A thesis submitted to the Department of Environmental Sciences and Policy of Central European University in part fulfilment of the Degree of Master of Science

Assessing flood risk for urban areas in the Lower Don River using GIS and Remote Sensing

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July, 2014

Budapest

Author's declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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ABSTRACT OF THESIS submitted by:

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for the degree of Master of Science and entitled: Assessing flood risk for urban areas in the Lower Don River using GIS and Remote Sensing.

Month and Year of submission: July, 2014.

Frequency of reported severe flood events and associated economic loss has been rapidly increasing in recent years. This trend might be explained by the combination of such factors as climate change and the expansion of urbanized areas into floodplains. The aim of this research is to explore the scale and consequences of floodplain urbanization of the Lower Don River (Rostov Oblast, Russia) and assess related flood damage threats. The environmental security of this area is a matter of great importance, since historically flood events were common for the region and even after the construction of the Tsimlyansk Dam and regulation of the water discharge, the risk of inundation still exist. The combination of various techniques was used in order to address the research questions: historical data collection, application of the Remote Sensing, GIS, hydrological modeling (FLO-2D). It was found that some rate of the urban growth is inherent in the study area. The simulations of the five flood events were conducted. The differences in flood hazard depending on the water discharge were analyzed. The most hazardous areas within the floodplain were defined, by the maximum flow depth and the maximum flow velocity. It was found that generally small villages on the river bank within the wide parts of the floodplain will experience the most intense flood, together with the territory right under the Tsimlyansk Dam. The results acquired through this research might be interesting for various stakeholders - researchers, urban planners, local population.

Keywords: GIS, Remote Sensing, Modeling, Floodplain urbanization, Lower Don River, FLO-2D, ArcGIS, supervised classification, flood intensity

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Acknowledgements

I would like to express my sincere appreciation to my supervisor Dr. Viktor Lagutov for his support and encouragement throughout the research.

I would also like to thank Karen O'Brien from FLO-2D Software, INC, for providing me with free version of FLO-2D Pro and assistance during the model development.

Finally, I would like to extend my deepest gratitude to the department's faculty, staff and students.

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List of Abbreviations

2D	Two-dimensional
DEM	Digital Elevation Model
GIS	Geographic Information Systems
GloVis	Global Visualization Viewer
ICT	Information and Communication Technologies
RGB	Red, green, blue
RS	Remote Sensing
USGS	United States Geological Survey

1. Introduction

1.1. Problem definition and background

Frequency of reported severe flood events and associated economic loss has been rapidly increasing in recent years. Regardless of the development scenario these numbers are estimated to grow further. As a rule this phenomenon is associated with climate change. However, in many cases the driving force in these disasters may not be climate change, but urbanization trends, leading to conversion of these territories into residential, industrial and agricultural lands (Yang *et al.* 2013). The recent reported increase in flood damage can be explained by the combination of different factors such as growing number of extreme precipitation events, expanding urbanized / built up areas into floodplains (EU 2007).

In this work I am going to study the section of the Lower Don River floodplain between the river's delta and the Tsimlyansk Reservoir (Rostov Oblast, Russia). The region is rapidly developing, as can be seen by demographic growth, infrastructure development, etc (Rostov 2007a). Inhabited by 2.7 million people the Rostov agglomeration is already the third largest agglomeration in Russia, after Moscow and Saint Petersburg (ROSSTAT 2014). Because of its strategic location and regional development plans, the region is experiencing rapid growth in urban population and corresponding expansion of built up areas concentrated along the Don river, the main water source providing multiple ecosystem goods and services.

Urbanization trends, which lead to conversion of floodplain territories into residential, industrial and agricultural lands, can be seen as one of the reasons of the recent reported increase in flood damage, along with the growing number of extreme precipitation events (Tripathi *et al.* 2014). Urbanization of floodplains elevates the threat to regional environmental security.

1.2. Research Aim

The aim of the research is to explore the scale and consequences of floodplain urbanization of the Lower Don River and assess related flood damage threats. The environmental security of this area is a matter of great importance, since historically flood events were common for the region and even after the construction of the Tsimlyansk Dam and regulation of the water discharge, the risk of inundation still exist.

1.3. Research Questions and Objectives

Research questions (RQ) and corresponding objectives are listed below:

RQ1: What were the urbanization patterns of the Lower Don River floodplain over the last decades?

- Explore the urbanization of the Lower Don using remote sensing.
- Develop a land cover maps of the study area for the 1985 and 2013.
- Study urbanization patterns.

RQ2: What are the flooding risks of the Lower Don River under different scenarios?

- Collect data on historical flood events and associated damage in the region.
- Develop a regional hydrological model using FLO-2D.
- Develop scenarios based on the calculated flood events of various probabilities.
- Delineate the flood-prone areas in different scenarios.

RQ3: How flooding threat of the urbanized areas had changed and what areas of the floodplain are at the most risk?

- Assess the changes in land use patterns in the historical and simulated flooded areas.
- Distinguish the most hazardous areas on the floodplain.

1.4. Outline

The chapters 2 and 3 provide the brief literature review on the issues of concern. In the **Chapter 2** the floodplain urbanization is described, covering such topics as global urbanization trends, risks and consequences of floodplain urbanization, the strategies for urban flood risk management. **Chapter 3** covers some of the existing techniques for studying urbanization, flood modeling, data analysis. The mentioned methods and theirs applications are GIS, Remote Sensing and Modeling. The next **Chapter 4** provides the research design and the short description of the utilized methods. In the **Chapter 5** the study area are defined, the main physical characteristics, hydrological patterns and population dynamics of the region are described. Chapters 6, 7 and 8 provide the description of the steps which were made in order to answer the research questions and the derived results. **Chapter 6** presents the urbanization patterns of the Lower Don River floodplain. **Chapter 7** provide the delineation and analysis of the inundated areas acquired from the flood simulations. **Chapter 8** presents the results and the analysis of the flooding threat changes in the region. **Chapter 9** discusses the overall results of the research. The concluding **Chapter 10** provides the summary of the work and short description of the achieved results. If not mentioned differently, figures, tables, maps and graphs were created by author.

2. Floodplain urbanization

This chapter represents the first part of the literature review. Global urbanization trends as well as patterns and risks of the floodplain urbanization are presented below.

2.1. Urbanization trends

The Earth's population is growing, and it has been predicted that the major part of this ongoing growth will belong to urban populations. In 2009 the global urban population exceed rural population (UN-DESA 2010). By 2030 60% of the total world population (or around 5 billion people according to forecasts) will live in cities (UN-DESA 2013; UN-HABITAT 2006). This will inevitably lead to the appearance of new settlements and to the rapid growth of the existing ones. Urban sprawl is a well know modern trend. The spread of built up areas not only has a great impact on the territories that surround cities, but brings with it a range of problems for urban planning and governance - housing, transportation system, access to clean water and sanitation, health, education, crime control etc. (Cocheci 2014).

2.1.1. Floodplain urbanization

Uncontrolled or sometimes even controlled growth of the city can lead to a situation when floodplains begin to experience urbanization. Floodplains are the low and plane areas near the river channel which are seasonally inundated (Goudie 2004). The width of the floodplains can vary from tens to hundred of meters or even more. Traditionally these territories are open fertile green spaces, sometimes used for agricultural purposes, quite often they can be found near cities or even in the very centers (Mitchell 2003; Oosterberg *et al.* 2005). After the construction of dams along the river, annual flood events are kept under control, and the territories which in the past constantly experienced inundation, now are seen as secure enough for new construction. One of the main reasons for this is the lack of the available space within the city limits.

2.2. Risks of floodplain urbanization

Nowadays, especially in view of climate change, urbanization of floodplains must be seen as an extremely risky process (Yang *et al.* 2013). These territories are vulnerable and they can be flooded after unpredictable heavy rainfall, snowmelt or dam accident. Flood is a temporal overflow of the water, inundation of the territories which normally are dry (EU 2007). Various case studies as well as European Union Directives support the idea that urbanization (the growth of cities, economic assets within the floodplains, land use change at the adjoining areas) combined with climate change have a great influence on the increased severity of floods (EU 2007; Tripathi *et al.* 2014; Yang *et al.* 2013; Zhu *et al.* 2007). Floods are among the most common hazard events and some of the most dangerous for people's life and destructive for property (Uddin *et al.* 2013). Flood risk includes the probability of flood event as well as the potential damage to the affected population, economy, cultural heritage and environment in case of the disaster (EU 2007).

2.2.1. Consequences of urbanization

At the same time urban development itself has an influence on the river flow. As the vegetation is removed and the territory is built up, the runoff to the river increases - as a result more frequent and severe flood events are recorded (Konrad 2003). One of the important problems is that often the poorest part of the urban population resettles to the floodplains, and these people are very vulnerable to natural disasters (Mitchell 2003).

Even though the growing number of flood events can be explained largely by climate change (EM-DAT 2014), the scale of the occurring disasters is growing because of the settlement patterns - the building up of the potentially unsafe areas (Tripathi *et al.* 2014). Floodplain urbanization must be seen as one of the reasons why the number of flood events, as well as the number of reported victims and amount of economic losses are increasing (Mitchell 2003).

2.2.2. Strategies for urban flood risk management

In the constantly shifting situation of climate change and growing urban population it is essential to implement some measures to mitigate potential damage from the flood events in the urbanized areas. Three main strategies can be defined (Oosterberg *et al.* 2005). Still, these strategies are always implemented in complex, as a combination of available measures:

1) the prevention of floods;
2) the restriction of the flood-prone zones' development;
3) the preparation of the urban areas for flood events.

In the cities where flood-prone areas are already urbanized, the building constraint is not an option anymore. So one of the remain way of damage mitigation is the decrease of flood event probability. The construction of the upstream dams and reservoirs sometimes is a feasible measure. The integration of an early-warning system is as well an essential action which must be done in highly populated urban areas (Oosterberg *et al.* 2005). In such vulnerable territories as floodplains there must be an appropriate rainfall drainage system, which will be able to sustain heavy precipitation. The construction of spillways and floodways upstream the urban area, as well as levees, can help mitigate the consequences of the flood. Flood insurance at a reasonable price can be a part of a complex flood policy (Oosterberg *et al.* 2005).

Strong protective status of the valuable floodplains and wetlands near the river can stop the development of these territories and direct urbanization trends to other, more safe and feasible areas (Oosterberg *et al.* 2005). The prevention of the floodplain building up is a good way to moderate the damage from the flood, but unfortunately occupation of these areas by the poorest part of the urban population is often uncontrolled by the city administration and thus the consequences can be unpredictably severe (Mitchell 2003; Oosterberg *et al.* 2005).

In some cases when the flood risk is too high and there is no applicable measure that can mitigate the danger to the acceptable level, the only remaining way is to relocate people from the hazardous areas (Oosterberg *et al.* 2005). However often it is the very last option, due to its expensiveness and complicacy.

3. Remote sensing, GIS, Modeling

Various techniques could be used for studying floodplain urbanization, such as GIS, remote sensing and different modeling programs. Still in most studies not single tool is used, but a combination of them (Herold *et al.* 2003; Jung *et al.* 2013; Samarasinghea *et al.* 2010; Uddin *et al.* 2013). Field exploration of the studied areas as well as search for potentially vulnerable territories can be not only more expensive, but also time consuming, depending on the total affected area, while application of listed distant techniques can be preferable in contrast with *in situ* approach (Voogt and Oke 2003).

3.1. Remote sensing

One method that is applied more often, sometimes can be used solely and can be regarded as easier in use is remote sensing (RS). The term occurred in 1960 (Campbell 2002). The most general definition describe remote sensing as the extraction of the data about an object from a distance, without any physical contact, most often from satellites and aircrafts (Schott 2007; Schowengerdt 2006) (Fig. 1). In some situations, for instance in developing countries, reliable information on the situation cannot be derived from government or local authority, and in such cases RS can be the best way to receive necessary data (Miller and Small 2003).

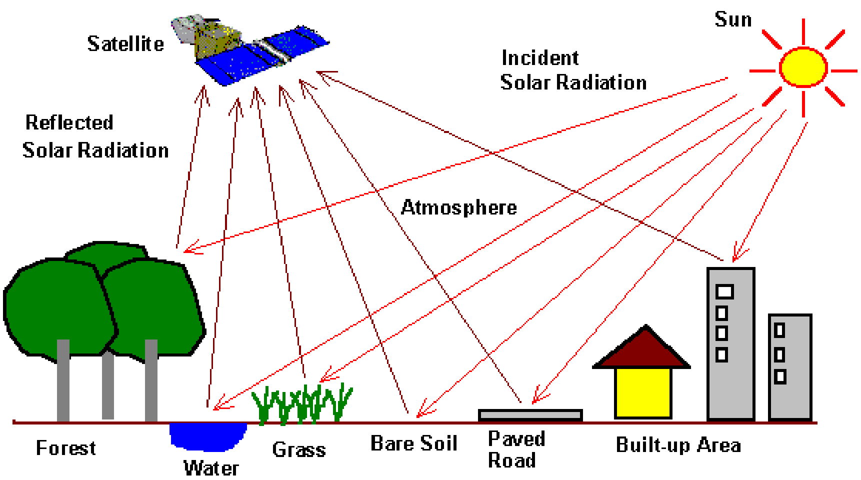


Fig. 1 Optical remote sensing. Sensors on the satellite detect solar radiation reflected from the objects. Source: (Liew 2001).

3.1.1. Applications of RS

RS in urbanization

Remotely sensed data can be successfully applied in the study of the transformation of the environment, in this instance the development of urban areas. In the last hundred years the growth of urban population and therefore urban areas increased in times (UN-DESA 2012). At the same time considering the advances of the information technologies in the recent years and the accessibility of the remotely sensed images with high resolution, the research in the field of urban environment now can be conducted at a new level. There is no doubt that urban areas are considerably different from the surrounding environment and this distinction is visible and can be identified and defined using satellite imagery (Miller and Small 2003). The great value of the RS is that the studied area can be appreciably bigger than in case of using traditional *in situ* measurements alone. Some of physical quantities as air and surface temperature, wind speed, humidity, which can be complicated to measure *in situ* on a great territory, can be monitored using RS tools. At the same time, to ensure reliability of the results, remotely sensed data should be calibrated with direct measurements, if there is a capacity for that (Miller and Small 2003; Uddin *et al.* 2013).

After the period of 1960-70, when the term "remote sensing" has been introduced, and the launch of the Landsat 1 in 1972 (Campbell 2002), the study of urbanized areas undergone a significant change as new RS methods now could be applied (Miller and Small 2003). Researchers found a great number of ways to implement satellite imagery in the urban studies. One of the earliest applications of the RS was the study of the urban heat island by Carlson *et al.* using measurements of surface temperature, extracted from remotely sensed imagery (Carlson *et al.* 1977). The availability of high-resolution data nowadays give an opportunity for decision makers to monitor current situation in urban areas and define historical trends (Netzband *et al.* 2005).

Depending on the specific task, assigned area and required particularity, images with different spatial resolution must be used. For instance, in order to identify urban infrastructure the essential resolution must be at least 0,5-10 m. Though such satellites as Landsat and SPOT do not fit this requirement, imagery from them can be successfully used in urban landcover change monitoring (Miller and Small 2003). RS provide the opportunity to study urbanization trends and patterns of the city development without seeking for any other additional data (Pham *et al.* 2011).

The use of the remotely sensed data can play essential role not only in dealing with local issues, but also in projects that can cover the whole world. Urban Environmental Monitoring (UEM, also called The 100 Cities Project) is one of them (CESA 2014). The project include 100 cities, but there is a proposal of the assessment of 400 biggest world urban areas. The UEM project uses various remotely sensed data - ASTER, Landsat, IKONOS, MODIS, LIDAR and so on (Netzband *et al.* 2005). Among the main threats to the urban population in the expanding cities, like the lack of such vital resources as pure water and food and vulnerability to terrorist attack, Netzband *et al.* (2005) mentioned the growing risk of crises and hazard events.

Some research areas, relevant for our study, where the remote sensing techniques are commonly used are: urban growth and land use; urban landcover change; urban population; urban infrastructure; urban heat island; urban geo-hazards; residential quality index; building area; digital elevation models (DEM); vegetation characteristics; etc.

RS in flood monitoring

One of the most common way to apply RS for flood risk analysis is to extract inundation area from the imagery of the actual flood event. This approach allow to define the real boundaries of the disaster, the total affected area and provide the opportunity to determine destructions by comparing satellite images before and after the flood (Haq *et al.* 2012;

Samarasinghea *et al.* 2010; Uddin *et al.* 2013). Using digital elevation models it is possible to approximately define the floodplain and to presume what areas may be in danger in case of flood event (Stenehjem 2014).

3.2. GIS

Information about the urban areas could be obtained from different sources, as governmental reports, population censuses, surveys and so on (Miller and Small 2003). In order to combine all various types of available information about the area (remotely sensed imagery, vector and point data) a Geographic Information System (GIS) could be used. The existing definitions of GIS can vary, but there are two general features that are inherent in them: spatial references and data analysis. GIS is a tool that is helping to collect, maintain, analyze and distribute spatial data as well as support decision making (Bolstad 2005; Fotheringham and Rogerson 2013).

3.2.1. Applications of the GIS

The application of GIS in cities' administration is quite widespread today so often the information is available in appropriate formats and can be easily incorporated. The case study of Sindh Province, Pakistan, gives a good example of the combined application of RS and GIS (Uddin *et al.* 2013). The project was focused on the flood hazard management, and while general data (flood extended area) were derived from satellite images, manipulations with various datasets and factors allowed to create not only flood hazard zoning map, but flood shelter suitability map as well.

Damage assessment

GIS can be effectively applied in the damage reduction and damage assessment projects. One of the determinant of such assessment is the precise estimation of the inundated area. If the initial affected area was calculated inaccurately, the final result could be unreliable, flood damage could be understated or overstated (Yi *et al.* 2010). After the flooded area are defined, expected economic loss can be estimated. To produce the most precise forecast great number of datasets must be used - predicted flood victims, infrastructure damage, traffic disruption, emergency costs and all others expected direct and indirect costs (Yi *et al.* 2010). Still this particular damage assessment approach includes only inundated area, which was directly affected by flood, ignoring nearby territory, which could be also damaged.

3.3. Modeling

Models can be used for the simulation of various processes and events. In the next section two most relevant, for our research, applications of the modeling are presented - urban growth modeling and flood modeling.

3.3.1. Applications of the Modeling

Urban growth modeling

Urban land use change models became a helpful tool for city planners and decision makers in recent years. These models can be created and processed using GIS. But the quality and reliability of the results strongly depends on the input data, and for the urban growth modeling it is remotely sensed data as basis (Herold *et al.* 2001). Different purposes require different models. Herold *et al.* (2001) provide some examples of the existing urban land use change models and it can be easily seen that each model needs special data and has necessary spatial and temporal criteria (Herold *et al.* 2001) (Table 1).

Table 1 Comparison of urban growth/land use change models. Data source: (Herold *et al.* 2001)

Model name	Spatial Framework	Temporal Framework	Examples of required Datasets
CUF 2 - California Urban Future 2	Raster-based: 100m x 100m grid cells	Fixed time steps for prediction of land use changed based on historical calibration time frame, typical 5 or 10 years	1. Topography 2. Transportation infrastructure
LUCAS - Land Use Change Analysis System	Raster-based, variable resolution	Variable time steps	1. Topography 2. Population density 3. Transportation infrastructure

What If	Vector-based	Variable time steps	1. Topography 2. Transportation infrastructure
UPLAN - Urban Growth Model	Raster-based, variable resolution: 200m x 200m for low density residential, all other - 50m x 50m	Variable time steps	1. Topography 2. Transportation infrastructure
UrbanSIM	Vector-based, parcels as model entities for land development, 150m x 150m grid cells used to link environmental model	Variable time steps	Several biophysical and socioeconomic parameters
SLEUTH or Clarke Urban Growth Model	Raster-based	Yearly prediction	1. Topography 2. Transportation infrastructure
LTM - Land Transformation Model	Raster-based, different spatial scales for processes (30m x 30m for parcel, 100m x 100m plat, 300m x 300m block, 1km x 1km local)	Variable time steps	1. Location of employment 2. Population distribution 3. Topography 4. Transportation infrastructure

One of the existing approaches in modeling is the use of the cellular automata concept. Cellular automata can be defined as a system composed of certain number of elements, which are characterized by some features. As the simulation goes on, at each time step all cells change their status at once, depending on the condition of the nearest cells (Dottori and Todini 2010). This concept was applied in the simulation of the urban growth of the Santa Barbara, CA region. The urban growth model used several parameters, urbanization trends were based on growth rules so the urban spread was predicted for 2050 (Herold *et al.* 2001).

Flood modeling

In order to determine an area vulnerable to flood event it is possible to simulate rainfall-runoff process in the river basin (Samarasinghea *et al.* 2010). Such simulation require various datasets and software to implement as well as the calibration to ensure the acceptable results.

To predict the flood discharge one-dimensional (1D) Hydraulic Model can be used. One of the examples of such models is Hydrologic Engineering Center-River Analysis

System (HEC-RAS), which can simulate water surface elevation in a river channel. HEC-RAS model has some limitation as every model, and a number of conditions must be met so simulation will be able to run: the river and the floodplains must be seen as a single channel, the boundaries must be determined, various datasets must be available (Jung *et al.* 2013).

Other type of models, two-dimensional (2D) (LISFLOOD-FP, TELEMAC-2D), are also used quite often and proved to be reliable. Even though not many studies in the field of comparing 1D and 2D models were conducted, results of the simulations are more or less similar and the selection of the particular model depends mainly on the issue and availability of the data (Dottori and Todini 2010; Horritt and Bates 2002).

Cellular automata-based 2D models (LISFLOOD, FLO-2D) proved to be very effective and reliable in flood modeling (Dottori and Todini 2010). Even though mentioned models are not as complicated as some others, the results they provide are more than acceptable, and the simplicity of the equation allow simulation to run faster and exclude additional errors in the calculations (Dottori and Todini 2010).

4. Methodology

In this chapter the techniques, that were applied in the research, will be described - data collection, remote sensing and hydrological modeling. Generally quantitative methods were used. While with some complicated technical issues, consultations as qualitative method, were carried out, particularly with practitioners in remote sensing and flood modeling.

4.1. Research design

In order to fulfill the aim of the thesis, to explore the scale of floodplain urbanization and related flood damage threats, the research can be divided into three main stages (Table 2). The flow of the research is moving gradually from historical information about the study area to the present state and then to the forecast.

Table 2 Research design

	Research question	Objectives	Steps	Methods
RQ1	What were the urbanization patterns of the Lower Don River floodplain over the last decades?	Explore the urbanization of the Lower Don using remote sensing	Finding historical data	Literature review Data collection Consultations ArcGIS
			Studying the development plans for the region	
		Develop a land cover maps of the study area for the 1985 and 2013	Remotely sensed data collection	
			Supervised classification	
		Define the urbanization patterns	Land cover maps creation	
RQ2	What territories of the Lower Don River floodplain may experience the inundation under different developed scenarios?	Collect data on historical flood events and associated damage in the region	Development of the hydrological model	Data collection Statistics analysis Consultations FLO-2D modeling ArcGIS
		Develop a regional hydrological model using FLO-2D	Scenarios development	
		Develop scenarios based on the calculated flood events of various probabilities	Inundated areas maps creation	
		Delineate the flood-prone areas in different scenarios		
RQ3	How flooding threat of the urbanized areas had changed and what	Assess the changes in land use patterns in the historical and simulated flooded areas	Integration of the results, acquired in the previous steps	Data collection ArcGIS Statistics
			Analysis of the created	

	areas of the floodplain are at the most risk?	Distinguish the most hazardous areas on the floodplain	maps	analysis

4.2. Data collection

The data collection is required at all three main stages of the research. Necessary information was collected from the number of sources:

- National scientific libraries.
- Internet data mining for databases, satellite imagery and remote sensing products.
- Consultations with practitioners in remote sensing and flood modeling.
- Review of mass media.

All collected data can be divided into two main group - historical and remotely sensed data.

4.2.1. Historical data

Historical data about the hydrological regime, development and experienced damage due to floods of the studied area was obtained through various sources, like books and journal articles, both in Russian and English, national statistics reports, mass media. The trip to Moscow provided the opportunity for the collection of the data essential for the research: detailed hydrological data; information about the resources of the studied area.

4.2.2. Remotely sensed data

In order to define and evaluate the changes in urbanized territories and land cover of the studied area in total, required remotely sensed data was collected. For these purposes the U.S. Geological Survey website was used, particularly the EarthExplorer (USGS 2014c) and the USGS Global Visualization Viewer (GloVis) (USGS 2014b) online search and order tools. The imagery was received for the two periods: 1985 and 2013. Images for 1985 were gathered from the Landsat 5 satellite, 2013 - from Landsat 8.

For the purposes of the studying previous severe flood events in the region and the FLO-2D model validation, 24 satellite images from the Landsat 2 and Landsat 3 were acquired through USGS GloVis online search and order tool. The spring months of the 1978, 1979, 1981 were selected, as these years were characterized as high-water, and the floodplain were inundated completely during these years (Rosvodresursy 2013). The imagery for other years, which might be interesting for analysis, could not be obtained, since in the selected dates the area was completely covered by clouds or the satellite imagery for the region was absent.

During the trip to Moscow, ScanEx Research and Development Center was contacted and the consultation with the expert in the Remote Sensing was conducted. Advises for the remotely sensed data gaining and processing were acquired. Remotely sensed data together with the information about the previous and future development of the study area provided the possibility to assess the flood damage using modeling software and GIS.

4.3. Remote data processing and map creation

Collected remotely sensed data was processed and analyzed using ESRI ArcGIS 10 software package. Where possible the collected data was organized in a way of GIS databases. Main functions which were used are Composite Bands (Data management toolbox) and Image Classification toolbar (Spatial Analyst extension).

4.3.1. Creation of satellite images database

After the satellite images for the area were acquired, they were processed using ArcGIS 10. In order to create land use change maps for the area and especially define urbanized territories it was necessary to fulfill a preliminary stage - produce images, from the raw remotely sensed data, which later were used in Supervised classification. To accomplish this the Composite Bands tool was used in order to create a multiple-band raster dataset, that can be displayed as red, green, blue (RGB) composite (Fig. 2). The purpose of these actions was the creation of the image on which urban areas were prominent. After the testing of various band combinations, acceptable was found - False Color (urban). For imagery from Landsat 5 it was the 7-5-3 combination; for Landsat 8 the combination was 7-6-4, since Landsat 8's data include additional bands, which vary from the bands of the Landsat 5 (USGS 2014a).

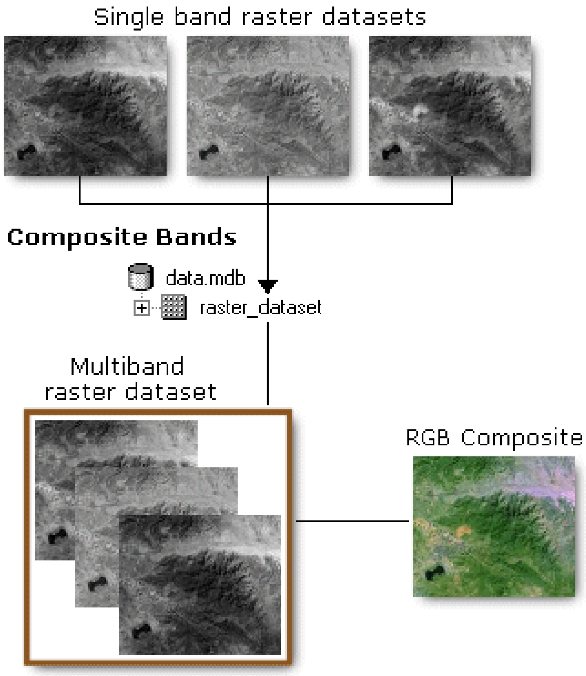


Fig. 2. Composite Bands tool. Source: (ArcGIS 2014)

4.3.2. Supervised classification

After the RGB composite images were created the Supervised classification could be conducted. For this purpose the Image Classification toolbar was used. This is a new tool, which was not presented in the previous versions of the ArcGIS. The process of image classification became much more easier for the users of the software. The creation of the signature file, essential for the classification, can be produced very fast, as well as the collection of the training samples. Besides, now they can be evaluated, by various methods (Histograms, Scatterplots and Statistics), before the classification will take place, to ensure the quality of the results. In addition, after the classification, the derived images can be processed using other Spatial Analyst tools in order to "clean" the imagery - Filtering, Smoothing and Generalizing. As a result of those actions, the series of land use change maps can be created.

4.4. Assessment of the potential flood damage

The potential damage for the area was assessed using the combination of remote sensing and modeling tools. Using satellite imagery and DEM it was possible to define territories, particularly urban areas, which are located in the hazardous floodplains. The application of the modeling program and simulation of the flood event provided us with the information about the territories at the most risk, characteristics of the possible flood, time required for the flood wave to reach particular settlement and other patterns of the flood.

4.4.1. Development of hydrological model

The hydrological model was developed using FLO-2D cellular automata-based model (FLO-2D 2014). This is a free two-dimensional flood routing model, that can simulate various properties of the flood, like channel flow, street flow, etc. The model is on FEMA's (The Federal Emergency Management Agency, USA) list of approved hydraulic models. The complexity of the final model depends basically on the purpose of the model itself and the availability of the data. There are a great number of details that can be added to the model: rainfall, levees, buildings, bridges, sediment transport, groundwater, dam break, etc. (O'Brien 2009a). But for the simplest simulation only two basic datasets are required: topographic data and water flow hydrograph. Infiltration, manning's n-values, outflow, as well as other parameters and elements can be edited for more complex simulation. Some of the relatively small details, like streets and buildings, may not be indicated in cases when the studied area is too big. FLO-2D model proved to be effective and reliable in flood modeling (Dottori and Todini 2010). E-mail consultations with the developers of this program helped to create credible hydrological model, which was used to run a number of simulations of flood events.

Datasets, required for the creation of the model, were obtained, using GIS, from DEM, created land cover maps, national statistics reports and other sources.

4.4.2. Scenarios development

Information for the development of the scenarios was acquired through data collection, archival research, journal articles, etc. Scenarios were formulated based on the statistics of the previous floods, calculation of the discharge rate in cases of high-water years of different probabilities (Rosvodresursy 2013). The simulations of the water overflow during flooding events were conducted using FLO-2D model, and then the results were processed using Mapper program and ArcGIS. Created maps represent the area, affected in the case of flood event, and some patterns of the flood. The validation of the inundation area, acquired in the process of the flood simulation, was conducted using the satellite imagery of the resent flood events and the functional zoning schemes of the Rostov oblast (marking of the catastrophic flood).

5. Lower Don River

In this chapter the study area will be defined and its physical characteristics as well as the description of the hydrological patterns and the population dynamics will be provided. In the history of the Lower Don development two main periods can be defined - before the construction of the Tsimlyansk Reservoir and after. The influence of that man-made "sea" on the downstream territories cannot be overestimated.

5.1. Physical characteristics

In this part the some relevant characteristics of the area will be discussed - geographical location, climate, description of the floodplain, and the changes that happened after the river flow was regulated.

5.1.1. Geographical location

The Don River is one of the major rivers of the European part of Russia. The River can be divided into three main sections - Upper Don, Middle Don and Lower Don. The Lower Don ranges from the town Kalach-on-the-Don to the mouth of the river (Rosvodresursy 2013). The current research concentrates on the part of the Lower Don, from the Tsimlyansk Dam to the Azov sea (Fig. 3). The study area is situated in the alluvial-marine plain which is slightly inclined to the sea-side. Present-day Lower Don river valley has been transformed greatly due to large-scale industrial and residential building, the creation of dams, artificial lakes, canals and roads. Cattle population was reduced since the soviet times, so nowadays some grasslands are not used for mowing.

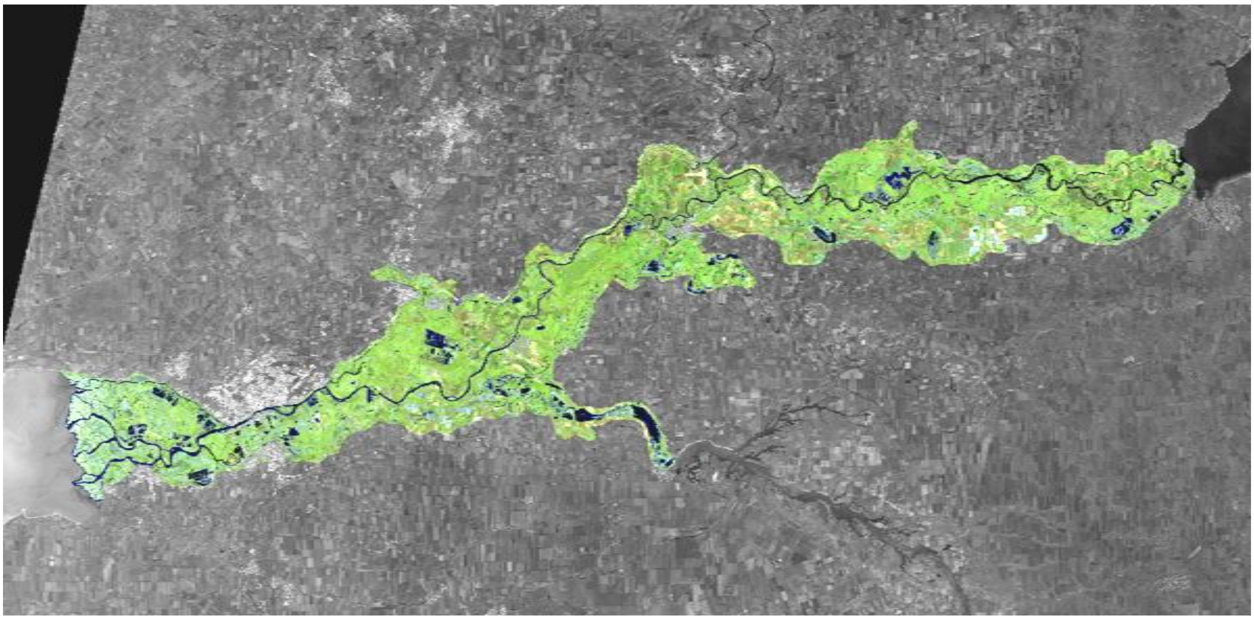


Fig. 3 Study area - the Lower Don River floodplain

Actual relief was formed by the natural floodwater regime. After the construction of the Tsimlyansk Reservoir and the regulation of the flow in 1952, the territory of the floodplain had changed significantly, partially it was converted into agricultural land. Hydrological regime of the floodplain also was changed - some areas became more swamped because of the construction of the transportation embankments (Kazakov 2014). The Lower Don lie within the area of the chernozem soils, so a lot of the territories are ploughed up (Kazakov 2014). The territory is characterized by the temperate climate, the zone of steppes with insufficient humidification. The climate is continental with rather cold winter and hot summer. Average annual precipitation is around - 400-500 millimeters, with minimum in July - 55-65 millimeters (Kazakov 2014).

The fish industry of the region depended greatly on such food fish as sturgeon, beluga sturgeon, stellate sturgeon, herring, vyrezub (kutum), vimba bream and other anadromous and semi-anadromous species. After the Don River was regulated, spawning and feeding conditions for these species worsen significantly, what resulted in the decrease of the fish population and, therefore, the yield (Kazakov 2014).

5.1.2. Lower Don River floodplain

Don River as a navigable waterway with a wide floodplain. Total area of the floodplain from the Tsimlyansk Dam to the river delta is around 284 000 ha (2840 km2). The floodplain is the most extensive near Novocherkassk (20 km) and stanitsa Melikhovskaya (10 km). Before the natural water flow regime of the Don River was altered the floodplain was inundated regularly. After the river flow was regulated, in the 1952, total area of the floodplain decreased significantly (170 000 ha). The floodplain was submerged completely only few times since then (in 1963, 1979, 1981 and 1994), in some years it was inundated partially. During the dry periods between floods, the valuable wetlands on the floodplain are shrinking (Kazakov 2014).

In the lower course, near the Rostov city, the vast delta is situated. The delta is located between Rostov and Bataysk, the total area is 54 800 ha (548 km2). Wetlands cover most of its territory, in the past it was regularly submerged during the high water. Nowadays the coastal part of it is inundated few times a year due to strong west winds. The banks near the delta have been built up by dachas (Kazakov 2014)

5.2. Don River hydrological patterns

The main source for the Don River runoff is the water from the snowmelt (Rosvodresursy 2013). In the present day the volume and the regime of the Lower Don water discharge are determined by the drawdown in the Tsimlyansk Reservoir, water losses on the irrigation, water supply, evaporation from a water mirror (Timofeyeva 2008). The water use for agriculture nowadays is not that significant.

5.2.1. Natural patterns (before 1952)

Average annual runoff of the Don River was around 27,7 km3 (11,8-52,0 km3). In the part of the Lower Don it was characterized by the high spring flood (71,3% of the total runoff) and low water level during the summer-autumn and winter periods (Rosvodresursy

2013). Average annual discharge rate was 840 m3/s (Timofeyeva 2008). As seen in the Fig. 4, it is typical for the Lower Don to quite frequently experiences high-water years and even periods of years.

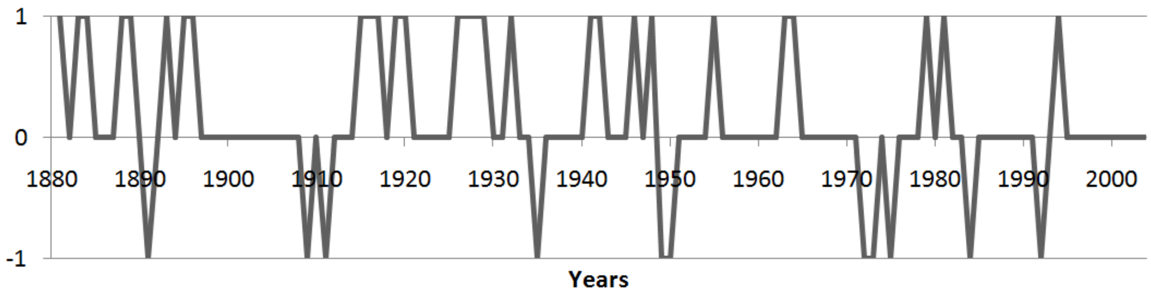


Fig. 4 The frequency of the high-water (>0) and low-water (<0) years, based on the Lower Don River annual flow (1881-2005). Data source: (Rosvodresursy 2013)

5.2.2. Impacts of the Tsimlyansk Reservoir construction

In the 1949 the construction of the Tsimlyansk Reservoir has started, in 1952 the filling begun (Zhuk 1957). This reservoir became one of the biggest in Russia (the 11th by its volume - 23,9 km3, and the 5th by its area - 2700 km2) (Yug 2014). The distance between the dam and the river mouth is 323 km. (Gidrotekhnologija 2014). The main purpose of the construction of the reservoir was the provision of water for navigation through Lenin Volga-Don Shipping Canal and downstream. As a consequence of the reservoir creation, not only the waterways between Baltic, White, Azov and Black Seas shorten, but the water flow downstream altered dramatically, the number of flood events decreased significantly (Zhuk 1957). The creation of the reservoir resulted in the smoothing of the Don River runoff through the year (Rosvodresursy 2013).

Before the construction of the Tsimlyansk Dam spring runoff consisted of 71,3% of the total runoff, after 1952 it decreased to 32,3% (Rosvodresursy 2013). After the construction of the reservoir average annual discharge rate reduced from 840 m3/s to 690 m3/s (Timofeyeva 2008). The water discharge during the year become more smooth, while during the spring months (March-May) the discharge had reduced for more than two times (now the average discharge is 563 m3/s); and during the summer-autumn period and the winter months had increased (438 m3/s and 316 m3/s accordingly) (Rosvodresursy 2013). The irretrievable loss of the runoff due to the construction of the Reservoir and the water withdraw from Seversky Donets River is 6,3 km3, average annual retained runoff of the Don River is 21,4 km3 (Rosvodresursy 2013). It was noticed that for the observed period the average discharge rate of the Don River decreased a little bit due to the climate changes in the watershed (Lurie and Panov 1999). Now the water availability on the Lower Don is assess as tight.

It can be easily seen that the years when the floodplain was inundated (1963, 1979, 1981, 1994) often concur with the periods when the water level in reservoir were not fully in control, when the amount of water in the reservoir significantly exceed the active (live) storage. Since the water flow of the Lower Don substantially depends on the Reservoir, the considerable water discharge in the mentioned years resulted in the floods downstream. The active storage of the Tsimlyansk Reservoir (36 m) was surpassed in 1953, 1955-58, 1963-64, 1968, 1971, 1979, 1981, 1994. In total, the level of 35,5 m was exceeded 27 times in the period from 1953 to 2012 (Rosvodresursy 2013).

The presence of the Reservoir play important role in the years when the spring high water threaten to flood the downstream territories. Reservoir can decrease and smooth the discharge, but only to a certain extent (Table 3). The most severe flood event for the enduring observations (approximately since 1876-78) happened in 1917, when the maximum river discharge reached 14436 m3/s (23.04.1917) (Rosvodresursy 2013).

Table 3 The impact of the Tsimlyansk Reservoir on the water discharge in the downstream, during the high water in the abounding years. Data source: (Rosvodresursy 2013)

Year	Maximum water discharge, 1000 m3/s		Decrease in maximum water discharge	
	inflow	downstream	1000 m3/s	%
1978	3,11	1,10	2,01	64,69
1979	6,00	2,27	3,73	62,17
1981	4,13	2,39	1,74	42,13
1986	4,60	1,48	3,12	67,83
1994	5,35	3,33	2.02	37,76

Nowadays the main document that regulate the work of the Tsimlyansk Reservoir is the "Fundamentals of the Terms of use of Tsimlyansk Reservoir water resources on the Don River", which is out of date and must be revised (Rosvodresursy 2013).

5.3. Dynamics of the population

For centuries the nomadic tribes prevailed in the region, at that time the population size and density were not significant. Since the XI century Slavic settlements started occurring in the area, mainly near the rivers, which provided the great opportunity for the trade (Dulimov and Tsechoev 2001). Starting from XV century the growth of the population increased due to fugitive peasants from Central Russia and Volga region, they were called Cossacks. While the number of people and settlements were growing, total population of the Rostov oblast didn't exceeded 1 million in the end of the XIX century (Martynova and Aleksenko 2009). Statistical data for the beginning of the XX is absent, but still it can be seen that in few decades the population of the region increased in times - in 1939 it was 2,9 million people. In 1979 the population reached 4 million, in 2000 - 4,4 million, and after that the slight enduring decrease of the population started (ROSSTAT 2003, 2013). The majority of the population in the Rostov oblast lives in urban areas (67,7% in 2012) (ROSSTAT 2013).

6. Development of the Lower Don River floodplain (RQ1)

In the following chapter the main steps to answer the research question will be presented. First of all the application of the remote sensing for studying situation in the region will be discussed. Then the derived results will be introduced. The future development plans of the biggest settlement (Rostov-on-Don) will be represented at the end.

6.1. Exploration of the situation using Remote Sensing

The application of the remote sensing techniques together with the GIS and simple simulation were used for the delineation and analysis of the study area and the following extraction of the urban areas from the satellite imagery.

6.1.1. Defining floodplain

The first step in studying floodplain urbanization is the identification of the area of interest. First of all it is necessary to define the boundaries of the Lower Don river floodplain. Since the maps of the floodplains for the whole study area were not discovered, we had to determine the limits of the flood-prone areas using other ways.

The Digital Elevation Model (DEM), with the resolution of 90 m, was obtained from the ASTER GDEM (ASTER 2014). Some defects and imperfections, like improbable sinks and hollows, were corrected using ArcGIS tools - Fill and Extract (Spatial Analyst). As the Lower Don River spreads to a length of more than 220 km in the direct line from the Tsimlyansk Dam to the Azov Sea, and the elevation can vary significantly within this distance, the capabilities of the ArcGIS were not enough to limit the floodplain acceptably accurate (Fig. 5).

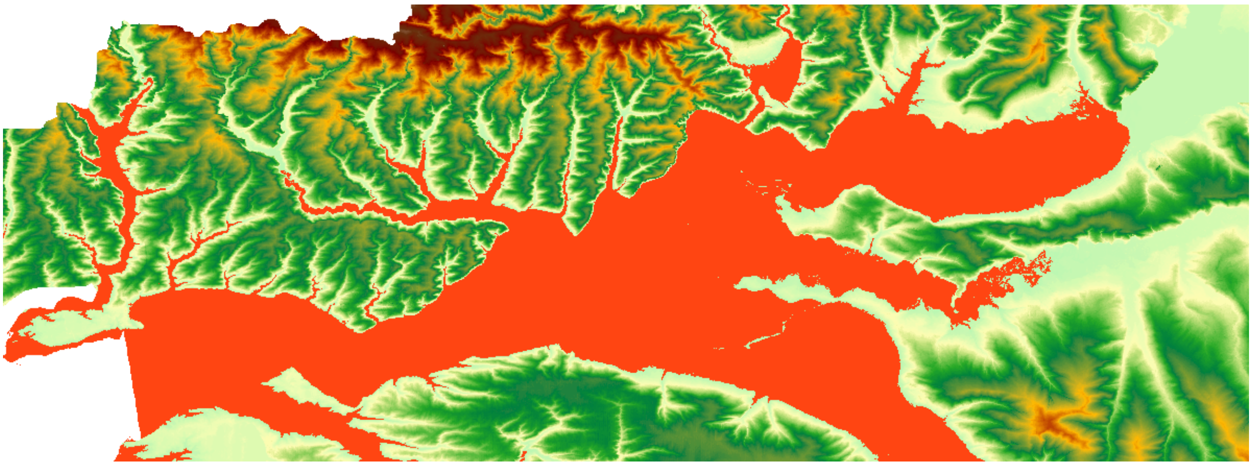


Fig. 5 An attempt to define the Lower Don floodplain using ArcGIS Raster Calculator tool (Spatial Analyst) (elevation < 25 m)

Therefore it was decided to use FLO-2D flood routing model to extract the floodplain. After the amendment, the elevation data was imported into the model. The simple simulation was developed, using discharge data of the severe 1917 flood (Rosvodresursy 2013). Generated shapefile of the inundated area with geographic references then was imported into the ArcGIS (Fig. 6). Finally we acquired preliminary boundaries of the floodplain. More details about the data processing and flood simulation using FLO-2D will be provided in the next chapter (7. Delineation of the flood-prone areas (RQ2)).

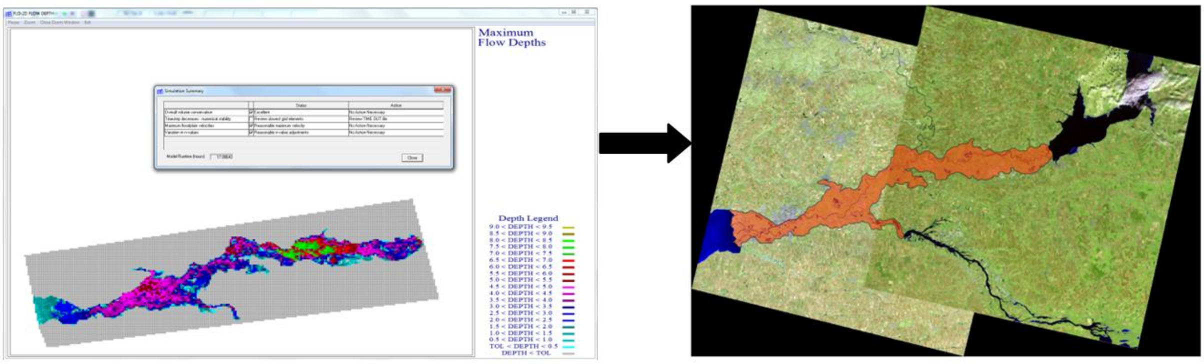


Fig. 6 Defining the floodplain: on the left - simple flood simulation in the FLO-2D; on the right - import of the results into the ArcGIS

6.1.2. Supervised classification

To explore the scale of the floodplain urbanization, the Remote Sensing techniques were used. For this purpose the satellite imagery for 1985 and 2013 years were obtained. The resolution of the selected images was 30m. Primary it was intended to study three periods -

1985, 1997 and 2013, in order to explore the changes in the urban areas more gradually. Unfortunately there was no available satellite images for the intermediate period of 1997-1998 of the adequate quality, the ones which were acquired were not adjoining each other, so they couldn't be used (Fig. 7).

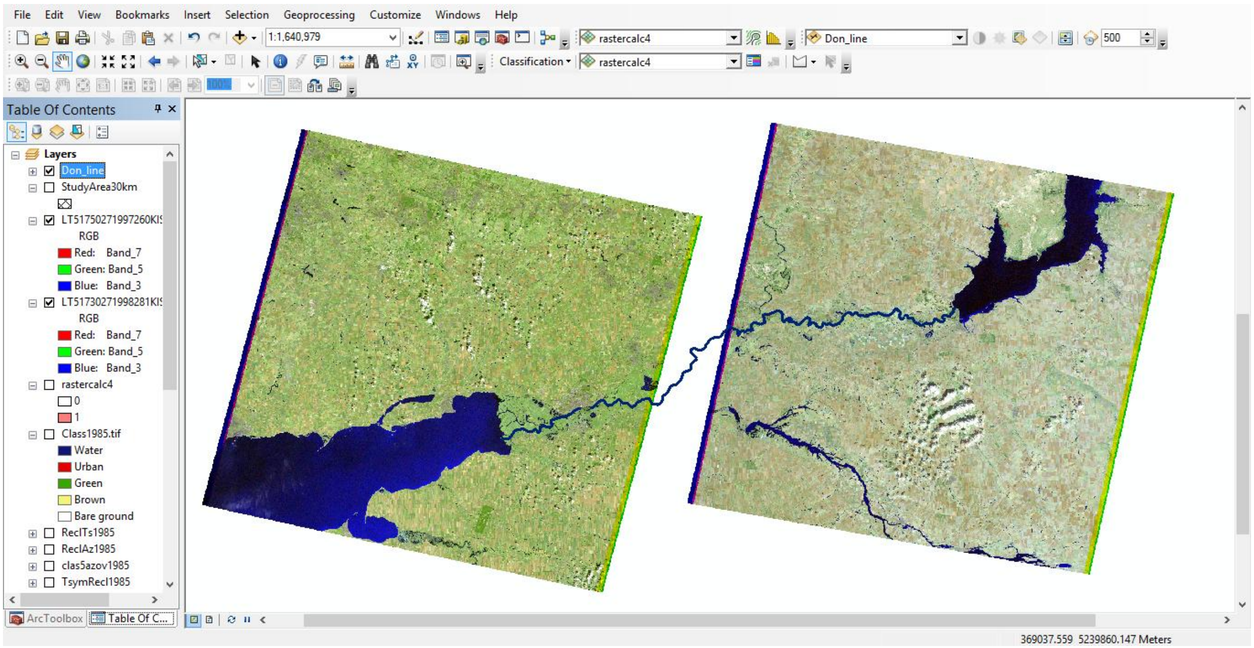


Fig. 7 Satellite images for 1997-1998

When it was decided which images can be used, they were imported into ArcGIS 10 one after another. The study area fits into two satellite images. For each of them, bands were composed to a single raster dataset (Data Management tool). The False Color (Urban) band combination was used in order to receive the most distinct image of urban areas. For Landsat 5 it was 7-5-3 combination; for Landsat 8 - 7-6-4 (USGS 2014a). It was necessary to move a little bit one of the rasters for 1985 using Shift tool (Data Management) so it will align with another image. Probably error in the position of the image appeared at some stage of the image processing on the USGS site.

Before the implementation of the supervised classification, it is preferable to reduce the area which is going to be processed. For our purposes we do not need the whole satellite image, only the floodplain and bordering areas. The relevant territory was limited by the rectangle with the width of approximately 72 km and length of 229 km. Using Spatial Analyst tools required areas were cropped from satellite images (Extract by Mask).

ArcGIS has a tool that can combine two extracted parts of the images into one (Mosaic to New Raster). In this case the process of the classification can be significantly accelerated, since there will be not four images, which needed to be processed, but only two. However since the images were made not at the same time (1985-05-29; 1985-06-05; 2013-10-24; 2013-11-02), the colors on them can slightly vary, due to associated reasons, like different cloudiness and illumination. This minor distinctions in the shades can influence the results of the classification considerably. So for the most accurate and reliable result of the supervised classification, it is better to process each part separately. Then the results of the classification can be merged into one image.

Before the classification is carried out, training samples must be created. The new feature of the ArcGIS 10 (Image Classification toolbar) provide the opportunity to evaluate them using scatterplots, as well as histograms and statistics (Fig. 8). After the validation of the samples, signature file is created and the Supervised Classification can be conducted. For the most accurate result the whole process was repeated few times in order to correct the samples, since some small divergent areas can be left unnoticed in the beginning.

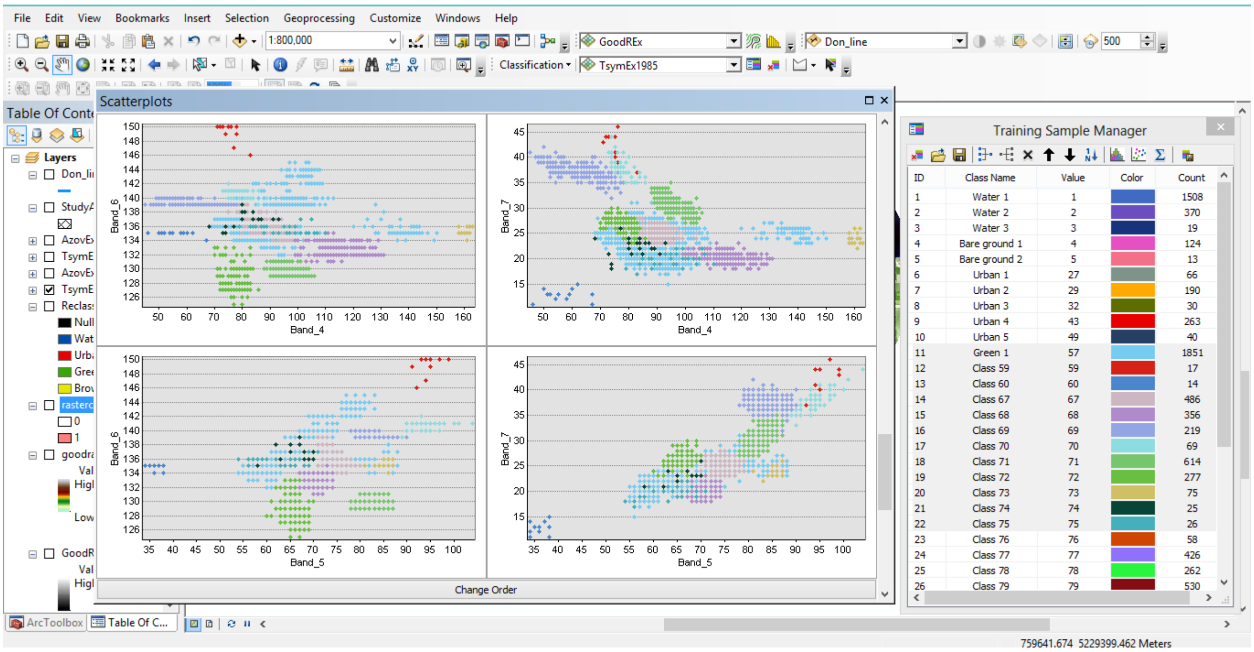


Fig. 8 Evaluation of the training samples using scatterplots

After the classification was carried out for all four images, they were united in compliance with the year. At this step we had in our possession two land cover maps, for 1985 and 2013, but before they can be analyzed and we can acquire some statistical data from them, one last thing must be done. Post-classification processing is an essential part of the map creation in ArcGIS, since there always will be some noise and small defects left, so the images must be cleaned up. The Majority Filter tool (Spatial Analyst) was used in order to accomplish that. It was decided not to used any other tools, like smoothing (Boundary Clean), or generalizing (Region Group, Set Null and Nibble tools), because after the implementation of these features minor urban areas, like small settlements or free-standing houses, disappear.

So after all steps of the processing were conducted, two land cover maps were created (Fig. 9). The blue color represents the water, red - urban areas, green - green vegetation, yellow - brown vegetation, white - bare ground. Since the Lower Don region is almost totally agricultural, as it was in 1985 and in 2013, the significant distinction between two maps is explained by the different seasons when the satellite images were made - for 1985 it was May-June; for 2013 it was October-November. But as we are interested in urbanization, not vegetation, our attention must be concentrated on the most important class - urban areas, which are clearly distinguished in the maps.

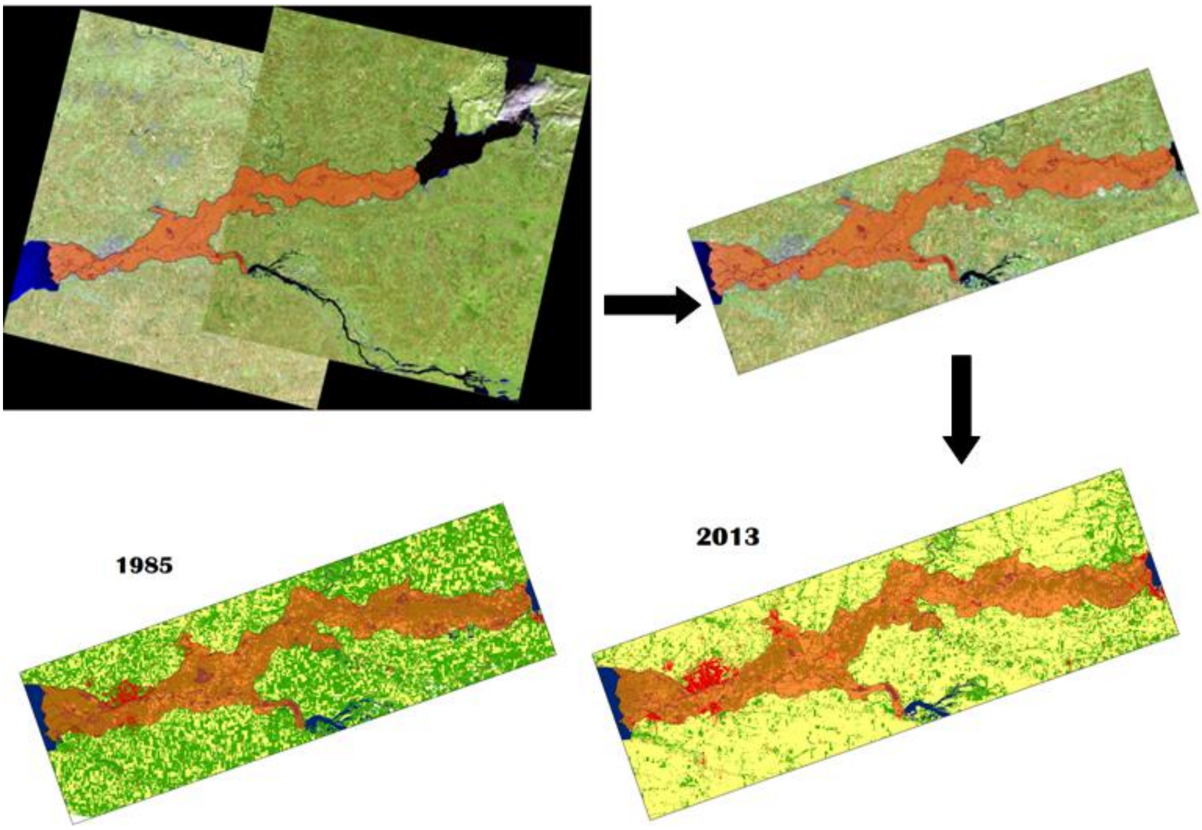


Fig. 9 The steps of the land cover maps creation

6.2. Results of the classification

Before the results of the flood simulation were obtained, actual floodplain was defined roughly. So first of all the analysis of the whole classified area was conducted (Fig. 10). Total area is around 16 481 km2. In the table below, territories occupied by three aggregated classes, water, urban areas and other (green, brown vegetation and bare ground), are presented (in km2 and in percentage) (Table 4). The last class, "other", is quite extensive, since the correlation between its components depends greatly on the season, and in current research we are not interested in this particular values.

Table 4 Statistics for the land cover maps

	1985		2013		Difference	
	km2	%	km2	%	km2	%
Urban	369	2,24	540	3,28	+171	+1,04
Water	934	5,67	597	3,62	-337	-2,05
Other	15 178	92,09	15 344	93,1	+166	+1,01

It can be easily noticed that the most significant changes experienced the area covered by water, since 1985 it territory reduced for more than 2%. Mainly is was replaced by "other" class. The most probable explanation is the presence of the fish hatchery in the area, as well as some shrinkage of the Vesyolovskoye Reservoir. First fish nurseries were created in the Lower Don area in the 50th, after the construction of the Tsimlyansk Reservoir, as the compensation measures for fish population - Rogozhkinsky (1956) and Aksai-Don (1958) fish hatcheries (Tarasyuk 1964). We can assume, that the total area covered by water declined, due to the different seasons, when the satellite images were made, so the number of active ponds of the fish hatcheries vary. The other assumption is that the number of ponds in the area has reduced since 1985.

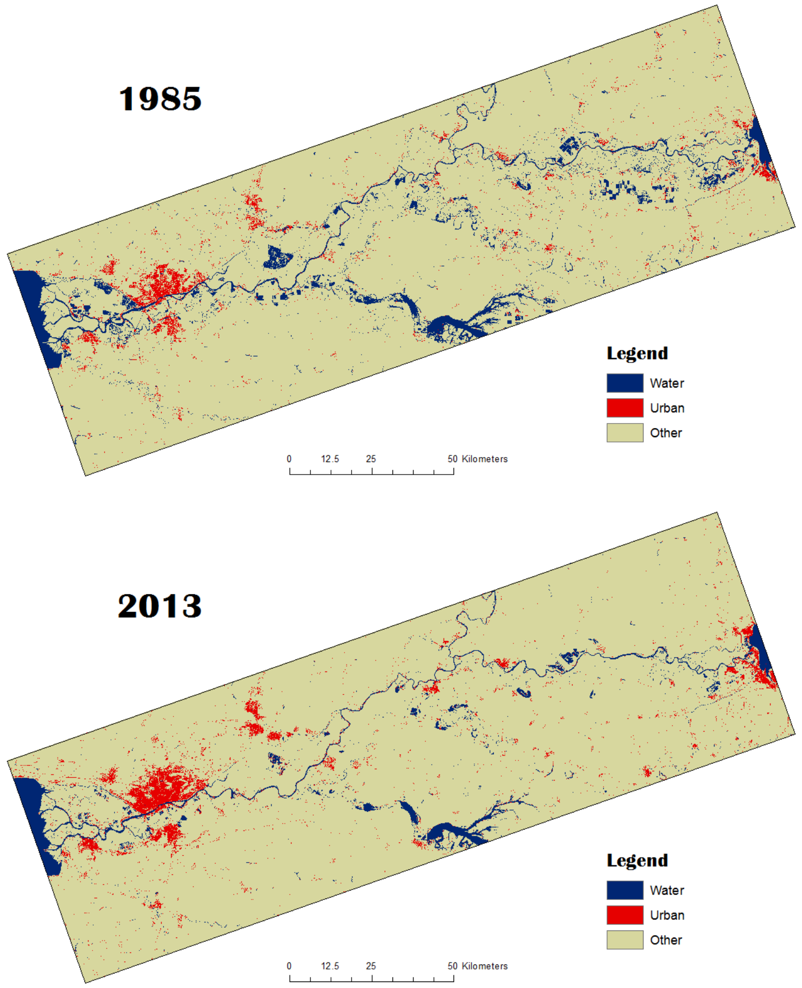


Fig. 10 Simplified urbanization maps

Even though the total population of the Rostov oblast in the period between 1989 (Soviet Census) and 2013 decreased (from 4 308 654 to 4 245 532) (ROSSTAT 2014; Weekly 2014), the population within the study area, especially in the big and economically important cities, had grown. The patterns of the urbanization can be clearly seen from the joining of two maps (Fig. 11).

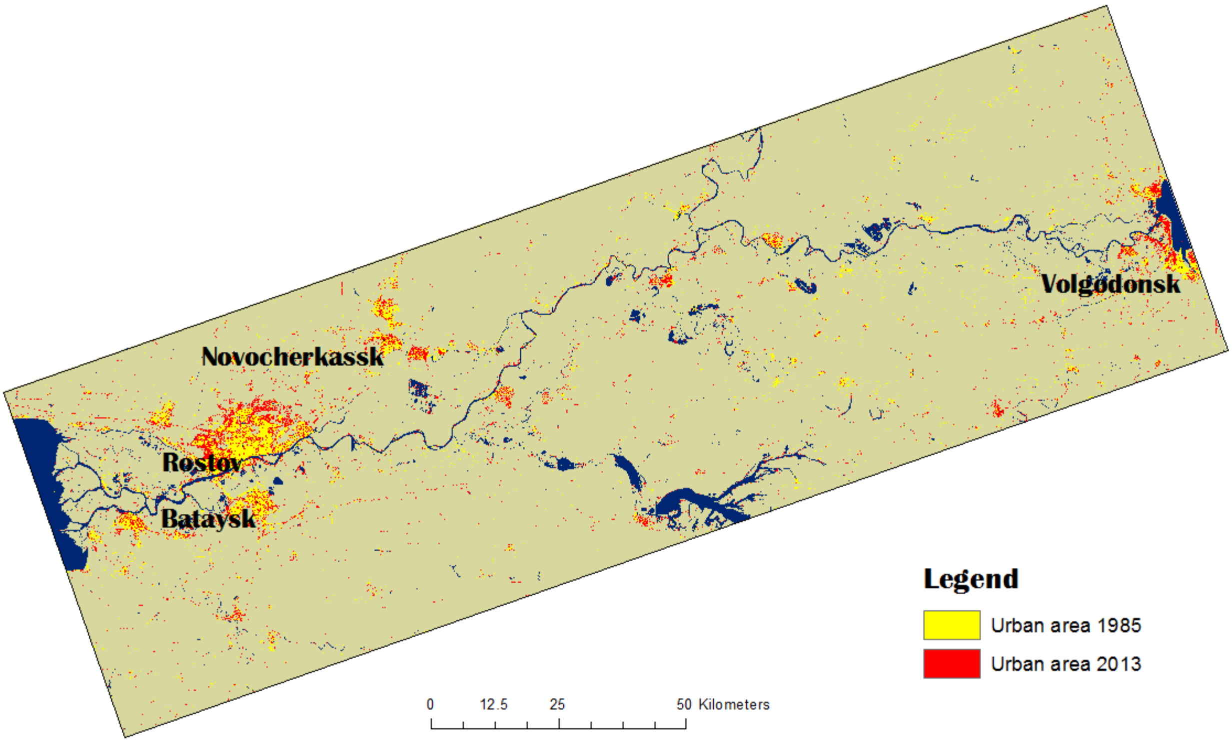


Fig. 11 Urbanization 1985-2013

Build up area of almost all relatively big settlements increased - Rostov-on-Don, Aksay, Bataysk, Azov, Novocherkassk, Semikarakorsk, Konstantinovsk, Tsimlyansk and Volgodonsk. Still some of the very same settlements, whose areas are enlarging, are constantly loosing population (Table 5). The situation with small villages and communities are different, as some of them became bigger, some didn't change their size and some even shrank slightly.

Table 5 Population of the big settlements of the region. Data source: (ROSSTAT 2014; Weekly 2014)

	1989	2014
Rostov-on-Don	1 019 305	1 109 800
Aksay	33 389	42 742
Bataysk	91 930	117 400
Azov	80 297	82 500
Novocherkassk	187 973	173 400
Semikarakorsk	22 704	23 110
Konstantinovsk	18 392	17 771
Tsimlyansk	15 343	14 778
Volgodonsk	175 593	170 100

6.3. Development plans of Rostov-on-Don

In the 2007 the "Rostov-on-Don Master Plan" was adopted. This document regulates the development of the biggest city in the region, for the period till 2025 (Yudenich 2007). City authorities plan to expand the city, which nowadays is mainly situated on the high right bank of the Don river, to the low left bank (Fig. 12). This development plans are as well supported by the preparations for the 2018 FIFA World Cup, which is going to take place in Russia. The preliminary work for the Rostov-on-Don Stadium (Levberdon Arena) construction had already started. Since the selected area is situated on the floodplain and the flood threat is recognized by the authority, the ground level is going to be raised by 5-6 m. Generally, this flood-prone area is going to be converted into the biggest recreation area in the country, with vast trading zones, stadium, water park, racetrack, etc. In the 2008 the simulation of the 100-flood and the Tsimlyansk Dam break were conducted by the Aquarius Research and Production enterprise, and this area was consider to be affected by the flood, the flow depth might reach 5,5 m in the area near the stadium (Aquarius 2008). The floodplain converges near the Rostov city, which can cause high flow depth and velocities in the submerged areas. Still, huge development projects are planned and implemented on the left bank. On the opposite side from the Rostov city, on the left bank, Bataysk town is situated, but on the high and safer territories, outside the floodplain.

Fig. 12 Rostov-on-Don left-bank and Zelyonyi island development areas (yellow hachures). Based on the (Yudenich 2007)

7. Delineation of the flood-prone areas (RQ2)

The acquisition of the inundation area's limits and the assessment of the flood strength are described in this chapter. The development of the flood routing model, scenarios formulation and verification of the derived results are presented in the first part of the chapter. In the second part the results of the simulations are described.

7.1. FLO-2D model

In order to define the potentially threatened areas it was decided to use the flood routing FLO-2D model. This model is available online and is free (http://www.flo-2d.com/).

7.1.1. Basic data input

All data, which is going to be inserted in a model must have the same coordinate system. In our particular case the Transverse Mercator projection was used (Projected Coordinate System: WGS_1984_UTM_Zone_37N). The data in other coordinate systems were projected in the ArcGIS.

The main required data for the model is the digital terrain model (DTM) data. The FLo-2D can use LiDAR data, but DEM with lower resolution also suits. In this research the ASTER DEM with the 90m resolution was used. The raster dataset was converted to point shapefile using ArcGIS, so that it can be introduced into the model (O'Brien 2009a). The satellite imagery of the study area was imported into the FLO-2D program in order to locate some features which are important for the flood simulation, like the river channel, levees, coastline, settlements.

When DTM data and image are inserted in the model, the next step is to define the project area. But before that it is necessary to select grid element size and create the grid. This parameter is extremely important since the particularity as well as the speed of the simulation depends essentially on the size of the grid cells (O'Brien 2009a). The size of the elements will determine the number of elements, depending on the project area. Since our study area occupy around 16481 km2, if the size of the cells will be too small, there will be enormous number of grid elements. Taking into account the available computer specifications and the provided recommendations (O’Brien 2010), in this particular case, when the simulated flood duration is more than 10 days, the selected grid element size was 500m x 500m. The number of grid cells within the project area were more than 60000. If the cell size were significantly smaller, the number of grid elements were too big, and the simulation runs for unfeasible long time. The small details in this instance are lost, but the inundated area still can be delineated quite accurately. The grid element elevations were interpolated and assigned from the DTM points.

The Manning's Roughness Coefficients (n values) were assigned to each grid cell. The shapefile of the land cover, derived from the satellite imagery supervised classification, was imported into the program. Manning's n values were indicated for each type of the land cover (Table 6). For water, cultivated land (green and brown vegetation) and bare ground the coefficients were acquired from (Chow 1959), but it was harder to assign the value for the urbanized areas. In urban areas roughness coefficients can vary from 0,08 to 20 (Syme 2008). Since the particularly of the our simulation does not allow to add such small features as buildings, the coefficient 0,3 was selected to define the build up areas as a whole. This particular value was chosen based of the (Syme 2008) research. The global infiltration parameters were determined by the FLO-2D program for the whole project area (O’Brien 2009b).

Table 6 Manning's n Values

Land cover type	Manning's n Values
Water (channels)	0,02
Urban	0,3
Cultivated land	0,03
Bare ground	0,025

In the next step the outflow grid elements were selected. Since the borders of the FLO-2D grid are seen as the insuperable barrier for the water flow, it is necessary to define the outflow nodes, which will act as sinks and will not influence the inundated area or water depth around them. In our case the grid cells composing the Azov coastline were defined as outflow grid elements (Fig. 13).

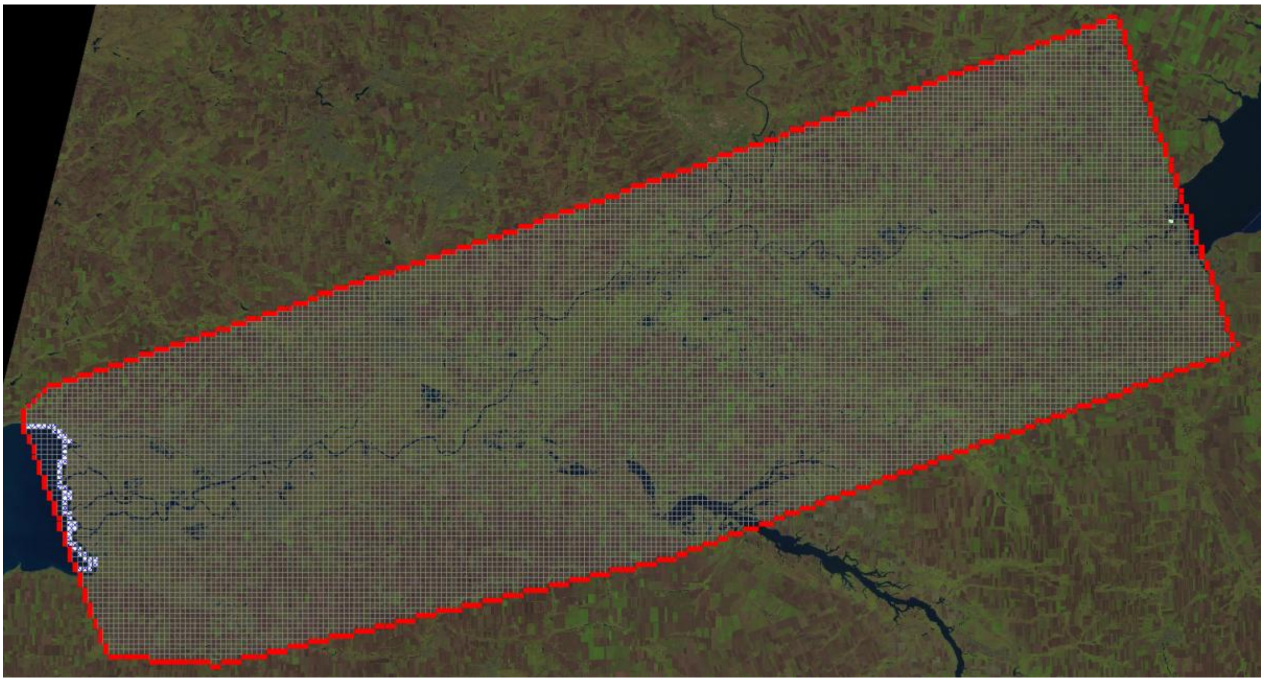


Fig. 13 Step in the FLO-2D model development. Red cells - the boarder of the project area. White cells - outflow grid elements

The last and one of the most important step, before the model can run, is the selection of the inflow grid element. If within the project area a few channels are present, for each of them an inflow elements can be determined. In our case only one element will be assigned, for the Don river, right near the Tsimlyansk Dam. This kind of grid elements must be characterized by the hydrograph, which can be imported from various file formats. The hydrograph can be visualized and edited within the program (Fig. 14). For this particular research a number of hydrographs were selected for the flood events of different probabilities.

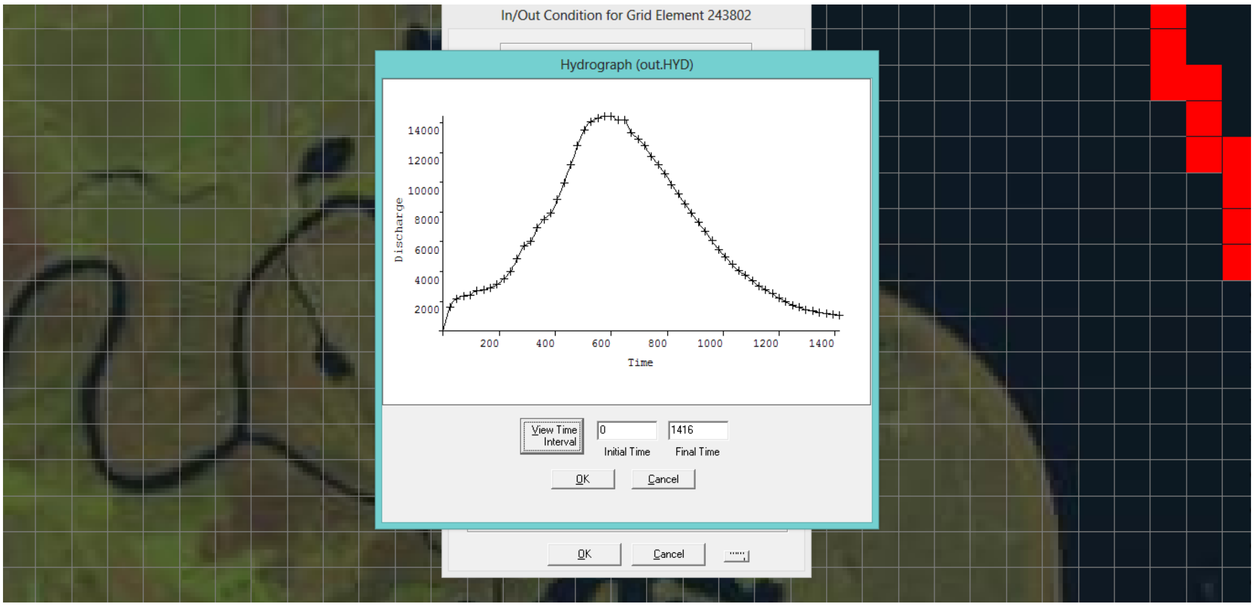


Fig. 14 Hydrograph of the 1917 flood imported into the FLO-2D program

7.1.2. Scenarios development

The main data for the scenarios development was acquired from the "Tsimlyansk Reservoir water resources Regulations" (Rosvodresursy 2013). This document contains the detailed historical data, as well as the rules of Dam management. The hydrograph of the 1917 flood is one of the most interesting and significant dataset, since it was the most severe and abounding in water event of the observed high spring floods. Predicted hydrographs of the spring floods with the 5%, 1%, 0,1% and 0,01% likelihood were calculated based of the historical observed data and generally on the 1917 flood (Table 7) (Rosvodresursy 2013).

Table 7 Characteristics of the calculated hydrographs, for the spring flood period (March-May). Data source: (Rosvodresursy 2013)

	The quantity of flow, million m3	Max water discharge, m3/s
1917 flood	34,2	14 436
20-year flood (5% probability)	26,3	9 863
100-year flood (1% probability)	34,9	13 215
1000-year flood (0,1% probability)	46,7	17 520
10000-year flood (0,01% probability)	58,1	21 532

The hydrographs were constructed by the average daily discharge rates, for the period from the 1st of March to the 30th of May. On the Fig. 15 the calculated hydrographs are present.

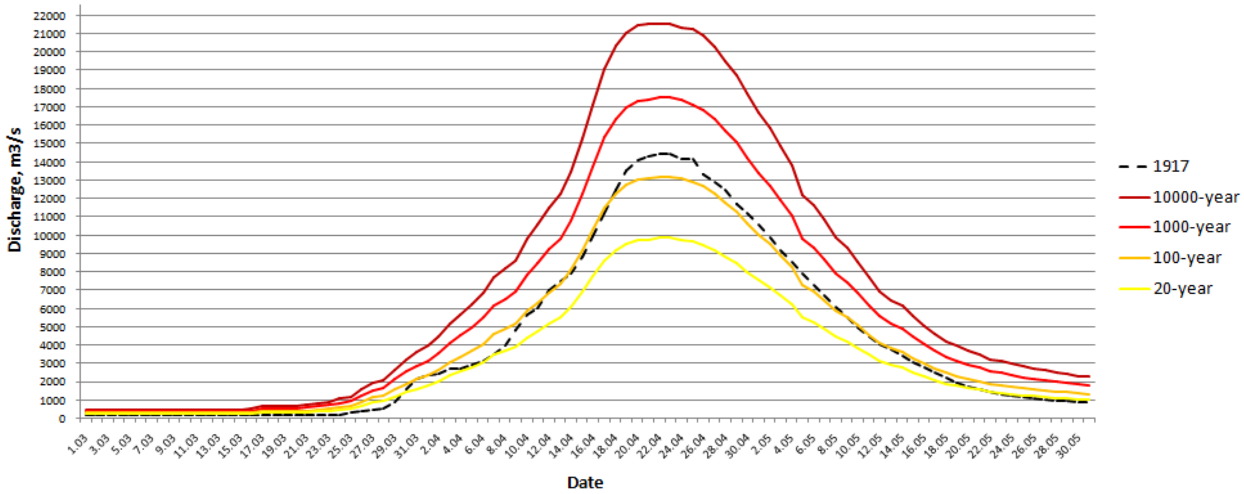


Fig. 15 Calculated hydrographs. Data source: (Rosvodresursy 2013)

At the time of the 1917 flood the Tsimlyansk Reservoir wasn't yet constructed, so the Lower Don floodplain experienced the flood, the water flow, as it is represented on the figure above. But since the Dam is now an inseparable part of the Don river water flow, in case of severe flood event, the water discharge will be altered, so that the hygrograph's peak can be cut off. On the graph below (Fig. 16) the differences between the natural and regulated discharge are represented.

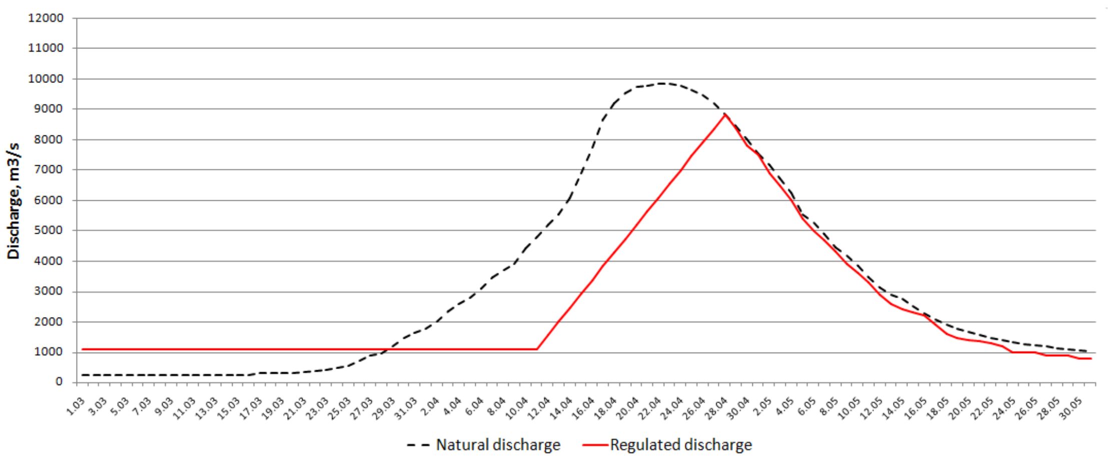


Fig. 16 20-year flood hygrograph. Data source: (Rosvodresursy 2013)

The "Tsimlyansk Reservoir Regulations" (Rosvodresursy 2013) provide three scenarios of water discharge per each calculated flood: without high-water spring flood warning; and two scenarios in case the flood was predicted. The last two have moderate differences. The basic principles of each variant are the constant and continuous increase in water discharge from the moment it is known that the flood is forthcoming. When the hazardous period, the peak, is passed, the discharge is slowly decreasing, more or less replicating the natural hygrograph (Fig. 16). This patterns are clearly represented on the Appendix 1, the hygrographs for 20-year, 100-year and 1000-year floods.

In all scenarios, presented in the "Regulations", safety of the Tsimlyansk Dam were ensured, the water level exceed the surcharge capacity (28,70 km3, water level 38m) only in the 10000-year flood event, in other cases only the reservoir's flood control capacity (22,97 km3, water level 36m) was surpassed (Rosvodresursy 2013). But the downstream territories, the Lower Don River floodplain, have to receive huge amount of water in such situations.

In order to determine the inundated area and to assess the flood risk for the settlements on the Lower Don floodplain, a number of scenarios were developed and interpolated into the FLO-2D model. The repetition of the 1917 flood was simulated. The hygrograph corresponds to the natural discharge rate as there is no Dam, regulating the river. The 20-year, 100-year and 1000-year flood were simulated as well (Fig. 17). The most unlikely scenario - 10000-year flood, was not analyzed. In order to accelerate the FLO-2D model a little bit, not the whole available hygrographs were used in the simulations, but from the beginning of the abrupt increase in the discharge rate. The table with the average daily water discharge for the selected scenarios from the "Regulations" can be found in the Appendices section (Appendix 2).

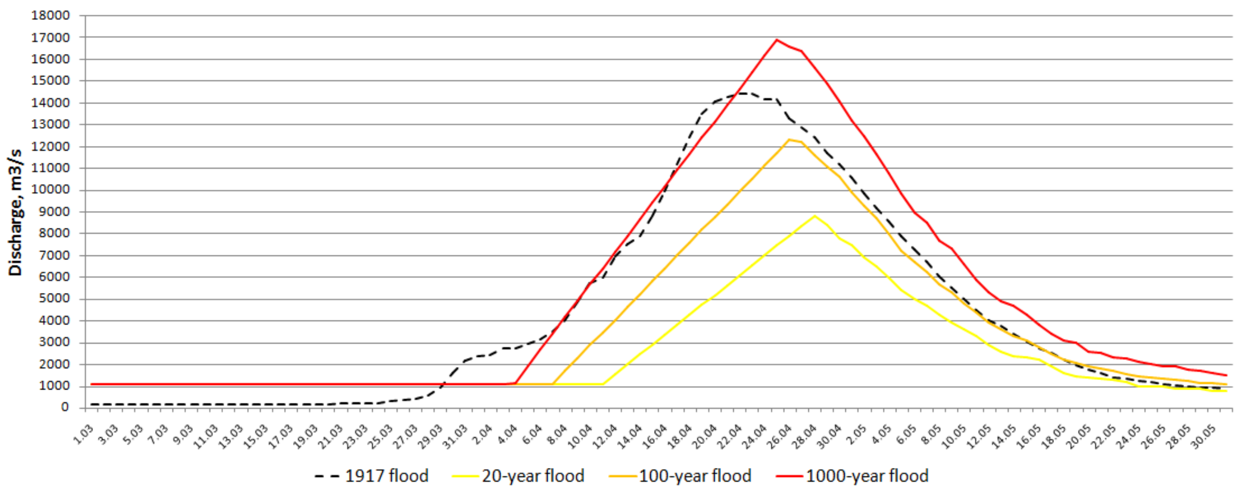


Fig. 17 The hygrographs of the scenarios. Data source: (Rosvodresursy 2013)

Finally, five credible scenarios were selected for the simulation in the FLO-2D flood routing model:

1) repetition of the 1917 flood;
2) 1979 flood - for verification (see 7.1.3. FLO-2D results verification);
3) 20-year flood (5% probability);
4) 100-year flood (1% probability);
5) 1000-year flood (0,1% probability).

7.1.3. FLO-2D results verification

The credibility of the created flood routing model was proved by running the test simulation, based on the real data of the previous flood. The inundation area derived from the FLO-2D program was compared with the available Landsat images of the flood event. Since the launching of the Landsat satellites (1972), there were five observed high-water years in the Lower Don region: 1978; 1979; 1981; 1986; 1994 (Rosvodresursy 2013). Through the USGS online search and order tool, the Landsat 2 and Landsat 3 imagery for the 1978, 1979 and 1981 floods was acquired. The satellite images of other flood events had poor quality or was absent for the desired period. The Appendix 3 presented all available satellite images with sufficiently good quality and relatively small cloud cover.

The images for 1979 were recognized as the best choice for the validation of the flood simulation results, since they had the best quality and were made quite frequently, so the flood progress could be seen clearly. Unfortunately the hydrograph for the 1979 was absent, but the main and the most important data of the water discharge and the flood patterns were available. In the 1979 the maximum inflow into the Tsimlyansk Reservoir was 6000 m3/s. The max water discharge to the downstream was 2270 m3/s. Max discharge was reduced by 62,17% (3730 m3/s) (Rosvodresursy 2013). Taking into considerations the discharge principles mentioned above (Fig. 16), the hydrograph for the 1979 flood was reconstructed, using the available hydrograph calculation methods and long-term statistics as a template. In the Fig. 18 below the generated hydrograph is present.

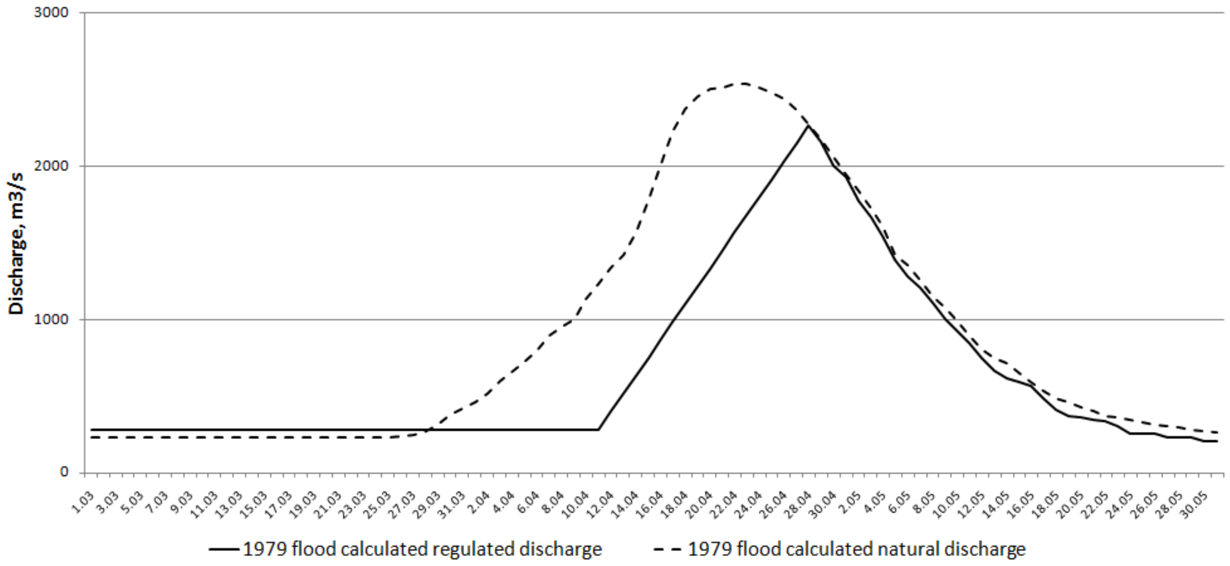


Fig. 18 Calculated hydrograph for the 1979 flood

The developed hydrograph was introduced into the FLO-2D model and the simulation ran. On the Fig. 19 below the acquired area of inundation is present. The shapefile of the flood-prone territories overlay the satellite images of the 1979 flood (30 and 31 May).

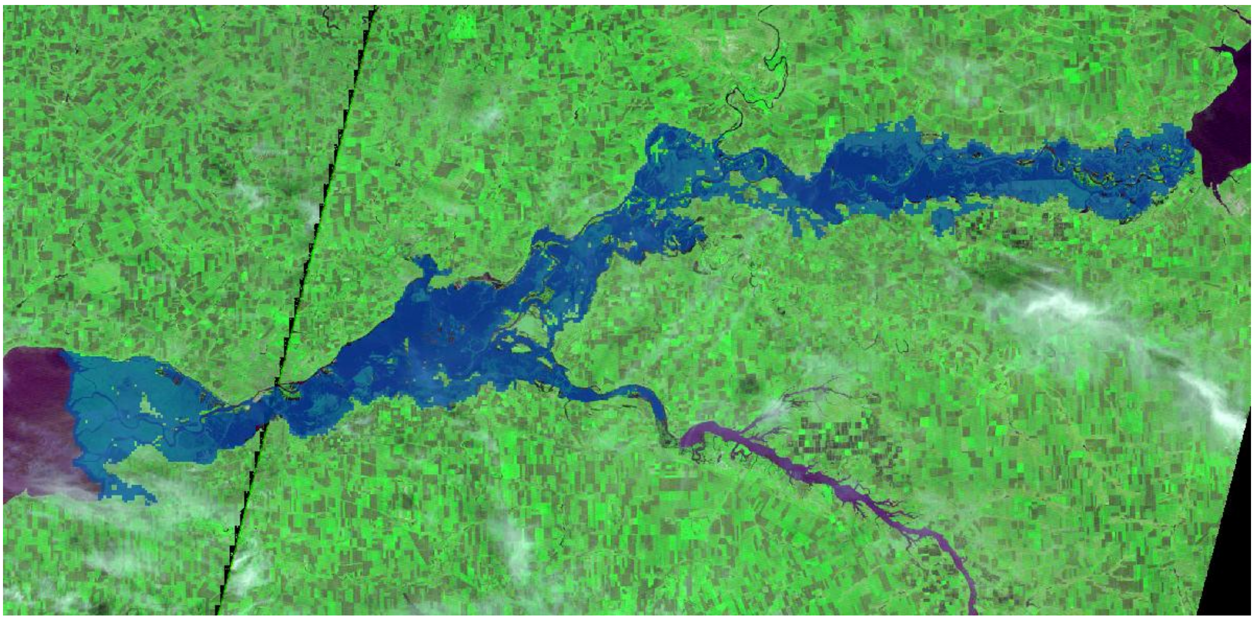


Fig. 19 Verification of the simulation results, 1979 flood

As a whole, the simulation replicates the flood quite precisely, some of the errors can be explained by the chosen size of the grid elements. On the Fig. 20 two enlarged example sections of the floodplain are shown - territory near Novocherkassk on the left and area near the Tsimlyansk Dam on the right, Rjiabichevsky rural settlement in particular. While on the major part of the floodplain the simulation demonstrates quite good results, some inaccuracy was observed within the area of the Rjiabichevsky settlement. The yellow line on the Fig. 20 indicates the territory which was bypassed by the water flow, even though the elevation here correspond with the neighboring submerged areas. After this territory was examined using the high resolution satellite images through the Wikimapia online mapping project (Wikimapia 2014), it was supposed that the levee was protecting the settlement. There was no available data about this levee, and without such basic information as height of this levee, it was impossible to import this feature into the FLO-2D model. But since in this research quite severe flood events are simulated, and according to the Functional zoning scheme of the East Intraregional district of the Rostov oblast" (Rostov 2007b) (see below), it was assumed that the presence of the levee will be insignificant for the simulated cases.

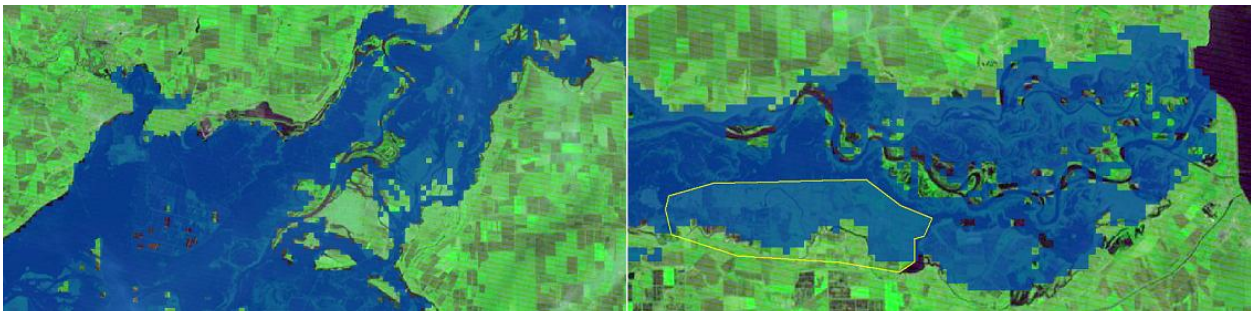


Fig. 20 Verification of the simulation results, example sections. Yellow line on the right - assumed levee, protecting Rjiabichevsky rural settlement

The additional validation of the derived results was conducted using "Functional zoning scheme of the East Intraregional district of the Rostov oblast" (Rostov 2007b). On this scheme the boundaries of the areas, that can be inundated during the catastrophic flood, are outlined. The flood-prone areas, received from the simulations of the floods with small probabilities (1%; 0,1%) were compared with the areas delineated in this scheme, since the term "catastrophic flood" was not specified within the scheme (Fig. 21). It is clearly seen, that the areas almost coincide with each other, while the expansion of the 100-year flood is a little bit smaller. The area of the Rjiabichevsky rural settlement, which was protected by the levee on the figure above (Fig. 20), falls within the hazardous area, according to the Functional zoning scheme. Unfortunately the inundated areas were delineated only for the east part of the Lower Don floodplain. On the scheme of the South-West part of the Rostov oblast the boundaries of the potentially threatened area are absent (Rostov 2007b).

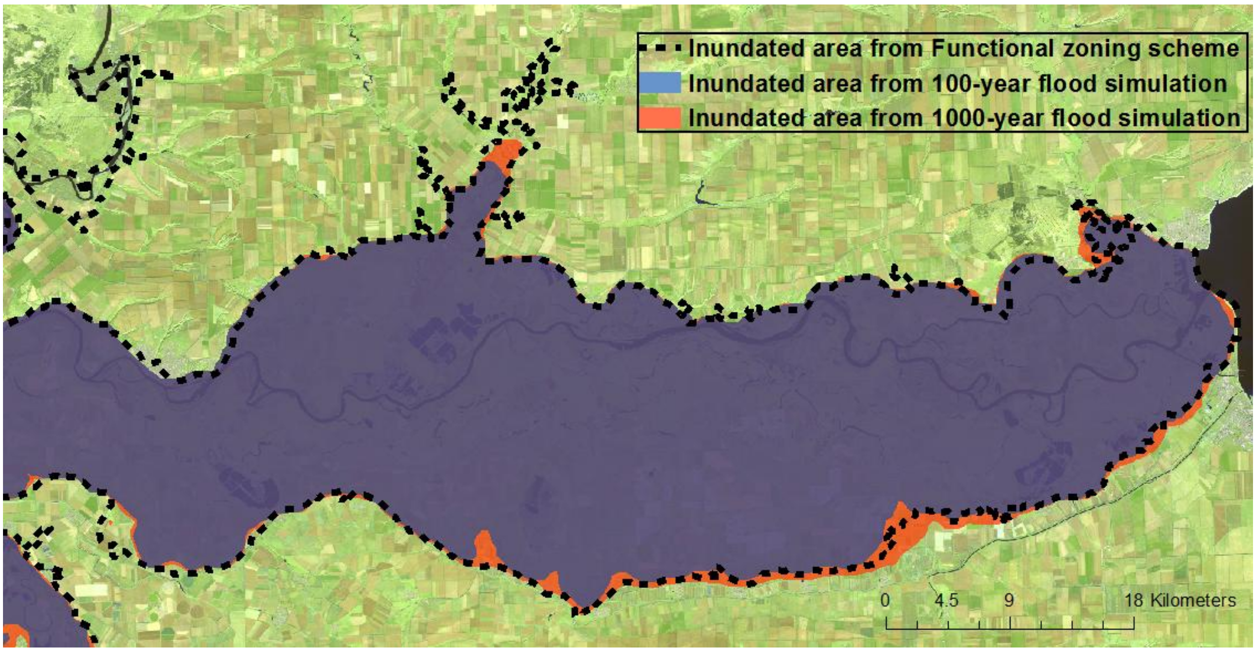


Fig. 21 Verification of the simulation results, catastrophic floods (100-year and 1000-year floods)

7.2. Results of the flood simulations

In the next section the acquired results of the flood simulations are introduced. In the first part the areas of inundation for five selected scenarios are presented. The second part consists the flood intensity maps of the threatened territories.

7.2.1. Inundation area

1979 flood

The simulation of the 1979 flood was the most smooth and nonhazardous among others. The water flow depth at a considerable part of the floodplain didn't exceed 1m. Maximum water discharge - 2270 m3/s (Rosvodresursy 2013). The total submerged area is around 3055,75 km2 (Fig. 22).

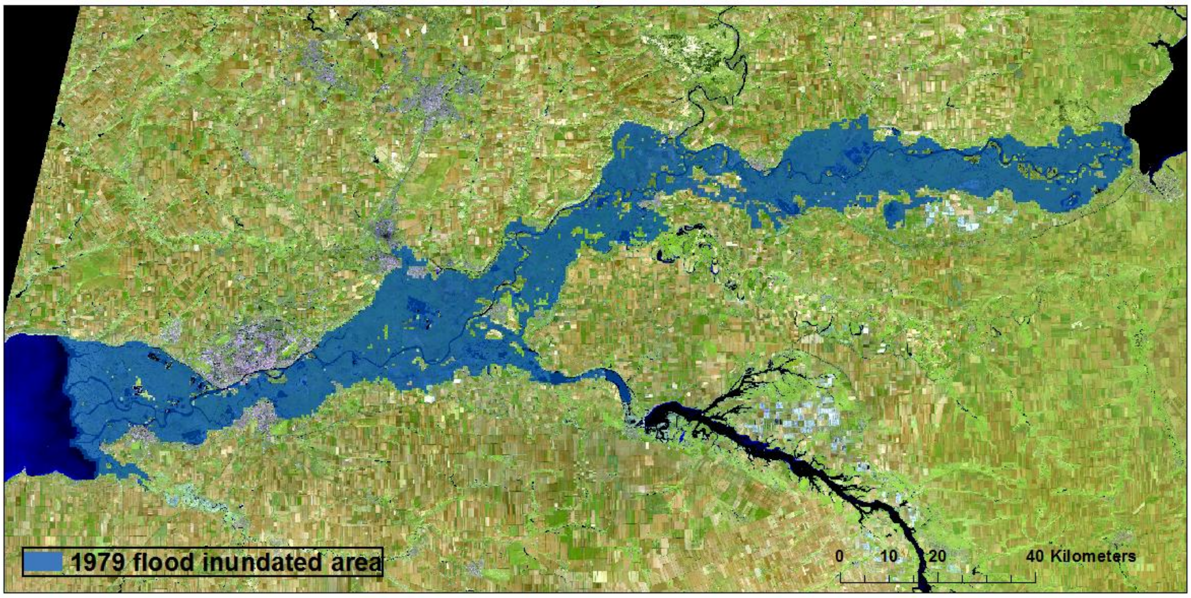


Fig. 22 Results of the 1979 flood simulation

20-year flood

This flood, with the probability of 5%, has the smoothest hydrograph among the three calculated scenarios, maximum water discharge reach 8818 m3/s (Rosvodresursy 2013). Total inundated area reached 4082 km2.

1917 flood

It can be noticed that the natural discharge for the 100-year flood in many respects replicate the hydrograph of the 1917 flood (Fig. 15). The simulation of these two scenarios can provide the information about the differences of the impact of the diverse types of discharge on the downstream territories - natural and regulated. For this flood the recorded maximum water discharge was 14436 m3/s (Rosvodresursy 2013). Total inundated area - 4736,75 km2 (Fig. 23).

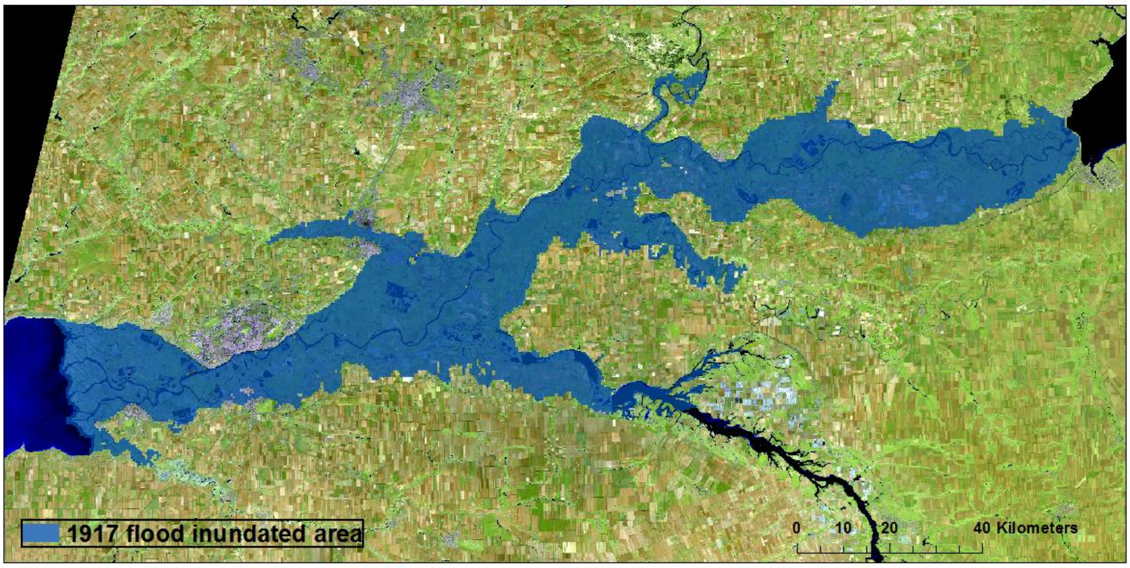


Fig. 23 Results of the 1917 flood simulation

100-year flood

The calculated maximum water discharge for this scenario was 12310 m3/s (Rosvodresursy 2013). Total flooded area - 4488,25 km2 (Fig. 24). So the difference in the submerged territories among the two simulations is 248,5 km2 (5,53% of the total inundated area). This dissimilarity provide the evidences of the flood impact on the downstream territories mitigation due to the regulation role of the Dam and the flood peak cutting off. More significant distinctions will be presented in the next part of the chapter - 7.2.2. Flood intensity.

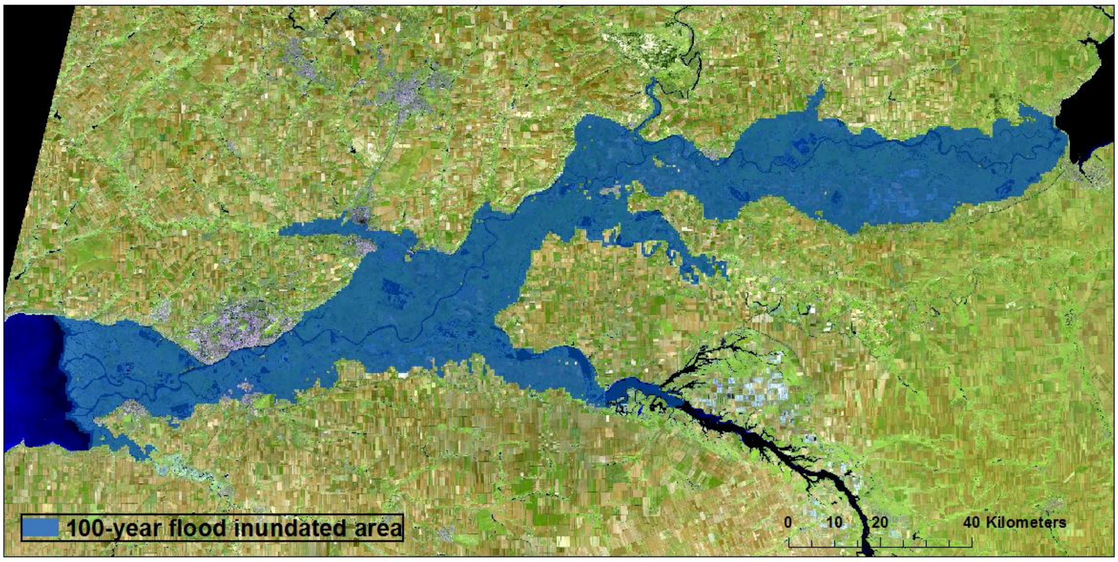


Fig. 24 Results of the 100-year flood simulation

1000-year flood

This the most severe scenario has the probability of the 0,1%. The calculated maximum water discharge reached 16915 m3/s (Rosvodresursy 2013). Total submerged area - 4804 km2. In area extent the impact of this flood can be compared with the 1917 flood.

The inundation areas for all scenarios can be found in the Appendices section (Appendix 4).

7.2.2. Flood intensity

Flood hazard maps were created using Mapper post-processing program, which is provided together with the FLO-2D model. The approach of this program follows European standards and is based on the flood intensity and flood frequency (probability). The flood intensity was selected as the main factor defining flood hazardous. The flood intensity is determined by the maximum flow depth and max velocity (O'Brien 2010). As a result, three flood intensity zones (high, medium, low) can be distinguished. For our project the following intensity level thresholds were chosen, based on the application and acceptability for all five flood scenarios (Table 8):

Table 8 Definition of flood intensity

Flood event intensity	Maximum depth (h), m	Logical operation	Product of max velocity (v) times max depth (h), m2/s
High	$h > 5$	OR	$vh > 5$
Medium	$2 \le h \le 5$	OR	$2 \le vh \le 5$
Low	$0,3 \le h \le 2$	AND	$0,3 \le vh \le 2$

Some significant differences between scenarios were discovered. First of all the less intense flood of the 1979 shows quite compact affected areas, especially compared with other scenarios (Fig. 25).

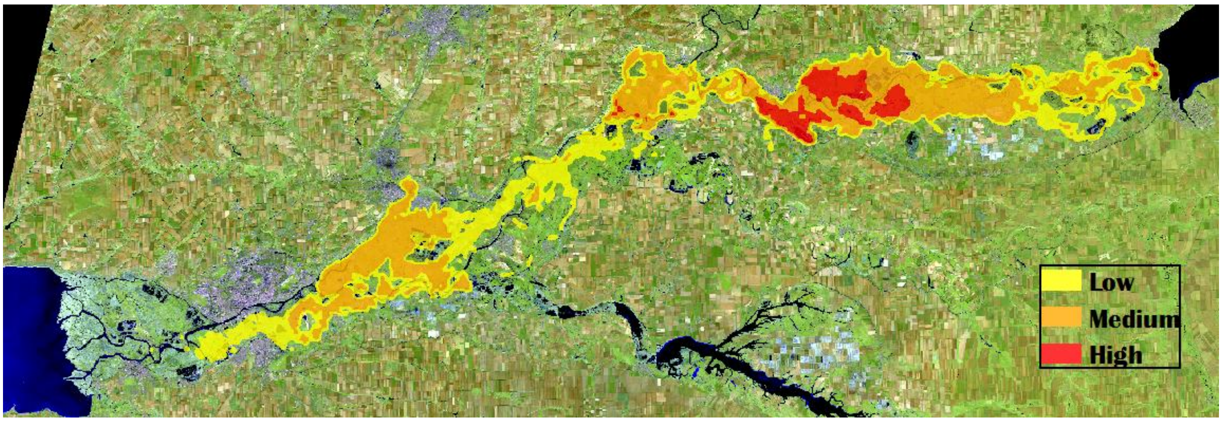


Fig. 25 1979 flood intensity

From the comparison of the 1917 flood and 100-year flood it can be noticed that the levels of flood impact differ, depending on the scenario, and that the high intensity areas had reduced quite significantly in the 100-year flood simulation, when the water discharge was regulated by the Dam management. Total reduction of the high intensity areas was 445 km2 (Fig. 26).

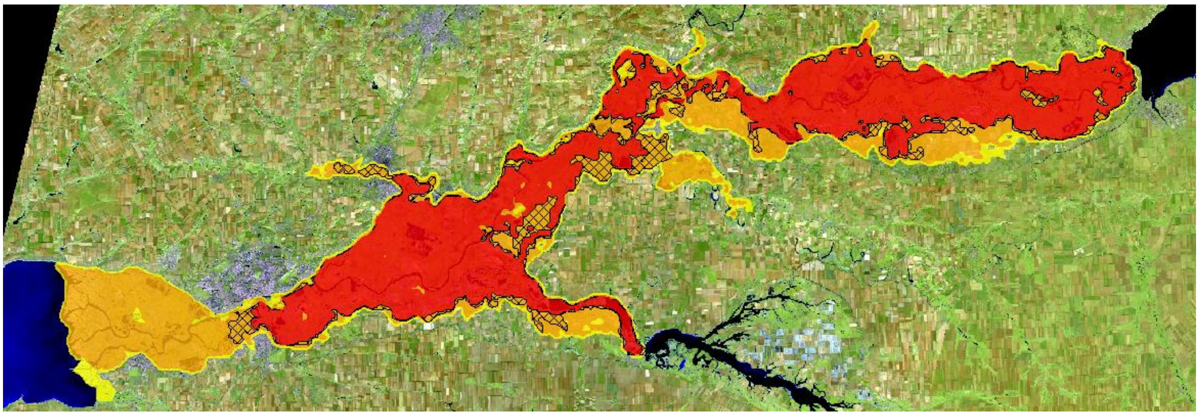


Fig. 26 Comparison of the 1917 flood and 100-year flood simulations. Crosshatch - high intensity areas reduction

The Table 9 consists the differences between the total flooded areas and the territories with flood intensity of at least low level for each scenario. This areas were identified as insignificantly affected - the flow depth and flow velocity at whose territories were too small, to be taken into account when the data for the flood intensity maps were processed by the Mapper program. This means that not all inundated area, simulated by the FLO-2D, experience the same flood hazard, for some territories this influence was minor.

Table 9 Insignificantly affected areas (difference between total inundated area and area with at least low intensity flood)

	Total inundated area, km2	Affected areas, km2	Insignificantly affected areas	
			km2	%
1979 flood	3055,75	1516,75	1539,00	50,36
20-year flood	4082,00	3572,75	509,25	12,48
1917 flood	4736,75	4304,75	432,00	9,12
100-year flood	4488,25	4045,75	442,50	9,86
1000-year flood	4804,00	4422,00	382,00	7,95

The 1979 flood is a striking example of the differences between the inundated area and affected area. While the total flooded area for this scenario is around 3055,75 km2, more than 50% of this territory were affected relatively insignificantly. For other more severe simulations this difference is not that remarkable, but still quite considerable areas experienced negligible flood (Fig. 27).

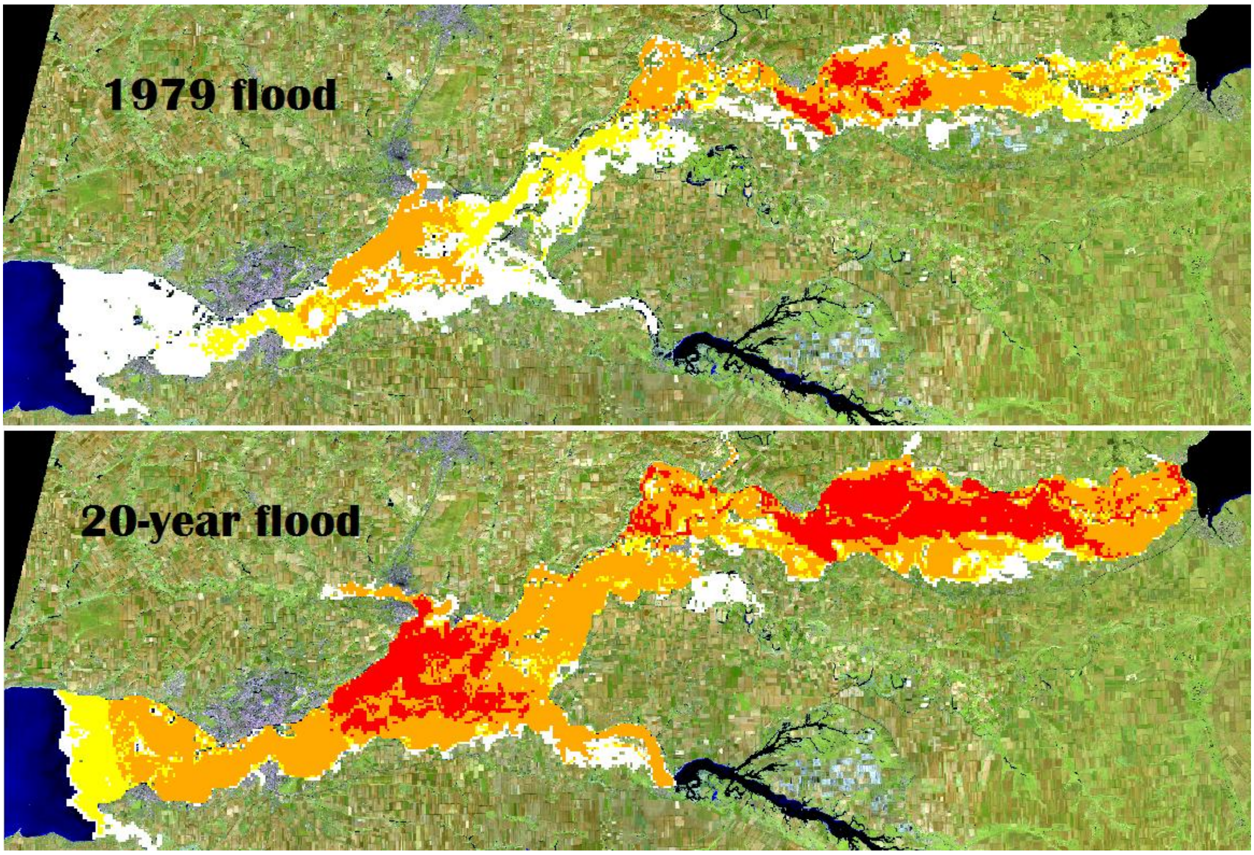


Fig. 27 Comparison of the insignificantly affected areas (white), 1979 flood and 20-year flood

The flood intensity maps for all scenarios can be found in the Appendices section (Appendix 5). The results of all simulations are gathered in the Table 10 below. It is apparent from this table that the zones with low flood intensity are quite small in all scenarios, while for the most severe floods (1917, 100-year, 1000-year) the high intense areas are expanded rather significantly.

Table 10 Affected areas, by flood intensity

	Flood event intensity						
	Total area, km2	Low		Medium		High	
		km2	%	km2	%	km2	%
1979 flood	1516,75	111,75	7,37	863,75	56,95	541,25	35,68
20-year flood	3572,75	505,75	14,16	2051,50	57,42	1015,50	28,42
1917 flood	4304,75	194,75	4,52	1661,00	38,59	2449,00	56,89
100-year flood	4045,75	235,75	5,83	1806,00	44,64	2004,00	49,53
1000-year flood	4422,00	182,50	4,13	1536,50	34,75	2703,00	61,13

8. Flood-prone urban areas (RQ3)

In the Chapter 6 the data about the urban area expansion was acquired. In the previous Chapter the areas of inundation for different scenarios were defined and analyzed by the flood intensity level. This Chapter brings the derived results together. The first part is devoted to the changes in submerged areas in total for different scenarios; the second part presents the most risky areas which can be harmed in case of flood event.

8.1. Urbanization on the flood-prone areas

The Table 11 assembles the acquired information about the urbanization growth on the floodplain for all five scenarios. The data is presented both for the totally affected area and for each flood intensity level.

Table 11 Urbanization on the flood-prone areas

Scenarios	Years	Total affected area, km2	Flood intensity					
			Low		Medium		High	
			km2	%	km2	%	km2	%
1979 flood	**1985**	18,81	**7,02**	37,32	**10,76**	57,20	**1,03**	5,48
	2013	19,04	**7,85**	41,23	**10,18**	53,47	**1,01**	5,30
20-year flood	**1985**	64,15	**14,58**	22,73	**38,27**	59,66	**11,30**	17,61
	2013	84,59	**22,50**	26,60	**51,85**	61,30	**10,24**	12,11
1917 flood	**1985**	88,92	**10,22**	11,49	**45,07**	50,69	**33,63**	37,82
	2013	121,17	**16,38**	13,52	**62,43**	51,52	**42,36**	34,96
100-year flood	**1985**	80,28	**11,46**	14,28	**44,71**	55,69	**24,11**	30,03
	2013	107,74	**15,82**	14,68	**63,45**	58,89	**28,47**	26,42
1000-year flood	**1985**	92,42	**9,26**	10,02	**42,11**	45,56	**41,05**	44,42
	2013	126,48	**14,42**	11,40	**59,98**	47,42	**52,08**	41,18

In the Chapter 6 it was noticed that the total build up area increased by 171 km2 (or 1,04%) within the whole study area (Table 4). From the table above it is apparent that urban expansion is typical for each scenario. The Fig. 28 below graphically presents the urban growth within the flood-prone areas in the period from 1985 to 2013 for different scenarios. Not only urban area spreading explains this growth, but increase in building density of the settlements as well. Almost no urban growth was noticed for the 1979 flood simulation.

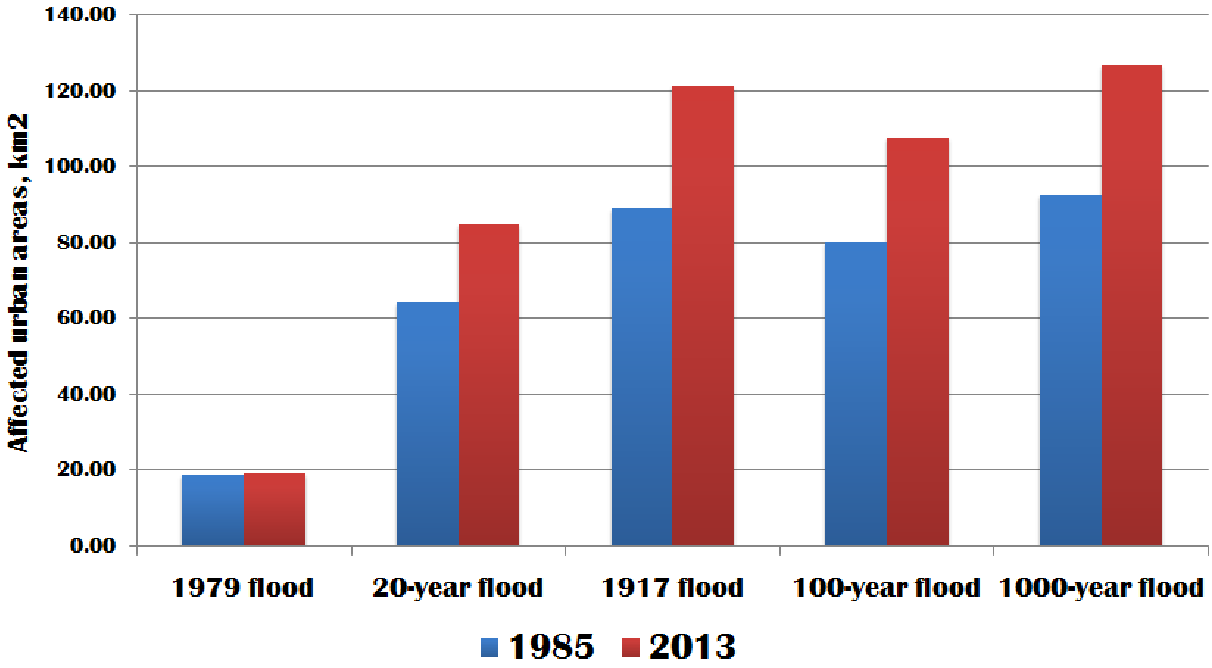


Fig. 28 The growth of the urbanized territories within the flood-prone areas

8.1.1. Affected urban areas by flood intensity

Low flood intensity

Wide distribution of the low level flood intensity is more typical for relatively soft flood events, like the repetition of the 1979 flood or 20-year flood (Fig. 29). Yet certain growth of the affected urban areas are noticeable in all scenarios.

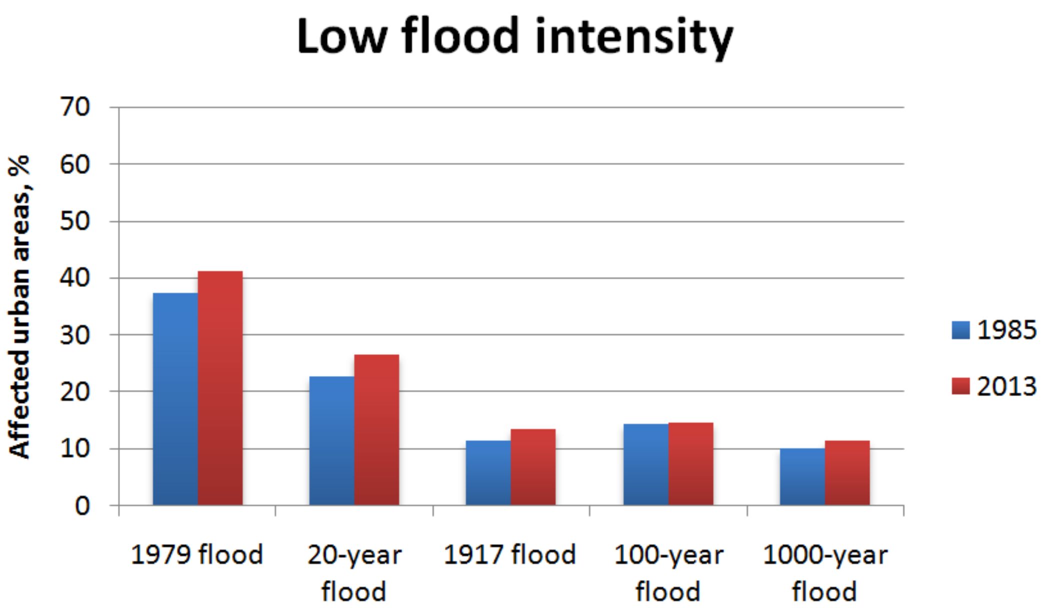


Fig. 29 Low flood intensity

Medium flood intensity

Medium flood intensity is the prevalent level for all scenarios in both time periods (Fig. 30). What is interesting is that for the 1979 flood simulation the affected area had decreased, while for other scenarios the increase of this value was typical.

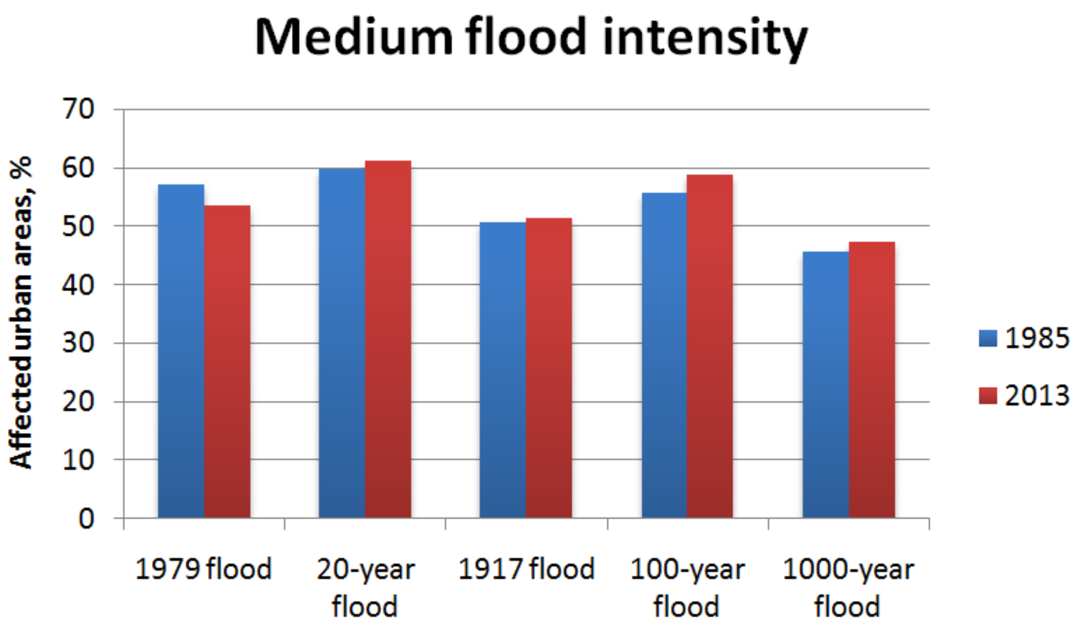


Fig. 30 Medium flood intensity

High flood intensity

The interesting characteristic of this level of flood intensity is that it has decreased from the 1985 to 2013, for all scenarios (Fig. 31). This pattern can be explained by the certain changes in human settlements development, probably after the series of significant flood events in the previous decades - floods in 1978, 1979, 1981, 1986, 1994 (last one was the most severe). People typically do not settle in the most risky areas. Also quite sizeable difference between 1917 flood and 100-year flood can be noticed (9,52 km2 in 1985 and 13,89 km2 in 2013) - the regulated discharge prevent some areas to experience highly intense inundation. High intensity areas are more typical for severe flood simulations.

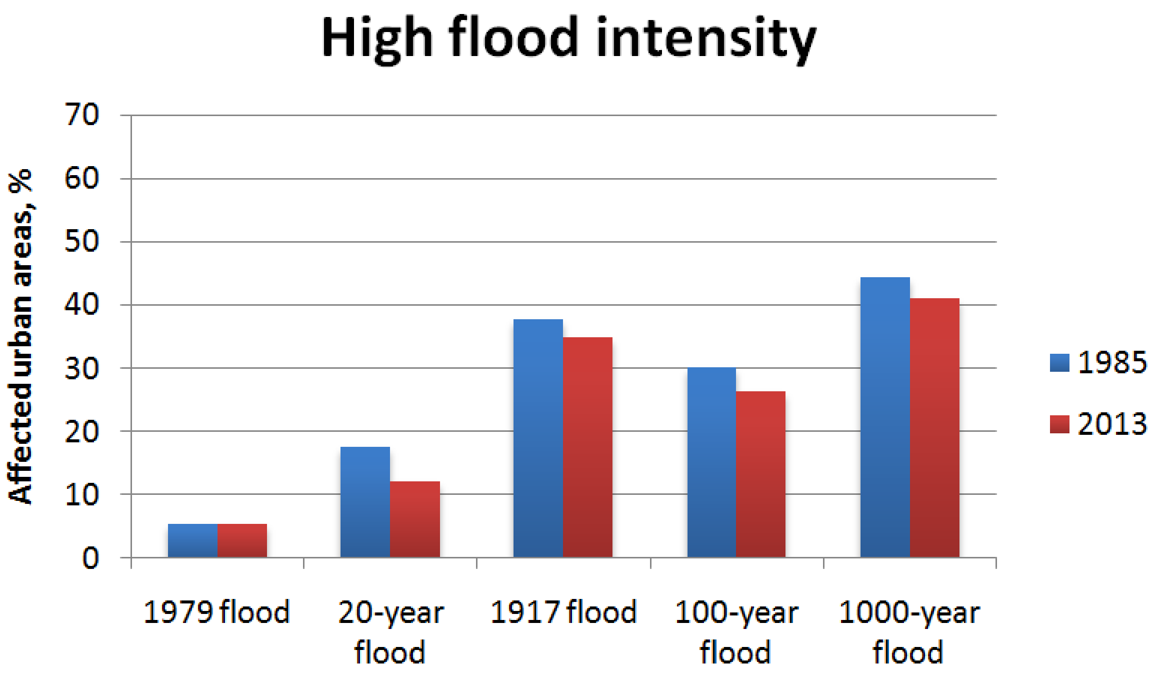


Fig. 31 High flood intensity

The histograms representing the affected urban areas by flood intensity for each scenario can be found in the Appendices section (Appendix 6).

8.1.2. Affected urban areas for each scenario

1979 flood

The settlements which might be affected by the 1979 flood simulation are the dachas near the Semikarakorsk town (medium flood intensity). The major part of the settlement is situated on the safe elevated territory, but the dachas adjoin the river. The village Visly also experienced some impact of the flood (medium). Stanitsa Zadono-Kagalnitskaya might get in the situation, when it will be surrounded by water during the flood event. But the impact of the flood will experience only periphery areas of the settlement (low-medium). The village Nikolayevskaya also can be slightly affected by the flood (low). The most significant influence of the flood will experience the areas near the Tsimlyansk Dam. The widely distributed recreation centers, dachas and gardens in this area might be flooded (flood intensity from low to high).

20-year flood

For this simulation the affected area is much more extensive, even the Don delta might be influenced. The settlements like Sinyavskoye, Kagalnik villages and slightly Azov city, which are situated on the high borders of the river delta might experience low level flood on the periphery parts. But a great number of small villages like Rogozhkino, Dugino, Obukhovka, Kazachiy Yerik, Kurgan,Yelizavetinskaya, Kosa, Gorodishche, Koluzayevo and Ust'-Koysug, which are situated right within the delta will be flooded almost totally (low-medium flood intensity). Industrial zone Zarechnaya and the roads between the Rostov-on-Don and Bataysk city, as well as some parts of the neighboring summer cottage areas might be flooded (medium). Half of the village Olginskaya might be inundated (low). Small villages situated near the river on the wide part of the Lower Don floodplain (approximately between Rostov and Bagayevskaya village - the width 10-25 km) will experience severe flood. These villages are: stanitsa Old Cherkassk, Ribatski, Cheryumkin, Arpachin, Manychskaya, Belyanin and so on. Bigger settlements Bagayevskaya and stanitsa Krivyanskaya also will experience quite intense flood (low-medium) (Bagayevskaya village will be even surrounded by water). Higher up the river small villages might by affected - Molchanov, Chebachye, Kochetovskaya. At this time village Visly might get submerged almost completely, together with small neighboring villages (low-medium). Next vast section of the floodplain (width up to 15 km) is characterized by quite severe inundation. Many villages might get affected - Zadono-Kagalnitskaya, Nikolayevskaya and a number of smaller settlements (low-medium). Once again the territories near the Dam will be under considerable danger - stanitsa Romanovskaya might be flooded almost completely, as well as numerous summer cottage areas and gardens (periphery of the Volgodonsk city) (medium).

1917 flood

The severity of this flood is much higher, compared with previous one, but the affected territory largely overlaps. The same small villages on the river delta might get submerged (medium flood intensity). More areas of the Bataysk city will be flooded in this case (medium). Olginskaya village and all small settlements within the wide lowland upstream area will be flooded (medium-high). Bagayevskaya village and stanitsa Krivyanskaya this time will be submerged completely as well as neighboring Elkin settlement (medium). Some small villages closer to the Vesyolovskoe Reservoir on the south, will be covered by water - Krasny, Malaya Zapadenka (medium). Upstream villages within the narrow part of the floodplain will be flooded - small settlements as Chebachye as well as Visly village (medium). The wide part of floodplain will experience severe inundation, great number of small villages together with bigger settlements will be flooded (medium). Area near the Dam stanitsa Romanovskaya and lowland part of the Volgodonsk, together with the outskirts of the Tsimlyansk city on the right bank of the river (medium-high).

100-year flood

In general the affected areas of this flood almost completely replicate the inundated areas of the 1917 flood simulation. The main difference is that the flood intensity is slightly weaker. It might be especially important for the areas near the Dam - in this case the intensity of the flood will be medium, not high.

1000-year flood

The most severe flood, among the proposed scenarios, cover the biggest area, which at the same time is not significantly greater than for example the area of the 1917 flood. The most important peculiarities are that the left bank of the Don river, opposite to the Rostov-on-Don, will experience really intense inundation, it might get flooded almost completely (medium-high flood intensity). Flooded areas within Bataysk city spread even wider (medium). Some territory of the Chotunok village on the north of Novocherkassk might get flooded only in this scenario (medium). The biggest destructions might experience the territories near the Dam - severe flood with high intensity will affect stanitsa Romanovskaya, lowland part of the Volgodonsk and periphery of the Tsimlyansk (high) (Fig. 32).

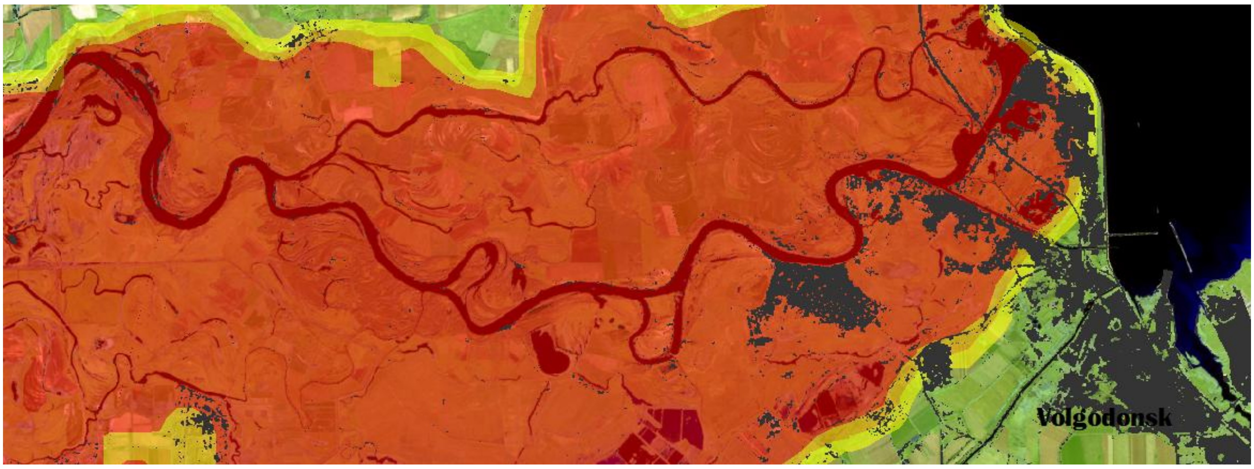


Fig. 32 Affected urban areas, 1000-year flood simulation. Grey - urban areas

8.2. The most hazardous areas on the floodplain

The high intense flood is typical for two, the most wide, sections of the Lower Don River floodplain - to the East from Rostov-on-Don (width 10-25 km) and to the East from Konstantinovsk (width 10-15 km). No big settlements are located here, apparently because it was historically known that this areas are periodically flooded, but some number of small villages nowadays can be found not far from the risky areas - Zadono-Kagalnitskaya, Titov, Pirozhok. The narrowing of the floodplain downstream from this territories result in the accumulation of the water, overflow and the deceleration of the water flow, while the flow velocity downstream is increasing significantly. Fish hatcheries and ponds can be found in abundance within these territories.

8.2.1. Static pressure and flow velocity

For the illustration of the static pressure and maximum flow velocity distribution, the most representative example of the 100-year flood simulation was chosen. The area to the East from Konstantinovsk is characterized by the highest static pressure (Fig. 33).

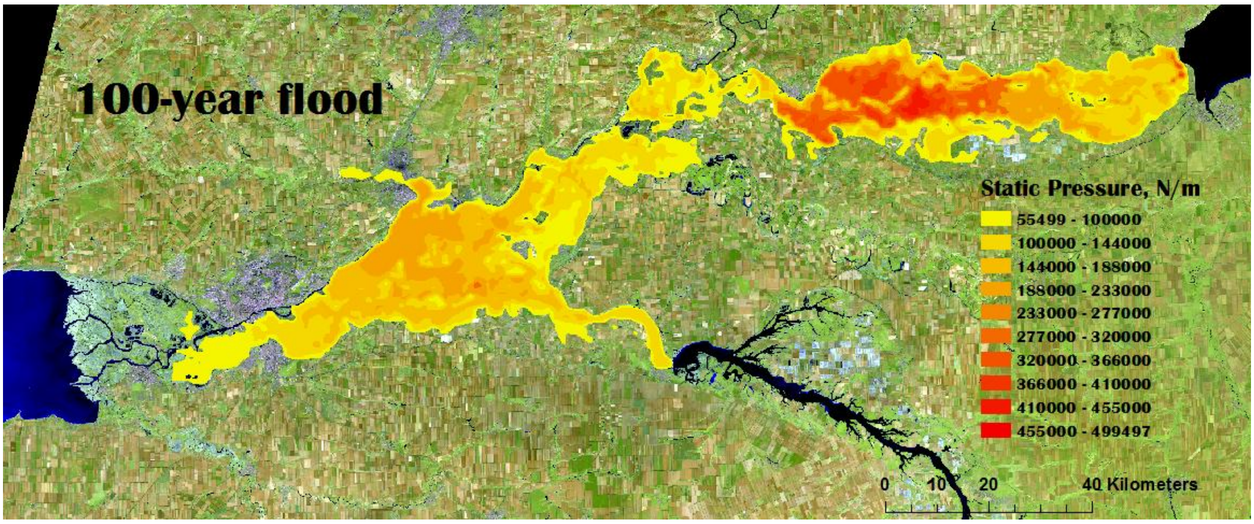


Fig. 33 Static pressure, 100-year flood simulation

The areas where the floodplain is converging are characterized by the highest maximum flow velocity - narrow spots near the Rostov-on-Don, Semikarakorsk and Konstantinovsk (Fig. 34). High velocity area near the Tsimlyansk Dam occurred due to the high discharge rate.

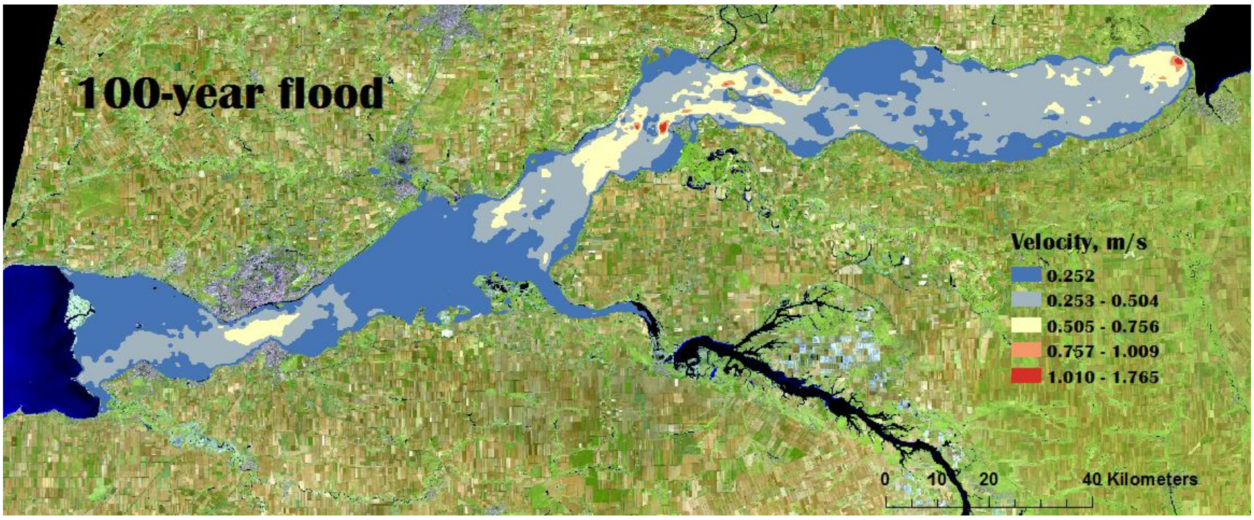


Fig. 34 Maximum flow velocity, 100-year flood simulation

8.2.2. Rostov-on-Don left bank development

Rostov-on-Don city master plan contemplates the development of the low left-bank territories across the river (Yudenich 2007). Even though during the "mild" scenarios (1979, 20-year floods) this areas are flooded just partly, more intense inundation is probable in other cases (100-year, 1000-year floods). Together with relatively high flow velocity (Fig. 34) this territories might be quite prone to flood threats.

9. Discussion

9.1. Urbanization patterns of the Lower Don River floodplain (RQ1)

RQ1: What were the urbanization patterns of the Lower Don River floodplain over the last decades?

9.1.1. Results

Through the supervised classification tools of the ArcGIS 10, land cover maps were developed and the expansion of the urban areas within the study area for 1985 and 2013 was defined (Fig. 11). As it was indicated in the Table 4, some changes in the land cover happen during the selected period of time. Overall build up area slightly increased (by 1,04%), yet total additional urbanized territory is around 171 km2. Even though the total population of the Rostov oblast decreased, the study area experiences the population growth, especially the big and economically important cities. So the build up areas of relatively big settlements increased - Rostov-on-Don, Aksay, Bataysk, Azov, Novocherkassk, Semikarakorsk, Konstantinovsk, Tsimlyansk and Volgodonsk.

The important urbanization trend within the Lower Don area is the development plans of the Rostov-on-Don. The Rostov Master Plan, adopted in the 2007, proposes the building up of the low left bank of the city (Yudenich 2007). The preliminary construction works had already started on this flood-prone areas.

9.1.2. Limitations

One of the general shortcomings of the current research is the absence of the *in situ* data collection especially about the extension of the urban area. However due to the vast study area (the width of approximately 72 km and length of 229 km) and limited time and sources, the serious and detailed field work was not an option. It was accepted that the use of the high resolution satellite images for the verification of the supervised classification final result was enough. The other characteristic of the remotely sensed data processing is the resolution of the utilized satellite imagery. In cases when the urbanization patterns of one city are studied, the resolution of the images play a great role (Miller and Small 2003; Pham *et al.* 2011). But when the project area is much more greater, as in our case, the application of the medium spatial resolution is acceptable (Netzband *et al.* 2005). So the use of the frequent and easily accessible Landsat imagery with the resolution of the 30 m was appropriate.

9.2. Flood simulations (RQ2)

RQ2: What territories of the Lower Don River floodplain may experience the inundation under different developed scenarios?

9.2.1. Results

The FLO-2D flood routing model was used for the delineation of the potentially inundated areas in different developed scenarios. The chosen scenarios represent the flood events of various probabilities and severity, the differences in flood hazard depending on the type of water discharge (natural versus regulated discharge) were analyzed as well. Five hydrographs were selected and imported into the program. As a result flood-prone territories for each of them were acquired. Based of the data, derived in the process of flood simulation (maximum flow depth, maximum flow velocity), the flood intensity maps were created as well. Based on the comparison of the totally inundated areas and areas with at least low flood intensity the insignificantly affected areas were distinguished (Table 9). It was noticed that the most mild scenario is characterized by the greatest part of this type of territory (1539 km2 or more than 50% of total inundated area). As the intensity of the simulated floods grow - the percentage of insignificantly affected areas decrease. The bordered nature of the floodplain can explain this relationship. The step-type low lands along the river were formed in times when there was no Dam regulating the water discharge. And these low-lands at some moment change into safe uplands. The mild flood is unable to cover the whole available flat area with water, while rare extreme flood events (like 1%, 0,1%) can submerge the whole territory.

Intensity of the flood events increased accordingly to the increase in the discharge rate (Table 10).

The differences between the natural and regulated discharge were discussed based on the examples of the 1917 and 100-year flood simulations. As it can be seen from the Fig. 15, the hydrographs of these two floods replicate each other quite precisely. So the natural discharge of the 1917 flood and the regulated discharge for the 100-year flood were chosen as the scenarios. The differences in the area of inundation and the flood intensity are rather sufficient (Table 9, Table 10).

9.2.2. Limitations

One of the initial problems with the FLO-2D is that the majority of the guidelines and case studies discuss the examples of flood events within the relatively small project area and with the duration of 24 hours or less (O'Brien 2010). Other shortcoming relates to the selected grid element size (0,25 km2). Such big cells deprived us of the elevation details, which might be quite important. But we had to chose this size of grid elements due to the vast study area and available computers, which could not process the simulation data with the bigger number of grid elements. Still, the inundated area could be delineated quite accurately. It should be noticed that in this case better results of the simulations were acquired for the severe floods, than for the mild one's.

9.3. Threatened floodplain areas (RQ3)

RQ3: How flooding threat of the urbanized areas had changed and what areas of the floodplain are at the most risk?

9.3.1. Results

The changes in the affected urban areas were analyzed. It was noticed that in the period between the 1985 and 2013 the territory of the flood-prone build up areas increased for each scenario (Table 11). Not only urban area spreading explains this growth, but increase in building density of the settlements as well. The affected area for the 1979 flood didn't changed a lot, since almost no settlement might get damaged during this, the most mild, simulation. The medium level of flood intensity prevailed in all scenarios.

The most endangered settlements on the floodplain can be distinguished. First of all there are small number of villages near the river on the most wide parts of the floodplain - this area get submerges almost in all scenarios. The settlements on the river delta are also at risk. Generally big old settlements do not get inundated, since they are situated on the upland, outside the floodplain (Rostov-on-Don, Azov, Novocherkassk). But some of the medium size settlements, like Bataysk, Krivyanskaya, Romanovskaya and the downstream part of Volgodonsk can be characterized as unsafe areas. The territories right under the Tsimlyansk Dam must be seen as the one of the most hazardous, since in case of flood this areas will be inundated first. It will take some time for the flood wave to reach the distant parts of the floodplain. For the example of the flood expansion, with indicated days from the beginning of the overflow, see Appendices section (Appendix 7).

Narrow parts of the floodplain as well can be characterized as dangerous, since the flow velocity at this areas increase significantly (Fig. 34). The development plans of the Rostov-on-Don may result in the appearance of the new risky area on the floodplain, as the territory, selected for the building up is located within the low-land.

9.3.2. Limitations

The limitations of this section are determined by the previous sections, since this part brings together and analyses the results of other chapters.

9.4. Practical implications and future research

The results acquired through this research might be interesting for various stakeholders - researchers, urban planners, local population. The knowledge of the hazardous areas on the Lower Don River floodplain can be used as a limiting factor in urban growth modeling by the researches and developers. The derived data about the flooding threats in the project area can help in studying regional environmental security. Some of the outcomes of this research are now available online for everybody interested on the Azov Center for Watershed Cooperation site (Azovcenter 2014) (Appendix 8).

Future research on this topic might include more detailed flood modeling, using DEM and satellite images with higher spatial resolution. The focusing on the specified important and potentially threatened urbanized area, like Rostov-on-Don or lower part of the Volgodonsk and stanitsa Romanovskaya, can become a substantial research. FLO-2D modeling program have a number of features which allow to indicate individual buildings, roads, bridges, as well as a method to assess the flood consequences in money equivalent, if the required data is available. Such research might become valuable, taking into account the existing urban growth in the region and increasing uncertainty and danger of flood events all other the world.

10. Conclusion

The main goals of the research were to determine the scale of the Lower Don River floodplain urbanization, study related flood damage threats and the application of the remote sensing, GIS and modeling for these purposes. In order to achieve these goals, three research questions were formulated so that urbanization trends and the expansion of the flood-prone territories within the study area can be defined:

RQ1: What were the urbanization patterns of the Lower Don River floodplain over the last decades?

RQ2: What territories of the Lower Don River floodplain may experience the inundation under different developed scenarios?

RQ3: How flooding threat of the urbanized areas had changed and what areas of the floodplain are at the most risk?

It was found that some rate of the urban growth is inherent in the study area. For the period from 1985 to 2013 the build up area increased by the 171 km2 (+1,04%). Not only urban area spreading explains this growth, but increase in building density of the settlements as well.

The simulation of the five flood events with various probability, intensity and features were introduced into the modeling program. As a result the areas of inundation for each scenario were acquired. The differences in flood hazard depending on the type of water discharge (natural versus regulated discharge) were analyzed as well, by the comparison of the 1917 and 100-year floods.

The settlements affected by the flood in each simulation were determined. The most hazardous areas within the floodplain were defined, by the maximum flow depth and the maximum flow velocity. It was found that generally small villages on the river bank within the wide part of the floodplain will experience the most intense flood, together with the territory right under the Dam (Romanovskaya stanitsa and lowland part of the Volgodonsk). Currently the major part of Rostov-on-Don city lies within the safe upland, but future development of the low left bank will result in the creation of the new city district, that might be submerged in case of severe flood.

The results acquired through this research might be interesting for various stakeholders - researchers, urban planners, local population. The derived data about the flooding threats in the project area can help in studying regional environmental security. Some of the outcomes of this research are now available online for everybody interested on the Azov Center for Watershed Cooperation site (Azovcenter 2014). Future research might include more detailed flood modeling, it can be focused on some specified potentially threatened settlements near the Don River. Such research might become valuable, taking into account the existing urban growth in the region and increasing uncertainty and danger of flood events all other the world.

References

Aquarius. 2008. *Моделирование волны прорыва Цимлянского гидроузла* [Tsimlyansk hydrosystem break wave modeling]. Aquarius Research and Production enterprise. Accessed July 15 http://www.npp-aquarius.ru/osnnaprdeyat/hydrav/chisl/5360b8b8/

ArcGIS. 2014. *Composite Bands (Data Management)* ArcGIS Help Library. Accessed July 15 2014. http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#//00170000009p000000

ASTER. 2014. *ASTER GDEM* Accessed 15 July http://gdem.ersdac.jspacesystems.or.jp/

Azovcenter. 2014. *Azov Center for Watershed Cooperation* Accessed July 15 http://azovcenter.ru/

Bolstad, P. 2005. An Introduction to GIS. In *GIS fundamentals.* ed., 1-24. White Bear Lake, MN, Eider Press.

Campbell, J.B. 2002. *Introduction to remote sensing*. 3rd. United States: CRC Press.

Carlson, T.N., Augustine, J.A. and Boland, F.E. 1977. Potential application of satellite temperature measurements in the analysis of land use over urban areas. *Bulletin of the American Meteorological Society* 58. (12): 1301-1303.

CESA. 2014. *The 100 Cities Project* Center for Environmental Science Applications. Accessed July 15 2014. http://cesa.asu.edu/urban-systems/100-cities-project/

Chow, V.T. 1959. *Open-channel hydraulics*. New York: McGraw - Hill Book Co.

Cocheci, M. 2014. Environmental Impact Assessment of Urban Sprawl in the Brasov Metropolitan Area. *Urbanism. Arhitectura. Constructii* 5. (2): 21-37.

Dottori, F. and Todini, E. 2010. A 2D flood inundation model based on cellular automata approach. Proc. XVIII International Conference on Water Resources. In Carrera J (ed) Barcellona, 1-8.

Dulimov, E.I. and Tsechoev, V.K. 2001. *Славяне средневекового Дона* [Slavs of the medieval Don]. Rostov-on-Don: Rostizdat.

Emergency Events Database. 2014. *The OFDA/CRED International Disaster Database* Brussels, Belgium: Universite catholique de Louvain. Accessed July 15. http://www.emdat.be/

EU. 2007. *Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks (Text with EEA relevance)* Official Journal of the European Union.

FLO-2D. 2014. *Flood routing model* Accessed July 15 http://www.flo-2d.com/

Fotheringham, S. and Rogerson, P. 2013. *Spatial analysis and GIS*. United States: CRC Press.

Hydrological databases. 2014. *Базы гидрологических данных* [Hydrological databases]. Accessed July 15. http://www.hydrotec.ru/

Goudie, A.S. 2004. *Encyclopedia of geomorphology*. London: Routledge.

Haq, M., Akhtar, M., Muhammad, S., Paras, S. and Rahmatullah, J. 2012. Techniques of Remote Sensing and GIS for flood monitoring and damage assessment: A case study of Sindh province, Pakistan. *The Egyptian Journal of Remote Sensing and Space Science* 15. (2): 135-141.

Herold, M., Menz, G. and Clarke, K.C. 2001. Remote sensing and urban growth models-demands and perspectives. Symposium on remote sensing of urban areas, 35, 1-10.

Herold, M., Goldstein, N.C. and Clarke, K.C. 2003. The spatiotemporal form of urban growth: measurement, analysis and modeling. *Remote Sensing of Environment* 86. (3): 286-302.

Horritt, M.S. and Bates, P.D. 2002. Evaluation of 1D and 2D numerical models for predicting river flood inundation. *Journal of Hydrology* 268. (1–4): 87-99.

Jung, Y., Merwade, V., Yeo, K., Shin, Y. and Lee, S. 2013. An Approach Using a 1D Hydraulic Model, Landsat Imaging and Generalized Likelihood Uncertainty Estimation for an Approximation of Flood Discharge. *Water* 5. (4): 1598-1621.

Kazakov, B.A. 2014. *Водно-болотные угодия России. Нижний Дон* [Ramsar sites in Russia. Lower Don]. Accessed July 15 http://www.fesk.ru/wetlands/141.html

Konrad, C.P. 2003. *Effects of urban development on floods* U.S. Geological Survey – Water Resources.

Liew, S.C. 2001. *Principles of Remote Sening* Centre for Remote Imaging, Sensing and Processing. Accessed July 15 http://www.crisp.nus.edu.sg/~research/tutorial/intro.htm

Lurie, P.M. and Panov, V.D. 1999. *Влияние изменений климата на гидрологический режим р. Дон в начале XXI столетия* [The impact of the climate change on the hydrological regime of Don River in the beginning of XXI century]. *Meteorology and Hydrology* 4. 90-97.

Martynova, M.I. and Aleksenko, V.N. 2009. *География Ростовской области* [Geography of Rostov oblast]. Rostov-on-Don.

Miller, R.B. and Small, C. 2003. Cities from space: potential applications of remote sensing in urban environmental research and policy. *Environmental Science & Policy* 6. (2): 129-137.

Mitchell, J.K. 2003. European river floods in a changing world. *Risk Analysis* 23. (3): 567-574.

Netzband, M., Redman, C.L. and Stefanov, W.L. 2005. Challenges for Applied Remote Sensing Science in the Urban Environment. *The international archives of the photogrammetry, remote sensing, and spatial information sciences* 36. (8/W27):

O’Brien, J. 2009a. *Pocket Guide. Basic FLO-2D Model*

________. 2009b. *Data Input Manual. Basic FLO-2D Model*

________. 2010. *Guidelines for applying the FLO-2D model to the Central Valley floodplain evaluation delineation program* Nutrioso, AZ. FLO-2D/Riada Engineering, Inc.

Oosterberg, W., Van Drimmelen, C. and Van der Vlist, M. 2005. Strategies to harmonize urbanization and flood risk management in delta's. 45th Congress of the European Regional Science Association, Vrije Universiteit Amsterdam, 23-27.

Pham, H.M., Yamaguchi, Y. and Bui, T.Q. 2011. A case study on the relation between city planning and urban growth using remote sensing and spatial metrics. *Landscape and Urban Planning* 100. (3): 223-230.

ROSSTAT. 2003. *Регионы России. Социально-экономические показатели* [Regions of Russia. Socio-economic Indicators]. Moscow.

________. 2013. *Регионы России. Социально-экономические показатели* [Regions of Russia. Socio-economic Indicators]. Moscow.

________. 2014. *Численность населения Ростовской области на 1 января 2014 года* [The population of the Rostov region on January 1, 2014]. Territorial authority Federal State Statistics Service of the Rostov region.

Rostov. 2007a. *Положение о территориальном планировании проекта «Схема территориального планирования Восточного Внутриобластного района Ростовской области (Волгодонской системы расселения)»* [The regulations on territorial planning of the "Territorial planning scheme of the East Intraregional district of the Rostov oblast (Volgodonskaya settlement system)"].

________. 2007b. *Положение о территориальном планировании проекта "Схема территориального планирования Юго-Западного района Ростовской области (Ростовской агломерации)"* [The regulations on territorial planning of the "Territorial planning scheme of the South-West part of the Rostov oblast (Rostov agglomeration)"].

Rosvodresursy. 2013. *Правила использования водных ресурсов Цимлянского водохранилища* [Tsimlyansk Reservoir water resources Regulations].

Samarasinghea, S., Nandalalb, H., Weliwitiyac, D., Fowzed, J., Hazarikad, M. and Samarakoond, L. 2010. Application of remote sensing and GIS for flood risk analysis: A case study at Kalu-Ganga River, Sri Lanka. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Science* 38. (Pt 8): 110-115.

Schott, J.R. 2007. *Remote sensing*. 2nd. New York, USA: Oxford University Press.

Schowengerdt, R.A. 2006. *Remote sensing: models and methods for image processing*. 3rd. Academic press.

Stenehjem, J. 2014. *Analysis of Potential Flood Elevations and Economic Losses in the Event of a Catastrophic Dam Breach, Using GIS and ENVI, with an Introduction to HAZUS-MH* Williston State College.

Syme, W.J. 2008. Flooding in Urban Areas-2D Modelling Approaches for Buildings and Fences. 9th National Conference on Hydraulics in Water Engineering: Hydraulics 2008, Australia, Engineers Australia, 25.

Tarasyuk, B.F. 1964. Анализ производственной деятельности осетровых рыбоводных заводов. *Russian Federal Research Institute of Fisheries and Oceanography (VNIRO)* 56. (3): 171-210.

Timofeyeva, V.V. 2008. *Морфодинамика русла Нижнего Дона и её изменения под влиянием антропогенных факторов* [Lower Don channel morphodynamics and its changes under the influence of anthropogenic factors]. MSU Faculty of Geography.

Tripathi, R., Sengupta, S.K., Patra, A., Chang, H. and Jung, I.W. 2014. Climate change, urban development, and community perception of an extreme flood: A case study of Vernonia, Oregon, USA. *Applied Geography* 46. 137-146.

Uddin, K., Gurung, D.R., Giriraj, A. and Shrestha, B. 2013. Application of Remote Sensing and GIS for Flood Hazard Management: A Case Study from Sindh Province, Pakistan. *American Journal of Geographic Information System* 2. (1): 1-5.

UN-DESA. 2010. *World Urbanization Prospects, The 2009 Revision.* New York, United Nations, Department of Economic and Social Affairs.

________. 2012. *World Urbanization Prospects, the 2011 Revision: Highlights*. New York, United Nations, Department of Economic and Social Affairs, Population Division.

________. 2013. *World Population Prospects, the 2012 Revision, Volume I: Comprehensive Tables*. New York: United Nations,

UN-HABITAT. 2006. *Urbanization Facts and Figures* Vancouver, Canada.

USGS. 2014a. *Frequently Asked Questions about the Landsat Missions* Accessed July 15 http://landsat.usgs.gov/L8_band_combos.php

________. 2014b. *Global Visualization Viewer (GloVis)* Accessed July 15 http://glovis.usgs.gov/

________. 2014c. *EarthExplorer* Accessed July 15 http://earthexplorer.usgs.gov/

Voogt, J.A. and Oke, T.R. 2003. Thermal remote sensing of urban climates. *Remote Sensing of Environment* 86. (3): 370-384.

Demoscope Weekly. 2014. *1989 Soviet Census* Accessed 2014 July 15. http://demoscope.ru/weekly/ssp/census.php?cy=6

Wikimapia. 2014. *Online mapping project* Accessed July 15 http://wikimapia.org/

Yang, L., Smith, J.A., Wright, D.B., Baeck, M.L., Villarini, G., Tian, F. and Hu, H. 2013. Urbanization and Climate Change: An Examination of Nonstationarities in Urban Flooding. *Journal of Hydrometeorology* 14. (6): 1791-1809.

Yi, C.-S., Lee, J.-H. and Shim, M.-P. 2010. GIS-based distributed technique for assessing economic loss from flood damage: pre-feasibility study for the Anyang Stream Basin in Korea. *Natural hazards* 55. (2): 251-272.

Yudenich, E.B. 2007. *Генеральный план Ростова-на-Дону* [Rostov-on-Don Master plan]. Rostov-on-Don.

Yug. 2014. *Объединенное диспетчерское управление энергосистемами Юга* [United supervisory control of the energy systems of the South].

Zhu, T., Lund, J.R., Jenkins, M.W., Marques, G.F. and Ritzema, R.S. 2007. Climate change, urbanization, and optimal long-term floodplain protection. *Water Resources Research* 43. (6): 1-11.

Zhuk, S.Y. 1957. *Технический отчет о строительстве Волго-Донского судоходного канала имени Ленина, Цимлянского гидроузла и оросительных сооружений* [Technical report on the construction of the Lenin Volga-Don Shipping Canal, Tsimlyansk hydrosystem and irrigation constructions]. Moscow.

Personal Communications

Antonyuk, Anna. Expert of operational satellite monitoring group, ScanEx Research and Development Center, Moscow. Telephone conversation. 19 May 2014.

O'Brien, Karen. Technical Support, FLO-2D Software, Riada Engineering, United States. Email communication. May-July 2014.

GIS Data sources

ASTER GDEM. http://gdem.ersdac.jspacesystems.or.jp/. Accessed 15 July 2014.

FLO-2D flood routing model. http://www.flo-2d.com/. Accessed 15 July 2014.

The U.S. Geological Survey Global Visualization Viewer (GloVis). http://glovis.usgs.gov/. Accessed 15 July 2014.

The U.S. Geological Survey The EarthExplorer. http://earthexplorer.usgs.gov/. Accessed 15 July 2014.

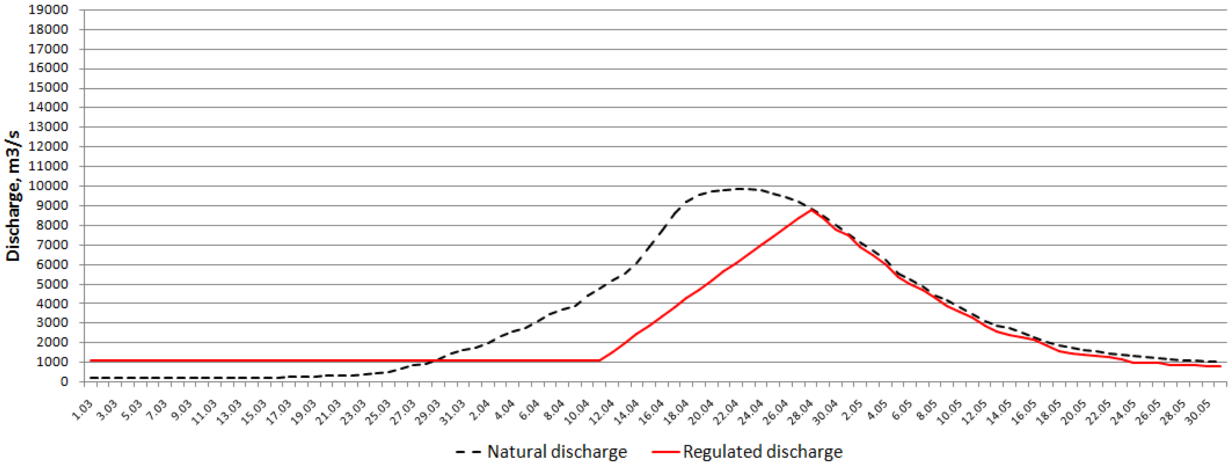
Wikimapia online mapping project. http://wikimapia.org/. Accessed 15 July 2014.

Azov Center for Watershed Cooperation. http://azovcenter.ru/. Accessed 15 July 2014.

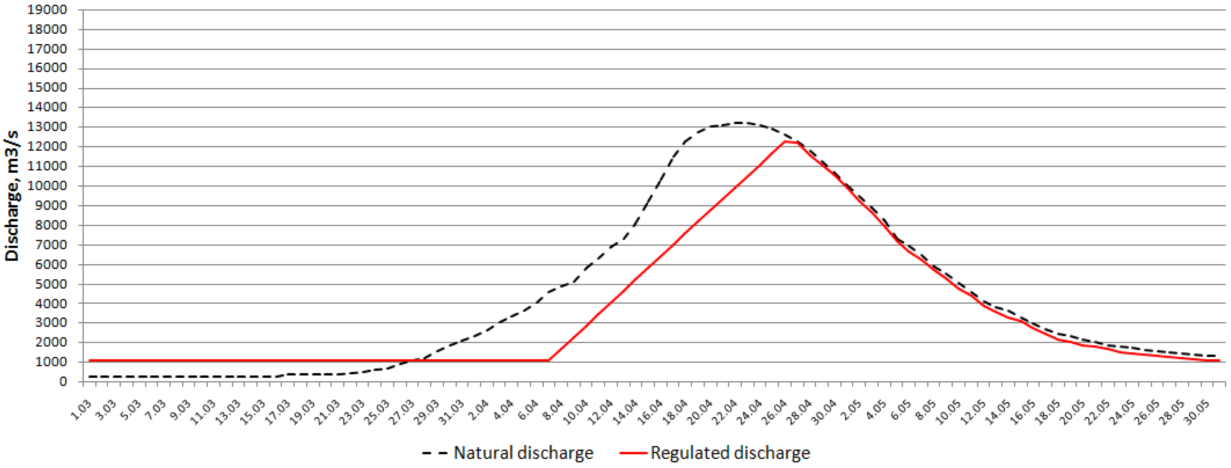
Appendices

Appendix 1 Flood hygrographs, without flood warning. Data source: (Rosvodresursy 2013)

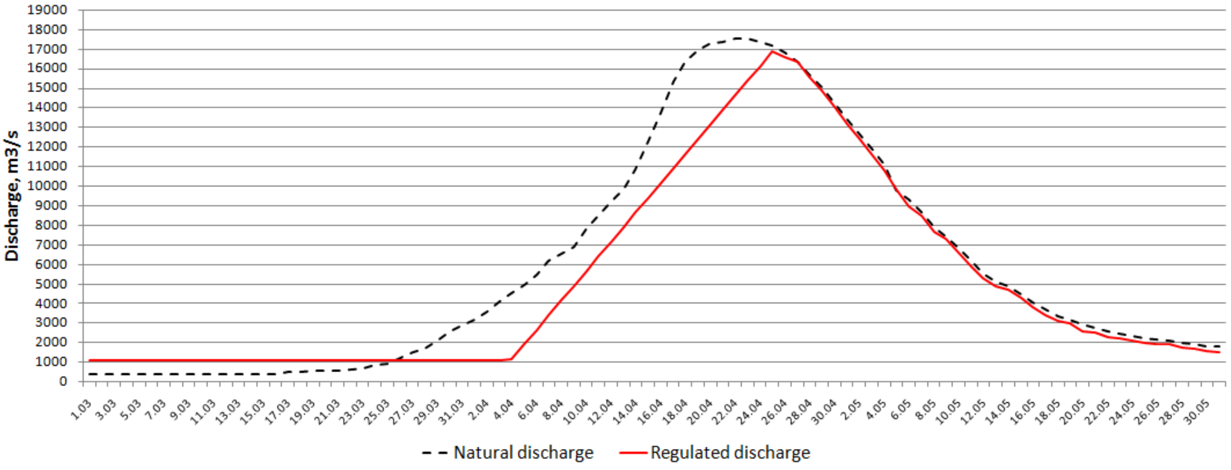
20-year flood



100-year flood



1000-year flood



Appendix 2 Water discharge for the selected scenarios, from March to May. Data source: (Rosvodresursy 2013)

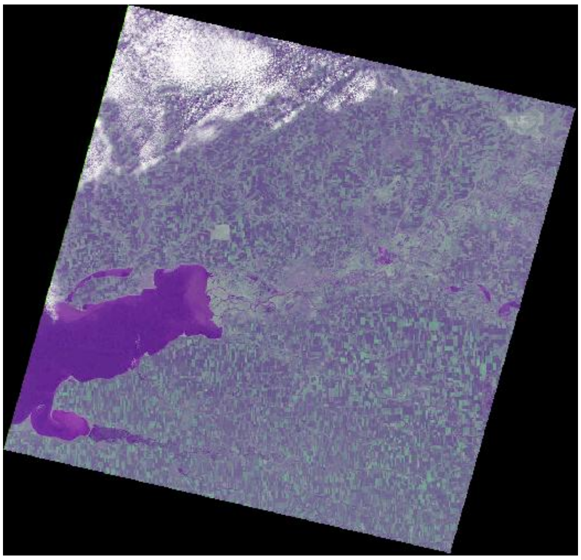
	Water discharge, m3/s			
Date	**1917 flood**	**20-year flood**	**100-year flood**	**1000-year flood**
1.03	170	1100	1100	1100
2.03	170	1100	1100	1100
3.03	170	1100	1100	1100
4.03	170	1100	1100	1100
5.03	173	1100	1100	1100
6.03	173	1100	1100	1100
7.03	177	1100	1100	1100
8.03	177	1100	1100	1100
9.03	177	1100	1100	1100
10.03	183	1100	1100	1100
11.03	183	1100	1100	1100
12.03	183	1100	1100	1100
13.03	183	1100	1100	1100
14.03	183	1100	1100	1100
15.03	186	1100	1100	1100
16.03	186	1100	1100	1100
17.03	186	1100	1100	1100
18.03	186	1100	1100	1100
19.03	186	1100	1100	1100
20.03	186	1100	1100	1100
21.03	202	1100	1100	1100
22.03	215	1100	1100	1100
23.03	225	1100	1100	1100
24.03	225	1100	1100	1100
25.03	313	1100	1100	1100
26.03	376	1100	1100	1100
27.03	444	1100	1100	1100
28.03	560	1100	1100	1100
29.03	914	1100	1100	1100
30.03	1619	1100	1100	1100
31.03	2182	1100	1100	1100
1.04	2368	1100	1100	1100
2.04	2426	1100	1100	1100
3.04	2722	1100	1100	1100
4.04	2751	1100	1100	1165
5.04	2923	1100	1100	1915
6.04	3147	1100	1100	2665
7.04	3511	1100	1100	3415
8.04	4001	1100	1690	4165
9.04	4851	1100	2280	4915

10.04	5704	1100	2870	5665
11.04	6000	1100	3460	6415
12.04	6970	1554	4050	7165
13.04	7506	2008	4640	7915
14.04	7904	2462	5230	8665
15.04	8841	2916	5820	9415
16.04	9951	3370	6410	10165
17.04	11201	3824	7000	10915
18.04	12450	4278	7590	11665
19.04	13505	4732	8180	12415
20.04	14072	5186	8770	13165
21.04	14280	5640	9360	13915
22.04	14436	6094	9950	14665
23.04	14436	6548	10540	15415
24.04	14176	7002	11130	16165
25.04	14176	7456	11720	16915
26.04	13301	7910	12310	16600
27.04	12910	8364	12200	16400
28.04	12450	8818	11600	15600
29.04	11700	8400	11100	14900
30.04	11201	7800	10600	14100
1.05	10568	7500	9900	13200
2.05	9857	6900	9300	12500
3.05	9206	6500	8700	11650
4.05	8542	6000	8000	10800
5.05	7904	5400	7200	9850
6.05	7290	5000	6700	9000
7.05	6694	4700	6250	8500
8.05	6060	4300	5700	7700
9.05	5503	3900	5300	7300
10.05	4996	3600	4800	6600
11.05	4481	3300	4400	5900
12.05	4049	2900	3900	5300
13.05	3744	2600	3600	4900
14.05	3408	2400	3300	4700
15.05	3038	2300	3100	4300
16.05	2759	2200	2800	3800
17.05	2510	1900	2500	3400
18.05	2198	1600	2200	3100
19.05	1969	1450	2050	3000
20.05	1740	1400	1900	2600
21.05	1587	1350	1800	2550
22.05	1423	1300	1700	2300
23.05	1345	1180	1550	2250
24.05	1257	1000	1450	2100

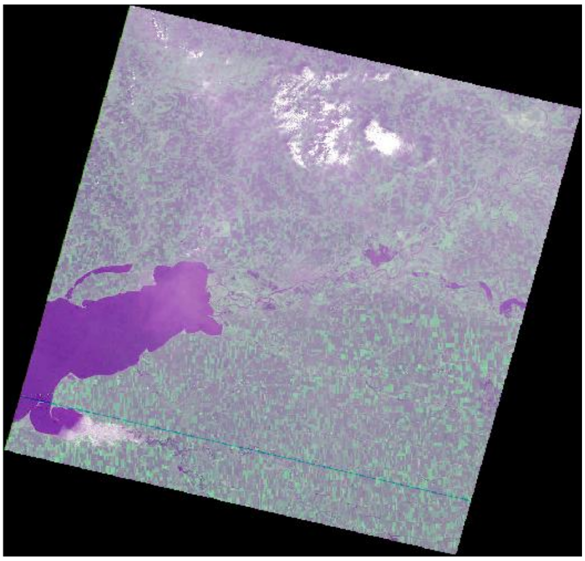
25.05	1174	1000	1400	2000
26.05	1110	1000	1350	1900
27.05	1052	900	1300	1900
28.05	976	900	1240	1750
29.05	933	900	1160	1700
30.05	914	800	1120	1600
31.05	877	800	1100	1500

Appendix 3 The satellite images of the 1978, 1979 and 1981 floods. Data source: (USGS 2014b).

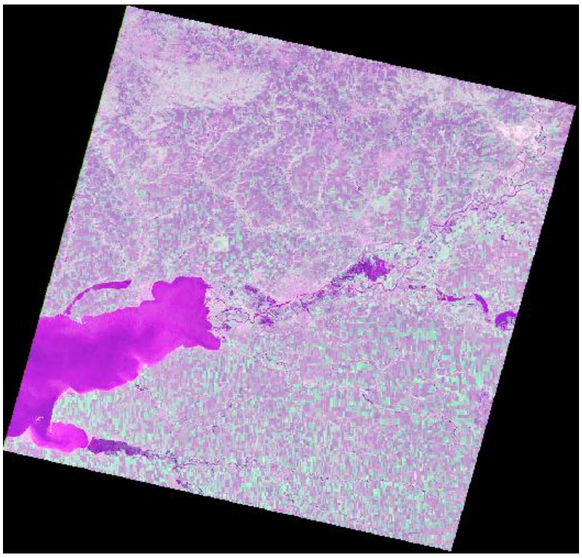
1978-03-16



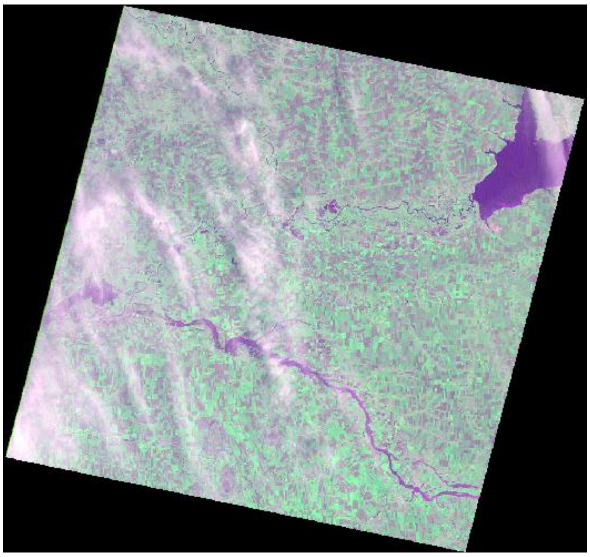
1978-04-03



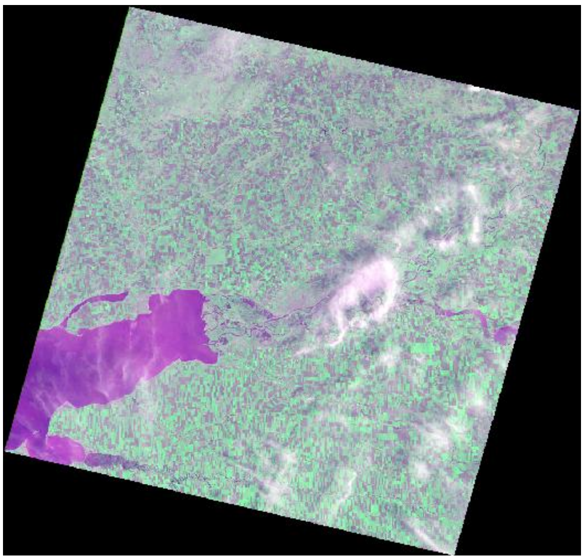
1978-04-21



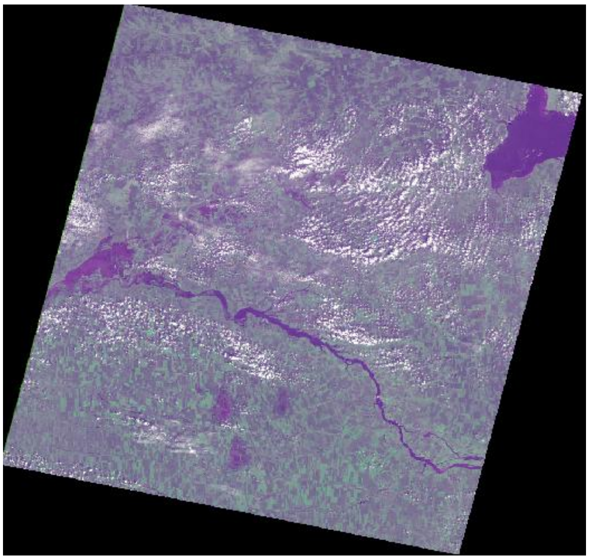
1978-05-08



1978-05-09

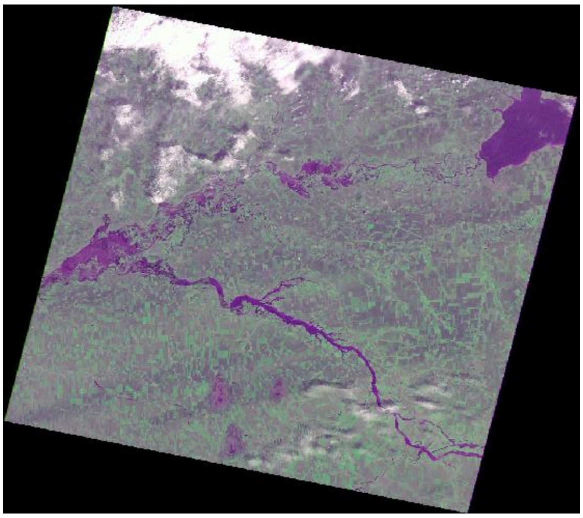


1979-03-28

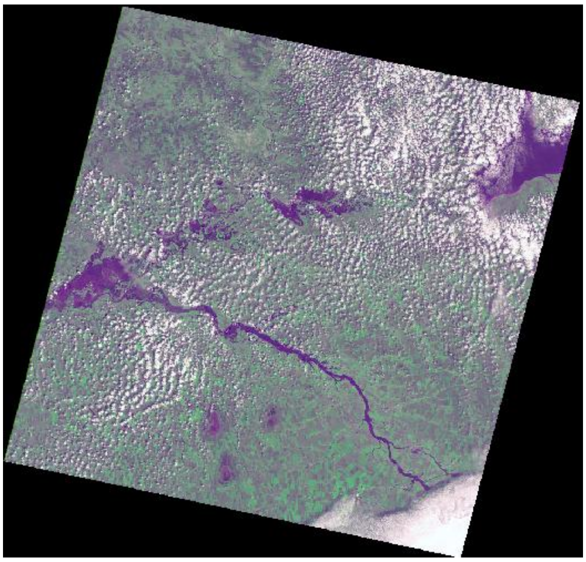


1979-04-06

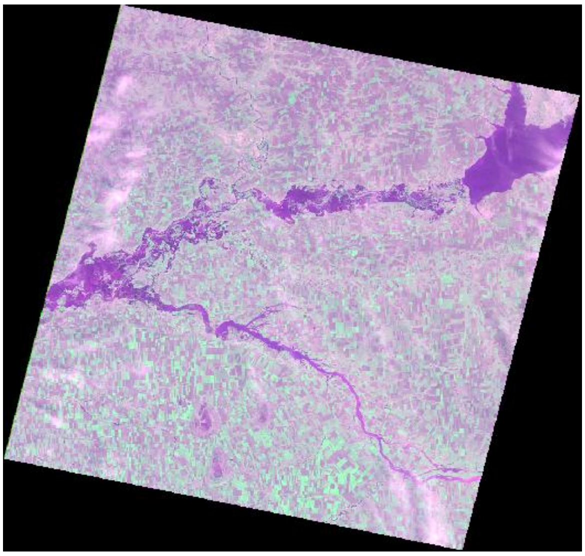
1979-04-15



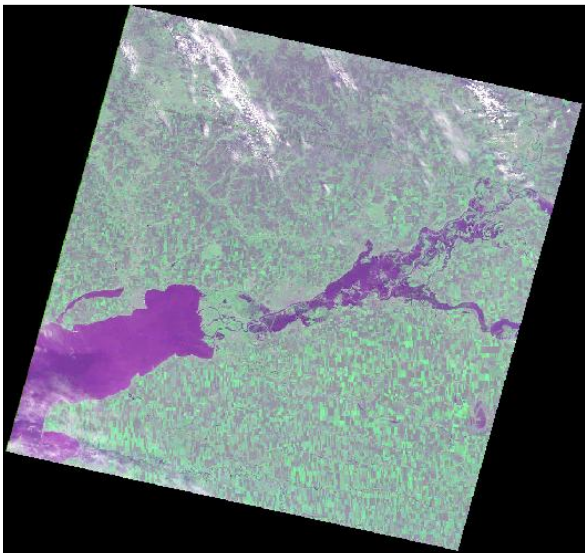
1979-05-03



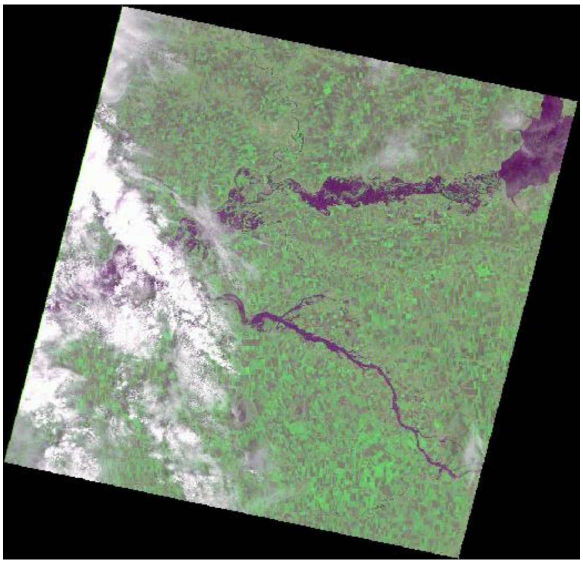
1979-05-04



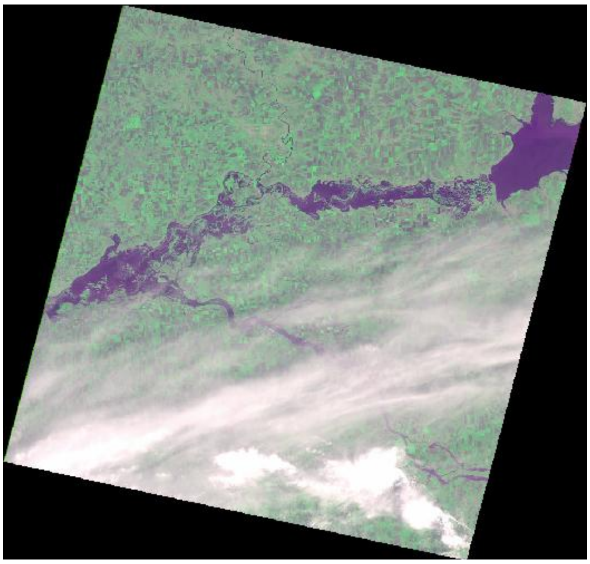
1979-05-12



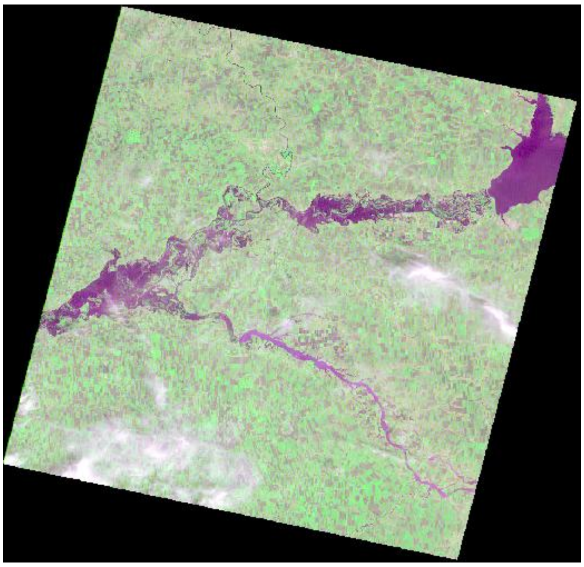
1979-05-21



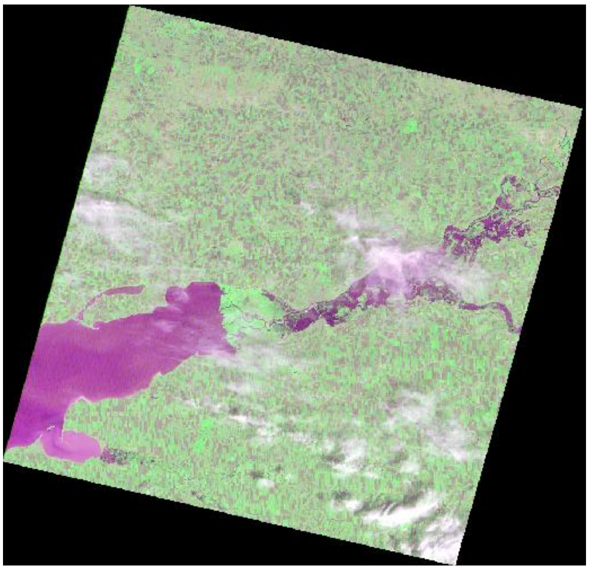
1979-05-30



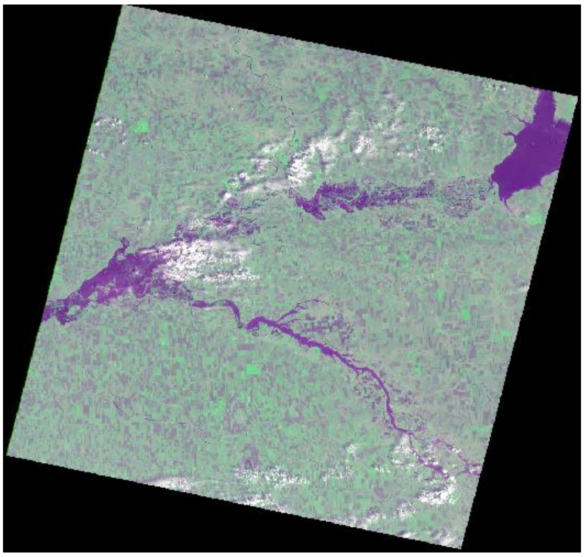
1979-05-31



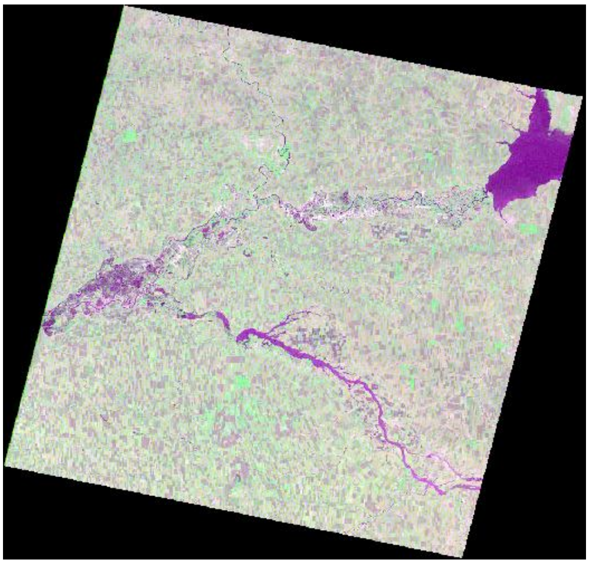
1979-06-08



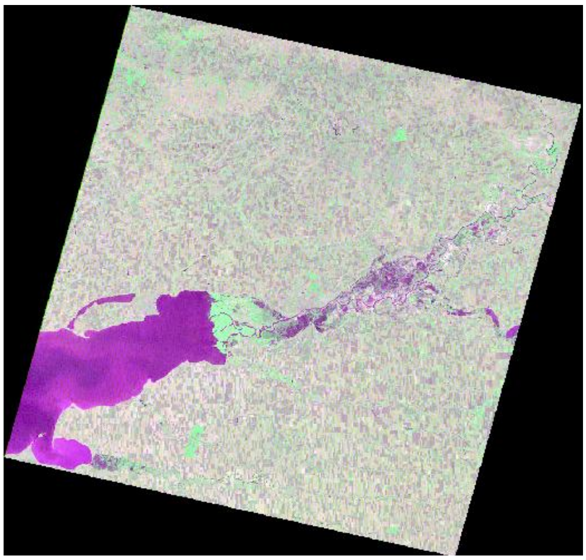
1979-06-17



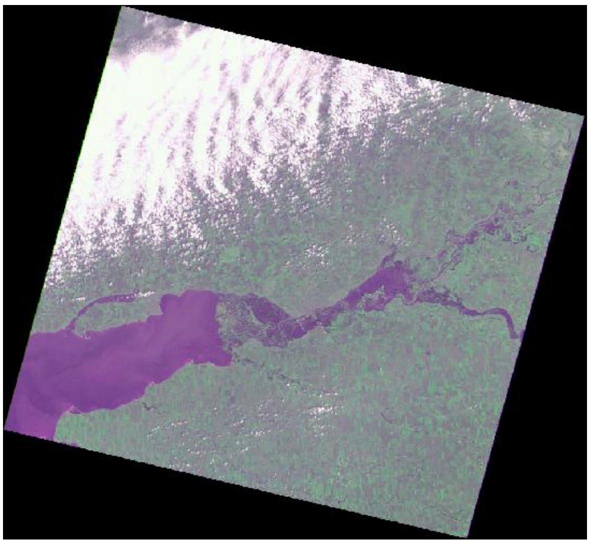
1979-06-18



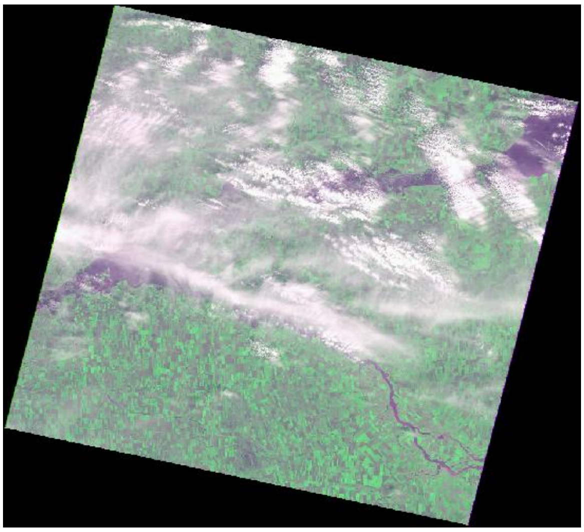
1981-04-23

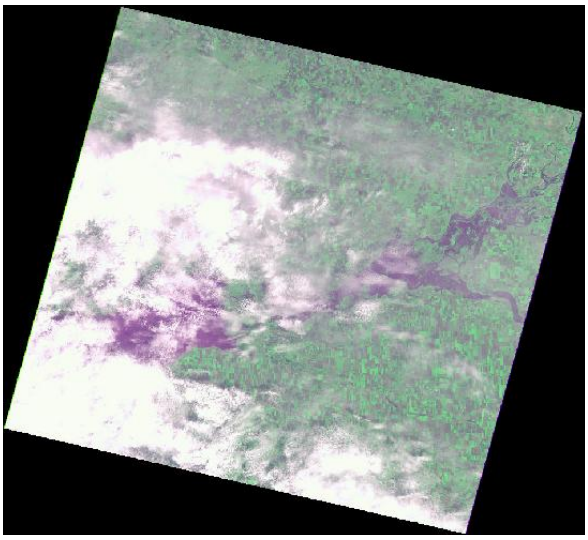


1981-05-10



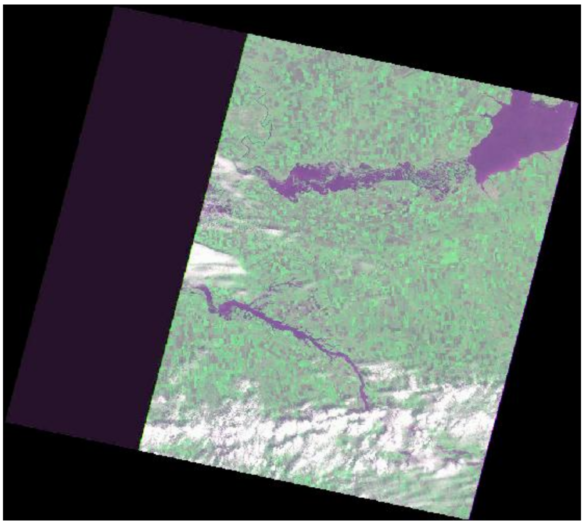
1981-05-11

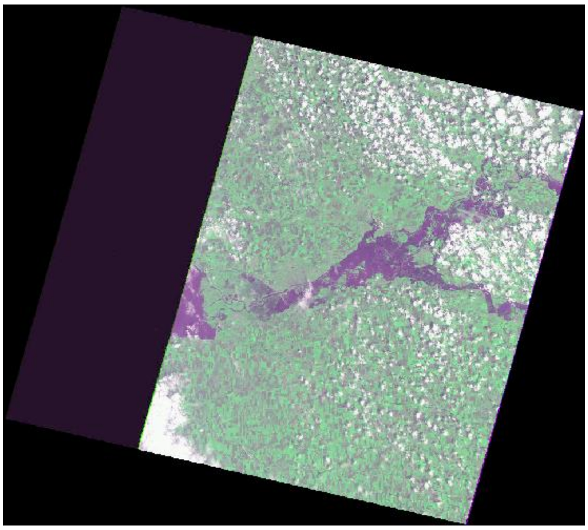




1981-05-19

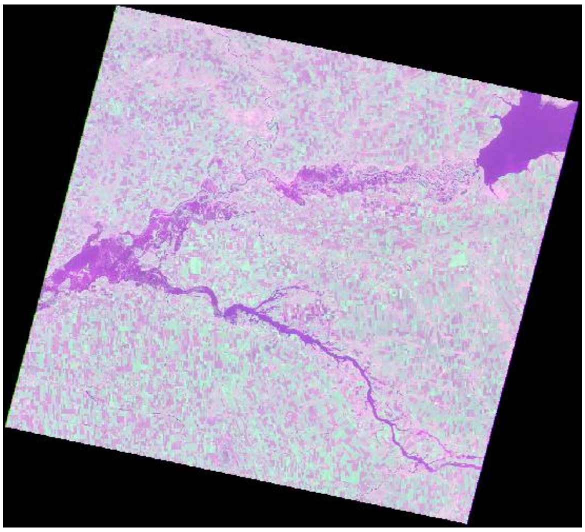
1981-05-20

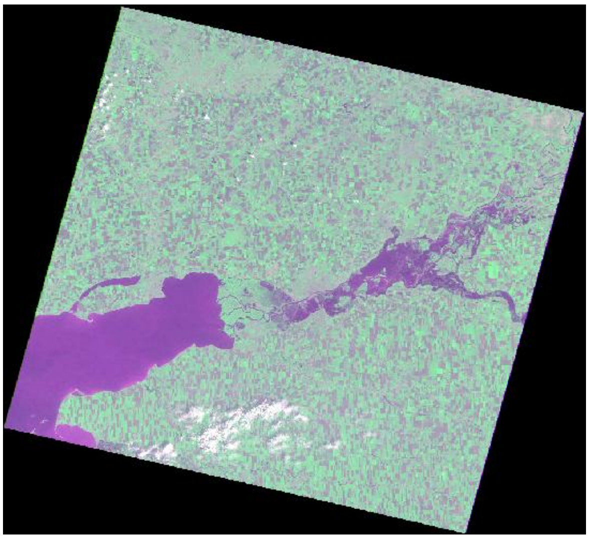




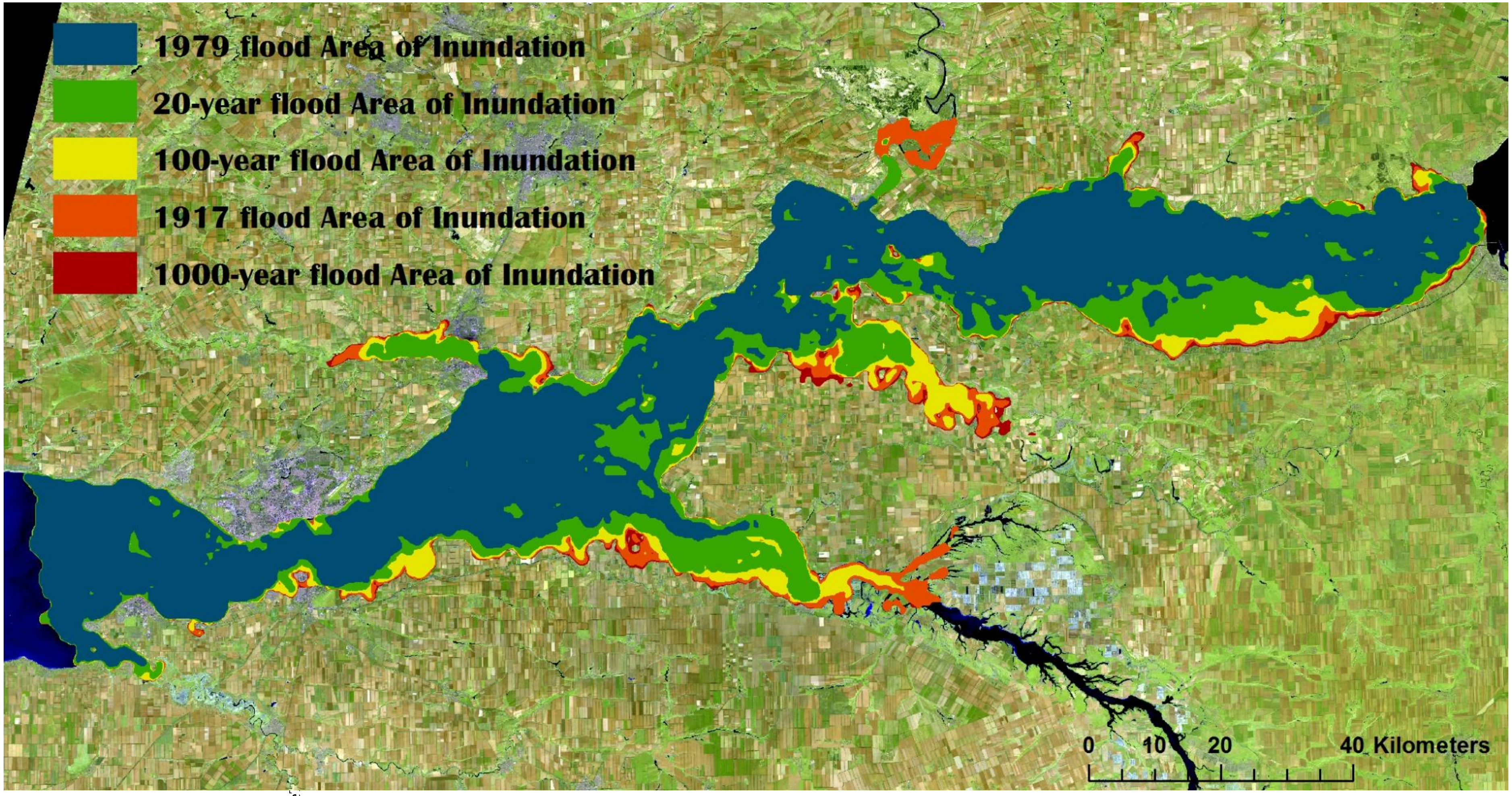
1981-05-28

1981-05-29

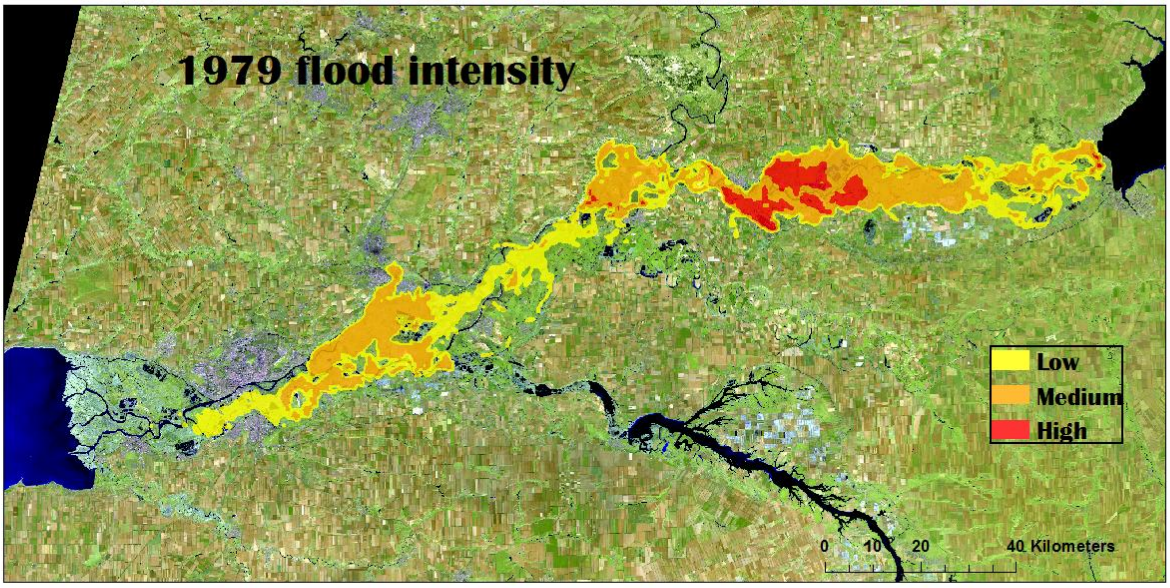


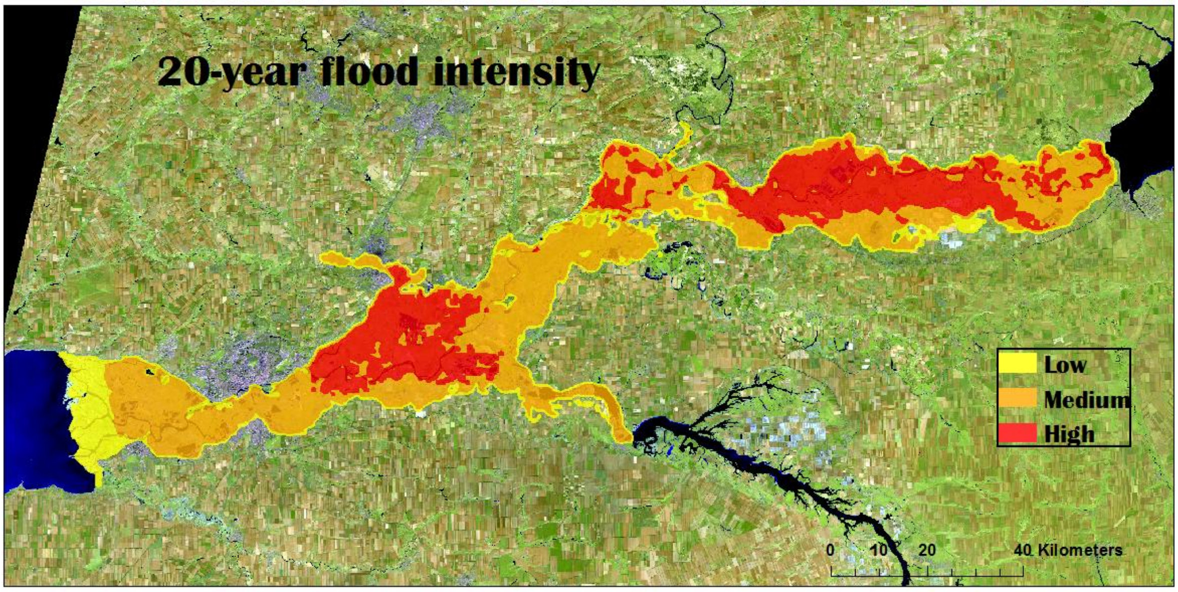


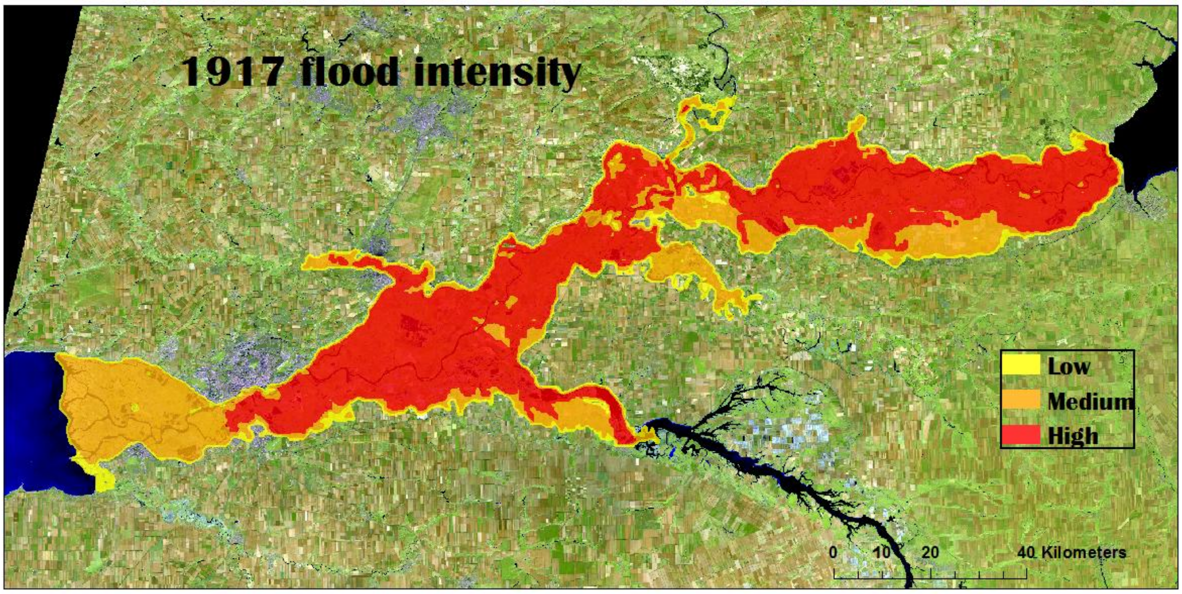
Appendix 4 Inundation areas

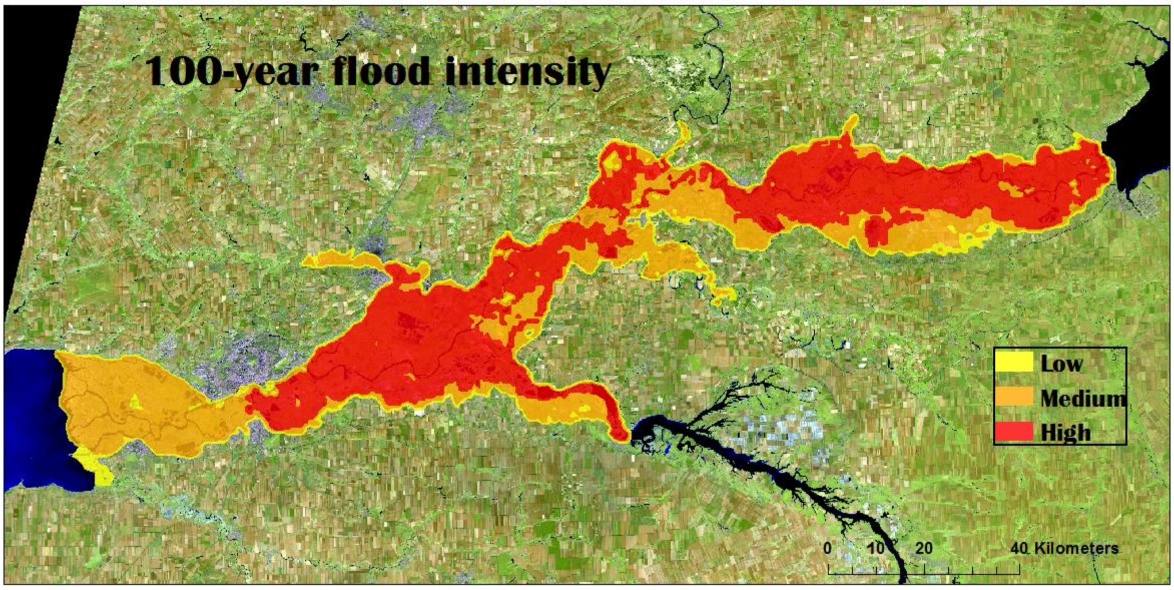


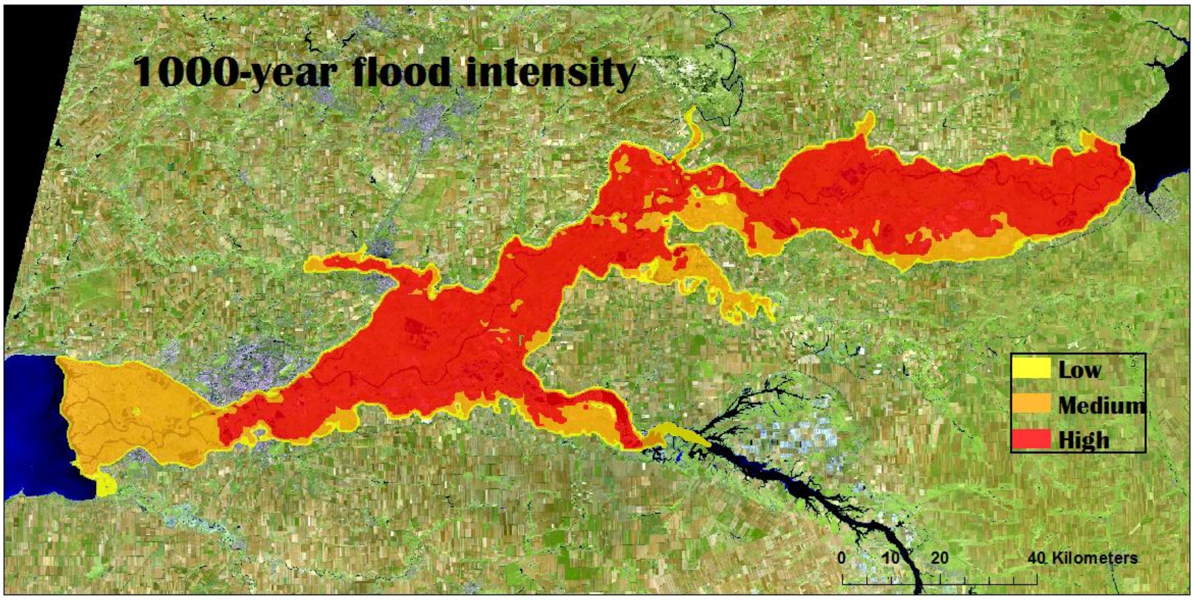
Appendix 5 Flood intensity maps



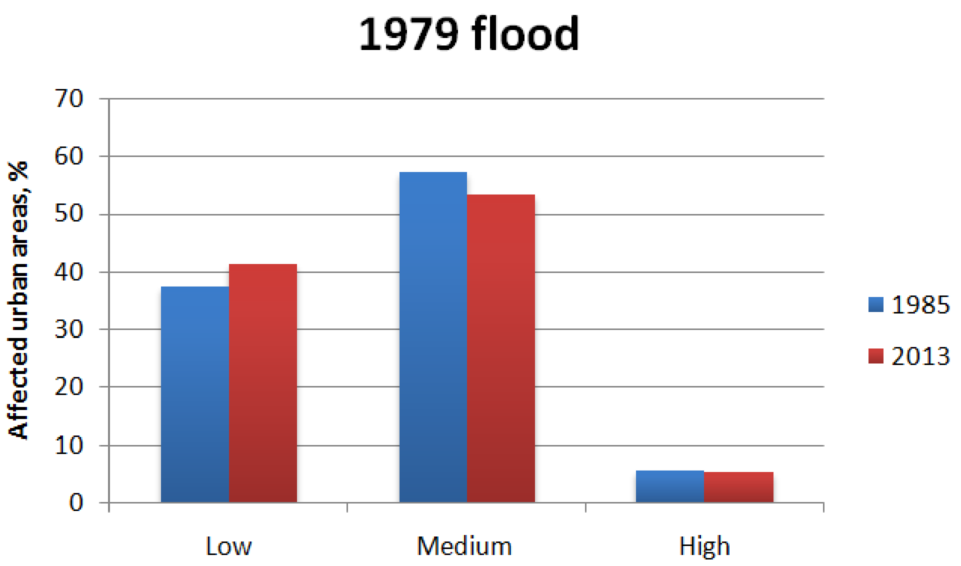


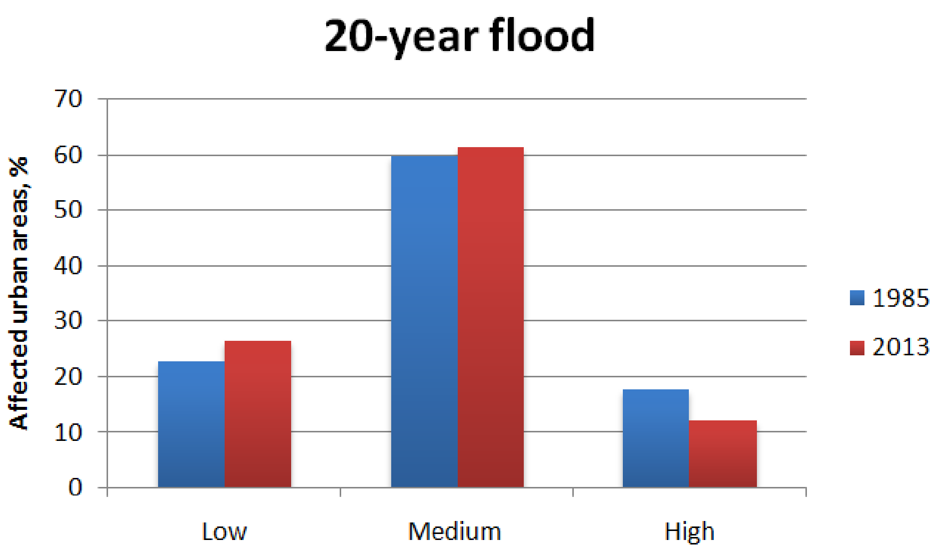


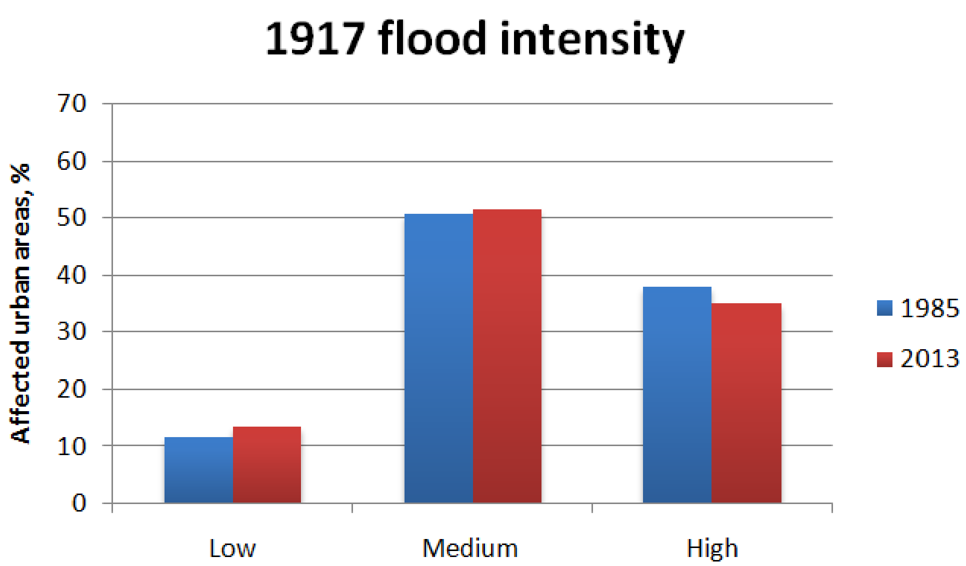

100-year flood intensity
Low
Medium
High
0 10 20 40 Kilometers

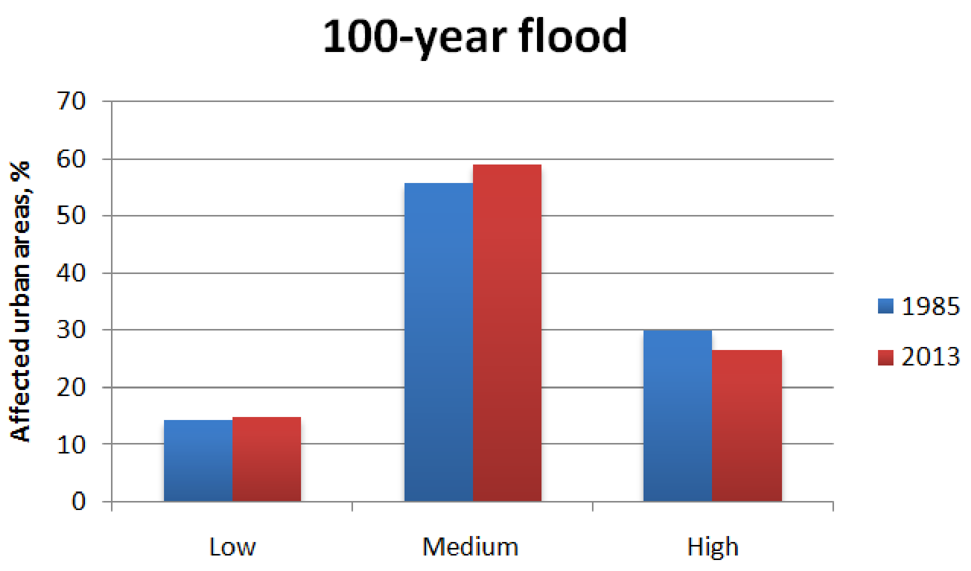

1000-year flood intensity
Low
Medium
High
0 10 20 40 Kilometers

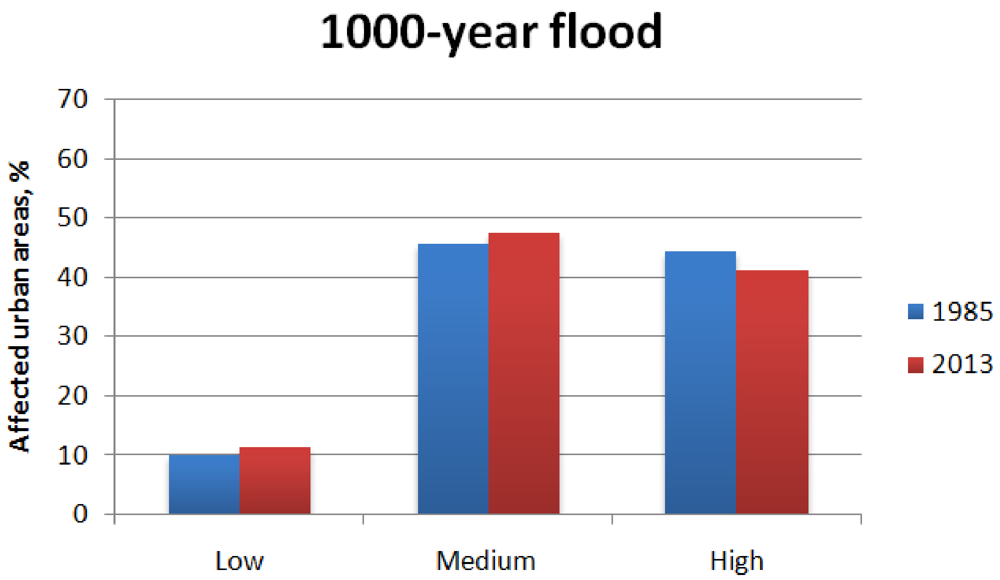
Appendix 6 Affected urban areas by flood intensity for each scenario



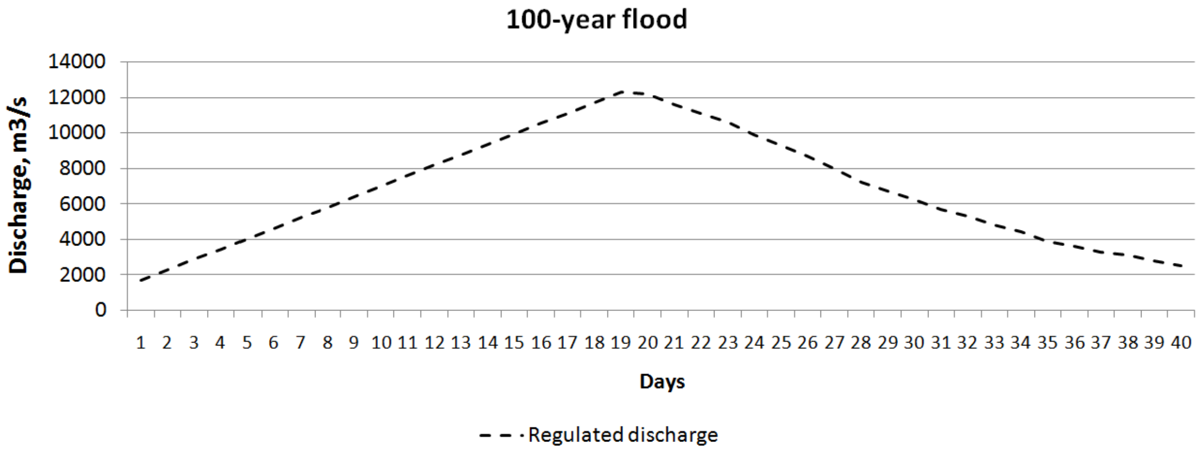




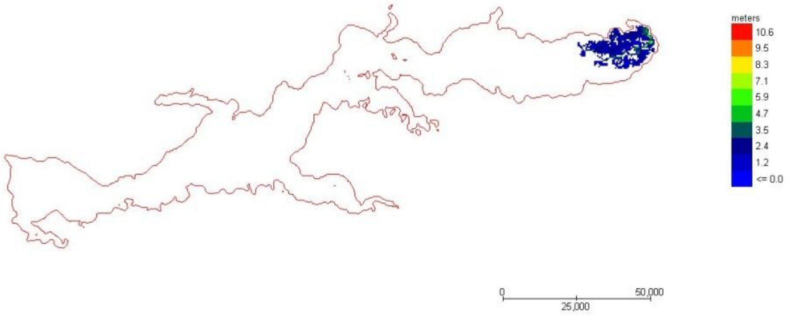

100-year flood
Affected urban areas, %
70
60
50
40
30
20
10
0
Low
Medium
High
1985
2013


1000-year flood
Affected urban areas, %
70
60
50
40
30
20
10
0
Low
Medium
High
1985
2013

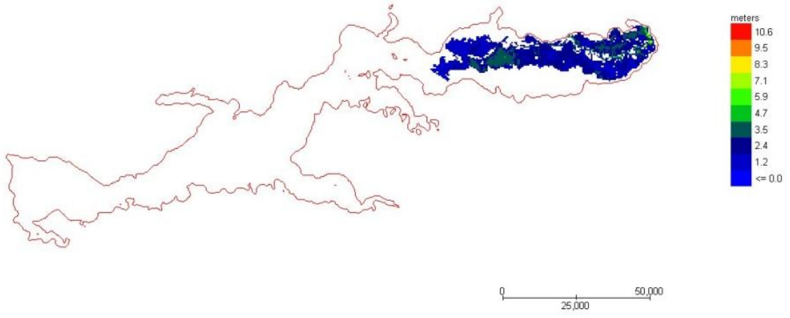
Appendix 7 100-year flood progression



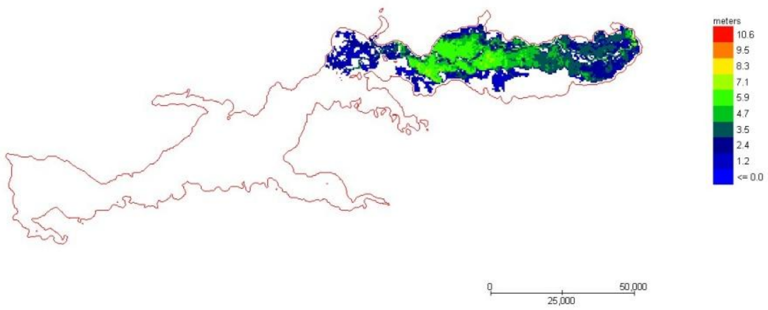
Day 2



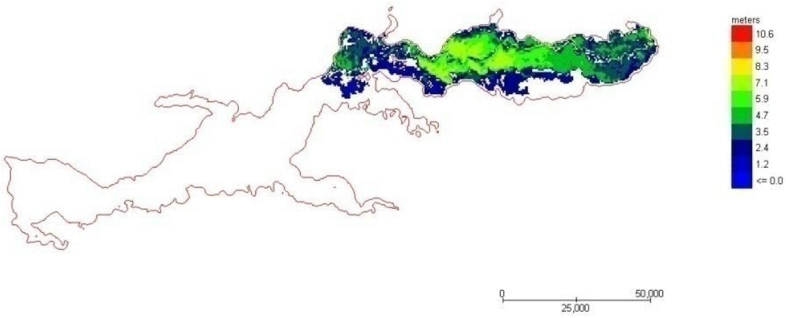
Day 5



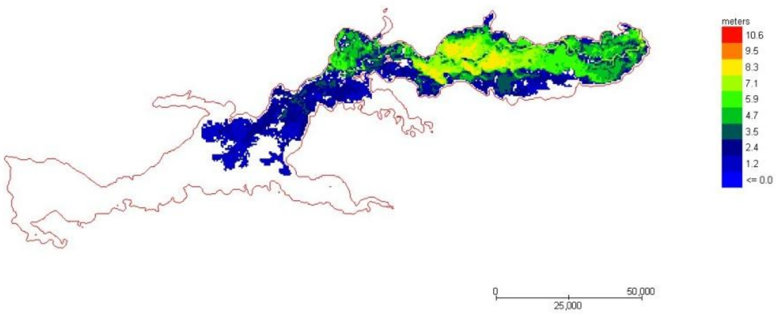
Day 10



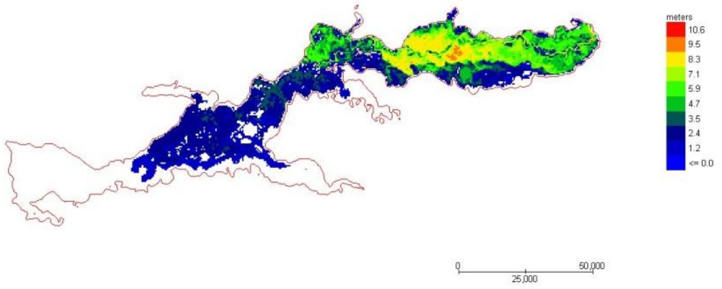
Day 12



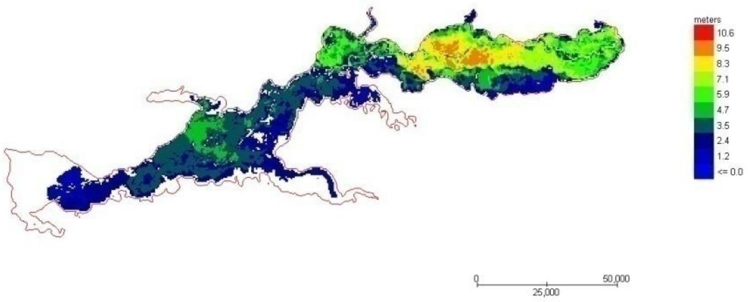
Day 15



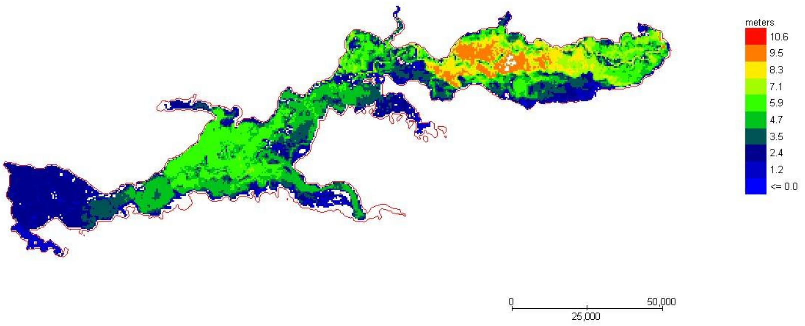
Day 17



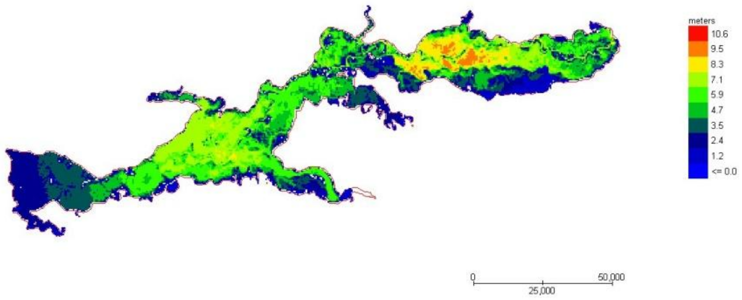
Day 20



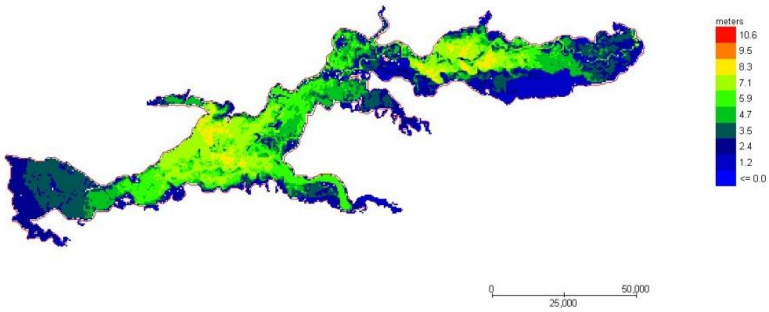
Day 25



Day 30


meters
10.6
9.5
8.3
7.1
5.9
4.7
3.5
2.4
1.2
<= 0.0
0
50,000
25,000

Day 40


meters
10.6
9.5
8.3
7.1
5.9
4.7
3.5
2.4
1.2
<= 0.0
0
50,000
25,000

Appendix 8 Screenshots of www.azovcenter.ru showing the results of the 100-year flood simulation