OVERLAYING AND LINKING LOW FLOW AND FLOODPLAIN RIVER REACHES FOR RAPID ASSESSMENT OF MITIGATION MEASURES

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ABSTRACT

Low flow channels and floodplains are linked elements in a river corridor. At low flows river channels often meander and at high flows meanders are frequently overtopped with floodwaters flowing out of bank through the floodplain. During high flows the flood water takes a short cut with the floodplain conveying a significant amount of flow and taking a much shorter route than the flow in the low flow channel.

Level of service requirements for rivers often only allow out of bank flow for events of ARI in excess of 5 years. In sections of the river where the level of service is not met mitigation can be achieved by identifying and protecting a formal overland flow path which follows a straight alignment within the river corridor.

This paper examines how a 1-D hydraulic model simulating the linkage and hydraulic behaviour between a low flow channel and floodplain was discretised (for a river corridor with a significant difference in flow length between channel and floodplain). It also describes how this setup enables the modeller to simulate mitigation options such as formalising a straight overland flow path and discusses the advantages, effects and constraints of mitigation options and the model setup.

KEYWORDS

Hydraulic Modelling, River Engineering, Overland Flow Paths, 1-D modelling

PRESENTER PROFILE

Bas is an Environmental Scientist with Pattle Delamore Partners Ltd and has 5 years of experience. His main focus in the last few years has been in hydrological and hydraulic investigations and analysis. He has experience with most current stormwater and river modelling packages.

1 INTRODUCTION

In an assessment of the flooding extent of rivers and streams during design flow conditions it is important to understand the flood mechanisms specific to the waterway. Different types of rivers exhibit different responses to flood flows and a correct representation of these flood mechanisms in a 1-D hydraulic model is essential to accurately predict flood levels during design flow conditions.

Some rivers are deeply incised and/or follow a straight alignment. In these rivers the flow path of low flows is similar in length to high flows and these rivers can be represented in a 1-D model with only 1 channel. Other rivers show a distinct difference in flow length (and hence travel time) between the low flow channel and floodplain. Meandering rivers for example show a long (meandering) low flow channel and at high flows these meanders are frequently overtopped with floodwaters flowing out of bank through the floodplain. During high flows the flood water takes a short cut with the floodplain conveying a significant amount of flow and taking a much shorter route than the flow in the low flow channel.

To illustrate this flood mechanism satellite images from the 2010 floods in Pakistan are shown below. Floodwaters from the Indus River broke through the banks at several locations flooding farmland and displaced millions of people.

Figure 1(27 August 2009) shows the Indus River during relatively normal water levels. The Indus is a narrow, meandering waterway with no signs of flooding and/or out of bank flow. Figure 2 shows the Indus River during the peak of the 2010 floods (28 August 2010). In this satellite image the Indus River has burst its banks and the floodwaters are flowing through the floodplain.

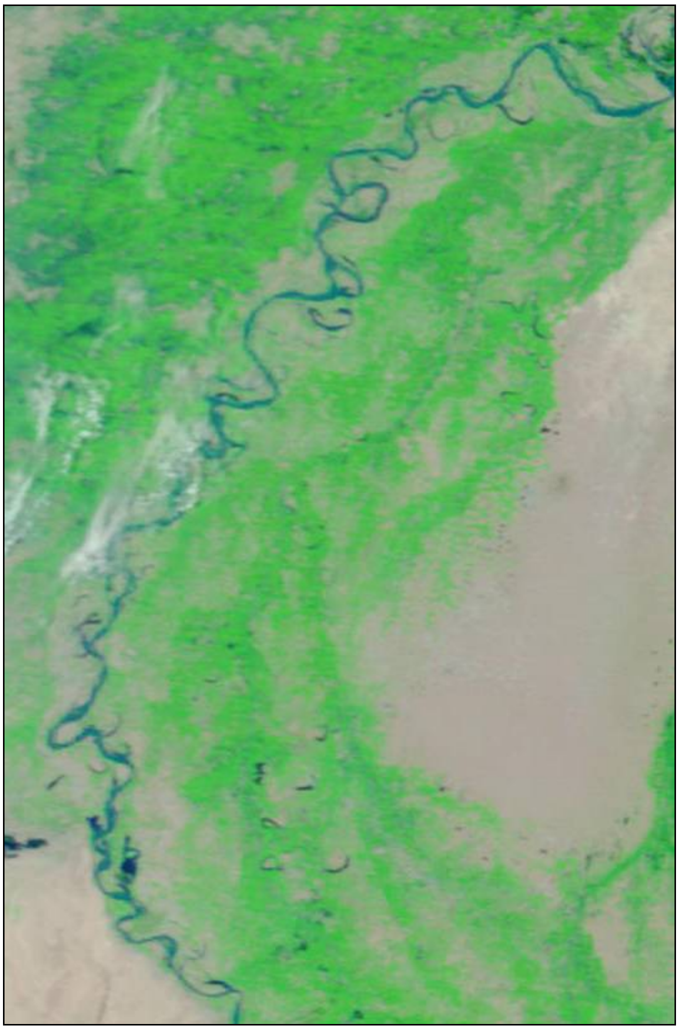


Figure 1: Indus River during 'relatively normal' water levels(Image: 27 August 2009), Image sourced from Earth Observatory NASA.

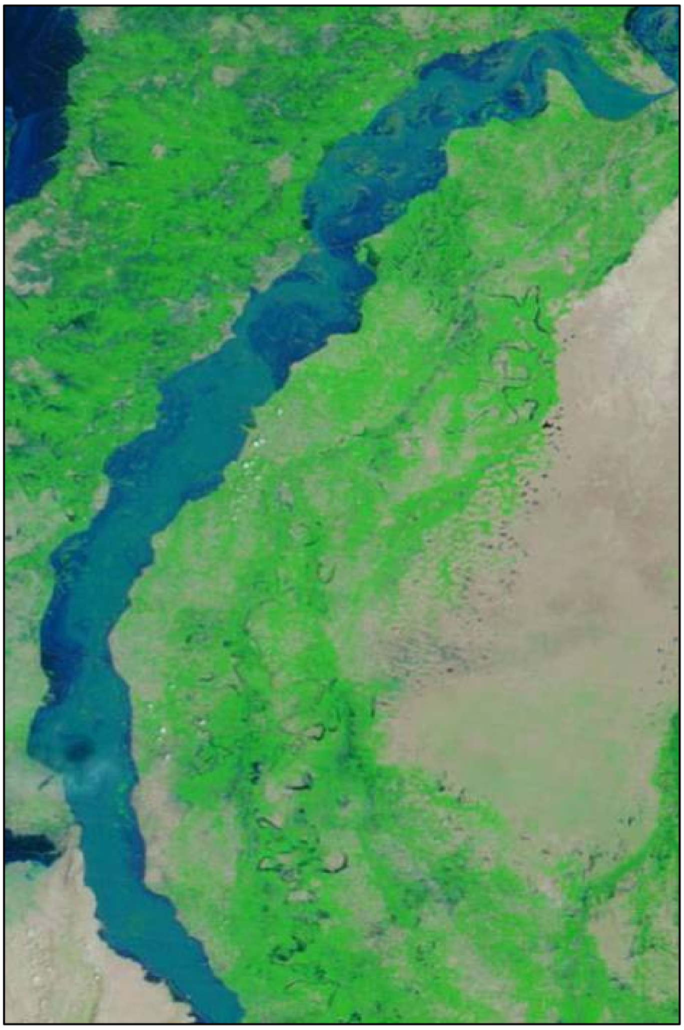


Figure 2: Indus River during the peak of the 2010 floods (Image: 28 August 2010), Image sourced from Earth Observatory NASA.

This paper focuses on how to discretise and setup a 1-D hydraulic model for a meandering/braided river and describes the advantages, effects and constraints of using this model setup when assessing mitigation options.

2 THE MODEL

In this section of the paper the discretisation/setup of a 1-D hydraulic model in HEC-RAS is described which was used for a flood assessment study in Whangarei. In addition, the input parameters, hydrology and downstream boundary conditions are described.

- Hydrology

The catchments were primarily delineated using LiDAR data provided by the Whangarei District Council (WDC) and were processed using GIS. The hydrology of the sub-catchments has been modeled using HEC-HMS (version 3.4) (U.S. Army Corps of Engineers) and MIKE URBAN (version 2009) (DHI) software. The SCS curve number loss method and SCS unit hydrograph methods were used to compute runoff and to develop hydrographs for each sub-catchment. Rainfall for the catchments was sourced from HIRDS V3 using a nested storm profile to distribute the rainfall for all events, in accordance with Auckland Regional Council's Technical Publication 108 (ARC, TP 108).

- Hydraulics

The hydraulic model was built in HEC-RAS (version 4.1) (U.S. Army Corps of Engineers) which can be used to perform one dimensional steady and unsteady river flow hydraulics calculations. The software splits the components of the model up into two files, the geometry file and the boundary and initial condition files. These files can be used to generate a results file which is required in the RAS Mapper section of the programme which can produce a gridded map of the flooding depths and velocities.

- Terrain and survey

LiDAR (Light Detection And Ranging) data was provided by WDC to provide land elevation data for the area of interest. This data provides reasonable accuracy of the land elevation in relatively flat areas with moderate changes in slopes. However when the land surface rapidly changes slope the LiDAR data often overestimates the actual land height (by up to 0.8 metres). An example of this occurs for the incised low flow channels. Therefore the depth of the low flow cross sections, culverts and bridges were adjusted based on real survey data to better reflect the true invert of the stream and in-stream structures. The cross sections of the floodplains were based on the LiDAR data.

- Boundary and initial condition

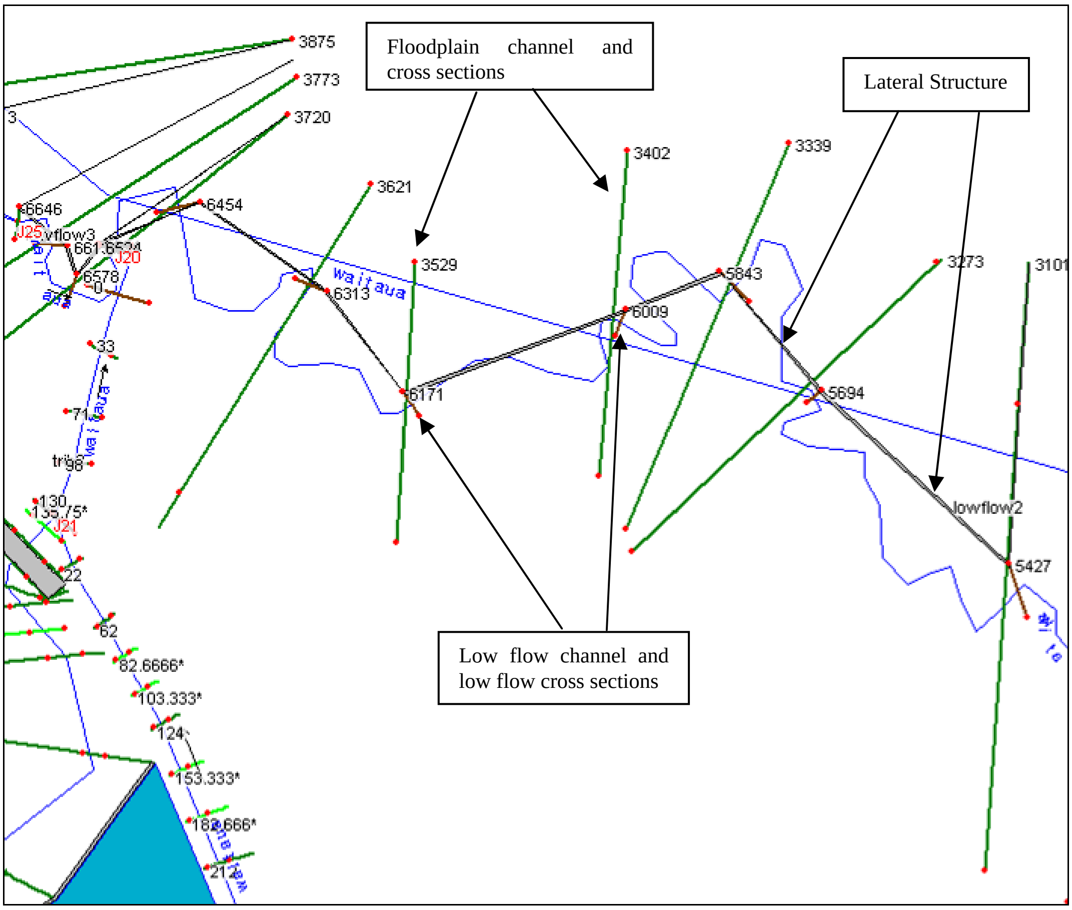
The initial conditions were created by simulation of a drawdown that started at the highest relative elevation in the model and finished at the lowest. A small constant flow was added as a boundary condition where needed. The last time step in the drawdown analysis was taken to be the steady state condition of the streams prior to a storm event. This steady state condition (i.e. Normal depth: Uniform flow depth with Q being constant) was used as the initial condition for the storm analysis. The hydrographs created in HEC-HMS were inserted as boundary conditions at the appropriate cross sections.

Ideally a downstream boundary is located downstream of a critical flow section, but in this case none was obvious in the immediate area. A waterfall was located much further downstream, however this would mean incorporating a large amount of catchments outside of the specific area of interest. Therefore the area of interest was isolated by using a downstream boundary condition (water level) sufficiently far downstream as not to influence the water level in the area of interest. Several different water levels at this location were tested to ensure that the water levels in the area of interest were not influenced by the downstream boundary condition.

2.1 DISCRETISATION OF LOW FLOW CHANNEL AND FLOODPLAIN

The geometry file contains all the geometry data for the streams such as cross sections, culverts and bridges. Some of the stream reaches were split into two sections, a low flow reach and a flood plain reach. This is to account for the fact that during major flooding events, the river takes a more direct route in comparison to normal flows. To define the transition between the floodplain and the low flow channel, a lateral structure along each low flow reach was placed. The top of bank of the low flow channel and the lateral structure were matched at all cross sections, this allowed the same water level to be kept in both the low flow and flood plain channels which is essential for mapping purposes. In other words when eventually running the simulations one needs to ensure that the water level in the low flow reach is the same as the water level in the floodplain when floodwater flow is out of the banks. In order to do this it is essential that the low flow cross section is located in the same position as the floodplain (i.e. floodplain cross section is overlaying the low flow cross section).

Figure 3 shows an example of the low flow channel and floodplain with their associated cross sections and the lateral structure connecting the channels. Figure 4 shows a long section of the lateral structure between low flow chainage 6523 and 5427.


Floodplain channel and cross sections

Lateral Structure

Low flow channel and low flow cross sections

Figure 3: Low flow channel, floodplain and associated cross sections. The lateral structure connects the low flow and floodplain channel.

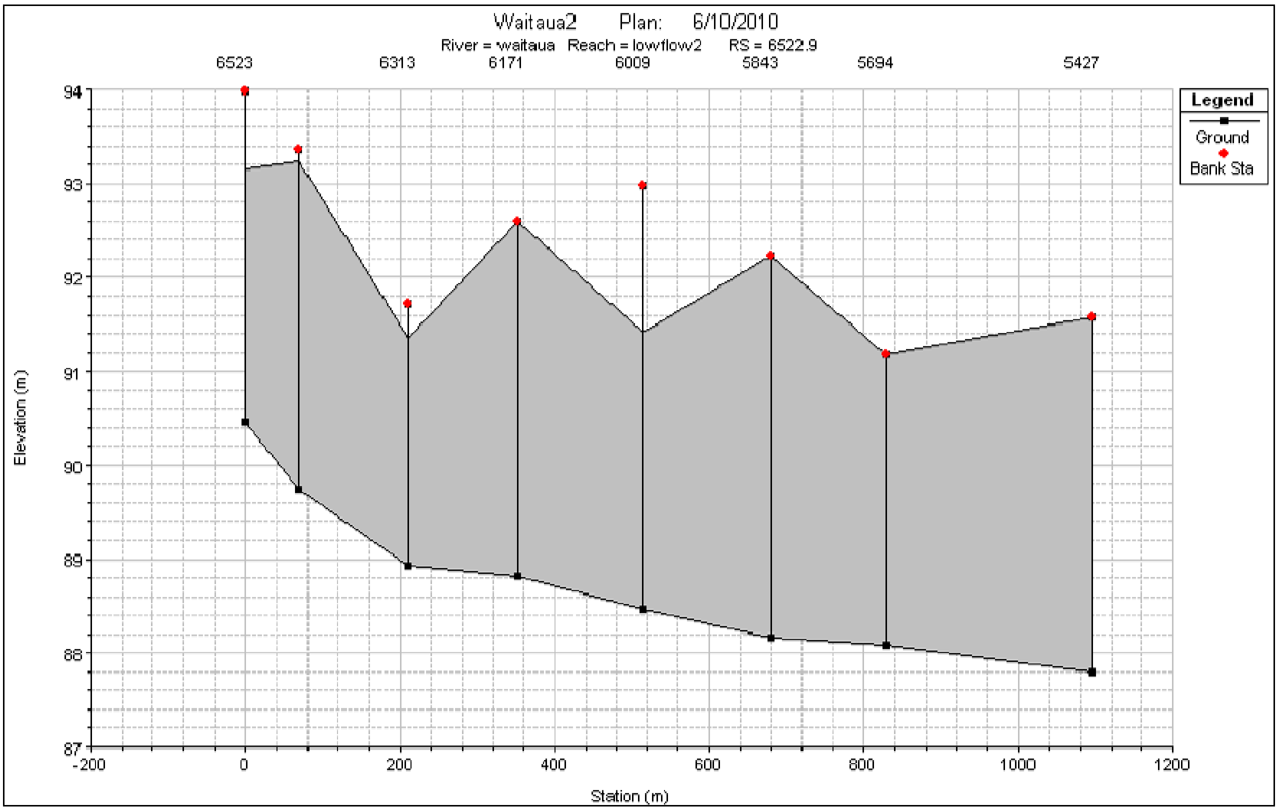


Figure 4: Long section of lateral structure between low flow chainage 6523and 5427

The low flow cross sections only represent the low flow channel and are connected to the floodplain at the lowest bank level of the cross section. Figure 3 clearly shows the different lengths in flow path between low flow channel and floodplain. For example the distance between low flow cross section 6009 and 5843 is 166 metres whereas the distance between the corresponding floodplain cross sections (3402 and 3339) is only 63 metres.

In Figure 4 the red dot represents the level of the left overbank (i.e. true left side) and the top of the grey area represents the level at which the low flow channel starts spilling water into the floodplain. At some of the chainages the left overbank of the low flow channel is higher than the right overbank (i.e chainage 6523, 6454, 6313 and 6009)

2.2 RAS MAPPER

RAS Mapper is a relatively new tool in version 4.1 of HEC-RAS and helps to visualise the extent and depth of flooding. The cross sections, storage areas and reaches from the geometry file are automatically loaded into RAS Mapper. With the land elevation data (LiDAR) maximum flooding depths can be mapped. For the areas with a separate low flow channel and floodplain the low flow channel was removed and only the floodplain was used in RAS Mapper to estimate the maximum flooding depth. By overlaying the low flow cross sections with the floodplain cross sections as explained in section 2.1 and ensuring that the water levels in both channels are the same (when out of bank flow is occurring) the mapping of just the floodplain is all that is required to produce a floodmap.

2.3 ALTERNATIVE METHODS

The discretisation/setup of a 1-D hydraulic model in HEC-RAS and the associated flood mapping as described above is one of the methods available to determine flood depths and assess mitigation options in flood studies. An alternative to the method described above would be a 2-D hydraulic model. The advantages and disadvantage of a 1-D and 2-D hydraulic model will be explained in more detail in section 5 of this paper.

3 SCENARIOS

The model was used to assess the flooding extent of Waitaua Stream (North Whangarei) as a result of the 5 year and 100 year design rainfall events, both with and without climate change and with and without proposed development.

3.1 5 Year Events and Level of Service

The 5 year events relate to the nested 5 year rainfall events with duration of 24 hours. There are two 5 year rainfall events, the 5 year with climate change and the 5 year without climate change. Flood maps were produced for three scenarios:

1. *Current* landuse, 5 year rainfall event *without* climate change and no mitigation
2. *Current* landuse, 5 year rainfall event *with* climate change and no mitigation
3. *Future* landuse, 5 year rainfall event *with* climate change and no mitigation

No changes were made to the hydraulic model for the different land use scenarios. Only the hydrological model was changed to account for changes in runoff as a result of land use change.

The second scenario represents the level of service requirement for the council. In other words no flooding should be experienced during this event and if the analysis reveal that the current infrastructure cannot cope with these flows then mitigation is required.

An example of a flood map produced for scenario 2 for the Main Stem of Waitaua Stream is shown in Figure 5. This map shows the modelled extent and depth of flooding as a result of the five year rainfall event with climate change, assuming that the catchment is in its current state of development.

Figure 6 shows that large parts of the main stem of Waitaua Stream experience out of bank flow. Therefore it is assessed that the current infrastructure does not meet the level of service required by WDC and mitigation is required.

An example of how the level of service can be achieved through modelling one of the mitigation options is further described in Section 4 of this paper. Section 4 of this paper will focus on the area shown in black on Figure 5.

3.2 100 Year Events

The objective of the modelling for the 100 year event was to provide flood maps showing the flood extent and flood depth as a result of the 100 year rainfall event. These maps were used to check areas earmarked for development that have the potential to be adversely affected by the 100 year event.

The 100 year events relate to the nested 100 year rainfall events with duration of 24 hours. There are two 100 year rainfall events, the 100 year with climate change and the 100 year without climate change. Flood maps were produced for three scenarios:

1. *Current* landuse, 100 year rainfall event *without* climate change and no mitigation
2. *Current* landuse, 100 year rainfall event *with* climate change and no mitigation

3. *Future* landuse, 100 year rainfall event *with* climate change and no mitigation

An example of a flood map produced for scenario 1 for the Main Stem of Waitaua Stream is shown in Figure 6. This map shows the modelled extent and depth of flooding as a result of the 100 year rainfall event, assuming that the catchment is in its current state of development.

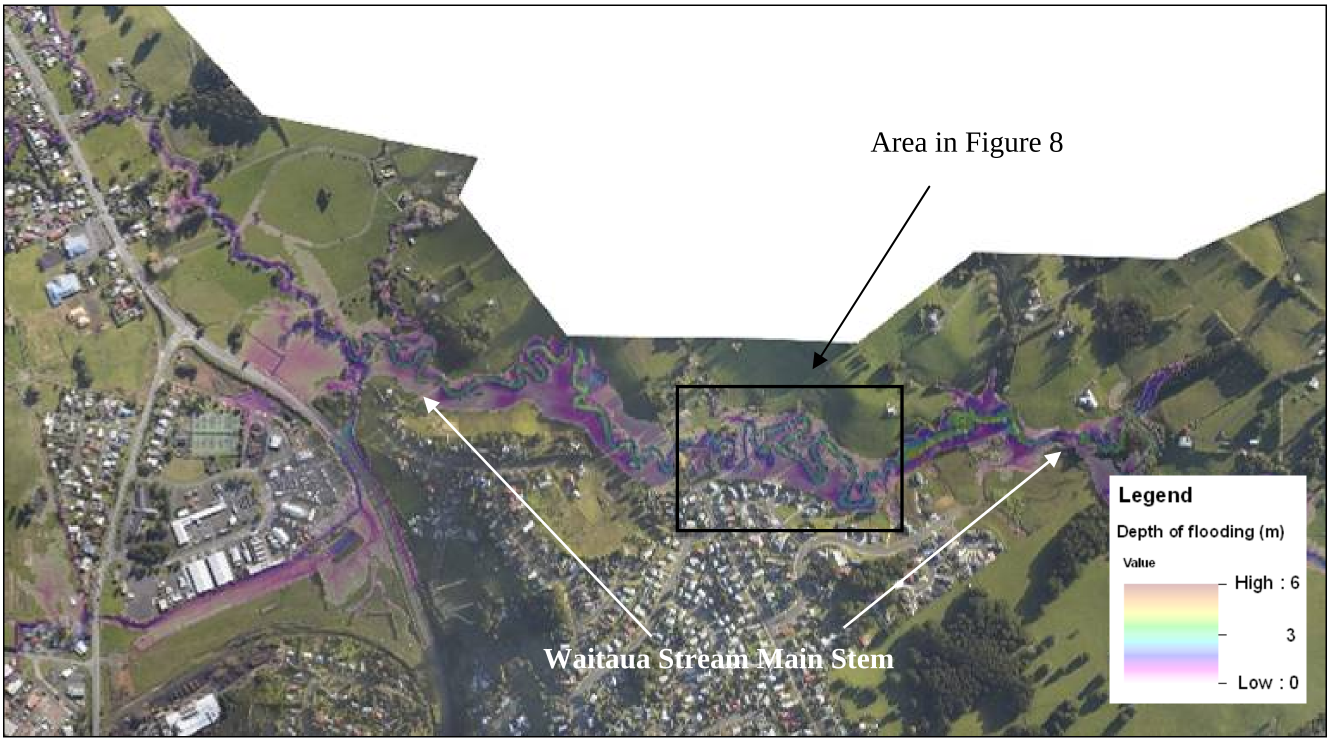


Figure 5: Map with flood extent and flood depth for level of service scenario

Figure 6: Map with flood extent and flood depth for 100 year event (Outline of flood extent for level of service scenario shown in white)

As can be seen the flooding experienced during this event is more extensive than for the level of service (5-year) event. The specific areas affected comprise primarily pastoral land, although areas in the developed industrial and residential areas of the catchment are also affected. The maps will be used to redefine the flood susceptibility layer in the District Plan, which must be considered for any future developments (i.e. it doesn't necessarily mean the areas will be unsuitable for development but measures will be required to mitigate the flooding for anyone wishing to develop in a flood susceptible area).

4 MITIGATION MODELLING

4.1 Mitigation to Achieve Level of Service

In order to achieve the level of service requirement for Waitaua Stream the out of bank flow experienced during the events of 5 year ARI needs to be mitigated. The example project in Figure 5 clearly shows that the main stem of Waitaua Stream does not meet this level of service requirement. Out of bank flow is experienced at several locations along this stream. Therefore formalising an overland flow path in the floodplain of the main stem of Waitaua Stream was considered between Chainage 2981 and 2644 (see Figures 3 and 4). This reach was chosen since it contains numerous meanders and lowering and straightening the floodplain in this section of the stream is expected to lower the flood level significantly. This example demonstrates the effect that may apply to other meandering rivers with a similar configuration.

In order to simulate the effect of a formalised overland flow path with the model setup as described in section 2.1 only the cross sections of the floodplain need to be changed. In this example it is proposed that low flow will continue down its current path and no changes are therefore required to the low flow channel and or lateral structure. Once water levels reach the bank of the low flow channel water will flow into the formalised overland flow path. The dimensions of this overland flow path have been increased until no more flooding was observed in the floodplain. In this example the dimensions of the overland flow path are approximately 20-30 metres wide with a depth varying between 1.2 and 2.5 metres depending on the land surface elevation in the floodplain at each of the cross sections.

4.2 RESULTS

Figure 7 shows the extent and depth of flooding for the level of service event with no flood mitigation in place and Figure 8 shows the extent and depth of flooding for the level of service event with a formalized overland flow path in place.

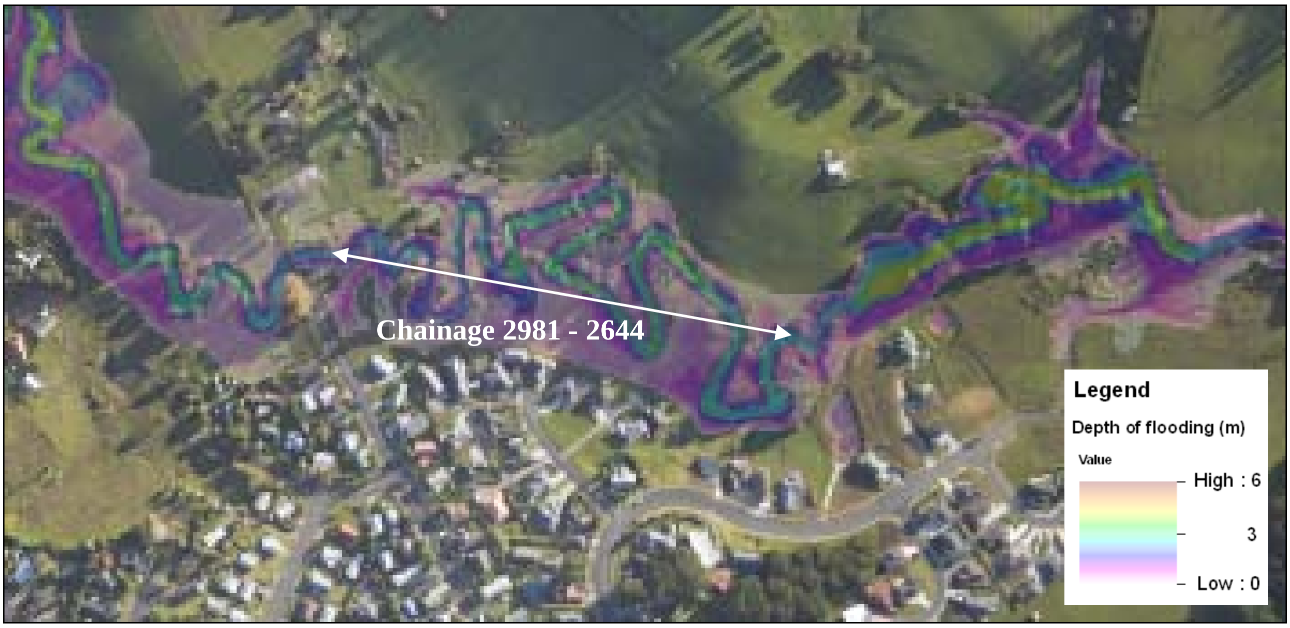


Figure 7: Extent and depth of flooding within Waitaua Stream. 5 year rainfall with climate change and no flood mitigation in place.

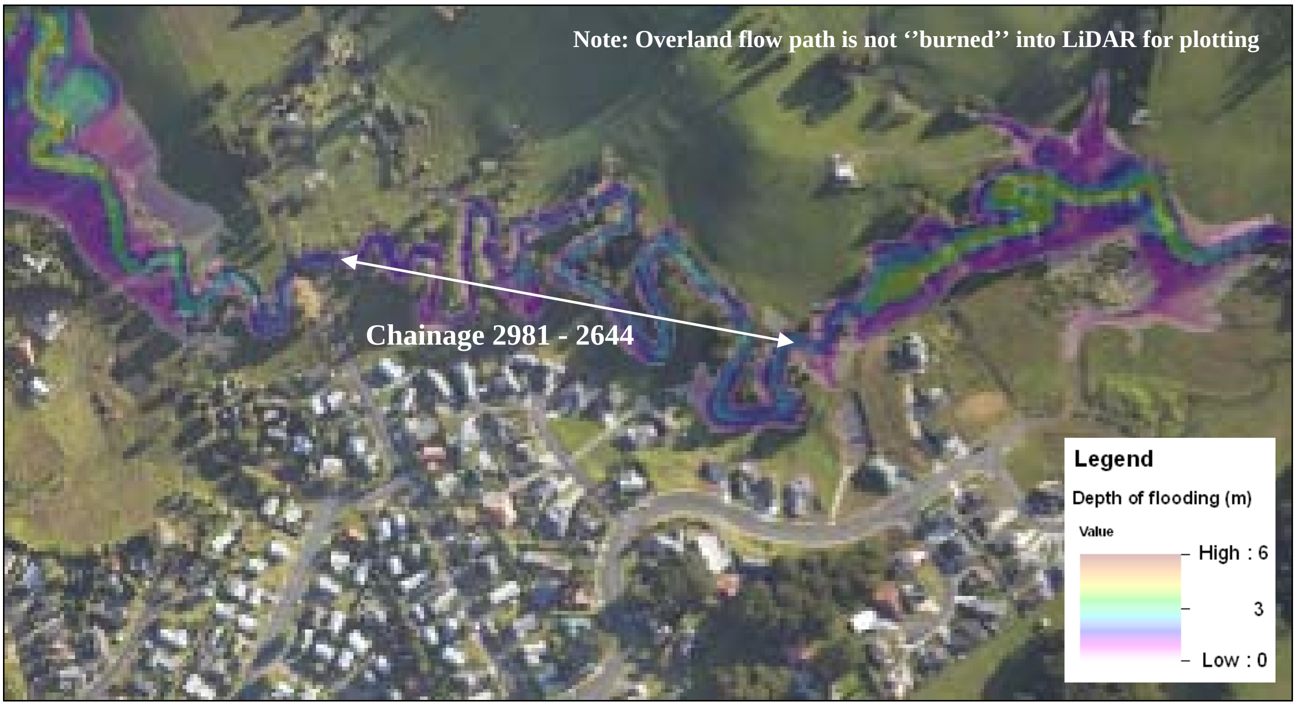


Figure 8: Extent and depth of flooding within Waitaua Stream. 5 year rainfall with climate change and a formalised overland flow path between main stem chainage 2981 and 2644.

As can be seen, formalising an overland flow path will significantly reduce the out of bank flow in this section of the river. Both the extent of flooding and depth of flooding is reduced and most of the flow is contained within the low flow channel and overland flow path.

It has to be noted that Figure 8 does not have the overland flow path burned into the LiDAR. Therefore no water depth is shown for the overland flow path. An alternative approach would be to burn the dimensions of an overland flow path into the LiDAR every time a simulation is run, however this would be very time consuming since several simulation runs are required in order to determine the correct dimensions of the flow path. Simply changing the floodplain cross sections is very quick and easy to do. Not only is the run-time of a 1-D model relatively short it also saves the time of burning the overland flow path into the LiDAR every time the dimensions of the overland flow path change. Should a more detailed floodmap with the water depth in the overland flow path be required one could choose to burn the overland flow path into the LiDAR once the final dimensions of the flow path are known.

5 DISCUSSION AND CONCLUSION

The flood modelling described in this paper provides an example of how the linkage and hydraulic behaviour between a low flow channel and floodplain can be simulated in a 1-D hydraulic model. The advantages and disadvantages of this setup are:

Advantages:

- Quick assessment of mitigation options

  When optimizing the size of an overland flow path the floodplain cross section can easily be changed for every model run. The runtime of a 1-D model is relatively short compared to a 2-D model so modifying the size of an overland flow path will be easy. Only one mitigation option was modelled for the example used in this paper. When multiple mitigation options need to be assessed the benefit of using a 1-D model (over a 2-D model) becomes more evident.

- No need to burn an overland flow path into the LiDAR

  Assessing whether the size of an overland flow path is sufficient to mitigate out of bank flow can be done in HEC-RAS without the need of burning an overland flow path into the LiDAR. The reduction in the extent and depth of flooding as a result of a mitigation option can be assessed by looking at the maximum water depth in the cross sections and/or RAS-Mapper. If required a more detailed floodmap (with an overland flow path burned into the LiDAR) can be produced once the final dimensions are known.

- RAS Mapper

  This relatively new tool in version 4.1 of HEC-RAS makes it quick and easy to produce flood maps with the maximum flood extent and flood depth. Therefore floodmaps for several different design rainfall events are quick and easy to produce.

- Flow Path

  Flow length during low flow and high flow conditions are accurately modelled due to a proper representation of the flow path during low flows and storm flow conditions. This cannot be accurately modelled by using a single channel in the model.

- Volume between cross sections

  HEC-RAS calculates the volume of water between cross-sections based on the downstream length at the center of the cross sections and between each of the banks. By splitting the river corridor into two channels HEC-RAS will calculate the volume of water stored between cross sections correctly for low and high flows. Cross section placement and alignment is fundamental to ensuring correct floodplain volumes are accurately represented in the model. This element of building a 1-D model can be time-consuming.

Disadvantages:

- Time involved with building model

  Building a 1-D model may take quite some time (compared to a 2-D model) and when only a few scenarios need to be assessed (i.e. only a few rainfall event and or mitigation option) it might be quicker (and easier) to setup and run a 2-D model.

- Model instabilities

  Having a lateral structure along the full length of a low flow channel may induce model instabilities (typically weir-oscillations) especially when the lateral structure is relatively flat. This can be prevented by increasing the slope slightly or by increasing the roughness of the lateral weir. One needs to keep in mind though that the lateral structure needs to reflect reality (i.e. realistic slopes) and water levels in the low flow channel and floodplain need to be the same at each overlaying cross-section.

When choosing a modelling package for a flood study it is important to understand the advantages and disadvantages of different hydraulic models. Which model to choose and how to setup a model does not only depend on the physical characteristics of the river but also depends on the type (and number) of scenarios that need to be run.

The 1-D hydraulic model with the setup as described above (i.e. a separate low flow channel and floodplain) is one of the options when modelling meandering rivers. The advantages and disadvantages of this setup are explained above and may assist with choosing a model package and/or discretising the model.

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