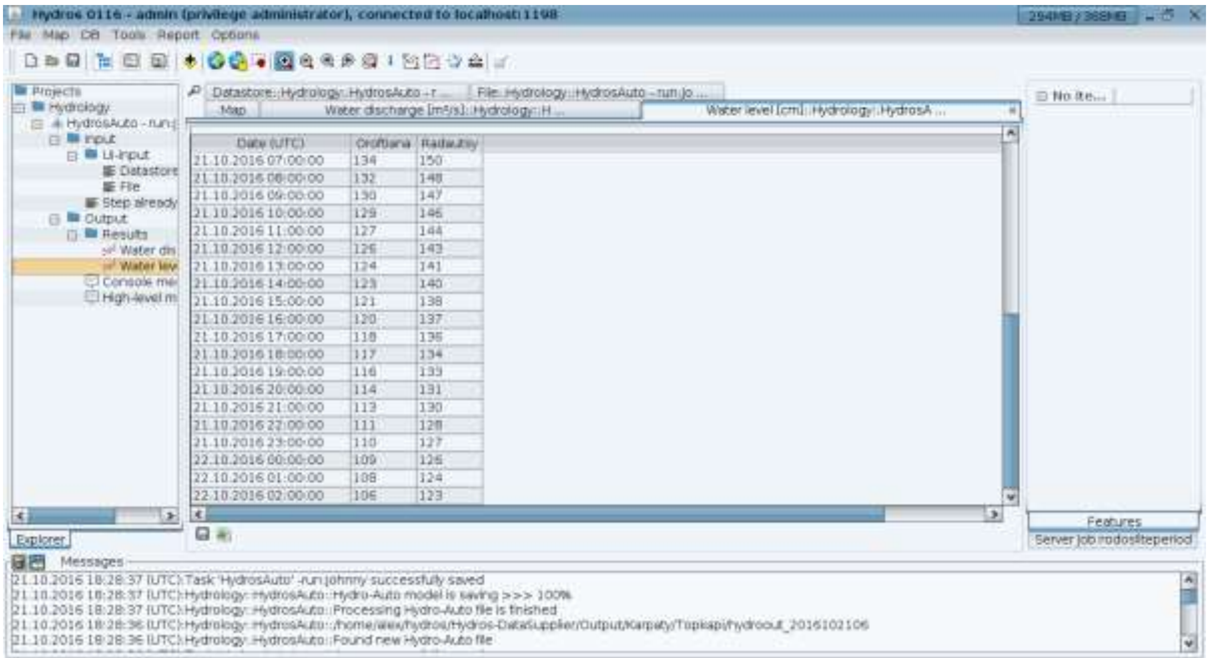


Fig. 32 – Table view. Water levels on stations Oroftiana and Radăuţi

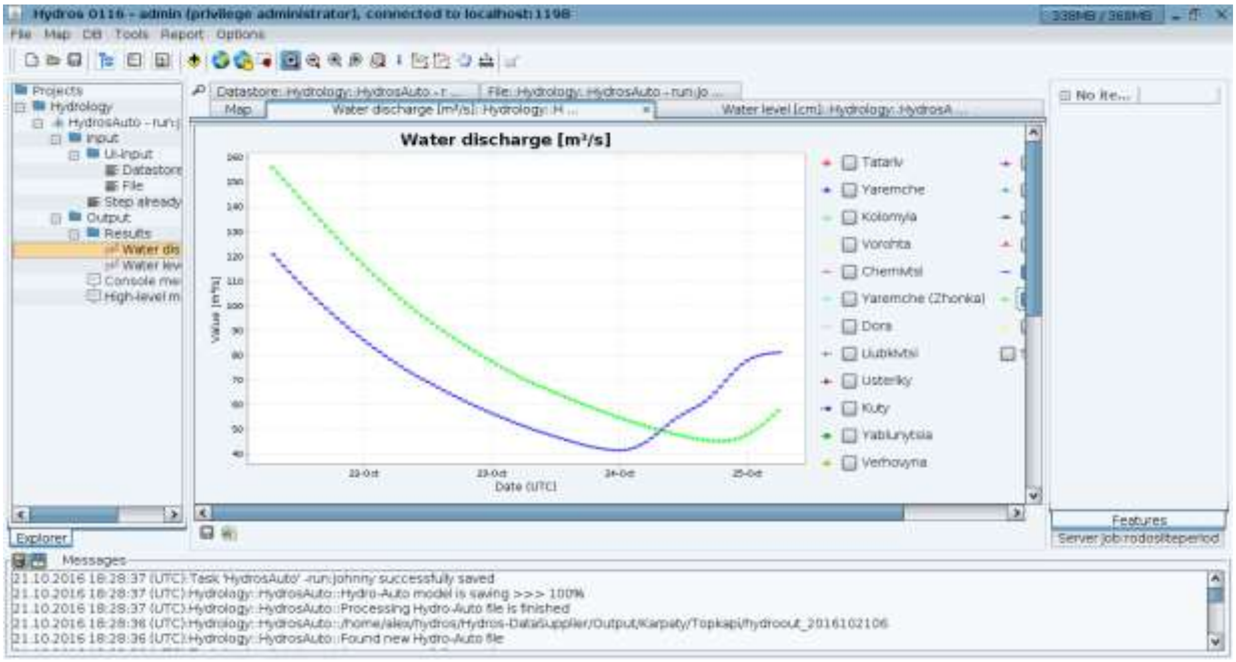


Fig. 33 Plot view. Water levels on stations Oroftiana and Radăuţi

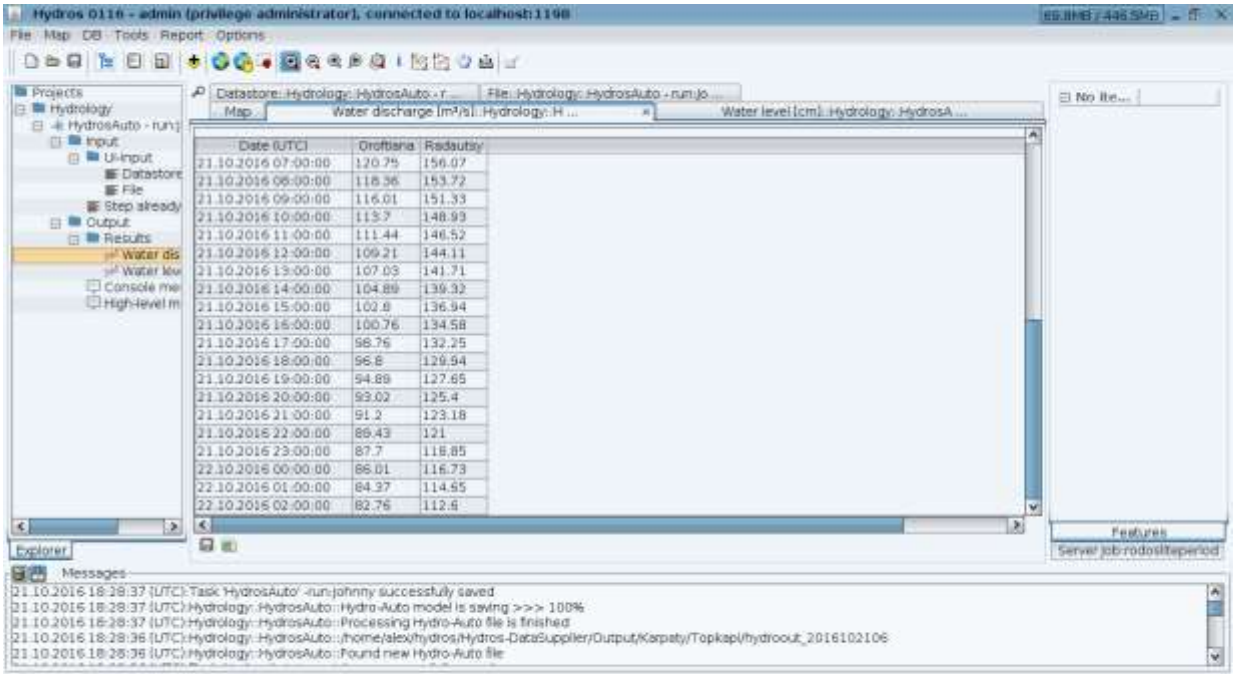


Fig. 34 Table view. Water discharge on stations Oroftiana and Radăuţi

Interface of 2D model COASTOX implemented for the modelling of "high rflood risk areas"

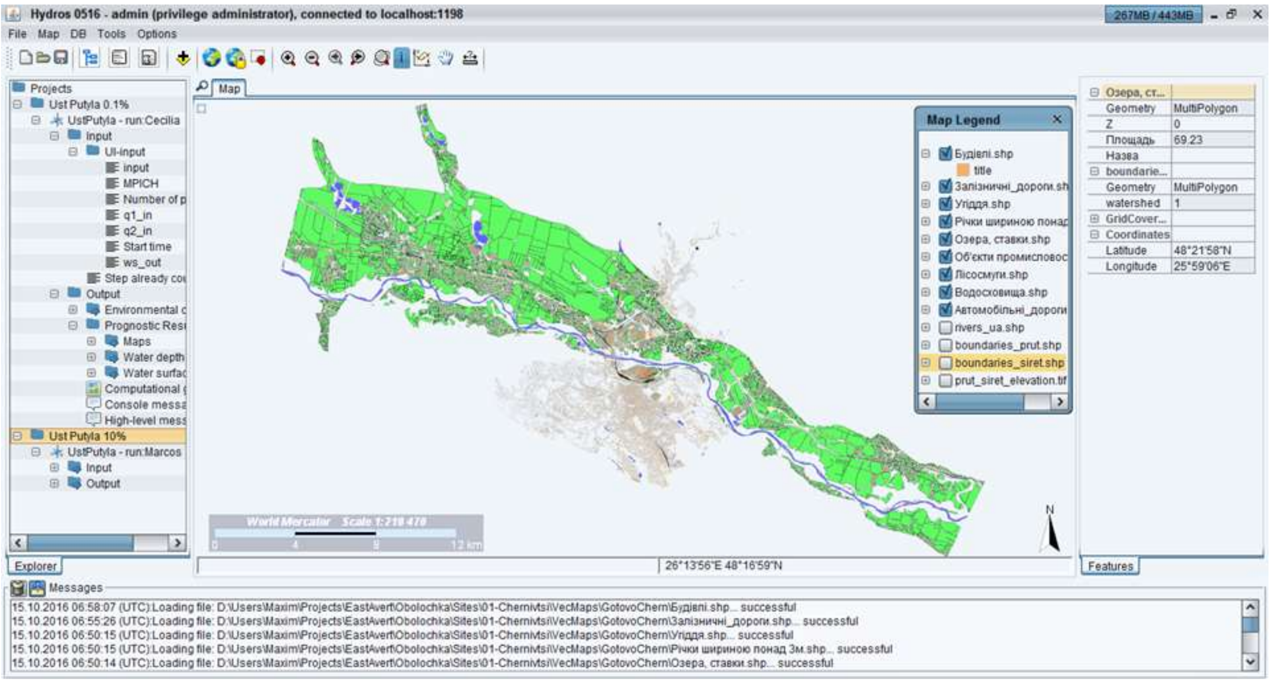


Fig. 35 Flooding zone Chernivtsi site

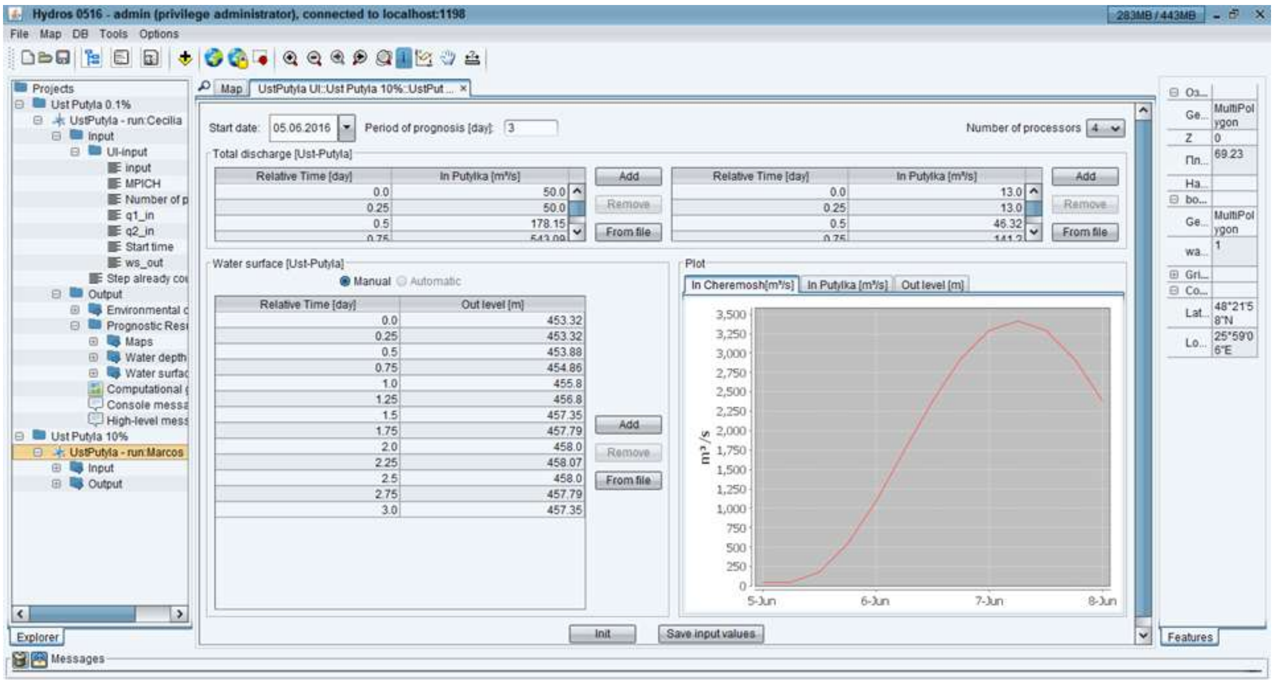


Fig. 36 Coastox model initialization window

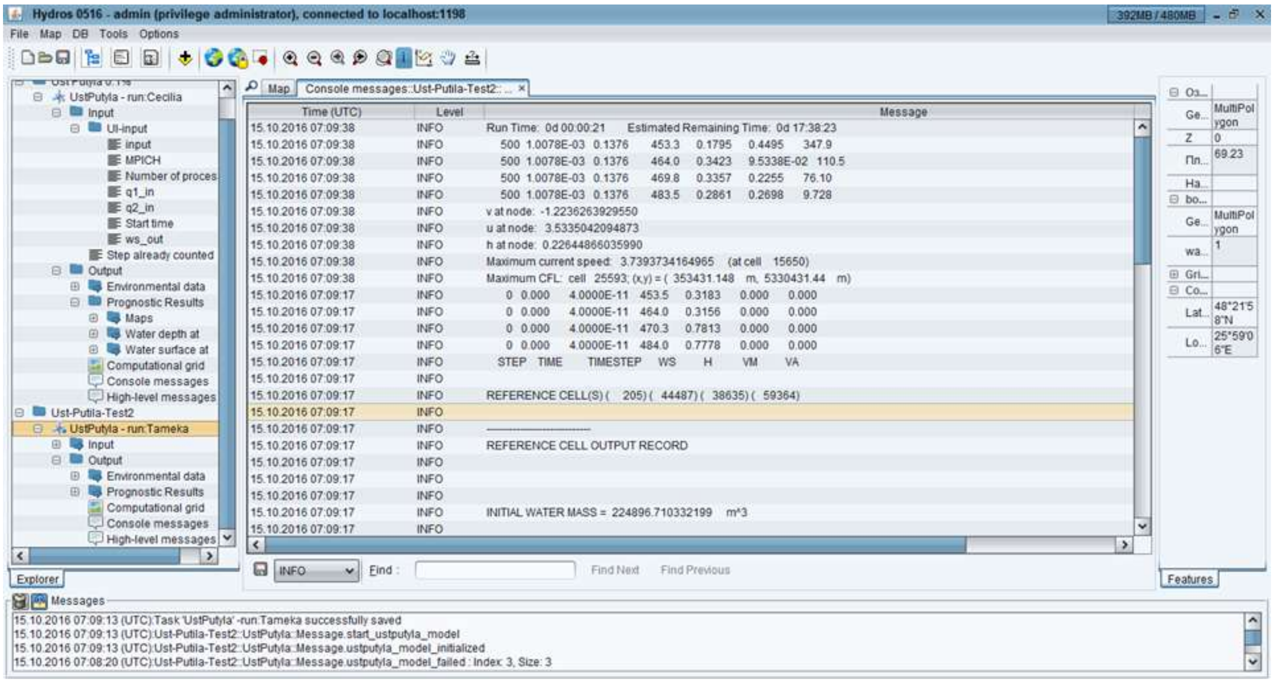


Fig. 37 Coastox model running

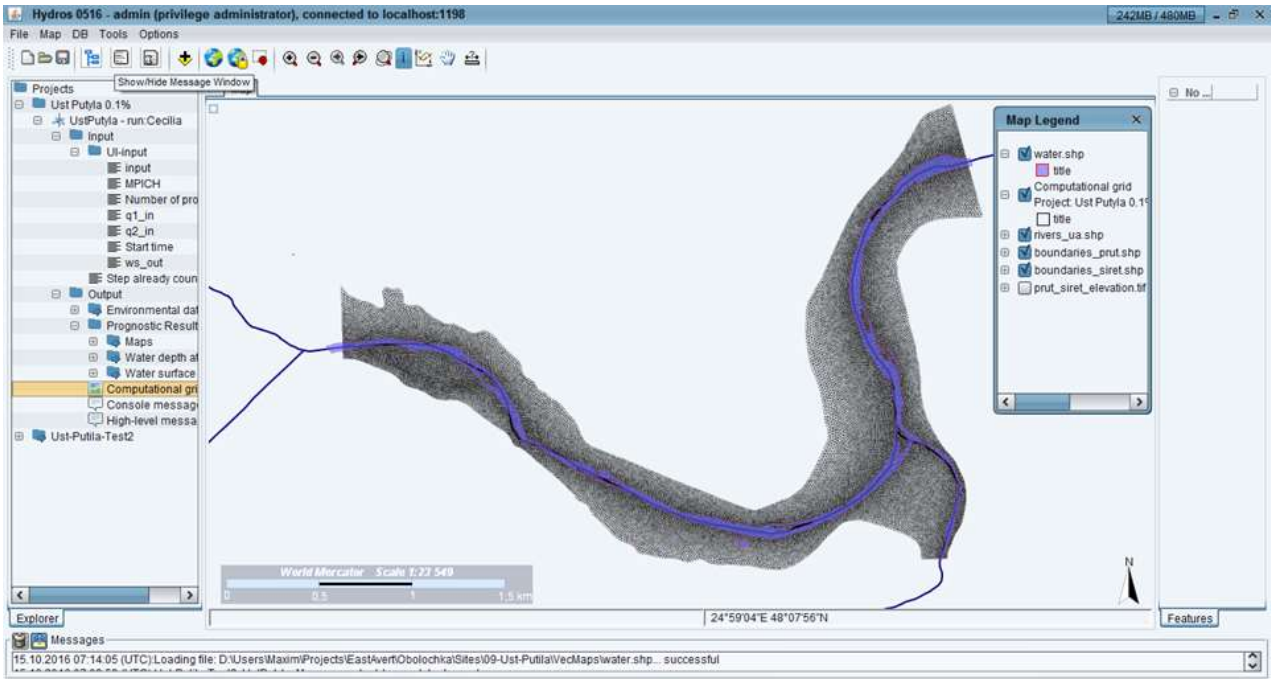


Fig. 38 Coastox model computational grid in user interface for Ust-Putila region

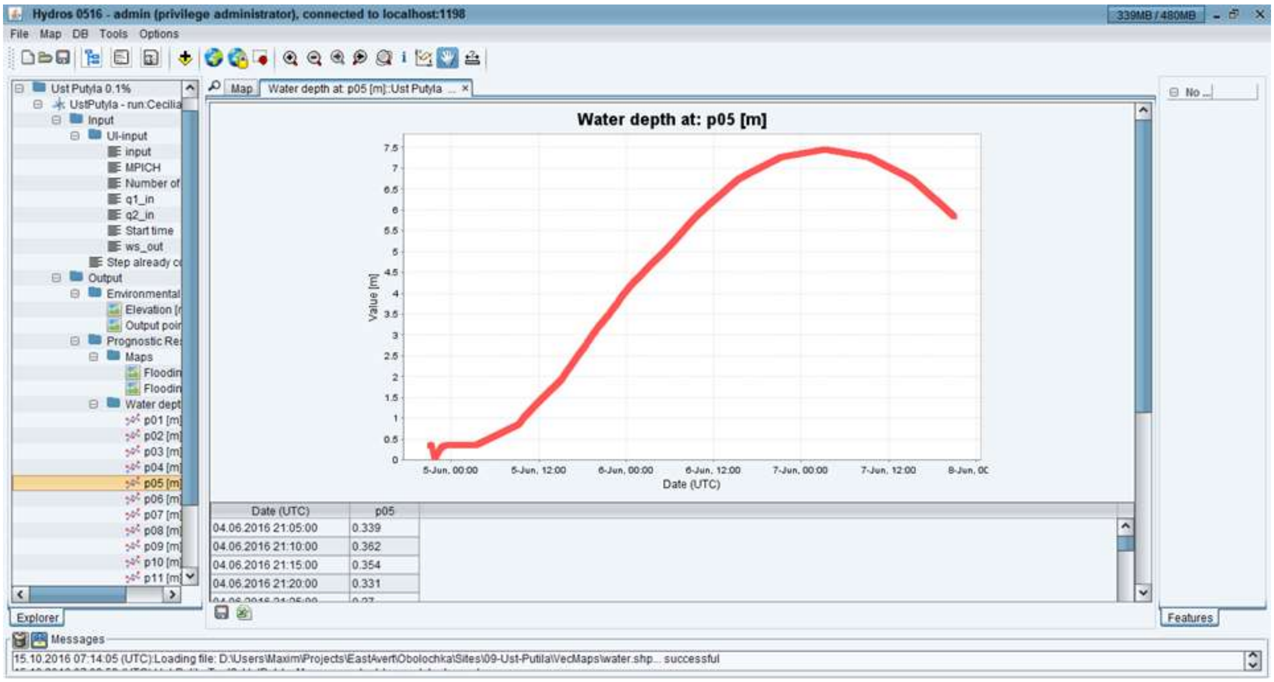


Fig. 39 Results of Coastox model. Water depth at point “p05”

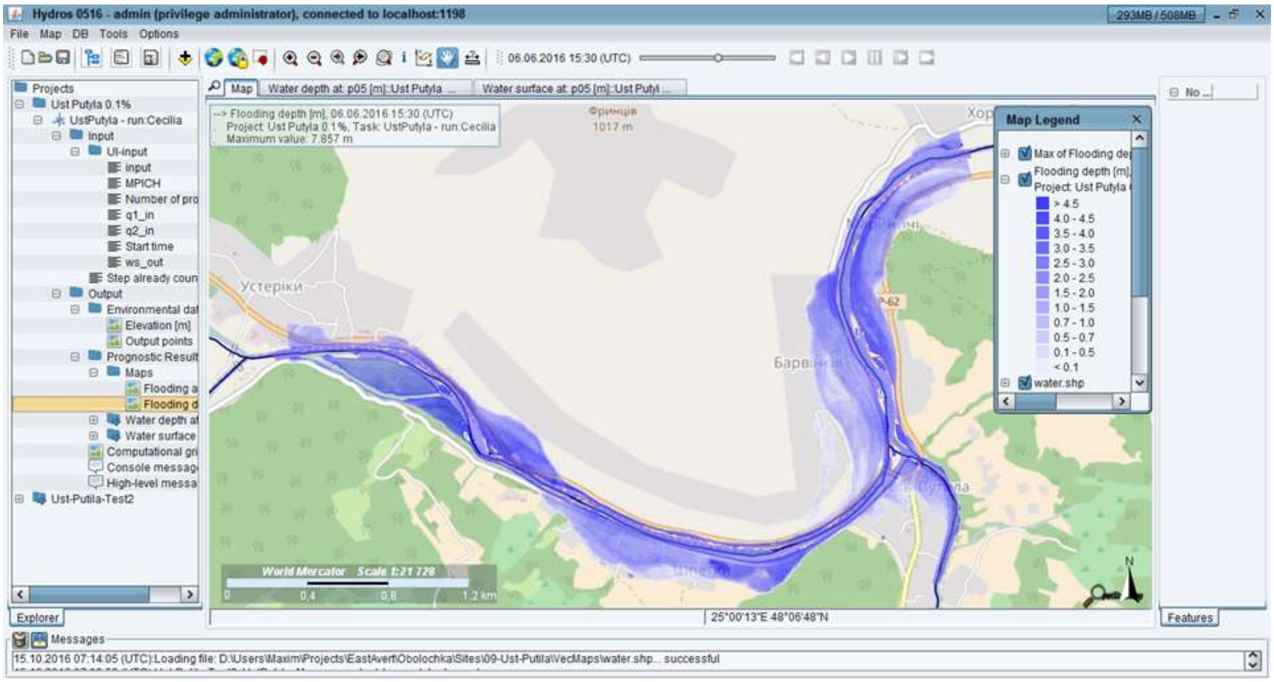


Fig. 40 Water depth map view of Ust-Putyla region

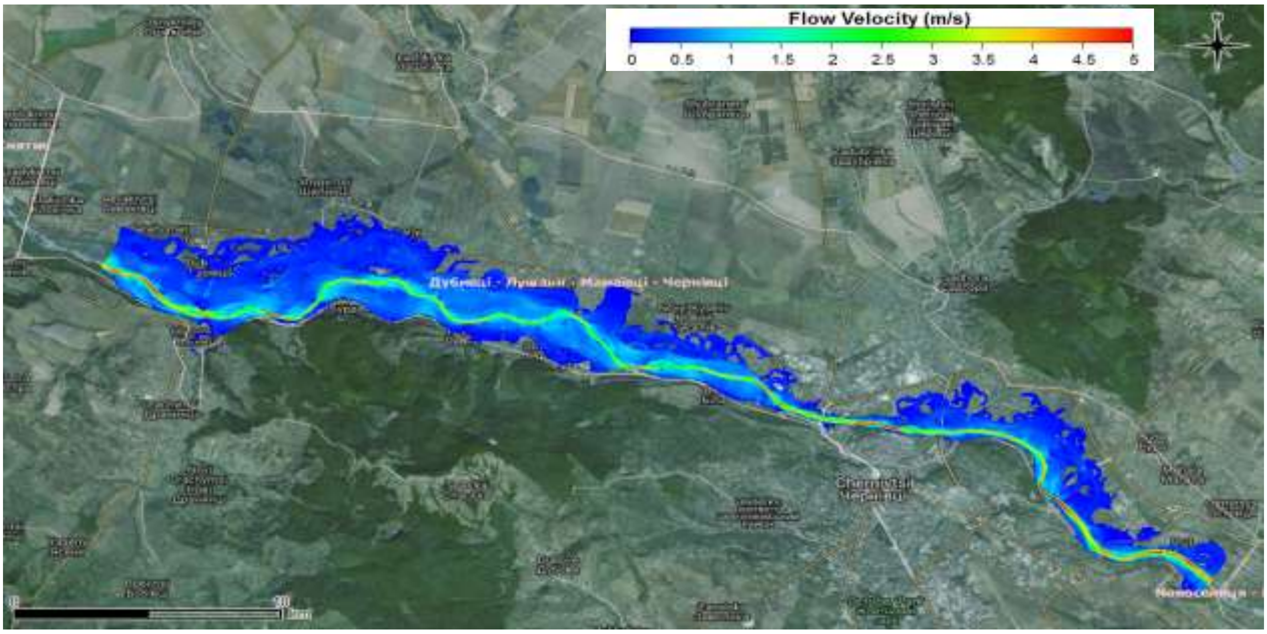


Fig. 41 1% Flood for site 01-Dubivtsi-Luzhany-Mamaivtsi-Chernivtsi. Full extent. CRS: WGS 84/Pseudo-Mercator

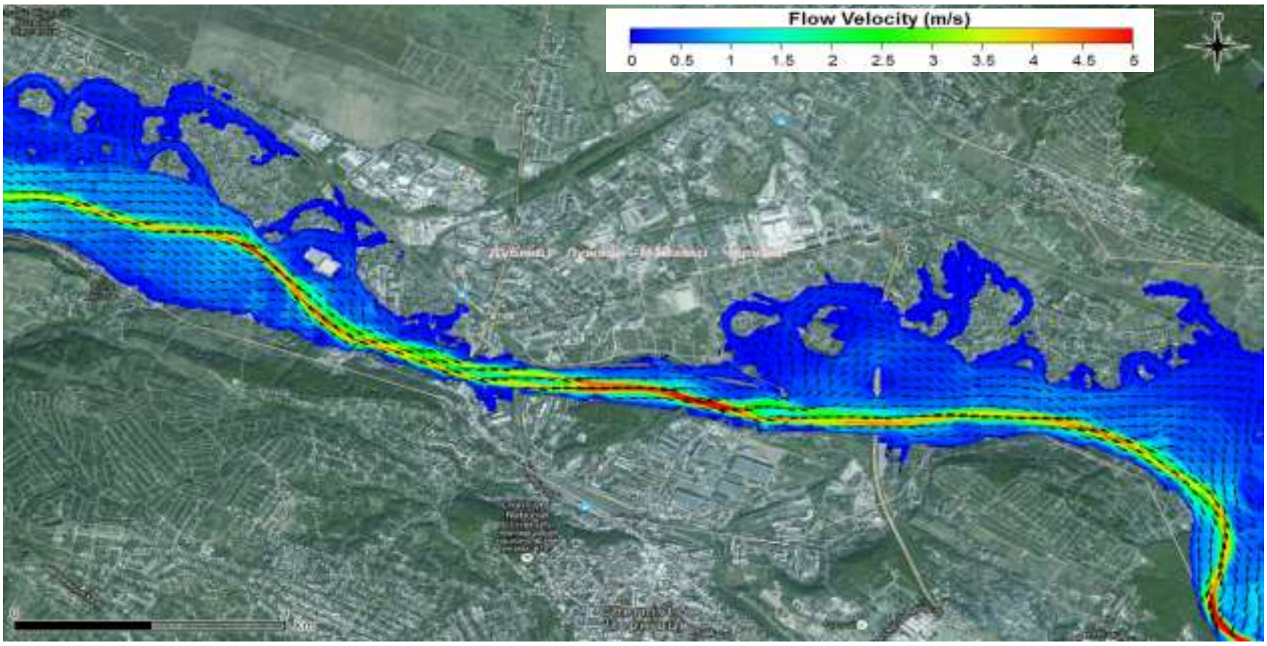


Fig. 42 1% Flood for site 01-Dubivtsi-Luzhany-Mamaivtsi-Chernivtsi. Zoom to Chernivtsi. CRS: WGS 84/Pseudo-Mercator

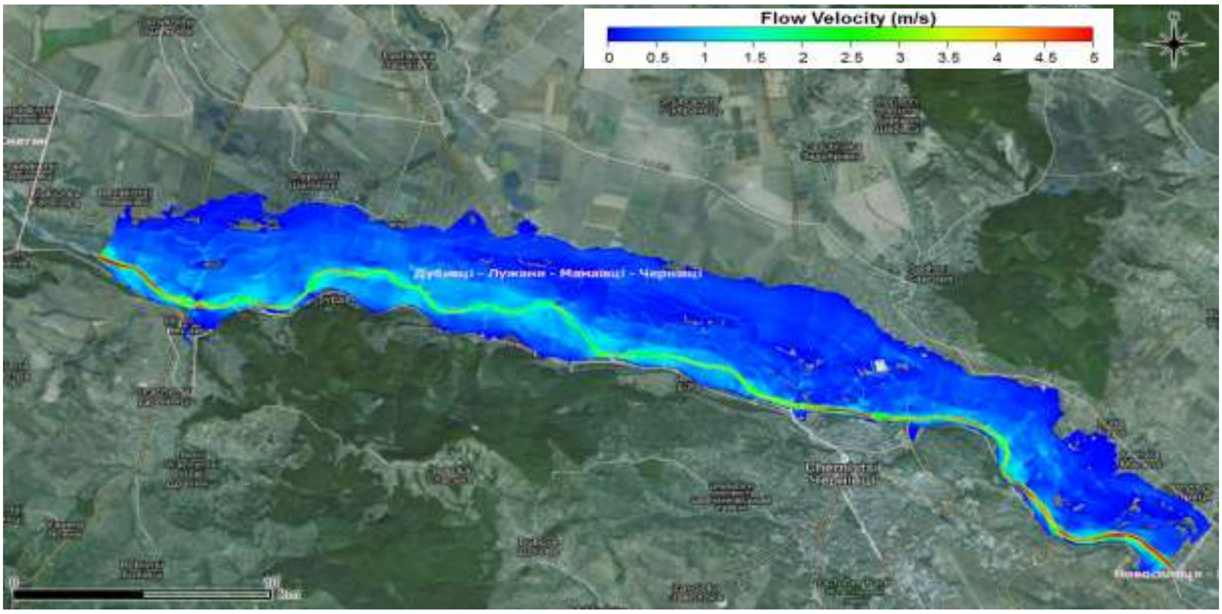


Fig. 43 0.1% Flood for site 01-Dubivtsi-Luzhany-Mamaivtsi-Chernivtsi. Full extent. CRS: WGS 84/Pseudo-Mercator

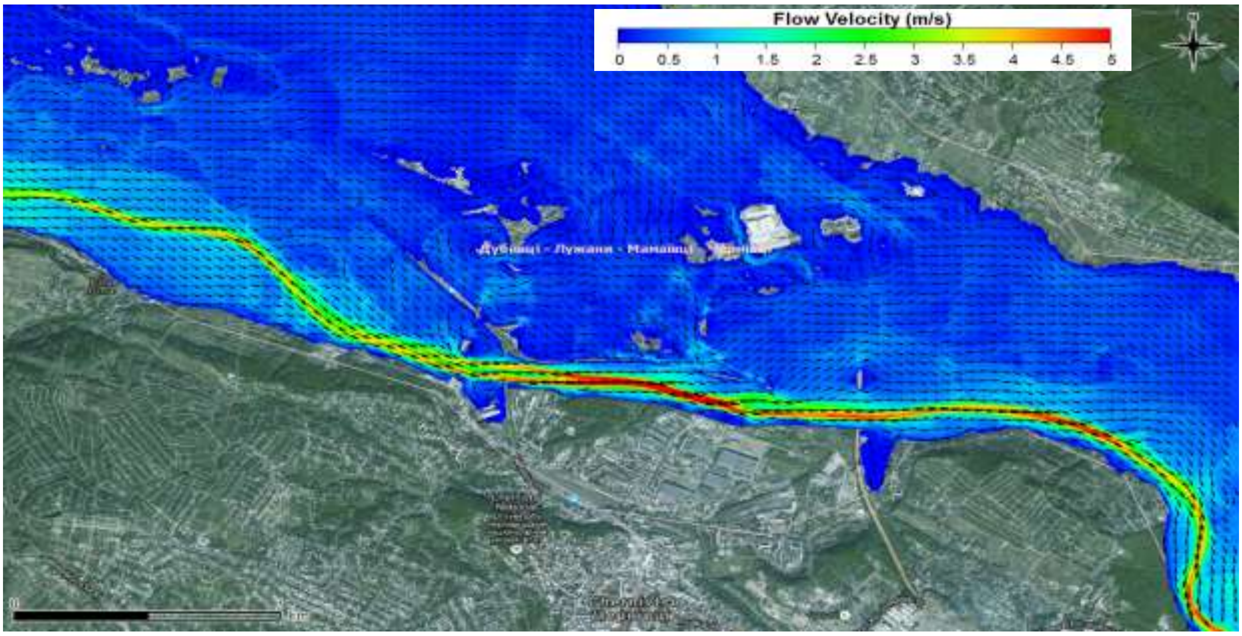


Fig. 44 0.1% Flood for site 01-Dubivtsi-Luzhany-Mamaivtsi-Chernivtsi. Zoom to Chernivtsi. CRS: WGS 84/Pseudo-Mercator

6. The medium term hydrological rainfallrunoff modeling system for upper Siret and Prut River Basin

In order to elaborate and provide medium term hydrological forecasts for the upper Siret and Prut river basins, at the entrance in Romania, a second conceptual rainfall-runoff model was implemented. These medium term forecasts are used in realtime to optimize the reservoirs operation in Siret and Prut River, downstream the entrance in Romania, during the flood events.

This rainfall-runoff model will provide the inflow forecasts to Stânca Costesti, in order to support by scenarios simulations this important reservoir operations for flood management, for real-time decision support.

Also, the short term forecasts elaborated with this system, could be used as a backup in real time, if situations when there are some problems / failure in running the detailed hydrological modeling system for the upper part of Siret and Prut River basins, in Ukraine.

The implementation was done using the RS Minerve System - https://www.crealp.ch/fr/accueil/outils-services/logiciels/rs-minerve.html, a freely distributed software that could be used for the simulation of free surface runoff flow formation and routing, in complex hydrological and hydraulic networks using a semi-distributed conceptual scheme.

In addition to particular hydrological processes such as snowmelt, glacier melt, surface and underground flow, hydraulic control elements (gates, spillways, diversions, junctions, turbines and pumps) could also be included (Fig. 45).

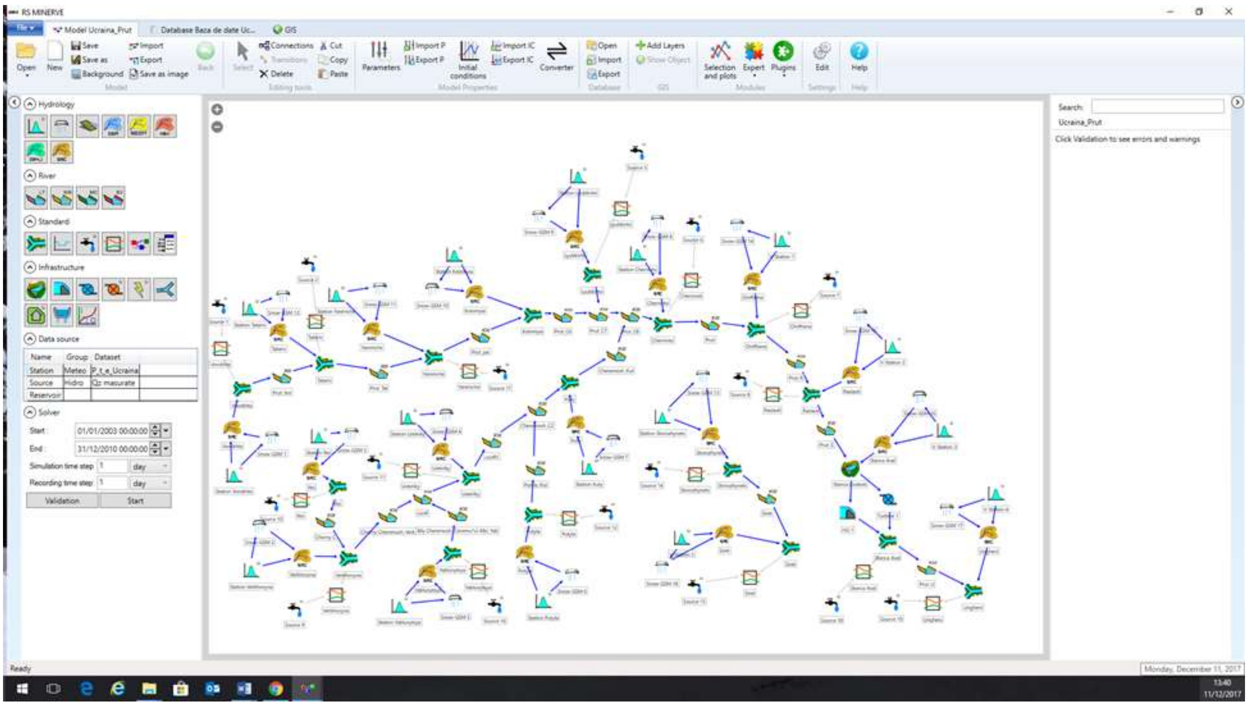


Fig. 45 General structure of the medium term hydrological forecasting system, for Prut and Siret River Basins, within the RS-Minerve modelling system

This hydrological forecasting system configuration is based on the Sacramento Soil Moisture Accounting System (SACSMA) as rainfall-runoff model, the same model that is implemented and used in HFMS-DESWAT National system in Romania, in order to benefit from the experience in model configuration and calibration, and for a better integration with the existing system.

The SAC-SMA (Sacramento-Soil Moisture Account) is a conceptual model This model that calculates the total discharge from the precipitation (P) and the potential evapotranspiration (ETP) depending on the parameters and initial conditions.

The SACRAMENTO conceptual rainfall-runoff model was selected, considering, on the one hand, the structure of this hydrological model (Fig. 46-48), the runoff generation processes that it can simulate and especially the very long period and the good results obtained internationally by using this hydrological model in hydrographic basins with different physico-geographical conditions, respectively applying the model to different space-time scales.

Another important aspect behind the selection of the SACRAMENTO rainfall-runoff hydrologic model as an internal model within the hydrological modeling module was the existence of some a priori parameter estimation methodologies based on the link between the main parameters of this hydrological model and physico-geographical conditions of a hydrographic basin, mainly depending on soil characteristics and land cover.

These relationships have been defined on the basis of the conceptual physical significance associated with the parameters of this model, and the development of GIS processing techniques in recent years as well as the existence of GIS data sets with the main features of the soil and land cover available globally, allow a first identification of the calitative model parameter values for any hydrographic basin, which is especially important for the case of system implementation in unmonitored river basins and/or in river basins where there is insufficient quantitative and qualitative data for calibration of the model based on historical data.

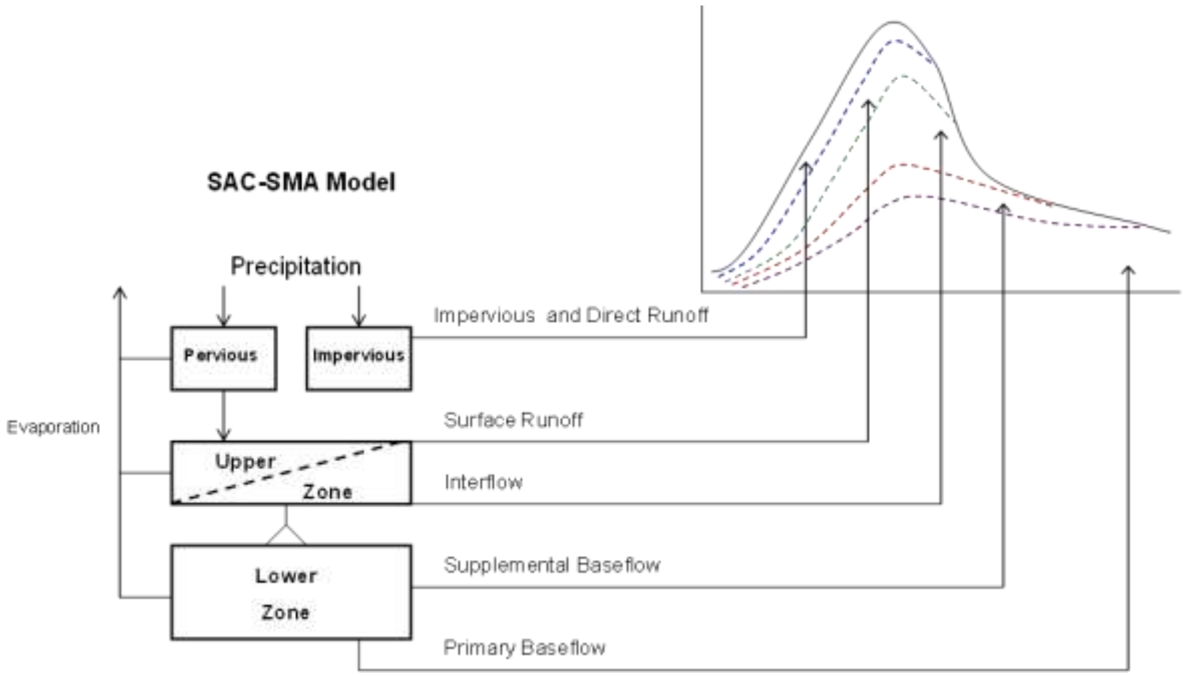


Fig. 46 The components of SAC-SMA conceptual hydrologic model

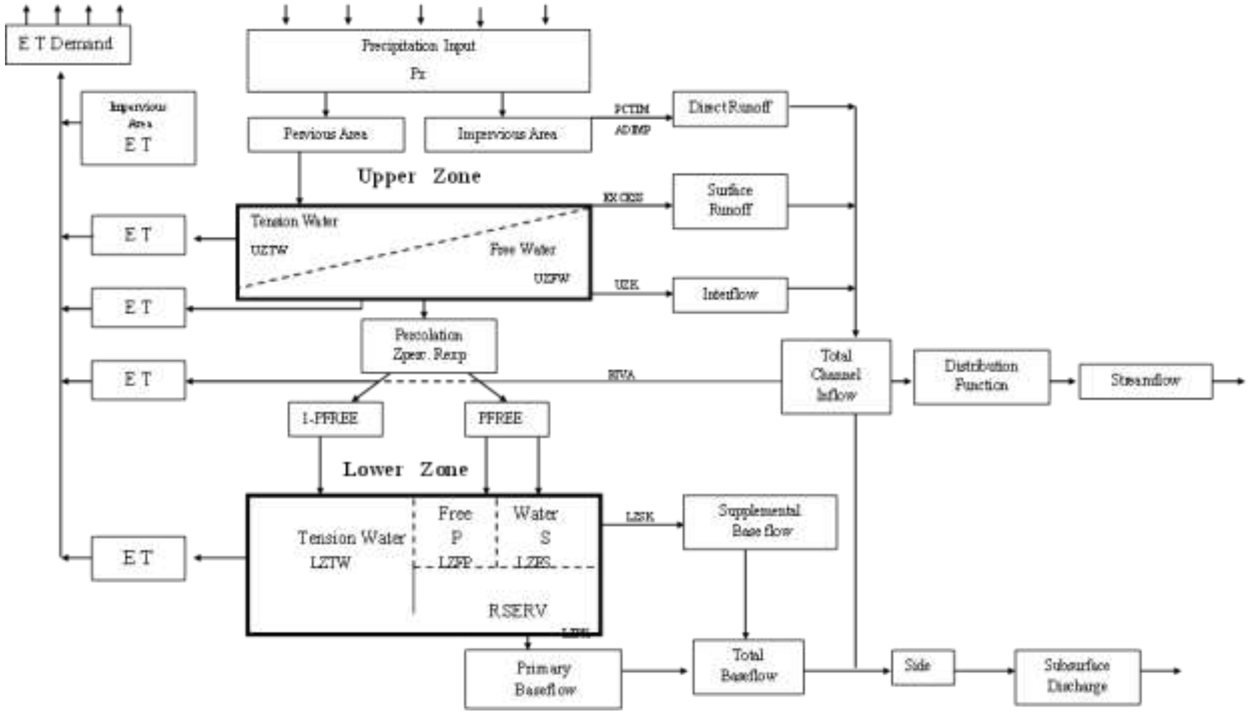


Fig. 47 The structure and parameters of SAC-SMA conceptual hydrologic model

The parameters of SACRAMENTO model are described as follows:

- UZTWM The upper layer tension water capacity
- UZFWM The upper layer free water capacity
- UZK Interflow depletion rate from the upper layer free water storage
- ZPERC Ratio of maximum and minimum percolation rates
- REXP Shape parameter of the percolation curve
- LZTWM The lower layer tension water capacity
- LZFSM The lower layer supplemental free water capacity
- LZFPM The lower layer primary free water capacity
- LZSK Depletion rate of the lower layer supplemental free water storage
- LZPK Depletion rate of the lower layer primary free water storage
- PFREE Percolation fraction that goes directly to the lower layer free water storages
- PCTIM Permanent impervious area fraction
- ADIMP Maximum fraction of an additional impervious area due to saturation
- RIVA Riparian vegetation area fraction
- SIDE Ratio of deep percolation from lower layer free water storages
- RSERV Fraction of lower layer free water not transferable to lower layer tension water
- STXT Soil texture of the upper layer
- TBOT Climatological annual air temperature

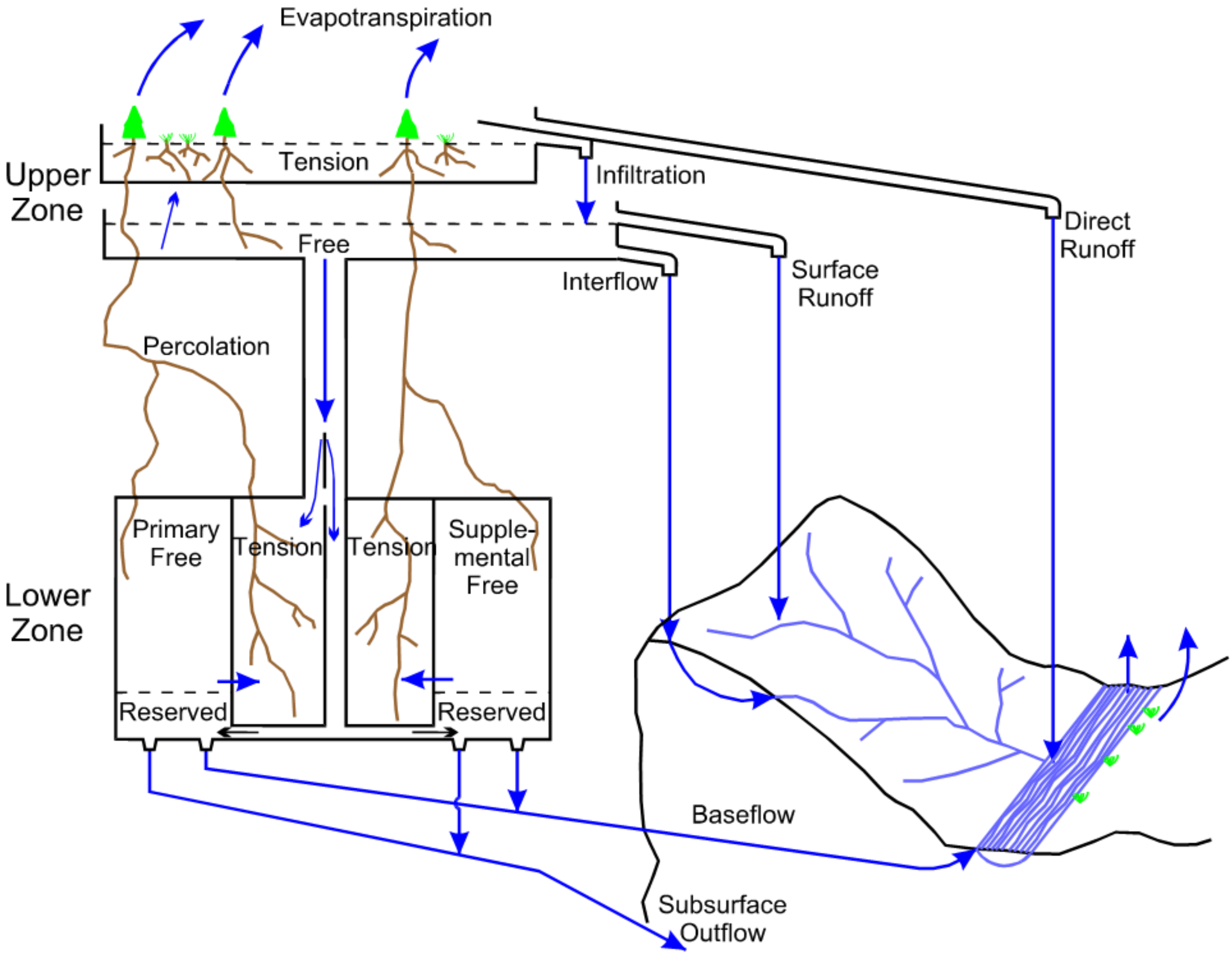


Fig. 48 The conceptualization of main processes in SAC-SMA

In the SACRAMENTO rainfall-runoff model, the soil horizons are structurally generalized in two specific areas, respectively an upper zone (generally considered to be the first 15 to 25 cm of soil) and a lower zone. The dynamics of water storage phenomena in the two areas is conceptually simulated by two categories of reservoirs: reservoirs with soil water content that is tightly bound to soil particles and does not move under the action of gravitational forces, water that does not contribute to the runoff, respectively free water reservoirs, which can move under the action of gravity forces and generate the surface runoff at the level of the hydrographic basin by different mechanisms.

7. HEC-RAS routing model for Prut River, downstream the entrance in Romania

The hydraulic model of the Prut River was elaborated by S.C. AQUAPROIECT S.A. using the HEC-RAS software within "The prevention and protection against floods in the upper Siret and Prut River Basins, through the implementation of a modern monitoring system with automatic stations" (EAST AVERT) project.

The HEC-RAS (River Analysis System) software has been developed by the Hydrologic Engineering Center (HEC), a department of the Institute of Water Resources (IWR) in the U.S. Corps of Engineer's.

This system of programs covers a wide range of applications such as rainfall-runoff analysis, flow analysis in case of natural flow regime / for rivers equipped with hydrotechnical works, flood extension analysis, real-time flow forecasting for the exploitation of reservoirs.

Input data needs to be as accurate and up-to-date as possible in order to achieve successful results.

Inputs for software are considered:

- topographic data – the channel cross sections, the engineering structures descriptions (bridges, weirs, dams, water intakes, etc.), situation plans, aerial photos, digital terrain models etc.;
- hydrological data - flow values in all interest sections, input hydrographs, measured hydrographs, rating curves, gate performance curves, historical flooded areas for calibration of significant events models etc.;
- data regarding the hydrotechnical works scheme;
- land use information, vegetation coverage, river bed and flooded area nature and in order to establish the roughness coefficients;

The goal is to obtain similar results to those determined by the real phenomenon. In order to achieve this, it is necessary to calibrate and validate the application.

It is possible to obtain output data in tabular and graphical format for the channel cross sections, longitudinal profiles containing variation of the water level, flooded areas, water depths.

The program consists of four main components:

- steady flow analysis;
- unsteady flow analysis;
- sediment transport;
- water quality analysis.

The hydraulic modeling of the Prut River was elaborated for a length of approx. 744 km, based on topobatimetric profiles measured in the field and / or DTM extracts within flooded area boundaries. An analysis of the morphological configuration of each area was carried out and all the significant morphological characteristics that influence the process of hydraulic propagation of flow were taken into account.

For areas where the flood flow is concentrated in one or more streams parallel to the main water course or in the flow areas behind the defense dykes, a loop system called quasi 2D modelling was used.

The current hydrotechnical works scheme consisting of defense dykes along the Prut River on one river bank or on both river banks on the downstream sector of Stânca Costeşti reservoir imposed the construction of a hydraulic modelling system consisting of:

- main channel of Prut River (between the dykes or between the dykes and the versant);
- 10 parallel streams and 9 storage areas on the right bank;
- 13 parallel streams and 20 storage areas on the left bank.

The connection between the main channel of the Prut River and the parallel secondary streams, as well as the storage areas, was made using reversible spillway as hydraulic structure with the lengths and elevations of the spillway crests corresponding to the lengths and elevation crests of the dykes. The overflow of defense dykes was treated without considering any dyke breach.

For the flow of synthetic flood waves for maximum discharges with the probability of exceedances of 0.1%, 0.5%, 1% and 10% through the Stânca Costești Reservoir, the provisions of the Regulation for the reservoir exploitation during the flood periods was taken into account.

The calibration of the hydraulic model was done taking into consideration the historical floods from 2008 and 2010.

The user interacts with the HEC-RAS software via an easy-to-use graphical interface (Fig. 49) with the following features:

- File's organization;
- Data entry and editing;
- Flow analysis;
- View input or results in tabular or graphical form;
- Mapping of flood extension;
- Reporting facilities;
- Online access to information related to the mathematical model used in software development and how to elaborate applications [9].

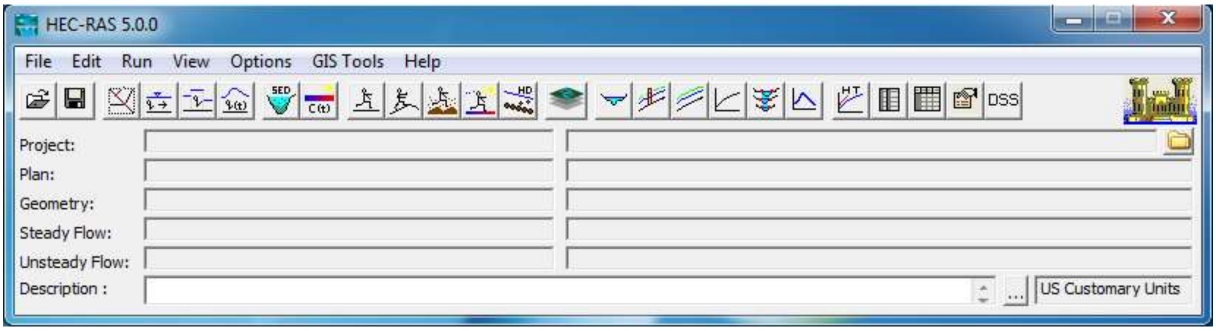


Fig. 49 The graphical interface of the HEC-RAS software

To create an application using the HEC-RAS software, you need to complete the following steps:

To name and save the application

By accesing the *File* menu, then the *New project* option, the project name must be mentioned and then it is necessary to save it into a dedicated directory (Fig. 50). From the *Options* menu, *Select Units Options* must be accessed to set the international measurement system.

In order to open an already elaborated application, the user slects the *Open project* from the *File* menu.

Fig. 50 Creation of a new project in the HEC-RAS software

To Introduce the hydrographic network scheme geometry data

In the Geometric Data editor (Fig. 51) following data must be specified:

- hydrographic network scheme;

- cross sections;
- engineering structures,

and saved (*Geometric Data -> File -> Save Geometry Data as*).

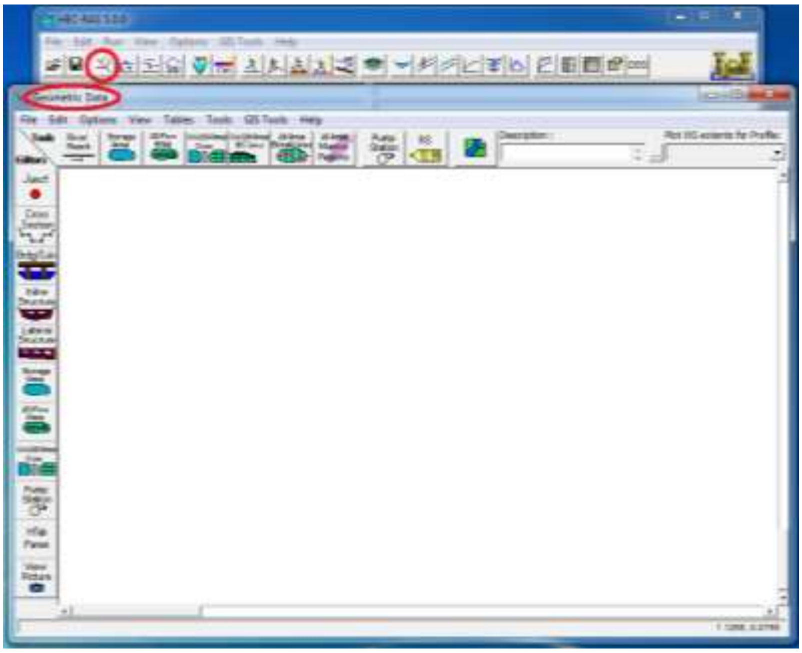


Fig. 51 Geometric Data editor

The scheme of the hydrographic network comprises the river invert line, the channel cross sections, the tributaries and the hydrotechnical works positions (Fig. 52).

For each watercourse, it is advisable to have separately hydrographic network scheme file in order to allow various flow scenarios to be created later.

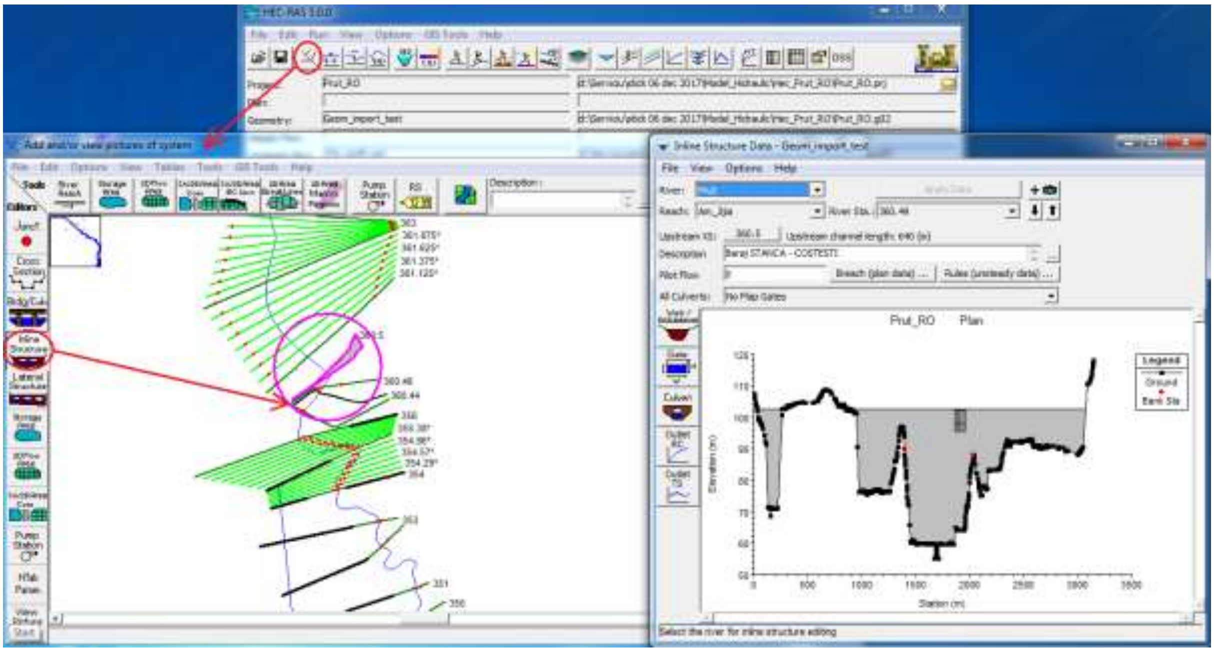


Fig. 52 View of the hydrographic network scheme

The rivers invert line is described into Stereographic 1970 planar coordinates (Fig. 53), either by importing in a program-approved format (*Geometric Data -> File -> Import Geometry Data*) or by using *Copy* and *Paste* functions from an .xls file in the *Reach Invert Lines Table* in *Geometric Data -> GIS Tools* (after pre-setting the number of lines required in the *Reach Invert Lines Table*).

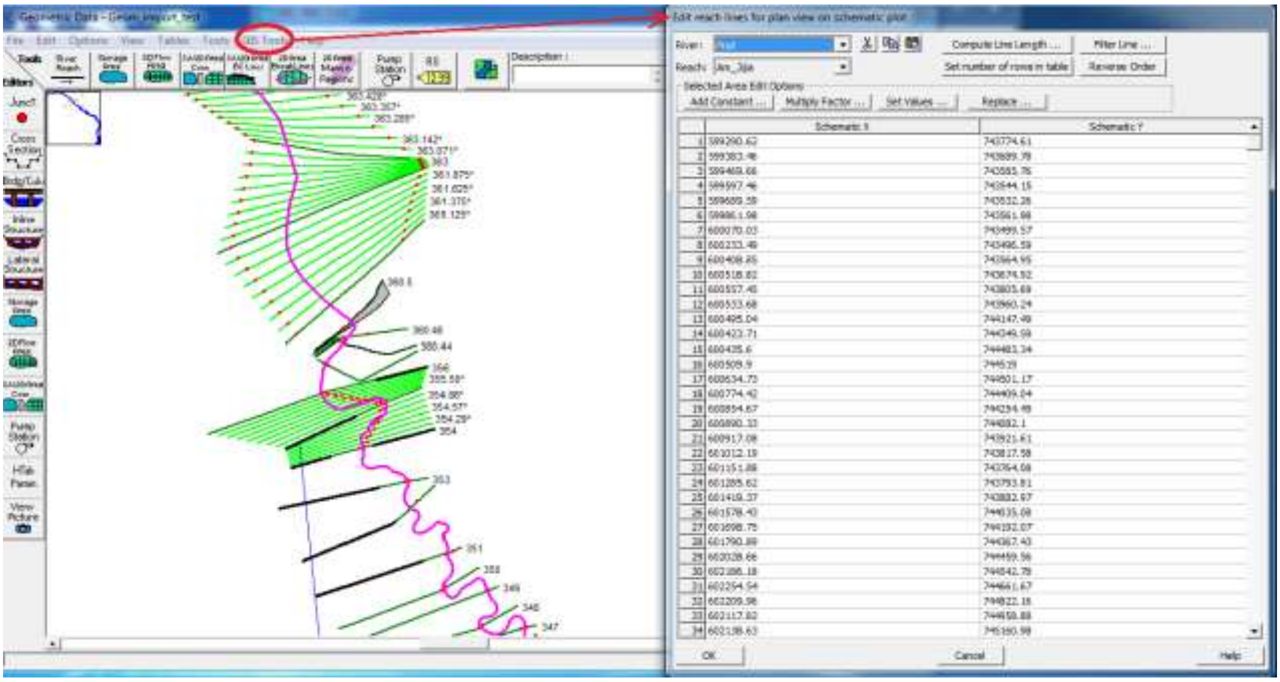


Fig. 53 River invert line description

For the description of river cross sections (Figure 54) the following data is required:

- the plane coordinates of measured points on the river cross sections (*Geometric Data -> GIS Tools -> XS Cut Line Table*);
- the river cross section identification number (*River Section* of *Cross Section Data*). The river cross sections are numbered along the river in ascending order from downstream to upstream;
- the distances between the points measured on the river cross section and the elevation corresponding to these points (*Station and Elevation* in the *Cross Section Data Editor*). River cross sections are described by points from left to right;
- a short description of river cross section, if it is the case, as text (for example: Gauge station cross section) to *Description* in *Cross Section Data*;
- the distances from the downstream cross section, measured along the invert line and the two over bank areas (*Downstream Reach Lengths* in *Cross Section Data*);

- the roughness values of the channel and of the two over bank areas (*Manning's n Values* in *Cross Section Data*);
- the banks channel position (*Main Channel Bank Stations* in *Cross Section Data*);
- cross section contraction and expansion coefficients (*Cont / Exp Coefficients* in *Cross Section Data*) - the default values may be retained or may be changed, where applicable.

The following additional information may be added to the river cross sections, where appropriate:

- the positions and elevations of dykes - *Cross Section Data -> Options -> Levees*;
- the positions and elevations of ineffective areas (ineffective areas contain water, but it is not actively transported) - *Cross Section Data -> Options -> Ineffective Flow Areas*;
- the positions and elevations of flow obstruction areas (these areas do not participate in the flow process, nor do they prevent the water flow from overcrossing them) - *Cross Section Data -> Options -> Obstractions*;
- the cross section rating curve - *Cross Section Data -> Options -> Add a Rating Curve*;
- ice cover (mentioning the thickness of the ice layer in the channel and on the over bank areas, as well as their roughness values) - *Cross Section Data -> Options -> Add Ice Cover*;
- the horizontal / vertical roughness value variation - *Cross Section Data -> Options -> Horizontal / Vertical Variation in n Values*.

Cross section information can be imported in a program-approved format or can be entered manually.

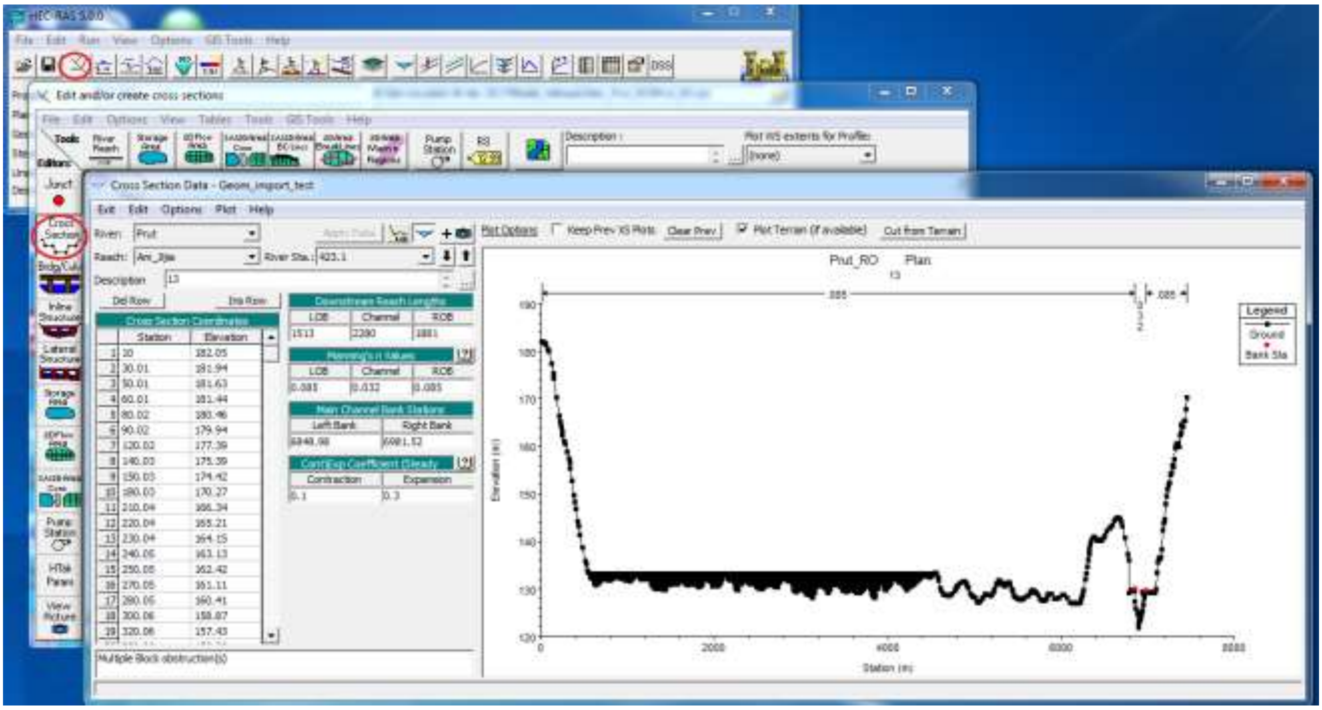


Fig. 54 Cross section description

The cross sections of the secondary parallel channels located in the over bank areas of the Prut River have been numbered with the same identification number as the main watercourse (Prut River) in order to facilitate the introduction of the lateral structures (the reversible spillways) through which they were connected.

Roughness data include estimates of the roughness coefficients of the channel and of the two over bank areas for each cross section, and they are considered to be data with a greater degree of uncertainty.

Among the factors influencing the value of channel roughness can be listed:

- the nature of the riverbed and the average particle size;
- irregularities of the channel;
- riverbed shapes (such as ripple marks, dunes, transition forms and flat shapes);
- river sector characteristics of erosion or deposition of alluvial material;
- tendencies of meandering;
- obstructions of the channel (tree trunks, dams built by the beaver, scraps of material that block the section, etc.);
- changes in geometry of the cross sections;
- the presence of vegetation on the riverbed and on the river banks.

The roughness coefficient varies considerably with the period of the year, so it is recommended to estimate roughness values for the year season in which floods occur.

In the estimation of the roughness coefficient, Chow's (1959) tables can be used, including the maximum, minimum and normal values of this coefficient for a variety of types of channel (natural / artificial, variable widths of cross section, different types of over bank areas).

The best method of estimating the value of the roughness coefficient is to indirectly determine it based on the records from the gauges stations.

In the *"HEC - RAS - River Analysis System - Hydraulic Reference Manual"*, the following roughness values are proposed according to nature of riverbed and river banks (Table 2):

Table 2:Manning coefficient recommended values

Type of channel and description	**Manning coefficient n values**		
	minimum	**normal**	**maximum**
1. Natural streams			
Clean, straight, full, no rifts or deep pools	0.025	0.03	0.033
Same as above, but more stones and weeds	0.03	0.035	0.04
Clean, winding, some pools and shoals	0.033	0.04	0.045
Same as above, but some weeds and stones	0.035	0.045	0.05
Same as above, lower stages, more ineffective slopes and sections	0.04	0.048	0.055

Type of channel and description	**Manning coefficient n values**		
	minimum	**normal**	**maximum**
Clean, winding, some pools and shoals, but more stones	0.045	0.05	0.06
Sluggish reaches, weedy, deep pools	0.05	0.07	0.08
Very weedy reaches, deep pools, or floodways with heavy stands of timber and brush	0.07	0.1	0.15
2. Mountain Streams, no vegetation in channel, banks usually steep, with trees and brush on banks submerged			
Bottom: gravels, cobbles, and few boulders	0.03	0.04	0.05
Bottom: cobbles with large boulders	0.04	0.05	0.07
Flood Plains			
a. Pasture no brush			
Short grass	0.025	0.03	0.035
High grass	0.03	0.035	0.05
b. Cultivated areas			
No crop	0.02	0.03	0.035
Mature row crops	0.025	0.03	0.04
Mature field crops	0.03	0.04	0.05
c. Brush			
Scattered brush, heavy weeds	0.035	0.05	0.07
Light brush and trees, in winter	0.035	0.05	0.06
Light brush and trees, in summer	0.04	0.06	0.08
Medium to dense brush, in winter	0.045	0.07	0.11
Medium to dense brush, in summer	0.07	0.1	0.16
d. Trees			
Cleared land with trees stumps, no sprouts	0.03	0.04	0.05
Same as above, but heavy sprouts	0.05	0.06	0.08
Heavy stamb of timber, few down trees, little undergrowth, flow below branches	0.08	0.1	0.12
Same as above, but with flow into branches	0.1	0.12	0.16
Dense willows, summer, straight	0.11	0.15	0.2
Linear or build-up Channels			
1. Concrete			
Trowel finish	0.011	0.013	0.015
Float finish	0.013	0.015	0.015
Finished, with gravel bottom	0.015	0.017	0.02
Unfinished	0.014	0.017	0.02
Gunite, good section	0.016	0.019	0.023
Gunite, wavy section	0.018	0.022	0.025
On good excavated rock	0.017	0.02	
On irregular excavated rock	0.022	0.027	
2. Concrete bottom float finished with sides of			
Dressed stone in mortar	0.015	0.017	0.02
Random stone in mortar	0.017	0.02	0.024
Cement rubble masonry, plastered	0.016	0.02	0.024

Type of channel and description	Manning coefficient n values		
	minimum	**normal**	**maximum**
Cement rubble masonry	0.02	0.025	0.03
Dry rubble on riprap	0.02	0.03	0.035
3. Gravel bottom with sides of			
Formed concrete	0.017	0.02	0.025
Random stone in mortar	0.02	0.023	0.026
Dry rubble or riprap	0.023	0.033	0.036
4. Brick			
Glazed	0.011	0.013	0.015
In cement mortar	0.012	0.015	0.018
5. Metal			
Smooth steel surfaces	0.011	0.012	0.014
Corrugated metal	0.021	0.025	0.03
6. Asphalt			
Smooth	0.013	0.013	
Rough	0.016	0.016	
7. Vegetal lining	0.03		0.5
8. Excavated or Dredged Channels			
Earth, straight and uniform			
Clean, recently completed	0.016	0.018	0.02
Clean, after weathering	0.018	0.022	0.025
Gravel, uniform section, clean	0.022	0.025	0.03
With short grass, few weeds	0.022	0.027	0.033
Earth, winding and sluggish			
No vegetation	0.023	0.025	0.03
Grass, some weeds	0.025	0.03	0.033
Dense weeds or aquatic plants in deep channels	0.03	0.035	0.04
Earth bottom and rubble side	0.028	0.03	0.035
Stony bottom and weedy banks	0.025	0.035	0.04
Cobble bottom and clean sides	0.03	0.04	0.05
Dragline-excavated or dredged			
No vegetation	0.025	0.028	0.033
Light brush on banks	0.035	0.05	0.06
Rock cuts			
Smooth and uniform	0.025	0.035	0.04
Jagged and irregular	0.035	0.04	0.05
Channels not mantained, weeds and brush			
Clean bottom, brush on sides	0.04	0.05	0.08
Same as above, highest stage of flow	0.045	0.07	0.11
Dense weeds, high as flow depth	0.05	0.08	0.12
Dense brush, high stage	0.08	0.1	0.14

The description of the engineering structures is also made in the Geometric Data editor:

- bridges and culverts (*Edit and / or create bridges and culverts*);
- inline structures (*Inline structure*);
- lateral structures (*Lateral structure*);
- water storage areas (*Storage area*);
- pump stations (*Pump stations*).

To describe a bridge (Figure 55), it is necessary to access the *Edit and/or create bridges and culverts -> Options -> Add a Bridge and/or a Culvert* window and indicate the identification number of the bridge (*River Station*). In the *Deck / Roadway Data Editor*, must be introduced the distance to the upstream cross section (*Distance*), the width of the bridge (*Width*), the deck description indicating the positions and elevations of the contact points with the terrain on both sides of the upstream and downstream cross section (*Upstream -> Station -> High Chord -> Low Chord și Downstream -> Station -> High Chord -> Low Chord*). In the *Pier Data Editor*, the piers are described and the sloping abutments in the *Sloping Abutment* editor (*Sloping Abutment Data Editor -> Options -> Add*).

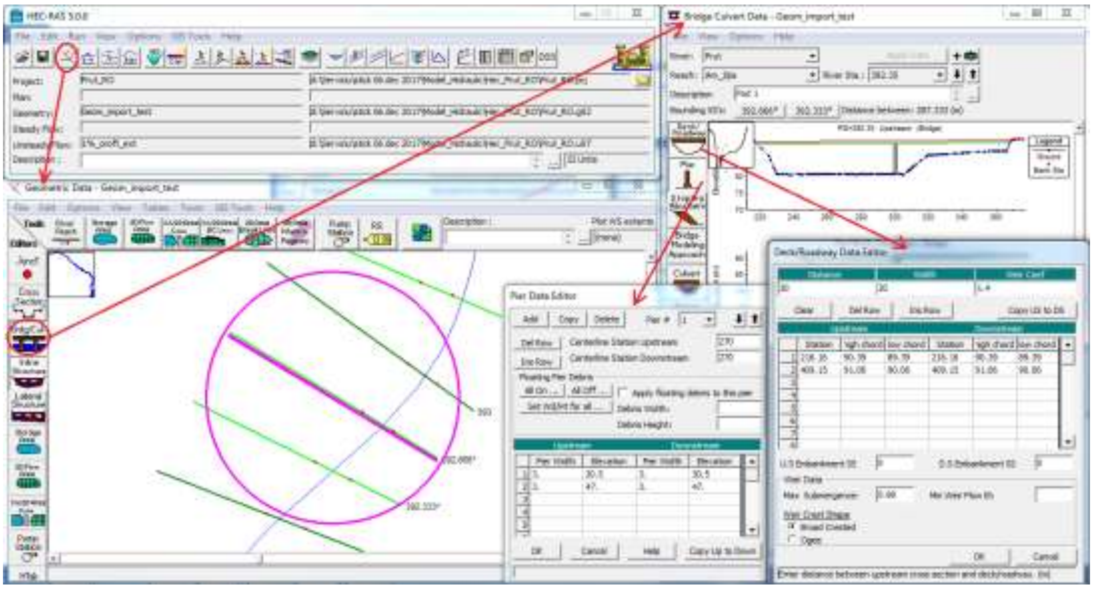


Fig. 55 Bridge description

To introduce the inline structure (Figures 56, 57) in the hydraulic model, the *Inline Structure Data* window (*Inline Structure Data -> Options -> Add an Inline Structure*) must be accessed and the identification number must be mentioned. In the *Weir / Embankment*, the information about the distance to the upstream cross section (*Distance*), the width at the base of the structure (*Width*), as well as the position and elevation of the construction beginning and end (*Edit Station and Elevation coordinates*). In the *Gate* window the dischargers of the dam are described, indicating the dimensions (*Height* and *Width*), the elevation base of dischargers (*Invert*), the positions (*Station*) and their performance curves (*Enter/Edit User Defined Gate Performance Curves*).

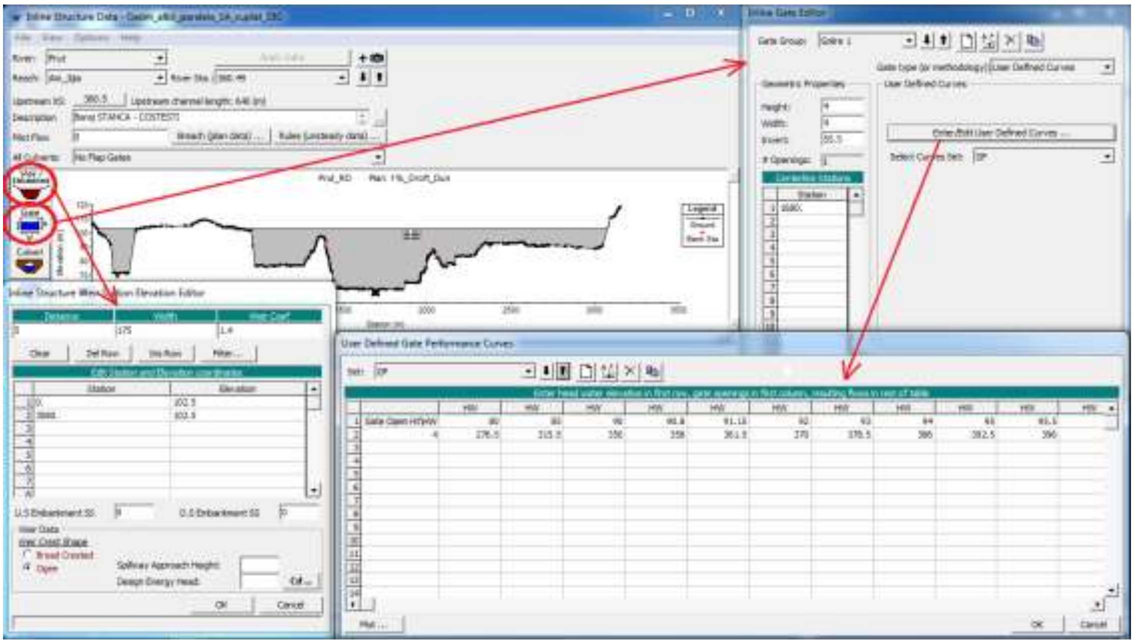


Fig. 56 Dam description – upstream

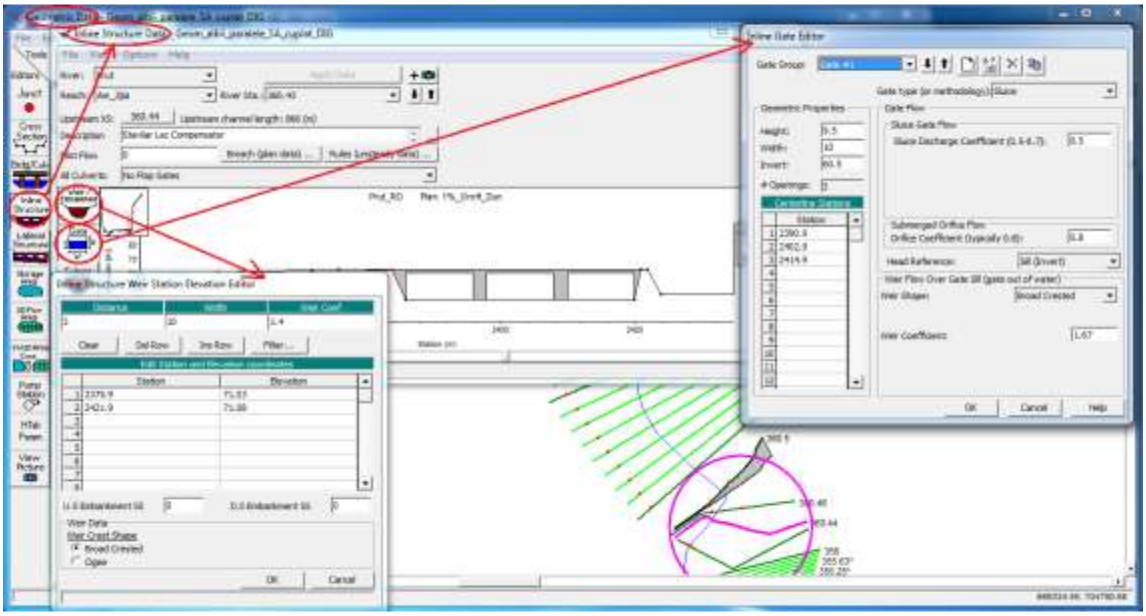


Fig. 57 Dam description – downstream

To describe lateral structures on the watercourse, it is necessary to click the *Lateral Structure Editor* (Figure 58) *-> Options -> Add a Lateral Structure* and to indicate the structure identification number in the *Lateral Structure Editor -> River Station*, the bank side of the main river (*Lateral Structure Editor -> HW Position*), the type (*Lateral Structure Editor ->* ***Cross Section (s) of a River / Reach*** or *Storage Area / 2D Flow Area* or *Out of the system*), the water course name and the sector (*Lateral*

Structure Editor -> Set TW RS -> River / River and *Lateral Structure Editor -> Set TW RS -> Sector / Reach*), the upstream and downstream cross sections between which the structure is positioned and with which the flow connection is made (*Lateral Structure Editor -> Set TW RS ->US RS* and *Lateral Structure Editor -> Set TW RS ->DS RS*) and the bank side of the water course (*Lateral Structure Editor -> TW Position*). In the *Lateral Structure Editor -> Weir / Embankment*, the information about the distance to the upstream profile (*HW Distance to Upstream XS*) is mentioned, how the discharge is flowing (*TW flow goes ->* ***To a point between two XS's*** or *TW flow goes -> Over multiple XS's*), *Weir Width*, as well as the highest elevation and the position of the construction begining and ending (*Embankment Station/Elevation Table*). The connection with the river (*HW Connections*) and the river sector (*TW Connections*) can be calculated automatically by selecting ***Computed Default Weir Stationing*** or can be introduced manually (*User Defined Weir Stationing*).

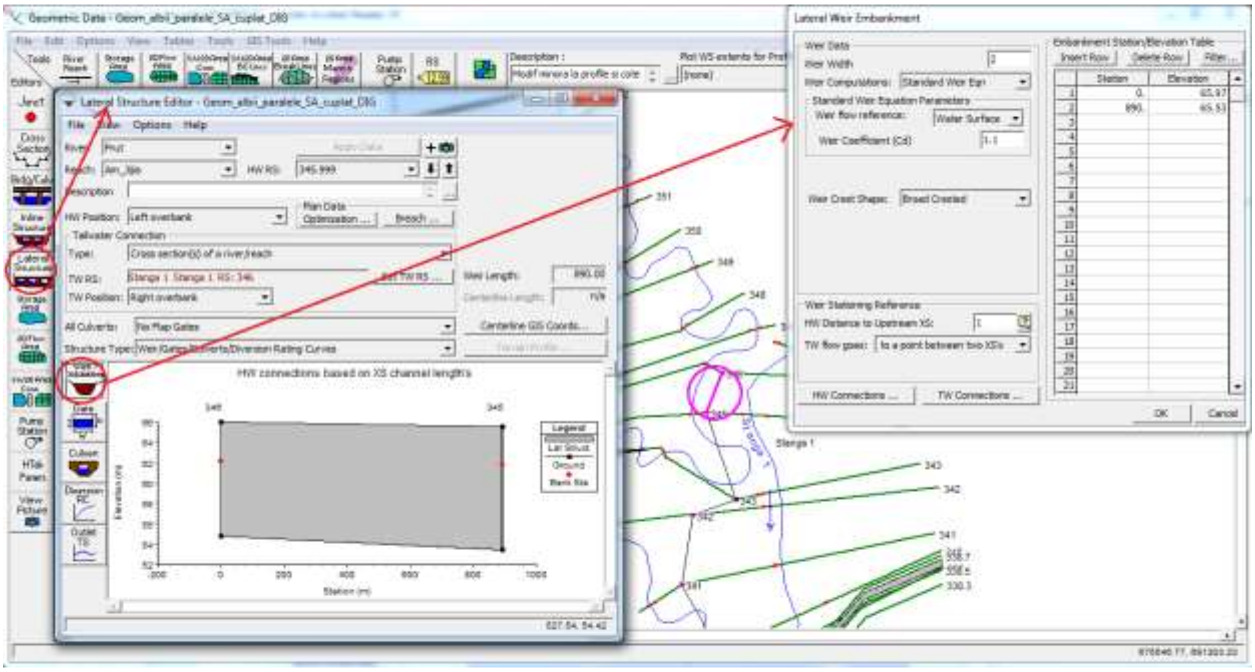


Fig. 58 Description of the reversible spillway

To enter the storage areas (Figures 59) connected to the spillways, in the *Lateral Structure Editor ->* ***Storage Area / 2D Flow Area*** is marked in the description of the spillway. Then, in the *Geometric Data Editor*, the *Storage Area* menu is activated and a polygon is drawn near the spillway and named. To enter the water volume that can be retained, right click on this polygon to select *Edit Storage Area*. For a 2D model, the *Area Times Depth Method* option can be ticked, and it is enough to indicate only the storage area surface (*Area*) and the minimum elevation area (*Min Elev*). For a 1D model, select the *Elevation versus Volume Curve* option and enter the capacity curve of the storage area. In the *Lateral Structure Editor* the storage areas are associated with the spillways (*Set SA / 2D FA*).

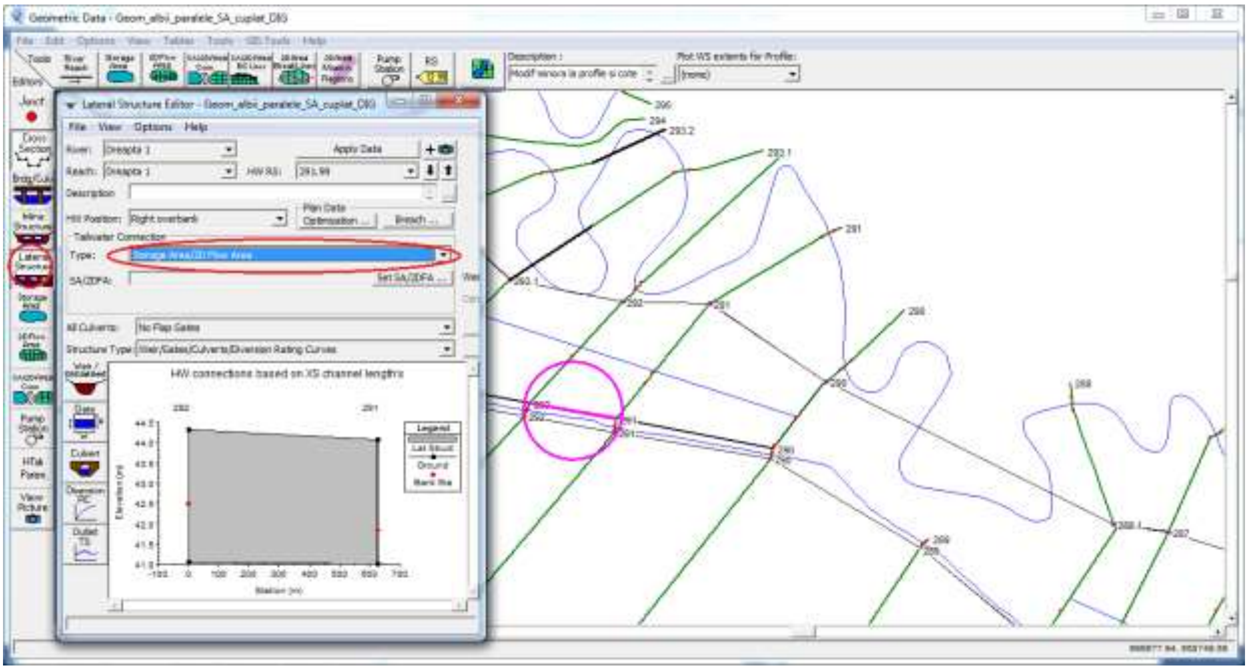


Fig. 59 a

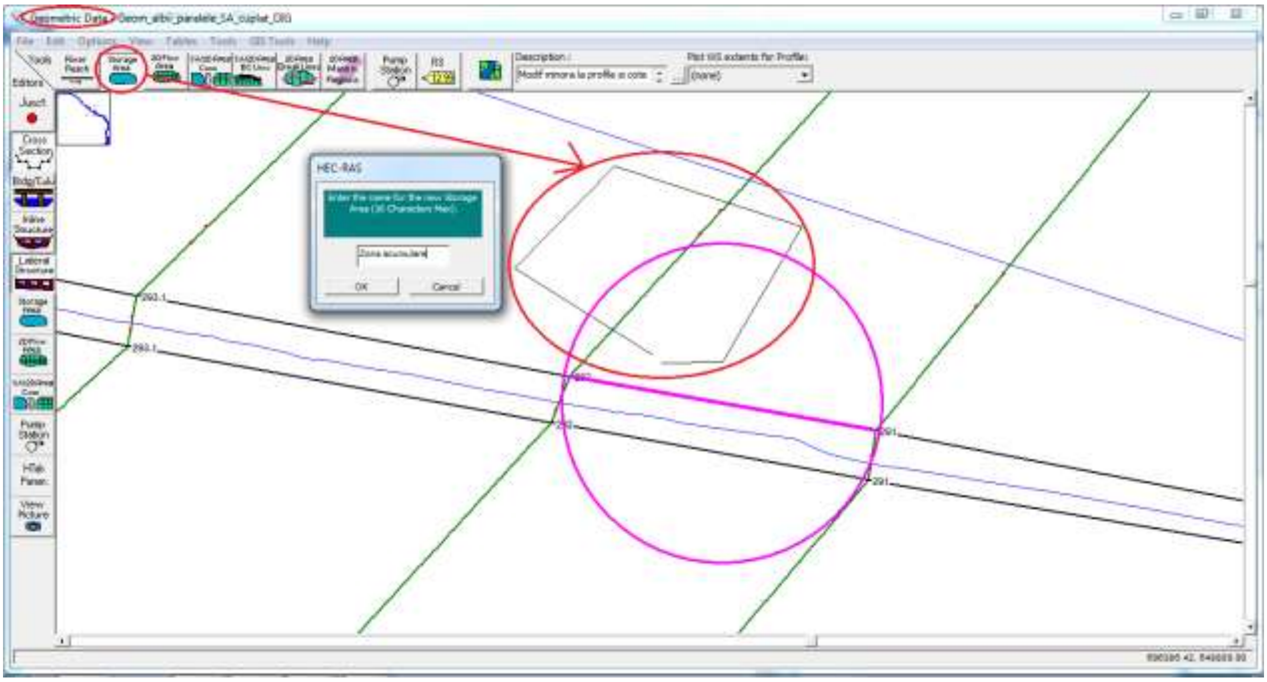


Fig. 59 b

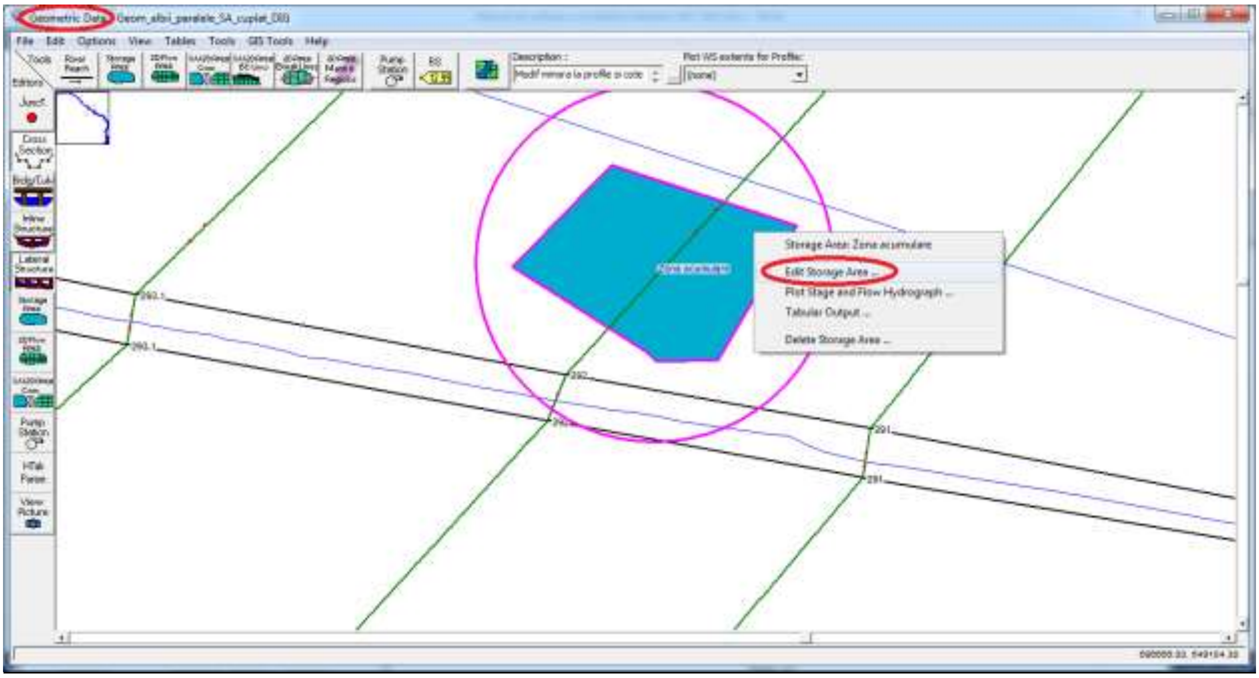


Fig. 59 c

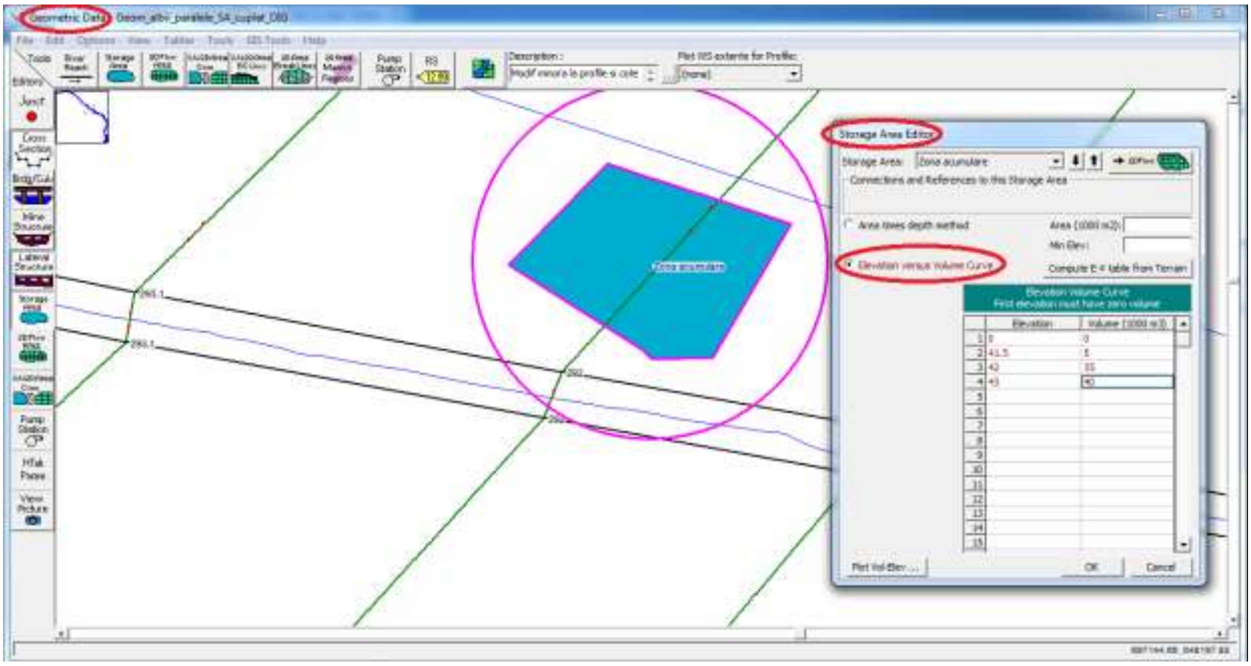


Fig. 59 d.

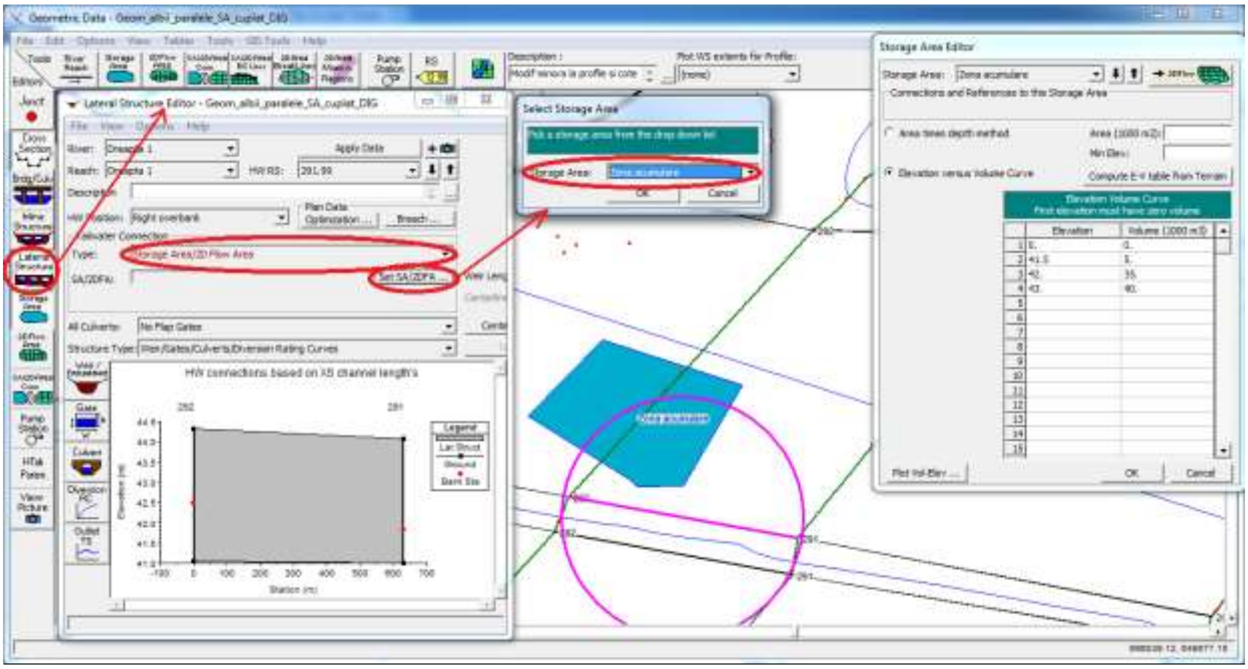


Fig. 59 e.

Fig. 59 Steps of storage area introduction in the hydraulic model

To achieve the conection between two water courses, *Geometric Data* editor should be find data on the hydrographic network geometry of both rivers. The rivers may be imported into this editor (*Geometric Data -> Import Geometry Data*) if they were previously described, or the second one can be introduced following the steps previously mentioned.

Using the *Move Points / object* function in the *Geometric Data -> Edit -> Move point / objects*, the most downstream point describing the riverbed invert line of the water course whose geometry has been imported must be moved in the way that is overlapping a point on the riverbed invert line of the other watercourse, in the confluence area. A dialog box opens which asks if you want to divide the main watercourse into two sectors in the next cross section downstream the confluence (*Do you wish to split Prut River on reach Jijia?*) and for the *YES* option, another dialog box appears where the name of the downstream confluence sector is completed (*A new reach will be created below split, enter the name: River – Prut, Reach – Prut downstream Jijia*), and then the junction is named (for example, *the Jijia confluence*). By activating the *Junction Data* (Figure 60), the method of calculating the water level in the confluence neighborhood can be selected (*Force Equal WS Elevation* or *Energy Balance Method*).

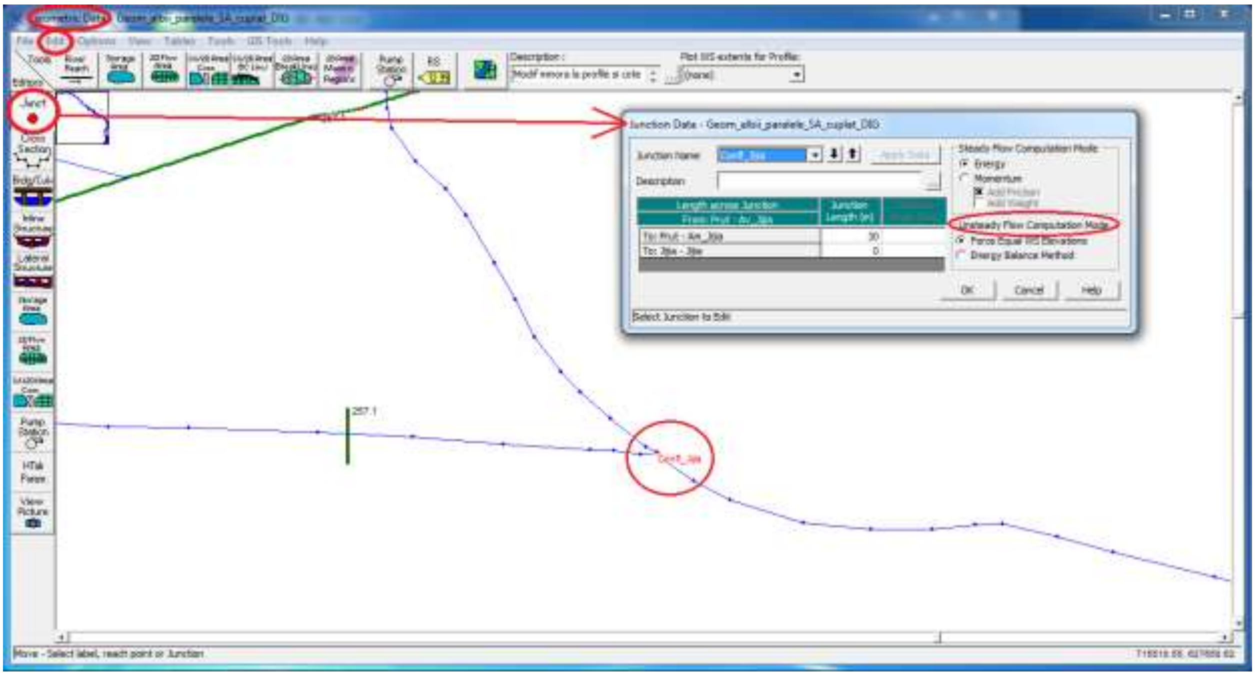


Fig. 60 Junction Data editor

To introduce the initial and boundary conditions

In the *Unsteady Flow Data* editor initial and boundary conditions can be specified.

Initial flow conditions (Figure 61) consisted of initial flow rates (*Initial Flow*) on both main and secondary water courses. In the *Storage Area*, the minimum elevation from which water volume retention begins is specified.

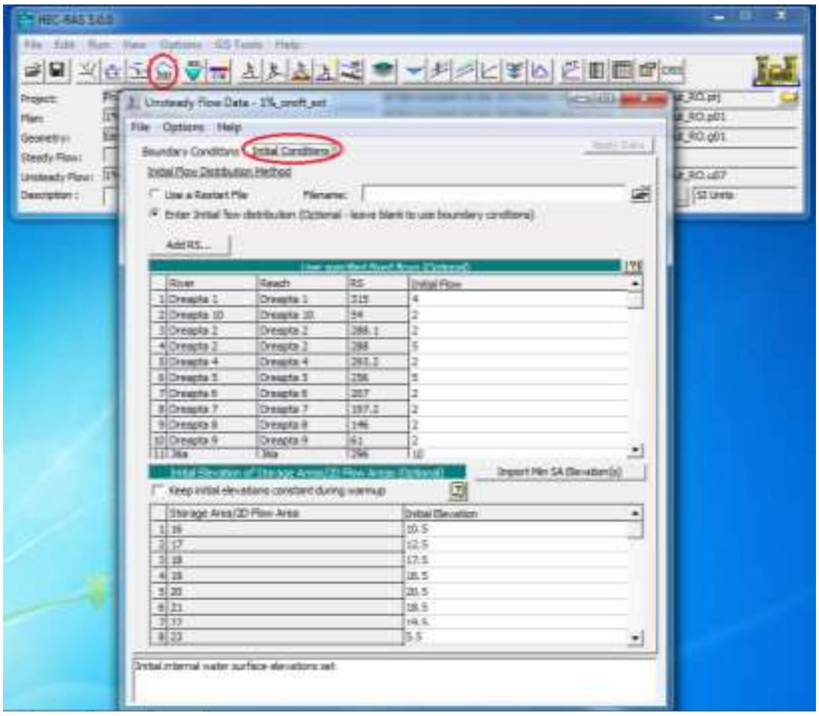


Fig. 61 Introduction of initial conditions

The boundary conditions used in this hydraulic model are the following:

- *Flow Hydrograph* - Figure 62. This condition has been introduced into the upstream sections of the watercourses;
- *Time Series of Gate Openings* - from the dam dischargers and lateral reversible spillways (Figure 63);
- *Normal Depth*. This condition was usually introduced into the downstream boundary sections of the watercourses, and allows a rating curve for the downstream cross section to be generated based on Manning's equation (Figure 64);
- Uniform distributed flow hydrograph between two sections, chosen by the user, on the water course (*Uniform Lateral Inflow*) - between cross sections 422.2 ÷ 407.5 and 407 ÷ 361 on the Prut River (Figure 65);
- Punctually *Lateral Inflow Hydrograph* - in the cross section 366 on the Prut River (Figure 66).

Other boundary conditions (Figure 67) such as rating curves, flow and level hydrographs, level hydrographs, etc. may be introduced in the hydraulic model by adding the cross section in which one of the conditions is to be entered and by selecting the boundary.

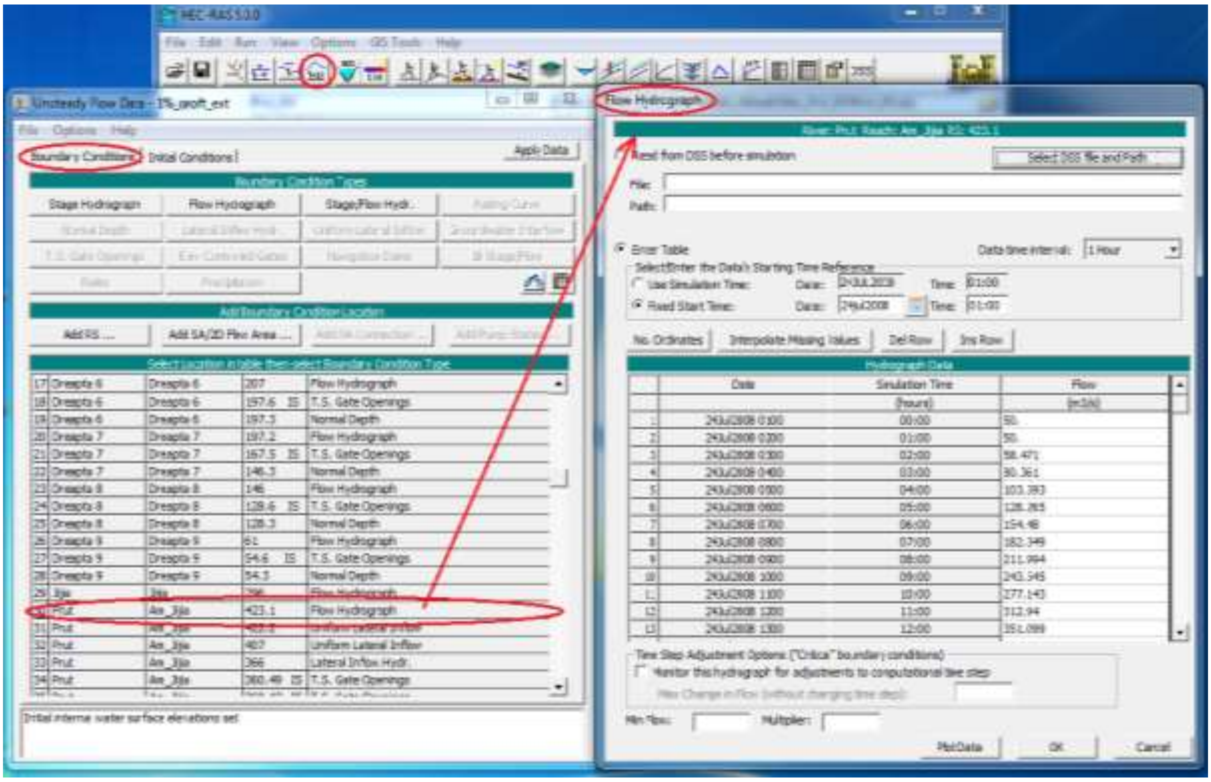


Fig. 62 Flow Hydrograph introduction

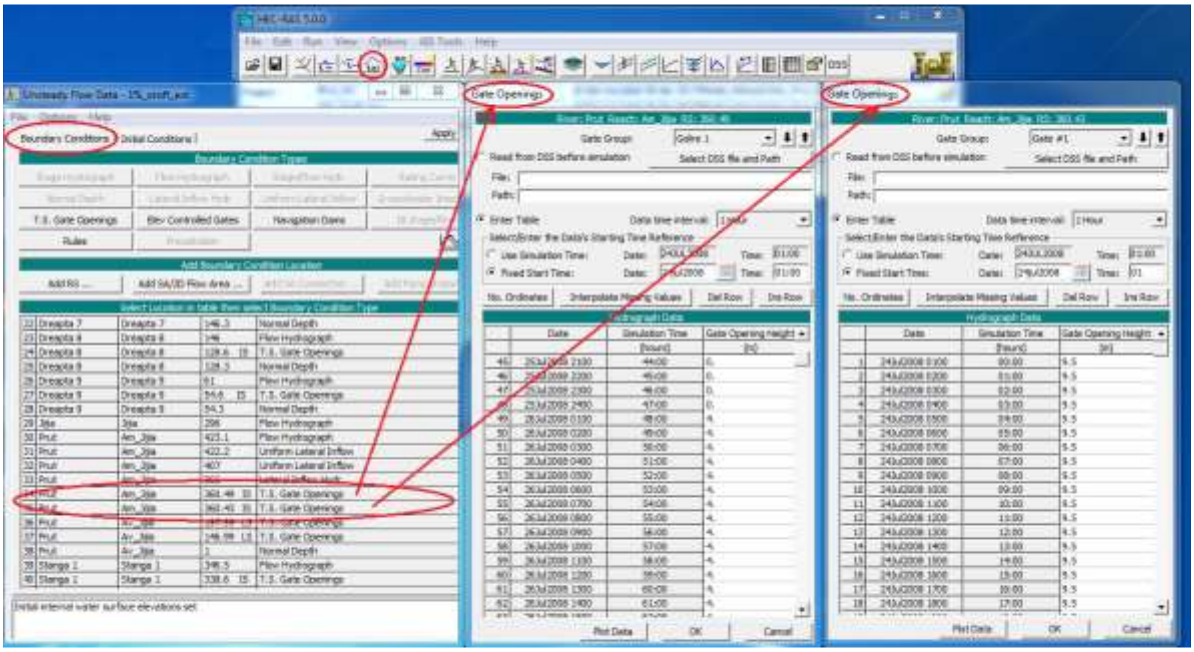


Fig. 63 Time Series of Dam Dischargers Openings introduction

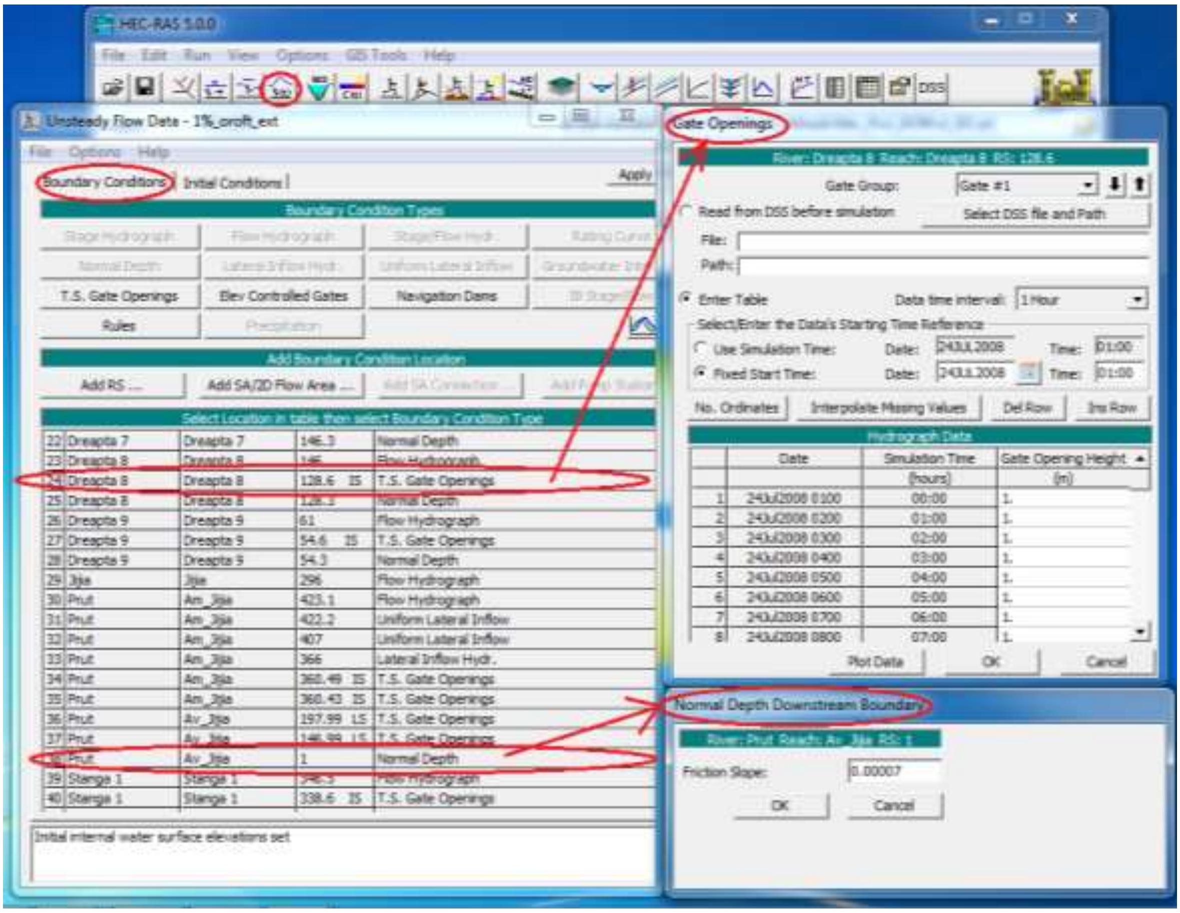


Fig. 64 Time Series of reversible spillways Openings and Normal Depth introduction

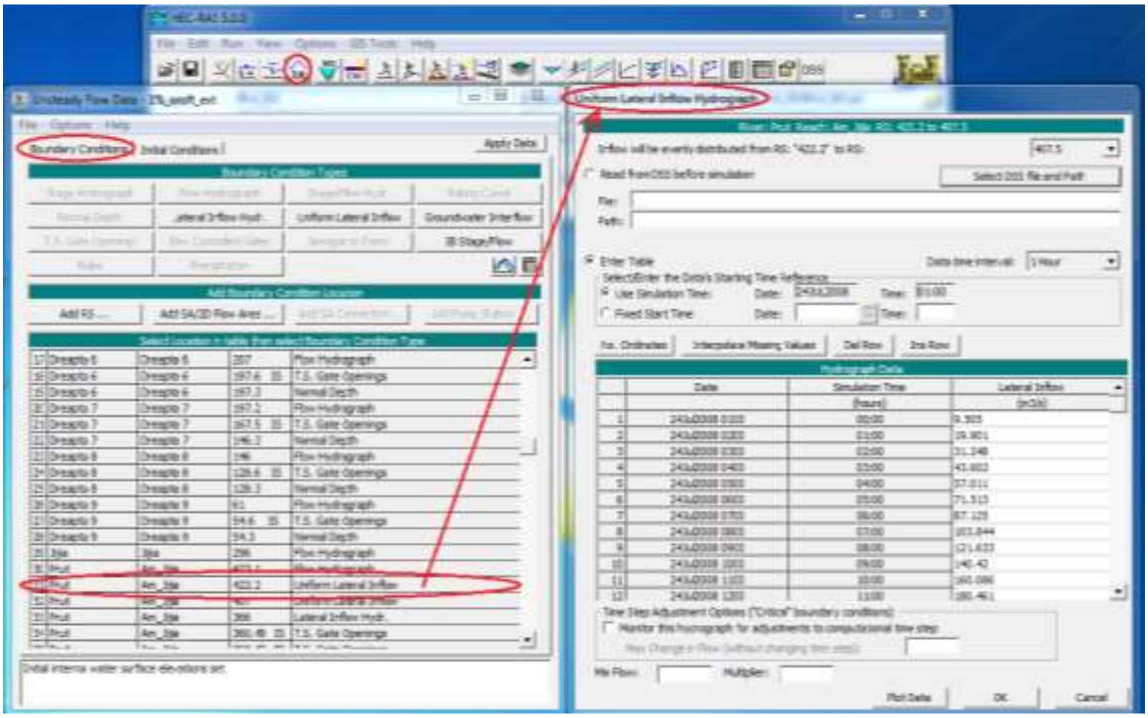


Fig. 65 Uniform Lateral Inflow Hydrograph introduction

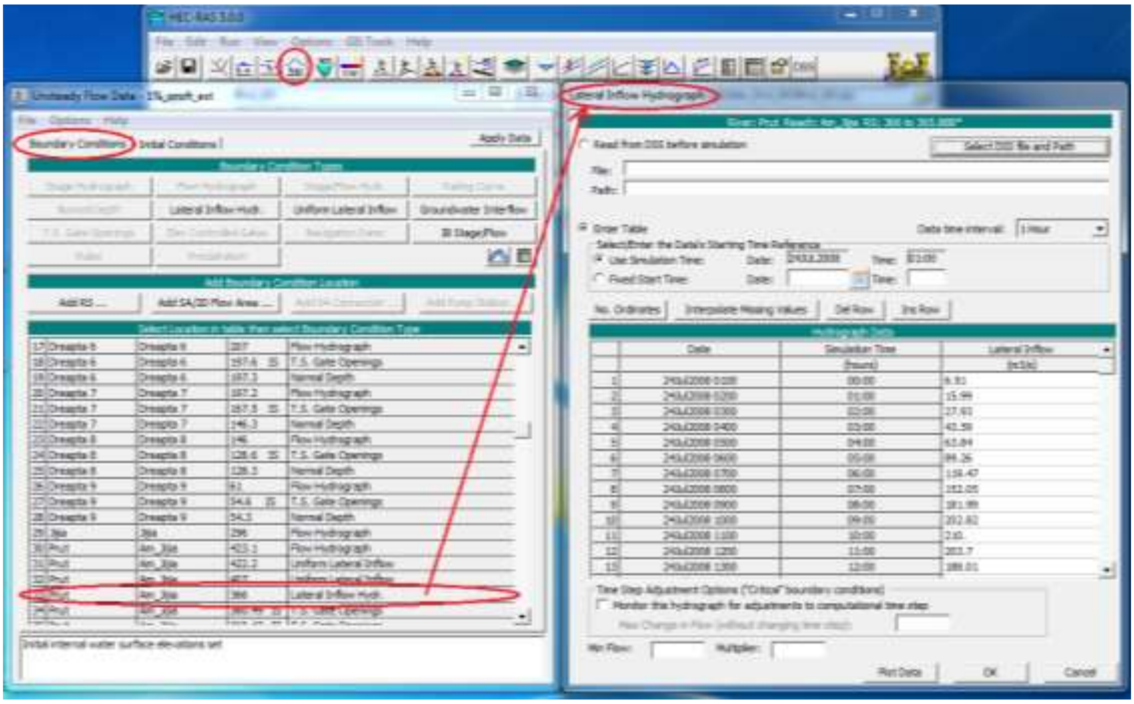


Fig. 66 Lateral Inflow Hydrograph introduction

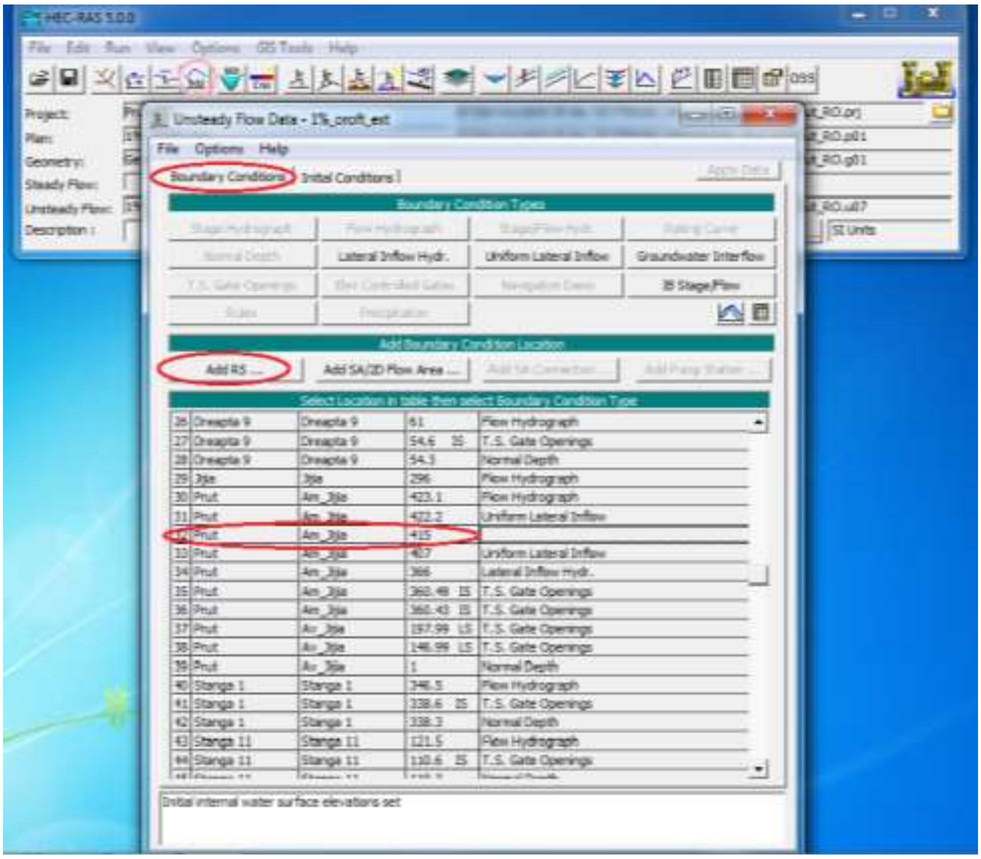


Fig. 67 Boundary conditions introduction

For each boundary condition involving a hydrograph, the *Data time interval* – 1 hour (this value can be chosen from the implicit values of the software), and the time for the begining of the simulation (*Fixed Start Time*) – *Date*: 24th of July 2008, *Time*: 1:00, were established.

After all conditions are introduced in the hydraulic model, the file is saved (*Unsteady Flow Data -> Save Unsteady Flow Data as*).

To run the application

To run a scenario simulation (*Perform an unsteady flow simulation),* it is necessary to create a file (*File -> New Plan*) in which the hydrographic network scheme file - *Geometry File* and the one reffering to flow conditions - *Unsteady Flow File* (Figure 68) must be mentioned, and to save it, also specifing a *Short ID* for the scenario.

The following information must also be mentioned:

- The start and the end time for simulation (date and time) - *Simulation Time Window;*
- The computation time step (*Computation Interval*);
- The time step for result presentation (*Mapping Output Interval, Hydrograph Output Interval, Detailed Output Interval*);
- The name of the result file (*DSS Output Filename*).

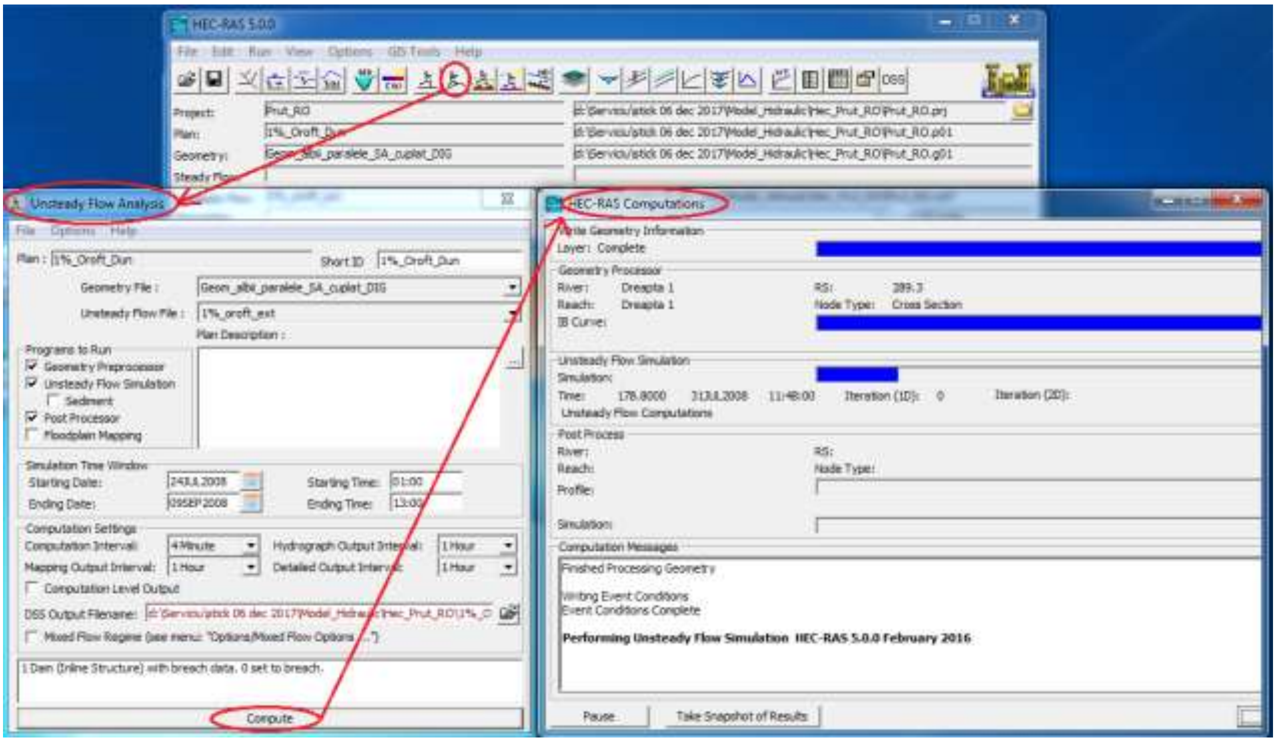


Fig. 68 Unsteady Flow Analysis editor

To visualize the results

The results of an unsteady flow simulation can be viewed in a tabular (Figure 69) or graphic form. These may consist of hydrographs (Figure 70), rating curves (Figure 71), water levels in cross section (Figure 72) or represented in a longitudinal profile (Figure 73), water velocity values (Figure 74), flood extension etc.

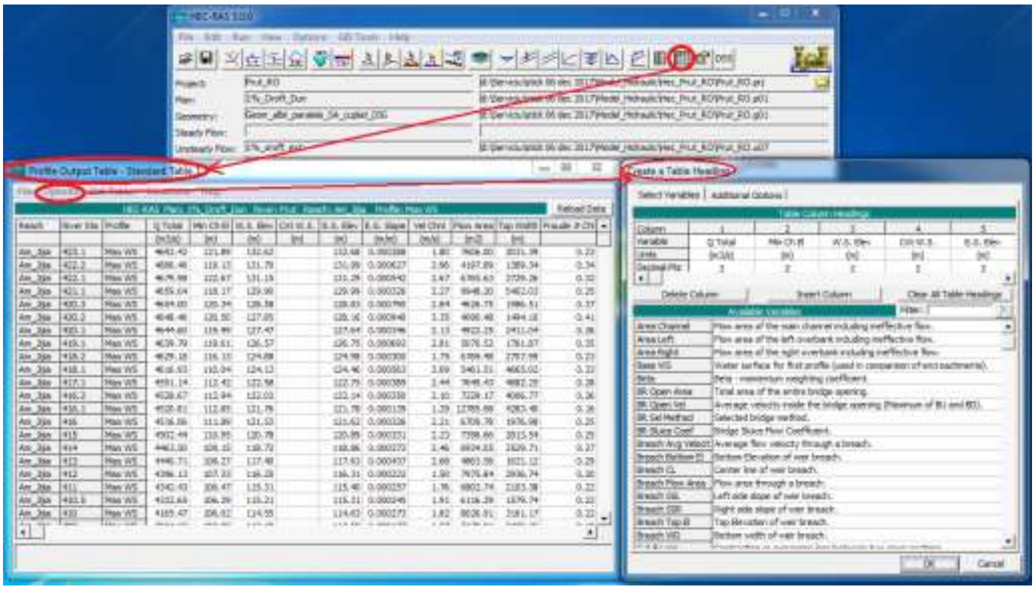


Fig. 69 Results visualization in a tabular form

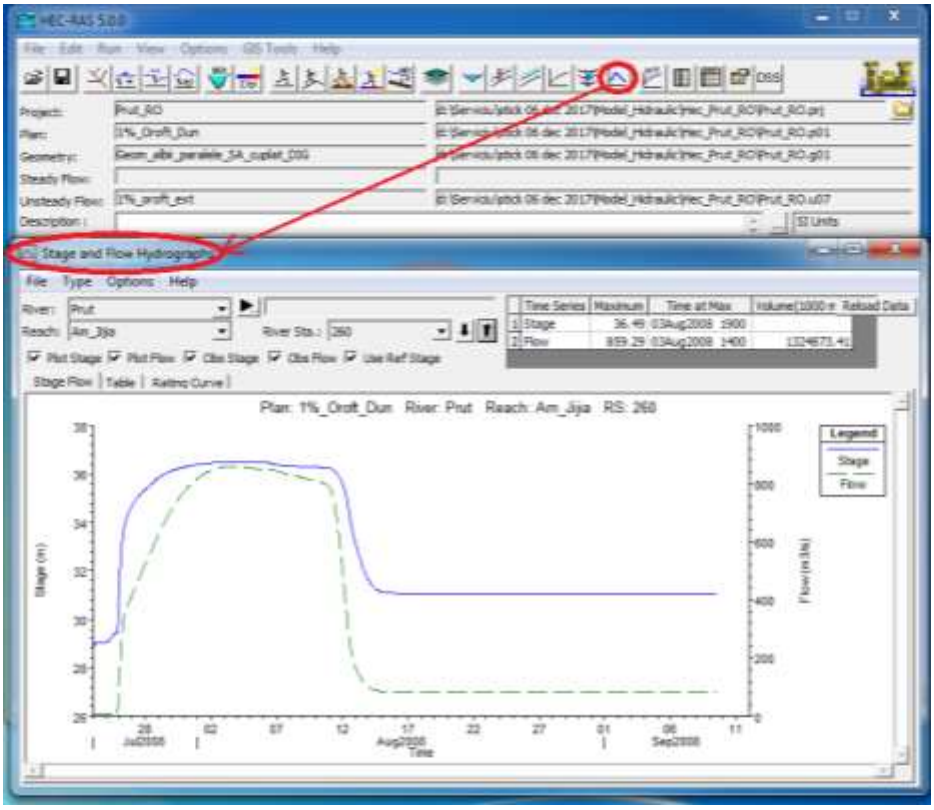


Fig. 70 Flow and water level hydrograph visualization

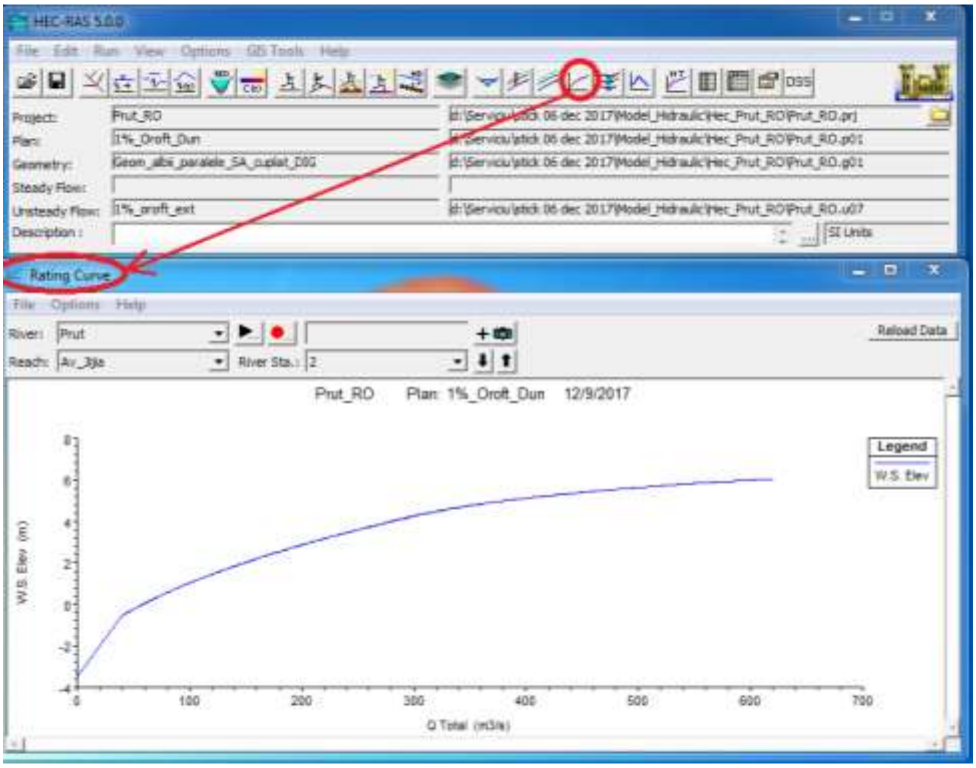


Fig. 71 Rating curve visualization

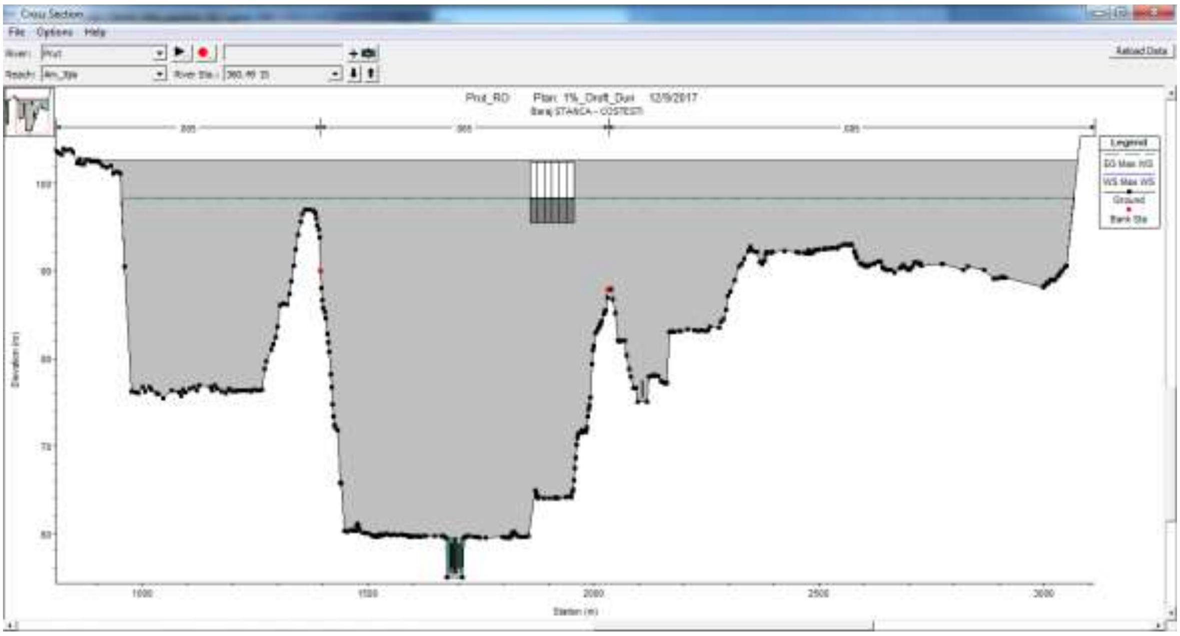


Fig. 72 Maximum water level in dam cross section visualization

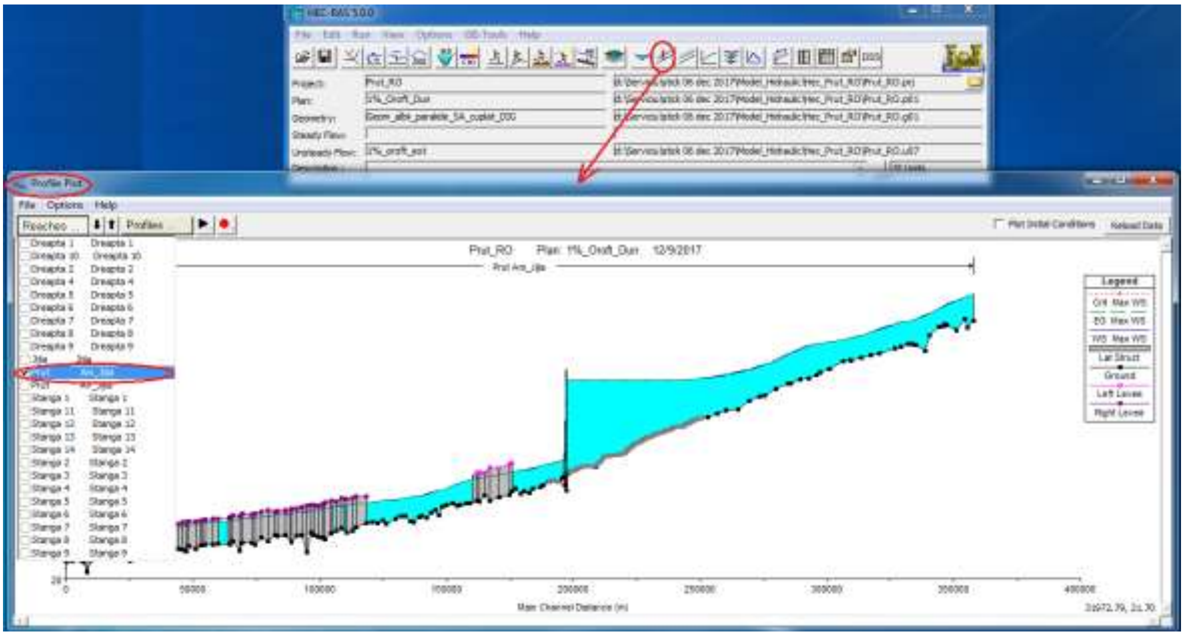


Fig. 73 Longitudinal profile visualization

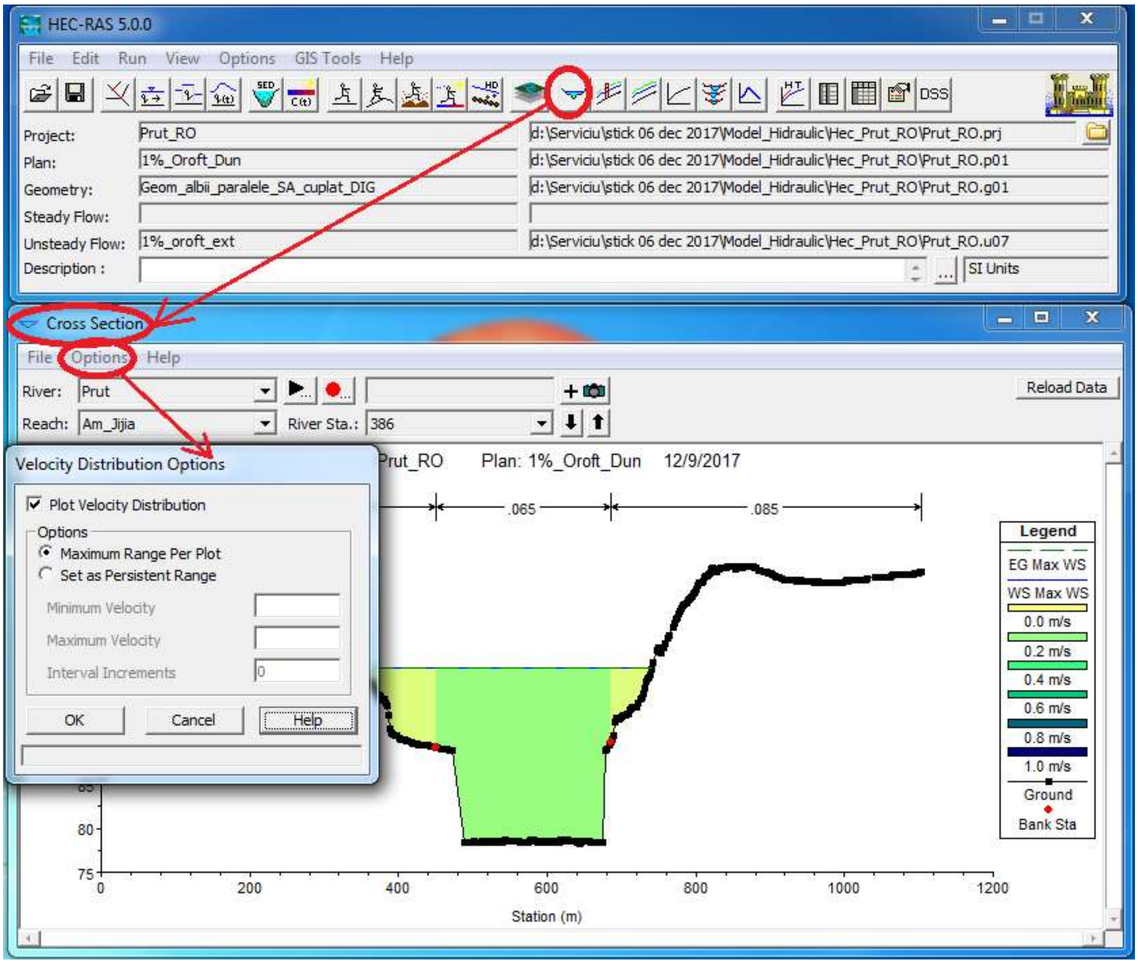


Fig. 74 Water velocity values in cross section visualization

8. Summary of role and responsibilities sharing between project partners

- PP6 will send to PP4 and PP7, in real time, the data from the automatic hydrometrical and meteorological stations data, using automatic data transfer procedures, for all the automatic stations installed within the EAST AVERT Project, using specific data communication and format agreed with PP4 and respectively PP7.
- PP7 will send to PP4 the NWP forecasts from the numerical meteorological forecasting model implemented within EAST AVERT Project, using specific data communication and format agreed with PP4.
- PP7 will send to PP4 the hydrological forecasts from the short term Hydrological Forecasting System implemented within EAST AVERT Project, using specific data communication and format agreed with PP4.
- PP4 will retrieve from PP3, in real time, the data from the automatic hydrometrical station installed within the EAST AVERT Project.
- PP4 will integrate and disseminate the data from the automatic hydrometrical and meteorological stations data received under this agreement, to all the

Dispatch and Forecast Centers of all project partners, using automatic data transfer procedures.

- PP4 will send to PP7 the hydrological forecasts from the medium term Hydrological Forecasting System implemented within EAST AVERT Project, using specific data communication and format agreed with PP7.
- PP4 will send to PP7 the meteorological forecasts used for the medium term Hydrological Forecasting System implemented within EAST AVERT Project, using specific data communication and format agreed with PP7.
- PP4 will integrate and disseminate the hydrological data from the automatic hydrometrical and meteorological stations data received under this agreement, to all the Dispatch and Forecast Centers of other project partners, using automatic data transfer procedures.
- PP4 will integrate the hydrological forecasts elaborated for the Upper Prut and Siret River Basins, with the hydrological forecasting systems implemented within EAST AVERT Project, and will generate specific hydrological forecasting and warning products, that will be disseminated to all the project partners.