P170526

Report on Hydraulic Modelling

Assessment of Suitable Flood Mitigation Measures (based on Dukniskhevi River Extreme Flood Analysis) in Tbilisi, Georgia

CTCN REFERENCE NUMBER: 2016000043

HYDROC

Document Information	
Date	17.05.2017
HYDROC project no.	P170526
HYDROC responsible	Juan Fernandez
Client	CTC-N/UNIDO
Reference No.	2016000043
Project No.	
Credit No.	

Contact
HYDROC GmbH
Siegum 4
24960 Siegum
Germany

Tel **-** +49 172 450 91 49
Email **-** info@hydroc.de

Executive Summary

The main objective of this technical assistance is to improve the flood risk management in the Leghvtakhevi River basin in Tbilisi (Georgia) through the implementation of a modelling framework, including climate change modelling, hydrological modelling and hydraulic modelling, the latter being the main focus of this report.

The overall hydraulic modelling approach, as described in the Deliverable 3 of this technical assistance ('Description of suitable methodology and technology for flood modelling and mapping'), is conditioned by the river characteristics, data availability and existing resources. The main objective of the hydraulic modelling exercise is to produce flood maps using the information from the climate change and hydrological modelling and to create a base product that will be use in the flood mitigation exercise.

The numerical model chosen to undertake the hydraulic modelling tasks within this consultancy is HEC-RAS 5.0.5. The fact that HEC-RAS is an open-source software with the same capabilities as other (commercial) software, with a proven track-record of having been implemented in a wide range of scenarios worldwide, is one of the main reasons for this model selection. HEC-RAS can be implemented in 1D, 1D-2D or 2D mode, and the mathematical approach to each of the dimensional modules is based on the Navier-Stokes equations.

The main steps required in order to implement a hydrodynamic model in HEC-RAS are common to all hydraulic modelling projects. A project has to be defined; the geometry of this project, including the river geometry, the cross sections and the structures has to be defined; boundary conditions, including upstream (flow) and downstream (water level or slope) conditions; the simulation parameters have to be defined and the output of the model have to be carefully checked.

In order to implement a hydraulic model, several data requirements exist, such as geometry information (including a digital elevation model, cross sections and structures), boundary conditions and historical information for calibration. It should be noted that within the framework of this project a cross section and structure survey of the river was undertaken covering the most important section of the river. A total of 119 river cross sections, 18 structures and 1m LiDAR DEM (covering the whole catchment) were acquired during the project data collection phase. It should be noted that no calibration information could be collected (historical levels or discharge), and the impact that this may have on the project results will be analysed in detail. In addition to that, several site visits were undertaken by HYDROC's and local experts to the catchment.

The initial model implementation was undertaken following a 1D-2D approach. In a 1D-2D implementation, the two models are implemented independently and then linked together once they are performing adequately. The 1D implementation was undertaken considering the model domain (covering all the surveyed watercourses), including all the cross section and structure information from the survey. Also, interpolated cross sections were added in order to increase the stability of the model, especially in areas where the cross section spacing was high or where there was a significant change in the river profile. Boundary conditions in the model were defined considering the input from the hydrological modelling study previously completed, whereas a constant water level was selected as the downstream boundary conditions.

The 1D modelling results were not satisfactory. This is because the peculiarities of this river including the very high gradient, the presence of several waterfalls, the presence of a long culvert (175m) at the downstream end and the significant changes in cross sectional area at some locations. A significant modelling effort was undertaken in order to increase the stability of the model and the accuracy of the results. Once this model was linked to the 2D domains in the floodplains and urban area, the stability of the model (due to the inclusion of the lateral links) was reduced drastically, and therefore a different approach was taken in order to produce sensible results.

To overcome the stability issues, it was decided to model the whole catchment in 2D, incorporating the information from the survey into the DEM in order to increase the accuracy of the terrain information. The implementation of the 2D model was similar to the one of the 1D domain. The model domain covered the main Leghvtakhevi River and all the tributaries. Further, all relevant structures were included in the model. Boundary conditions were defined in the same locations and using the information from the hydrological modelling. Also, the model domain was extended further down in the Kura River in order to avoid any problem in the boundary definition causing an impact on the results in the study area.

The model stability with the 2D approach was significantly higher. Several sensitivity tests, including time-step, roughness and downstream boundary condition tests, were undertaken in order to probe the model stability with satisfactory results. The main drawback with the implementation of the model in 2D is computational time. Nonetheless, significant computational resources were used in order to limit this impact.

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List of Abbreviations

CTC-N	Climate Technology Centre and Network
DEM	Digital Elevation Model
ED	Environment and Development
EMA	Emergency Management Agency
FEMA	Federal Emergency Management Agency
GIS	Geographical Information System
GPM	Global Precipitation Measurement
HEC	Hydrologic Engineering Center
MPE	Multisensor Precipitation Estimate
NEA	National Environment Agency
RMS	Root Mean Square Error
SCS	Soil Conservation Service
TRMM	Tropical Rainfall Measuring Mission
UNFCCC	United Nations Framework Convention on Climate Change
WFD	Water Framework Directive

1 Introduction

The main objective of this consultancy is to improve the flood risk management in the Leghvtakhevi River basin in Tbilisi (Georgia). This will be accomplished through the implementation of a modelling framework, the inclusion of climate change impacts, the definition of flood maps and the designation of flood mitigation and adaptation measures. Capacity building and technological transfer activities will be undertaken too, and will be at the core of the project.

This consultancy started in August 2017 and it is due to finish in August 2018 (duration of 12 months). The contract between UNIDO and HYDROC was signed on the 14th of August 2017.

This technical assistance is managed by the CTC-N, the National Designated Entity is the Ministry of Environment and Natural Resources Protection of Georgia, while key stakeholders are the National Environmental Agency Request (request applicant), the Tbilisi Municipality and the Emergency Management Agency under the Ministry of Internal affairs.

This report will describe the methodology that will be followed during the implementation of this technical assistance.

2 Overall Hydraulic Modelling Approach

Leghvtakhevi River is located in Tbilisi and it is a permanent right tributary of the Mtkvari (Kura) River. The river originates at the mountain Udzo and its headwaters are situated at 1,200m above sea level, whereas the elevation at the junction with the Mtkvari is 385m. The Leghvtakhevi River is characterised with floods in spring and powerful flash-floods. The project area covers the whole Leghvtakhevi basin.

From a modelling point of view, the Leghvtakhevi catchment can be divided into the upper, middle and lower catchments. The upper catchment is characterised by undefined and steep channels; steep slopes, gorges and narrow passages are present in the middle catchment; the lower catchment is characterised by several waterfalls, a long culvert and milder slopes.

There are no significant reports of flooding in the last decades in the Leghvtakhevi River. The last time a flood event occurred in this catchment (in 1956), it occurred in the downstream end of the river, close to the sulphur baths. Nonetheless, the following should be considered:

- The land use has changed significantly in the upper catchment in recent years. There are numerous new developments close to the river channels that can lead to booth additional run-off and new areas at risk.
- Most of the dams that were constructed after the 1956 flooding are non-operational at this stage.
- Climate Change impacts in this catchment are considered to be an issue from a flooding point of view.
- There are plans to develop this catchment further.

In order to model this river, the following approach has been initially proposed:

- The river channel to be modelled in 1D. This is to speed up simulation times and because in the river channel there are no specific technical benefits to use 2D modelling, especially in the narrow (gorge) sections.
- The floodplains to be modelled using a 2D approach. The urban area in the lower catchment has been linked to the 1D channel through lateral structures.
- Thus, in order to be able to undertake flood mapping for the whole catchment, and considering all the information previously outlined, a combined 1D+2D type of model has been initially selected.

3 Numerical Model Technical Description

As it was detailed in the methodology described in the Deliverable 3: "Description of suitable methodology and technology for flood modelling and mapping", HEC-RAS 5.0 has been selected as the numerical modelling software for this study. As described in this methodology report, there are several reasons behind that decision, but the main ones are:

- HEC-RAS is one of the most widely used and accepted modelling software worldwide.

- HEC-RAS has been evaluated by several flood responsible agencies worldwide and it is accepted by relevant organisations such as the Environment Agency of England and Wales or the Federal Emergency Management Agency (FEMA) in the US.
- HEC-RAS capacities and results are comparable to the ones from any other software. In fact, as per the experience of the hydraulic modelling expert, HEC-RAS capacities to model long culverts are considered better than the ones by other similar modelling software.
- HEC-RAS is free of charge and there are no associated issues related to license maintenance.
- HEC-RAS can be used as a forecasting software.

HEC-RAS is an integrated system of software, designed for interactive use in a multi-tasking environment. The system comprises a graphical user interface (GUI), separate analysis components, data storage and management capabilities, graphics and reporting facilities. The HEC-RAS system contains the following river analysis components for:

- Steady flow water surface profile computations
- One-dimensional and/or two-dimensional unsteady flow simulation
- Quasi unsteady or fully unsteady flow movable boundary sediment transport computations
- Water quality analysis

A key element is that all four components use a common geometric data representation and common geometric and hydraulic computation routines. In addition to the four river analysis components, the system contains several hydraulic design features that can be invoked once the water surface profiles are computed.

HEC-RAS is designed to perform one-dimensional and two-dimensional hydraulic calculations for a full network of natural and constructed channels, overbank/floodplain areas or levee protected areas.

3.1 Overview of the 1D engine

The physical laws which govern the flow of water in a stream are:

- The principle of conservation of mass (continuity), and
- The principle of conservation of momentum.

These laws are expressed mathematically in the form of partial differential equations.

3.1.1 Implicit Finite Difference Scheme

The most successful and accepted procedure for solving the one-dimensional unsteady flow equations is the four-point implicit scheme, also known as the box scheme. Under this scheme, space derivatives and function values are evaluated at an interior point. For each river, a system of simultaneous equations results. The simultaneous solution is an important aspect of this scheme because it allows information from the entire reach to influence the solution at any one point. Consequently, the time step can be significantly larger than with explicit numerical schemes.

The HEC-RAS Unsteady flow engine combines the properties of the left and right overbank into a single flow compartment called the floodplain.

Hydraulic properties for the floodplain are computed by combining the left and right overbank elevation vs. area, conveyance, and storage into a single set of relationships for the floodplain portion of the cross section. The reach length used for the floodplain area is computed by taking the arithmetic average of the left and right overbank reach lengths.

The average floodplain reach length is used in both the continuity and momentum equations to compute their respective terms for a combined floodplain compartment (left and right overbank combined together).

3.2 Overview of the 2D engine

The Navier-Stokes equations describe the motion of fluids in three dimensions. In the context of channel and flood modelling, further simplifications are imposed. One simplified set of equations is the Shallow Water (SW) equations. Incompressible flow, uniform density and hydrostatic pressure are assumed and the equations are Reynolds averaged so that turbulent motion is approximated using eddy viscosity. It is also assumed that the vertical length scale is much smaller than the horizontal length scales.

As a consequence, the vertical velocity is small and pressure is hydrostatic, leading to the differential form of the SW equations derived in subsequent sections. In some shallow flows the barotropic pressure gradient (gravity) term and the bottom friction terms are the dominant terms in the momentum equations and unsteady, advection, and viscous terms can be disregarded. The momentum equation then becomes the two dimensional form of the Diffusion Wave Approximation. Combining this equation with mass conservation yields a one equation model, known as the Diffusive Wave Approximation of the Shallow Water (DSW) equations. Furthermore, in order to improve computation time, a sub-grid bathymetry approach can be used. The idea behind this approach is to use a relatively coarse computational grid and finer scale information about the underlying topography. The mass conservation equation is discretised using a finite volume technique. The fine grid details are factored out as parameters representing multiple integrals over volumes and face areas. As a result, the transport of fluid mass accounts for the fine scale topography inside of each discrete cell. Since this idea relates only to the mass equation, it can be used independent of the version of the momentum equation. In the sections below, sub-grid bathymetry equations are derived in the context of both; full Shallow Water (SW) equations and diffusive wave approximation of the shallow water equations (DSW) equations.

Modern advances in the field of airborne remote sensing can provide very high resolution topographic data. In many cases the data is too dense to be feasibly used directly as a grid for the numerical model. This presents a dilemma in which a relatively coarse computational grid must be used to produce a fluid simulation, but the fine topographic features should be incorporated in the computation. The solution to this problem that HEC-RAS uses is the sub-grid bathymetry approach. The computational grid cells contain some extra information such as hydraulic radius, volume and cross sectional area that can be pre-computed from the fine bathymetry. The high resolution details are lost, but enough information is available so that the coarser numerical method can account for the fine bathymetry through mass conservation. For many applications this method is appropriate because the free water surface is smoother than the bathymetry so a coarser grid can effectively be used to compute the spatial variability in free surface elevation.

3.3 Overview of the linking method

The 1D and 2D domains link can be carried out in HEC-RAS through different means, depending on the particular location and in the purpose of the linking:

- Standard Link: where one or more 2D grid cells are linked to the end of a 1D river branch. This type of link is useful for connecting a detailed 2D mesh into a broader 1D network. The standard link is explicit
- Lateral Link: a lateral link allows a string of 2D grid cells to be laterally linked to a given reach in 1D, either a section of a branch or an entire branch. Flow through the lateral link is calculated using the weir equation. This type of link is particularly useful for simulating overflow from a river channel onto a flood plain. For lateral links, flow from the river model goes via a lateral structure, which is then applied into 2D domain. A structure is required to calculate the flow between the 1D and the 2D domains.

4 General Steps in Developing a Hydraulic Model with HEC-RAS

A brief description of the required process to implement a hydraulic model in HEC-RAS will be outlined in this section. It should be noted that a more thorough description of all the processes and more practical recommendations for best practices in hydraulic modelling will be given during the training activities associated to this technical assistance.

There are five main steps in creating a hydraulic model with HEC-RAS:

- Starting a new project
- Entering geometric data
- Entering flow data and boundary conditions
- Performing the hydraulic calculations

- Viewing and producing results

4.1 Starting a New Project

The first step in developing a hydraulic model with HEC-RAS is to establish which directory you wish to work in and to define a new project.

4.2 Entering Geometric Data

The next step is to enter the necessary geometric data, which consist of a background map layer (optional), connectivity information for the stream system (river system schematic), cross-section data, and hydraulic structure data (bridges, culverts, weirs, etc.).

The modeller can develop the geometric data in HEC-RAS by first drawing in the river system schematic. After the river system schematic is drawn, the modeller can start entering cross-section and hydraulic structure data. The River, Reach and River Station identifiers are used to describe where the cross section is located in the river system. HEC-RAS requires cross sections to be ordered within a reach from the highest river station upstream to the lowest river station downstream.

The required data for any cross section consists of station-elevation data (cross section point coordinates); downstream reach lengths (distances from the current cross section to the next cross section downstream); Manning’s n values (at a minimum you must have a left overbank, main channel, and right overbank Manning’s n value.

Once the cross-section data are entered, the modeller can then add any hydraulic structures such as bridges, culverts, dams, weirs and spillways.

It should be added that some of this information can be prepared using external resources, such as the HEC-GeoRAS module within ArcGIS. Using this module the modeller can prepared the river network and the cross section information and then export that to HEC-RAS.

4.3 Entering Flow Data and Boundary Conditions

Once the geometric data are entered, the modeller can then enter either steady flow or unsteady flow data. The type of flow data entered depends upon the type of analyses to be performed. Boundary conditions are required in order to perform the calculations.

4.4 Performing the Hydraulic Computations

Once all of the geometric data and flow data are entered, the modeller can begin to perform the hydraulic calculations. There are five types of calculations that can be performed in HEC-RAS: Steady Flow Analysis, Unsteady Flow Analysis, Sediment Transport/Mobile Boundary Modelling, Water Quality Analyses, and Hydraulic Design Functions.

4.5 Viewing and Printing Results

Once the model has finished all of the computations, the modeller can begin viewing the results.

5 Data Analysis

One of the most crucial stages in any hydraulic modelling exercise is the analysis of the data available. The following data was acquired for the implementation of the hydraulic model in the Leghvtakhevi River Basin.

5.1 Topographic data

The topographic data acquired for the implementation of the hydraulic model can be divided into the field data and the digital elevation model data.

5.1.1 River Survey

The topographical survey of the Leghvtakhevi River in Tbilisi, Georgia was undertaken following short survey instructions as detailed in the deliverable 2 previously mentioned. The Leghvtakhevi catchment includes a main water body and several major tributaries. The following survey information was collected (Figure 1).

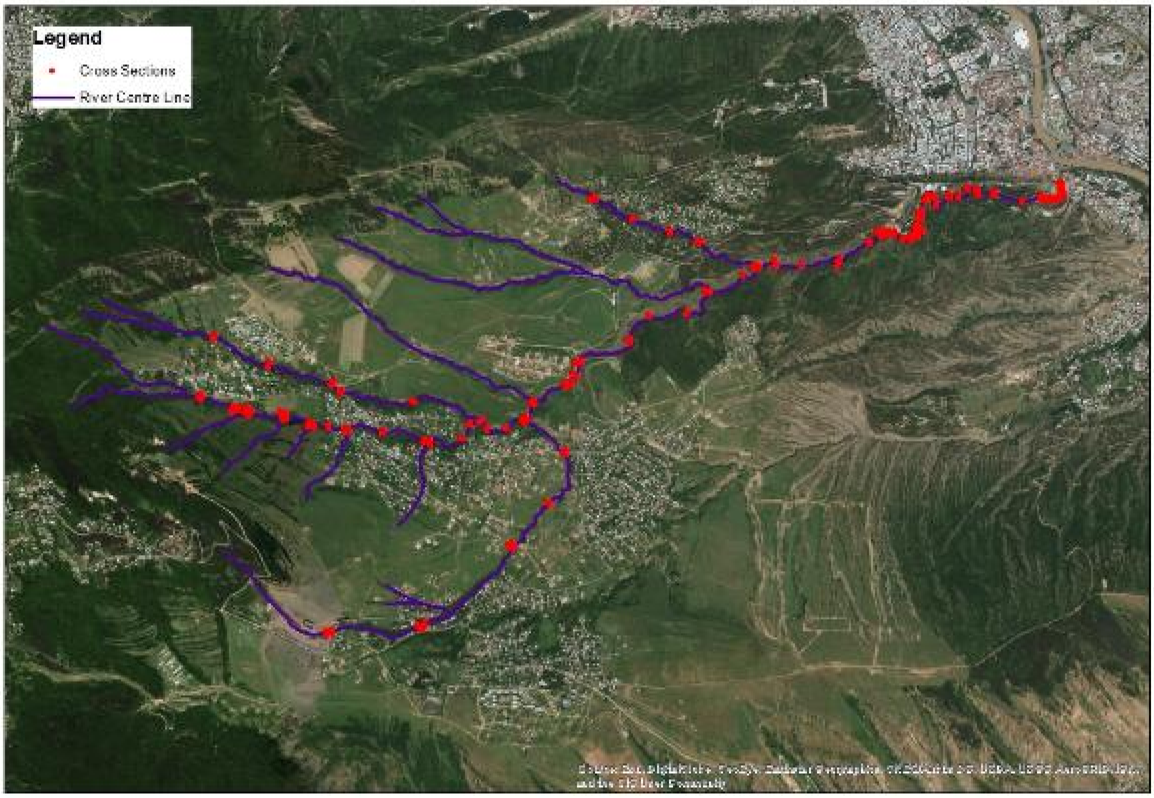

Figure 1 – Cross Section Data collected

A total of 119 cross sections were measured during the survey campaign. The data from the cross section survey field campaign was received in Excel format and it was analysed and processed prior to the inclusion in the hydraulic model.

5.1.2 Digital Elevation Model

A Digital Elevation Model (DEM) of the study area was made available. A 1m LiDAR DEM obtained by the Tbilisi City Hall was collected and processed before the inclusion in the hydraulic model (Figure 2). It should be noted that the DEM will be used during the hydraulic model for both the flood mapping and for the hydraulic modelling of the areas not covered by the cross section field survey.

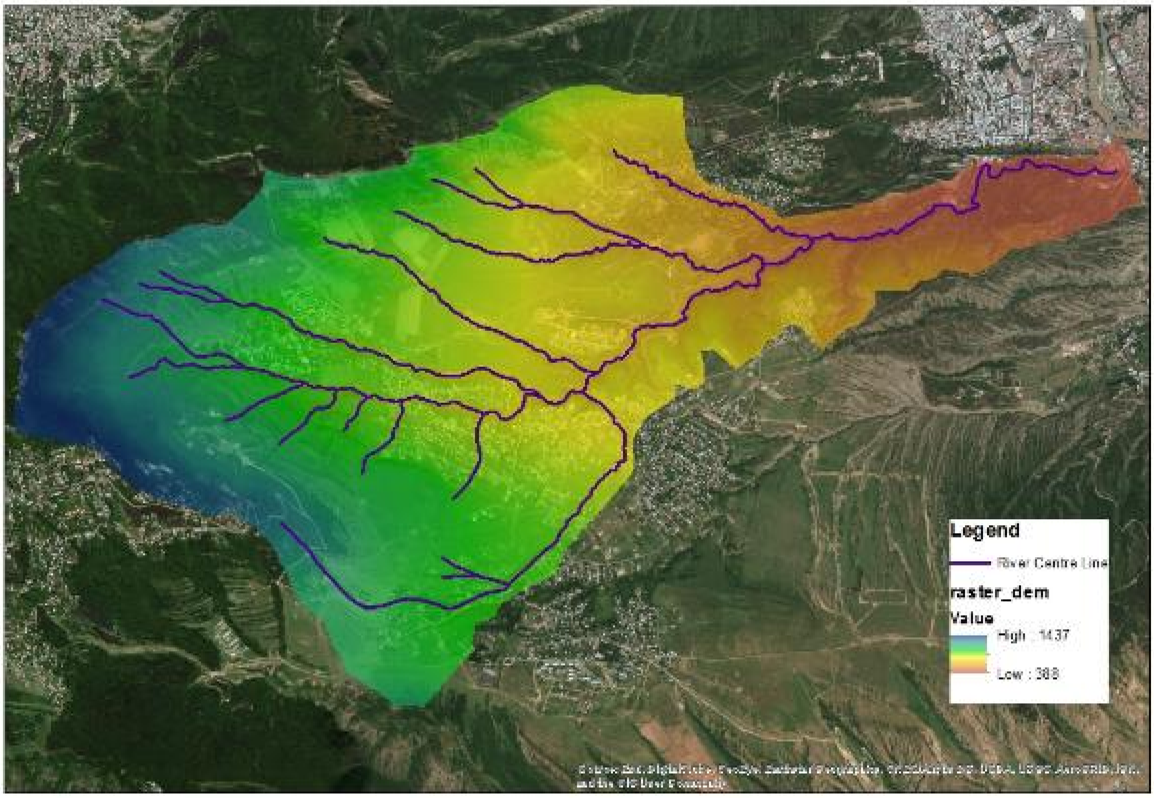

Figure 2 – Digital Elevation Model

5.2 Rainfall/hydrometric data and historical flooding data

All the available rainfall and hydrological monitoring data was collected during the data collection phase. All these data have been previously described and analysed in Deliverable 2: "Report on data acquisition" and Deliverable 3: "Description of suitable methodology and technology for flood modelling and mapping". The main idea behind the collection of these data, from a hydraulic modelling point of view, is to use them in the calibration and validation of the hydraulic model. The collected data was not useful for this purpose, because no water level data is available within the catchment for calibration. There is information about historical flooding available, but this flooding occurred before significant interventions in the catchment (in 1903 and 1955); also there is not enough information available to be able to simulate those events.

5.3 Site Visit

Several site visits were undertaken by the hydraulic modelling expert within the framework of this project to the study area.

- During the first mission to Tbilisi, the hydraulic modelling expert visited the Leghvtakhevi River Basin in two occasions, once with staff from the Emergency Management Department and in another occasion with staff from the National Environment Agency.
- During the third mission to Tbilisi, the hydraulic modelling and flood mitigation experts visited the study area with local experts in order to analyse the possible flood mitigation options and to verify the first results from the hydraulic modelling exercise.

The information collected during the site visits was useful for:

- Identification of the correct roughness and resistance for the hydraulic modelling implementation.
- Identification of possible issues during the hydraulic modelling implementation.
- Verification of the areas pre-defined as flood susceptible during the initial stages of the hydraulic modelling implementation.

6 Model Implementation

As previously explained, the flooding mechanism in the study area recommends the implementation of a 1D+2D hydraulic model. In the first place, using the information from the survey, a 1D model was implemented. In a second stage, the 2D model was implemented using the information from the DEM acquisition. Initially the two models were implemented separately and then they were linked. This process was followed in order to facilitate the modelling implementation.

6.1 1D Model Build

The implementation of the 1D model was undertaken in the following stages.

6.1.1 Model Domain

The model domain was selected based on the project objectives and the hydraulic modelling limitations. Flood mapping and flood mitigations have to be undertaken for the whole Leghvtakhevi River Basin, and therefore, the domain for the 1D model covered the whole Leghvtakhevi River (Figure 3). Several other small watercourses draining into the Leghvtakhevi were also include into the 1D domain. These watercourses were connected to the Leghvtakhevi using junctions.

Figure 3 – 1D Model Domain

The longitudinal profile of the Leghvtakhevi River is shown in Figure 4. As it can be observed, the whole length of the river is almost 10 kilometres, the upstream end point in the model being at 1024m while the model junction with the Kura River is located at 389m. This differs slightly from the minimum and maximum elevations of the catchment area.

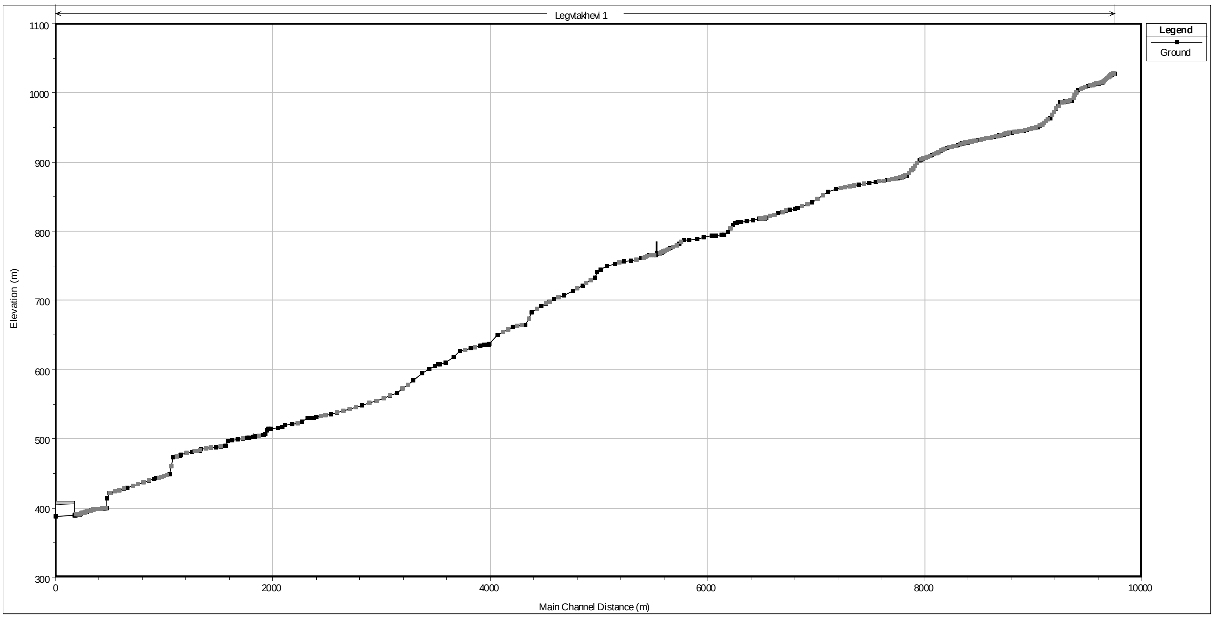

Figure 4 – Longitudinal Profile of the Leghvtakhevi River

6.1.2 Geometry

The implementation of a 1D hydraulic model requires the input of several data sources, as previously described. The cross section data from the field survey was analysed and include in the model. The final number of cross sections in the model was increased to 585, because of interpolated cross sections. The interpolated cross sections were included after initial assessments of the model stability and were required in the following cases:

- When there was no upstream and/or downstream cross section close to structures
- When there was a significant river length between surveyed cross sections. The stipulated maximum length between cross sections varies depending on the model stability. In high steep sections or close to the downstream boundary more cross sections were required.
- It should be noted that due to the high gradient present in this river, a great number of interpolated cross sections was required.

6.1.3 Structures

The following structures have been considered in the Leghvtakhevi numerical model.

- Bridges
- Culverts
- Dams

In total, 18 structures have been included in the hydraulic model. It should be noted that some of them do not represent a constraint from a hydraulic point of view, because they are either small structures or because even during peak flow conditions, the water level does not reach the soffit of the structure.

6.1.4 Roughness

The definition of the roughness coefficient is one of the critical steps for the successful implementation of the hydraulic model. As an initial approach, land cover information has been used. This land cover information has been extracted from the GlobCover database. This has been completed with input data from field visits photographs and from the field campaigns.

6.1.5 Boundary conditions

The following boundary conditions are required for the numerical model.

6.1.5.1 Hydrological inputs

Hydrological inputs will be obtained from the hydrological study for both selected events and for a range of design events. Locations for these inputs have been agreed between the hydrological and the hydraulic expert (Figure 5). The selection of these locations were agreed considering the size of the catchment and subcatchments and also with the purpose of providing a proper representation of the changes in flow across the catchment.

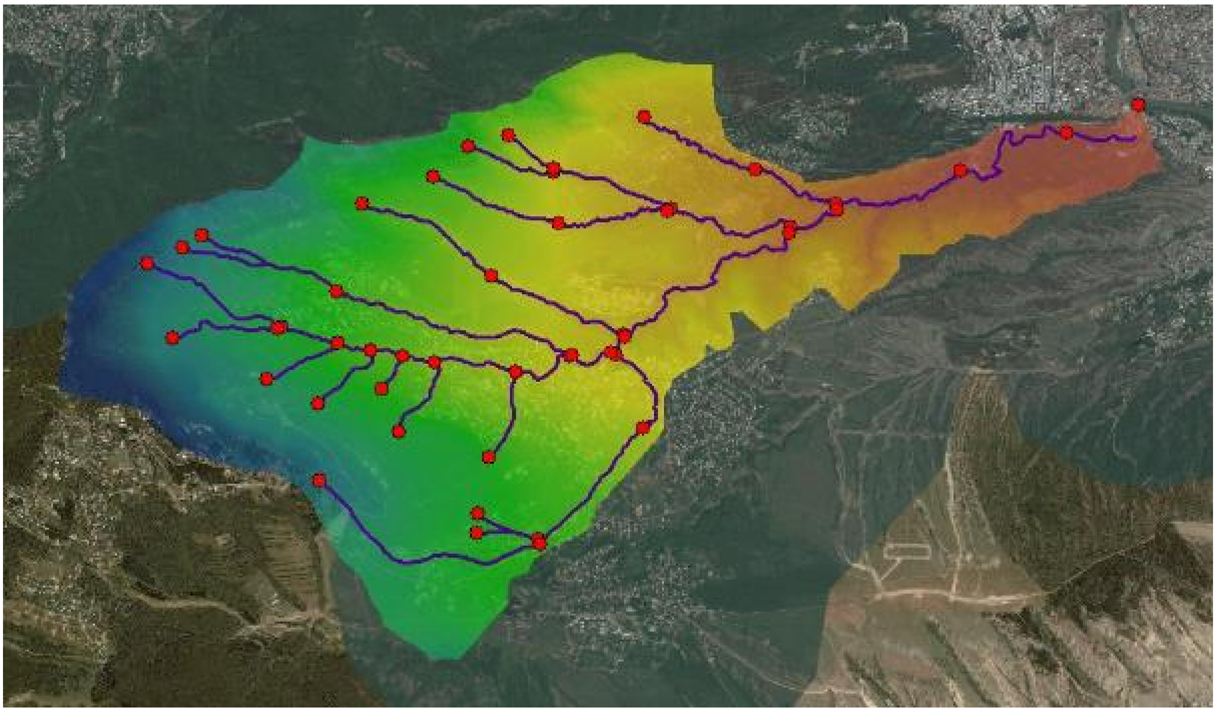

Figure 5 – Hydrological input locations in the Leghvtakhevi River

All the hydrological inputs were included in the model. When the hydrological input was within the 1D domain, they were included in cross sections within this domain. On the other hand, when the hydrological input locations are not located within the 1D domain, these hydrological inputs have been included in the 2D domain as it will be described in the 2D section.

6.1.5.2 Downstream boundary

In this case, because the model extent has been taken down to the Mtkvari River, the downstream boundary of the model will be the water level of this river. During the 1D model implementation, a normal depth approach has been used in order to facilitate the model implementation. This, however, will be changed during the 1D-2D implementation in order to provide a more realistic boundary condition for the Leghvtakhevi River.

6.2 2D Model Build

6.2.1 Model Domain

A two-dimensional grid has been implemented in the areas where no field data was collected and in the vicinity of the 1D model when overland flow is probable. Four different domains have been implemented in order to cover the whole area (Figure 6).

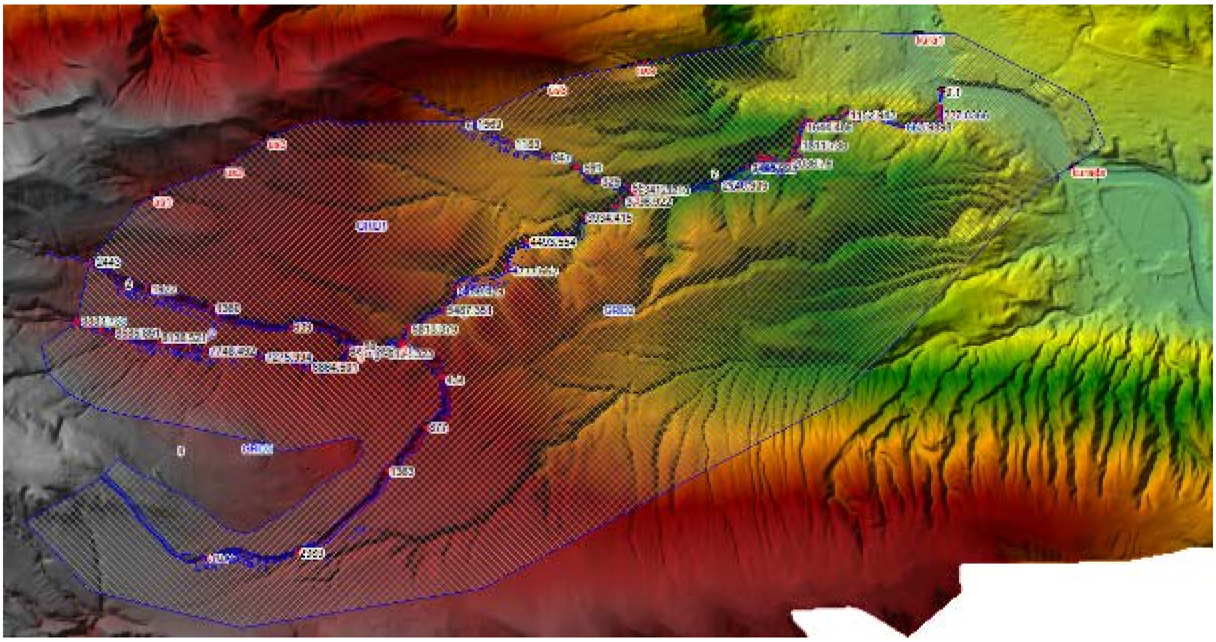

Figure 6 – 2D Domain for the Leghvtakhevi River

The 2D grid has been implemented using a 10m grid size. It should be noted that one of the best features of HEC-RAS on this respect is the fact that there is not a single elevation assigned to each of the grid cells within the domain. As it can be observed in the figure above (Figure 6), the 2D domain has been extended in order to cover the Kura River too. This is because the Leghvtakhevi River discharges into the Kura, and one of the key areas to be investigated is the mouth of the Leghvtakhevi, both from a 1D and a 2D point of view. Therefore, the boundary has been extended further downstream, in order to avoid any possible issue because of the boundary conditions in the modelling results in this area.

6.2.2 Geometry

The four 2D grids have been implemented covering the whole domain, when not covered by the 1D model. The four grids have the following details (Table 1).

Table 1 – Grid details

Grid No.	Area (km^2)	Grid Size (m^2)	Number of Cells
1	5.09	10	50,651
2	0.69	10	6,756
3	2.96	10	29,268
4	13.27	10	172,009

In order to implement the 2D domain, a terrain model was generated in HEC-RAS, using the DEM-LiDAR data previously described. No smoothing was undertaken to this DEM in order to increase the accuracy of the model. As previously stated, the grid size for all the domains is 10m.

6.2.3 Boundary conditions

The following boundary conditions are required for the 2D numerical model.

6.2.3.1 Hydrological inputs

Hydrological inputs has been included in the 2D domain in order to cover the watercourses that are not represented within the 1D domain. The same boundary condition approach has been followed in this case.

6.2.3.2 Downstream boundary

A normal depth downstream boundary condition has been used in the Kura River. As previously stated, the location of this boundary condition is sufficiently far from the area of interest. Nonetheless, the efficiency of this boundary condition will be further assessed during the sensitivity tests activity.

6.3 1D-2D Model Build

The implementation of a 1D and 2D model depends on the two different models to be working before the link is undertaken. The implementation of the two different dimensionality models has been described in previous sections. However, it should be noted at this stage, that the stability of the 1D domain is poor. There are some reasons behind this:

- The gradient of the Leghvtakhevi River is high. The difference in elevation from the headwaters to the Kura is significant (from 1024m to 389m) for the less than 10km river length.
- The channel is not very well defined in some locations.
- There are some abrupt changes in the river morphology.
- The river basin, however, is not significantly extensive, and therefore, the derived discharges by the hydrological model, especially at the beginning of the events, is very low. This leads to river sections being dry at some point.
- There are several structures that create issues from a hydraulic modelling point of view. Especially the long culvert (177m) located at the downstream end of the Leghvtakhevi River.
- The presence of several waterfalls in the model creates instability issues.

The hydraulic modelling expert has undertaken every possible action in order to increase the stability of the model, such as:

- Increase the number of cross sections, using both interpolated cross sections and DEM-extracted cross sections. This is because in some sections of the river there are abrupt changes and/or the river length between surveyed cross sections is too long.
- Include in-line structures in the location of waterfalls. This is because when using in-line structures, the hydraulic model uses the weir equation instead of the usual Saint-Venant equations. This is supposed to be more stable in abrupt gradient changes.
- The number of computational points has been extended as much as possible.
- The calculation tolerances has been increased as much as possible.

Nonetheless, it should be noted that at this stage the 1D model of the Leghvtakhevi River is still slightly unstable, and therefore the results from the 1D model should at this stage be taken and considered with extreme care. On the other hand, the 2D model is stable.

The 1D and 2D domain of the Leghvtakhevi River have been linked using the two different linkage methods described above, standard link and lateral link.

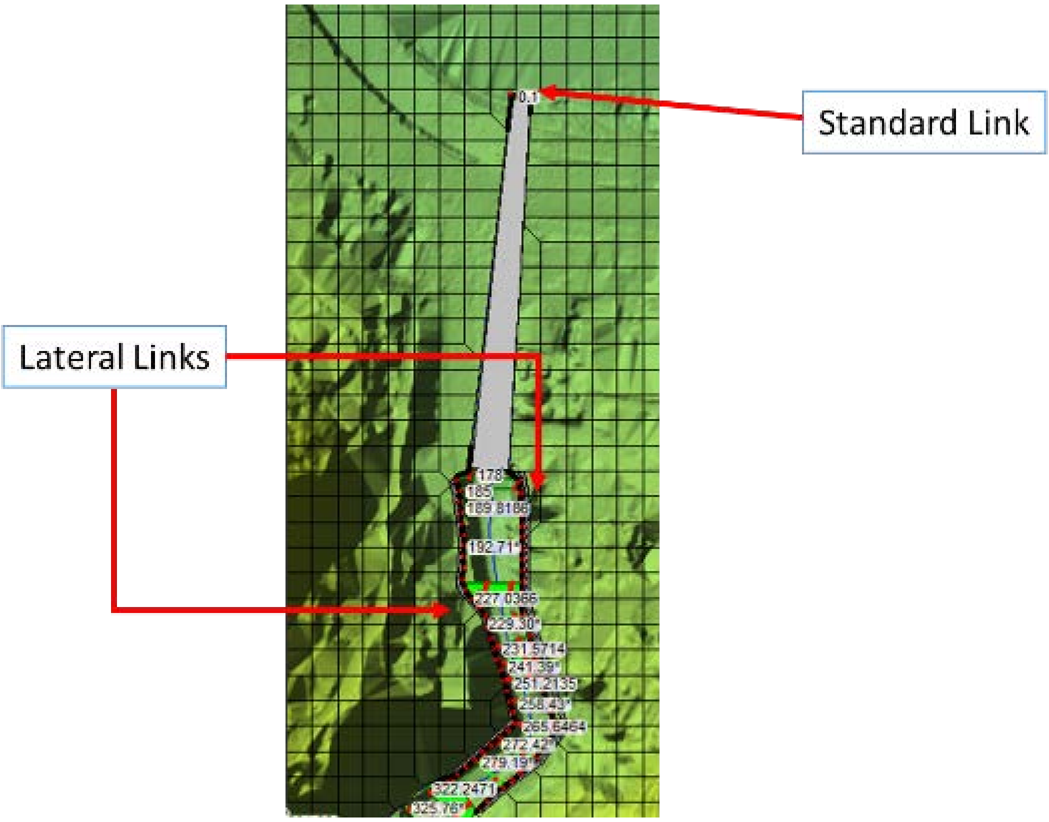

Figure 7 – 1D-2D Links

6.3.1 Standard Link

One standard link has been defined in the downstream end of the Leghvtakhevi River, immediately downstream of the last culvert and connecting the Leghvtakhevi 1D river to the Kura River (in the 2D domain).

6.3.2 Lateral Links

Lateral links has been used in the model implementation in two different situations:

- When connecting a Leghvtakhevi tributary to the main watercourse. In this case, the tributary has been just defined in the 2D domain, and in order to connect the watercourse to the main river, a lateral structure has been used.
- In some specific areas, where the water may overtop the banks during particular events, the 1D river has been connected to the 2D domain in order to assess the overland flow.

In both cases, lateral structures have been defined to connect the 1D and the 2D domains. These lateral structures have been defined based on the existing topography and DEM, and using the cross sections limits to select the location of the lateral structures.

It should be noted that the stability of the model was reduced due to the inclusion of the lateral structures. This was the case even when the calculation tolerance of the lateral structures was increased to its maximum value (3.0). The description of hydraulic processes occurring in lateral structures, and especially when the flow from a 1D domain to a 2D domain is considered, is very challenging, and therefore, the increase of the tolerance to its maximum value would result in a decrease in the accuracy of the results in those locations.

7 Model Results Analysis

In this section, an evaluation of the results for the 1D-2D model will be undertaken.

7.1 General Comments on the Results

There are some general comments regarding the results from the implemented 1D-2D model.

- The implementation of the 1D-2D model required a significant work effort. This is due to the peculiarities of this river system, especially the waterfalls, the high gradient and the long culverts.
- The results of the 1D-2D model simulations showed very high water depths, much higher than expected.
- The subsequent sensitivity tests undertaken with this model showed that the results are not consistent and that the model is at this stage unfit for purpose.
- Even if the 1D-2D modelling approach seemed the most suitable at the start of the modelling process, it is clear after this exercise that this approach is not the best suited for flood mapping and flood mitigation purposes in this specific river.

Therefore, it can be concluded that the 1D-2D results at this stage are not fit for purpose and that the results from the 1D-2D modelling exercise cannot be used for flood mitigation or flood mapping purposes.

8 Alternative Hydraulic Modelling Approach

As discussed above, even after a significant effort in the modelling implementation, the hydraulic modelling results of the 1D-2D model did not yield the plausible results.
In order to address this issue and in order to provide an accurate base for flood mapping and flood mitigation activities, an alternative modelling approach was followed.

8.1 2D Modelling Approach

In this case, the hydraulic modelling expert, in close consultation with other experts within the HYDROC team, decided to adopt a pure 2D approach to model the whole Leghvtakhevi river system. The model was implemented using the following procedure.

8.1.1 Model Domain

Because in this case, the whole domain is going to be represented using a 2D approach, there is just one grid implemented covering the whole area of interest (Figure 8).

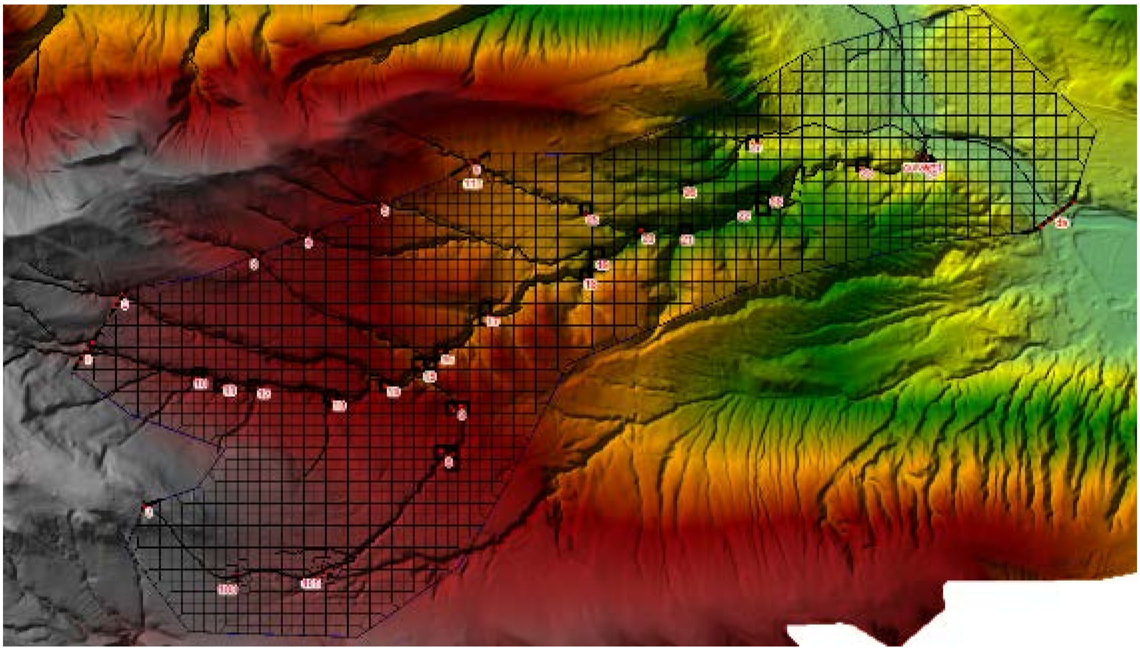

Figure 8 – 2D Modelling domain

8.1.2 Geometry

The 2D grid has been implemented covering the whole domain and it has the following details (Table 2).

Table 2 – Grid details

Grid No.	Area (km^2)	Grid Size (m^2)	Number of Cells
1	21.24	10	211,892

As per the previously explained 2D implementation, in order to define the 2D domain, a terrain model was generated in HEC-RAS, using the DEM-LiDAR data previously described. No smoothing was undertaken to this DEM in order to increase the accuracy of the model. As previously stated, the grid size for this domain is 10m. In addition to that, the collected survey information was also used, incorporating these data in the terrain model to use in the simulations.

8.1.3 Structures

The following structures have been considered in the Leghvtakhevi 2D numerical model.

- Bridges
- Culverts
- Dams

In total, 18 structures have been included in the hydraulic model. It should be added that even if the structures are included in the 2D domain, the equations used to solve the flow within these structures are based on a 1D approach.

8.1.4 Roughness

As an initial approach, land cover information has been used. This land cover information has been extracted from the GlobCover databases.

8.1.5 Boundary conditions

The following boundary conditions are required for the 2D numerical model.

8.1.5.1 Hydrological inputs

Hydrological inputs have been included in the 2D domain to cover all the inflows as defined in the hydrological model (Figure 5).

8.1.5.2 Downstream boundary

A normal depth downstream boundary condition has been used in the Kura River. As previously stated, the location of this boundary condition is sufficiently far from the area of interest. Nonetheless, the efficiency of this boundary condition will be further assessed during the sensitivity tests activity.

9 2D Modelling Results

The results of the 2D modelling exercise will be described in this section.

9.1 Sensitivity analysis

Several sensitivity analyses have been carried out in order to ascertain the impact the roughness and boundary conditions may have in the modelling results. It should be noted that the sensitivity analysis are a very critical stage in the implementation of the hydraulic model. This is because:

- There is no reliable data for the calibration and validation of the model.
- The topographical and physical characteristics of the model has led to severe instabilities in the 1D and in the 1D-2D modelling approach. A brief sensitivity test in the 1D domain has resulted in very different results, and therefore the 1D model is at this stage unfit for purpose as previously noted.

Any (hydraulic) model is a simplification of the existing situation. The implementation of a hydraulic model, therefore, should always be treated with caution and it should be proven during the implementation that the model is behaving as expected, from a hydraulic modelling point of view. That is the reason behind the sensitivity tests.

The main objective of the roughness sensitivity test is to probe the stability of the model and the sensibility of the results. Two different tests are undertaken, one decreasing and another one increasing the roughness coefficient throughout the whole domain. The expected results will be that a decrease in water depths for the scenario where the roughness coefficient has been decreased, and therefore, an increase in the roughness coefficient should yield an increase in water depths. This is because, when the roughness coefficients are reduced, the resistance of the terrain to the flow decreases, the flow velocity increases and therefore for the same discharge, the water depth is reduced. The inverse effect occurs when the roughness increases. This increase or decrease should be more or less homogeneous across the whole domain. The roughness coefficient has for testing purposes been decreased as well as increased by 5% in the whole domain.

The results from this exercise can be observed in Figure 9 and Figure 10. As it can be observed, the results from this assessment are moderately satisfactory. They are satisfactory in the main channel (except in sharp river bends and close to structures, although this is expected). However, the results do not behave as expected in low flow areas. This is because the water depth in these areas is very low and therefore, the results are compromised by the roughness.

Nonetheless, analysing the results more carefully, and especially in the most relevant areas, a higher roughness yields a uniformly distributed higher water depth, and a lower roughness yields a uniformly distributed lower water depth. Therefore, although the results show some inconsistency in low water depth areas, in general the assessment results was satisfactory.

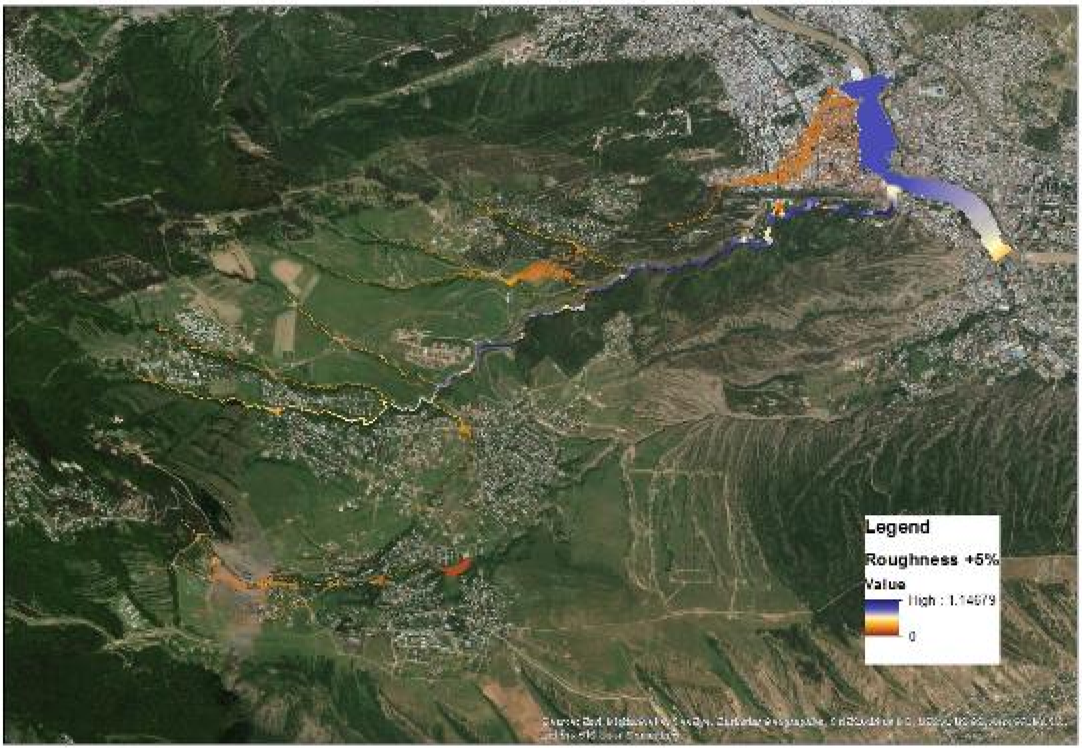

Figure 9 – Roughness Sensitivity test (increase of 5%)

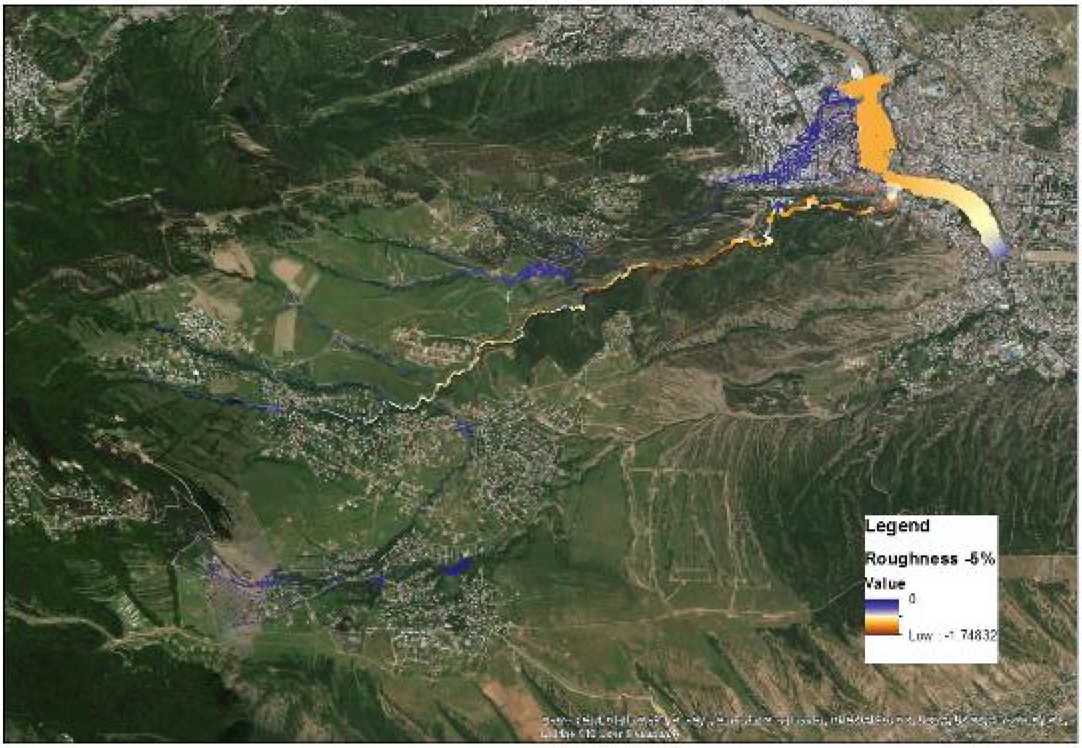

Figure 10 – Roughness Sensitivity test (decrease of 5%)

The downstream boundary condition test is also very important from a hydraulic modelling point of view. When implementing a hydraulic model, it is important to locate the boundary conditions sufficiently far away from the area of interest to avoid boundary effects. This is not always practical or possible because of computational resources, data availability of the geometry of the river system. In this case, it is possible to locate the boundary condition relatively far away from the area of interest. However, extending the model further has implications regarding computational time. The results of this analysis are shown in Figure 11 and Figure 12.

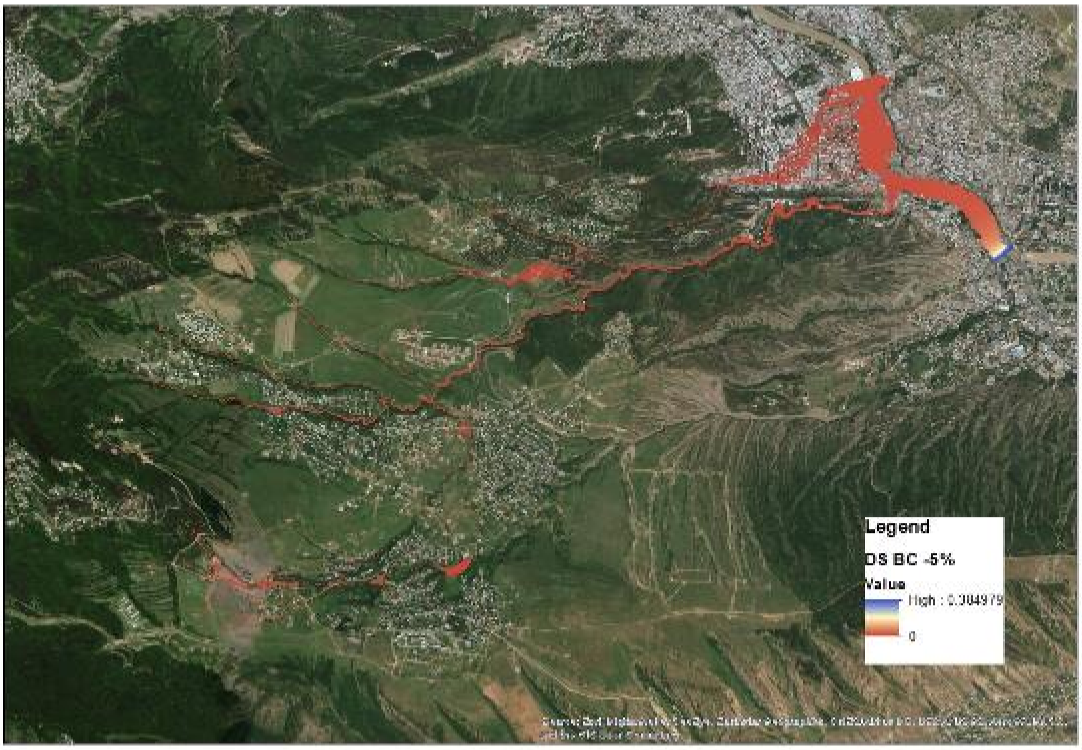

Figure 11 – Downstream Boundary Condition Sensitivity test (increase of 5%)

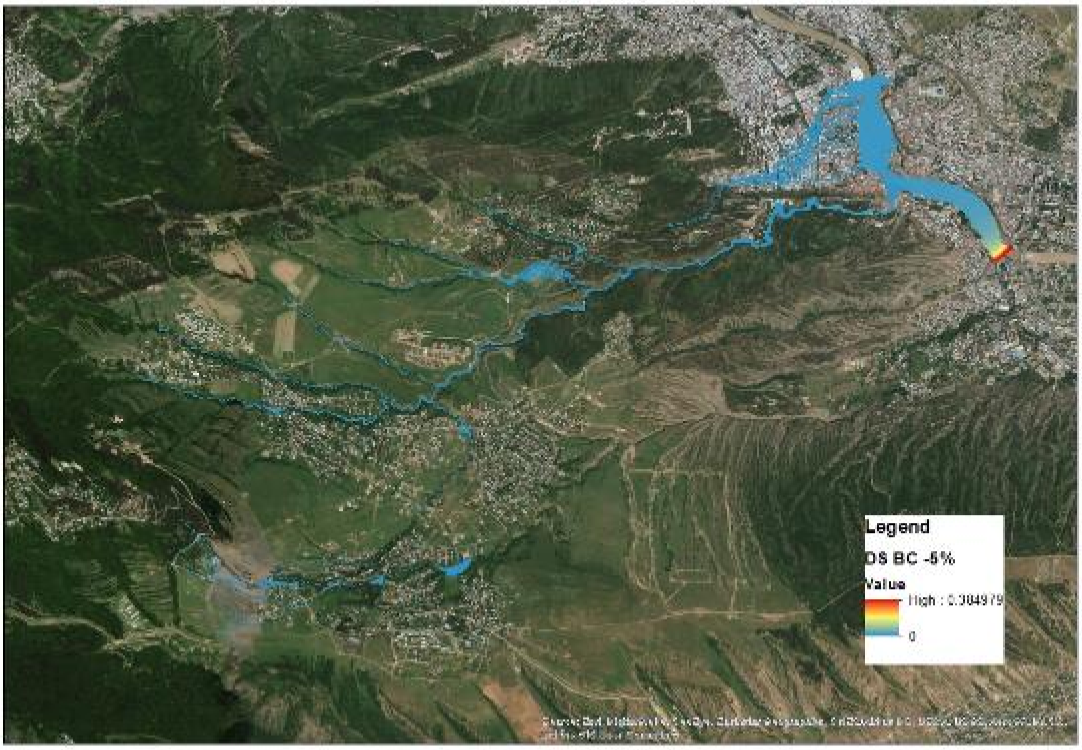

Figure 12 – Downstream Boundary Condition Sensitivity test (decrease of 5%)

As it can be observed, the location of the downstream boundary condition does not have an impact in the results in the target area for either the decrease or the increase in the normal depth.

Finally, it should be noted that the time-step used in the simulation was also assessed from a sensitivity point of view. This is because, based on the modeller experience, the results of 2D models can be sensitive to the time-step, especially if the courant number is greater than 1. In this case, simulations using 10 seconds, 5 seconds, 1 second and 0.5 seconds were undertaken. The results from the 1 second and 0.5 seconds were almost identical, whereas the results from the 10 and 5 seconds were not comparable to the 1 second one; therefore yielding the fact that the use of a simulation time-step of 1 second is appropriate. This time-step may appear low for some hydraulic modelling applications, but considering the terrain, the flow velocities and more importantly, the grid size (10m) for this extensive domain, 1 second is a suitable value.

9.2 Design events

Hydraulic models have been run for the 1:5, 1:25, 1:50, 1:100 and 1:500 year events for both baseline and climate change allowance scenarios.

The geometry, boundary conditions and hydraulic model set-up is identical for all the runs.

10 2D Model Result Analysis

The results from the 2D hydraulic modelling exercise have been analysed carefully across the whole domain. The following can be concluded:

- The 2D results showed a much higher stability than the 1D or 1D-2D results in the whole hydraulic modelling domain.
- The 2D model implemented can be considered to be fit for the purpose of flood mapping under the given conditions and for the flood mitigation process.
- The 2D model responded satisfactorily to the different sensitivity tests.
- All the significant structures were implemented in the 2D model and therefore the assessment of these structures can be undertaken during the flood mitigation stage.
- The resulting 2D model was used to produce results for all the return period events (baseline and climate change scenarios).
- The use of a 2D modelling approach limits the reduction in accuracy that occurs in the linking process between 1D and 2D models.

11 Conclusions and Next Steps

Several hydraulic models for two different approaches (1D-2D and 2D alone) have been implemented during the hydraulic modelling exercise. The implementations of the models have been challenging due to the natural conditions in the area of interest, leading to some issues during the modelling process.

In the methodology report, the hydraulic modelling approach was detailed. Here, a 1D-2D approach was initially considered the most appropriate one, both from a hydraulic modelling and from a computational resources point of view. A 1D-2D implementation requires to have both the 1D and the 2D models working separately before linking them together. The 1D implementation of this combined approach, however, proved to be extremely unstable, and the model had to be customised in a way that the accuracy of the results could be compromised. Thus, although the 2D model was working separately, when linking the two models, the results were not satisfactory. The results for these instabilities have been discussed in this report, but the significantly high gradient, the long culverts and the change in the river profile are the main reasons.

Therefore, a 2D approach has been adopted. The use of this approach has no limitations from a hydraulic modelling point of view in terms of the quality of the results. The only limitation of a whole 2D approach is computational time. Respectively, the computational effort to run all the different scenarios has been significant. This is not an issue at this stage, but it will need to be considered if this model would be implemented in an operational mode (for flood forecasting purposes). In that respect, the modeller has completed a simpler 1D model, removing some structures, shortening the river length and some cross sections. This model is useful for flood forecasting purposes, because it conveys the main flow along the main river channel and the main structures are present in the model. This will be further explained in further deliverables under this project.

The next steps to be taken are:

- Flood mapping: the results from the hydraulic modelling exercise will be further analysed during the flood mapping exercise. Flood maps for different return periods and scenarios and for different variables will be produced.
- Proposal of flood mitigation options: during the flood mitigation process, the hydraulic performance and the flooding mechanism of the river will be carefully

reviewed. Different flood mitigation options (structural and non-structural) will be proposed at this stage.