Contents

1. Introduction & Motivation

1.1 Overview

The Bin Brook is one of river Cam’s tributaries and is located in the southwest of Cambridge. It extends from the area of Hardwick to the centre of Cambridge where it joins the Cam. In its course, it flows through a number of residential areas, such as properties on Barton Road, the Gough Way estate, Clare Hall College and Robinson College. This can be seen in Figure 1, a map extracted from the Halcrow 2002 Pre-feasibility report that shows the course of Bin Brook.

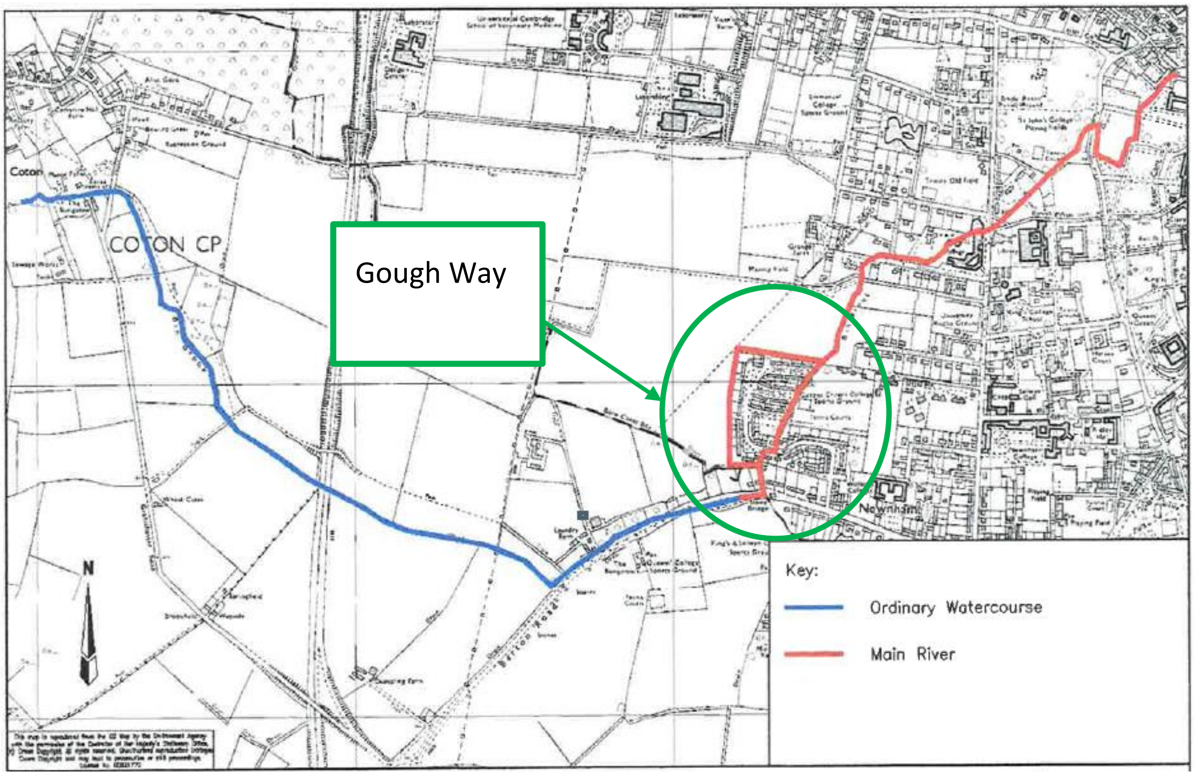

Figure 1 Map of the Bin Brook area

The Gough Way estate was constructed beginning in around 1962, on fields previously owned by Corpus Christi College. At the same time as the estate’s construction, Bin Brook was culverted under part of the estate in order for the main road to go over the brook. After the 1978 flood, when 22 houses were flooded and 9 more were surrounded by water [1], it was observed that the Gough Way culvert had insufficient capacity to pass flood flows. A flood relief by-pass channel was thus built around the estate to increase flow capacity, which provides a standard of protection of around 1 in 40 years, resulting in significant damage occurring only at relatively extreme events. Despite the construction of the relief channel, flooding occurred again in 2001, when approximately 38 properties along the Gough Way road were flooded [2]. Figure 2, below shows photos of floods in the areas of interest.

Figure 2 Flooding of the Bin Brook in the Gough Way area (top left is a photo form the 1978 flood, top right and bottom left are taken during later floods) and Robinson College (bottom right, photo taken in 2012)

The residents in the area have formed the Gough Way Residents Association (GWRA), a group that has been active in promoting a new flood alleviation scheme in the area. Over the years, several reports have been conducted on the flooding of Bin Brook. These focused on finding a new flood alleviation scheme that would increase the current standard of protection. The flood alleviation schemes proposed in these reports included maintaining the existing standard of protection, the creation of flood a flood storage pond, the erection of flood walls and increasing the channel capacity. These options were taken forward for further consideration and the preferred option, resulting from following the guidelines that the

Department for Environment & Rural Affairs (DEFRA) has created, was to maintain the existing level of protection, although that is less than the indicative standard.

1.2 Objectives

The principal purpose of this project is to assess the viability of a new set of proposed alleviation methods. The objectives of the project are summarised as follows:

- Contact the Gough Way Residents Association in order to gain knowledge of the geography of the area and the existing protection system, and discuss ideas for new flood mitigation measures.
- Conduct simple field surveys to become more familiar with the area and its geographical features.
- Study previous reports to obtain an understanding of the flood mechanism and previous attempts to improve the flood protection levels in the Gough Way area
- Construct a model of the system using FLOOD MODELLER (ISIS) and manipulate the model that was obtained from the Environment Agency.
- Calibrate the model to agree with findings of previous reports and the model obtained by the Environment Agency.
- Assess the proposed alleviation options, which include the construction of a new diversion channel and the change in size and material of the Gough Way culvert.
- Recommend one of the assessed schemes as a solution to the problem, and if none of the alleviation schemes examined here prove suitable, propose other solutions.

2. Previous Work

After the 2001 flood, several studies were carried out to investigate potential mitigation measures for the Gough Way area.

2.1 Bin Brook Flood Alleviation Scheme - Pre-Feasibility Report

In 2002, Halcrow conducted a pre-feasibility report for the Environment Agency, whose main aim was the assessment of the flood risk relating to the area of Bin Brook and the viability of alleviation works [2]. A large part of the study focused on the collation of data about the flooding problem. This was done using a variety of methods, outlined below:

- Topographic Survey: A survey of the channel cross-sections and ground levels was carried out, and previous surveys were consulted.
- Questionnaires: Gough Way residents were interviewed and provided a useful insight to the 2001 flood, as they gave details about the flood start time, its finish time and the severity of damages it caused.
- Data from Consultees: As Bin Brook flows through a number of residential areas, several organisations were consulted in order to obtain information. These included the GWRA, Clare Hall, Robinson College and St Johns College.
- Digital Terrain Model (DTM): The DTM developed of the Bin Brook Area provided a flexible means of determining relatively accurate elevations throughout the study area. This was created using LiDAR (Light Detection and Ranging) topographic information, which is a laser technology operated from aircraft that created a 2m grid spacing [2].

The FLOOD MODELLER (ISIS) open channel modelling suite, which is an open channel hydraulic modelling software, was used to develop a hydraulic model of the channel system. A description of the software is given on page 17. This model was developed using the collected data about channel cross-sections and ground elevations, and it represents Bin Brook from the area of Coton to its confluence with the Cam. A hydrological analysis was also conducted, using the Flood Estimation Handbook approach and incorporating both statistical and rainfall/runoff methods.

The hydrological analysis was carried out to provide boundary inflow hydrographs for the hydraulic model. The model was then calibrated against the 2001 flood event. It was found that flooding of the Bin Brook was controlled by key structures along its flow, such as the Barton road and Gough Way culverts and the Robinson College sluice gate. Therefore, the channel roughness was a less significant concern in the model calibration process, with more emphasis given in the model inflows, bypass flow paths around structures and the structure capacities.

Below, the flood alleviation options considered in the study are mentioned:

- Do nothing: Abandon the current flood defences and watercourses, with no further expenditures and work carried out
- Maintain existing: Carry out works and continue expenditure in order to maintain the current standard of flood defence.
- Increase channel capacity: This option considers the increase of the watercourse capacity through Gough Way, which is protected by the combined capacity of the Gough Way culvert and the relief channel. The enlargement of each one is considered in this report, namely widening the relief channel by 50% and replacing the 1.5m culvert with a box section 2.4m by 1.8m. As increasing the culvert size would be more expensive and would have the same result as widening the relief channel, only the latter option was considered further.
- Flood storage: An upstream storage area, adjacent to the M11 motorway, as shown in Figure 4 was considered.

The above options were taken to economic appraisal following the DEFRA Flood and Coastal Defence Project Appraisal Guidance document for Economic Appraisal [2]. An environmental assessment of the options was also carried out, in order to identify the impact of each on the environment and incorporate any constraints in their implementation.

The report concludes that the current standard of protection of the Gough Way ranges from 1 in 10 years to 1 in 40 years, which is below the indicative standards for dense urban areas (1 in 50 to 1 in 200 years). With the predicted climate change, the current standards are expected to fall below 1 in 20 years by 2050. As far as the alleviation options are considered, they were identified as technically and environmentally possible.

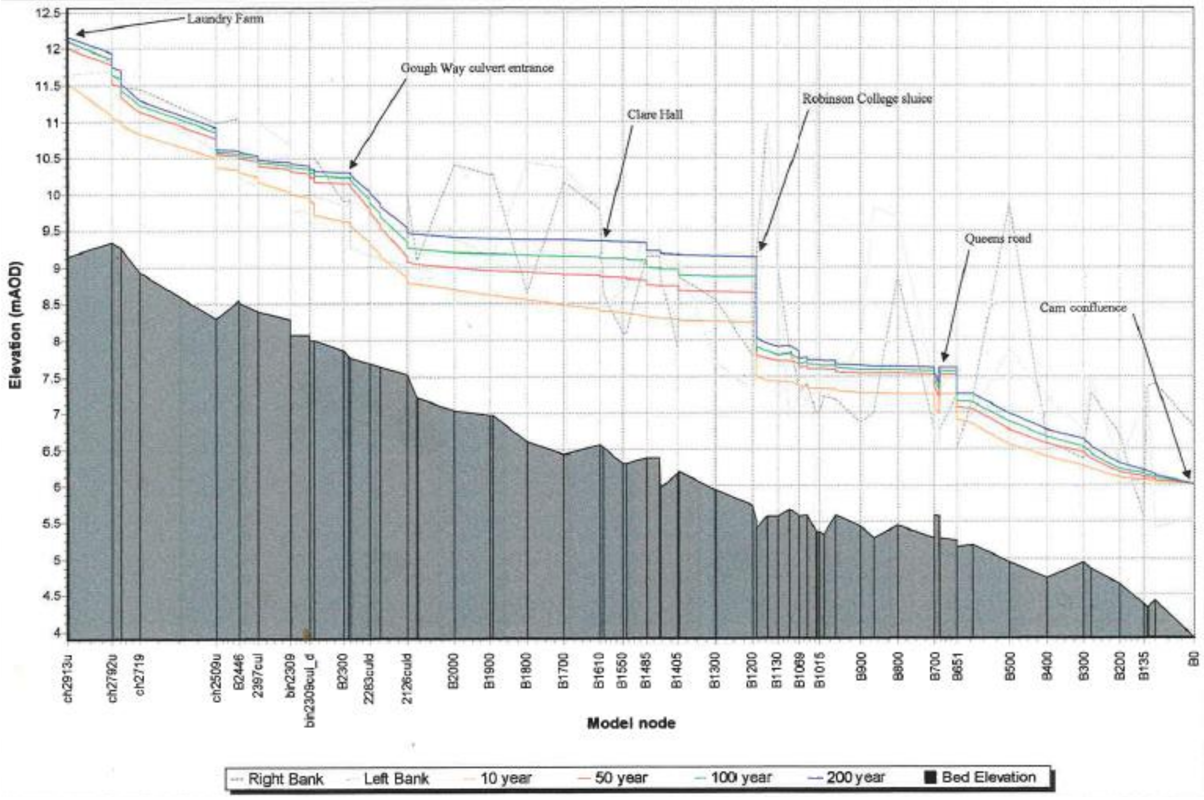

Figure 3 Flood flow level along Bin Brook for different intensity events, from a study conducted in 2002

The results of the models that were created for this study can be seen in Figure 3, which shows the flood flow levels along Bin Brook for four different flooding events (1 in 10, 1 in 50, 1 in 100 and 1 in 200 years return periods). Also on the figure some of the Bin Brook features are highlighted, such as the Robinson College sluice gate, where large head loss of more than a meter can be observed.

The option nearest to fulfilling the desired 1 in 50 year protection at a considerable cost was the enlargement of the relief channel. Under the DEFRA guidelines, none of the options that were considered were eligible for grant aid, as they did not meet the economic criteria, and none of the options was recommended for a detailed appraisal study [2].

2.2 Bin Brook Flood Alleviation Scheme – Project Appraisal Report

The key objective of this report was to confirm that it is viable to continue maintenance of the current protection system and that it is not viable to alleviate flooding problems in the Gough Way area [3]. Several flood alleviation options were again considered, and can be summarised as follows:

- Do nothing: Stop maintenance of channels and culverts, thus reducing the current standard of protection
- Maintain existing: Carry out works to maintain the current level of protection, less than the recommended standard
- Flood storage: Different types of flood storage, providing levels of protection from 1 in 50 years to 1 in 100 years, including a proposal that combined that with the placement of flood walls along Bin Brook at Gough Way. The proposed flood storage area can be seen in Figure 4, below.

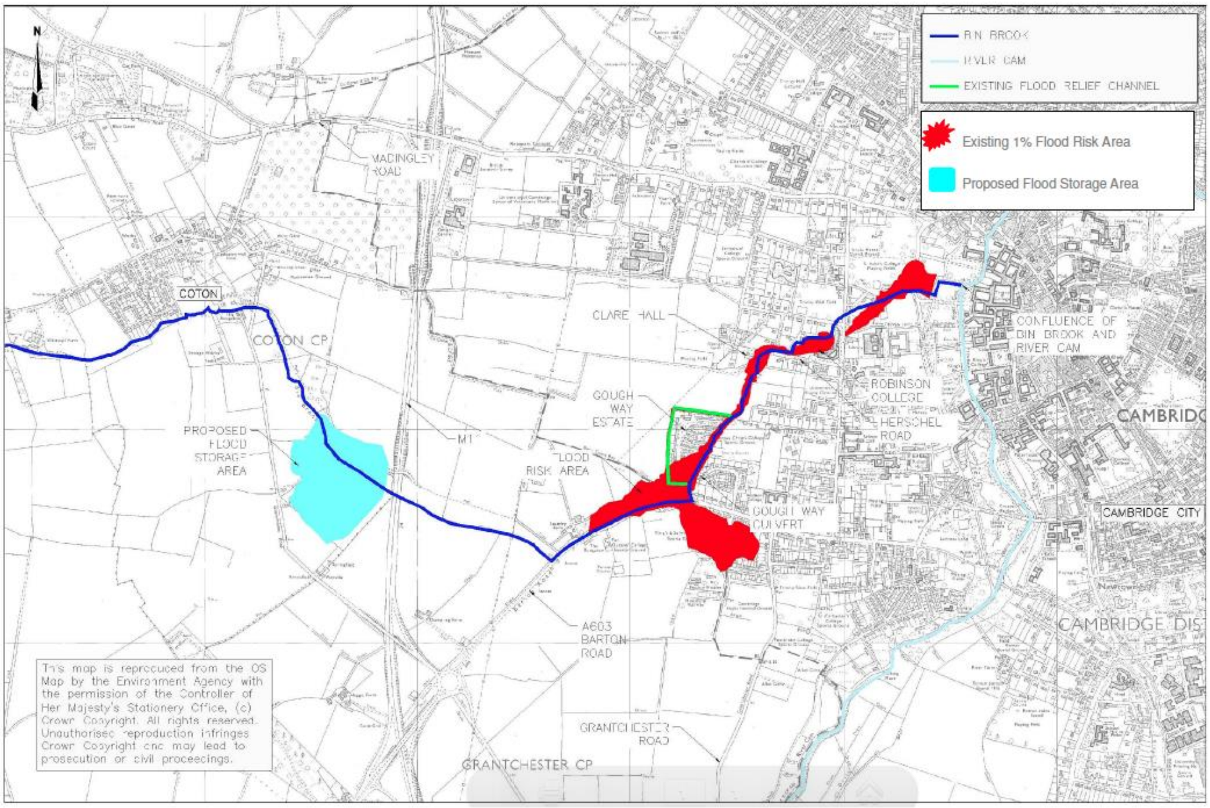

Figure 4 Map of Bin Brook showing the proposed location for a flood storage pond and the high flood risk area

After carrying out economic and environmental analyses of the above options, the preferred option was chosen to be to maintain the existing level of protection, which is less than the indicative standard. Creating a flood storage area, would have been the preferred option for increasing the protection, but it cannot be justified under the DEFRA Decision Rules because the incremental benefit cost ratio above the maintain option is less than unity [3].

Figure 4, above, shows a map of the west Cambridge area, where Bin Brook flows. The map indicates the proposed flood storage location, adjacent to the M11 motorway. It also indicates the high flood risks zones on Bin Brook. These are on the main part of the brook (Figure 1) and have a 1% flood risk.

2.3 Bin Brook Hydraulic Model QA Report

The aim of this report was to link the one dimensional flow model with the two dimensional model of the flood and create a combined model that would better represent flooding events. This was done using the one-dimensional and two-dimensional tools that the ISIS software suite contains. In the report, details about the structures on the watercourse are given, which are of particular importance for the model's accuracy. [4]

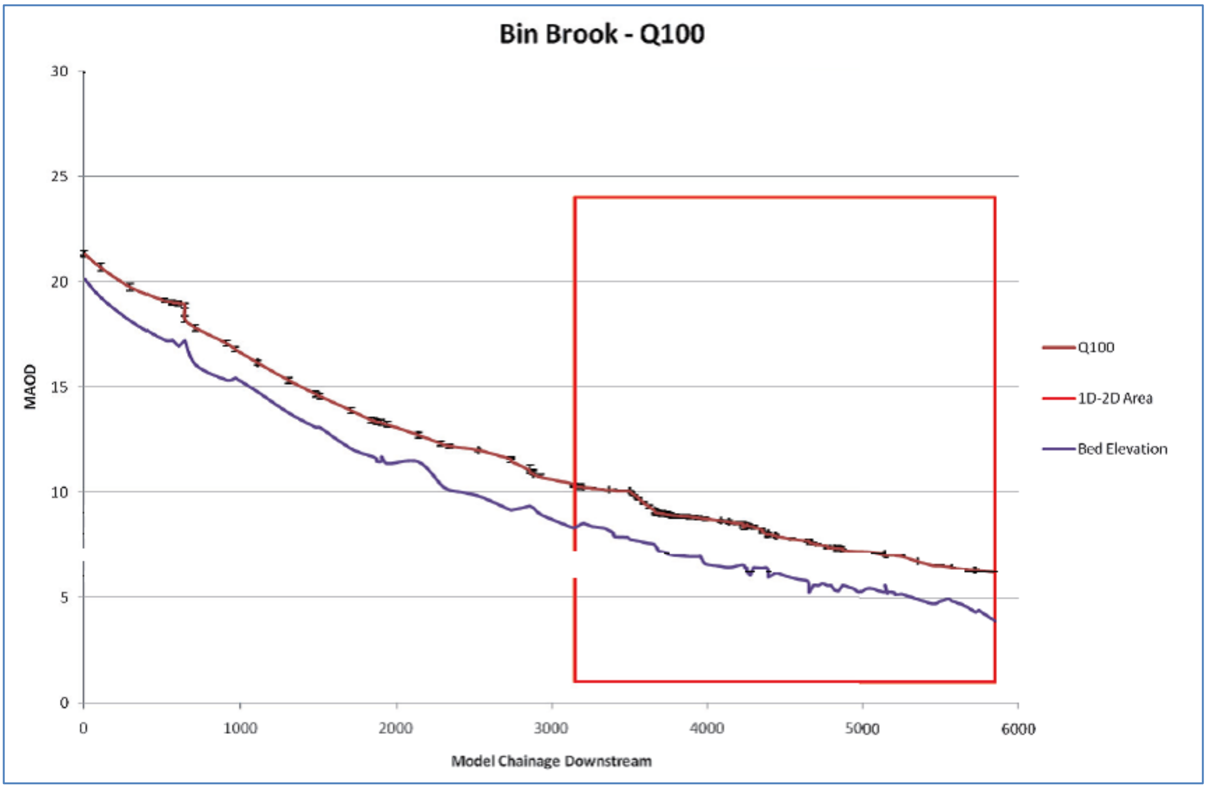

Figure 5 Flood level along Bin Brook for a 1 in 100 year event in 2007. The red box signifies the area where 1D and 2D models were combined

Revised flood flow levels were calculated, now using the combination of 1D and 2D modelling. In Figure 5, above, the results for a 1 in 100 year flood can be seen. The red box signifies the area where 2D modelling was used, and is the area downstream of Barton Road. One thing that can be noticed is the absence of the head drop at the Robinson College sluice gate. This is because the college now uses a different mechanism to flood the water feature its gardens contain, and thus the sluice gate remains open at all times.

The effect of Manning's roughness was also assessed in this report, as it can be seen in Figure 6. The flow seems to vary very little with the change in Manning's roughness, suggesting, as above (2.1 Bin Brook Flood Alleviation Scheme - Pre-Feasibility Report), that the most important factor determining the flow is the presence of hydraulic structures rather than the channel roughness.

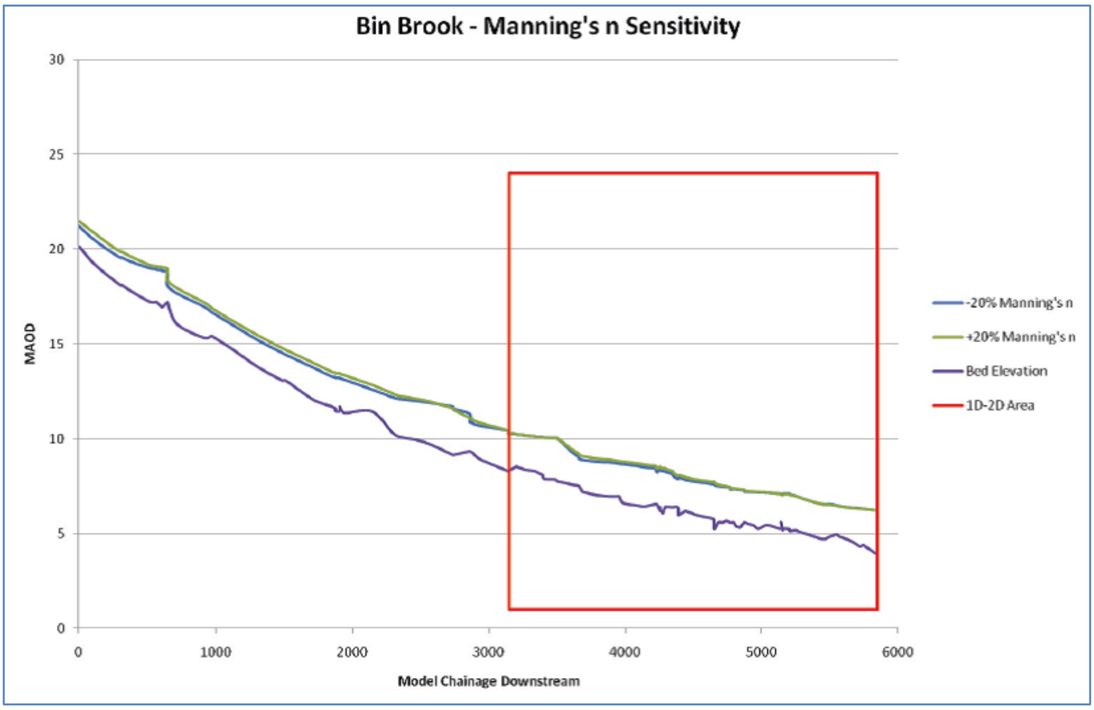

Figure 6 Effect of change in Manning's roughness coefficient on flood levels along Bin Brook

3. Computational Methods

3.1 Open Channel Flow

Open channel flow is characterised by the existence of a free surface, where the pressure is atmospheric, and across which, the shear forces are negligible. The profile of the free surface determines the hydraulic gradient and the cross-sectional area of the flow, thus introducing a new variable [5]. Below, the types of flow are explained:

3.1.1 Steady Uniform Flow

This type of flow is defined as having constant depth, both with time and distance. Steady uniform flow is a fundamental flow type that is considered in open channel flow, in which the gravity forces are in equilibrium with the resistance forces [5].

There are two most commonly used equations in uniform flow.

- Firstly the Manning's equation, which is derived by balancing the gravitational and boundary shear forces, and can be used to determine steady uniform flow and evaluate the normal depth of flow

  $$Q = \frac{1}{n}\frac{A^{5/3}}{P^{2/3}}S_0^{1/2}$$

  Where, Q is the flow (m^3/s), n is Manning's roughness coefficient, A is the cross-sectional area of flow (m^2), P is the wetted perimeter (m), and S_0 is the bed slope
- Chézy equation:

  $$V = C\sqrt{RS_0}$$

  Where, R is the hydraulic radius, defined as R=A/P and C is the Chézy coefficient
- Chézy coefficient is defined as:

  $$C = R^{1/6}/n$$

3.1.2 Steady Non-uniform Flow

This type of flow can either be gradually varied or rapidly varied.

3.1.2.1 Rapidly varied flow

Rapidly varied flow occurs whenever there is a sudden change in the channel geometry or the flow regime, such as flow over sharp-crested weirs, or when hydraulic jumps occur (where flow with high velocity and small depth is rapidly changed into flow with low velocity and large depth). As the change in the flow profile is rapid, assumptions of parallel streamlines and hydrostatic pressures do not apply. Thus, energy and momentum concepts are applied, which are of sufficient accuracy. More accurate solutions can be found using ideal fluid flow concepts in association with finite element techniques [5].

- **Specific Energy:**

  Specific energy (E_s) is defined as the energy of the flow referred to the channel bed as datum.

  $$E_s = h + \frac{\alpha u^2}{2g}$$

  Where, h is the distance between the streamline and the channel bed and u is the velocity of the flow. For steady flow, u=Q/A, hence the above equation can be rearranged and a cubic equation can be derived,

  $$h^3 - E_s h^2 + \frac{\alpha q^2}{2g} = 0$$

  Where q is the flow per unit width. The above equation has 2 real roots and one imaginary, implying that for given values of E and q, two depths of flows are possible. This can be seen in the graph in Figure 7. The correct depth is dependent on the flow regime.

- **Froude number:**

  The Froude Number (Fr) is the ratio of inertial forces to gravitational forces and can be expressed as

  $$Fr = u/\sqrt{gD_m}$$

  Where D_m is the hydraulic mean depth of the open channel flow. For critical flow, Fr=1, for sub-critical flow, Fr<1 and for super-critical flow Fr>1. For a sub-critical flow, the water velocity is less than the wave velocity ($c = \sqrt{(gh)}$), which implies that any disturbances travel both upstream and downstream, hence upstream water levels are affected by a downstream control. For a super-critical flow, the water velocity is greater than the wave velocity, implying that disturbances travel downstream, so upstream water levels are unaffected by a downstream control [6].

- **Momentum Principles:**

  Conservation of momentum is used in cases where energy conservation is difficult to measure, such as in the case of hydraulic jumps. Here, a large amount of energy is lost in the turbulence of the jump, while momentum is still conserved since it is only affected through external forces

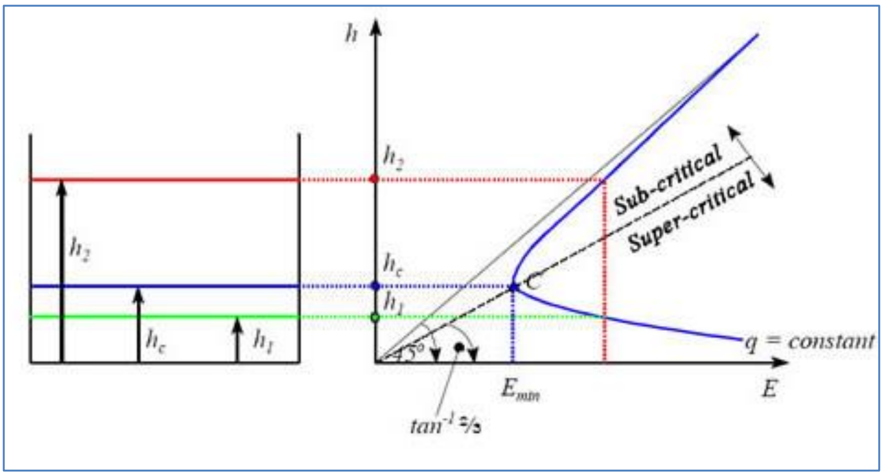

Figure 7 Graph of depth against Specific Energy

3.1.2.2 Gradually varied flow

Gradually varied flow is defined as steady flow in a channel where there are gradual changes in the water depth. For rapidly varied flow, the influence that the bed slope and channel friction have can be ignored as changes take place over a small distance. In gradually varied flow, these influences become very important because they determine the flow regime [5]. The governing equation for a gradually varying flow is:

$$\frac{dh}{dx} = \frac{S_0 - S_f}{1 - Fr^2}$$

Where S_f represents the friction slope. The above equation can be solved in three ways, using direct integration, graphical integration and numerical integration. The first two methods were quite popular before the widespread use of computers, so only the numerical method is discussed further here.

The ways of implementing numerical integration are listed below:

- The direct method, a simple method applicable to prismatic channels, where the gradually varied flow equation is rewritten in finite difference form and mean values for slope friction are obtained.
- The standard step method is applicable to non-prismatic channels and can therefore be used in natural rivers. Station positions are predetermined and objective is to calculate the surface elevations, and hence depths, at the stations, employing a trial and error method [7]

3.1.3 Unsteady Flow

Unsteady flow is defined as the flow in which depth varies both with time and distance. Examples of unsteady flow are river floods, estuarial flows and surges resulting from gate operation or dam failure [7]. For unsteady flow situations, it is no longer possible to represent the flow simply by stating a single value for the discharge. An inflow hydrograph must be used. The outflow hydrograph depends in the inflow hydrographs, the channel characteristics, such as the storage and hydraulics, and the initial conditions of the reach.

Saint-Venant first published the equations that govern one-dimensional unsteady flow. These are the continuity and dynamic partial differential equations seen below:

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = 0$$

$$\frac{\partial y}{\partial x} + \frac{V}{g}\frac{\partial V}{\partial x} + \frac{1}{g}\frac{\partial V}{\partial t} = S_0 - S_f$$

Where Q is the discharge at section located at x, with cross-sectional area A at time t, y is the depth at position x and time t, and V=Q/A. S_0 and S_f are the bed slope and energy gradient respectively as previously [7].

The above equations cannot be solved analytically, so they have to be evaluated at discrete space and time intervals using numerical methods, such as finite-difference methods.

3.2 River Modelling

River modelling involves the interaction between the channel, the external controls (e.g. boundary conditions) and internal controls (e.g. hydraulic structures). The governing equations for each of the above are combined. Inevitably, these can be both empirical and theoretical, and in most cases they are non-linear. To be solved, the equations are first linearised, and the solution to the linear problem is found using matrix inversion. Iterative procedures are then used to account for the original problem's non-linearities.

3.2.1 Governing equations

3.2.1.1 Saint-Venant Equations

The motion of the water in an open channel is described by the Saint-Venant equations discussed above that express mass and momentum conservation. These two equations establish a balance between the rate of rise of water level and the water storage, and a balance between the inertia, diffusion, gravity and friction forces.

3.2.1.2 Hydraulic Structures

In a one-dimensional network representation of a river, reaches are separated by control structures, which impose boundary conditions and relationships between the stages and discharges at the adjacent sections. The general form of the equation that relates the two is shown below:

$$Q = ah^b$$

Where h is the water depth, *a* is a coefficient that depends on the structure and b is a coefficient that depends on the flow (it is usually greater than or equal to 1.5 for weir type flows and greater than or equal to 0.5 for free flow under a sluice gate). The above equation is a semi-empirical relationship and might require calibration [6].

3.2.1.3 Conveyance

Channel conveyance is a quantitative measure of the discharge capacity of a watercourse [8] and is defined as

$$K = \frac{Q}{S_f^{1/2}}$$

Where K (m^3/s) is the conveyance Q is the flow discharge (m^3/s) and S_f is the friction slope. To calculate the conveyance at a given water level, the cross-section is split into a set of vertical panels and summing the contribution of each panel.

3.2.2 Numerical Solution

Since the Saint-Venant equations cannot be solved analytically, numerical solutions are implemented. The most popular numerical scheme, which has become the accepted standard, is the Preissmann implicit finite difference scheme, also called the 4-point Box scheme [6].

3.3 FLOOD MODELLER (ISIS)

The FLOOD MODELLER (previously ISIS) suite is a widely used simulator for modelling flows and levels in open channels. It has the ability to model a wide range of hydraulic structures, such as bridges, sluice gates, culverts and others. Standard equations are incorporated into the system wherever possible to calculate the level and discharge relationships. The suite consists of a number of tools, each designed for a specific purpose. The 1-D tool is aimed at modelling channel flow and the 2-D tool is a shallow water flow model which is designed to model flows in floodplain environments. The two models can be linked dynamically using the TUFLOW tool of the suite.

The tool that was used throughout this project was the free version of the FLOOD MODELLER, called FLOOR MODELLER FREE. This is a fully functional suite that is limited to 250 1D nodes. Thus all models used in the process were limited to the set above number of nodes. FLOOD MODELLER FREE has the capability to inspect larger models, but cannot perform any runs. It also cannot combine 1D and 2D models, as the TUFLOW tool is not included.

4. Model Verification

During Michaelmas term, time was spent getting familiar with the FLOOD MODELLER interface. Trial networks were created to check the functionality of the suite and simple models of the Gough Way area were constructed in the end.

In that time, the Environment Agency was contacted in order to obtain the full Bin Brook models that were created for the previous studies of the area and contained accurate cross-section data and elevations. At the end of the term, the models were obtained, and work focused on manipulating these models.

4.1 The Environment Agency Model

The model that was obtained from the Environment Agency was the most up-to-date model of the Bin Brook network, last edited in 2007. It combined both one dimensional and two dimensional components using the tools described above. The model consisted of approximately 500 nodes, meaning that it could not be analysed unaltered by the free version of the modelling suite. A visual representation of the model can be seen in Figure 8, below.

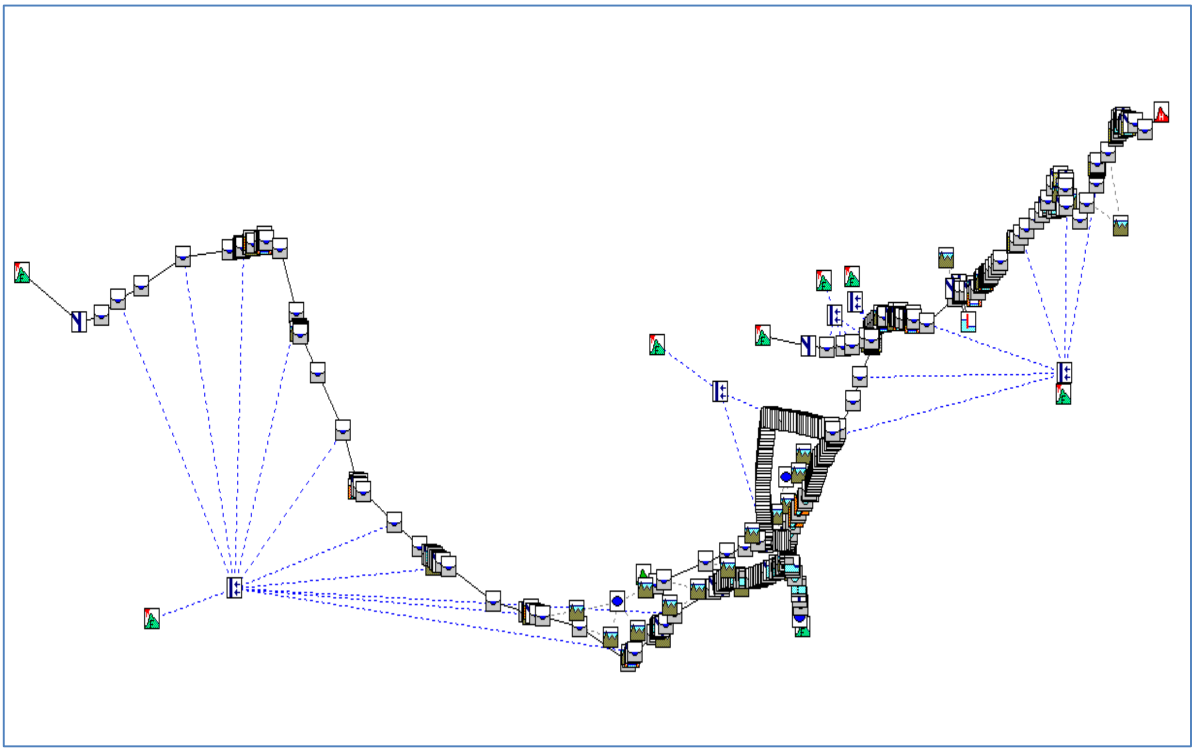

Figure 8 The Environment Agency Model

4.1.1 Features of the model

The Brook is modelled from the village of Coton to its confluence with the river Cam. Through its course, which can be seen in Figure 1, there are a number of structures that determine the flow and play important roles in the way flooding is caused. These structures were discussed in the reports carried out for previous alleviation schemes of the Bin Brook. The structures of importance to the area of interest lie in the main part of the brook (red part of the river as seen in Figure 1). Brief descriptions are given below.

- The Gough Way culvert is one of the key structures in the course of Bin Brook. It is a 200m long, 1.55m diameter circular culvert [3], with the capacity to pass up to approximately 2.3m^3/s of flow [2]. Additional flows pass down the diversion channel. A photo of the Gough Way culvert entrance and the diversion channel can be seen in the bottom left photo of Figure 2. However, once flows reach a certain level, they pass into Gough Way through the back gardens and down the footpath [2].
- The relief channel is a part natural, part concrete prismatic channel that runs around the southern, western and northern boundaries of the Gough Way estate. It was built after the 1978 flood which was calculated to being a 1 in 130 year event [1] and provides protection of approximately 1 in 40 years. A photo of the relief channel can be seen in Appendix ii.
- The Robinson College sluice gate is another structure that can determine the flow. When the college was first built, the sluice gate was constructed in order to create a water feature (pond) in the college gardens. The sluice gate thus remained closed in order for the pond to remain stable. In the 2000's, a request was made to the college to open the sluice gate and a new mechanism was implemented for the pond. The sluice gate now remains open at all times. The effect that the sluice gate has on upstream water levels can be noticed in Figure 3, above. Photos of the sluice gate can be seen in Appendix ii.
- The Barton Road culverts are two culverts that were constructed during the enlargement of Barton Road. They have diameters of approximately 1.5m and are located at the position where Bin Brook becomes a main river. Peak flood flows through the culverts are limited to approximately 3.8m^3/s. Therefore, significant flows

will bypass them through the filed towards the diversion channel [2], which is lower than the other bank.

4.1.2 Model Inputs

4.1.2.1 Inflows

As it can be seen in Figure 8, the model contains 7 inflows, represented by FEH (Flood Estimation Handbook) Rainfall Runoff Method Boundaries. The FEH boundary derives an inflow hydrograph from a catchment, which then becomes a boundary condition for the system. For each inflow, the catchment details have to be specified, as well as the event data for runoff (e.g. storm duration and area) and rainfall (e.g. rainfall return period). The software then calculates the hydrograph based on the information provided. An example of the calculated hydrograph can be seen below, in Figure 9.

The upper part of the diagram shows the rainfall profile (dark blue blocks represent the total rainfall and light blue the net rainfall, after infiltration is removed), while the lower contains the unit hydrograph (purple line) and the calculated hydrograph (red line), which acts as the network boundary. From this graph, the peak inflow can also be found.

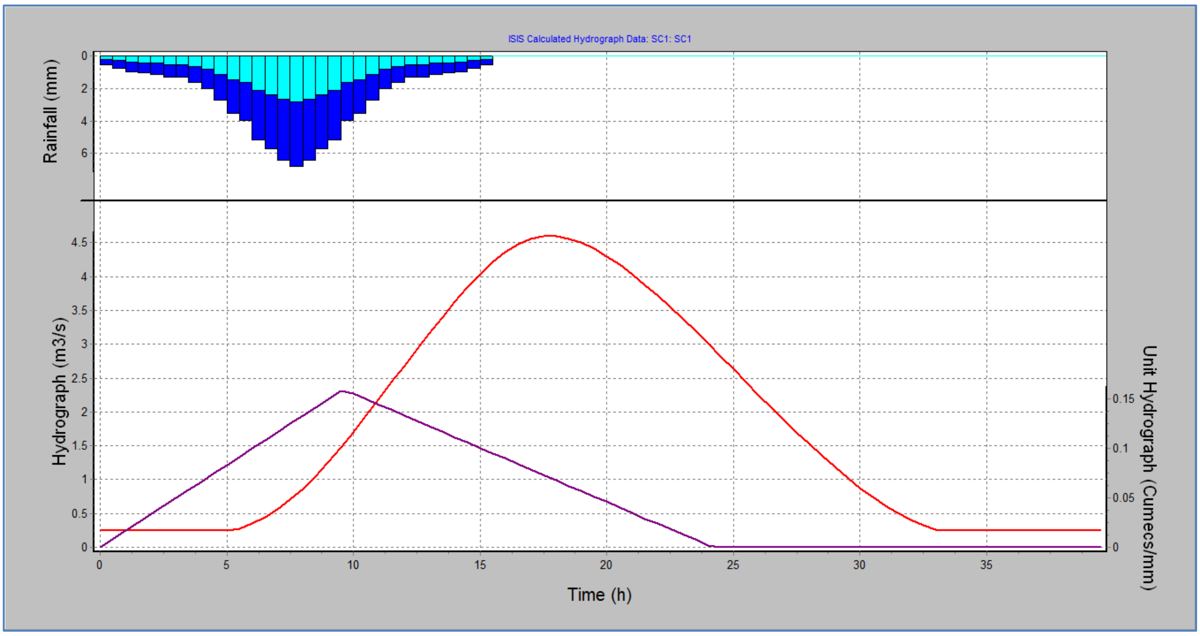

Figure 9 Calculated hydrograph from model inflow

4.1.2.2 Channel Sections

Detailed channel sections have been incorporated in the Environment Agency model of the Bin Brook network. This was achieved using the surveying techniques discussed above (2.1 Bin Brook Flood Alleviation Scheme - Pre-Feasibility Report). A typical river section can be seen below, in Figure 10. As it can be seen, some distance away from the channel has also been modelled, in order to account for the overflow.

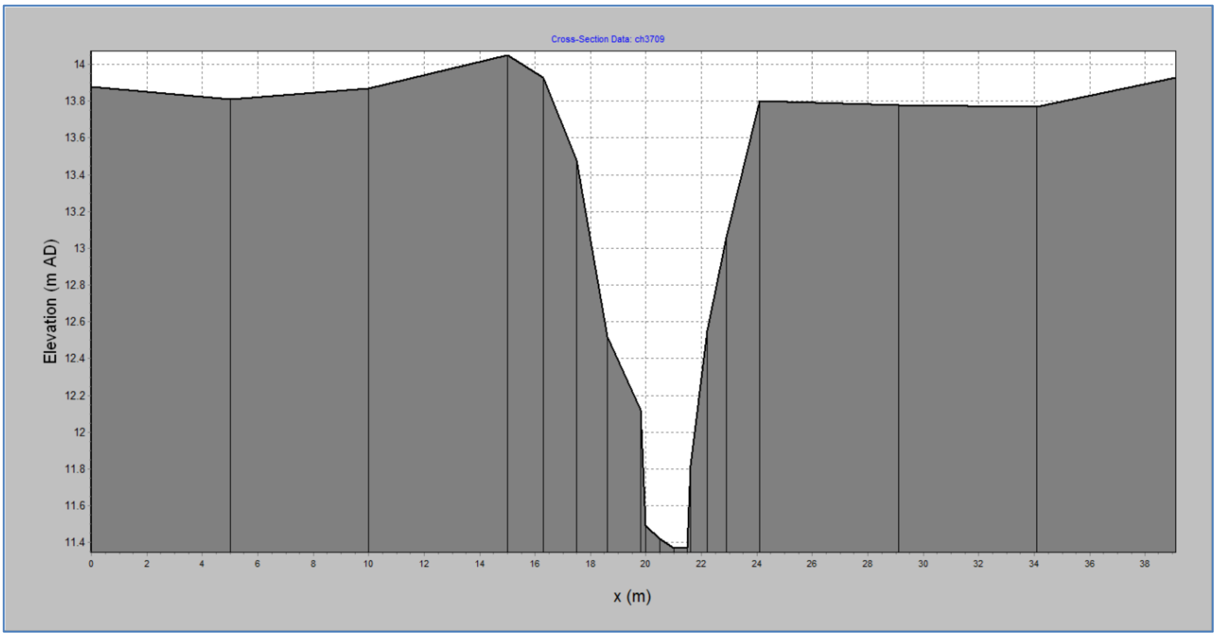

Figure 10 Typical channel section of the Environment Agency Model

In many cases, interpolation sections have been used. These sections add a higher degree of accuracy and are used when there are no changes in the channel section for long distances.

Junctions are a very important part of the model as it is quite complex. Junctions are applied at the divisions and the confluences of the channels. The equations used are flow continuity (Kirchhoff's Law, $Q_1+Q_2+Q_3+\ldots+0$) and equality of water surface level ($h_1=h_2=h_3=\ldots$).

4.1.2.3 Hydraulic Structures

Various hydraulic structures are used in the model, including culverts, bridges and sluice gates.

- Bridges: There are a total of 22 bridge structures in the model. For each bridge, details about its shape were input to the software, including the positions of any openings.

- Culverts: There are 8 culverts in the model. For each one, the inlet type has to be specified (for example whether the entrance is unsubmerged or submerged) in order for the correct loss coefficients to be applied. The culvert dimensions also have to be inserted, including the length and the shape. In the case of the Environment Agency model, all culverts are circular. Any bends in the culvert also have to be taken into consideration, and the appropriate manning coefficient has to be included in the calculation.
- Weir: A sharp crested weir is incorporated into the model close to the confluence of Bin Brook with the river Cam. The geometry of the weir was input into the software as well as the relative bed elevations before and after the weir.
- Sluice gate: The Robinson College sluice gate is modelled as a vertical sluice gate that is always kept open with an opening of 0.5m.

4.1.2.4 Spills

The spill unit calculated the flow over an irregular weir. Spill units are used in cases such as flows through hydraulic structures, where lateral flows might occur. They are also connected to reservoir units, which ensure conservation of mass so that spills can be accounted for and can drain back, once the flood subsides.

4.1.2.5 Outflow

A Stage Time Boundary is modelling the outflow of the Environment Agency Model, which represents the confluence of the Bin Brook and the river Cam. This was chosen to be the model outflow boundary as the water level of the Cam does not depend heavily on the Bin Brook flood levels. The Stage Time Boundary allows the water level to be specified at the outflow of a network. In the case of the model outflow, this is kept at a constant depth of 2.12m from the channel bed.

4.2 The simplified Model

Time was invested in simplifying the original Environment Agency model, in order to perform runs and make the appropriate tests and changes to the network. The original model had to be reduced to 250 nodes, while still providing the correct results that would correlate well with the results of the original model. The nodes that were deleted were chosen to be nodes that were outside of the area of interest, and that would only have minor effects in the model accuracy. The method used to do that was:

- Remove repeated sections and increase the distance between sections while maintaining approximately equal distances between nodes. If more nodes need to be removed,
- Remove some interpolation nodes as those are only used to increase the accuracy of the model. If more nodes need to be removed,
- Remove hydraulic structures such as bridges that were outside of the Gough Way area. In case there are still more than 250 nodes in the network,
- Remove parts of the network that have minor effects on the water levels within the area of interest.

Below, in Figure 11, the simplified version of the Environment Agency model can be seen.

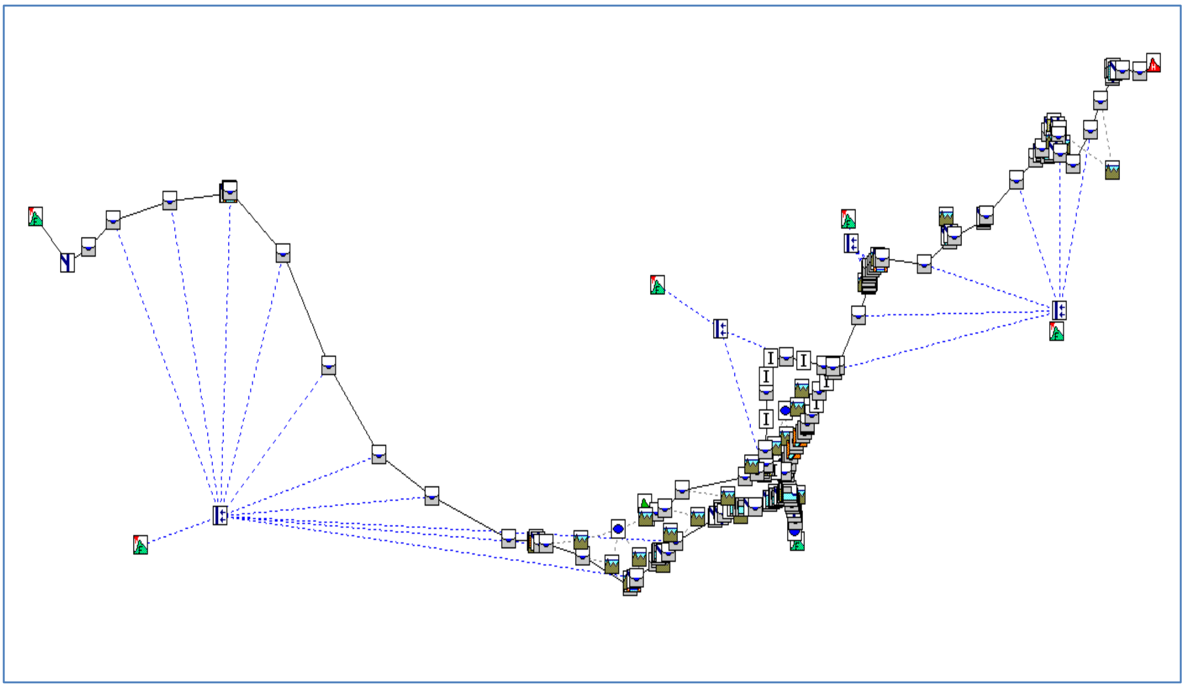

Figure 11 The Simplified Model

The peak flows of the seven model inflows can be seen in Table 1, on page 24. The inflows labelled CH_ditch_us and CH_ditch_lat, were decided to be removed, as their contribution to the network water levels was thought to be negligible. This decision was also reinforced by the fact that the two inflows that were removed were situated downstream of Gough Way estate, which is the area of interest in this study.

INFLOW NAME	SC1	SC2	SC3	SC4	SC5	CH_BB_LAT	CH_ditch_us	CH_ditch_lat
PEAK FLOW (m^3/s)	4.5	4.5	0.8	1.1	2.75	0.09	0.016	0.007

Table 1 Peak flows of Environment Agency model inflows

The output of the simplified model can be seen in Appendix ii.

4.3 Verification of the simplified model

The simplified model was verified against the results from the previous studies and the model obtained from the Environment Agency. The time of peak flow was chosen to verify the model.

The shape of the water level along the long section of the river was compared against the Halcrow Report (2002) and the JBA Report (2007). As predicted, since the Robinson sluice gate is remained open at all times, the steep fall seen in Figure 3, does not ex ist in Figure 5 and the output of the simplified model. The shape of the last two seems to correlate well, although only approximate measurements can be carried out for this observation.

As FLOOD MODELLER FREE could not run the original model, that was sent to CH2MHILL where it was ran and the results were sent back. The results were then input back into the original model. These could only be viewed and not manipulated in any way as FLOOD MODELLER FREE would not allow for this action. The model verification was made by overlaying the two model results as seen in Figure 12. The Gough Way area extends form approximately the 2500m mark to the 3250m mark, and a closer view of it can be seen in Appendix ii.

The water levels at the cross-sections in the Gough Way area were compared and it was found that the two models correlated quite well, with most cross-sections varying approximately 0.05m of depth. As it can be seen in, the area downstream of the Gough Way estate does not correlate very well, with differences in depth reaching up to 0.5m. This is expected as many structures were removed from that area. As these points were outside of the area of interest, the model was accepted for its close correlation to the original.

It should be noted that the due to the removal of some downstream structures, the water level in the Gough Way area resulting from the simplified model is consistently less than the original.

The result of the verification was deemed sufficient for the consequent study, which focused on the initial evaluation of new alleviation schemes for the area. For more detailed studies, the simplified model would not be an accurate model of the brook as more detail is important.

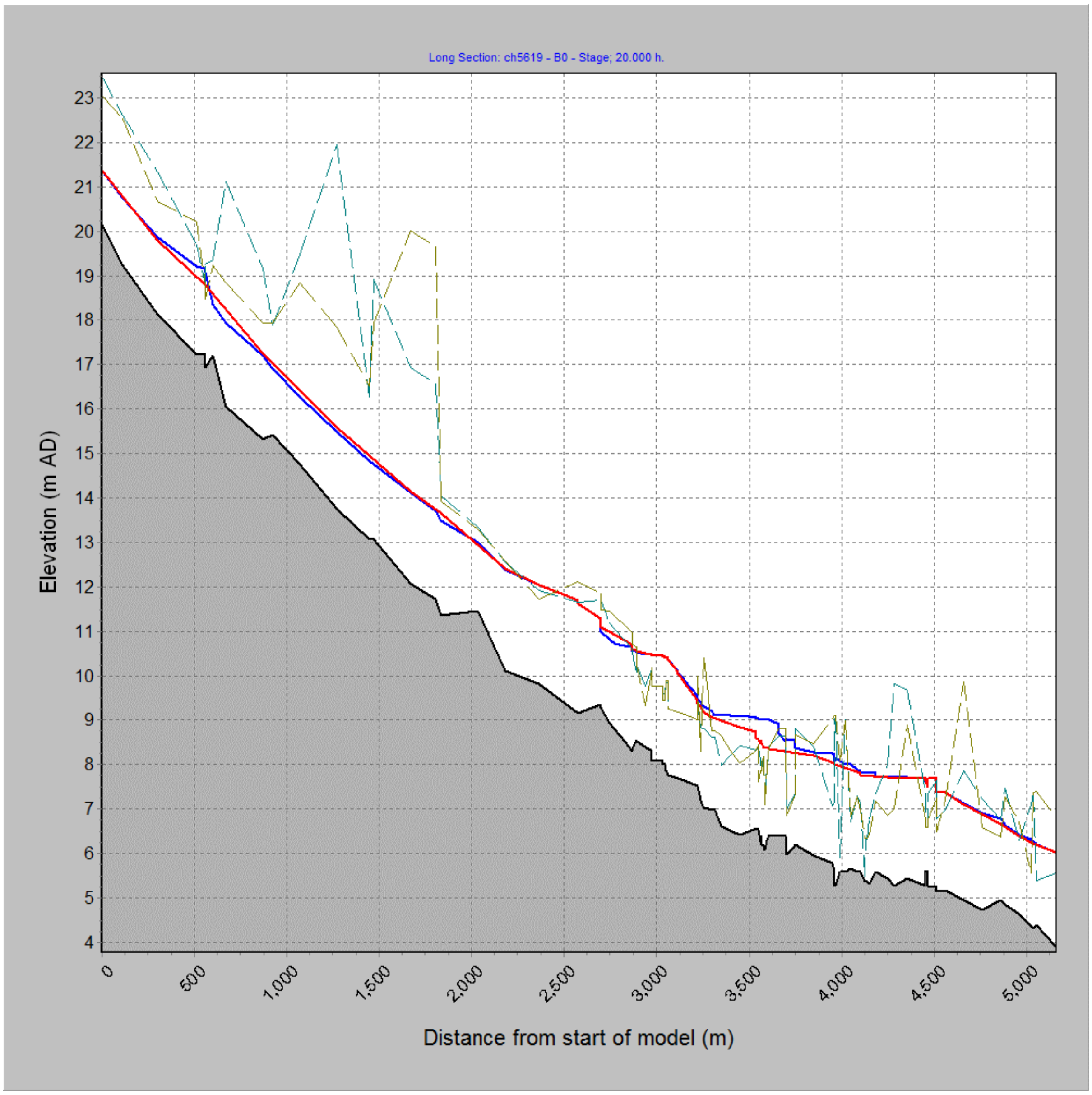

Figure 12 Comparison between the Environment Agency model (blue line) and the simplified model (red line)

5. Assessment of Mitigation Measures

As mentioned above, two main scenarios were assessed during the project. These were the construction of a new diversion channel and the change of size and material of the Gough Way culvert. Below, the two scenarios are discussed in more detail and the findings of their assessment are presented.

5.1 New Diversion Channel

5.1.1 Overview

This proposal suggests the creation of a new diversion channel upstream of the Gough Way culvert. A schematic representation of the proposed channel can be seen in Figure 13. The flow is to be diverted before the inlet of the first Barton Road culvert. The water would then be passed across the paddock with the creation of a new channel and via the existing drain, to the existing relief channel at its south-western corner. Some of the issues that have to be considered in this proposal are:

- The existing drain would have to be modified (widened or deepened) in order to accommodate the increase in water flow.
- Another culvert would have to be installed in order to facilitate the access to the fields adjacent to the relief channel.
- A Cambridge Water pipe runs under the paddock, where the new channel is to be constructed. The Gough Way Residents Association contacted the authority to determine the exact location of this pipe, but it was found that the exact position and depth of the pipe is not known. The guidelines for from Cambridge Water indicate that a cover of at least 750mm should exist over the pipe at all times. The proposed channel thus has to be shallow and wide.

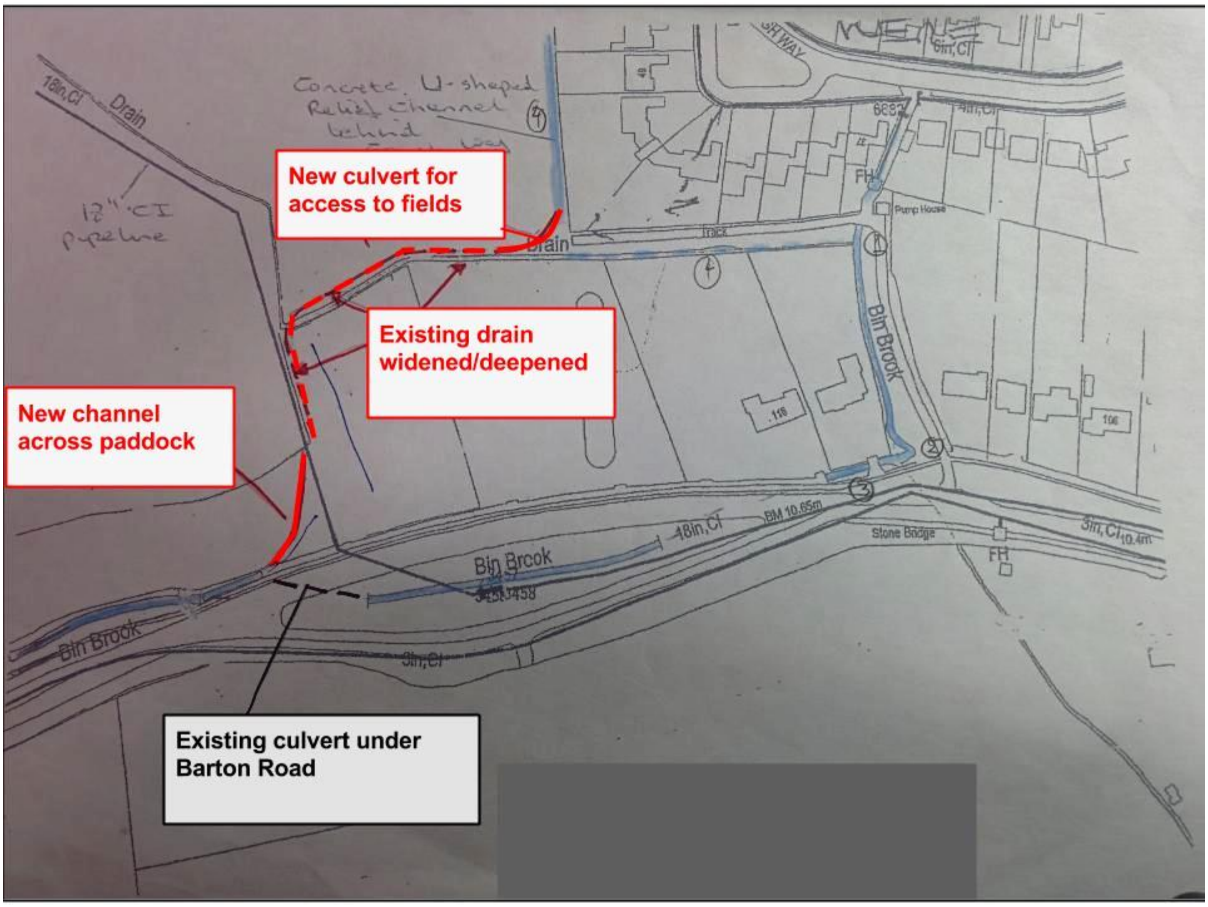

Figure 13 The proposed new diversion channel, diverting flow from upstream of the first Barton Road culvert to the existing relief channel

5.1.2 The trial model

After some filed surveying, approximate cross-sections of the channels were measured. Bank elevations were also monitored using a GPS device. The accuracy of these dimensions was not of particular importance as the main aim of this exercise was to get familiar with the FLOOD MODELLER software. Two versions of that model were created and the layout and profiles scan be seen in Figure 14. The top left figure shows the layout of the model including the new diversion and top; top right represents the profile of the brook flowing through the diversion channel. The bottom left figure shows the layout of the model created to represent the existing river network, and the bottom right figure is the output of this model, with the steep dip representing the entrance to the Gough Way culvert.

The inflow boundary was determined from the flood frequency curve presented in the Halcrow 2002 report for a 1 in 50 year flood. For the outflow boundary, an additional channel of constant cross-section was added to the model in order for a simple open channel steady flow calculation to be carried out. The entire model only uses open channel sections, and no hydraulic structures are present. Thus the flow levels are higher than the actual ones seen in the Environment Agency model.

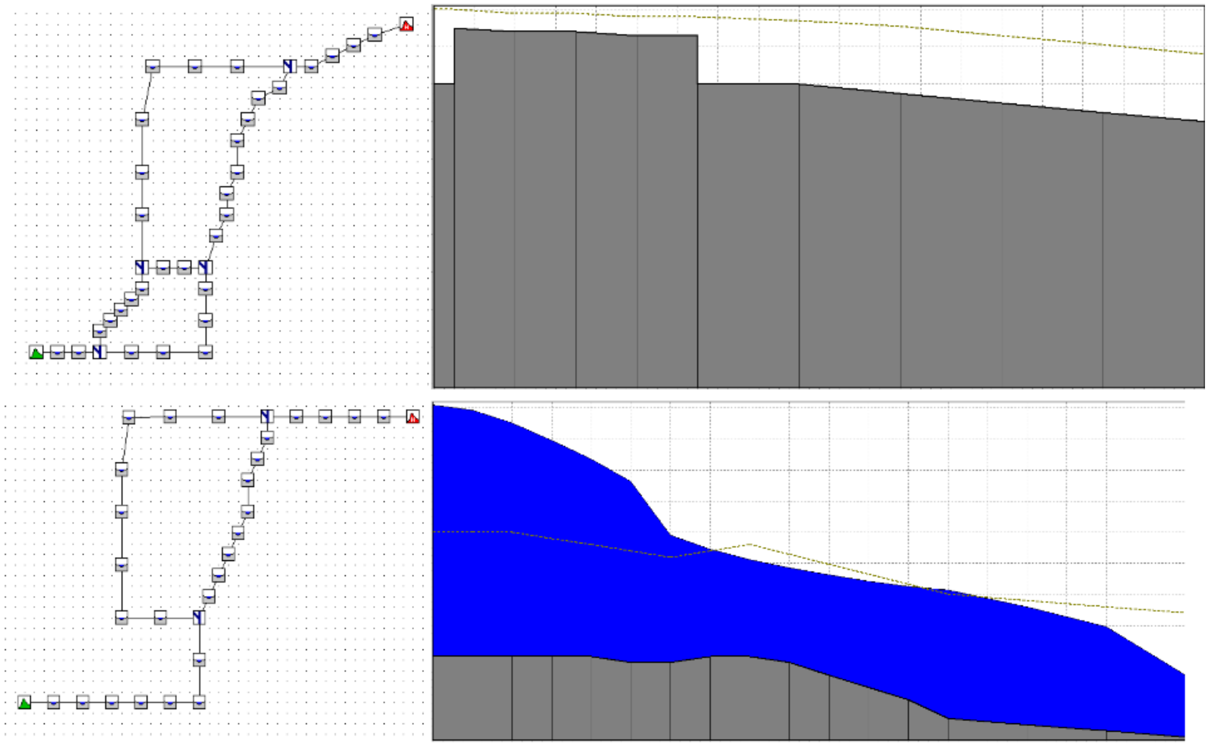

Figure 14 The trial models, created as an exercise. The top two figures show the model including the diversion channel while the bottom two, the current situation

Although these crude models might not have given accurate results, they were used as an exercise for the later stages of the project, which will involve manipulating the existing ISIS model that the Environment Agency has provided.

<u>5.1.3 Modified Environment Agency model</u>

The simplified Environment Agency model was manipulated in order to check how the network would react to the addition of a new diversion channel. Four new sections were added and their shape can be seen below, in Figure 15. On the left, a cross-section of the new channel can be seen, while on the right, the figure shows the long section of the channel, with the new sections being the ones with a higher bed level. The new channel is modelled as a prismatic channel with width 3m and depth 0.83m, with a total length of 90m. The width at the bed of the channel was set to be 2m. This was thought to be a good approximation of what the actual channel would look like if constructed.

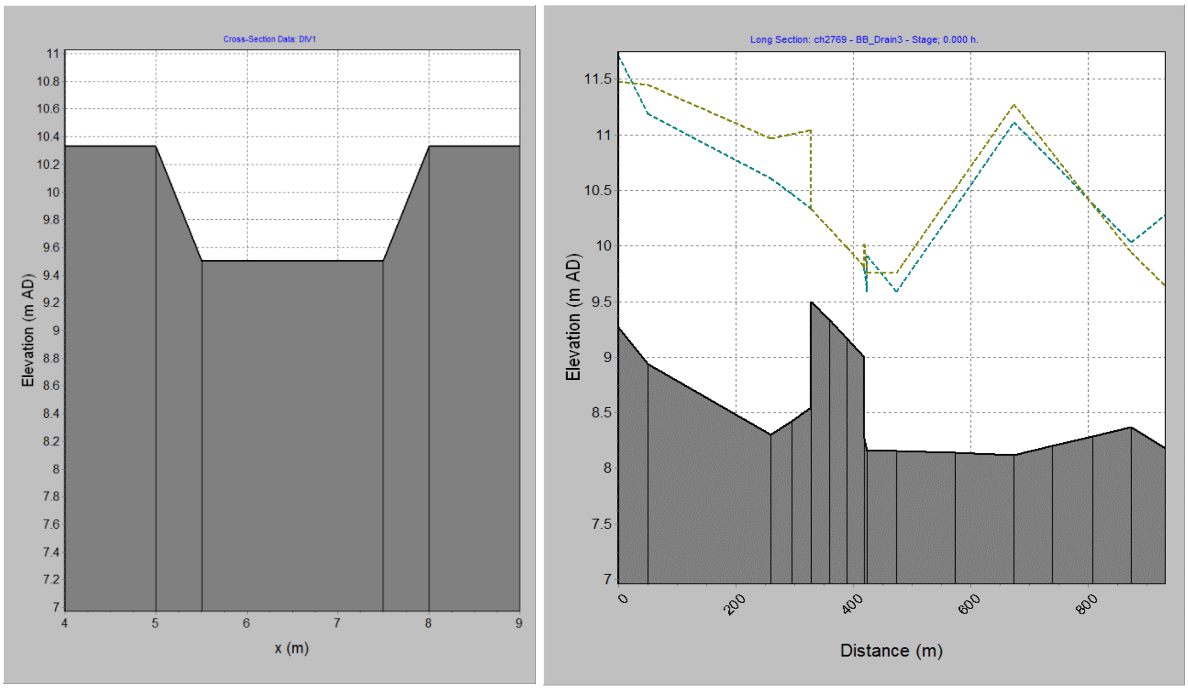

Figure 15 The dimensions of the new diversion channel. On the left, the diversion channel cross-section and on the right a profile of the river through the diversion channel

5.1.4 Results

The channel was tested against a 1 in 50 and 1 in 100 year event. The test performed in both cases was a 40 hour event, with the peak flow occurring at 20 hours. For both tests, it was found that the maximum water level difference between the existing protection system and the addition of the new channel occurred before the peak flow.

In Figure 16, below, the maximum difference can be seen for a 1 in 50 year event. In the figure, the model can be seen from upstream of Gough Way (where the new diversion channel splits the flow), to the confluence of the old relief channel with the main part of the brook. Significant differences in water level can be seen in the section of the river that is on Barton Road, with the water level difference being around 0.75m. At peak flow, the maximum difference is approximately 0.1m.

Figure 17, below, shows a comparison of the maximum difference in water levels for a 1 in 100 year event. Here too, the maximum depth difference is approximately 0.75m at the region of Barton Road. More importantly, the difference at peak flow is much less, around 0.05m.

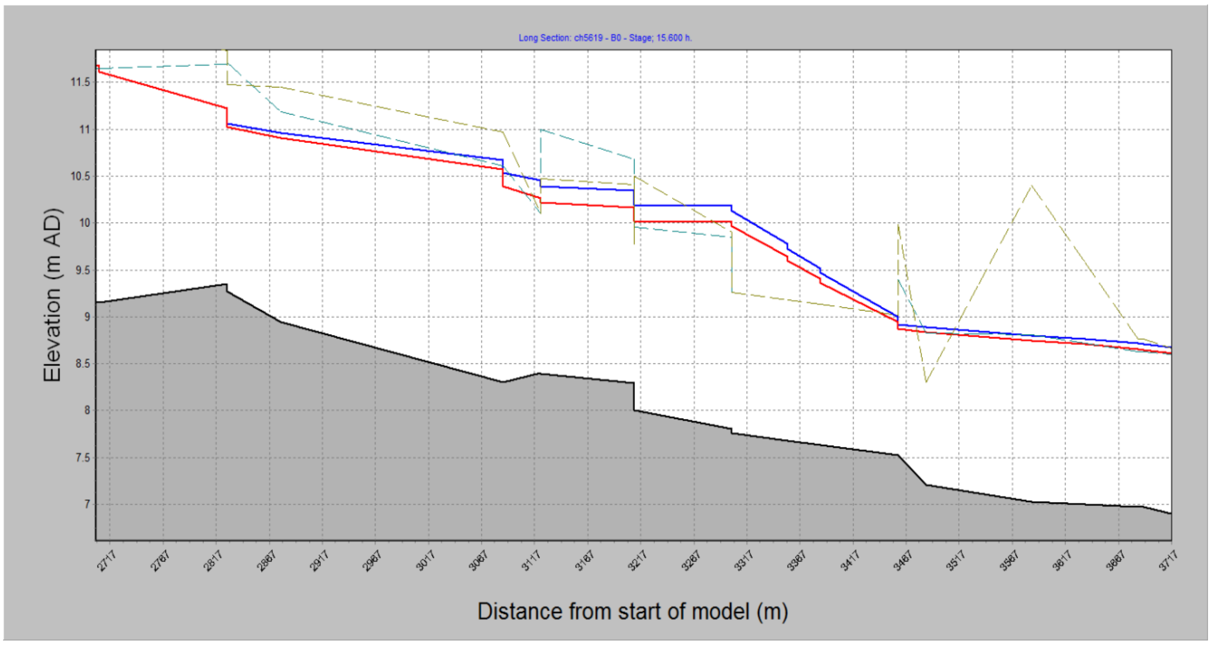

Figure 16 Results of new diversion channel. Red line plots the new diversion results; blue line plots the existing channel results. 1 in 50 year test

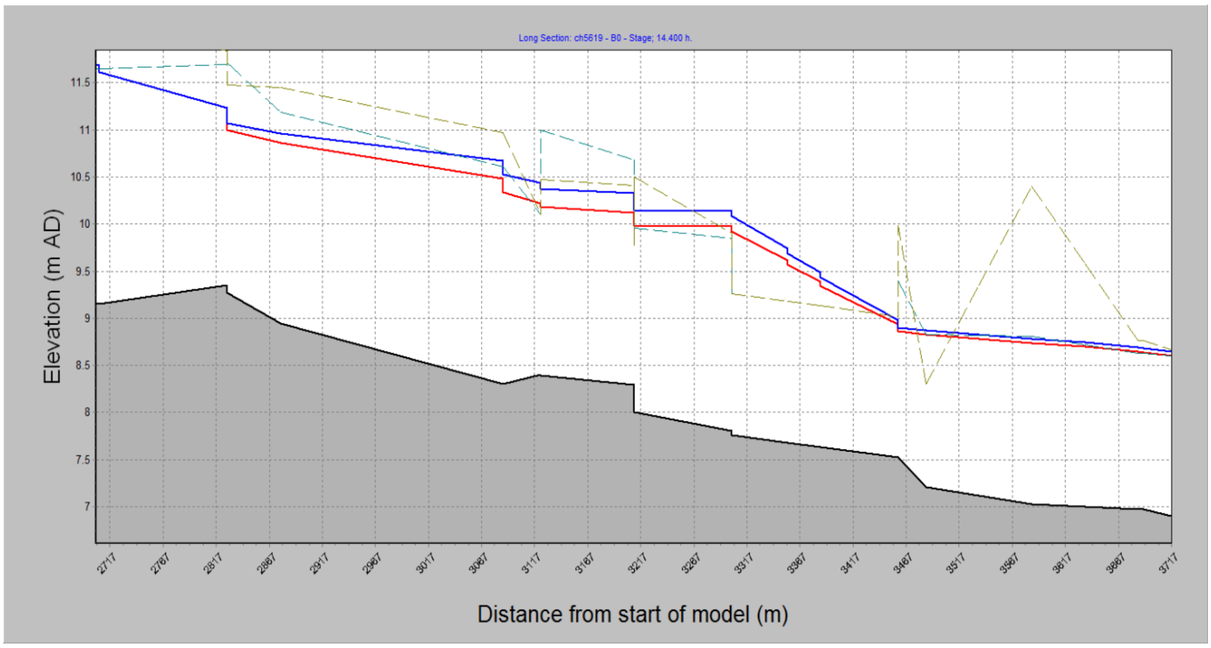

Figure 17 Results of new diversion channel. Red line plots the new diversion results; blue line plots the existing channel results. 1 in 100 year test

5.2 Change in size of Gough Way Culvert

5.2.1 Overview

Earlier in 2015, after surveying of the Gough Way culvert, it was found by the Environment Agency that it was in need of maintenance works. This lead to a renewed interest in assessing the effect a new culvert would have in the Bin Brook network. Although the Environment

Agency has expressed plans for constructing a new culvert in Gough Way, they have not mentioned whether this would be of the same, smaller or larger capacity. It was thought to be beneficial to check the flood flow levels for both the case of a smaller and a larger Gough Way culvert.

Three cases are examined here, and are compared to the current culvert of 1.55m diameter. Firstly, a culvert of the same size as the current, but built using different material, secondly an enlarged culvert of 2m diameter and lastly a culvert of diameter 1m.

The runs performed to evaluate the impact a change in size and material of the Gough Way culvert would have on the brook, were for a 1 in 100 year event.

5.2.2 Models

Three models were created for this section. One contained a culvert with a reduced Manning's roughness coefficient, one contained the 1m diameter culvert and the other, the 2m diameter culvert. For all three, the simplified model was modified to accommodate the changes in material and size of the culvert, while all other model inputs were kept the same as before.

5.2.3 Results

5.2.3.1 Different material

After researching the different types of materials used for culvert construction, it was decided that the most suitable alternative material for the Gough Way culvert would be PVC. This is commonly used in smaller sized culverts as is the case of Bin Brook. The Manning roughness coefficient for PVC is 0.009-0.011, so a value of n=0.010 was chosen as the new Manning roughness for the Gough Way culvert. Figure 18, below, shows the results of this test, with the dotted pink line representing the new material and the blue line representing the current culvert. As it can be seen the flows are almost identical, suggesting that the roughness of the culvert does not play an important role in the network flow.

This result is also verified by the Halcrow report, where it is stated that the channel roughness is a less significant concern than the inflows and structure capacity of the network, which includes bypass flow paths around structures and blockages [2].

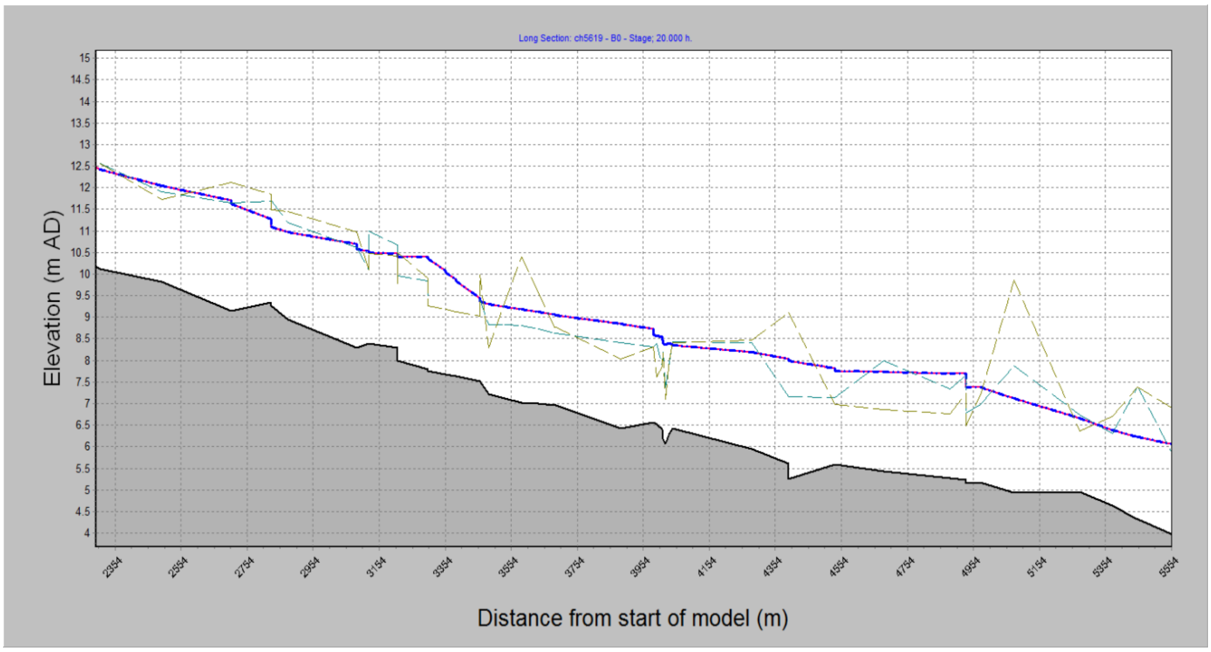

Figure 18 Result of changing the material of Gough Way culvert

5.2.3.2 Different culvert size

As stated above, two new culvert sizes were tested, a 1m and a 2m diameter. The same material as the current culvert material was chosen, as a result of the findings in the above section.

The figure below (Figure 19) shows the effect a change in the Gough Way culvert size would have on the network. All three options are shown on the graph, with the blue line representing the current, 1.55m diameter culvert, the red line representing the 2m culvert and the green one representing the 1m culvert.

In the case of changing the culvert size, as before, it was observed that the maximum difference in water level occurred at a time before the peak flow, suggesting that at a 1 in 100 year event, the culvert size would not play an important role in the flooding of Gough Way.

Choosing to install a culvert with diameter 2m would decrease the water level by a maximum of 0.3m at the entrance of the culvert, while decreasing it by 0.5m would increase that head by approximately 0.25m. At peak flow, the differences in head are smaller, with the increased capacity culvert only providing a 0.1m water level difference to the current situation.

Another observation that can be made is that a change in culvert size would affect the downstream water levels, increasing the risk of flooding in the residential areas downstream of the Gough Way estate.

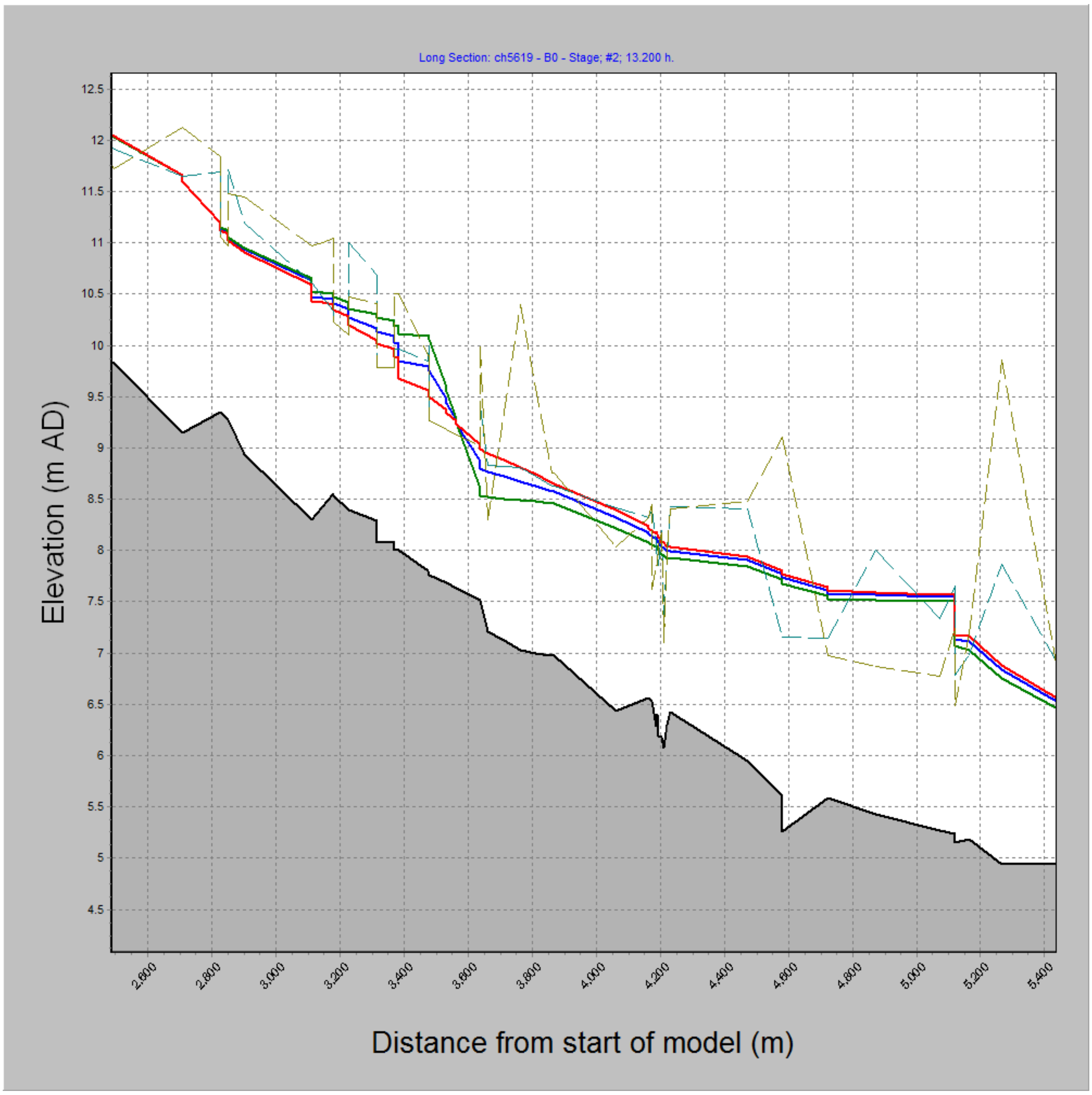

Figure 19 Results of changing the Gough Way culvert size. Red line shows 2m culvert, green line shows 1m culvert and blue line shows the current culvert. The dashed lines represent the banks

6. Discussion

6.1 Model Accuracy

In order to put the results in perspective, some attention has to be paid to the model that was used in obtaining the above results. As mentioned above, it is a simplified version of the model the Environment Agency has in their files. The full model contains many inputs and sections in order to achieve high accuracy in its results. It also combines one-dimensional and two-dimensional components in the main part of Bin Brook, from Barton Road to its confluence with the Cam, as seen in Figure 1 and Figure 5. These two dimensional components can only be designed with FLOOD MODELLER 2D and can be combined with the 1D components using FLOOD MODELLER TUFLOW. The two programs mentioned above are part of the full software suite, and thus the simplified model does not have any 2D inputs as it was created using the free version.

This means that the capabilities of the model in predicting accurately the flow levels of an event are limited. Hence, the results obtained can only be used as an early stage indication of whether or not a proposed alleviation scheme would have a positive effect on the river network, rather than to accurately evaluate the level of protection that proposal would provide.

6.2 Effectiveness of the proposed schemes

The proposal for the creation of a new diversion channel was based on the assumption that it would activate the existing relief channel at an earlier stage, thus, lowering the flood flow at the entrance of the Gough Way culvert. The reality of having a shallow diversion channel proves a drawback in this situation, as flows do not pass through it at small flows. At low flows, the diversion channel does not take any flow, and thus the network functions as it does with the current protection system. Once the diversion channel is activated, it provides some protection, during medium events, such as 1 in 20 year events. In extreme events, the protection it provides is less than 0.1m for a 1 in 100 year event, suggesting that the capacity of that part of the brook is still too low to protect the nearby properties. This can also be seen in Figure 17, where the red line (representing the flood flow levels with the addition of a new diversion channel) lies above the dashed line (representing the bank elevation).

Changing the material of the culvert was another option considered. Using a material with lower roughness, such as PVC, higher flow rates through the culvert could be possible. The results obtained from this model run suggested that such a change would not be very beneficial, as the flow does not depend as much on the channel roughness as on the various hydraulic structures of the network, giving two almost identical flow lines both for concrete and plastic culvert. Although this is suggested in previous reports, larger variations can be seen due to change in Manning's roughness coefficient (Figure 6). This could mean that the simplified model, due to the degree of simplification it has undergone might not be able to incorporate the roughness and its significance in the channel at a substantial level.

Lastly, the effect of a different size culvert was investigated. Two cases were taken into account, a 1m diameter culvert and a 2m diameter culvert, in order to consider the effects of both the best case (2m diameter) and the worst case (1m diameter) scenario. In the case of the 2m culvert it was found that at a 1 in 100 year event the head difference at the culvert entrance would drop by approximately 0.1m. By observing Figure 19, it can be seen that this would result to the water levels being below the bank levels at the Gough Way culvert entrance, suggesting that this could be a viable option for further consideration. In the case of the 1m diameter culvert, it is visible that the flow level at the culvert entrance would be increased by approximately 0.1m. This would suggest that in case the Environment Agency decided to reduce the culvert diameter, that would have quite a large effect on the nearby properties and their flood protection levels would be reduced even more.

It should also be mentioned that changes in the river network at Gough Way would affect downstream areas of Bin Brook, as the capacities would change. This has to be taken into account, as releasing flow from the area of Gough Way might create flood areas further downstream. These changes of the downstream river capacity can be seen clearly in Figure 19.

7. Conclusions and Recommendations

7.1 Conclusions

The following conclusions can be drawn from this study:

- The FLOOD MODELLER (ISIS) software is an effective means of analysing complex open channel flow problems such as the Bin Brook network. Combining 1-D and 2-D models can give accurate representations of the network flows.
- Change in material of the Gough Way culvert would not provide significant flood protection, as the flood flow levels depend on the hydraulic structures of the area, and the channel roughness plays a minor role.
- Increasing the Gough Way culvert diameter would provide some protection to the area upstream of the Gough Way culvert. An increased culvert would alleviate the flood levels of the properties at the Gough Way culvert from a 1 in 100 year flood to the levels of a 1 in 50 year flood in the current protection system, reducing the flow levels by approximately 0.1m.
- Decreasing the size of the Gough Way culvert by 0.5m would increase the levels of flow at the entrance of Gough Way culvert by approximately 0.1m. This means that it would increase the damage to properties to an equivalent 1 in 200 year event with the current protection.
- Changing the size of the Gough Way culvert would affect the downstream flow levels of Bin Brook. Increasing the culvert size, would increase flood risk of the downstream areas as any flow accumulated in Gough Way would now be passed more easily. Decreasing the size of the culvert would have the opposite effects. The downstream effects should be considered further in order for a precise indication of the increased downstream flood risk to be evaluated.
- The addition of a new diversion channel could provide some protection, but only in small events. When tested in 1 in 50 year and 1 in 100 year events, the flood flow levels appeared to be the almost the same as the ones observed with the current protection system and thus flooding would still occur at the estate entrance.
- A more detailed study should be carried out in order to determine flood flow levels more accurately. This study should include both one-dimensional and two-

dimensional modelling components in order to correctly model both in-plane an out-of-plane flows. This study should also include environmental and economic factors as this report has not focused on that side of the alleviation scheme.

7.2 Recommendations

From the above study, the alleviation scheme that seems to provide higher levels of protection if the enlargement of the Gough Way culvert as it appears to have the potential to increase the flood protection level of the area to a satisfactory point, on par with the current DEFRA guidelines. Further economic and environmental studies have to be made in order to fully assess this scheme, as well as determining the level of damage its implementation might cause to residential areas downstream of the Gough Way estate.

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Appendix

i. Risk Assessment

At the start of Michaelmas term, a risk assessment form was submitted to the department detailing any hazards that might be encountered in the course of the project. These risks focused on the field survey that would be done on Bin Brook and included working near busy roads and water and lone working. In Michaelmas term, numerous visits were paid to the area in order to obtain a better view of the geography and the river network. No equipment was used other than a GPS device, and only some approximate measurements were taken.

As the model from the Environment Agency was obtained at the end of Michaelmas term, the need to survey the Bin Brook area was no longer necessary. Thus, time was not spent in the area in order to obtain accurate geographical details. None of the above hazards were thus encountered. The majority of the time after the Environment Agency model was obtained, was spent on its manipulation, and the development of the other models included in this report. This meant that a lot of time was spent working on a computer, and thus hazards such as bad posture were more relevant to this project.

ii. Additional Figures

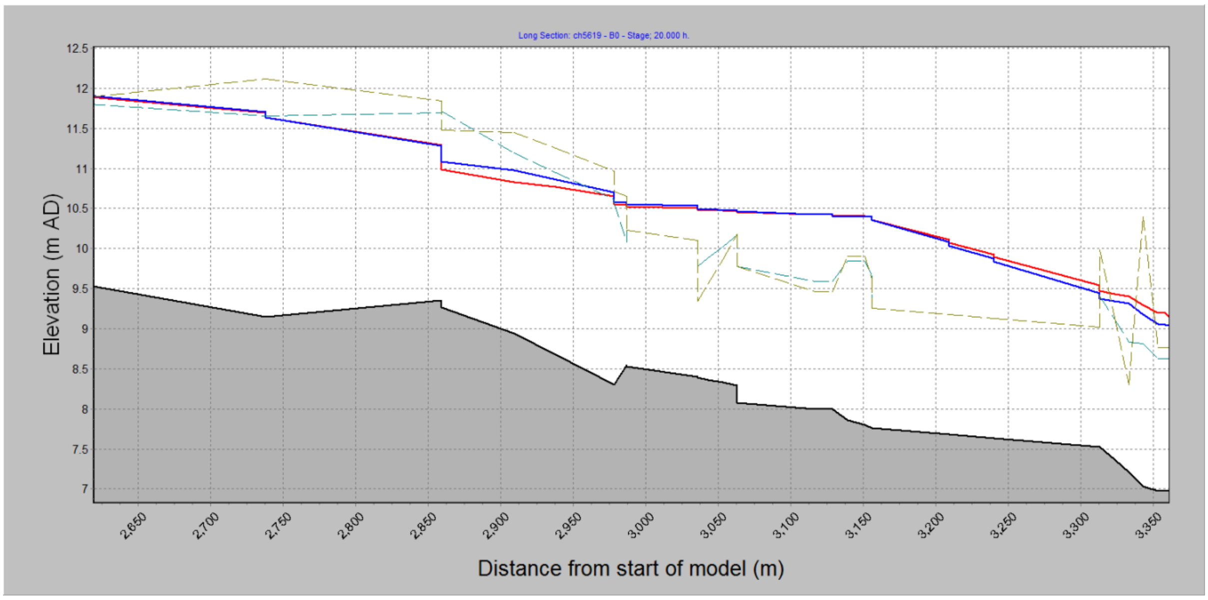
Additional photos of hydraulic structures, included to provide a better visual understanding of the Bin Brook flood network.

Top left: The diversion channel. Photo taken from the southwest corner, facing north

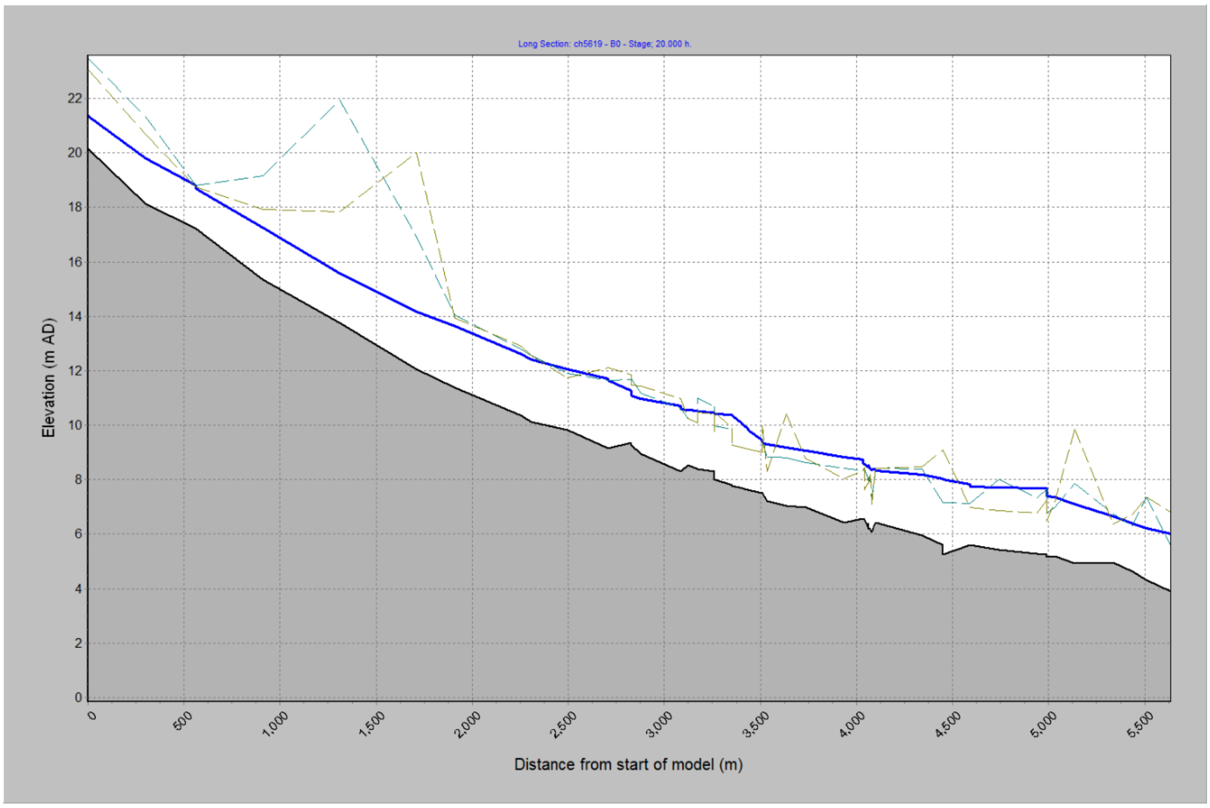
Top right: Robinson College sluice gate

Bottom left: The exit of the Gough Way culvert

Bottom right: Bin Brook at the entrance of Gough Way, facing Barton Road



Closer view of the Gough Way area in the model verification. Red line indicated the Environment Agency results, blue line indicates the output of the simplified model.



Output of the simplified model, representing the brook from Coton to its confluence with the Cam.