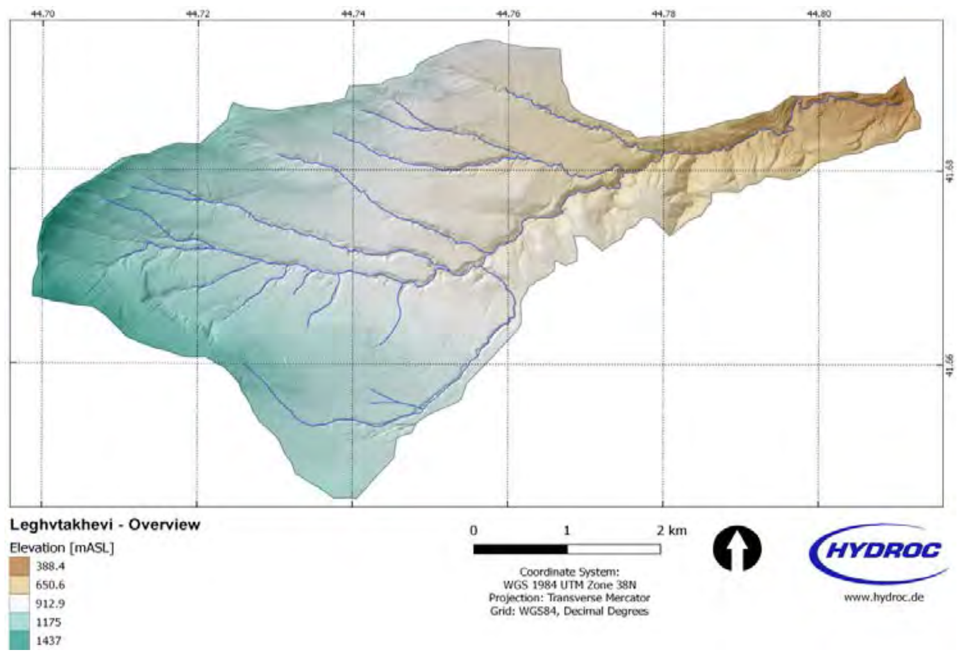
P170526

Description of suitable methodology and technology for flood modelling and mapping

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

CTCN REFERENCE NUMBER: 2016000043



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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 14^{th} 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 Methodology

The overall methodology for the flood modelling and mapping within this technical assistance (Figure 1) is the following:

- Initial site visit: the information during the field visit is paramount in order to have a better understanding of the different processes in this catchment and to be able to define a methodology suitable for this specific catchment.
- Data Collection: flood modelling is a very data-demanding activity. During the data collection activity the data required to undertake the modelling is collected. This activity supports all the modelling activities within this methodology.
- Hydrological Modelling: the objective of the hydrological modelling activity is to produce the discharge data that will be used in the hydraulic modelling, flood mapping and mitigation activities. The information from the data collection activity is being used

to implement a hydrological model that will be using hydro-meteorological data to simulate hydrological variables, including the discharge data. The hydrological model will be run for historical events and for design events, and it will be linked with both the climate change and the hydraulic modelling. The climate change modelling will provide input data regarding estimated impact on the different meteorological variables to the hydrological modelling. Therefore, discharge predictions by the hydrological model will consider the climate change impact.

- Climate Change Modelling: the climate change modelling will calculate the variation of temperature and precipitation at several times in the future using different set of projections and existing data. As previously noted, this will be included in the hydrological model in order to predict the climate change impact in the resulting discharge.
- Hydraulic Modelling: the hydraulic modelling activity will use the information obtained in the data collection activity and it will route the discharge data from the hydrological modelling activity to produce water level and discharge data in pre-defined locations.
- Flood Mapping: the hydraulic modelling results will be combined with topographical information in order to produce flood inundation maps. The maps will be produced for several variables and for several historical and design scenarios.
- Flood Mitigation Measures: flood mitigation measures will be undertaken in order to mitigate the flooding impact in this catchment. The results from the flood modelling will be used as the basis for the mitigation activity, although the local and historical information will be used too. The mitigation options will be tested with the hydraulic model and flood maps will be produced for all of the pre-selected options.

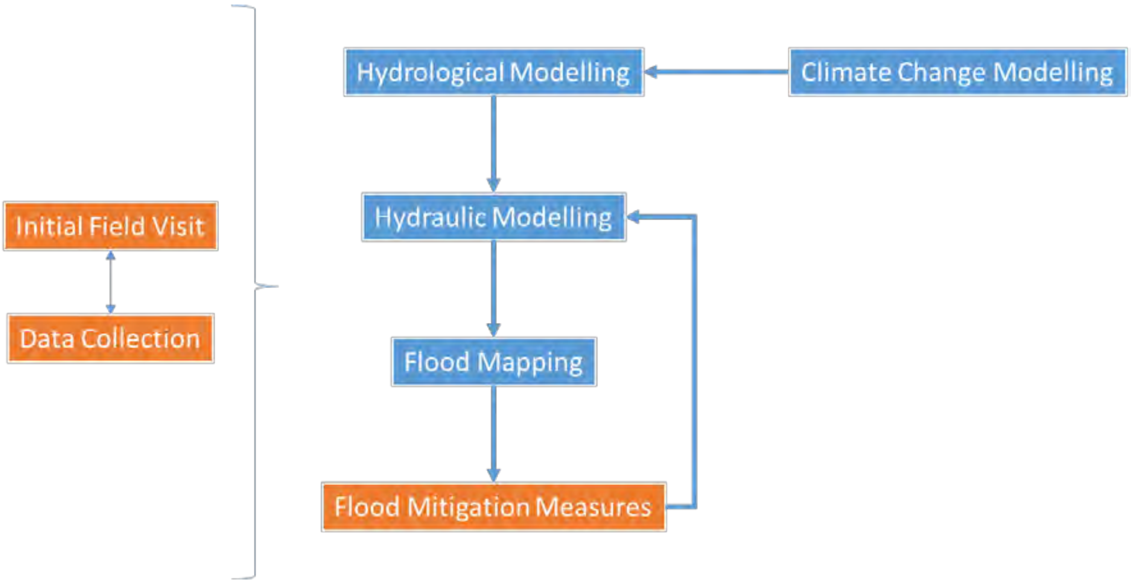


Figure 1 – Overall Methodology for flood modelling and mapping

3 Data Collection and Analysis

The data collection activity has been fully detailed in a separate deliverable (Deliverable 1 - Report on Data Acquisition). Nonetheless, in order to facilitate the understanding of the entire methodology, a brief data collection section has been included in this report. All, the river survey requirements and approach is fully detailed below.

3.1 River Survey

The topographical survey of the Leghvtakhevi River (Figure 2) in Tbilisi, Georgia will be undertaken following the short survey instructions below. The Leghvtakhevi catchment includes a main water body and several major tributaries (solid lines Figure 2). For this assignment, all major waterbodies (solid blue lines in Figure 2) will be surveyed.

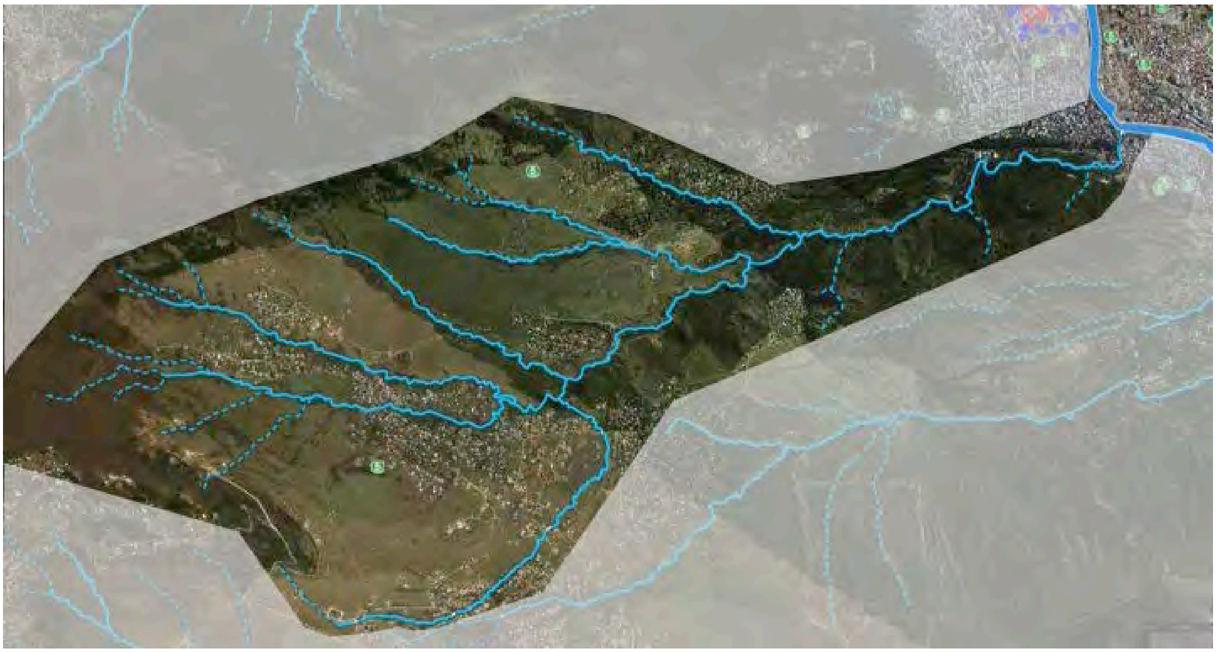


Figure 2 - Catchment of Leghvtakhevi River with the main waterbody and several tributaries (solid blue lines)

3.1.1 Catalog all Structures

In an initial survey, all structures (Table 1) in the catchment will be catalogued. Information will be provided in a one page PDF document for each structure, including all information in a table as well as two representative photographs. In regard of this information the terrestrial survey can be planned and conducted. The PDF files will be named with the code of the structure (Table 1, e.g.: WF-Y-Z-026.pdf for waterfall #26 in catchment Y, river Z). Positions should be taken with a global navigation satellite system (GNSS).

Table 1 - Necessary information for the structure catalogue

Structure	**Necessary information**
Bridge Code **BR**	- GNSS position - pictures (two pictures of the structure from different perspectives) - short description of structure
Confluence Code **CN**	- GNSS position - pictures (two pictures of the structure from different perspectives) - short description of structure including the names of the waterbodies
Culvert Code **CU**	- GNSS position - number of openings - shape of opening - pictures (two pictures of the structure from different perspectives) - short description of structure
Dam Code **DM**	- GNSS position - number of bottom outlets - number of spillways - pictures (two pictures of the structure from different perspectives) - retention area available (yes/no(filled with sediment)/partly - short description of structure
Waterfall Code **WF**	- GNSS position - approx. height of structure - pictures (two pictures of the structure from different perspectives) - short description of structure

Further structures if necessary	- GNSS position - pictures (two pictures of the structure from different perspectives) - short description of structure - further describing parameters (as above)
Coding of Structures: **XX-Y-Z-00n** **XX** → code of Structure **Y** → code of river catchment **Z** → code of waterbody **00n** → continuous numbering from downstream towards upstream	

3.1.2 Terrestrial Survey

3.1.2.1 Survey Equipment

To ensure an efficient survey the following equipment will be used for the topographical terrestrial survey:

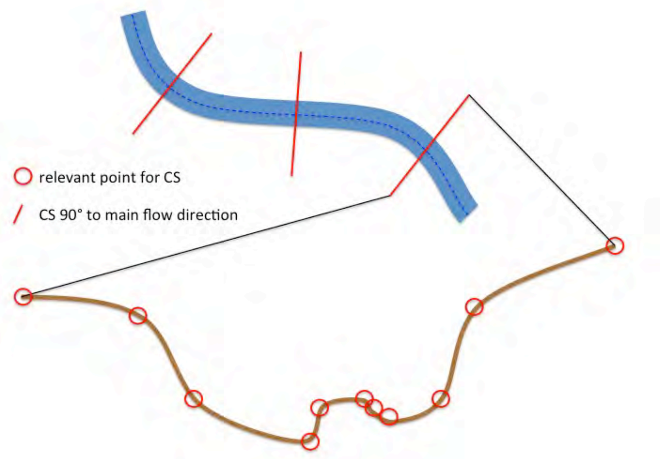
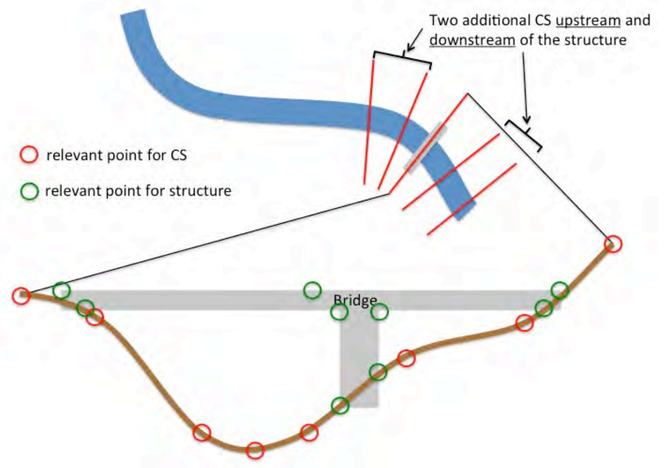
- (Robotic) Total Station with the capability of taking points without a prism (prismless feature)
  - This ensures the capability of surveying points and structures which are not accessible with the prism e.g.: waterfalls, bridges etc.
  - The robotic feature ensures an efficient and fast survey with the total station
- Differential GNSS
  - to reference local point clouds and cross sections in global coordinates
- Measuring Tape
- Camera (with internal GNSS)
- Further tools and equipment will be needed as some cross sections should be cleaned from vegetation for the survey

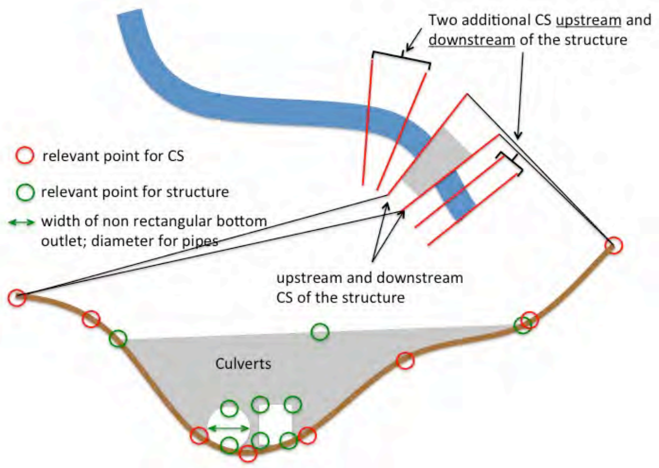
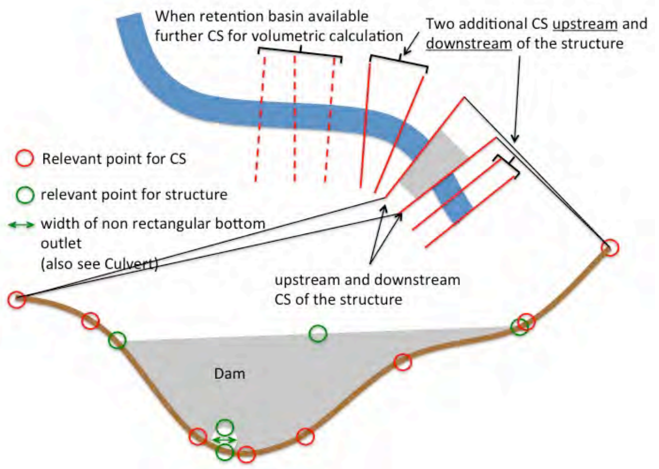
3.1.2.2 Survey Method

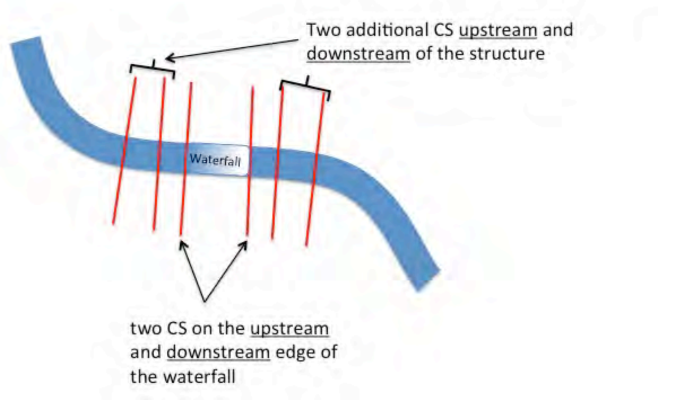
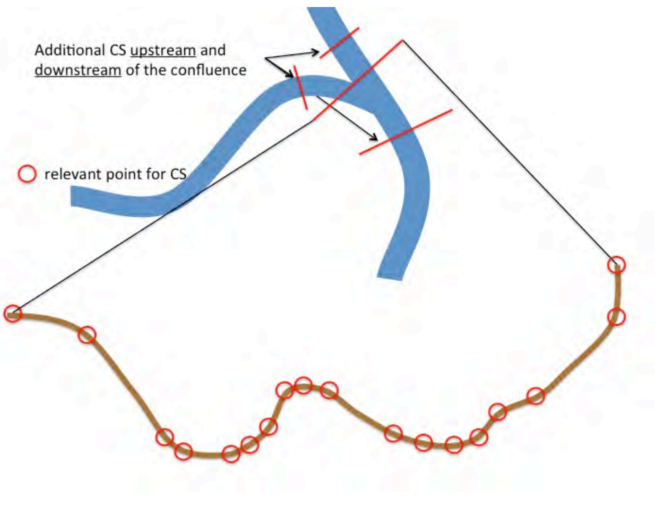
The hydraulic model for flood evaluation will be based on cross section (CS) and structural point input from terrestrial surveys as well as existing LiDAR (Light Detection And Ranging) data. For the CS and structural survey a general description can be found below. Further Examples are given in section 3.1.4.

The code of all survey points will be consistent, one particular code (e.g.: CS0235) cannot be used for two or more different CS survey points.

Table 2 - Description of important features for the survey of cross sections and hydraulic structures

Type of Cross-section (CS)	Description of Survey	Example
Regular	Survey of all breaking lines and edges in the CS Code for cross section survey points: CS…	
Bridge	Survey of all breaking lines and edges in the CS Survey of all relevant structure points Code for bridge survey points: BR… Code for cross section survey points: CS…	

Culvert	Survey of all breaking lines and edges in the CS Survey of all relevant structure points Code for culvert survey points: CU… Code for cross section survey points: CS… Accessible culverts with changing diameter and bends should be surveyed inside where slope/direction/diameter/height is changing	
Dam	Survey of all breaking lines and edges in the CS Survey of all relevant structure points Code for dam survey points: DM… Code for cross section survey points: CS…	

Waterfall	Survey of all breaking lines and edges in the CS Code for waterfall survey points: WF… Code for cross section survey points: CS…	
Confluence	Survey of all breaking lines and edges in the CS Code for the particular confluence cross section survey points: CN… Code for additional cross section survey points: CS…	

3.1.3 Data

All survey data will be provided in a Microsoft Excel (or similar software) sheet (Figure 3) with the code of the structure (see section 3.1.2). Each category (regular CS, bridges, culverts etc.) will be placed on a separate sheet including a sheet with all data at the end. In addition, a directory will be established within the excel file describing the data and cross reference to all additional data, such as pictures etc. in different folders.

	A	B	C	D	E	F	G	H
1	Structure	Point Name	Northing	Easting	Elevation			
2								
3	**CYZ-001**	CS0001	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
4		CS0002	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
5		CS0003	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
6		CS0004	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
7		CS0005	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
8		CS0006	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
9		CS0007	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
10		CS0008	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
11		CU0001	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
12		CU0002	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
13		CU0003	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
14		CU0004	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
15		CU0005	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
16		CU0006	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
17		CU0007	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
18								
19	**CYZ-002**	CS0009	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
20		CS0010	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
21		CS0011	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
22		CS0012	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			
23		CS0013	XXXXXXXX	YYYYYYYYY	ZZZZZZZZZZ			

Bridges | Culverts | Dams | Waterfalls

Figure 3 - Example for survey data delivery

3.1.3.1 Coordinate System

The coordinate system used for each GNSS measurement will be noted. In addition to the coordinate system, the plane of reference, in which elevation is measured, will also be noted. This additional information will be given within the Microsoft Excel sheet. This ensures that all coordinates can be transferred to another coordinate or elevation system, if necessary.

3.1.4 Further Examples

In this section, a few examples for the survey in the Leghvtakhevi river catchment can be found. Red lines show CS positions. Green dots show important survey marks on the structures, a short description is included in the picture.

Figure 4 – Cross section example on a bridge

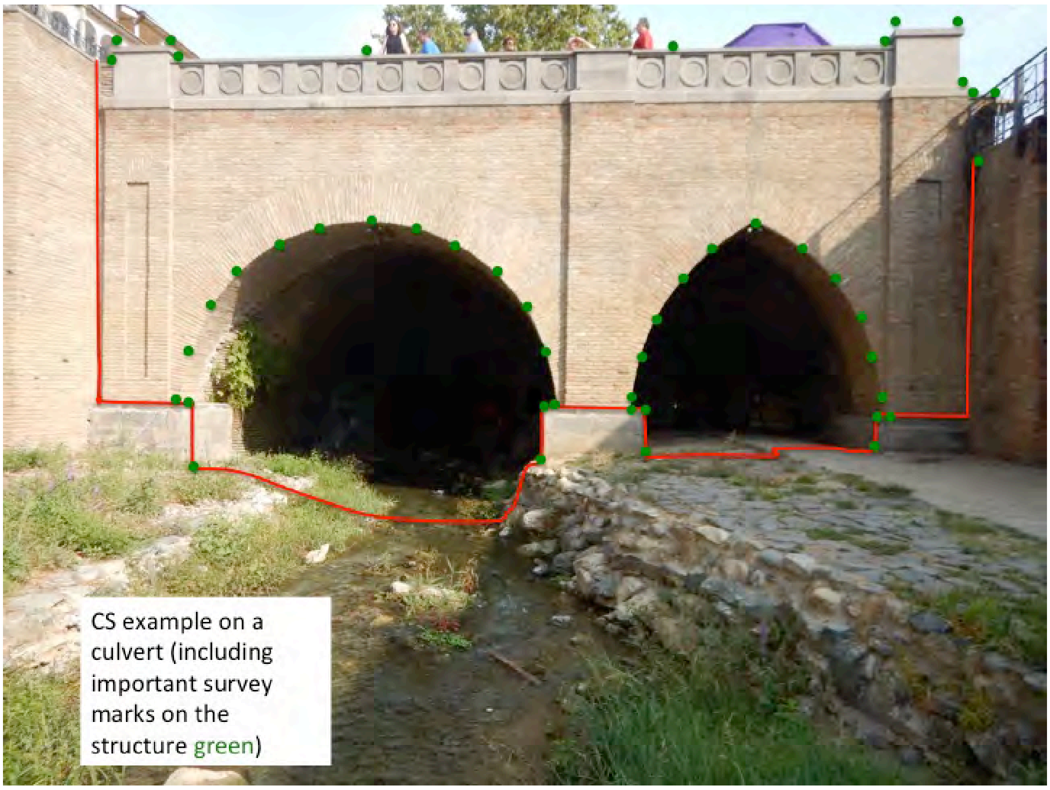


Figure 5 – Cross section example on a culvert entrance

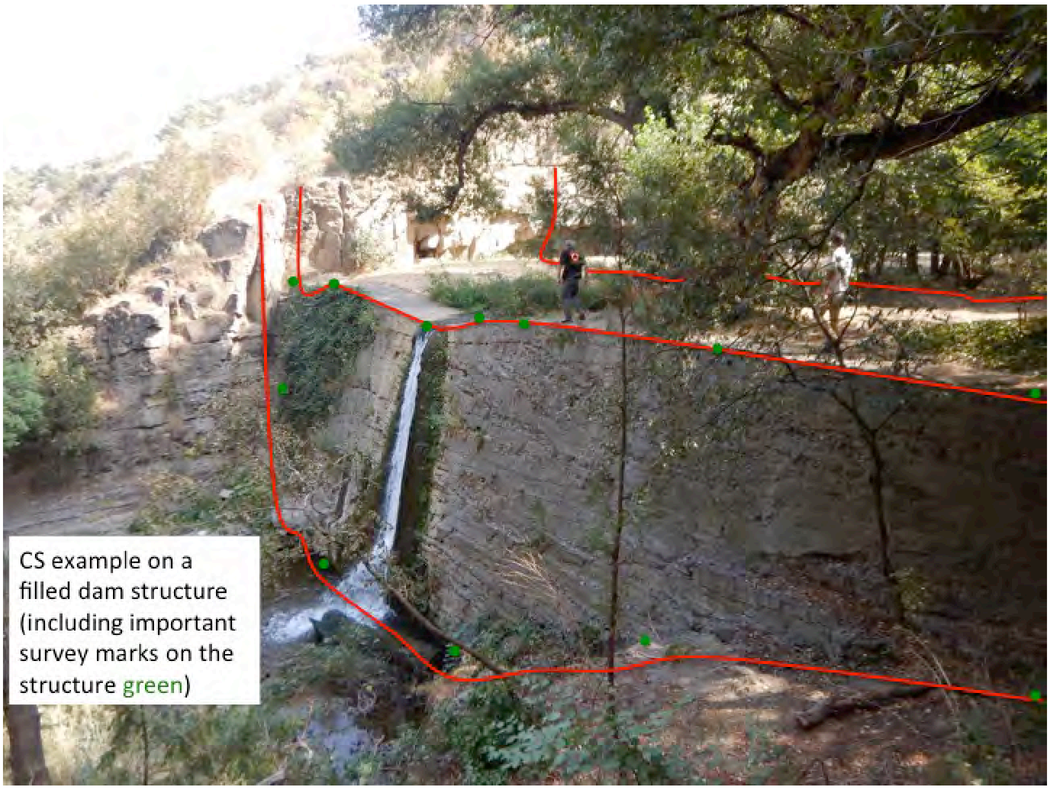


Figure 6 – Cross section example on a dam

Figure 7 – Bottom outlets and culverts

Figure 8 Cross section example on culverts

Figure 9 – Cross section example in potential flood area

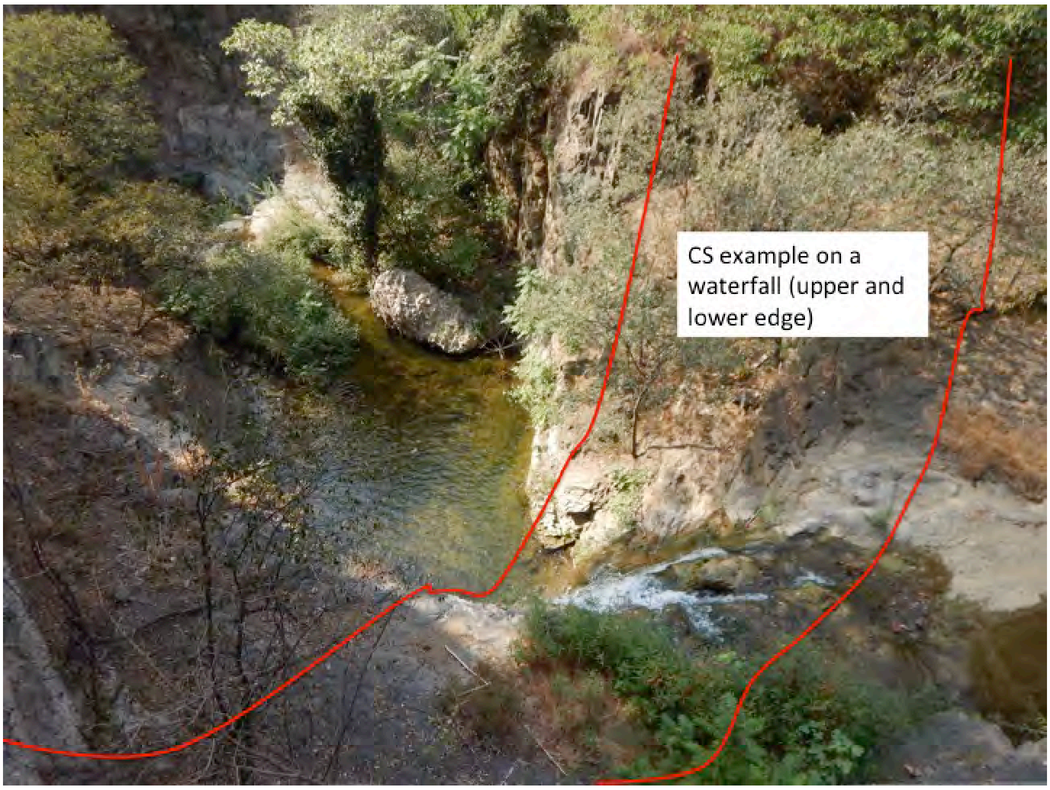


Figure 10 – Cross section example on a waterfall

3.2 Data Collection

As previously noted, a dedicated deliverable for the data collection activity has been prepared. Nonetheless, a brief description of the collected data can be found in the Table 3 below.

Table 3 – Data Collected

Description	Details	Source	Year	Used for	Assessment
Leghvtakhevi River catchment	NA	NEA		Hydrologic, climate change and hydraulic modelling	Sufficient.
River network	NA	NEA		Hydraulic modelling. flood mapping	Sufficient. This will be improved during the modelling
Hydrography	NA	Tbilisi City Hall	NA	Hydraulic modelling. flood mapping	Sufficient. This will be improved during the modelling
Land Cover	Old 1:50,000 scale soviet topographic map	NEA	NA	Hydrologic modelling	Insufficient. Global data will be used.
Geology	Digitised from old soviet map	NEA		Hydrologic modelling	Sufficient.
Soil map	Source: 1:200,000 map of M. Sabashvili, 1965	NEA	1965	Hydrologic modelling	Sufficient.
Leghvtakhevi River characteristics/historical floods	NA	NEA	NA	Hydrologic and hydraulic modelling.	Sufficient.
Meteorological Station details	Location of meteorological	NEA	NA	Hydrologic, climate change and hydraulic modelling	Sufficient.

	stations nearby the catchment.				
Tbilisi, Vashlojvani meteorological station characteristics	Daily information from 1961 to 2016, specifically: • Air average temperature, ◦C • Air maximum temperature, ◦C • Air minimum temperature, ◦C • Precipitation amount, mm • Air relative humidity, % • Average wind speed, m/sec Average maximum wind speed, m/sec	NEA	1961-2016	Hydrologic, climate change and hydraulic modelling	Sufficient.
Tbilisi, airport station meteorological station characteristics	Daily information from 1980 to 2010, Specifically: • Air average temperature, ◦C • Air maximum temperature, ◦C • Air minimum temperature, ◦C	NEA	1961-2010	Hydrologic, climate change and hydraulic modelling	Sufficient.

	• Precipitation amount, mm • Air relative humidity, % • Average wind speed, m/sec Average maximum wind speed, m/sec				
Tbilisi, airport meteorological station characteristics	Daily information from 1961 to 2005, Specifically: • Air average temperature, ◦C • Air maximum temperature, ◦C • Air minimum temperature, ◦C • Precipitation amount, mm • Air relative humidity, % • Average wind speed, m/sec Average maximum wind speed, m/sec	NEA	1961-2005	Hydrologic, climate change and hydraulic modelling	Sufficient.
Radar data	NA	Delta	2015-2017	Hydrologic, climate change and hydraulic modelling	Sufficient.

Data on water level of bore wells within the Leghvtakhevi River	Water levels in the bore wells within the Leghvtakhevi River basin is as follows:	NEA	1990-2017	Hydrologic and hydraulic modelling	Sufficient.
Climate change scenarios	Climate change scenarios for 2021-2050 and 2071-2100 (in Georgian language)	NEA	NA	Hydrologic and climate change modelling	
Collectors	Information from 2 collectors within the catchment	Tbilisi City Hall	NA	Hydraulic modelling and flood mitigation	Sufficient
DEM	1 meter resolution	Tbilisi City Hall	NA	Hydrologic, hydraulic modelling	Sufficient
Aerial images	NA	Tbilisi City Hall	NA	Hydrologic, hydraulic modelling and flood mitigation	Sufficient
Planned project file in Abanotubani area	NA	Tbilisi City Hall	NA	Hydrologic, hydraulic modelling and flood mitigation	Sufficient
3D topography of Abanotubani area	NA	Tbilisi City Hall	NA	Hydraulic modelling and flood mitigation	Inconsistent and this stage (wrong geographical projection)

Tbilisi districts	NA	Tbilisi City Hall	NA	Flood mapping and flood mitigation	Sufficient.
Roads	NA	Tbilisi City Hall	NA	Flood mapping and flood mitigation	Sufficient.
Buildings	NA	Tbilisi City Hall	NA	Flood mapping and flood mitigation	Sufficient.
Functional zones	NA	Tbilisi City Hall	NA	Flood mapping and flood mitigation	Sufficient.
Points of interests	NA	GeoLand	2009	Flood mapping and flood mitigation	Sufficient.
Settlements	NA	GeoLand	2014	Flood mapping and flood mitigation	Sufficient.

4 Hydrological Modelling

An instruction will be given to hydrological modelling and the classification of available models. The major processes governing the forming of flood flows will be outlined and the applicability of the different types of models to these processes will be described. Based on this, a recommendation will be given for the most suitable model to be used for this project.

Hydrological modelling describes the process to depict the land phase of the hydrological cycle within a catchment in mathematical equations, which are nowadays usually solved in sophisticated software packages – hydrological models. The focus of this depiction (conceptualization) can lie on parts of the hydrological cycle, emphasizing certain processes (e.g. surface runoff) and/or neglecting others (e.g. percolation to groundwater). The conceptualization of the hydrological system depends on the task at hand, emphasizing the need that hydrological models either need to be very flexible or custom-built for a specific task. In addition to this, hydrological modelling is always a simplification of the physical processes in process detail. This focus on different parts of the hydrological cycle and the amount of simplification can be used to classify hydrological models.

4.1 Overview of Hydrological modelling

Hydrological models can either be *deterministic* or *stochastic*. Deterministic models produce the same result with each application, while stochastic models have a random element, creating different solutions with each model run. While stochastic models can be used for scenario simulations and depicting uncertainties in the simulations, they are rarely applied because the user has more control about the relationship between in- and output using deterministic models. Hydrological models are furthermore classified into *physically*-based (e.g. the Richard's equation for movement of water in soil), *empirical* (e.g. the United States Soil Conservation Service Curve Number for surface runoff) or *mixed-type* representation of processes. Most state-of the art models contain different or multiple representations of processes and are hence referred to as mixed-type. Physically based equations are usually harder to solve mathematically, but have less unknown parameters and ranges of parameters that influence the result. Empirical equations on the other hand are easier to solve since they are a statistically derived, simplified relationship of a physical process, but usually contain more parameters with wider ranges that must be properly defined to arrive at a meaningful solution. The definition of the values of these parameters (model *calibration*) is usually carried out fitting simulation results to observed data in a manual or automatized trial-and-error approach.

The process depiction in models is furthermore simplified in space and time. If catchment properties (e.g. slopes, land-cover, soils…) are averaged over the whole catchment, the model application is *lumped*, while a spatial disaggregation of properties in spatially explicit areas is called *distributed*. Again, a model application can have both lumped and distributed components (e.g. distinction in spatially explicit sub-basins in which catchment properties are lumped) which is called "*semi-distributed*". The temporal simplification is defined as the time step for which a specific model stage is calculated and for which results are available as an average over this time step. As a rule of thumb, the larger and less steep the catchment, the more inert is the hydrological response (e.g. runoff) to a rainfall event. Probably due to our mostly daily observation of hydro-meteorological variables, the most widely used time step in hydrological modelling is daily, which is a reasonable simplification if catchments are sufficiently inert. If the hydrological response is significantly faster, i.e. runoff changes significantly at the point of interest over one day, sub-daily or even sub-hourly time steps are needed. This is a significant challenge for the input data since rainfall and runoff are rarely observed in short time intervals over long time periods.

The duration for which a model is applied can either be for single *events* or in a *continuous* fashion. Event-based simulations are short, targeted simulations of specific storm events where long-term components such as evapotranspiration and groundwater processes can be negligible. Also, model parameters need to be calibrated for a targeted range of hydrological states only, but the initial conditions at the start of simulation (e.g. how much water is stored in the soil) greatly influence the overall result (e.g. surface runoff) and must hence be defined properly. Continuous simulations on the other hand are run over long time periods from years to decades which means that all long-term processes like storage-changes (in soils, reservoirs, groundwater, snow), changes in evapotranspiration, groundwater processes, land use changes etc. must be considered. Also, model parameters must be adjusted to reasonably fit to the widest possible range of hydrological conditions. The initial conditions however lose their importance after a few simulated seasons.

All the above described model properties and distinctions must be considered when choosing a hydrological model for a specific task.

4.2 Approach for software selection

The most important step in choosing an appropriate model is the clear and comprehensive definition of the task for which the model will be applied. In this case, the task is the simulation of multiple representative flood flows in a small, mountainous catchment. Beyond that, multiple additional requirements arise which are the linkage to a hydraulic model and possible integration into an early warning system. The characteristics of the task and the associated requirements on the hydrological model are summarized in Table 4.

Table 4 – Summary of task characteristics in this project and needed model capabilities

Task characteristics	Required model properties
Simulation of representative flood flows	Event-based simulation
Possible integration into an early warning system	Continuous simulation, batch-runs with externally modified input data
Small, steep catchment with rapid response times	Sub-hourly time step simulation
Linkage to a hydraulic model	Distributed or semi-distributed spatial discretization
Possibly depict impact of dams on discharges	Reservoir simulation algorithms
Used as a tool to teach hydrological modelling for long-term usage at NEA	User-friendly interface, compatible with standard Operation Systems, wide application, easy to learn, well maintained and constant development, good documentation and help manuals, low maintenance costs

The listed constraints limit the model selection to high-quality, state-of the art hydrological models that are sufficiently flexible. Though the requirements are high, a range of models exist that can theoretically fulfil those, of which the three most suitable, SWAT, MIKE-SHE and HEC-HMS have initially been considered. All models contain a suite of algorithms for each hydrological process and can be used for a wide range of tasks ranging from rainfall-runoff processes in natural catchments to complex simulations in anthropogenically influenced river basins.

After evaluating the above-mentioned requirements, and after close coordination with NEA experts, HEC-HMS has been chosen for this study due to the following reasons:

- HEC-HMS is constantly developed by the U.S. Army Corps of Engineers, and freely available. This is especially important, considering long-term usage, dissemination to multiple work-places and organisations or sharing the model and results with research institutions.

- The history of HEC-HMS dates back over 30 years, benefitting from an unprecedented experience in hydrologic modelling and software development at the Hydrologic Engineering Center (HEC).
- The implemented hydrologic approaches in HEC-HMS are the best available combination for both event-based and long-term simulations
- HEC-HMS is one of the hydrologic models approved by FEMA (Federal Emergency Management Agency).
- HEC-HMS is linked to the GIS interface HEC-GeoRAS which can be used to produce the spatial model input files within ArcGIS. It must be noted however, that the next version of HEC-HMS (version 4.3) will contain a user-friendly internal interface, which will make the dependence on external software obsolete.
- HEC-HMS can be easily linked to the hydraulic model chosen for this study (HEC-RAS), sharing the same type of database (HEC-DSS).

4.3 Input data selection and preparation

The type and quality of spatial and temporal input data for model setup and runoff data for calibration of the model essentially influences the quality of the results. As described in Chapter 3, where all input data is summarized, extensive efforts were made to obtain the best-possible data basis for the simulations. All input and calibration data for the hydrological modelling can be grouped in spatial and temporal data.

4.3.1 Spatial data

Topographic data is required to derive the catchment boundaries, discretise the catchment in suitable sub-basins, derive the stream network and calculate overland- and channel slopes. This information is essential for calculating the amount of water and time it requires to translate rainfall to the flood-wave in the channel at the points of interest. The available 1m digital elevation model (DEM) provides a sufficient resolution and quality for that task (Figure 11).

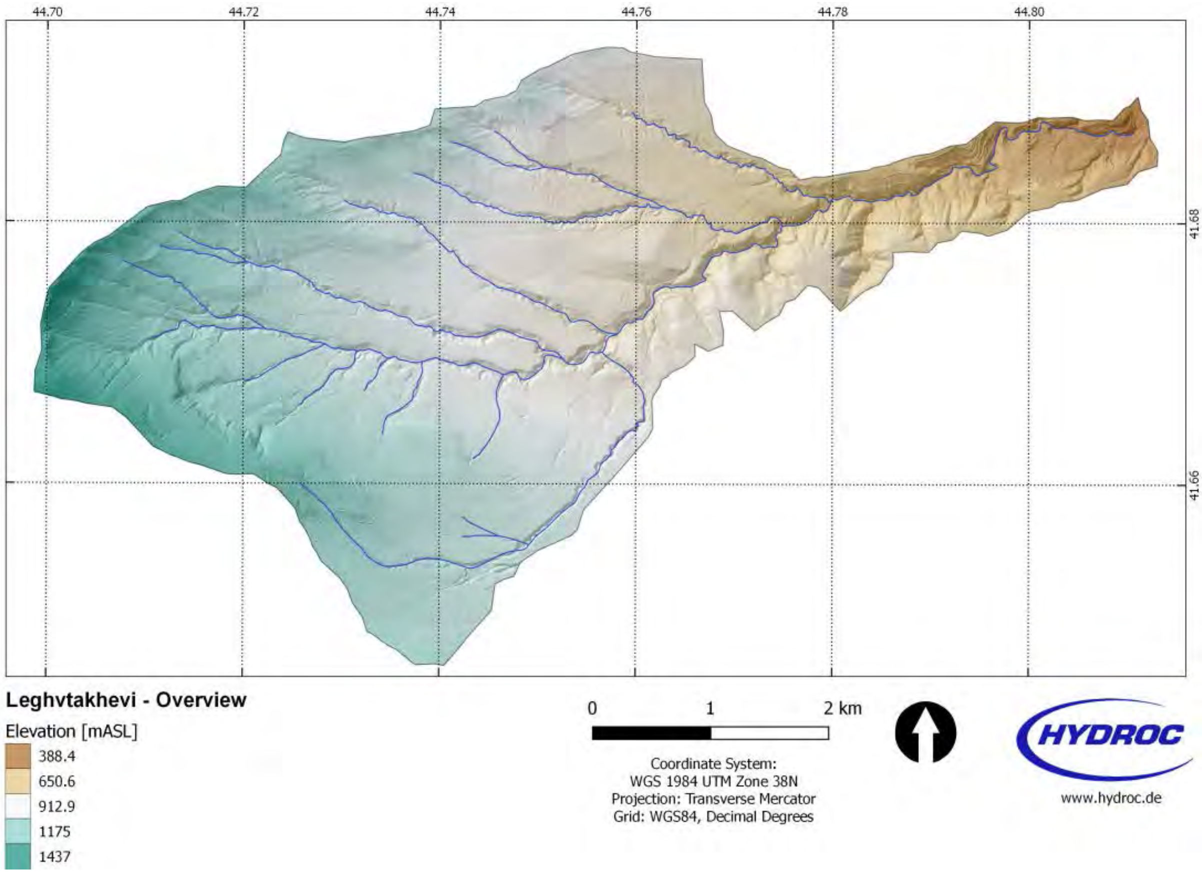


Figure 11 – Digital Elevation Model, stream network and hillshaded elevation

In hydrologic modelling, land-cover data is required to derive surface roughness for calculating overland flow velocities, initial losses of rainfall (interception), runoff coefficients for infiltration rates and evapotranspiration from plants. The available land-cover data distinguishes eight classes and the distribution of the land-cover types within the catchment is shown in Figure 12.

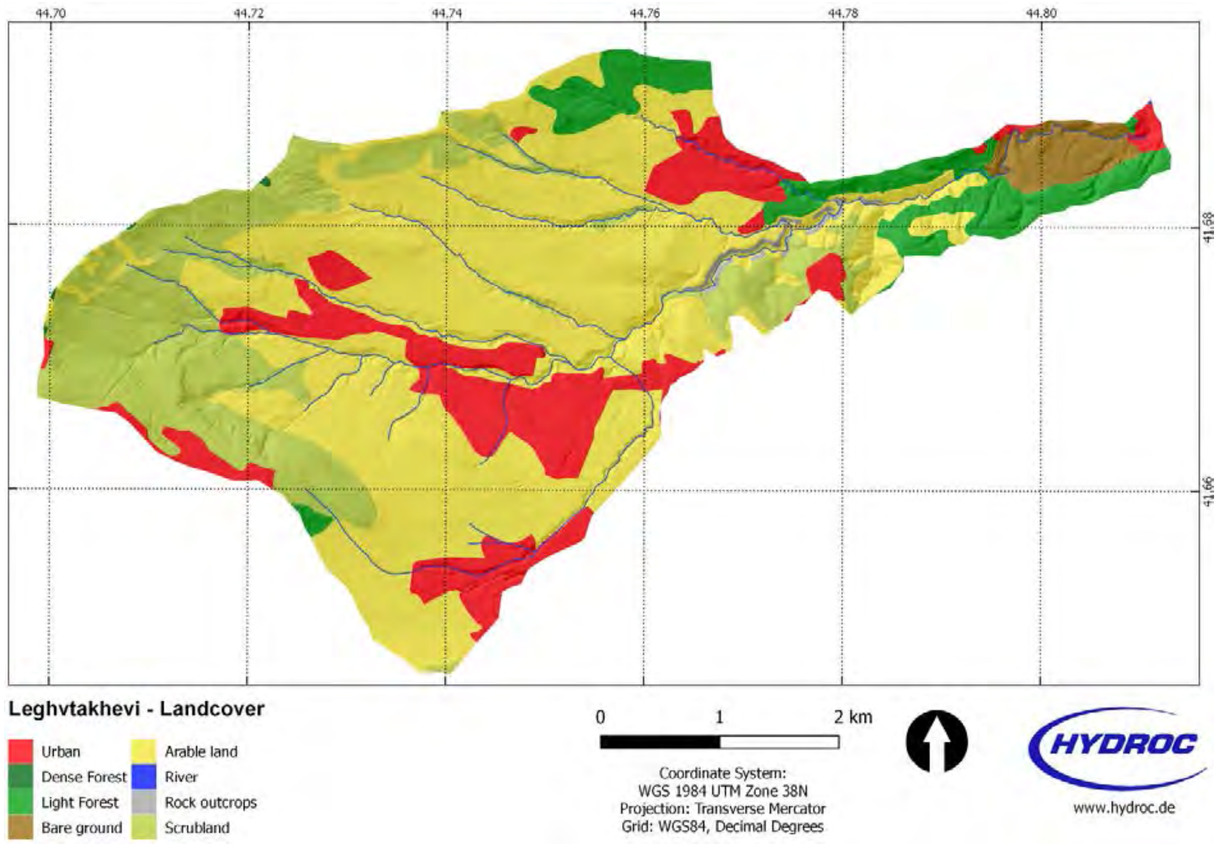


Figure 12 – Land-cover data of the Leghvtakhevi catchment

Information on soil type distribution and soil properties are used to derive infiltration values into the soil and vertical water movement. Especially for continuous simulations, high-quality soil information is important. The distribution of soils in the catchment is shown in Figure 13.

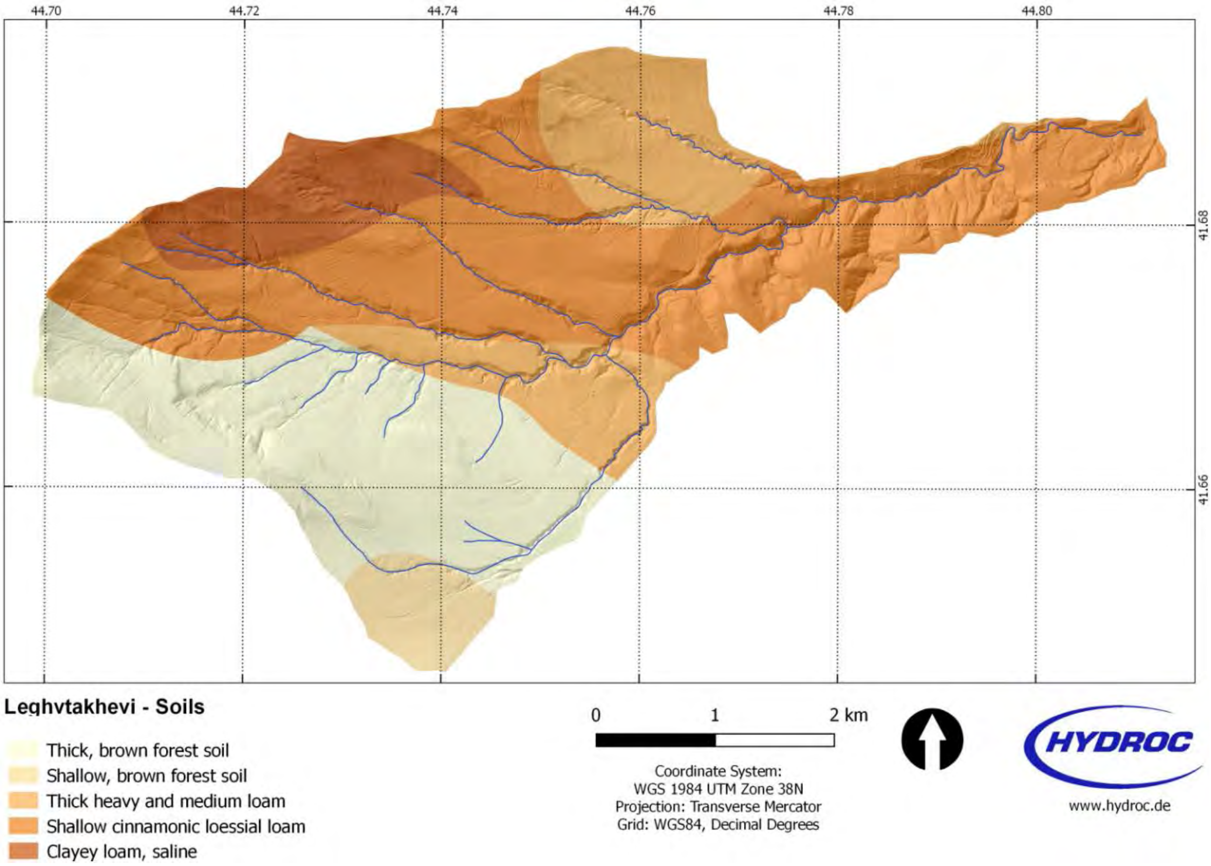


Figure 13 – Soil distribution in the Leghvtakhevi catchment

4.3.2 Temporal data

Most important input and calibration data is rainfall and discharge observations. Due to the relatively small catchment size and high slopes, the response time of the catchment is assumed to be very low. This makes sub-hourly simulation time steps necessary for being able to sufficiently capture and resolve the flood peak including rising and falling limb of the hydrograph.

Long-term, sub-hourly rainfall data for the Leghvtakhevi catchment is unfortunately not readily available. Possible solutions are the usage of TRMM and GPM satellite observations, radar data (if available from the Tbilisi station) or the MPE product from EUMETSAT to temporally downscale daily gauge-readings from the stations Vashlijivari, Kojori or Tbilisi Airport. From these time series, representative events will be extracted for which information about river discharges are available. Unfortunately, no discharge observations took place in the Leghvtakhevi catchment. Therefore, regionalization approaches have to be used to extrapolate observed storms (e.g. the June 2015 and May 2012 flooding events in the Vere river basin) and depict those in the hydrologic model which can then be used for calibration.

The calibrated model must then be forced with design storms. The envisioned return periods of the design storms to be simulated are 1:5-, 1:25-, 1:50-, 1:100- and 1:500-years. These design storms can be generated using two options[1]:

(1) Event-based runoff modelling: Based on the above described rainfall data, Intensity-Duration-Frequency (IDF) curves can be developed. Using the time of concentration (the duration until the whole contributing area of a location conveys runoff) for the points of interest and a chosen return period, the critical storm depth can be derived. The temporal distribution of the storm depth over the time of concentration is then defined to obtain the design hyetographs for the respective return periods.

(2) Monte-Carlo simulations with a continuous rainfall-runoff model: Fitted to observed rainfall statistics, a rainfall generator is used to derive long-term (e.g. 1,000 years) of sub-hourly rainfall data. This data is run in the calibrated hydrological model and using flood frequency analysis, the respective events are selected that fit to the respective return periods. If option (2) is used, daily temperature data is also needed, which is available for the stations Vashlijivari, Kojori or Tbilisi Airport.

4.4 Model setup

HEC-GeoHMS version 10.3 for ArcGIS 10.3 is used to prepare the input files for HEC-HMS.

[1] Rogger M et al. 2012. Runoff models and flood frequency statistics for design flood estimation in Austria – Do they tell a consistent story?. Journal of Hydrology 456-457, 30-43.

4.4.1 Spatial discretization

Based on the described DEM, pre-processing is carried out to obtain the spatial delineation of the Leghvtakhevi catchment in sub-basins and streams. The workflow includes the processes *Fill Sinks, Flow Direction, Flow Accumulation, Stream Definition, Stream Segmentation, Catchment Grid Delineation, Catchment Polygon Processing, Drainage Line Processing, Adjoined Catchment Processing*. A threshold is given for the initiation of a stream which is based on the total catchment size and amounts to 0.2km² (200.000 cells of the flow accumulation raster).

The obtained spatial discretization is furthermore refined to obtain sub-basin outlets at the exact location of the linkage points to the hydraulic model. The linkage points are defined in Chapter 7.4.1.5.1 and represent the points where simulated discharges are transferred to the hydraulic model.

4.4.2 Derive sub-basin and reach parameters

The obtained spatial discretization is furthermore refined to obtain sub-basin outlets at the exact location of the linkage points to the hydraulic model. The linkage points are defined in Chapter 7.4.1.5.1 and represent the points where simulated discharges are transferred to the hydraulic model.

Sub-basin and reach parameters (*Areas, River Length, River Slope, Basin Slope, Longest Flowpath, Basin Centroid, Centroid Elevation, Centroidal Longest Flowpath*) are then calculated using HEC-GeoHMS based on the delineated geometries.

4.4.3 Calculation methods selection

The basin file generated from HEC-GeoRAS is imported to HEC-HMS. Within HEC-HMS, the appropriate algorithms have to be selected for the hydrological processes that will be simulated. Table 5 lists the simulated processes in HEC-HMS and the selected algorithms depending on the design storm option (Chapter 5.3.2).

Table 5 – Depicted processes in HEC-HMS and chosen algorithms depending on design storm option

Process	Selected Algorithm	
	Design storm option (1)	Design storm option (2)
Canopy storage	Simple Canopy with Simple Reduction	Dynamic Canopy with Tension Reduction
Surface depression storage	Simple Surface	Simple Surface
Infiltration (loss) method	SCS Curve Number	Soil Moisture Accounting
Transformation method	SCS Unit Hydrograph	SCS Unit Hydrograph
Baseflow	Linear Reservoir	Linear Reservoir
River Routing	Muskingum-Cunge	Muskingum-Cunge
Channel losses/gain	Percolation (infiltration rate)	Percolation (infiltration rate)
Precipitation	Specified Hyetograph (external)	Inverse Distance
Evapotranspiration	Monthly Average	Priestley-Taylor
Snowmelt	None	Temperature-Index

4.5 Model Calibration (optimization)

The selected algorithms listed in Table 5 contain variables (parameters) which cannot directly be estimated or observed. These parameters need to be adjusted (calibrated) so that model output matches observations sufficiently.

4.5.1 Parameter definition and ranges

The first step in achieving a good calibration result is the selection of parameters that should be calibrated. A selection of parameters is needed to reduce the dimensionality of the optimization problem. Also, the parameter ranges (minimum and maximum values) of the parameters need to be defined. Those are based on physically meaningful values as well as algorithm-specific ranges. Both, parameter-, and ranges selection is aided by a sensitivity analysis.

4.5.2 Objective functions and fitting algorithm

The objective function assesses the skill of the model simulation in terms of agreement with observations. Different objective functions are included in the built-in optimization tool of HEC-HMS. The peak-weighted RMS (Root-Mean-Square-Error) for instance is a suitable objective function for flood simulations that can be minimized using the univariate gradient search method.

4.6 Scenario simulations

Climate change impacts on flooding will be investigated with the calibrated model. Therefore, alterations of the derived design storms (Chapter 5.3.2) under climate change will be defined in a climate change analysis (Chapter 6). The altered design storms will be run in the model and after plausibility checks, analysed according to their changes on discharges.

4.7 Model coupling to HEC-RAS

Discharge hydrographs for each design storm will be available for the baseline as well as climate change scenarios at all hydrological input locations to the hydraulic model (Figure 21). The hydrographs will be stored in HEC-DSS – the data storage system that both HEC-HMS and HEC-RAS share.

4.8 Hydrologic modelling limitations

Hydrologic modelling is always subject to a simplification of the naturally occurring processes. This simplification in both space and time introduces uncertainties in the simulations. These uncertainties can be minimized by selecting appropriate algorithms for the depiction of the processes as well as through choosing physically meaningful parameter values during the calibration process.

The quality of the hydrologic modelling is directly related to the input data, especially rainfall and runoff data. Both data types are lacking in the Leghvtakhevi catchment so that extrapolation, downscaling and regionalization approaches need to be used. These approaches inevitably introduce additional uncertainties into the predictions, which can to a certain extent be quantified through validation (if observation data are available) or multiple runs under input data modification.

5 Climate Change Modelling

5.1 Overview

The purpose of the climate change scenarios is to judge the changing likelihood of high impact flooding events in the region of interest over the next 100 years. In this project, a set of climate change scenarios will be produced for the Tbilisi region of Georgia. The scenarios will be presented in the form of bias corrected, downscaled time series, and associated metrics. The time series will be produced for selected representative concentration pathways (RCPs) and for two time slices.

To represent uncertainty in scenarios resulting from model diversity, 17 climate models from the 5th Climate Modelling Intercomparison Project will be considered. The data presented will be bias corrected, as part of the downscaling procedure.

5.2 Downscaling methodology

For this project, the well-established MarkSim downscaling method will be used (http://www.cgiar-csi.org/475). The algorithm uses 720 classes of weather to derive the stochastic parameters required to drive a third order Markov rainfall generator. This approach ensures that the resulting time series represent local weather regimes.

Following the IPCC 5th assessment, MarkSim was implemented for 17 of the GCMs that contributed to the 5th Coupled Model Intercomparison Project (CMIP5). To achieve this, the downscaling process was developed to encompass a bias correction, and to account for future changes in weather regimes (Jones and Thornton, 2013).

5.3 Time horizons

The following time slices will be considered:

- 2030 – 2050 (near term change)
- 2070 – 2090 (long term change)

Unless otherwise stated, all anomalies are derived relative to the 1960-1990 mean. Student T-Tests for the difference between time-slice mean and 1960-1990 mean are displayed on all maps.

The rationale for choosing 2030-2050 to describe ‘near term’ climate change is that closer to the present day, it is difficult or impossible to distinguish signals of change from natural year-to-year variation in the weather (Hawkins and Sutton, 2012).

5.4 CO_2 concentration scenarios

Lack of knowledge of future emissions is a key source of uncertainty in climate projections. The CMIP5 approach is to carry out climate model simulations for a range of greenhouse gas concentration trajectories, described by Representative Concentration Pathways (RCPs) (Van Vuuren et al, 2011). Although the RCPs are based on CO2 concentration, rather than emissions, the two are closely related (see Figure 14 and Figure 15).

To give an idea of uncertainty related to future emissions, the following RCPs are considered in Section 3:

- RCP 2.6: Low emissions scenario, with CO_2 emissions stabilizing and declining after ~2020
- RCP 4.5: Medium emissions scenario, with CO_2 emissions gradually increasing until ~2040 and then declining
- RCP 8.5: High emissions scenario, with CO_2 emissions increasing at close to present day rates throughout the 21st Century

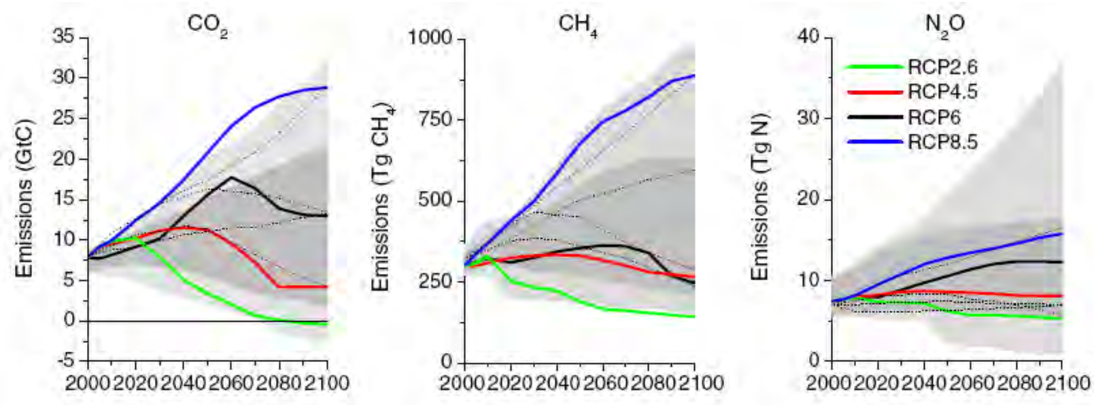


Figure 14: Emissions of main greenhouse gases across the RCPs. Grey area indicates the 98th and 90th percentiles (light/dark grey) of the literature. The dotted lines indicate four of the SRES marker scenarios. (from van Vuuren et.al. 2011)

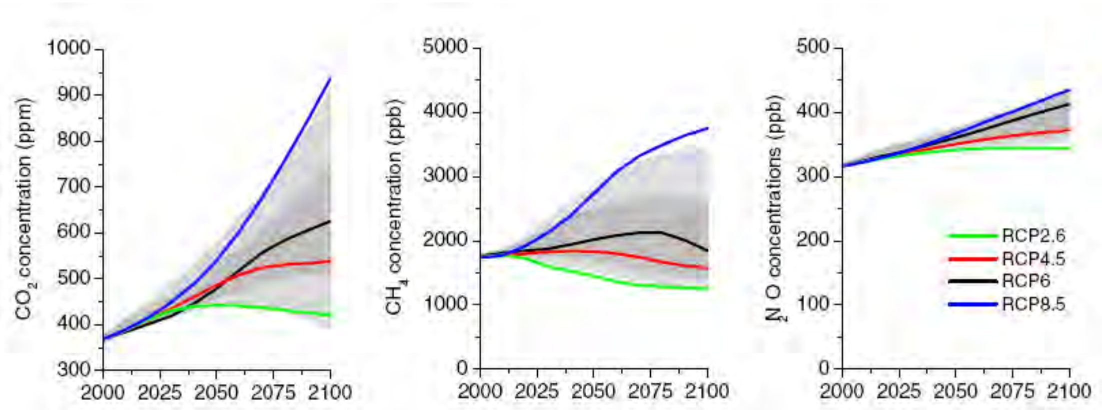


Figure 15 - ***Trends in concentrations of greenhouse gases (van Vuuren 2011). Grey area indicates the 98th and 90th percentiles (light/dark grey) of a recently published climate change control scenario study (Clarke et al. 2009)***

5.5 Climate models

Time series will be derived based on the 17 models available in the MarkSim downscaling system (Table 1). The models were chosen to include a variety of modelling centres, as well as different implementations of related models. These particular models were chosen:

Table 6 - Native spatial resolution of climate models used in the analyses

	Model	Resolution: Lat x Long (degrees)
1	BCC-CSM 1.1	2.8125 x 2.8125
2	BCC-CSM 1.1(m)	2.8125 x 2.8125
3	CSIRO-Mk3.6.0	1.875 x 1.875
4	FIO-ESM	2.812 x 2.812
5	GFDL-CM3	2.0 x 2.5
6	GFDL-ESM2G	2.0 x 2.5
7	GFDL-ESM2M	2.0 x 2.5
8	GISS-E2-H	2.0 x 2.5
9	GISS-E2-R	2.0 x 2.5
10	HadGEM2-ES	1.2414 x 1.875
11	IPSL-CM5A-LR	1.875 x 3.75
12	IPSL-CM5A-MR	1.2587 x 2.5
13	MIROC-ESM	2.8125 x 2.8125
14	MIROC-ESM-CHEM	2.8125 x 2.8125
15	MIROC5	1.4063 x 1.4063
16	MRI-CGCM3	1.125 x 1.125
17	NorESM1-M	1.875 x 2.5

5.6 Metrics

The primary output will be daily precipitation time series, which will be used to calculate return periods for intense rainy events, to inform the hydrological modelling assessments.

To get a wider view of precipitation change in the region, these will be supplemented with analysis of the several standard extreme indices (Table 2). The metrics were selected from the ClimDex project (http://www.climdex.org/).

Table 2 - Extreme metrics investigated in this project

Long name	**CMIP5/Climdex name**	**Description**
Maximum five day cumulative precipitation	rx5day	Let RR_{kj} be the precipitation amount for the 5-day interval ending $_k$, period j. Then maximum 5-day values for period j are: $Rx5day_j = \max(RR_{kj})$
Total annual rainfall when the daily rainfall exceeds the 95th percentile	r95p	Let RR_{wj} be the daily precipitation amount on a wet day w $(RR \geq 1.0mm)$ in period i and let $RR_{wn}95$ be the 95th percentile of precipitation on wet days in the 1961-1990 period. If W represents the number of wet days in the period, then: $R95p_j = \sum_{w=1}^{W} RR_{wj}$ where $RR_{wj} > RR_{wn}95$
Simple precipitation intensity index	SDII	Let RR_{wj} be the daily precipitation amount on wet days, w $(RR \geq 1mm)$ in period j. If W represents number of wet days in j, then: $SDII_j = \frac{\sum_{w=1}^{W} RR_{wj}}{W}$
Maximum dry spell length	CDD	Let RR_{ij} be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where: $RR_{ij} < 1mm$
Maximum wet spell length	CWD	Let RR_{ij} be the daily precipitation amount on day i in period j. Count the largest number of consecutive days where: $RR_{ij} \geq 1mm$

6 Hydraulic Modelling

Different tools and softwares are available for flood inundation modelling, each with their advantages and disadvantages. Defining the appropriate approach, first different choices of numerical models that can be used have to be analyzed and the capabilities of these tools compared to the different flood sources and flood processes that take place in the catchment, describing the applicability of the different types of models to these processes. Based on this analysis, a recommendation for the type of model to use for this project will be undertaken.

6.1 Flood inundation models

Model types are classified according to their dimensionality. Flood modelling methods widely in use currently can be characterised by their dimensionality or the way they combine approaches of different dimensionalities. The most significant ones are the 1D, 1D+2D and 2D methodologies, because these cover most of the modelling applications necessary to support the implementation of flood risk management strategies. Three-dimensional numerical models are also available, based on the 3D Reynolds-averaged Navier-Stokes equations, but significant practical challenges need to be overcome before such models can be routinely applied at the scale necessary to support flood risk management decisions.
Actually, all the numerical model types are based on the same Navier-Stokes equation, and the dimensionality depending on how that equation is integrated.

6.1.1 1D Numerical Models

One-dimensional models are based on some form of the one-dimensional St-Venant or shallow water equations, which can be derived by integrating the Navier-Stokes equations over the cross-sectional surface of the flow. The assumptions used in the derivation of the St-Venant equations limit their use to where the direction of water movement is aligned to the centre line of the river channel. The 1D approach poses two main issues:

1) Floodplain flow is assumed to be in one direction parallel to the main channel, which is often not the case;
2) The cross-sectional averaged velocity predicted by the St-Venant has a less tangible physical meaning in a situation where large variations in velocity magnitude exist across the floodplain.

In the other hand, one of the principal strengths of 1D river models is their capability to simulate flows over and through a large range of hydraulic structures such as weirs, gates and sluices.

6.1.2 2D Numerical Models

Two-dimensional hydrodynamic numerical models are based on the two-dimensional shallow water equations (SWE). The SWE can be derived by integrating the Reynolds-averaged Navier-Stokes equations over the flow depth. In this integration process, a hydrostatic pressure distribution is assumed. A solution to these equations can be obtained from a variety of numerical methods (such as finite difference, finite element or finite volume) and use different numerical grids (such as Cartesian or boundary fitted, structured or unstructured) all of which have advantages and disadvantages in the context of floodplain modelling.

6.1.3 Computational Grids

The numerical method outlined above is implemented on a discretised representation of space called either a mesh or grid. There are two types of grids, namely structured and unstructured grids. A structured grid is a grid that can be conceptually represented on a rectangular matrix. Any point in the matrix is physically connected to the four points on either side. An unstructured grid is a grid that cannot be represented on a rectangular matrix. The main strength of unstructured grid models lies in the possibility to follow irregular floodplain contours, and to apply a non-uniform resolution. It can be refined locally to take into account fine features in the flow, while keeping a low resolution in areas where refinement is not needed, thereby ensuring optimal use of computer power. However, the finer areas usually dictate that a smaller time step be used which can increase computation time.

Structured square grids have an obvious advantage over unstructured grids in that the construction of the physical geometry of the grid is straightforward and entirely defined by a small number of user-defined parameters, for example resolution, lower left corner coordinates, and dimensions (alternatively, an irregular GIS defined outline can also be used). The issue of grid generation for unstructured grids can be more complicated and time-consuming.

6.1.4 1D+2D Numerical Models

A number of commercial software packages include the possibility to link a 1D river model to 2D floodplain grids. This has become popular in recent years because it allows the modeller to take advantage of the established tradition of 1D river modelling while at the same time modelling floodplains in two dimensions. This also results in computational savings over structured fully 2D approaches where a finer grid would be required to correctly represent the river channel geometry.

Several techniques exist to date to link 1D and 2D models. The most widely used technique for 1D river and 2D floodplain linking is the lateral link, where the exchange flows are typically modelled using broad crested weir equations or depth-discharge curves, based on water level differences. A limitation of the approach is that the complicated momentum exchange processes that characterise the river-floodplain boundary are not modelled (due to the fact that these processes intimately depend on complex 3D flow patterns in the river, which by definition are not resolved in a 1D river model).

Other linking approaches include the longitudinal link, which one may use to model a watercourse partly in 1D (upstream) and partly in 2D (downstream), or to connect the downstream extremity of a 1D model to a 2D grid. In this approach the flow from the 1D enters the 2D model as a “source”, and the water level in the 2D model at the junction is used as a downstream boundary condition in the 1D model. Some combined 1D+2D models also offer the possibility to use small 1D components to represent pipes or culverts within an otherwise 2D model.

6.1.5 Advantages – Disadvantages of 1D, 2D (or 1D+2D)

The choice between a 1D or 2D (or 1D+2D) model is relevant primarily in the context of river floodplain modelling. One-dimensional models are appropriate for narrow floodplains, typically where their width is not larger than three times the width of the main river channel. The underlying assumption should be that the contribution of the floodplains to conveyance can be quantified using recent advances in the estimation of compound channel conveyance. An additional condition for such models to be valid is that the floodplains should not be separated from the main channel by embankments, levees or any raised ground, where the channel floodplain unit effectively behaves as a single channel.

One-dimensional river models have limitations that can become significant in many practical applications. The flow is assumed to be unidirectional (generally happening in the direction parallel to the main channel flow), and where this is not true (recirculation areas) conveyance predictions can be severely overestimated. Situations where floodplain flow "makes its own way" are frequent, but perhaps an even more significant issue is the fact that 1D cross-sections will offer a rather crude representation of floodplain storage capacity in the case of large floodplains.

On the other hand, 2D modelling of river floodplains can itself be divided into two important classes of approaches, namely the one where only floodplains are modelled in 2D (as part of a combined 1D+2D model) and the one where floodplain flow and channel flow are modelled as part of the same 2D grid. The main advantage of 2D modelling (over any other approach for floodplain modelling) is that local variations of velocity and water levels and local changes in flow direction can be represented. The approach does not suffer from the limitations of the 1D. It allows in principle a better representation of floodplain conveyance, but a major limitation of combined 1D+2D models for river and floodplain systems is that the exchange processes between the river and the floodplains are still modelled crudely (momentum transfer is not modelled). A major drawback of 2D models is their computational cost. Thus, the approach where the whole river and floodplain system is represented as part of a 2D unstructured grid deserves special attention.

The different advantages and disadvantages of every type of model are summarised in Table 7.

Type of Model	Advantages	Disadvantages
1D	• Accurate hydraulic description in rivers/channels which are one-dimensional flow; • Less computational points relative to 2D model; • Easy to analyse and extract results.	• Flow paths must be known beforehand; • Substantially more effort required for model schematisation • Depth and width averaged flow; no detailed flow descriptions in floodplains
2D	• 2D flow simulated dynamically without prescribing flow patterns; • Flexibility for tailoring grid resolution within the model (unstructured grids); • Detailed information on velocity, depths etc. on floodplains;	• Requires fine grid in rivers/channels in order to define conveyance accurately. • Requires more computational effort than 1D engine
1D+2D	• Contains the benefits from both 1D and 2D Engines • Integration of floodplains, rivers and coasts systems • Visual presentation of flood results • Allows sub-grid scale features (hydraulic structures) to be accurately represented	• Two models must be maintained instead of one; • Computational effort

Table 7 – Summary of numerical model types advantages/disadvantages

6.2 Flood sources

One important factor to consider in the selection of the modelling approach is flood sources and their associated flood process. The most significant flood sources are fluvial, coastal, sewer, pluvial (surface water), groundwater and from dam break and flash floods.
Regarding this project, fluvial and dam break-flash floods are the most significant ones to consider.

6.2.1 Fluvial

Fluvial flooding is usually associated to high flows, due to heavy or continuous rain and/or snow melting. Flooding impact, however, can be exacerbated due to a combination of other factors both natural (sea-level, erosion, sedimentation, vegetation) or anthropogenic (river channel modifications, structures, blockages). Fluvial flooding process differs depending on the river characteristics (slope, topography, river channel, and meandering ratio), flow quantities and human modifications.
The fluvial flooding will be considered first. The Leghvtakhevi catchment can be divided into the upper catchment and the middle and lower one. In the upper catchment the presence of not very well defined channels through forested area is predominant, where the water can escape the main channel easily if flow exceeds a certain threshold. In this areas a 1D-2D approach would be needed in order to predict properly what occurs when water escapes the channel.
The middle catchment is characterised by steep slopes and flows through gorges and narrow passages. This leads to high erosion rates. In this area there are numerous waterfalls and dams. As a general approach, in these areas a 1D model would seem to be sufficient to study these flooding issues and to carry out flood mapping because the floodplain and storage processes do not seem to be too significant and the flow path is defined in most cases.
In the lower catchment (downstream of the last waterfall, in the vicinity of the sulphur baths and close to the discharging point into the Mtkvari River), however, there is a very low slope and there are man-made embankments at both sides of the main river channel. Once the

water escapes the main channel, the processes will be fully 2D, and therefore a 1D model will not be sufficient in this area. It should be noted that even the embankments are significantly high, it cannot be excluded at this stage that water would reach these high levels during extreme events. Thus, in this lower section, a 1D-2D model should be implemented.

6.2.2 Dam breaching and flash floods

Very rapid events characterised by complex hydraulics and changes of flow regime from subcritical flow to supercritical flow and back again. Simulating floods of this nature can be difficult with 2D hydraulic packages at or near to the dam face. However, a 2D modelled is very useful tool for simulating the flood wave down a valley in these scenarios, because the flow path restriction within 1D models does not occur with 2D models.
As previously noted there are several dams in the Leghvtakhevi catchment. One of them is operational but the rest of them are overgrown and they do not represent a major risk from a dam breaching point of view. However, as a first indication, it is considered that these dams present an opportunity for flood mitigation if restored. Thus, a dam breaching assessment will be undertaken in the existing dam and in the other ones if rehabilitated. A dam breaching assessment will be undertaken using the latest techniques available, combining a dam breaching model with progressed erosion (1D model) with a 2D routing model to evaluate the fate of water and the resulting impact.

6.2.3 Other flood issues to consider

There are some other factors that may increase the flood risk in the study area and that will be considered while designing the hydraulic modelling methodology:

- Mtkvari River: as it can be observed in the Figure 16 below, the outlet of the Leghvtakhevi into the Mtkvari River is through two culverts. These two culverts are half-submerged in conditions of normal flow in the Mtkvari, and therefore it is expected that the water level in the Mtkvari can play a major role in the water level in the lower section of the Leghvtakhevi one. It should be added that even if the

Mtkvari is a highly regulated river, water levels can raise considerably due to operational and/or hydrological reasons. Therefore, during the modelling framework implementation, the impact of the Mtkvari River water levels on the Leghvtakhevi lower section will be analysed thoroughly.

Figure 16 – Mtkvari and Leghvtakhevi confluence

- Culvert blockages: there are numerous culverts in the Leghvtakhevi River, most of them under road crossings, such as the ones in Figure 17. The possibility of culverts getting blocked in this catchment is really high, especially due to the high amount of debris available in the upper catchment (forested area), the waste management situation, and the high water speed (high erosion). If culverts get blocked, the road embankment will hold water until it reaches the deck of the road crossing, and then it will flow, depending on the topography, back to the river in the downstream side of the culvert or somewhere else. A 2D approach would be needed in order to assess this. Different percentages of culvert blockages will be tested during the modelling implementation.

Figure 17 – Culverts in the upper Leghvtakhevi River

6.3 Approach for software selection

There are some key questions to consider before choosing a type of numerical model, such as what are the phenomena to study, the required results, the study area or the available data and resources (time and budget).

The main objectives concerning the hydraulic modelling for this project are flood hazard mapping and flood mitigation options. The flood mapping and the flood mitigation options will be undertaken at a catchment scale.

Thus, in order to be able to undertake flood mapping for the whole catchment, and considering all the information previously outlined, a 1D+2D type of model will be selected. Therefore, it will be possible to address gorge and steep areas in the mid-section with the 1D model, whereas the upstream and downstream, will be fully addressed with the combination of 1D+2D model.

There are several commercial software packages with 1D, 2D and 1D+2D capabilities, each of them with weaknesses and strengths for this project. In order to select the most appropriate software, HYDROC's team has evaluated different relevant aspects for every package, such as the 1D engine, the 2D engine, the linking method, NEA experience, learning difficulty, interfaces, project objectives, updating possibilities, acquisition and maintenance costs, support (external and by the software company if available) and forecasting possibilities SOBEK, InfoWorks ICM, MIKE FLOOD and HEC-RAS have been initially considered as suitable software for this assignment.

After evaluating all the above-mentioned aspects, and after close consultations with NEA experts, HEC-RAS (version 5.0) has been selected for this study. There are several reasons to justify this:

- HEC-RAS is software developed by the U.S. Army Corps of Engineers, and it is freely available in their website.
- HEC-RAS 5.0 has a recently developed (more than a year ago) 2D engine. This 2D engine has already been used by relevant institutions (such as the Federal Emergency Management Authority (FEMA) of the United States of America) and it is an approved 2D engine by this institution.
- HEC-RAS hydraulic approach for culverts is superior to the ones provided by similar software packages such as MIKE FLOOD, InfoWorks ICM or SOBEK. This is of paramount importance in this project due to the existence of several culverts in the study area.
- HEC-RAS can be dynamically linked to several forecasting platforms, especially to DELFT-FEWS, the flood forecasting platform used by NEA.

- HEC-RAS can be easily linked to the hydrological model chosen for this study (HEC-HMS), sharing the same type of database (HEC-DSS).

In general, all the software packages analysed comply with the project requirements. All of them have been used internationally in similar studies. In this case, the fact that HEC-RAS is freely available is a big bonus for several reasons:

- The modelling results can be easily distributed to universities and research centres. In case that the modelling framework were implemented with any of the above-mentioned software models, license and cost issues would exist with the model distribution.
- The maintenance and upgrade to latest versions of SOBEK, InfoWorks ICM or MIKE FLOOD is not free of charge. The annual amount for this maintenance vary from software to software in between 3,000€ to 5,000€. The maintenance of HEC-RAS is free of charge, with new version being widely available in the U.S. Army Corps of Engineers website.
- There is a wide support network available for HEC-RAS, especially through specialised forums.

6.4 Hydraulic modelling methodology

This section will detail the proposed hydraulic modelling methodology with the main aim of producing flood maps and undertaking flood optioneering (mitigation). The main purposes of the project, from a hydraulic modelling point of view, do obviously define the strategy to follow.

6.4.1 Numerical model implementation

The strategy for the model implementation will define the initial steps required for the hydraulic modelling, namely the management of the topographic data, the definition of the model extents, the definition of the grid and the required physical parameters such as roughness and viscosity.

6.4.1.1 Topographic data

The topographic data available for his study has been defined in previous sections of this deliverable. Nonetheless, in this section the data requirements and the data processing to be done during the model implementation will be discussed.

The topographic data to be used in the hydraulic modelling will be a combination of DEM data and topographic data from the survey campaign. The survey campaign has been previously described (Deliverable 2: Data Collection). It should be noted that the cross section scoping has been carried out for the whole catchment (Figure 18). Figure 19 shows the selected cross sections in the lower part of the river.

The cross section scoping has been undertaken considering:

- Cross section spacing is shorter in steeper areas.
- In lower and flatter areas, the cross section spacing is higher.
- Cross section spacing is shorter around flood issues. All the reported flood issues from the upper catchment were briefly analysed, and cross section to be surveyed selected accordingly.
- Cross sections were selected upstream and downstream of every structure and of significant junctions.
- Tributaries were selected for survey when flooding issues were reported or when the tributary could have a significant hydraulic impact in the model implementation.

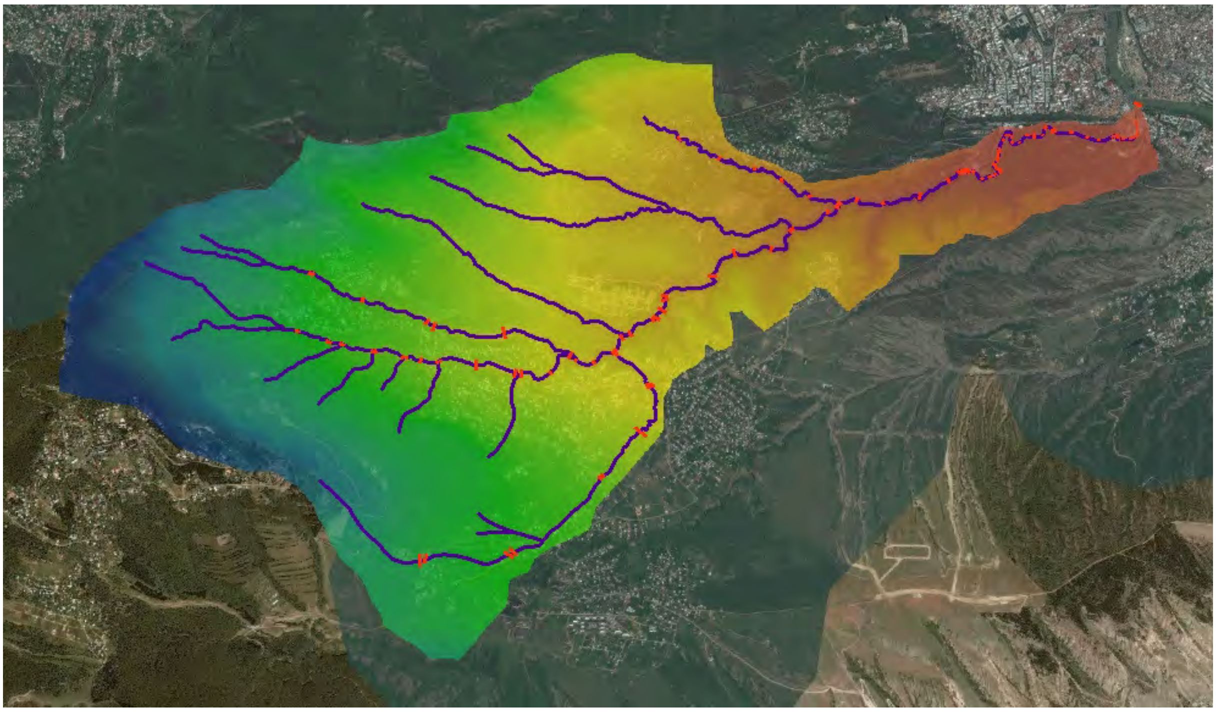


Figure 18 – Cross section scoping for the whole Leghvtakhevi River (showing river network and digital elevation data on satellite image background)

Figure 19 –Cross section scoping for the lower Leghvtakhevi River (showing river network and digital elevation data on satellite image background)

6.4.1.2 Model extent

The purpose of the hydraulic model is to provide the necessary information for the flood mapping in the whole catchment, and therefore the model to be implemented will cover the whole catchment.

6.4.1.3 Geometry files - modelling approach

The first key input file required in the numerical model will be the geometry file, for both the 1D and the 2D engine. A very thorough analysis of the topographic data will be carried out before this stage.

As a very initial approach, the middle catchment will be primarily modelled in 1D and the upper and lower catchment in 1D-2D. Reasons for this are based on the different processes occurring in the upper, middle and lower catchment.

This approach, however, may change during the implementation process. The following things should be taken into account:

- In the middle catchment the main river channel is usually well defined, and velocities are very significant due to the high slope. Therefore, floodplains are not very extensive, and 1D processes dominate in this area. In these areas a 1D model is recommended.

- It should be noted that in some areas in the middle catchment, the distance between cross sections may be significant, especially in areas where no issues have been identified. These areas are important for continuity processes, but these areas may be not fully represented with the field campaign data. Cross sections will be created using interpolating processes and extracting data from the DEM.

- In the upper and lower catchment there are structures in the river channel that may affect the flow, creating scenarios where a 2D approach may be more appropriate. In those areas a combination or 1D and 2D approach, will be more appropriate.

- Also, once the flood mapping has been carried out, during the optioneering process, it may be required to have some of the models in 2D in order to fully assess the proposed options.

- In the lower catchment, a 1D+2D approach is recommended. This is especially due to the very low gradients and to the existing embankments at either side of the river channel. As previously noted, once the flow escapes from the river channel, 2D processes will dominate. This means that the river channel up to the top of the embankments will be modelled in 1D and the floodplain will be modelled in 2D (Figure 20).

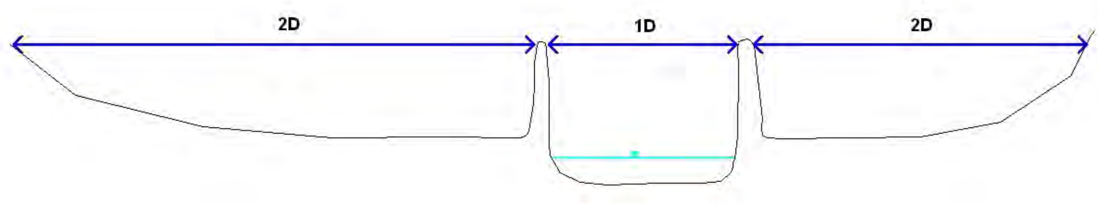


Figure 20 – Modelling approach for lower section

- Especial attention will be paid to the linking method between the 1D and the 2D model, and to the crest height of the embankment.

6.4.1.4 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 use information will be used. This will be completed with input data from photographs and from the field campaigns. It should be noted that seasonal variations of the roughness may be taken into account, mainly during the calibration process. Initially the Manning roughness approach will be followed. Literature reviews and software recommendations for Manning´s roughness coefficients will be used. These coefficients may change during the calibration process.

It should be noted that this is one of the few things that can be modified during the calibration process, although any change should always be supported by evidences in order to avoid force-fitting issues.

6.4.1.5 Boundary conditions

The following boundary conditions are required for the numerical model.

6.4.1.5.1 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 21).

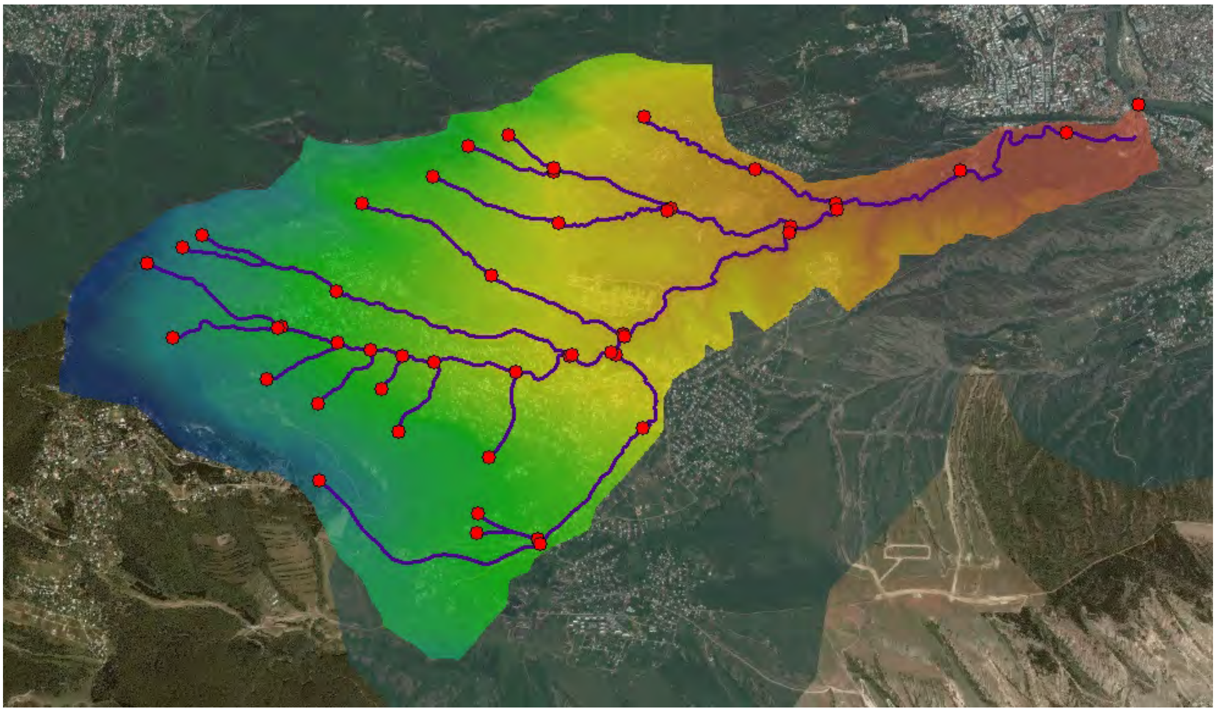


Figure 21 – Hydrological input locations in the Leghvtakhevi River (showing river network and digital elevation data on satellite image background)

6.4.1.5.2 Downstream boundary

In this case, because the model extent will be taken down to the Mtkvari River, the downstream boundary of the model will be the water level of this river. During the calibration and validation of the models, the actual water level in the Mtkvari will be used if available. In case that that data is not available, information about the discharge in the Mtkvari will be used. The influence of the Mtkvari water levels in the Leghvtakhevi will be assessed during the sensitivity test stage, and the values for the design events will be chosen accordingly.

6.4.1.6 Events selection - Calibration

The model will be calibrated against recorded events when data are available. The information from the hydro-meteorological stations will be analysed, and taking into account the flooding events historically reported, a series of events will be considered. Historical visual data may be used too.

During the calibration process special attention will be paid to:

- The Manning´s coefficient. Depending on the season and based on local experience the roughness coefficient will be adjusted. However, analyses will be carried out in order to decide roughness coefficients for design events.

- Land uses and geometry. Depending on when the selected events took place, the river geometry or the land use in the catchment may have changed considerably. This will be taken into account.

6.4.1.7 Sensitivity analysis

Several sensitivity analyses will be carried out in order to ascertain the impact the roughness and boundary conditions may have in the modelling results. Regarding the roughness sensitivity test, several models will be run, increasing and decreasing the Manning coefficient by a certain percentage in the whole catchment. Results will be analysed and the stability of the model will be ascertain if results are sensible, i.e. a decrease in Manning coefficients will yield lower water levels and an increase in Manning coefficients will result in higher water levels through the whole catchment.

6.4.1.8 Design events

Hydraulic models will be run for the annual, 1:5, 1:25, 1:50, 1:100 and 1:500 year events. These events will be initially defined by the hydrological input. However, depending on the Mtkvari water-level influence in the Leghvtakhevi River, and especially depending on how far upstream these effects are noted, it may be the case that a joint probability approach would be taken to define those design scenarios.

The validated model will be run for the whole catchment for those scenarios.

6.5 Hydraulic Modelling Limitations

The results from an implementation of any mathematical model should always be treated with caution. The aim of any numerical model is to describe reality through the simplification of some events and using all the available collected data. The lack of some data and the low accuracy of some other may have a significant effect on the results:

- The lack of reliable hydrological and meteorological information may have a significant impact on the definition of the inflows used in the numerical model.
- The lack of suitable calibration information may also prevent the hydraulic model to be properly calibrated.

Therefore, during the implementation of the modelling framework, HYDROC's experts will limit the impact these issues may have on the results.

7 Flood Mapping

The flood mapping activity will use the results from the flood modelling (hydrological modelling climate change modelling and hydraulic modelling) in order to derive different flood maps.

The flood mapping process depends on the hydraulic modelling approach. As previously explained, a 1D+2D modelling approach will be used in order to properly ascertain water levels at discharges at pre-defined locations.

In a 2D model, the results from the hydraulic model would be the initial step for a flood map, because the water levels and the discharges are routed through the existing topography. The results from the 2D model will be thoroughly reviewed in order to prevent any flooding in areas where the 2D topography may not be properly represented.

In a 1D model, however, the flood mapping requires further processing. A 1D model (in unsteady mode) will calculate water level and discharges at the predefined cross sections. These cross sections are extracted from both the existing DEM and the information from the river survey. The locations for these sections (Figure 18 and Figure 19) have been carefully selected, in areas where flood risk have been previously identified, potential risk areas identified during the site visit, structures and junctions. There are the areas where a higher accuracy in the water level prediction is required. The results from the 1D model will be compared with a topographic grid at every single point, and whenever the predicted water level is higher than the topographical level, that cell will be flagged as a flooded cell.

The results from the 1D and the 2D model will be combined using GIS resources, and the flood maps for the selected scenarios and variables will be produced.

7.1 Design events

Flood mapping will be carried out for the 1:5, 1:25, 1:50, 1:100 and 1:500 year events. These events will be initially defined by the hydrological input. The validated model will be run for the whole catchment for those scenarios.

7.2 Production of maps

Flood maps will be produced for the whole Leghvtakhevi catchment. Depth and velocity information will be provided for the whole catchment for the abovementioned events. Special attention will be paid during this process in order to ensure consistency between the topographic data used in the model and the topographic data used by the flood mapping process. Also, identified areas will be compared against historically reported areas and flooding occurring in unreported (populated) areas will be thoroughly investigated.

8 Flood Mitigation

8.1 Methodology Approach

The flood mitigation component of the study will comprise consideration of both structural and non-structural flood mitigation measures.

The flood hydraulic modelling for existing conditions will provide information in respect of the main flood-prone areas: a range of potential structural flood mitigation measures will be considered in each instance on the basis of the three main themes of flood mitigation, namely, prevention, protection and preparedness.

Prevention measures aim to reduce the peak flood flow in order to reduce the area flooded: this may involve upstream flood storage, channel enlargement or diversions. Where extensive deforestation has taken place upstream, re-forestation can be useful as a long term measure but takes some years to be effective.

Protection measures increase the capacity of the river to convey floodwaters: they provide a physical barrier between the river and the flood-prone area and may include levees (or embankments, flood protection walls, channel enlargement. Where river bed and bank erosion is significant, protection works such as bank protection works, grade control works and river training works can be included to ameliorate these effects. These will be considered if warranted.

Preparedness measures are essentially non-structural and include: raising community awareness of flooding issues by the production and explanation of flood maps, flood forecasting and flood warning, and the timely dissemination of flood warnings.

At this point of time, we are not able to speculate on the most appropriate flood mitigation measures. However, the approach will be:

- Identify main flood prone areas and identification of priorities from discussions with the client and key stakeholders – this will include an assessment of number of persons, houses, businesses at risk, together with the ability of the communities to respond or conversely, their vulnerability; broad environmental impacts;

- This process will enable a “long-list” of potential measures to be formulated. These will then be subject to a first level option analysis based on broad assessment criteria (to be agreed with the client) – the result of this phase will be a short listing of those measures considered to have the most merit; during this phase the effectiveness of the identified measures in reducing flood risk will be evaluated by modifying the hydraulic model to include each measure and possibly combination of measures;
- The short listed options will then subject to further analysis by developing each to a concept design stage to enable broad cost estimates to be made;
- Providing sufficient data are available in respect of flood damages, the direct damages will be estimated for a range of flood probabilities allowing the average annual damage to be estimated;
- A cost-benefit analysis will then be carried out using a present value approach using discount rates to be agreed;
- The results of the cost-benefit analysis will then be used to prioritise the possible projects on an economic basis, then these results will be combined with those from environmental and social impacts to determine the overall prioritisation between potential projects;
- Recommendations will be made in respect of the proposed projects based on the above.