

Caribbean Handbook on Risk Information Management



GFDRL
Global Facility for Disaster Reduction and Recovery

ACP-EU Natural Disaster Risk Reduction Program
An initiative of the African, Caribbean and Pacific Group, funded by the European Union and managed by GFDRL

Flood modelling for Integrated Watershed Management

Bois d'Orange watershed St Lucia

Caribbean Handbook for Risk Information Management

(Deliverable 5.16)

FINAL VERSION

1 July 2016

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With financial support from the European Union in the framework of the ACP-EU Natural Disaster Risk Reduction Program

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1 Introduction

The Government of Saint Lucia has recognized the importance of a national integrated watershed management plan to ensure sustainable use of its water resources, because the country depends primarily on surface water for its potable, agricultural, commercial and industrial needs. With increasing demands due to increasing socio-economic development, and competing uses among the various sectors, this water supply is highly vulnerable. Some watersheds experience multiple environmental problems that are interrelated. One of the most re-occurring problems are flash floods from tropical storms and hurricanes, that affect most watersheds once in 5 year if not more, leading to loss of lives and damage to houses and infrastructure. In spite of the extremeness of these weather events, it is often possible to mitigate the effects in a catchment, usually with a mixture of land use planning and engineering. Added to these challenges are the impacts of climate change, which are expected to reduce water quantity and quality within rivers.

Other problems are also part of integrated watershed management: loss of productivity, guarding ecosystem services, salinization close to the sea etc. However, floods and drought cause very different processes for different stakeholders, often needing different analysis techniques and different solutions and strategies. This super-use case focuses on flash floods only, fitting within the context of the CHARIM project. Nevertheless there are two clear links between flash floods and other processes: upstream water harvesting can be a solution to prevent flash floods, while this water becomes available for other uses (e.g. agriculture), and soil erosion often leads to blockage of the drainage system during storm events, leading to flooding. Therefore prevention of soil erosion (and even landslides) can be a necessary tactic in watershed management. However, soil erosion and landslides are not part of this report and analysis.

The development of the IWRM plans is part of the St. Lucia Disaster Vulnerability Reduction Project, supported by the World Bank. It was therefore suggested that the development of the CHARIM “super use-case” – one of the CHARIM deliverables – could contribute by informing the creation of watershed management plans with flood hazard information. The target organization is the St. Lucia Water Resource Management Agency (WRMA) that has been charged with the development of the watershed management plans.

Objectives of the super use case:

The first objective is to develop a practical approach for flood modeling with existing information complemented with limited data collection for one watershed – which can be replicated in other watersheds. This watershed is used as an example case study, to illustrate the steps that have to be taken to do a model analysis for integrated watershed management.

The second objective is to increase the capacity at WRMA to carry out/plan hydrological and hydraulic analyses for flood modeling using a hands-on approach with the above mentioned flood model.

For this purpose, a 2 week hands-on training was organized, for which all materials (powerpoints, exercises, literature, software and data) are added to the charim.net website. They can be downloaded and used for learning purposes. Note that the objective of this super-use case is not to do a full analysis of the Bois d’Orange watershed, only to use it as an example of where flood modelling is used in IWM. A full IWM analysis involves all stakeholders and is a long and intensive process to find out the best possibilities for watershed management for this particular catchment, and do a cost-benefit analysis of different scenarios that are discussed with stakeholder groups to create acceptance. This is beyond the scope of this super use case.

2 Study area

The WRMA selected the **Bois d'Orange watershed** in Saint Lucia as a case study site. The watershed has a size of 9.98 km² (Fig. 1) and is located in the North of St. Lucia, North of its capital Castries. It is representative for a series of watersheds north of Castries, such as the Choc River and stream leading into Rodney Bay. These rivers are prone to flooding, and have inhabitation all along the central valley near to the stream channel. This is in contrast with some locations know to be flood prone in the west of the island, such as Canaries and Soufrière, which consist of a township and the downstream end of a relatively 'empty' catchment, i.e. with little upstream settlements.

The national scale flood hazard map shows that there are flood problems near the river channel and in the downstream part, north of the bridge where the main road crosses the river. This northern area is mainly an uninhabited coastal wetland and as such free of flood risk.

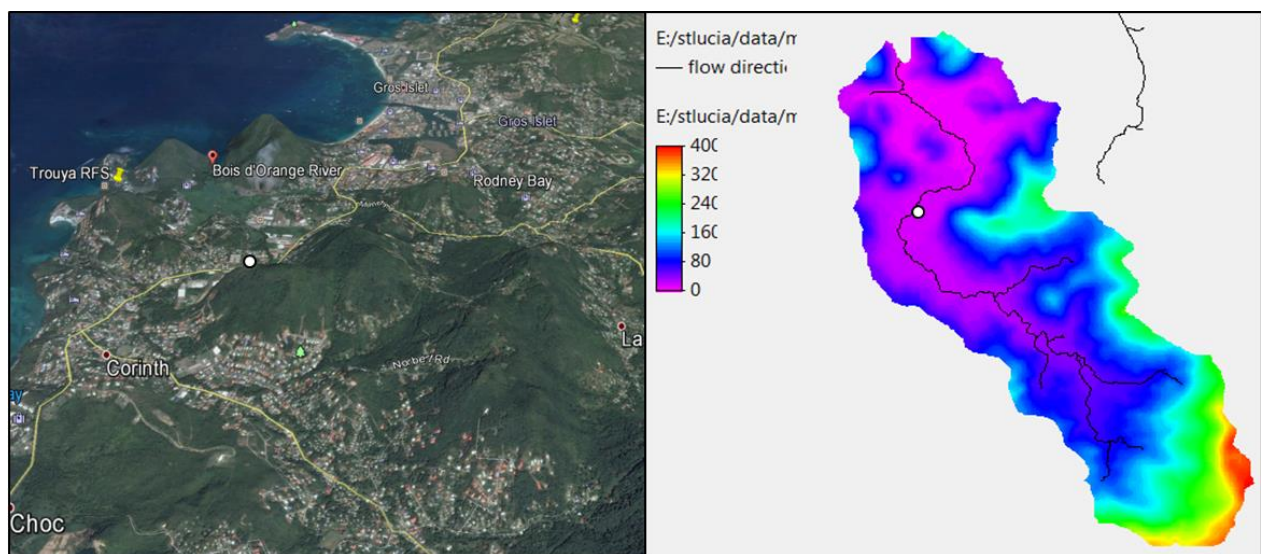


Figure 2.1. Google earth image of the Bois d'Orange river watershed (left) and ground elevation (m) with the main river channel (right). The white dot is an approximate reference point in both images.

The main buildup areas are in the middle and upper reaches of the watershed (South of the main road) where dense housing areas have been constructed especially in the neighborhoods 'Corinth' and 'Morne Serpent'. In the last 15 years the area has seen some increase in development but not much.

The highway (the ring road around the island) crosses the catchment and the river channel with a bridge close to a commercial zone. During Hurricane Tomas in 2010 this bridge had been severely damaged and reconstruction was finalized end of 2014. Figure 2.2 gives an impression of the bridge location. From our own observations in the field (see figure 5), we noticed sedimentation under the bridge, which may be the result of recent channel modifications. The sedimentation reduces the capacity of the bridge and this may increase in future flood problems.

As part of the CHARIM project, a 10m raster database was produced for the purpose of integrated watershed modelling. Details of this database, describing Bois d'Orange watershed, are discussed in below.



Figure 2.2 Left: Bridge of the main road across the river in the Bois d'Orange watershed. Right: Oblique view over the downstream parts of the Bois d'Orange watershed. The red circle indicates the bridge.

3 Integrated Watershed Management

Integrated watershed management (IWM) tries to look at our environment in a holistic way, whereby the area under consideration is a watershed, instead of for instance an administrative area. A watershed naturally concentrates all rainfall to a river channel and since many climate and environmental processes are water related, it is a logical unit to work in when dealing with development and conservation.

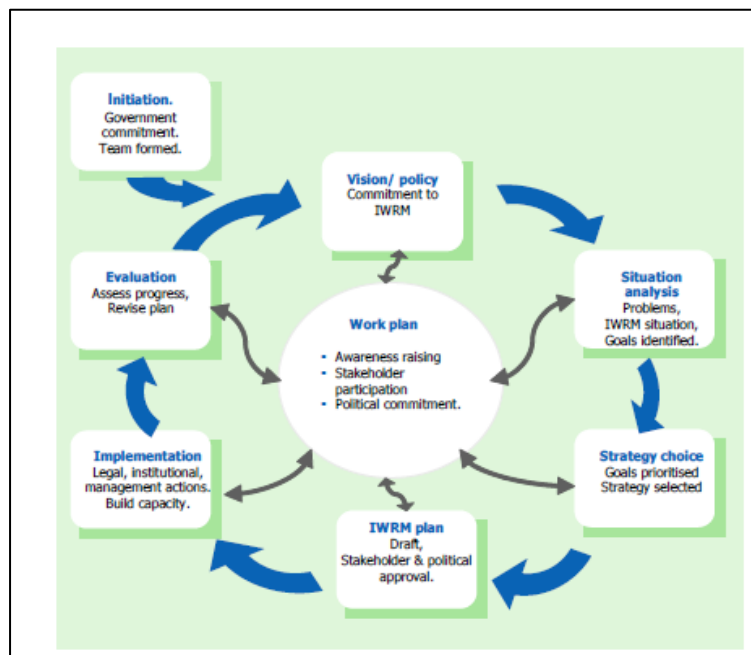
In the document “Applying Environmental Assessment for Flood Management “, WMO and the Global Water Partnership (2007) gives an excellent overview of the steps that need to be taken in IWM, with many practical considerations.

The integrated nature of watershed management refers to several main things:

- the physical/technical context, looking at natural pathways of water and substances, including sources and sinks;
- the socio-economic context, include all stakeholders in the process of analysis, planning and implementing changes in a watershed;
- the policy context that defines what type of flood mitigation is envisioned and the political embedding of decisions made.

Figure 3.1 gives an overview of the process of designing an integrated watershed management plan. Often the response of a government to a problem is to “fix it” at the location where a problem arises. This may lead to technical solutions without trying to understand the source of those problems or attempt to intervene in other ways, in particular if floods can be mitigated through intervention upstream. In this context it is important to realize that the term ‘stakeholders’ is not only used for the people affected by a flood in the area under consideration, but all groups involved

are stakeholders in this process: people affected, building companies, WRMA, ministries, consultants etc. This is inherent to the multi-disciplinary nature of disasters.



- What role do the flood plains play in the economy of the country/region?
- What issues in National development vision/policy have relevance to the condition of floods or flooding and its management?
- How flood management can contribute to the national development?
- How flood risks can be appropriately factored in national development planning?
- How/Why the existing policies have/have not fulfilled their desired objectives?
- How national development vision/policy should be aligned to the existing and future flood risks?
- How flood risks mitigation costs are shared between federal, state, and local governments on one hand and the individual on the other?
- What role do the different institutions play in flood management?

Figure 3.1. The cycle for developing and adjusting an IWRM plan, and type of questions asked in this process (WMO, Global water partnership, 2007).

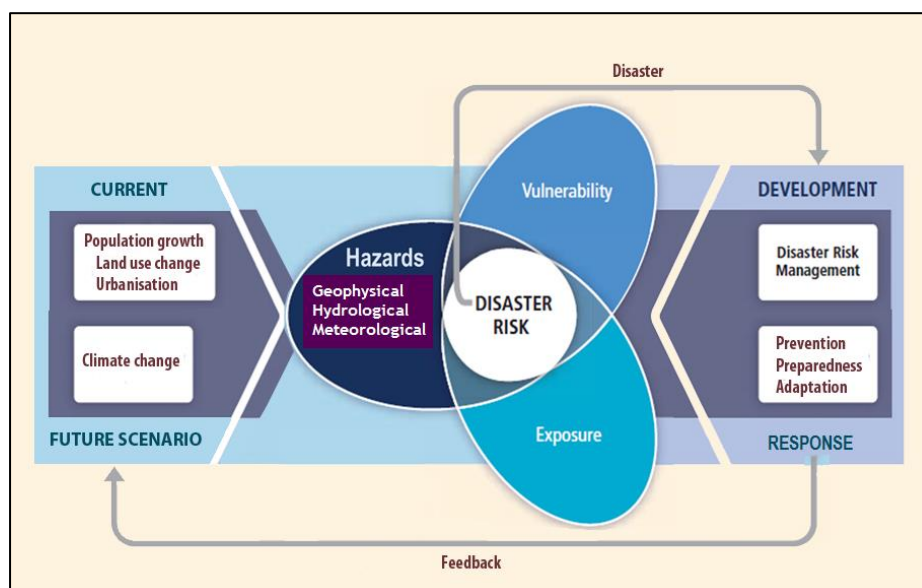


Figure 3.2. Principles of disaster risk reduction with drivers affecting hazards and vulnerability (based on IPCC, 2012).

Central to flood mitigation is the principle of “risk”, which can be defined as the potential damage or impact of a given set of “hazards” in this case flash floods. When the impact involves the vulnerability and resilience of the areas exposed to flooding, a framework can be defined that brings these elements together (figure 3.2).

Recognizing that a flood problem is a combination of the flood process and its probabilities, the vulnerability and exposure gives a theoretical list of mitigation actions that can be taken. Figure 3.3 gives an overview of possible mitigation measures, divided in decreasing the hazard, the exposure and the vulnerability. Some of these interventions are technical/engineering in nature, other are based on land use changes or changes in behavior of people. The socio-economic and governance parts are very important when designing a solution on a catchment scale, whether they consist of engineering, planning, early warning, or a combination. The costs and benefits, the level of protection expected, the associated actions that should be taken, have to be communicated and discussed with all stakeholders involved, in order to have a successful strategy.

Reduce hazard	Reduce Exposure	Reduce Vulnerability
<ul style="list-style-type: none"> • Retaining water where it falls (increasing infiltration, rooftop storing) • Retention basins (natural wet lands or depressions, man made e.g., school play grounds, household underground tanks) • Dams and reservoirs • Diversion channel • Land use management (e.g., house building codes in urban areas, infrastructure building practices, appropriate landscape planning) 	<ul style="list-style-type: none"> • Structural measures on the river (Dykes, river training work such as channelization, flood walls, raised infrastructures such as roads and railways) • Structural and non-structural measures/actions by individual (flood proofing) • Land regulation • Flood emergency measures (flood warning and evacuation) 	<ul style="list-style-type: none"> • Physical: by improving the infrastructure, well-being, occupational opportunities and living environment • Constitutional: by facilitating equal participation opportunities, education and awareness, providing adequate skills and social support system • Motivational: by building awareness and facilitating self organisation

Figure 3.3. Overview of strategies available for flood mitigation, divided into hazard reduction, exposure reduction and vulnerability reduction (WMO and Global water partnership, 2007)

From the mitigation strategies it can be seen that in case of reduction of hazard and exposure, the aim is to alter the hydrological and hydraulic processes: reduce runoff or prevent it from happening entirely, interrupt flows or contain water levels in areas where they are harmless. These kind of mitigation measures are a combination of technical interventions (engineering) and spatial planning, to determine the best locations for these interventions. A strategy can also be to allow flooding, but ensure that it happens in places empty of inhabitation, so that the risk is minimized.

Given this strategy, it is essential for WRMA to understand the hydrology of the catchment under consideration, and to have a good grasp of the hydraulics related to river flow and flood dynamics. Because there are no measurements of discharge in the catchment, catchment modelling provides a good framework to understand these processes and to simulate out different mitigation strategies to have a best guess of their effect in discussions with stakeholders.

4 Flood modelling and model selection

There are many flood models that can be used for this purpose. Table 1 gives an organization of available methods, arranged from more static observation based method to dynamic modelling. Appendix 1 gives an overview of the methodologies available and their advantages and disadvantages. This information is also elsewhere available on CHARIM.NET but is included here as an appendix for the sake of completeness.

Type	Method	Data source
A - Observations	Community based	Questionnaires
	Visible/NIR wavelengths	Images
	Radar wavelengths	Images
B - Multivariate statistics	Weighed combination of flood related factors	GIS layers
C1 - Modelling, decoupled: upstream	Incoming discharge measured	Measurements or statistics (design discharge)
	Incoming discharge modelled	Runoff from runoff fraction of upstream area (curve number)
	Incoming discharge hydrology	Runoff derived from hydrology of upstream area
C2 - Modelling, decoupled: downstream	Flood modelling from channel system	Physically based 2D modelling
D - Modelling, integrated	Full catchment modelling	1D/2D hydrology and hydraulics

Table 4.1. Overview of methods for flood hazard assessment

It is common to approach a flood problem such as presented here with two decoupled models (category C in table 1), whereby the flooded area is considered to be hydrologically separated from the runoff delivering area, in an upstream-downstream configuration. This also assumes that the upstream part does not experience any flooding and the discharge wave coming from this area has a regular shape, fully contained in the channel. A discharge influenced by flooding is normally longer in duration and has a flat top because of the overflow process upstream and the slow surface drainage of a flooded area. In fact, promoting flooding upstream is a well-known strategy to protect downstream areas. Such processes are not included in the category of models in C1, and are considered less suitable for integrated catchment management.

The flood models in category C2 are usually very good in hydraulics and taking into account man-made elements (drainage systems, sewers, bridges and culverts etc.). For this reason they are popular for engineering purposes. Perhaps one of the most popular is the combination HECHMS and HECRAS (US Army Corps of Engineers, freeware), because it has a large user experience database to draw from.

All modelling approaches need a large amount of detailed spatial and temporal information. Floods are complex phenomena, especially when taking into account the entire catchment and rural and urban elements in it. There is no easy way out, and generally it is not a good idea to do any hydrological and hydraulic modeling uncalibrated. A good input dataset is not a guarantee for a good (e.g. realistic) flood estimate, when calibration and validation have not taken place.

In the CHARIM project, the integrated flood model LISEM is used. LISEM a runoff and erosion model that has been in use since 1992, and was extended with a 2D flood model in 2012. It is used for the national flood hazard map (Jetten, 2016), based on a 20m grid GIS database (explained below). LISEM is also one of two models used in this Bois d'Orange example. It simulates the surface

hydrology of the catchment, and has a full hydraulic 1D/2D numerical solution for the surface water flow. However, it does not model the river cross sections and man-made flood mitigation measures in detail and it cannot be used for engineering design. For that purpose, HECRAS was included in this case study, simulating a stretch of the Bois d'Orange River.

Because there were no known plans for engineering activities along the Bois d'Orange river channel, the use of HECRAS was limited to explaining how the model works, and giving an example of how a HECRAS dataset has to be constructed. The incoming discharge for HECRAS is provided by LISEM, which can provide discharge curves for any point in the model domain.

5 Methodology for integrated flood modelling

Based on the availability of information collected in CHARIM, and existing information on St Lucia, figure 5.1 shows a possible way of arriving at a series of likely mitigation strategies for flash floods, designed specifically in the context of St. Lucia (or one of the other islands in the CHARIM project). In this flowchart, moments are indicated where consulting with stakeholders should be done, but this was not part of this case study.



Figure 5.1. Processes and actions leading to simulation and selection of mitigation strategies.

5.1 Data requirements

The data requirements depend on the model you use to analyze different scenarios of flood mitigation. In this example the integrated flood model LISEM is used (see also CHARIM use case 8.7). This model combines the hydrology of a catchment to simulate the water available for runoff during a rainfall event, with runoff routing, river flow and flooding (1D and 2D simulation processes). The LISEM model needs a dataset based on the DEM, land use and soil data, river channel data and data on infrastructure (houses, roads). In this case the data is available in continuous raster datasets, on a 10m resolution (see also annex 2). A resolution of 10m or 5m is recommended, to accurately simulate water flow in a catchment.

5.2 Step1 - Evaluate background information.

Inspect visually the catchment to understand the situation. The national scale flood hazard map for this catchment is shown in figure 5.2. All along the river the flat valley floor is prone to flooding. This is logical as the valley floor is relatively flat so as soon as the river channel overflows, the flood water spreads out. The right hand image shows the shaded relief map with housing footprint. Discuss this with inhabitants and other knowledgeable people to get a first idea on the locations of floods.

We assume here that the attention areas are circle 1, where flooding of houses is indicated, circle two which has several large buildings and the highway crossing the valley. The northern area indicated as flood prone in the national flood hazard map, is a coastal swamp and flooding there is harmless as there are no inhabitants.

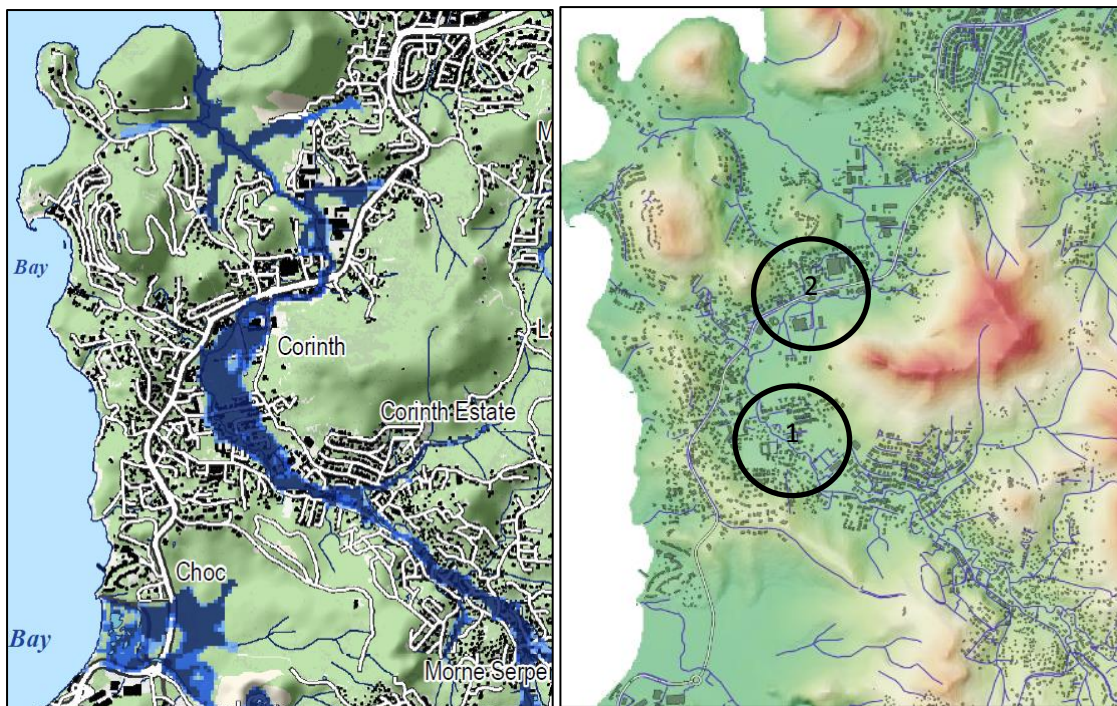


Figure 5.2. Bois d'Orange river national scale flood hazard map and shaded relief map indicating 3 areas of attention.

From a first general analysis, and evidence of flooding in the past, the entire valley along the river is at risk. This makes finding a solution difficult, if there would be a clear upstream area and a downstream township at risk, limiting runoff might be a good strategy. In this catchment the runoff is generated on the hills surrounding the flood plain so limiting runoff would mean a strategy that separates the runoff from the river along the entire valley.

The second part of the analysis is to analyze a range of existing rainfall events from the nearest rainfall station (Trouya station) that are known to have flooded the area in the past. This is done also for the early warning system analysis (use case 5.1). There were 40 events between June 2011 and July 2014 larger than 20mm. The largest event is the Christmas event 2013, which caused massive damage on Saint Lucia. In the north however, this event was less pronounced, resulting in a total of 155 mm, while the total average rainfall for the island surpassed 300 mm. One additional event was used that occurred on the 6th of November 2015, that also caused flooding in the catchment, the rainfall depth of that event was 128.8 mm, making the total 41. Table 5.1 shows the dates and characteristics of 6 typical events in increasing magnitude. On the dates of the largest two events flooding actually occurred in the catchment. LISEM simulates floods for these two events but not for the other four in table 5.1 (conform reality).

	Date	Depth mm	Peak intensity mm/h	Duration min
1	21-Oct-11	25.4	84.0	44
2	19-Apr-13	34.8	120.0	68
3	15-Aug-11	64.2	144.0	168
4	2-Aug-11	81.2	96.0	518
5	6-Nov-15	128.8	132.0	450
6	24-Dec-13	155.0	144.0	1382

Table 5.1. Rainfall event characteristics of events with increasing size, the largest reported to give flood problems according to the people in the area.

From this preliminary analysis, a threshold level for rainfall causing flooding could be set at an event that is larger than 100 mm in size and has peak intensities of more than 120 mm/h.

5.3 Step 2 – Simulate the baseline flooding situation

Annex 2 provides a more detailed step by step explanation of the data needed to run LISEM and the structure of the database. In the training provided with this case study the steps are done in detail.

Table 5.2 Shows the catchment totals, during a flood (1st column) and without flooding (2nd and 3rd column). The runoff fraction of the non-flood events is approximately 20% which is rather high for a densely vegetated catchment, because the soils are rich in clay. The soil structure determines the infiltration rate, which in the database is assumed to be high for natural vegetation but low for built-up areas and areas without natural vegetation (see fig 5.4, explained below). During a flood the runoff fraction increases to 42 % simply caused by the flooding itself, that cannot infiltrate and flows back into the channel, contributing to the overall catchment runoff fraction. The model calculates a total flood volume of slightly more than 96000 m³ (for the November 2015 event) which is a large amount if that needs to be contained in for instance storm water buffers. Furthermore the runoff pattern in figure 5.3 shows that runoff contributes to the channel along the entire catchment. There is not clearly and upstream downstream situation in this catchment.

Variable	6 Nov 15	2 Aug 11	15 Aug 11
Total rainfall (mm)	128.8	81.2	63.5
Total interception (mm)	1.6	1.4	1.4
Total infiltration (mm)	63.3	60.7	50.3
Total discharge (mm)	64.5	17.1	12.8
Discharge/Rainfall (%)	42.0	21.1	20.2
Total discharge (m3)	609073.9	158732.6	131847.3
Flood volume (max level) (m3)	96055.8	0.0	0.0
Flood area (max level) (m2)	304900.0	0.0	0.0
Peak discharge for outlet 1 (l/s)	63626.7	23684.1	20552.4
Peak discharge for outlet 2 (l/s)	61413.1	20450.5	20275.9
Peak discharge for outlet 5 (l/s)	37301.5	9532.3	9354.2

Table 5.2. Catchment totals, baseline simulation event 6 Nov 15. Outlet 1 is the sea, outlet 2 the highway bridge, outlet 5 a bridge in the center of the catchment with an early warning system.

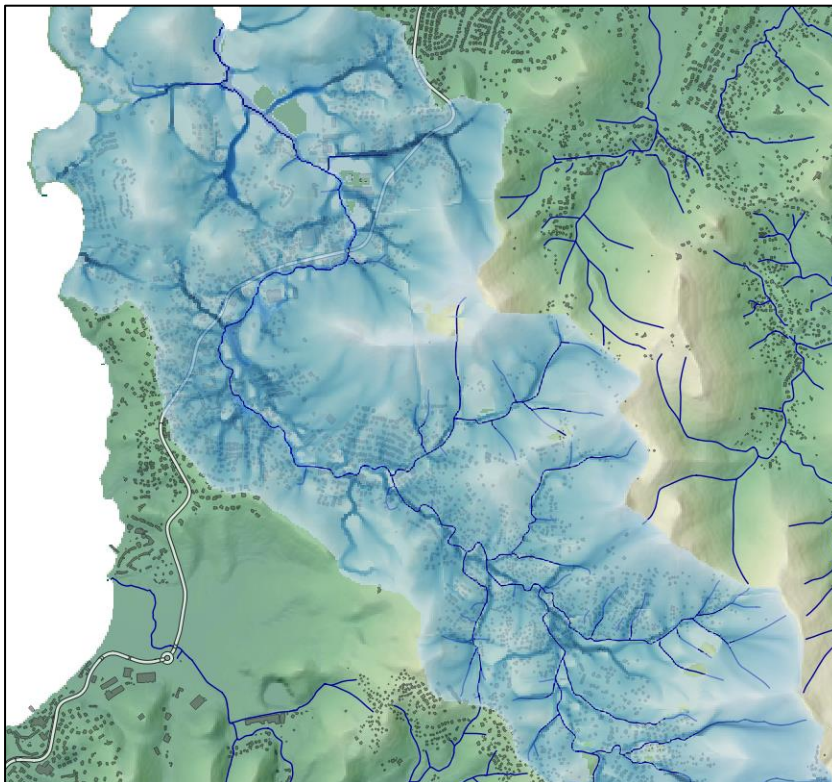


Figure 5.3. Runoff pattern for the November 2015 event showing a diffuse contribution to the river system over the entire catchment.

5.4 Step 3 – Stakeholder meeting, select strategies

A stakeholder discussion has a certain format and its goal is to go over the following steps:

- Explain the context and the purpose of the meeting. The purpose is to come to a selection of possible flood mitigation measures, and because it is a participatory exercise, to create some ownership in the final selection of preferred measures. Note that the scientists/technicians themselves are also stakeholders, and they may also add their preference.

- b) Discuss evidence of past floods and collect evidence/stories. Let people indicate on a large map where they live and where they think flooding generally takes place. Create a community map.
- c) Explain the basic principles of flooding in laymans language, and point out the cycle: rainfall – infiltration/runoff – flooding. The purpose of this is to later be able to discuss better the various mitigation measures, and how and why they are supposed to work
- d) Go over potentil mitigation measures, using images from other countries. A list of possibilities is given in fig 3.3, and these can be evaluated in a first discussion simply by the existing knowledge. Not every scenario has to be extensively simulated to evaluate it. The purpose is to have a few mitigation measures selected and if make ranking that reflects the preferences of the group. The ranking forces people to take the exercise seriously as it involves giving a reason why you have certain preferences.

Below is a list of strategies and reasons why they might work for this catchment. It is not based on a group discussion, but simply based on expert opinion. It serves here as an example.

Strategy 1: prevent runoff from occurring. In catchments that have had strong alterations of land use, assuming this is from natural vegetation to agriculture or an increase of built up areas, the infiltration may have decreased. As is common in tropical environments, the organic matter rapidly decreases with depth because of the high degree of decomposition. This was confirmed by Pratomo (2015), who determined the saturated hydraulic conductivity from 64 sample rings and porosity from 72 sample rings on Grenada, in the Gouyave and St John watersheds as part of a comparative catchment study in the CHARIM project. It is clear from figure 5.3, that the saturated hydraulic conductivity value (ksat in mm/h) under natural vegetation is on average much higher than the values under agriculture. Furthermore soil around inhabited areas tends to be compacted and cause even more runoff.

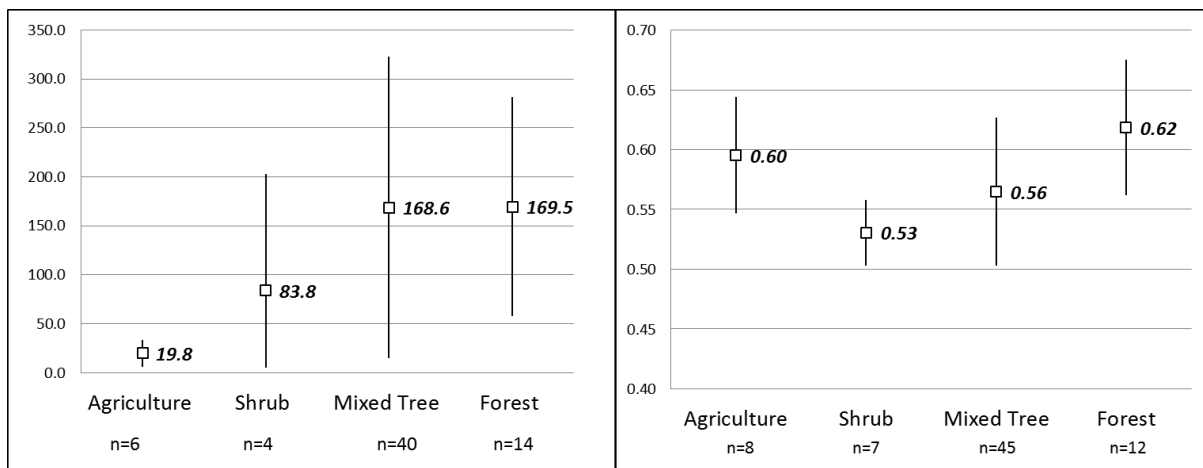


Figure 5.4. Left: saturated hydraulic conductivity (mm/h) and right: porosity (-) organized per main land cover type. The measurements are from Grenada, taken in the Gouyave and St John watersheds (Pratomo, 2015). The values in bold are the average, the lines show one standard deviation around the mean.

However in this watershed there is no evidence of major changes in land use. In general there is a high infiltration (see figure 5.4). There is little to gain with large land use changes.



Figure 5.5. Left: an example of strip cropping following contour lines, alternating Maize with grass in the UK. Right: Small terrace like structures perpendicular to the slope, alternated with trees and Banana (Rwanda).

Strategy 2: prevent runoff from developing. A possible way of preventing runoff to develop into a flood is to interrupt the process. In many agricultural areas this is a preferred way and has led to strip cropping and creating vegetation obstructions perpendicular to the prevailing runoff direction (see figure 5.5), where you alternate between root crops and denser grass or grass like crops. This also prevents erosion from erosion prone crops such as Maize. There is widespread inhabitation, with many small agricultural fields or vegetable home gardens below the tree canopy. In this area there is no large scale agriculture that would benefit from a change in cropping pattern and tillage management. However, infiltration zones at strategic places can be simulated and evaluated. They are a low-cost (relatively low maintenance) solution.

Strategy 3: capturing runoff at an early stage. In this case structures are made (small dams) that are located at strategic points, that capture runoff or stream flow. On the one hand, if these structures are too far downstream the amount of water quickly becomes too much to contain. On the other, the dams do not need to capture all water in flow, only enough to prevent the stream channel from overflowing and developing a flood. Even slowing down water may be sufficient to alter the discharge characteristics, to prevent overflow. A slower release of runoff water from the slopes surrounding the channel, may lead to a lower discharge wave. A model can be used to evaluate different designs and placement of runoff retaining structures. This was in fact the strategy adopted in the Province of Limburg in the Netherlands, where approx. 400 small buffers (several 1000 m³ each) are created to prevent flood and sediment damage downstream. Their dimensions were calculated with the model used in this project, LISEM. Generally these buffers have an outflow point that slowly releases the water, they do not function as a permanent storage, as permanent water bodies of breed diseases in tropical countries.

Strategy 4: calculate a maximum discharge and alter the channel or add flood defence constructions: dikes and/or retaining walls. A model can be used to estimate the discharge expected that can be used to dimension such engineering structures. When combined with strategy 3, an optimum plan could be made that does not involve very large and costly engineering constructions.

Strategy 5: increase flood resilience of housing: construct houses on stilts or high foundation. There are many examples world wide where people live next to rivers without any problems, and have adapted their way of life.

Strategy 6: do nothing but make sure an insurance system is in place to compensate people for losses. Insurance can be part of the government policy, together with a scheme of protection. The

Federal Emergency Management Agency (FEMA) in the US uses a hazard zonation based on a “1% annual chance flood” or a 100 year flood. The hazard classes are based on a degree of exposure of the property, and are related to insurance policies. Insurance premiums go down if people take protective measures or behave in a desired way to mitigate flood problems. In that way an insurance can trigger a higher resilience. An example of resilience/adaptation is shown in the photo below of a house just south of the highway bridge where flood water reached the 6th step. There was no further damage.



5.5 Step 4 – Deinf model scenarios

The preferred mitigation strategies are implemented in the model dataset and simulated. In the examples above, three scenarios are simulated in this use case:

- A. Large water buffers in the flood plain, upstream of locations with a higher housing density. The buffers consist of a buffer, a low earthen dam spanning the floodplain that is 1-2 meter high, and an excavated area upstream of the dam, of for instance 1 meter depth. The river crosses the dam bu the cross section is made that is very narrow, or it is replaced for instance by a box culvert, so that in times of regular flow the buffer is not inundated, while in times of storm discharge the opening limits the discharge and the buffer is filled. An example of a grass storm water buffer is shown in figure 5.6.
- B. A zone is defined along the central river at the bottom of the slope, that has a high infiltration rate. It can be a mixture of strips with natural vegetation, or gravel pits to capture the water. These zones have to have a subsurface drainage towards the river so that they remain relatively dry and there storage capacity is large drain. The exact design is to be dertmined and adapted to the situation. This is sim,ulated by defining a strip of two gridcells wide on both sides of the central part of the river, that has ahigh ifiltration rate (corresponding with natural forest) and a high storage capacity (water content below field capacity).
- C. A low wall along both sides of the river of 1 meter high, serving as a small flood barrier. This wall does not have to be evraywhere, only in the central part. Upstream there is not enough discharge to cause flooding, downstream the channel is deeper from itself and drains in a wetland.



Figure 5.6. Example of surface storage buffers for rainwater from the UK (Photos from, left: Pinnacle Consulting Engineers, right Unda Flood Risk Consultants).

5.6 Step 5 – Run model simulations

The strategies can be simulated with different rainfall events. It is good practice to include recent events that have happened and caused flooding, and to include design events with a known return period. The real event serves as a reference for the stakeholders as a basis for discussion. The design events with increasing return period serve to find out if the mitigation measures stop working for events beyond a given magnitude.

The most recent rainfall causing know flood was the one of 6 Nov 2015. In the CHARIM project 4 design rainfall events are defined with return periods between 5 and 50 years. Furthermore we have the baseline (no mitigation) and 3 scenario's. In principle that gives us the following simulation matrix with 5 events * 4 scenarios = 20 runs. Simulating and evaluating all the runs is beyond the scope of this use case.

		Baseline		Buffers		Infiltration		Wall	
Event	Area flooded (m2)	Build. affected	Area flooded (m2)	Buildings affected	Area flooded (m2)	Buildings affected	Area flooded (m2)	Buildings affected	
06-11-15	175700	128	204600 (171500)	168	88500	24	72600	22	
5 year									
10 year									
20 year									
50 year									

Table 5.3. Example of an analysis table. The number of buildings affected is based on an average building size of 100 m². All values are based on flood water deeper than 10 cm. Also the northern flooded part in the uninhabited area is not counted in this analysis. Scenarios for return periods 5 to 50 years are not simulated in this example.

NOTE: the examples below are not tested for realism and it may not be possible to realize them. Dimensions or locations may not be optimal, land may be owned privately where mitigation measures are to be installed, or general assumptions on the effects may be unrealistic.

Strategy 1 – water buffers. Two water buffers of sizes were put in the database, located in the central valley upstream of areas that are flooded in the base line scenario. Their sizes are 51200 m³ and 15000 m³ (figure 5.7), the total area of the buffers is 33100 m². The idea is to slow down the water and capture part of the flood volume and lower the flood level downstream or alter the dynamics. The throughflow for the river channel is set to 15 m³/s resembling a large box culvert. That means sufficient discharge can pass but it remains in the river channel downstream of the buffers. If the maximum outflow is too small the buffers simply fill up but they are too small to capture an entire flood and overflow.

This mitigation measure has a mixed result (figure 5.9). Downstream of the buffers the flood has disappeared, so that works well, but upstream more houses have been flooded. The buffers do contain a lot of flood water, but they fill up and eventually the water backs up in the upstream direction, flooding additional houses upstream of the southern buffer. The end result is that a slightly smaller area is submerged than before (not counting the buffer itself). Possibly a different design may work better. Creating water buffers in this case is possibly costly both in construction but especially maintenance.



Figure 5.7. Configuration of four water buffers with varying size as half circular low dykes across the valley floor (indicated with arrows). Note that these are put in areas where the map does not show housing. This has not been checked with reality. From north to south the buffers have a size of 51200 and 15000 m³. Where the river crosses the barrier a maximum discharge of 15 m³/s has been assumed.

Strategy 2 – infiltration strips. The strips absorb up to 500 mm of water (the event is 86 mm in total) so about 6 times the direct rainfall (see fig 5.8). The effect of this is a reduction of direct contribution of runoff to the river. The effect is quite a strong reduction of the flood water level and therefore successful. A variation can be to have a second infiltration barriers further upslope, parallel to this one, or extend the vegetation strip upstream. If new housing projects are established in the area, such measures could be included in the spatial planning design. The effect is maximized in the model so it should be tried in the field before implementing this. Nevertheless it is worthwhile examining its effect however, creating such a buffer zone is not very complicated. In the field of “Sustainable

Urban Drainage Systems” or SUDS, there are many designs available with combinations of gravel pits, small barriers and vegetation strips) and especially the maintenance cost are low.

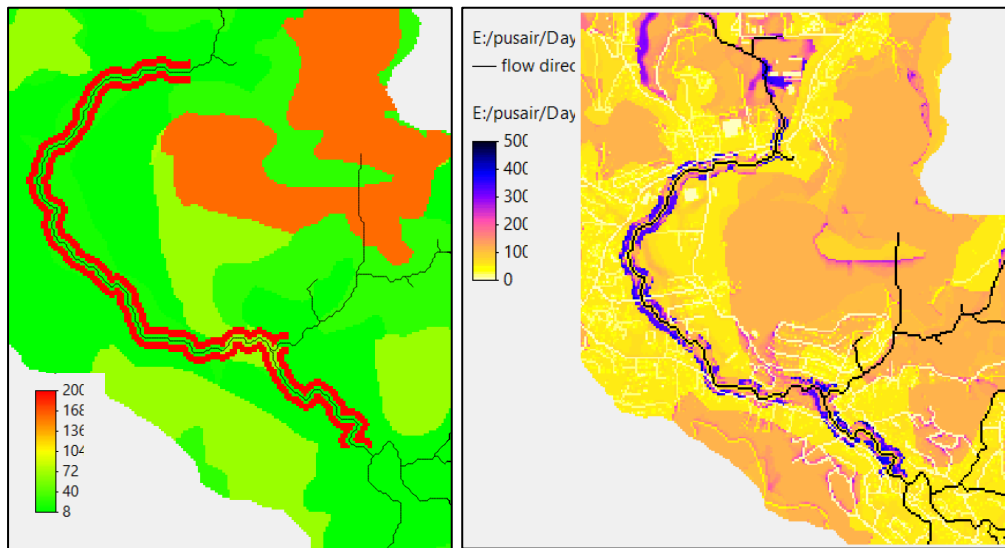


Figure 5.8. Left: a 20m infiltration strip perpendicular to the river (Ksat in mm/h) and right: Cumulative infiltration (mm) during the November event. The strip absorbs approximately 6 times the rainfall amount.

Strategy 3 – flood defense wall. This seems the best option for this particular case, although events of larger size and intensity might still flood the area. The flood remains between the walls on both sides of the river, effectively making the channel deeper. The channel itself cannot be deepened in most places as the bedrock is visible at the bottom. The wall should have possibilities of drainage of runoff water to the river. The wall works as long as the flood remains inside so this analysis should be followed up by simulations with the design events. Nevertheless once the initial costs are met, there is little maintenance cost. A model analysis should be done with a second type of model, that is better suited for the detailed engineering aspects of this measure. A model like HECRAS is commonly used for this purpose, but also TUFLOW is gaining a lot of recognition recently. Note that additional detailed data must be collected to execute such a model analysis. This could also be part of the tender procedure.

The flood maps of these scenarios are shown in figure 5.9. The buffers clearly have a negative effect, spreading out the water and forcing it in areas where before there was no flood. The infiltration zone lowers the overall flood level and decreases slightly the area. The flood wall contains the flooded area in a narrow zone.

Further analyses in this step:

- Repeat the analysis for the design rainfall of 5, 10, 20, 50 year. The flood maps should be printed and checked in the field to see if the mitigation measures are in strategic locations, or if they are in impossible locations. If needed redo the simulations with adapted datasets based on field evidence.
- Do a field feasibility study for the proposed mitigation measures.
- Do a cost-benefit analysis for the realisation, including potential compensation for inhabitants when the mitigation measures infringes on their property, and including an estimated *annual maintenance* schedule. Possibly a part of the maintenance can be put at stakeholder level, such as unclogging drainage pipes.

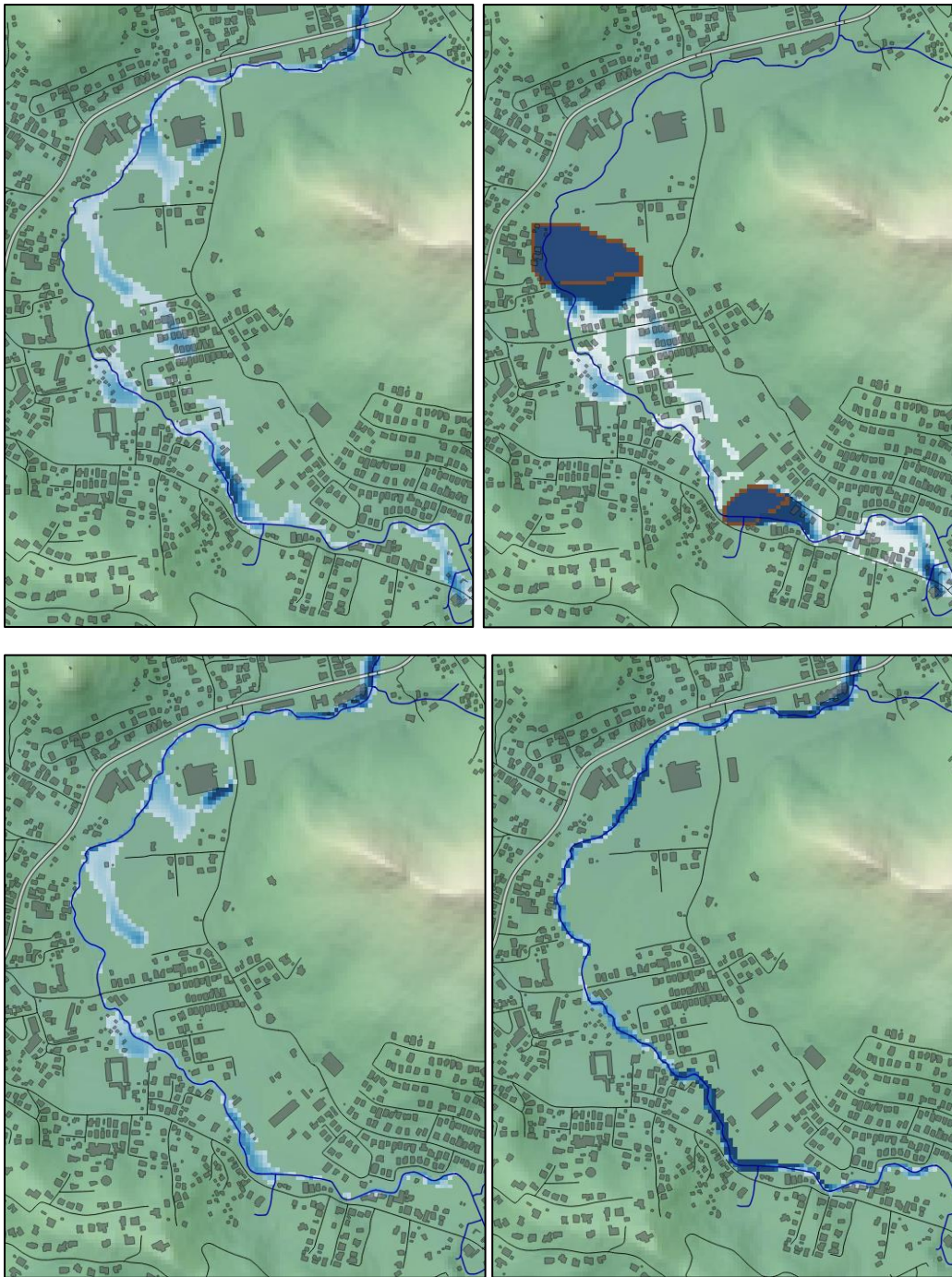


Figure 5.9. Maximum flood level ranging from 0.1 (light blue) to >0.5m (dark blue). Top left: base level flood, top right: water buffers (scenario 1), bottom left: infiltration zone (scenario 2), bottom right: flood wall (scenario 3).

5.7 Step 6 – Stakeholder evaluation

The results of step 5 should be discussed with all stakeholders involved, so that it is clear what will be done, how long it will take and to what level people and property are now protected. Based on the outcome of these discussions and a final draft catchment development plan, a tender can be written. It is possible, and even likely, that steps 2 to 5 have to be done several times in an iterative process, as more information becomes available.

This use case is an example of how such an analysis can be done. However detailed field checks are needed to improve the modelling.

5.8 Step 7 – Engineering

In case the preferred solution involves engineering construction, it is wise to do a site investigation and simulate the hydraulic effects in detail, using an appropriate model. The next chapter highlights such a mode: HEC-RAS. In Appendix 1, various models are mentioned.

6 HEC-RAS modelling and data collection

6.1 Introduction

From the catchment scale analysis it appears that mitigation measures will involve probably engineering structures. One of the well-known models with which local-scale hydraulic design and road related structures can be modelled is HEC-RAS, and its equivalent inside ARCGIS, HEC-GeoRAS.

The HEC-RAS manual (US-ACE, 2016) described the system as follows. The Hydrologic Engineering Center's (HEC) River Analysis System (HEC-RAS) software allows the user to perform one-dimensional (1D) steady and 1D and two-dimensional (2D) unsteady flow river hydraulics calculations. HEC-RAS is an integrated system of software. The system is comprised of a graphical user interface (GUI), separate hydraulic analysis components, data storage and management capabilities, graphics, mapping (HEC-RAS Mapper) and reporting facilities. The HEC-RAS system contains four hydraulic analysis components for: (1) steady flow water surface profile computations; (2) 1D and 2D unsteady flow simulations; (3) movable boundary sediment transport computations (cohesive and non-cohesive sediments); and (4) water temperature and constituent transport modeling. A key element is that all four components use a common geometric data representation and common geometric and hydraulic computations routines. In addition to the four hydraulic analysis components, the system contains several hydraulic design features that can be invoked once the basic water surface profiles are computed. The software also contains tools for performing inundation mapping directly inside the software.

The extent to which HEC-RAS is used in this part of the Super use Case depends on the data available. For that reason, it is important to take a look at the basic data structure. Figure 6.1 top shows the input screen of “RAS mapper” used to generate cross section transects of elevation data, perpendicular to the streamline, extending into the floodplain. HEC-RAS simulates 1D river hydraulics and 2D flooding along these transects. Inside the riverbed, the transects should be measured in the field with geodetic equipment, outside the river channel, transects can be generated using a DEM if it is accurate enough, or also by field measurements. If the floodplain contains many irregular elements that interfere with the flow, measurements are better.

The input for HEC-RAS is a discharge wave (hydrograph) at a given inflow point that marks the boundary of the domain. The downstream boundary can be defined as free flow. In the Bois d'Orange case study, the input hydrograph is generated by LISEM, as this is currently the best model that takes into account hydrological details of the catchment.

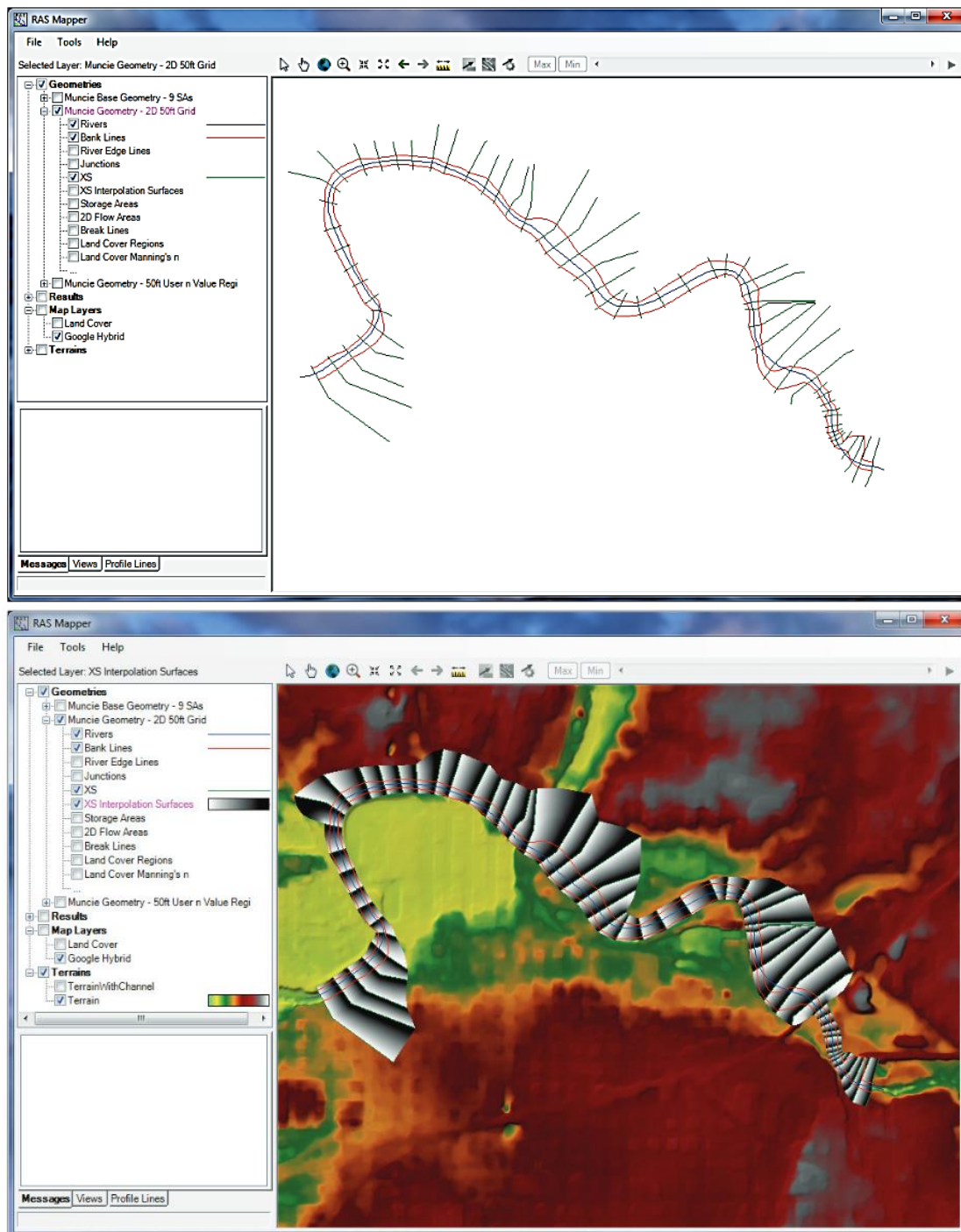


Figure 6.1. RAS mapper input for transect digitization: top: without additional data layers loaded, bottom: with shaded relief map and showing the 2D flood interpolation areas between transects (HEC-RAS manual, 2016).

HEC-RAS simulates bank overflow and flooding into the floodplain, along the transects. It then interpolates the flood depth between transects (figure 6.1 bottom). To do this properly, the number of transects has to be high, and they should extend far enough into the floodplain (HEC-RAS cannot simulate beyond the transect end). Furthermore, each transect is characterized by flow resistance, manning's n . Hydrological processes (infiltration of flood water for instance) are not considered.

HECRAS is able to simulate the hydraulic behavior of a considerable number of structures, either parallel or online to the main river flowlines. It can be used for evaluation of present situation and potential alternatives, and possible future scenarios. However, while HEC-RAS is proven to work in many situations, it is not easy to do. HEC-GeoRAS makes these procedures somewhat easier, but it is still a non-automatic procedure: the GIS data available for St Lucia cannot be used directly.

In view of the above:

This part of the superuse case concentrates on the principles of HEC-RAS, the input and output datasets, and gives examples of how to get information from the field in the Bois d'Orange catchment into the model. However, possible mitigation measures are not simulated.

6.2 Using LISEM for discharge input

The LISEM and the HEC-RAS models cover different domains. The LISEM model works at the catchment level and is able to operate with spatial input at different level of discretization. The most relevant

output of LISEM for this particular case is the simulated hydrograph at a certain cell in the network mesh. When the cell is selected in the flowing river network, the calculated hydrograph is used as the main input for the hydraulic model. HEC-RAS can use this hydrograph upstream and with the assistance of a DEM is able to calculate the flood depth, the flood timing, the flood permanence and the water speed at any point of the HEC-RAS domain, *i.e.* the alveolar river floodplain and the river itself.

Figure 6.2 gives examples of the hydrographs LISEM produces at the inflow point of the selected HEC-RAS domain.

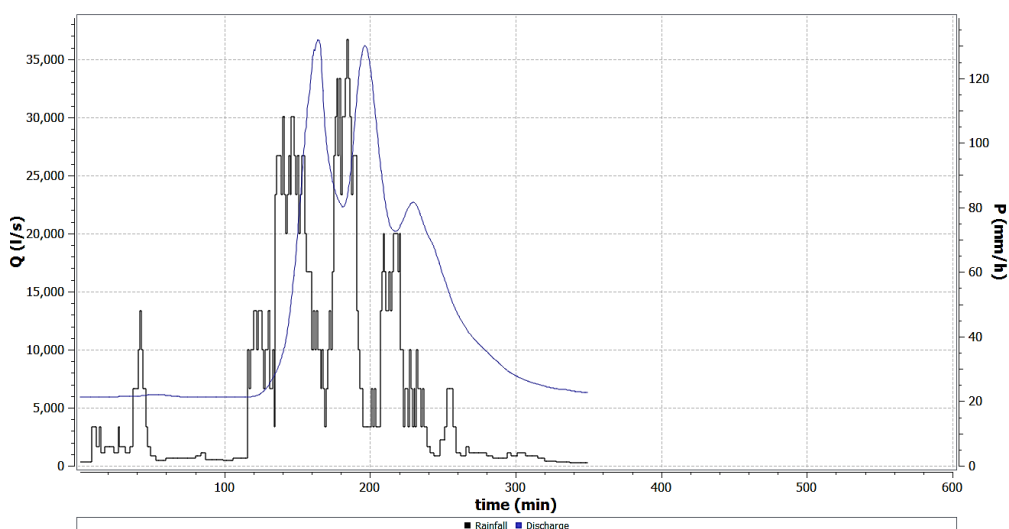


Figure 6.2. Hydrograph produced by LISEM at the entry point of the HEC-RAS domain for the Nov 2015 flood situation.

6.3 Operating HEC-RAS

HECRAS is a hydraulic model. As such, the movement of free water is ruled by the equation of preservation of mass and energy. Simplifications in the full equations solving the dynamic of the flowing water in three directions (longitudinal, depth and transversal to the river flow) lead to a 1-D model where speed is assumed constant in all direction but longitudinal to the flow.

In order to achieve reasonable results with these simplification, a number of geometric and hydraulic parameters defining the model domain need to be accurately assessed, namely: the river slope, the roughness and the stress that the rest of the environment imposes over the model, *i.e.* the “boundary conditions”. The training aims the explanation of the tasks sequences that comprises a HEC-RAS modeling.

The HEC-RAS comes with a number of manuals that are compulsory documentation to understand this model in depth: the User manual, the Hydraulic Reference manual and the Application guides. More than 20 full exercises for steady and unsteady flow compose the application guide covering the major aspects of the modelling. The last version of HEC-RAS counts with more than 1500 pages, and from them a dedicated set was taken for this course.

The typical training of HECRAS starts by having getting acquainted with the three manuals of the model followed a set of customized exercises aiming to cover the three input data groups mentioned before. In short:

- Accurate river slopes result from adequate cross section data
- Roughness coefficients that are associated with the cross section input, are obtained by comparing river and floodplain land cover with hydraulic standard tables. The effect of changing roughness is evaluated by analysis of water depths and speeds for different roughness scenarios.
- Finally, boundary conditions are highly associated with the river regime. If the regime is supercritical (water speed higher than the water celerity) the boundary upstream is needed. If it is subcritical (celerity higher than water speed) the boundary downstream applies. For alternating regimes in a river, both are needed. Regimes and boundary conditions are explained by teaching the different boundary condition alternatives, running the model and comparing the coincidence or divergence of the model water surface with the critical line calculated by the model.

Appendix 3 gives the sequence of steps needed in more detail.

6.4 Computation of hydraulic losses caused using field data

6.4.1 Site selection and survey

Given de vulnerability that bridges over streams have shown during flood events in the Bois d’Orange catchment, we selected this type of structure as an example of local scale design. An initial bridge reconnaissance along the main stream was carried out at the end of the first week, from which the bridge at the River Stone location was selected (14° 02’ 34.57”N, 60° 57’ 28.25” W). The criteria for selection were based on the accessibility and simplicity of the structure that resulted appropriate for training purposes. The selected bridge showed water marks in the low chord probably as a result of

high water levels during peak events. A detailed survey of a short stretch of the stream was organized with the collaboration of the Survey Crew from the Ministry of Physical Development, Housing and Urban Renewal.

In order to give the participants a general idea of what a river survey means, they were taken to the selected site where they were able to observe the topographic crew taking the measurements and get acquainted with the instruments and methods. In a different day the actual measurements were taken: the 4 typical cross sections required for calculation of the hydraulic losses caused by the bridge, together with 1 extra cross section upstream (ideally, more sections would have to be measured, but time availability did not allow for more. Additionally, several pictures and notes were taken to assist the channel and floodplain characterization. Figure 6.3a shows the bridge during the topographic campaign.

6.4.2 Additional data

Complementary maps of soils, and the road and drainage systems were incorporated in a GIS-based preliminary layout. The DEM in reference is the result of interpolation of an original 20m-resolution DEM, and therefore does not show the topographical details needed for hydraulic modeling, confirming in this way the need of the topographic campaign.

6.4.3 Cross sections

Despite the good collaboration and efficient work of the topographical crew, the resulting data encountered problems related to geo-referencing. These problems were related to the transition that the current geographical data of Saint Lucia have experimented from the old Saint Lucia BWI Grid 1955 to a UTM-related coordinates system. The final solution was based on a tentative adjustment of the coordinate system parameters. The clean data corresponding to the 4 sections of the Bridge + 1 section upstream the bridge are presented in the attached file XS_River_Stone.xls (sections 6 to 10 on the HECRAS nomenclature).

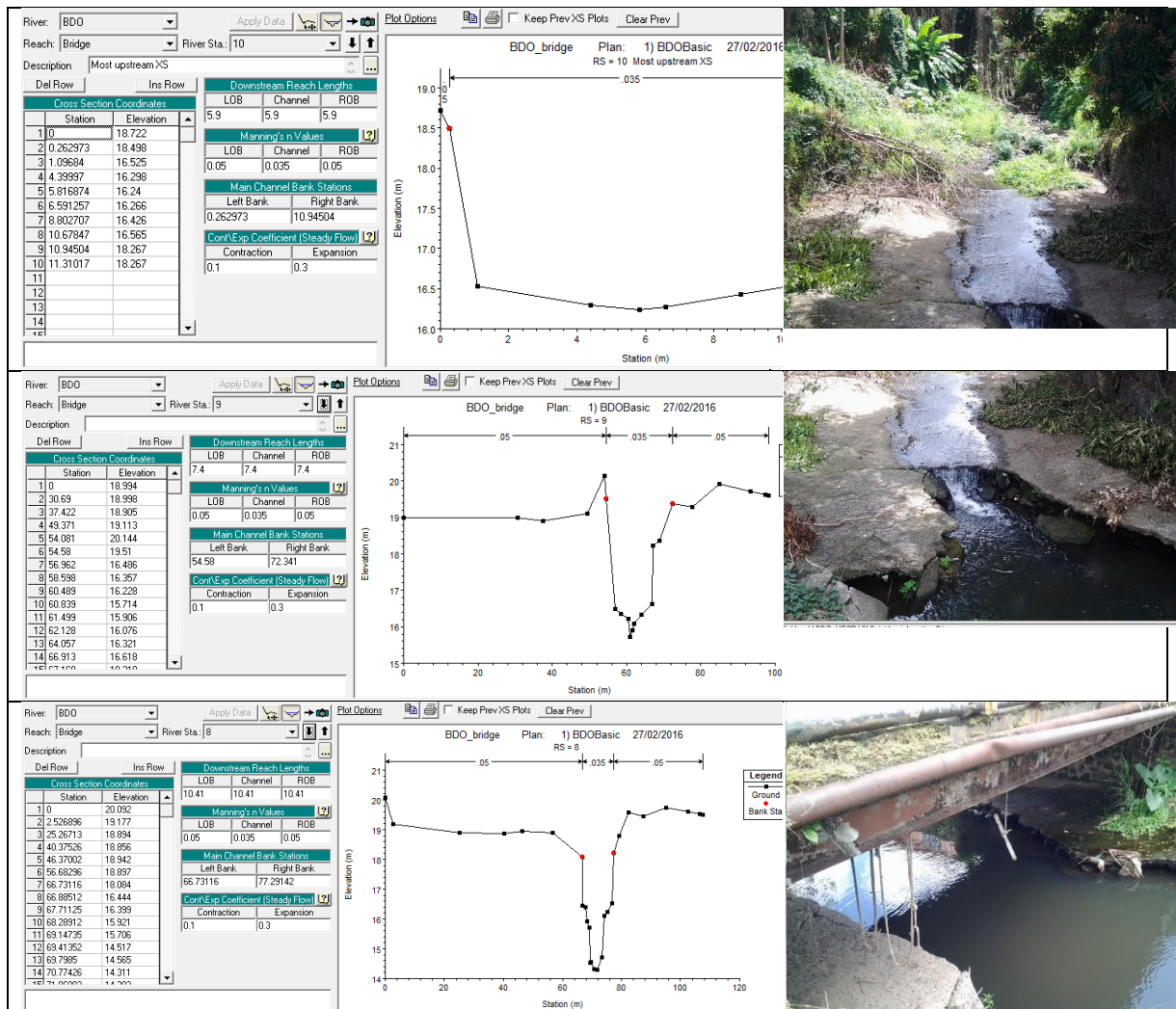
6.4.4 HEC-RAS Geometry layout

The initial HEC-RAS geometry layout of the river stretch was incorporated using the measured 5 cross section. For every cross section, left overbank LOB, Channel and right overbank ROB manning coefficients and distance between sections were defined and incorporated in the model as showed in Figure 6.3b. The resulting general geometry layout is presented in Figure 6.4.

Once the topographical data was implemented in HEC-RAS, a discharge profile was created taking the catchment-level results resulting.



Figure 6.3a. River Stone Bridge survey



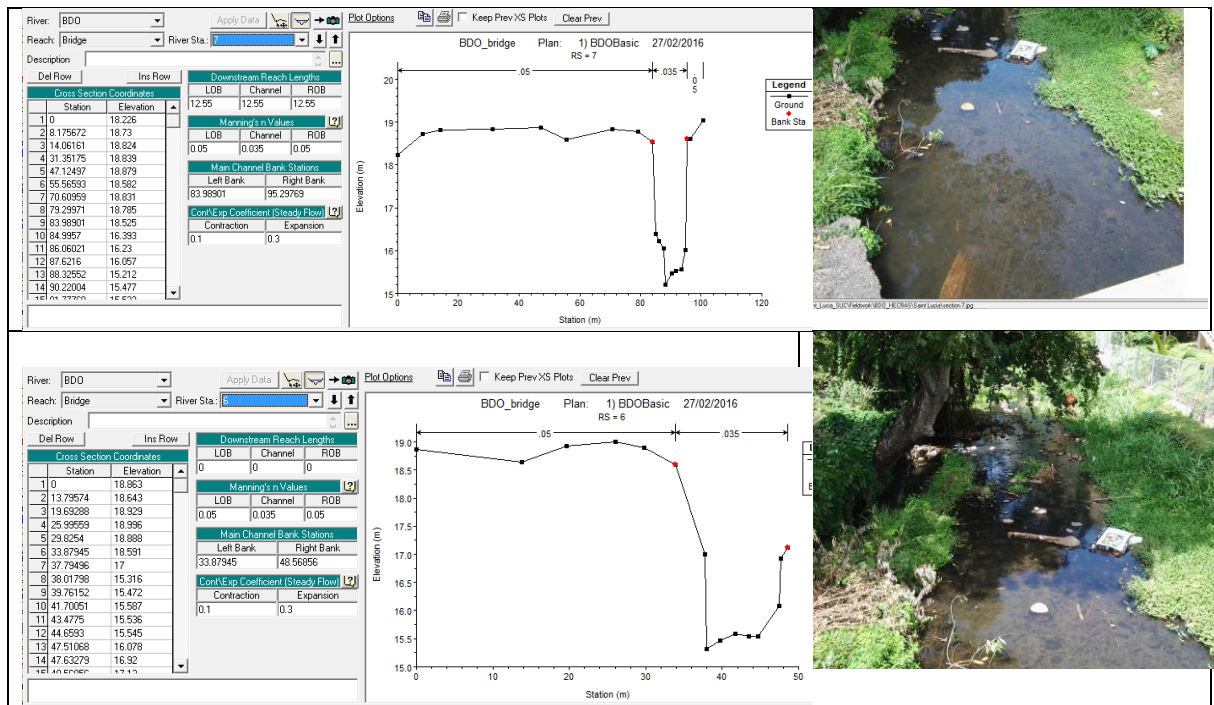


Figure 6.3b. River Stone Bridge cross sections in HEC-RAS (sections 6-9 correspond to the typical cross sections for the calculation of hydraulic losses due to the bridge – Chapter 5 HEC-RAS Reference Manual)

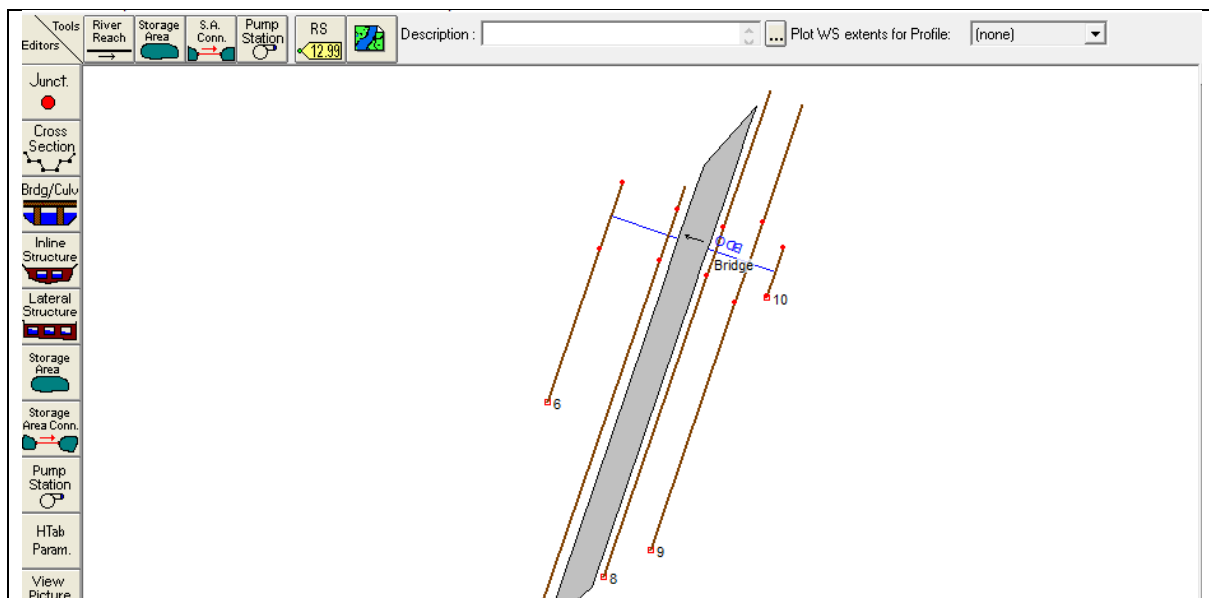


Figure 6.4. General geometry layout.

6.4.5 HEC-RAS discharges profile

LISEM model yielded a discharge of ~40 m³/sec for a 10-year return period, however to give a more complete picture of the river behavior, HEC-RAS was run for a series of discharges ranging from 10-50 m³/sec. Boundary conditions were set at Normal Depth for Upstream and Downstream conditions using an average slope $S_f = 0.02$. Flow regime was initially assumed to be Subcritical (Figure 6.5).

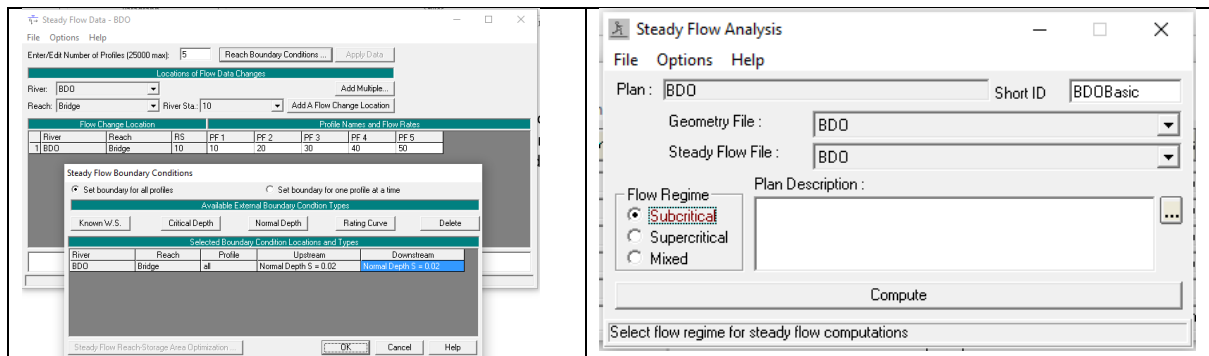


Figure 6.5. Discharge profile and HEC-RAS Plan .

6.4.6 Bridge Geometry

Using the data provided by the surveyor the geometry of the bridge was given to the model presented in Figure 6.6.

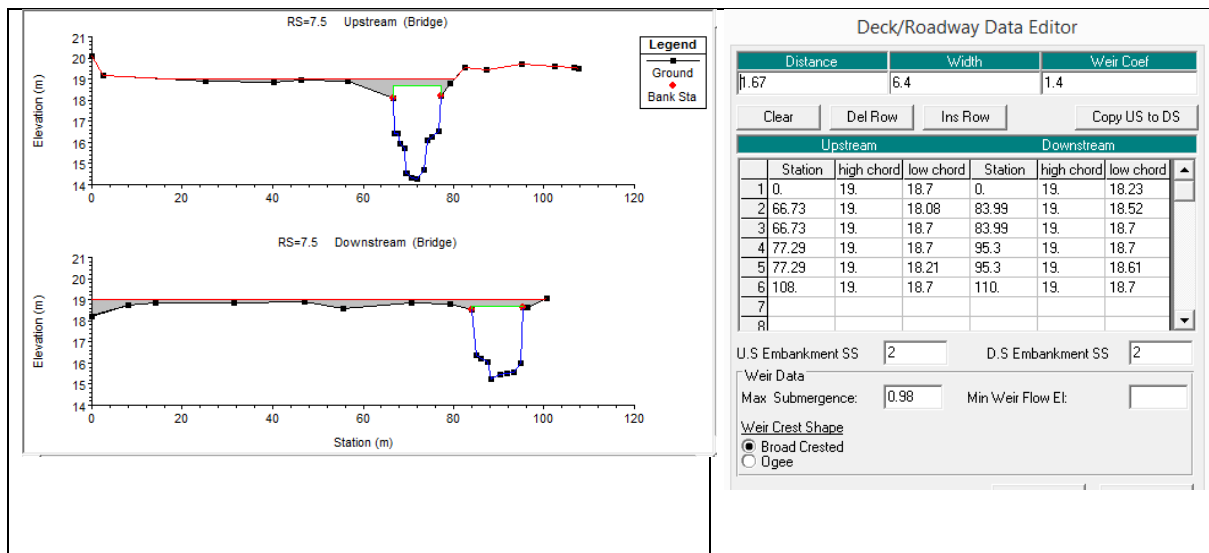


Figure 6.6. Bridge data editor from HECRAS

6.4.7 Model results

Initial run of the model reported difficulties in the energy balance and the need of additional cross sections. The initial assumption of subcritical flow was not confirmed. (Figure 6.7)

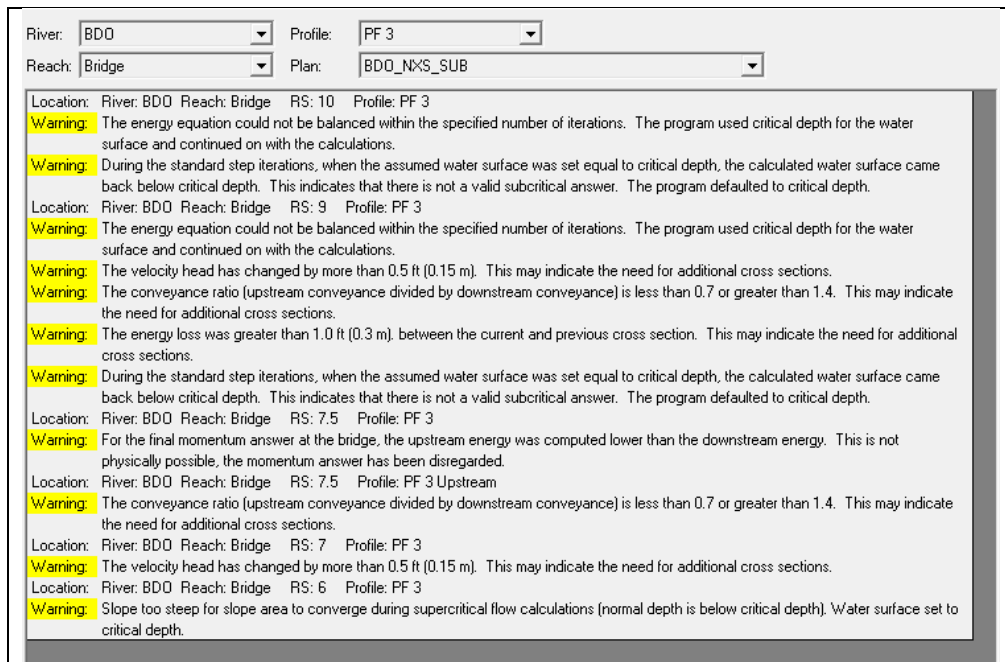


Figure 6.7. Model Warnings related to initial conditions and assumptions. Subcritical flow.

For a new run, additional cross sections were geometrically interpolated using the HEC-RAS method (max. 1m). This configuration improved the calculations but the model suggested that the flow regime assumption was incorrect, and as a result this was changed to Mixed Flow. The new geometry for the modeling and modified flow regime assumption is presented in figure 6.8.

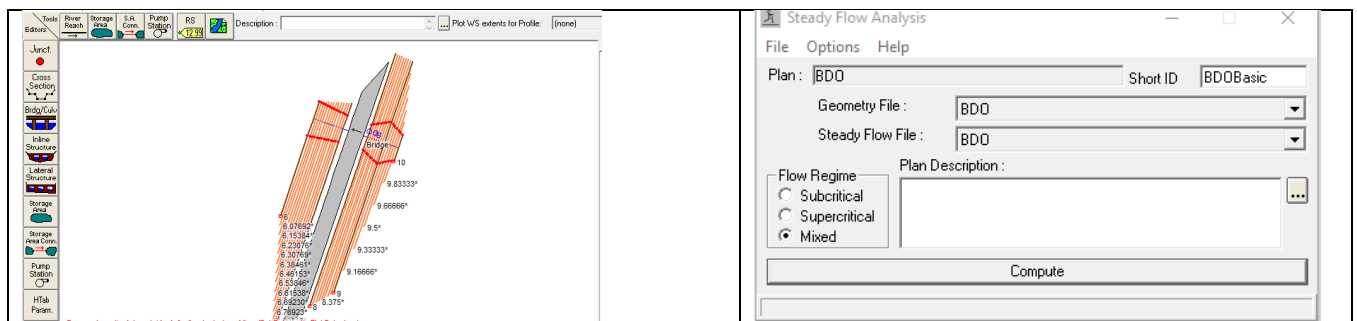


Figure 6.8. Geometry layout with interpolated cross sections and new Mixed-flow Plan.

The results of this final run confirmed the Mixed-flow assumption and showed that for the series of discharges the water under the bridge flows under a free regime (figure 8). However the small amount of measured cross sections used for the model suggests that these results must be taken with caution. Figure 6.9 presents a summary of the hydraulic calculation at the bridge (cross sections 8-7) and figure 6.10 the calculated rating curves for the 5 cross sections measured, and the model-built cross section precisely under the bridge axes (cross section 7-5).

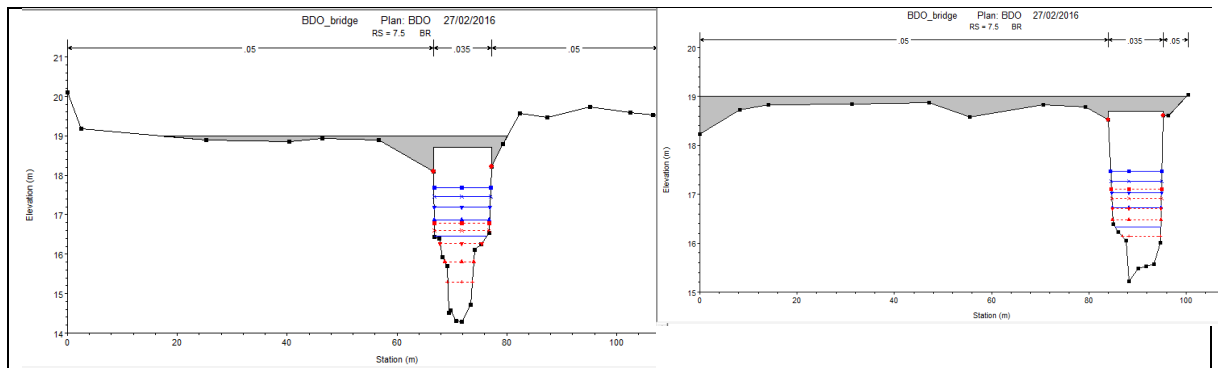


Figure 6.9. Modelled water levels under the bridge for discharges ranging from 10-50 m³/sec according to the table presented in Figure 7.10. U.S. and D.S. bridge cross sections. (Discharges were applied at cross section 10, i.e. the most upstream).

HEC-RAS Plan: BDOBasic River: BDO Reach: Bridge												
Reach	River Sta	Profile	Q Total (m ³ /s)	Min Ch El (m)	W.S. Elev (m)	Crit W.S. (m)	E.G. Elev (m)	E.G. Slope (m/m)	Vel Chnl (m/s)	Flow Area (m ²)	Top Width (m)	Froude # Chl
Bridge	8.125*	PF 1	10.00	14.47	16.45		16.50	0.001363	1.06	9.43	7.50	0.30
Bridge	8.125*	PF 2	20.00	14.47	16.86		16.98	0.002643	1.51	13.27	10.72	0.43
Bridge	8.125*	PF 3	30.00	14.47	17.18		17.35	0.002926	1.79	16.75	10.88	0.46
Bridge	8.125*	PF 4	40.00	14.47	17.45		17.66	0.003220	2.03	19.66	11.02	0.49
Bridge	8.125*	PF 5	50.00	14.47	17.68		17.94	0.003516	2.25	22.18	11.13	0.51
Bridge	8	PF 1	10.00	14.29	16.45	15.29	16.50	0.001348	0.97	10.30	9.48	0.30
Bridge	8	PF 2	20.00	14.29	16.87	15.81	16.97	0.001979	1.38	14.48	10.03	0.37
Bridge	8	PF 3	30.00	14.29	17.19	16.28	17.34	0.002426	1.69	17.72	10.16	0.41
Bridge	8	PF 4	40.00	14.29	17.46	16.59	17.65	0.002838	1.96	20.42	10.27	0.44
Bridge	8	PF 5	50.00	14.29	17.68	16.79	17.93	0.003228	2.20	22.75	10.36	0.47
Bridge	7.5		Bridge									
Bridge	7	PF 1	10.00	15.21	16.29		16.45	0.008273	1.78	5.61	9.16	0.73
Bridge	7	PF 2	20.00	15.21	16.70		16.92	0.006427	2.06	9.69	10.07	0.67
Bridge	7	PF 3	30.00	15.21	17.00		17.29	0.006248	2.35	12.75	10.27	0.67
Bridge	7	PF 4	40.00	15.21	17.24		17.59	0.006557	2.64	15.17	10.43	0.70
Bridge	7	PF 5	50.00	15.21	17.43		17.86	0.007032	2.91	17.21	10.56	0.73
Bridge	6.92307*	PF 1	10.00	15.22	16.26		16.44	0.009086	1.90	5.26	8.31	0.76
Bridge	6.92307*	PF 2	20.00	15.22	16.67		16.91	0.007625	2.17	9.23	10.23	0.73
Bridge	6.92307*	PF 3	30.00	15.22	16.98		17.28	0.006825	2.41	12.45	10.45	0.71
Bridge	6.92307*	PF 4	40.00	15.22	17.22		17.59	0.006939	2.67	14.97	10.63	0.72
Bridge	6.92307*	PF 5	50.00	15.22	17.42		17.86	0.007297	2.93	17.08	10.77	0.74
Bridge	6.84615*	PF 1	10.00	15.23	16.24		16.43	0.008910	1.93	5.18	7.78	0.76

Figure 6.10. Model results for discharges ranging from 10-50 m³/sec.

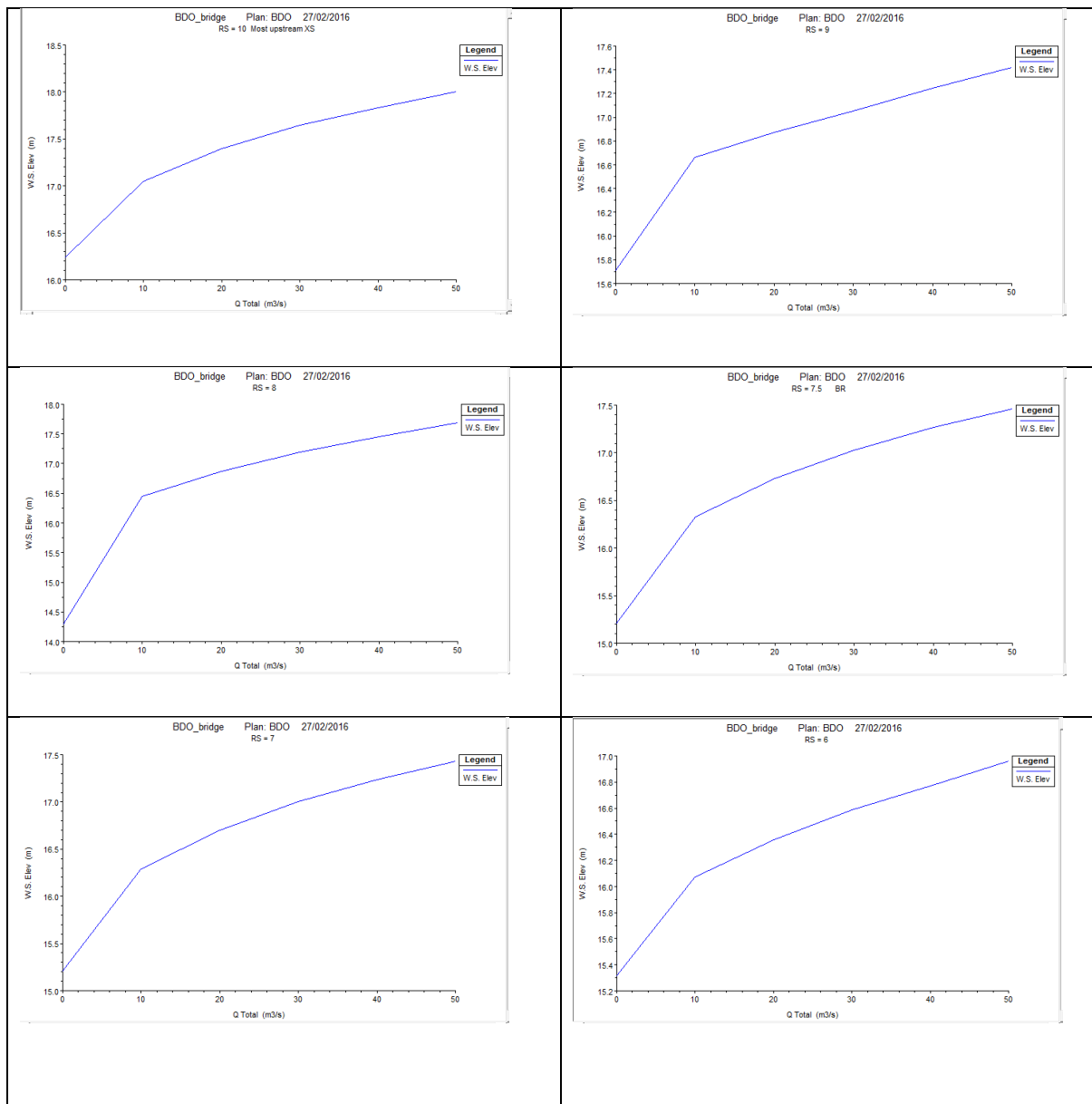


Figure 6.11. Rating curves.

The HRC-RAS modeling presented in this report showed an initial approach for calculation of hydraulic losses at the River Stone Bridge. The results indicate sufficient hydraulic capacity of the bridge to handle flows within the studied range. However it is important to emphasize that this exercise, despite using realistic data was conceived for training purposes. A more realistic modeling of the same bridge should include at least 5 additional sections both U.S. and D.S. of the bridge, as well as a more extended coverage of each section at the left and right overbanks. This essential data was not possible to acquire during the time allocated for the training. Nevertheless these results give a general indication that the bridge in question will not be overflowed for discharges up to 50 m³/sec assuming that the current cross sections are not clogged with debris.

6.5 GIS-Based HEC-RAS overview: GeoRAS demo

Despite of the availability of good thematic maps presented and the adequate format, as previously indicated the GIS-based version of HECRAS was not used for the exercise due to two main reasons:

- Lack of a high-quality DTM at a resolution that allows cross sections delineation
- Poor or non-existing GIS background of the participants.

The GIS tool was however presented in the format of a demo and the many advantages of a GIS-based modeling explained. Figure 612 shows some of the maps used for the explanation.

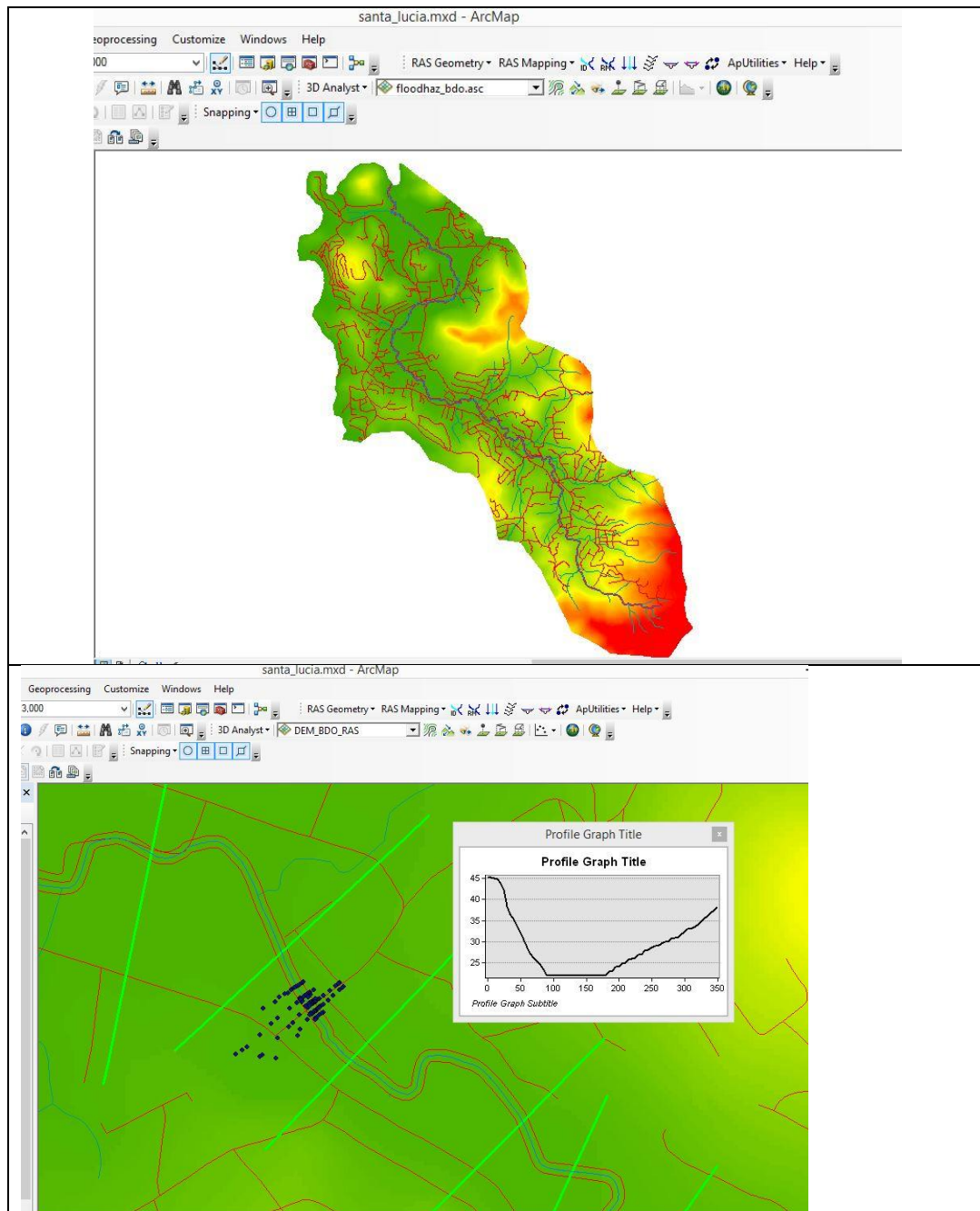


Figure 6.12. Example of HEC-GeoRAS layout.

7 Conclusions integrated watershed modelling

The calculations in this document are meant as an example, and a more extensive analysis can be done using design rainfall for 5, 10, 20 and 50 years. Above all, a good integrated watershed analysis involves stakeholder groups, to discuss the results with and to create understanding and acceptance in the watershed. The result of an IWM project is not usually not only about establishing mitigation measures, but the better understanding leads to increased resilience, adaptation and to a sense of responsibility. Even the best mitigation measures will not guarantee a 100% safety, because in the context of hurricanes this is hardly possible.

Nevertheless, based on these preliminary assessments, some conclusions can be drawn:

- Planning issues have not been discussed in this use case. Nevertheless it is clear that people live next to the stream in areas where frequently (every 5 years or more) inundation takes place. These properties are not safe and very likely may never be entirely safe. Some people living next to the river have houses on stilts, which greatly decreases their vulnerability.
- In a storm situation the Bois d'Orange valley floods when the rainfall in an event exceeds a 100 mm and intensities exceed 120 mm/h. The return period for such a situation is 5 years or even less. The river overflows in the entire central section and the flood propagates towards the coastal swamp. The flood is not only caused by the discharge but is increased by runoff from the surrounding slopes.
- Along the entire central channel buildings are exposed, and large water buffers in the central valley are hard to design. They can have positive effects but also negative effects because they may overflow or water may back up. Proper engineering design is needed for this by experienced people.
- A better option seems to be to make the capacity of the channel higher, i.e. build a flood defense wall, at least along the central section. The building requirements for this are not evaluated here. Alternatively the runoff water could be delayed with one or more buffer strips perpendicular to the river.
- The last alternative is to accept that areas will flood, and move people out of these areas. The financial and governance context of this option is not evaluated.
- The 10m database allows for a catchment based flood hazard assessment, but for a site investigation, such as may be done with HEC-RAS, additional field data is necessary, which needs a geodetic survey of the areas involved.

Note: in the centre of the catchment a Flood Early Warning system is present, with an ultrasonic water level meter. Its functioning could not be established at the time of this workshop. It is strongly advised to store the water level, so that it can be compared to the detailed rainfall data (which is in fact excellent). This will help calibrate any model, which is necessary for realistic results.

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Appendix 1 - Flood modelling overview

Several methods exist to determine or simulate floods, which range from static to dynamic these range from observations with remote sensing, via GIS methods to combine flood related information layers, to dynamic flood models. For each of these examples are given below, with advantages and disadvantages with respect to the Caribbean context. Table a.1 shows the possible methods available for flood detection and modeling.

Table a.1. Overview of methods for flood hazard assessment

Type	Method	Data source
A - Observations	Community based	Questionnaires
	Visible/NIR wavelengths	Images
	Radar wavelengths	Images
B - Multivariate statistics	Weighed combination of flood related factors	GIS layers
C1 - Modelling, decoupled: upstream	Incoming discharge measured	Measurements or statistics (design discharge)
	Incoming discharge modelled	Runoff from runoff fraction of upstream area (curve number)
	Incoming discharge hydrology	Runoff derived from hydrology of upstream area
C2 - Modelling, decoupled: downstream	Flood modelling from channel system	Physically based 2D modelling
D - Modelling, integrated	Full catchment modelling	1D/2D hydrology and hydraulics

All modelling approaches need a large amount of detailed spatial and temporal information. Floods are complex phenomena, especially when taking into account the entire catchment and rural and urban elements in it. There is no easy way out, and generally it is not a good idea to do any hydrological and hydraulic modeling uncalibrated. A good input dataset is not a guarantee for a good (e.g. realistic) flood estimate, when calibration and validation have not taken place.

A – Observations methods that recreate a maximum flood level and extent

Community based

After a flood event the inhabitants of an area are asked through a questionnaire about the flood level they experienced, and traces on houses are marked. The relative water heights are tied to a known elevation of an official datum or a landmark in the area (see fig a.1). There is a relatively narrow window of opportunity after a flood to do this. A pattern of transects perpendicular to the river can be used to find the flood extent.

Advantages: obtain flood extent in the field and pay attention to hydraulic properties of the flood area (breached walls, channels etc.), and it is a good opportunity to get information about the hazardous aspects of the flood. A questionnaire gives information on the duration of the flood.

Disadvantage: the questionnaires have to be done soon after a flood or people mix up memories of the most recent and earlier floods. Also, the water level information is uncertain and based on the precision of information (10-20 cm uncertainty in elevation) and quality of the underlying DEM and the ability to find a fixed datum. Only the maximum flood level is obtained. There is no information on probability, which comes from auxiliary data (such as meteorological data).

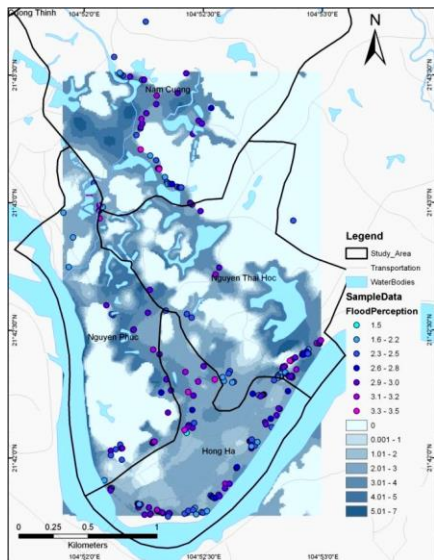


Figure a.13. Left: PGIS (community based) flood depth and extend map of Yenbai city, Vietnam, after flooding by the Red River during the Typhoon Kumari. Right: flood trace inside a house near the deepest flood level (Trang, 20XX).

Remote Sensing based

In the visible and near infrared spectrum water does not reflect incoming radiation very well and flooded areas show as darker areas generally. However all remote sensors suffer from clouds, except for active systems like radar. Because flash floods have a relatively short lifespan and are the result of heavy rainfall, the chance to get a cloud free image of a flash flood are very small. Fig 3.2 (left) shows a flooded area along the Magdalena River in Colombia, which was a river flood lasting several weeks (Jaramillo-Vasquez, 2016), detected with Landsat-TM (30m resolution) using a combination of visible bands. This flood lasted several weeks and two cloud-free Landsat images exist of that period, which are valuable to trace the extent of a flood at a given moment. Flood depth information can be obtained with a good DEM which is then combined with the extent of the flooded area. Unfortunately for the Magdalena area only a SRTM derived DEM exists, which is a digital *surface* model, it is not corrected for vegetation and has no information under water.

Note that the land use can be very important when using remote sensing: if Paddy Rice is the main land use as in large parts of Asia, the detected water level may not be a hazardous flood but simply inundated rice fields. It is possible to filter out rice fields with time series of images and certain band ratios (variations in the Enhanced Vegetation Index), but this is not straight forward and needs detailed ground information. The same goes for floodplains that contain wetlands, these will be detected as flooded areas as well.

Radar systems are active systems sending out radiation with different wavelengths that are reflected by objects on earth and partly retrieved by the sensor (backscatter). Smooth surfaces such as flooded areas reflect radiation away from the sensor and appear as darker areas. The great advantage is that radar penetrates clouds. The resolutions differs per sensor type and methodology (forward-backward looking or sideways looking) and can be between 5 and 50m (see fig a.2 right).

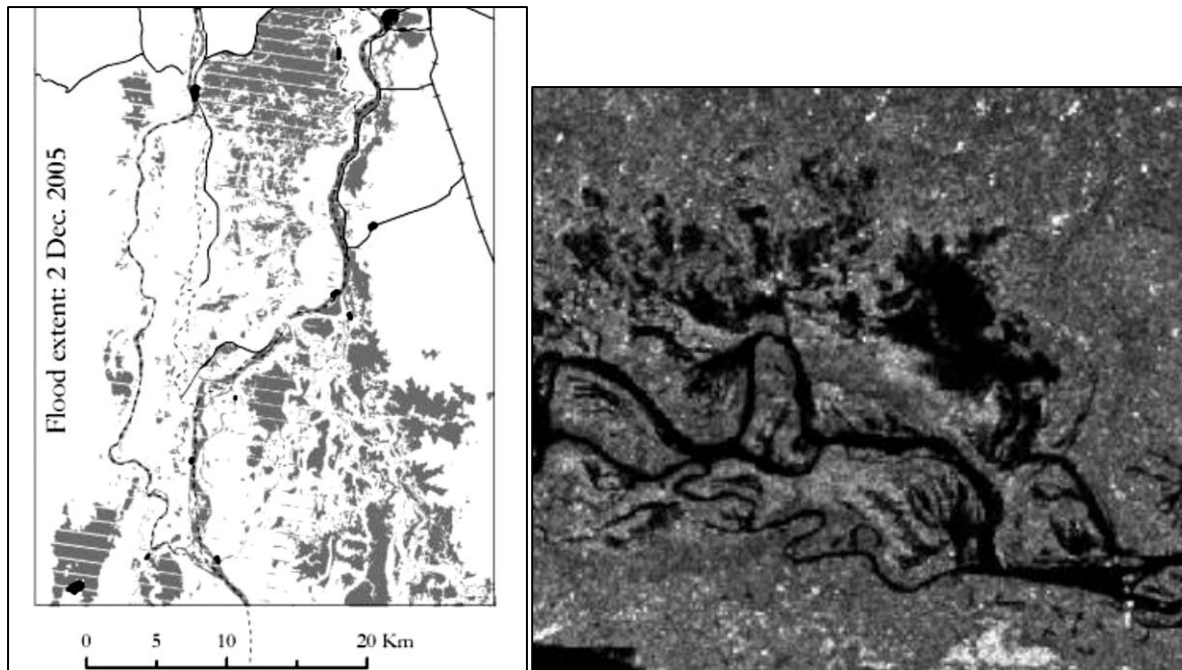


Figure a.14. Left: flooded areas detected with Landsat TM (30 m resolution) along the Magdalena river, Colombia 2 Dec 2005 (Jaramillo-Vasquez, 2016); right: flooded areas in Bhagalpur Bihar, India on 04 Aug 2013 (8.33 m resolution) derived from the Indian RISAT-I radar satellite (Mohan, 2014).

Advantages: a representation of what really happened. If multiple images exist there may be some idea on the duration and behavior of the flood. Radar can look through clouds and with long duration floods (weeks to months) it is possible to determine flood dynamics. Depth information can be obtained by using a DEM of the inundated area (depends on DEM quality).

Disadvantages: flash floods happen quickly so there is only a small chance the satellite captures the flood, and the area will be cloudy shortly after the flood occurred. Radar systems have a relatively low resolution but the newly launched Sentinel 1 mission has a much higher resolution. Because other surfaces than water have different degrees of backscatter, extensive filtering is needed, which leads to a degree of uncertainty. Generally remote sensing is only applicable to larger river floods that lasts several days or weeks. Information on probability of occurrence comes from other datasets (for instance rainfall time series). Advanced remote sensing skills are needed, to filter out effects of land use.

B - GIS based multivariate methods

Cooper and Opadeyi (2006) executed a flood hazard analysis on Grenada and Dominica, based on a weighted combination of GIS layers (fig 3.3). These are combined in 3 groups of 'risk' information: runoff (CN, curve number, derived from soil type and land use), daily rainfall and slope, each of which is classified in 3 severity classes. Slope is given extra weight compared to the other factors. The flood risk areas are determined by the class boundaries, which are given in fig a.3.

Advantages: the method is simple and the class boundaries can be adapted to the local circumstances. Daily rainfall classes are used that can be related to a probability of occurrence for a given set of catchment characteristics and circumstances.

Disadvantages: the logic may not work for certain areas, where the water delivering areas provide water to a floodplain. It is possible that an area with a low runoff factor (because of e.g. landuse) in

the flood plain is classified as medium risk, while this area in fact receives water from upslope and should be classified as high risk. Furthermore, the very low slope values need a high quality DEM, and the “low flood risk” covers the entire island not classified as medium or high flood risk, so it is not clear how to interpret it (there is no non-flooded area). The flooded area is not related to a river system, it is purely DEM based. So areas that are not within a reach of a river may still be classified as high risk. The map needs to be checked and possibly hand corrected.

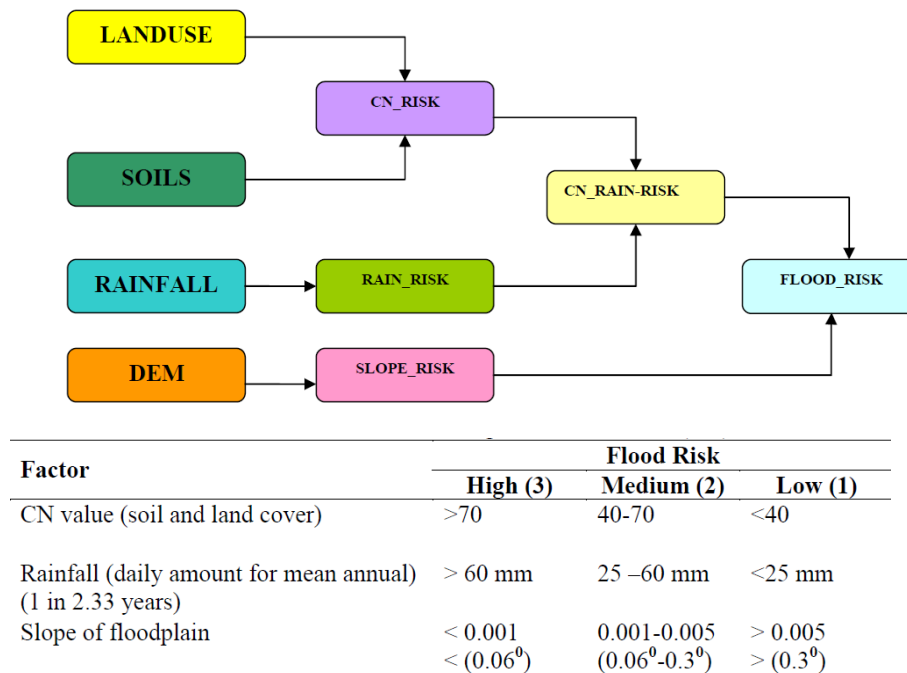


Figure a.15. GIS based flood hazard analysis, general outline and class boundaries used on Grenada. Note that a slope of 0.001 indicates 0.1% (Cooper and Opadeyi, 2006).

C1 - Modelling, decoupled: *upstream discharge generation*

In general flood hazard assessment is done by using a flood model. These models generally need boundary conditions specified by the user. These means in practice an incoming discharge wave is given to the channel, and the flood model simulates overflow and flooding. There are different ways to generate an incoming discharge.

Measured and design discharges

Discharge simply can be measured, by means of a submerged pressure sensor, or for instance an ultrasonic water level meter above the water. A stage discharge relationship is needed to convert the measured river water level to a discharge flux. The wet cross sections and average water velocities for different water levels are needed for that. If a long time series of peak discharge waves is available, General Extreme Value statistics can be used to determine the return periods of discharges, and the shape can be generalized into design discharges. It goes beyond the scope of this introduction to explain how this can be done. Note that the water level measurements have to be frequent (< 30 minutes intervals) in order to capture peak discharges and not only groundwater related baseflow. Daily discharge measurements are not usable for flood hazard analysis.

Design hydrographs are sometimes constructed in a more simple way, which allows for a greater use of available data. From measure time series, return periods for peak discharges can be established,

and an asymmetric triangular shape is assumed for the hydrograph, with a duration that is derived from observation or from an analysis of the flow resistance of the river stretch in question (Manning's n). This method is used for the Belize flood hazard assessment (see CHARIM use case 8.6).

Advantages: discharges based on measurements are always better than uncalibrated simulated discharges. Upstream flooding is automatically accounted for, giving more realistic hydrographs. Also changes in the catchment automatically are accounted for. Measure discharge is also needed to calibrate catchment models.

Disadvantages: long time series of high temporal resolution data are needed and if there are changes in equipment, frequency of measurement etc., these must be documented and accounted for. Extreme events such as hurricanes may not be well measured, equipment frequently breaks down. Stage-discharge relationships are needed, and should be regularly updated, in case major changes in the catchment and channel cross section take place.

Simulated discharges

The most common way of supplying a flood model with an incoming discharge wave is by simulating it. The big advantage is that the input data consists of rainfall data which is much more commonly available than direct discharge measurements. Depending on the goal of the simulations different types of rainfall data are needed: continuous water balance modelling needs at least daily rainfall and evapotranspiration, storm based modelling needs high resolution rainfall data (hourly or better). The probability of occurrence of a flood event is related to the return period of the rainfall event. This is not necessarily true, because a more frequent low intensity storm can result in flooding when the catchment is very wet and has little storage capacity, compared to a less frequent more intense event that falls on a drier catchment (which depends on the soils, land use and antecedent rainfall). The catchment characteristics and circumstances therefore effect the frequency-magnitude.

There are many models available that can do this (see table a.2) listing commonly used models. Note that there are many erosion models that in principle can be used to produce a peak discharge related to surface runoff. They are normally used for sediment dynamics, but some simulate also detailed surface hydrology. Jetten and Favis-Mortlock (2006) discuss and compare over 25 erosion models on various scales, of which several could be used in the context of providing a peak discharge. Kauffeldt et al. (2016) give a technical overview of 24 large-scale models that are used for flood simulations. Many of these models are generally used in a research environment and less used in consultancy context, and a full description of all models is beyond the scope of this introduction.

The models mentioned in table a.2 have similar characteristics:

- The upstream catchment is divided in sub-basins, whereby SWMM allows for a further subdivision of a sub-basin in a few large homogeneous units, like farms or vegetation units. Theoretically small spatial units can be defined, but in general these models are used for larger basins.
- All models can simulate long continuous periods, and include hydrological principles to do this. The time step varies per model, but they can also be used to generate storm events.
- The runoff is generated from a water balance, or by looking at the SCS Curve Number method, which calculates a runoff fraction based on land use and hydrological soil type. The models differ in hydrological relations used in the water balance, depending on underlying research. Also differences can be found with regard to snowmelt, the way urban areas are included, and the way chemistry and sometimes sediment movement is included.

- Runoff water is added to the channel system with a delay function (based on Manning's velocity), and a kinematic wave is used to combine the contributions of the stream network into one hydrograph.
- Channel flow can be more or less complex, depending on the cross sections used. Numerical solutions differ per model.
- SWMM focuses on water management aspects such as subsurface drainage systems and many other man made elements.
- The models use their own internal data management system. But integration with ARCGIS exists for some models.

Table a.4. Main upstream catchment models used in flood modelling.

Model	Link
SWAT – Soil Water Assessment Tool	http://swat.tamu.edu/
SWMM - Storm Water Management Model	https://www.epa.gov/water-research/storm-water-management-model-swmm
HEC-HMS - Hydrologic Modelling System	http://www.hec.usace.army.mil/software/hec-hms/
MIKE-11 (and MIKE HYDRO)	https://www.mikepoweredbydhi.com/products/mike-11

Advantages: catchment models have been long in use, with extensive experience and documented simulations all over the world. Support can be obtained e.g. from user groups. The models are in constant development and maintained. Watershed based discharge models are fast and efficient in computing time, relative to grid based models. The modelling allows the use of daily or sub-daily rainfall (depending on the goal) which is more commonly available than discharge measurements.

Disadvantages: this approach assumes that there is no upstream flooding, or that the flooding upstream does not influence the peak discharge that is modelled. This may not be true, mountain valleys may flood first and in fact provide already some level of mitigation for the downstream areas. Also some areas have a flood hazard along the entire channel and the incoming water is both diffuse direct runoff as well as discharge in a channel. Outside the US, the SCS Curve Number method is less well applicable, so the hydrological modelling solution is needed. This uses a lot of input data, in particular hydrological properties of soils and land cover. Finally, models that have (sub-)watersheds as units are not equipped to handle remote sensing derived data.

C2 - Modelling, decoupled: *downstream flooding*

There are many flood models simulate overflow of river channels into a flood plain, using physical laws describing the flow of water based on conservation of mass and conservation of momentum. In practice this means that the spread of flood water is modeled in 2D based on pressure differences, terrain elevation differences and acceleration of water, using a depth average velocity. Hydraulic changes in flow such as supercritical to subcritical flows are taken into account.

Well known are MIKE-FLOOD, HEC-RAS, FESWMS-2DH and SOBEK Suite. In this model group there are differences in the way time and space are discretized. Numerical solutions are based on finite difference, finite elements and finite volume methods, implemented on a fixed grid or variable sized elements. HEC-RAS is an exception as it does not do full 2D simulation, but propagate water perpendicular to the river in transects and then interpolates between them. Models differ mostly in the way they deal with manmade elements (channels, roads, spillways, gates, bridges, culverts etc.), and to which extend they include hydraulic processes such as sub-critical and supercritical flow. Not all of them simulate sediment distribution in flood water.

Table a.5. Main downstream flood models and their characteristics. Full STV means that the full St Venant equations are used.

equations are used.				
Model		Space	Organization	Link
HEC-RAS	Pseudo 2D	Transects across floodplain	US army corps of engineers (freeware)	http://www.hec.usace.army.mil/software/hec-ras/
MIKE 21 FM (and MIKE FLOOD)	2D, full STV	Irregular mesh, drainage channel network, engineering (culverts, sewers etc.)	DHI (commercial)	https://www.mikepoweredbydhi.com/products/mike-flood
SOBEK	2D, full STV	Regular grid, drainage systems, engineering (culverts, sewers etc.)	DELTARES (freeware)	https://www.deltares.nl/en/software/sobek/
FESWMS-2DH	2D, full STV	Irregular mesh, drainage systems.	USGS (freeware)	http://water.usgs.gov/software/FESWMS-2DH/
Flood Modeller Suite	2D, full STV	Regular grid & different numerical optimizations, drainage systems, engineering (culverts, sewers etc.), sediment.	CH2M (commercial, links also to other packages)	https://www.floodmodeller.com/en-us/
3Di water management	2D, full STV	Variable grid size, increasing detail when zooming in, interactive, urban drainage systems	Nelen en Schuurmans consultants (commercial)	http://www.3di.nu/en/

Note that the use of two separate models, such as HEV-HMS with HEC-RAS, is becoming outdated with the development packages that combine 1D and 2D catchment modelling, such as MIKE FLOOD and the SOBEK suite). The “3Di water management” flood model is less well known but is included because it is currently being used in Grenada and St Lucia.

Advantages: these models are very well suited to simulate floods in flat areas, taking into account urban and rural hydraulic factor on a very detailed level. They can be used for detailed engineering design. They mix vector type information related to drainage systems (channels, sewers) to grid based information for the 2D water movement. The grid based models can relatively easily use remote sensing based information (e.g. housing footprint). Also the channel flow is modelled in a detailed hydraulic way. Physically based models give also a lot more information above observations:

Disadvantages: The flood models need clear pre-defined boundary conditions and do not always include hydrological processes: evaporation, infiltration, and vertical groundwater movement. The modelling can be slow when runoff a PC if a large amount of detail is needed.

D – Integrated catchment modelling

Integrated catchment models are models that model the entire catchment water balance and flood dynamics in one model. Technically they are a logical development from organizations/companies that have couple their separate models in one ‘suite’, with increasing PC computing power over the last 10 years modelling large complex areas has become possible. Apart from technically possible, integrated catchment models are a response to integrated watershed management (see [CHARIM use-case 8.4](#)). In the integrated watershed management approach there is a need to evaluate the effect of flood mitigation measures that are related to changes in land-use, spatial planning and engineering, and often a combination of these. This is easier to achieve if a model combines all

processes in one system without the user having to switch models with possible data conversion between models. All models have an easy integration with GIS software such as ARCGIS and QGIS.

Table a.6. Commonly used integrated watershed models.

Model	Space		Organization	Link
LISEM	1D/2D	Small scale, regular grid (1m-50m). Event based. Detailed surface hydrology. Channel network simplified. Full sediment dynamics.	University of Twente - ITC (open source)	http://blogs.itc.nl/lisem/
LISFLOOD/ LISFLOOD-FP	1D/2D	Large scale, regular grid (50-500m). Continuous/event based. Simplified surface hydrology, simplified channel network.	EU-JRC and Bristol University (freeware)	http://www.bristol.ac.uk/geography/research/hydrology/models/lisflood/
FLO-2D	1D/2D	Regular grid (1-50m), includes erosion and debris flows. Event based.	FLO-2D Software, INC (commercial)	http://www.flo-2d.com/
MIKE-SHE	1D/2D	Regular grid (1-50m), continuous or events based, full hydrology (including groundwater).	DHI (commercial)	https://www.mikepoweredbydhi.com/products/mike-she
TUFLOW	1D/2D	Regular grid (1-50m), combined with linear systems. Continuous or events based, surface hydrology, urban drainage systems.	TUFLOW Products (commercial)	http://www.tuflow.com/

Appendix 2 - Database preparation for LISEM modelling

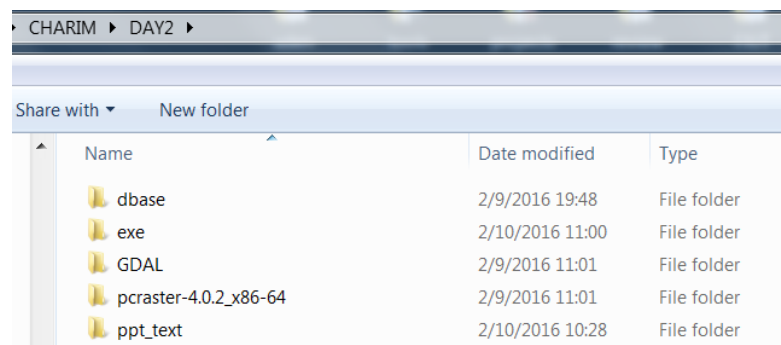
LISEM and PCRaster Software

Integrated Flood Management is done with specialized software. Finding solutions for flash floods requires a model that can analyse both the generation of runoff upstream, and the effect of different scenarios, as well as the problems downstream.

In this course we use two freeware packages: the GIS and spatial modelling language PCRaster (pcraster.geo.uu.nl), and the freeware runoff and flood model **LISEM** (blogs.itc.nl/lisem). The GIS **PCRaster** is used to create an database for the model and look at model simulation results. The model **LISEM** is a spatial runoff and erosion model developed for detailed analysis of soil conservation measures at farm field level, specifically the effects of single rainstorms. Recently a flood module was added so that it can be used to simulate flash floods. It has been in development since 1989 and is used in many countries. It is an event based model, so evapotranspiration and groundwater movement are not simulated, only the surface hydrology during and immediately after a rainfall. It models the hydrological and sediment processes in detail: timesteps of less than 1 minute and gridsizes of less than 100m. The size of the catchment is technically not a constraint: the model has been used in catchment of a few hectares to several 100 km².

There is no Windows type installation necessary for both the GIS and the model, simply copy the entire course database to a directory on your computer. BUT: do not use spaces in your pathname where you copy everything at this point. Do not install the database directly on your desktop.

When you copy the DAY2 set to your PC, it should look like this:



dbase is the with the St Lucia database for LISEM

exe has the LISEM model and the LISEM database generator (lisemdata.exe).

NOTE: the LISEM model exists only in 64bit!

GDAL is a library to convert PCRaster GIS to GeoTIFF

pcraster-4.0.2_x86-64 PCRaster GIS and GDAL

ppt_text course texts

LISEM SOFTWARE AND DATABASE PRINCIPLES

The method is based on the open source integrated watershed model LISEM. This model is based on the well-known LISEM erosion/runoff model (see e.g. Baartmans et al., 2012, Hessel et al., 2003, Sánchez-Moreno et al., 2014), combined with the FullSWOF2D open source 2D flood package from the University of Orleans (Delestre et al., 2014). As a runoff model LISEM has been used in many

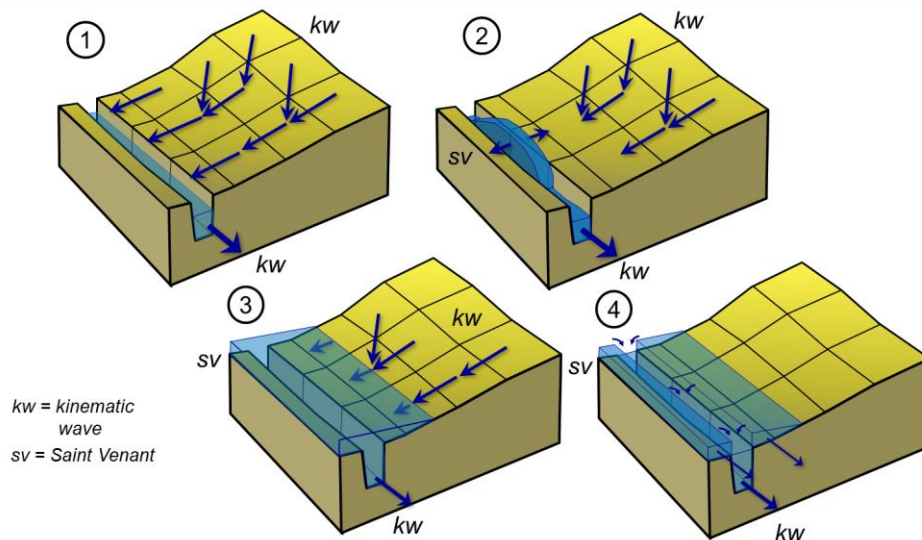


Figure a2.2. Schematic representation of flow processes from 1D kinematic wave runoff and channel flow (1), to overflow of channels (2), spreading out of water from the channels outward using 2D full Saint-Venant equations (3), and flowing back into the channel when water levels drop, most likely the runoff has stopped by now (4). Runoff continues to flow into the flood zone for a short distance.

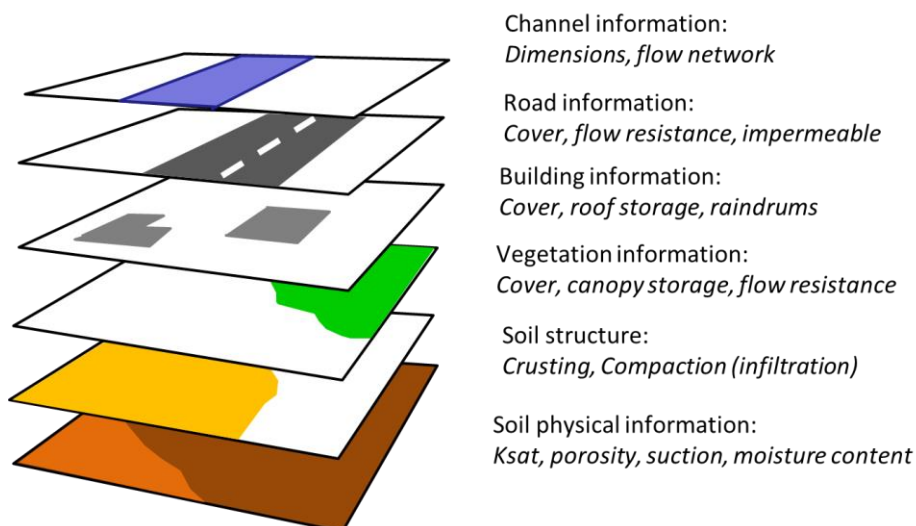


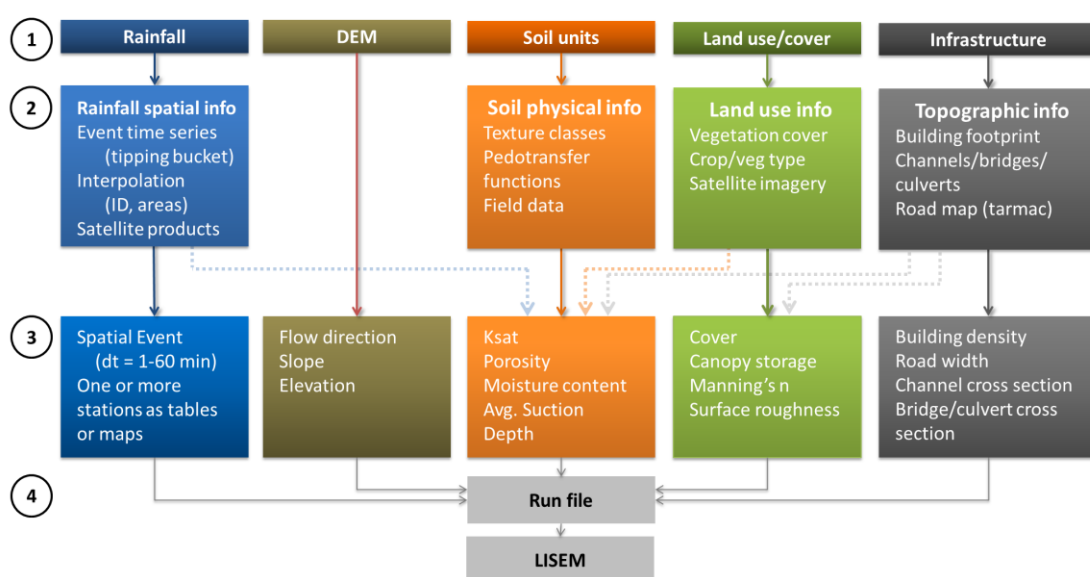
Figure a2.3. Different information layers are combined into one set of information per gridcell. Vegetation and building information is given as a fraction per cell, roads and channels are given as width in m. The soil layer is the base layer so that we always know what for instance the infiltration beside a road or house is. Infiltration and flow resistance are determined as a gridcell weighted average response.

This setup needs a lot of data, because in a raster GIS, that is essentially what LISEM uses, each property is defined in a new map layer. For instance the channel is characterized by 7 maps, for width, depth, angle of the channel sides, bed slope, flow resistance, and areas with imposed maximum flows (for bridges and culverts). The total number of input maps for LISEM looks daunting at a first instance, but they are all derived from 6 basic maps and several tables with soil and vegetation properties. This is explained in detail below.

Basic GIS maps and derivatives

LISEM uses input data directly to determine the hydrological processes that it simulates. There are very few built-in assumptions. For instance LISEM does not handle units like "Maize" or "Forest". This information is broken down into hydrological variables related to interception of rainfall and resistance to flow. The user has to break these classes down into hydrological variables for cover, infiltration related parameters and surface flow resistance.

Nevertheless in this project a PCRaster script is made to create the 5 data groups for a model run (columns in fig 5.1), for which basic maps are needed (row 1). Using a combination of field data and literature (row 2) the input database for the model is created (row 3). Table 5.1 describes briefly the main base maps, their origin if known, and how they are used in LISEM.



1. Basic maps needed, raster format, minimum resolution defined by user (min resolution wider than channel, no max area size)
2. Additional area information on rainfall distribution, soil and land use parameters, and infrastructure parameters. Derived from imagery, available maps, literature, field work, other models etc.
3. LISEM input database, generated automatically in PCRaster GIS (macro language script, combining base maps and knowledge to create maps for all input variables)
4. Define a run file for the job, specifying all options and map names for this run.

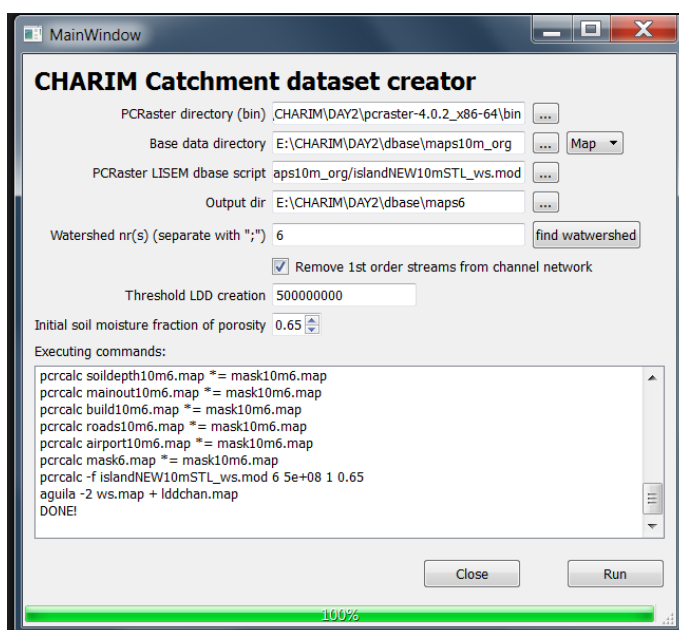
Figure a2.4. Flow chart of the creation of an input database for LISEM from 5 basic data layers. The database is generated automatically in a GIS (PCRaster) with provided software.

Basic data	Created from	Method
DEM	From contour shape files with 2m intervals (origin unknown).	Kriging interpolated using an exponential semivariogram to a 10m DEM, resampled to a 20m DEM using 2x2 window average.
Soil Map	Shape file. Origin 1966 soil map made by UWI Imperial College of Tropical Agriculture.	Soil units in the map have a standard USDA texture class. Texture classes are used to derive soil physical properties with pedotransfer functions, taking into account stoniness.
Land cover map	Based on classified images 2014, Pleiades and RapidEye images, British Geological Survey.	Has 18 classes for land cover information, interpreted directly to hydrological parameters.
Road map	Shape file of all roads in 3 classes (incl. highway).	Assumed all roads to be tarmac/concrete slabs, narrow width (4m and 6m) and highway 10m wide.
Building map	Shape file from FUGRO digitized building information.	Rasterized to 1m resolution and resampled to 10m and 20m building density (m2 building/m2 cell)
River map	Shape file, two classes, natural and artificial. Consists of many separate disconnected branches.	Combine the digitized natural river channel information in the coastal zone, with automatic DEM generated river channel location in poorly visible (inland under vegetation cover).

Table a2.1. List of main data layers for St Lucia and their origin and main GIS operations

Generating a catchment database

Under CHARIM the 10m GIS database of St Lucia was converted to a format the LISEM needs. This is the format of the freeware GIS PCRaster. At the moment a library is created so that LISEM can read GeoTIFF maps, but that is not ready yet. The database of the whole island is in the directory [..\DAY2\dbase\maps10m_org](#). A small tool was created to select from this database one or more catchments that we need to model. This tool is called **lisemdata.exe** and is in the directory [..\day2\exe\](#). Go to that directory and open **lisemdata.exe**, the screen looks as follows:



Make sure the fields point to the right directories. For instance if everything is installed in `d:\charim\day2\` then the following fields should be given:

PCRaster directory (bin): `d:\charim\day2\pcraster-4.0.2_x86-64\bin`

Base data directory (bin): `d:\charim\day2\dbase\maps10m_org`

PCRaster LISEM dbase script:

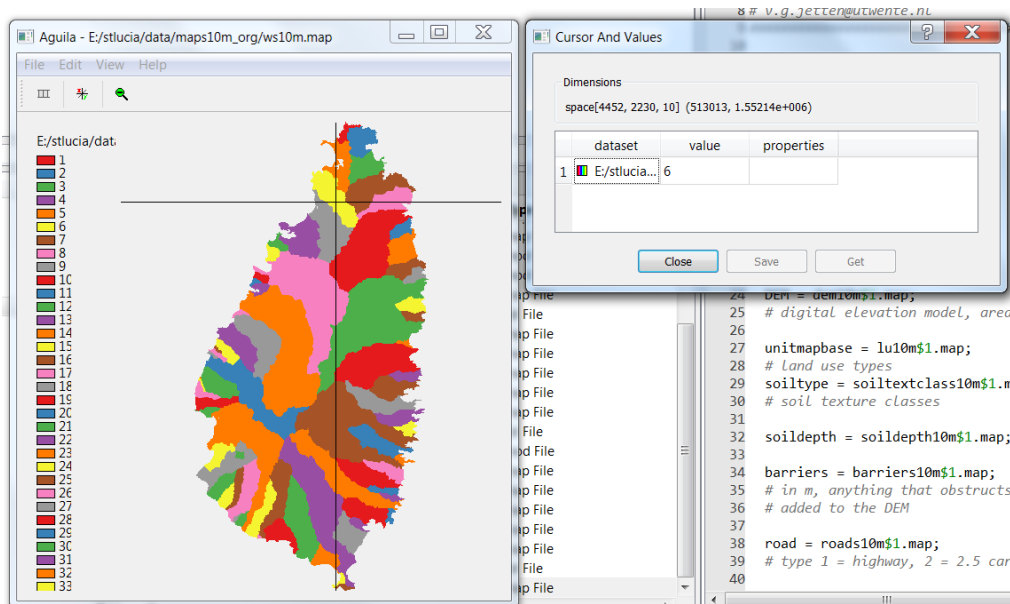
`d:\charim\DAY2\dbase\maps10m_org\islandNEW10mSTL_ws.mod`

Output dir: `d:\charim\day2\dbase\maps6`

And the other values as shown.

NOTE: the output dir name is of your own choice. If it doesn't exist it will be created.

Click on **"find watershed"** which opens a simple map of st lucia with all the watersheds coloured. *If nothing happens the path names are likely wrong!* These are not the "official" watersheds as known by the hydrological services, but delineations based on the 10m DEM in the database. The picture looks like the figure below.



The Bois d'orange watershed is in the top left corner and has value **6**. So we have to extract from the total dataset, the basemaps that are related to this watershed. The software will isolate this watershed 6, and cutout the maps to form a rectangle around the watershed. We tell the software to store the new maps in the output directory: `..\day2\dbase\maps6`.

The software also calculates the complete LISEM database behind the screens, so converts the basic data to the input maps that LISEM needs. This will take some time. When all is done a map pops up with the watershed and the main river.

Appendix 3 – HECRAS step by step learning approach

	Learning Sequence	Learning Objective: At the end of this session the participant learns / is exposed /is able to...
Day 1: INTRODUCTION AND GEOMETRY	Overview of HECRAS capabilities	<ul style="list-style-type: none"> • Use and limitations of the model • Overview of schematics and X-Section input • Overview of roughness input • Overview of multi-input quick modifications • Overview of joining rivers using junctions or nodes • Overview of initialization for steady flows (upstream flow profiles) • Overview of boundary conditions alternatives for steady flows and their meaning • The Plans (scenarios) in HR. • Overview of viewing results in graphical and tabular forms for XS and longitudinal profiling
	A quick understanding of river hydraulics. (For engineers only)	<ul style="list-style-type: none"> • Glossary on cross section river morphology and XS geometric parameters • Differentiate different type of long. slopes (energy) • Differentiate different types of flow regimes • Differentiate flow conditions: subcritical, critical and supercritical • Understand the difference between 1-D, 2-D, and 3-D models. Limitations of 1-D. • Understanding the governing equations of flow (advance) • Learning water flow transitions for gradual and abrupt change of slopes.
Day 2: GROUND TRUE and EXTENDED THEORY	Field data techniques: Cross Section Survey (For engineers and surveyors only) How to measure the XS to be input in HECRAS	<ul style="list-style-type: none"> • The equipment needed for the XS levelling • The optical level reading: (during the course a Total Station was used, but the principle remains the same) • ZIG-ZAG cross section plan of survey to cover a short river reach. (Adequate for HR) • XS calculation steps (in detail) • XS measurements boundaries (extension of the XS, Where it ends?) • Differences in the river banks and channel X-sections in HR: Perpendicular to the flow lines. • Estimation of the longitudinal and transversal separation between station: hints • How to look at a river section: where is the channel and where is the bank • Evaluating potential boundary conditions in the field: tips. • Advance XS survey with special electronic sounders. • Tips to observe flow and decide upon the selection of a XS making for the case of islands (flow division) • Observing and detecting flowlines, and ineffective areas (storage but not conveyance) • Translating the field measurement into HECRAS crude input.
	Field true data for calibration and validation analysis: Discharge measurements. How to measure discharges in a river to calibrate or validate a HECRAS run	<ul style="list-style-type: none"> • What to observe in a river to select an optimal XS place to do a direct discharge measurement • Tips to select a safe, accessible and adequate XS. • The instruments required for discharge measurement (currentmeter propeller only) • How to set and mark a XS perpendicular to the flow

	Learning Sequence	Learning Objective: At the end of this session the participant learns / is exposed /is able to...
		<ul style="list-style-type: none"> Planning the XS crossing: Stations and progressives. Understanding the velocity-area method: calculating the equivalent averaged XS speed with 2 current meter measurement in a statin vertical. Defining the number of XS and the number of stations per XS. Instrument calibration curves: the conversion from rotations to water speed. Integration of the area-speed measurement in a spreadsheet: the equations How to build a real rating curve out of repetitive measurements.
	Theoretical information and detailed hands-on for the HEC-RAS input	<ul style="list-style-type: none"> Understand the input process with a better inside and hints. Set the cross section orientations and different separation lengths in the channel, and overbanks Establish a routine compatible with the XS survey How the survey is done in the XS at the proximity of a bridge (not in the bridge) Follow step by step the setting of a HR project Follow step by step the input of the stream geometric data: schematics, cross sections and auxiliary tools. Prevention of wrong data input, what cannot be input: avoiding more than 1 station per progressive and selecting the right extension for the XS to avoid vertical walls. Prevent the appearance of depressions as “islands”. Guide a good practice in the building of interpolation among XS. Input good expansion and contraction coefficients for flow. Establishing ineffective and blocked areas in a XS. Dealing with blocked obstructions in the XS. Entering longitudinal levees Entering steady flow data profiles for a river scheme Understanding and entering boundary conditions Input “observed” information How to perform pre-checks and the hydraulic computations Output viewing; graphics and tables (multiple options) <ul style="list-style-type: none"> Special: rating curve building 3D-perspective. Analysis of Notes, Warnings and Errors. Report Generation
Day 3: MORE FUNCTIONS & LOCAL CASE	Overview of the advance functions in HECRAS for detail analysis and project records.	<ul style="list-style-type: none"> Understanding the difficulty of programming cross section interpolations: options <ul style="list-style-type: none"> Mastering cords: Main and auxiliary cords to steer interpolations of XS. Interpolating non-conveyance (ineffective areas) Understanding scenario combinations: The multiple plan feature. <ul style="list-style-type: none"> Graphical and tabular analysis of multiple plans. Picture and ground true evidence support <ul style="list-style-type: none"> Background imagery supporting a project. Downloading and understanding Log files. A glance to professional options for scouring, weirs, ice, sediment and bridge analysis
	Understanding the effect and importance of hydraulic	<ul style="list-style-type: none"> The roughness concept Differential roughness for channel and floodplains. Partition of roughness in a section.

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	roughness: The Manning coefficient.	<ul style="list-style-type: none"> • Roughness calculation: methods • Roughness estimation: tables • Tools in HR for the access to ready-made roughness tables. • Roughness examples and information on “roughness websites”
Day 4: STRUCTURES IN HECRAS	Understanding the theoretical basis of the calculation of structures (bridges and culverts) and the hands-on in the input and processing	<ul style="list-style-type: none"> • Understanding the effect and influence of the bridges in the water flow. • Recognizing the type of flow in a Bridge. • Setting the calculation approach for different types of flows. • Dealing with energy loss coefficients in bridges and piers. Tables. • Dealing with free (low) flow, pressure flows and overtop flow in a bridge. • Flow evidences and water marks. • Input of a bridge in HR: establishing the 4 control sections based on flow lines contraction and expansion. Simplifications for difficult cases. • Expansion and contraction coefficients based on energy loss transitions • Ineffective areas in a Bridge. • Bridge data collection: the filed forms • Bridge input in HR step by step: deck, abutments and piers • Selection of the calculation model • Dealing with bridges under floods: debris • Special cases: parallel bridges and bridges on a skew angle.
	Understanding the culvert design based on the geometric aspects of the culvert and the upstream and downstream submergence conditions	<ul style="list-style-type: none"> • Understanding the typical culvert profile and main geometrical features. • Culvert type of controls: <ul style="list-style-type: none"> ○ outlet control in submerged and unsubmerged situations. ○ Inlet control in submerged and unsubmerged situations. • Factors affecting the inlet and outlet configuration • Hydraulic equations for different types of configurations • Understanding the effect of culver entrance shape in the energy loss and efficiency. Tables • Performance under operation: free flow and pressure flow, and eventual overtopping. • HECRAS and the culvert calculations: <ul style="list-style-type: none"> ○ Culvert shapes ○ Location of the 4 controls sections (similar to bridges) ○ Evaluation of ineffective flows • Input of Culverts in HECRAS details <ul style="list-style-type: none"> ○ Adding a culvert ○ Setting the control sections between 2 XS ○ Culverts components: deck and geometry ○ Special features: Treatment of debris, multiple culvert configuration and multiple openings

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Day 5: JUNCTIONS, DESIGN HINTS and FINAL STUDYCASE HECRAS	Dealing with river confluences in HECRAS and 1-D flooding at river crossings	<ul style="list-style-type: none"> • Using HR in a confluence and in a diversion of a river. Data acquisition and procedures. • Types of junctions as a function of flow regime in river splits and joins • Understanding the sequence of constructions of a junction: reach-junction order • Step by step construction of a joint. • What to measure in a joint? • Joint examples • Mathematical solution of a junction: hints for the selection of the method.
	Adaptation of road experiences during floods. Information hints	<ul style="list-style-type: none"> • Avoidance of blocked structures by debris (main cause of bridge failure) • Selection between culvert and bridges: criteria • Awareness on the consequences of a poor design. The importance of structural modelling • Design of a structure: a good definition of the structure objective • Data requirements as a function of scale: an example • Design: the flow chart and an example of application with use of Remote Sensing information • A description of available and accessible tools for adequate road and structural design with specification.