International Conference "Water, Environment, Energy and Society" (WEES–2009)
New Delhi, 12–16 January 2009

The Development of a Flood Risk Model for Romania

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ABSTRACT: Spatially explicit hydrodynamic flood models can play an important role in natural hazard risk reduction. A key element of these models that make them suitable for risk reduction is the ability to provide inundation information of a hazard event. Such information can be critical for landuse planning, for mapping evacuation routes, and for locating suitable emergency.

The most important part of flood risk identification and management is the flood-prone area (extent) delineation. Flood-prone areas are those areas subject to inundation as a result of flooding with certain frequency. The determination of flood prone area requires considerable collation of historical data, accurate digital elevation data, discharge data and number of cross-sections located throughout the watershed. A region-specific probabilistic model is developed combining information on (1) the probability of flooding, (2) the spatial extent of floods for different severity levels (or return periods), and (3) the consequences of these floods (e.g. damage assessment). Probabilistic flood events, is done by modeling events featuring the same statistical characteristics as the catalogue of historical flood events, but projected to span a period of several thousand years. It enables insurers to identify the flood risk of individual locations in detail and to substantially improve underwriting for flood risk.

A flood risk model was developed for the Romania for damage assessment due to floods. A regional specific probabilistic hazard model has been developed at commune level resolution. The model was GIS based, making use of a SRTM ~90m horizontal resolution DTM and a network of the major rivers in the country, commune level residential exposure as of year 2006. The building stock is estimated in terms of material, age and height using data from the National Statistical Institute. A review of historical flooding was undertaken to define the worst and most widespread flood events. A number of synthetic events have been generated each providing peak flows at gauging stations throughout the country. The flood flows are propagated using one-dimensional hydraulic simulation of flood wave and then converted into flood levels using elevation data sets from DEM. The flood depths are then combined with maps of the communes to define an average flood depth per commune. Multi-variate Generalized extreme value distribution has been used in generating synthetic flows at the gauge station preserving the inter site correlation among the gauges. The flows were routed using of one-dimensional analysis using Hec-RAS. The extent of and depth of flooding were determined in GIS environment using ESRI's ArcView. The flood depths were combined with maps of the communes to define an average flood depth per commune. The model was calibrated using maps of the observed flood extents from 2005 and 2006. This study will help in formulating the catastrophe insurance schemes as a part of World Bank Hazard Risk Mitigation and Emergency Preparedness Project.

Keywords: Flood Risk Management, GIS, Romania, HEC-RAS, Hazard Risk Mitigation.

INTRODUCTION

Floods result from complex interaction between precipitation, land and streams . Streams and rivers are nature's way of collecting and carrying rainfall from higher grounds to lakes and oceans. When unusually large amounts of collected water build-up along a watercourse, flooding occurs. The land areas adjacent to the streams, rivers, lakes and oceans that are inundated when flooding occur. Triggered by heavy or prolonged rainfall, rivers and streams periodically overtop their banks, spreading floodwaters onto adjacent lowlands or floodplains. Under purely natural conditions, this flooding causes little or no damage. Damage does occur, however, when man attempts to occupy the floodplain.

The development of a probabilistic model is needed for flood mitigation and control. The estimation of flood extents is not straightforward because the extent of the inundation is dependent on the topography and it changes with time (dynamic). When bank full flow

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depth is reached in a flood event, water ceases to be contained solely in the main river channel and water spills onto adjacent floodplains. These make flood prediction a very complex and time-consuming process. The visual display of flood information helps in better planning. Geographic Information Systems (GIS) can be used to visualize the extent of flooding, and also be applied to analyze the flood maps to produce flood damage estimation maps and flood risk map etc. To estimate the extent of flood associated with a given return period, however, the GIS must be combined with an applicable hydrological/hydraulic method for estimating the flood profile.

The objective of the study is to develop a region-specific probabilistic model combining information on (1) the probability of flooding, (2) the spatial extent of floods for different severity levels (or return periods), and (3) the consequences of these floods (e.g. damage assessment). Probabilistic flood events, is done by modeling events featuring the same statistical characteristics as the catalogue of historical flood events, but projected to span a period of several thousand years. It enables insurers to identify the flood risk of individual locations in detail and to substantially improve underwriting for flood risk.

STUDY AREA

Romania is located in Central and Eastern Europe having neighbors Hungary in the North-West, Serbia in the South-West, Moldova in the North East, Ukraine in the North part of Danube Delta and Black-Sea in the South-East, Bulgaria in the South and Ukraine again in the North. Romanian territory is nearly all part of the great Danube Catchment Area, which is over 800,000 km^3 and totally part of the Black Sea Catchments Area.

Romania has an area of 237,391 km^2 with 97.4% of it being located in the Danube River Basin. In terms of area, Romania represents 29% of the entire surface area of Danube river basin. The Danube River has 37.7% of its length on the Romanian territory and is the collector and carrier of all wastewater discharges from the upstream and middle stream riverine countries to the Black Sea, affecting both the water quality of the Danube Delta and of the Black Sea coastal area.

The main Romanian relief units are harmoniously balanced: 31% mountains, 36% hills and plateaus and 33% plains. The climate is a temperate continental one and the annual precipitation varies between 400 mm/year in Dobrogea and 1400 mm/year in Carpathian Mountains.

Romania has a hydrographic network with a length of 78,905 km of watercourses. Water resources from the in-land rivers are about 40 billion m^3, which represent 20% out of water resources of the Danube river. The specific water resource is of 1,840 m^3/inh/years, representing the 13th position in Europe from this point of view. On the Romanian territory there are upper and middle sectors of a high number of rivers, which cross the border of Romania with neighboring countries; also the Tisa, the Prut and the Danube rivers form a part of Romanian border.

Floods frequently affect the Romanian territory. The most important floods (historical floods, in certain sections of rivers) were registered during the years 1969, 1970, 1975, 1981, 1991, 1995, 1998, 1999, 2000, 2004, 2005, 2006. Major basins of Romania are shown in Figure 1.

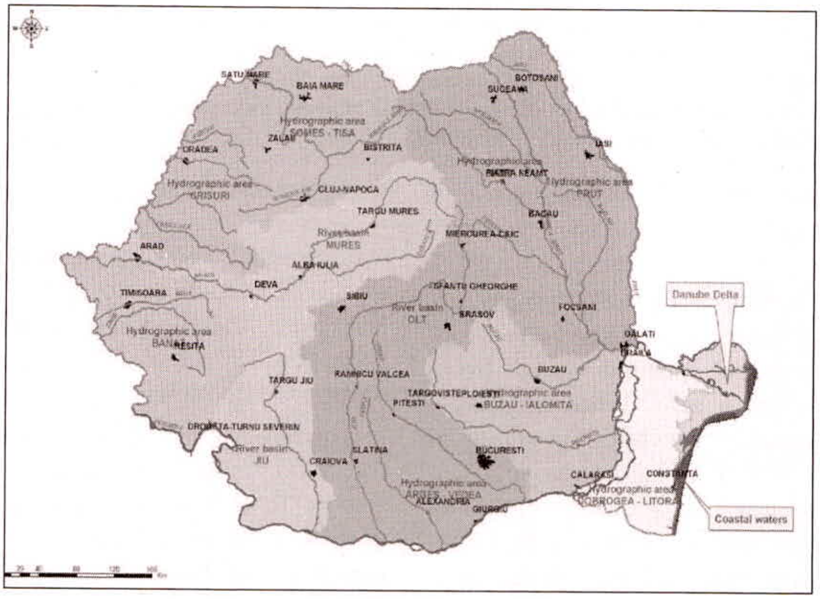

Fig. 1: River Basins map of Romania

MODELING FRAMEWORK

The framework of the probabilistic flood risk model consists of five standard modules i.e. Stochastic event, Hazard, Vulnerability, Exposure and Loss modules. The Stochastic event module comprises stochastic events generated using a probabilistic approach for runoff events; the Hazard module generates hazard intensities (in terms of flood depth) at population-weighted centroids of communes for each stochastic event. The vulnerability module relates flood depths with damage susceptibility of exposed residential assets, the Exposure module computes inventory of residential buildings at commune level and the Loss module quantifies losses caused to assets defined by the Exposure module both in terms of total replacement costs and insured losses. The model is validated for 2005 flood extent.

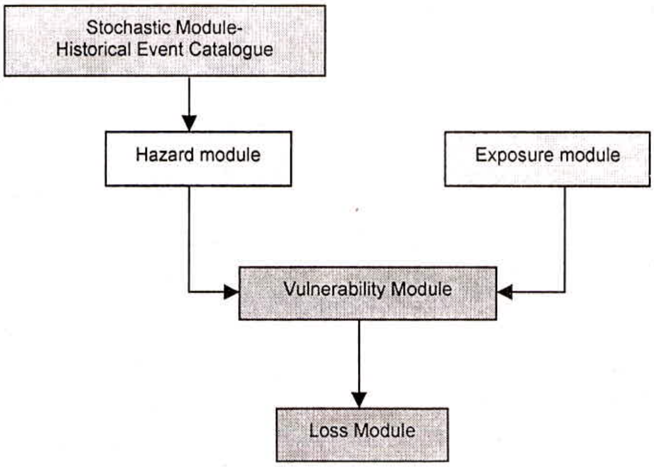

Fig. 2: Modeling Framework

However scope of the present paper is limited to the assessment of flood hazard for varied range of stochastic events.

STOCHASTIC MODULE

A region-specific probabilistic model is developed combining information on (1) the probability of flooding, (2) the spatial extent of floods for different severity levels (or return periods), and (3) the consequences of these floods (e.g. damage assessment).

The stochastic event module generates stochastic events from the characteristics of historical events using simulation techniques. The simulation is carried out on occurrence parameters of the peril and the probability of occurrence of all events likely to cause damage to assets. The occurrence parameters in case of flood are flows and their associated frequency. This method ensures that hazard computed in terms of annualized risk severity-frequency relationships is based on a complete set of possible events ranging from low return period -high probability-low conequence-events to high return period -low probability-high consequence-events spread across both space and time.

Discharge information has been collected from GRDC (Global River Data Center), UNESCO-IAHS catalogue of world largest floods, and Romania Waters department. No. of gauge stations are 18 from UNESCO-IAHS Catalogue, 18 stations from GRDC and about 185 stations from Romania waters department. Period of observations varied from source to source. Longest period of observations is from 1931–2002 and least period is 1973–1998. Data has been tested for homogeneity and consistency. For stochastic modeling the common data sets in the form of annual peak flows for the corresponding period has been used. Since data availability is for limited period, it requires an extrapolation using extreme value theory. Generalized Extreme value distribution has been used for extreme flows. In the current study the probabilistic model uses peak discharge data to compute return period of flood events using Generalized Extreme Value (GEV) distribution function, $G(\mu, \sigma, \xi)$. The cumulative distribution function is given by,

$$G(x) = \exp\{-[1 + \xi((x - \mu)/\sigma)]^{\wedge}(-1/\xi)\} \quad \ldots (1)$$

The parameter ξ is referred as the shape parameter, while μ and σ (>0) are location and scale parameters respectively. For Type I extreme value distribution (Gumbel), shape parameter $\xi = 0$. Type II and Type III classes of extreme value distribution correspond respectively to the cases $\xi > 0$ and $\xi < 0$ respectively.

Parameters have been estimated using maximum likelihood method. Log likelihood function is,

$$\ln(\mu, \sigma, \xi) = \sum \{-\log\sigma - (1 + 1/\xi)\log[1 + \xi((x_i - \mu)/\sigma)] - [1 + \xi((x_i - \mu)/\sigma)]^{\wedge}(-1/\xi)\} \quad \ldots. (2)$$

Flood quantiles corresponding to different return periods have been estimated using a regional flood frequency analysis based on L-moments. Distribution tested for suitability includes log-normal, generalized extreme-value, log-Pearson distributions.

Suitability of the distribution to check whether the flows are coming from same population has been tested using L-Moment ratio diagram (Hosking and Wallis, 1997). L-Moment ratio diagram for the gauges is shown in Figure 3. This figure also shows the L-Moment ratio for Gumbel distribution. Further, it can be inferred that the gauges are coming from a population that could be represented well by means of

GEV distribution. Diagnostic plot for Zimnecia station on river Danube is shown in Figure 4.

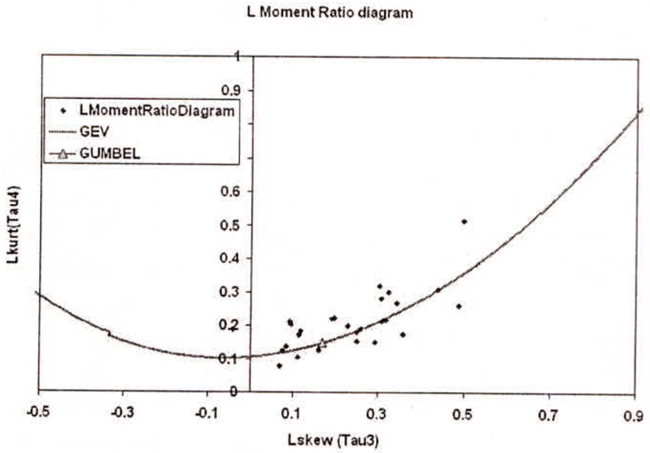

Fig. 3: L-Moment ratio diagram

GENERATING CORRELATED MULTIDIMENSIONAL VARIATES

A Common requirement of simulation models is a set of randomly generated variates. When a model involves multiple non-independent variables, the problem of specifying multivariate distribution and sampling from it arises. Dependence among the variables is completely characterized by the correlation matrix, hence only a single number is required to characterize the dependence between each pair of variables. The method described below can generate dependent random variables with any marginal distributions and where the dependence is specified by a correlation matrix.

Correlated Standard Normal Deviates (CSND's) were generated using MVN program developed by John Uebersax has been used to generate random multivariate normal numbers. MVN program first generates random univariate normal numbers using the TOMS algorithm 712 by JL Leva, 1992. The algorithm uses the ratio of uniforms method of AJ Kindermann and JF Monahan augmented with quadratic bounding curves. Uniform random number, used by the algorithm, is supplied by default random number function of Fortran 90 compiler. The matrix of CSND's was converted to Correlated Uniform Standard Deviates (CUSD's) one vector at a time. This process used the inverse transform method described by Richardson, James W (2004).

Let X be an n-dimensional variable with the ith variable having a cumulative distribution function F_i. The usual product-moment correlation (Pearson correlation) is sensitive to non-linear transformation of variables. An alternative is the fractile correlation, which is Spearman, or rank correlation is invariant to monotonic transformations.

Random variates with arbitrary marginal distributions and a specified fractile correlation matrix is obtained by generating a set of variates U_i with uniform marginals and same fractile correlation matrix and then applying probability transform to each variate individually,

$$X_i = F_i^{-1}(U_i) \quad \ldots (3)$$

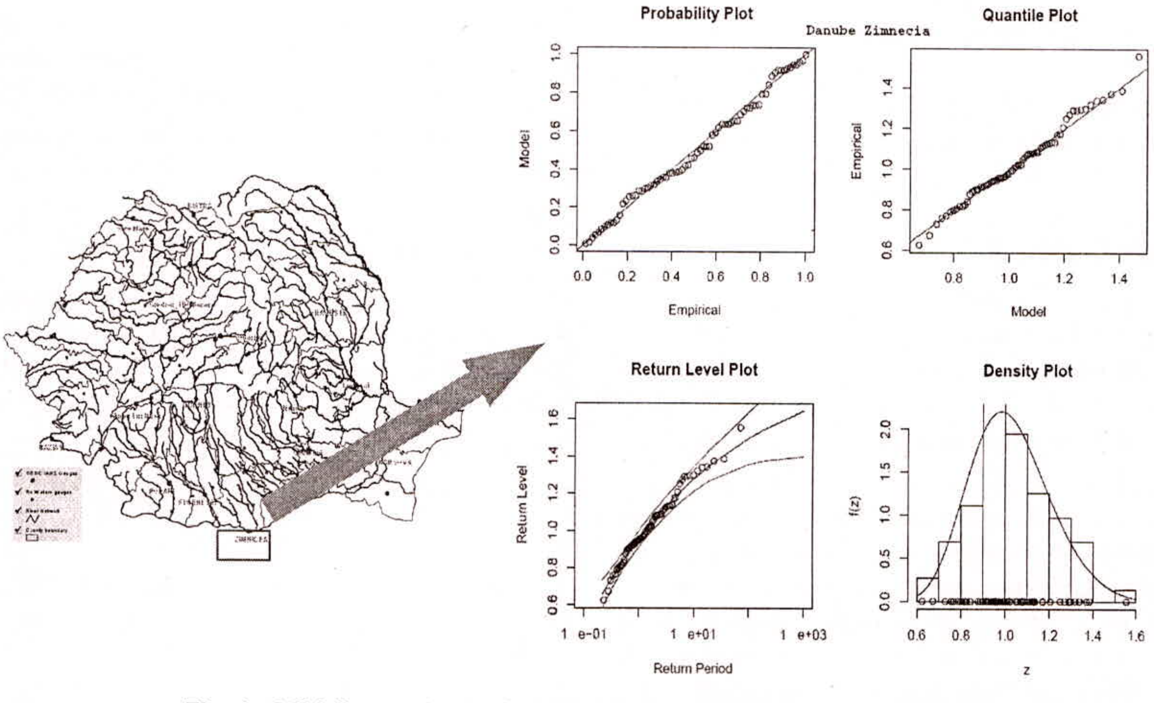

Fig. 4: GEV diagnostic plot for Zimnecia gauge station on river Danube

The most convenient way is to generate normal variates with the specified fractile correlation and then transform them each individually to have uniform marginals. Random normal variates are generated using,

$$Y = Z\,Q \qquad \ldots (4)$$

Where Zi are independent standard normal variates and Q is matrix such tha $QQ^T = C$ (Cholesky decomposition of correlation matrix). Then Y_i is then transformed to have uniform marginals by applying the transform,

$$U_i = \Phi\,(Y_i) \qquad \ldots (5)$$

where Φ is the standard normal CDF. It is illustrated in Figure 5.

Stochastic generated events are in the range of 2 to 1000 year return periods. From large set of stochastic events, 25 events were sampled for each gauge station preserving the correlation matrix among the station using stratified sampling. Observed and simulated cumulative distribution function for Ceatal Izmail gauge station on Danube is shown in Figure 6.

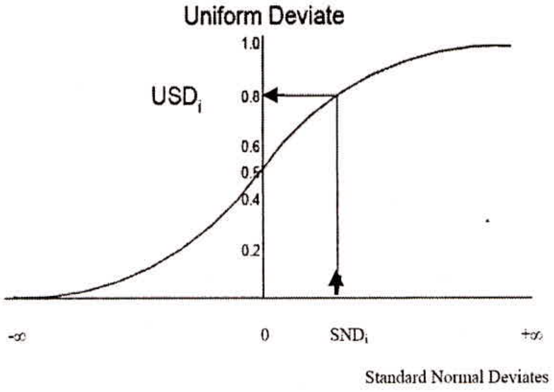

Fig. 5: Transformation of Standard Normal Number to Uniform standard number

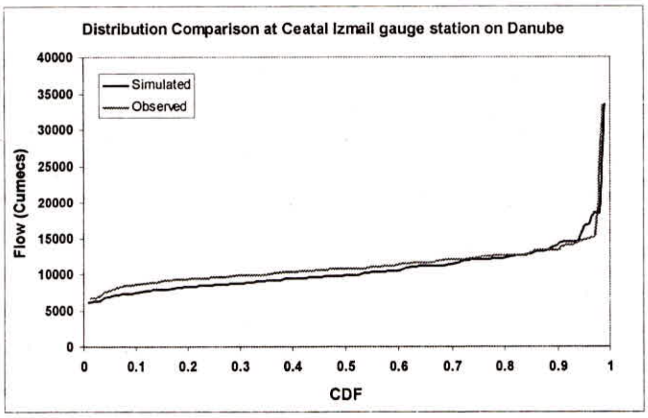

Fig. 6: CDF comparison of observed and simulated peak flows at Ceatal Izmail gauge station

HAZARD MODULE

Once the parameters of each event in stochastic set are defined, the Hazard module analyses the intensity at a location given an event in the stochastic set has occurred for flood hazard expressed in terms of flood depth.

In many applications of river flood modeling, a one-dimensional full hydrodynamic modeling system is used. To model the floodplains with such a system, a quasi two-dimensional approach can be applied. The quasi-2D approach has the advantage that compared with the 2D approach, the computational load is limited. In this way, the model is able to describe the embanked river and the flooding conditions over its full length. By means of the spill units, both flooding by over-topping, and flooding by dam-break can be considered. It is proposed to use the quasi-2d flow model in this study. In this approach, the flooded areas are modeled as separate 1D river branches that are connected to the main river by means of spills or overflow structures. These structures represent the dikes or embankment elevations between the riverbed and the floodplains. The cross-sections perpendicular to the direction of stream are derived from a Digital Elevation Model (DEM). In this way, the volumes along the flooded areas can be described accurately. By making appropriate assumptions for the roughness coefficients along these areas, the model is also able to describe the water surface profile along the flooded areas. A GIS system is used to draw geometrical data for the river branches and spills/overflows from the DEM. Proposed methodology adopts HEC-RAS in the determination of flood extent and flood depths for all stochastic events.

DEM (Digital Elevation Model) represents a topographic surface in terms of set of elevation values measured at finite number of points. SRTM (Shuttle Radar Topographic Mission) ~90 m resolution DEM will be used in the inundation analysis. Necessary corrections have been carried out to make the DEM hydrologically correct and suitable for inundation calculations.

Major rivers, where flood occurrence is more frequent and passing through urban areas has been selected for inundation modeling. River network has been checked for positional accuracy using Landsat images. River network used for hazard modeling is shown in Figure 7. In this study, water surface profiles for reaches have been determined using one-dimensional steady flow analysis using HEC-RAS software. HEC-RAS is an integrated system of software, the system contain one-dimensional hydraulic analysis components for steady and unsteady flow simulation for a full network of natural and constructed channels. Basic computational procedure is based on the solution of the one-dimensional energy equation. Energy losses evaluated by friction (Manning's equation) and expansion and contraction losses. The momentum equation is utilized in situations where the water surface profile is rapidly varied. The situations include mixed flow regime.

The river system schematic has been determined using Hec-GeoRAS in GIS environment using ESRI's Arcview. Boundary geometry for analysis has been specified in terms of ground surface profiles (Cross-sections) and measuring distances between them. Cross-sections are extracted from TIN (Triangulated Irregular Network) at spacing of about 100 m. Figure 8 shows the geometric data for Siret basin.

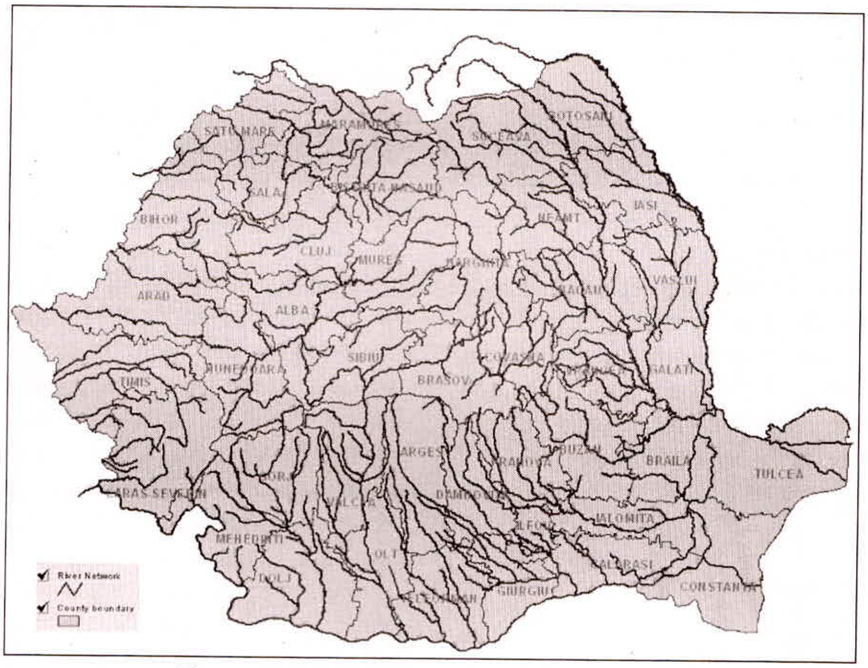

Fig. 7: River network used for flood modeling

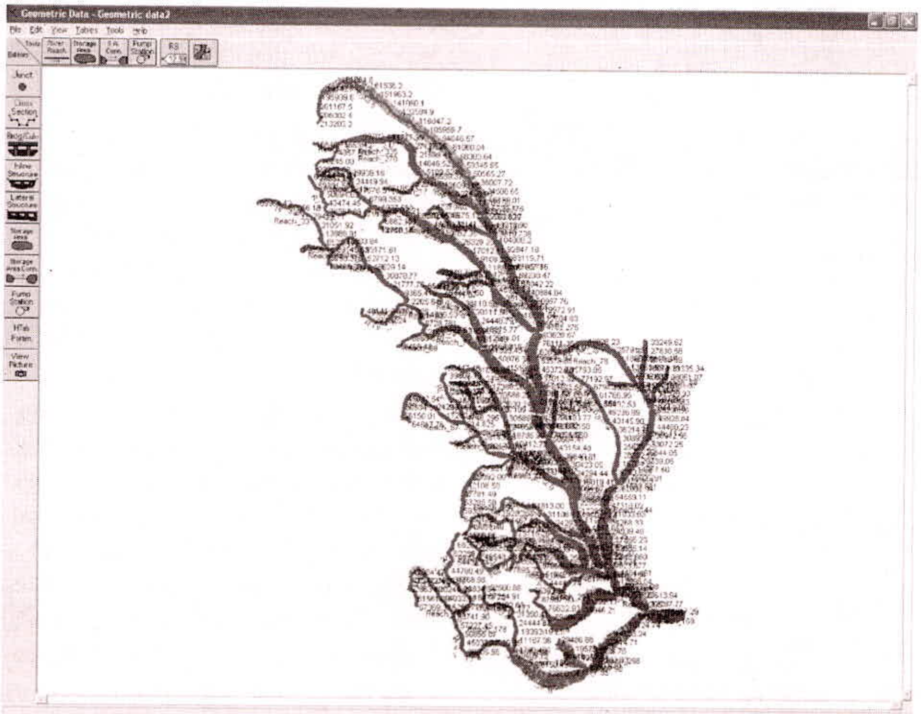

Fig. 8: River system schematic for Siret basin

Flood extent and flood depth maps have been generated by post-processing the simulated results of Hec-RAS in ArvView environment with Hec-GeoRAS extension. Flood plain boundary and inundation depth data sets are generated from exported cross-sectional water surface elevations. Flood extents have been validated for 2005 flood. Sample validated areas are shown in Figure 9. From the figure, one can see that the modeling flood extents are in close match the observed extent. Flood extent maps of 100 year return period is shown in Figure 10.

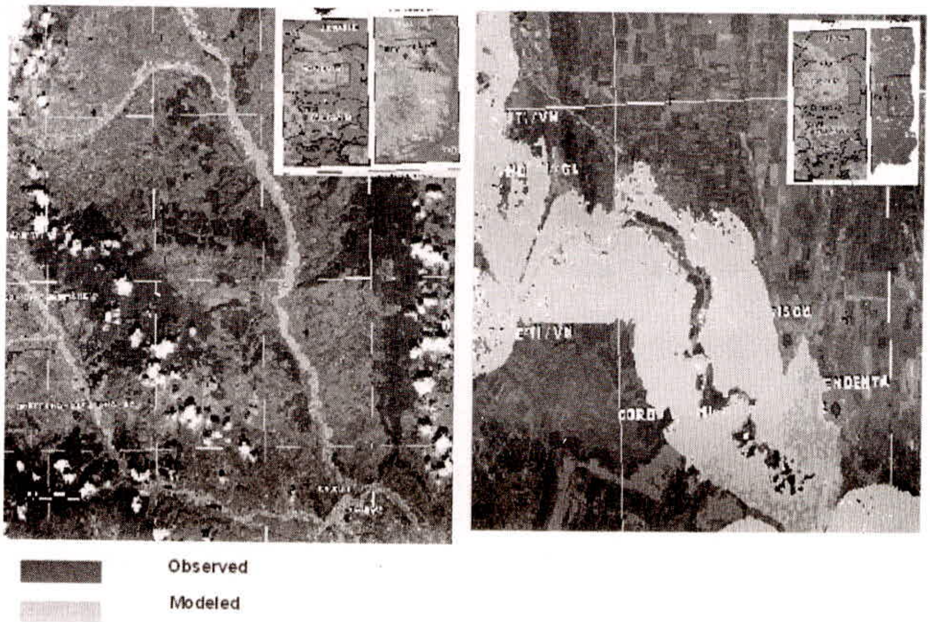

Fig. 9: Modeled and observed flood extent for 2005 flood

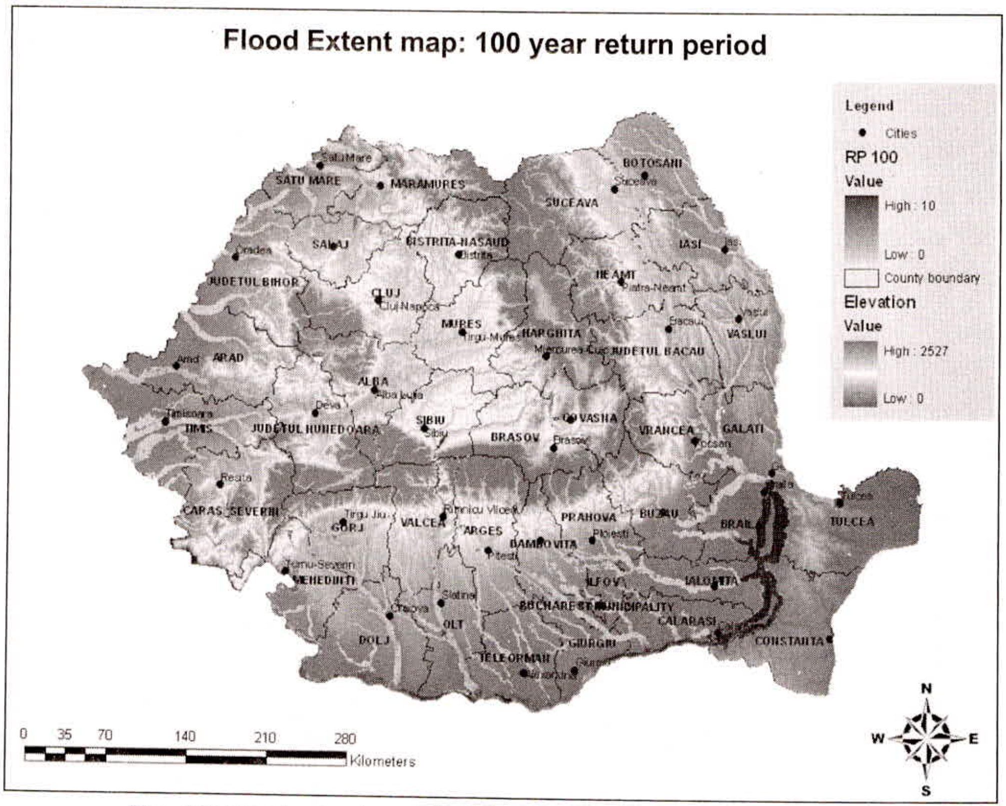

Fig. 10: Flood extent map for 100 years return period for Romania

CONCLUSION

A region-specific probabilistic model is developed combining information on likelihood of flooding, spatial extent of floods for different severity levels, and this model can be used for the damage assessment. As this model is GIS based, it helps in preparing the contingency plans for disaster management.

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