MATH3001: Project in Mathematics

UNIVERSITY OF LEEDS

Introducing FEV Analysis and Using it to Quantify the Magnitude of Recent Floods on the River Ouse in York and Perform a Cost-Effective Assessment of Planned Mitigation Activities

Antonia Feilden
Student ID: 200989495

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1 Introduction

December 2018 marked three years since the Boxing Day floods of 2015 where Storms Desmond, Eva and Frank caused extreme flooding in many parts of the UK. 17,000 properties were affected by flooding in the winter of 2015-2016 in the North of UK [3] and the total economic cost associated with this flood ranges from £1.3 to 1.9 billion [4].

Since then, authorities have been working to reduce the risk of flooding and minimise its potential impact. Despite their efforts, three years later on 17th March 2019, 29 areas in the UK were issued acute flood alerts and properties and roads along the Rivers Aire, Calder, Irwell, Wharfe and Ouse were reported to have experienced flooding [1].

Figure 1: Parked car in York flooded by the River Ouse on 17th March 2019 [1], more than three years after the devastation caused to York during the 2015 Boxing Day floods.

Rivers can be found running through many cities and towns due to the role they played historically in supporting their growth. Once beneficial for these urban settlements,rivers now pose the risk of flooding and damaging properties, businesses and people's lives. In 2017, flooding was a natural hazard identified as being a major threat on the UK Risk Register [5]. The challenges cities and towns current face are planned to get harder. 68% of the worldpopulation is predicted to be living in urban areas by 2050 [6] and climate change is predicted to increase the likelihood of extreme weather. Cities and towns are currently faced with the challenge of using limited resources to design, finance and implement Flood Risk Management Plans (FRMPS) which will protect lives and assets. FRMPs outline the areas at risk of flooding and detail ways in which flooding can be mitigiated [23].These are prepared regionally for the 7 river basin districts in the UK [24] and locally for specific areas such as towns and cities.

Government money is typically applied for by the Environment Agency representing a local area and awarded with spending conditions[25]. The Environment Agency are then responsible for the spending of this money inorder to optimise the reduction in flood risk[26]. Flood mitigation solutions can be engineering based (e.g flood walls, reservoirs) and nature based (e.g beaver dams, tree planting)[7][10] and are suitable for different areas. Flooding caused by rivers overflowing from their banks in termed *fluvial* flooding. The cause of fluvial flooding is the volume of water in the river being greater than the volume of the river channel and hence effective mitigation solutions typicallyreduce the volume of water in the river channel. How effective are the combination of solutions chosen by local authorities at reducing fluvial flooding and is government money being spent in the best way?

This report introduces the concept of *flood-excess volume* (FEV) - a concept used to quantify the magnitude of a flood. It then describes different ways the *flood-excess volume* can be estimated using hydrological data. *Flood-excess volume* analysis is then conducted on two flood events on the River Ouse in York in November 2000 and December 2015. The flood mitigation strategy for York is discussed and a detailed assessment of the effectiveness and cost of one specific area is performed. These are then summarised, with their limitations discussed before performing a cost-effective analysis. In conclusion, all observations and findings are summarised and reinforced before a discussion of recommended and further work for this project.

2 Introducing Flood-Excess Volume

2.1 Definitions [7] [10]

"*Flood-excess volume (FEV) is defined as the volume V_e of water which causes flooding*" [7].

Calculating this volume during a flood event is not commonly done. The nature of flooding can be complex. This study assumes flooding is completely fluvial in nature. For rivers where hydrological models exist, this volume can be estimated via computation of an ensemble of different flood simulations. In the absence of these models, hydrological data from river monitoring stations can be collected and analysed to make estimations.

River monitoring stations in UK directly record variables of interest for hydrology such as river level h (units m), precipitation and, less commonly, discharge Q (units $\mathrm{m}^3\mathrm{s}^{-1}$) at regular time intervals (typically 15 minutes). Assuming the free-surface height varies little, each direct measurement of the river level can be taken to be representative of the whole cross-section $h = \overline{h}$.

For river monitoring stations without the permanent technology to directly record discharge, a relationship between the discharge Q and the recorded river level $\overline{h}$ can be established called a *rating curve* where $\hat{Q} = \hat{Q}(\overline{h})$. Non-routine direct measurements of discharge and river level are recorded and a curve is fitted to the data. The form of the fitted curve depends on the nature of the raw data [8], however all curves provided by the Environment Agency so far have the following form.

$$\hat{Q}(\overline{h}) = C_j(\overline{h} - a_j)^{b_j} \quad , \quad j = 1, ..., N \tag{2.1.a}$$

where parameters $[C_j, a_j, b_j]$ are valid for different intervals of river level known as *stages* or *limbs*.

$$h_{j-1} \leq \overline{h} \leq h_j \quad , \quad j = 1, ..., N \tag{2.1.b}$$

During a flood event, it is common that $\overline{h} > h_N$ where h_N is the upper-bound of the interval $h_{N-1} \leq \overline{h} \leq h_N$. In this region, the discharge is estimated by extrapolating the final limb and using the parameters $[C_N, a_N, b_N]$. Discussion of the validity of this extrapolation and the unusual dimensionality of the fitted parameters can be found in [7].

$$V_e = \int_{T_f} (Q - Q_T) dT_f \tag{2.1.c}$$

The threshold discharge Q_T is the discharge associated with $\overline{h} = h_T$. For discharge data generated using the rating curves $\hat{Q} = \hat{Q}(\overline{h}(t))$ and the threshold discharge is $Q_T = \hat{Q}(h_T)$. Three approximations of FEV given introduced in [7] [10] are detailed below.

j	h_j m	C_j m^{3-b_j}/s	a_j m	b_j
1	0.52	78.4407	0.2230	1.7742
2	0.931	77.2829	0.3077	1.3803
3	1.436	79.5956	-0.3400	1.2967
4	3.58	41.3367	-0.5767	1.1066

Table 1: A table showing the parameters $[C_j, a_j, b_j]$ for different stage thresholds h_j with $h_0 = 0$ m for the rating curve function (2.1.a) for the River Don at the Hadfields monitoring station. These are the parameters for rating curve F from the Environment Agency's rating curve report and are deemed valid from 1st March 1990 to 27th November 2014 [9]. This rating curve function was used to perform FEV analysis of the flood event in June 2007 [10].

2.2 Estimations [7][10]

The *first* and most accurate estimate V_{e_1} is appropriate for situations which have automatic river level monitoring and rating curves. It requires knowledge of the threshold river level h_T, a rating curve $\hat{Q} = \hat{Q}(\overline{h})$ (2.1.a) and a set of river level data recorded at regular time intervals $\Delta t = (t_k - t_{k-1})$ such that $\overline{h}_k = \overline{h}(t_k)$ and k is the discrete time index. If Δt is the same for all values of k, the FEV can be estimated by the equation below (2.2.a). As $\Delta t \to 0$ and $N_m \to \infty$, $V_{e_1} \to V_e$. This can be visualised as blue region in **Figure 2**.

$$V_e \approx V_{e_1} = \sum_{k=1}^{N_m} \big(\hat{Q}(\overline{h}_k) - \hat{Q}(h_T)\big)\Delta t \tag{2.2.a}$$

The *second* estimate V_{e_2} requires knowledge of the threshold river level h_T, a rating curve $\hat{Q} = \hat{Q}(\overline{h})$ and the mean discharge $\overline{Q}$ during the flood duration T_f .The FEV can then be estimated as the difference between the values of discharge multiplied by the flood duration.

$$V_e \approx V_{e_2} = \big(\overline{Q} - \hat{Q}(h_T)\big)T_f \tag{2.2.b}$$

The *third* estimate V_{e_3} is appropriate for situations where automatic river measurements and rating curves are inaccessible. It is an extension of (2.2.b) and provides a way of estimating $\overline{Q}$ and Q_T. It requires knowledge of the threshold river level h_T, the maximum discharge Q_{max} at peak level h_{max} and the duration of flooding T_f. The maximum discharge Q_{max} can be estimated if the (mean) maximum depth h_{max}, the (mean) river width W_r and the maximum mean surface velocity $\overline{V}_{max}$ are known. Discharge is equal to cross-sectional area multiplied by velocity hence maximum discharge can be estimated as $Q_{max} = \overline{V}_{max} h_{max} W_r$. Assuming the flood duration T_f can be established for a given threshold h_T and the mean water level for the flood duration h_m can estimated e.g $h_m \approx \frac{1}{2}\,(h_{max} + h_T)$. Using linear interpolations, the mean discharge $\overline{Q}$ and the threshold discharge Q_T can be estimated in the following way.

$$\overline{Q} \approx \frac{h_m}{h_{max}} Q_{max} \quad \text{and} \quad Q_T \approx \frac{h_T}{h_{max}} Q_{max} \tag{2.2.c}$$

Inputting $\overline{Q}$ and Q_T into (2.2.b), an rough estimate for the FEV is obtained in (2.2.d)

$$V_e \approx V_{e_3} = \frac{Q_{max}}{h_{max}} \big(h_m - h_T\big)T_f \tag{2.2.d}$$

All estimates of the volume $V_e = V_e(h_T)$ are functions of h_T which itself if often estimated from a range of possible values. For the rivers studied so far the discharge Q for a respective $\overline{h}$ can be 2 orders of magnitude greater. Small changes in h_T can result in large changes in discharge and hence the volume calculated. The threshold river level h_T for a given location for a specific flood event is not always known. It can be estimated using eye-witness accounts, reviewing historical flood data and by performing field investigations.

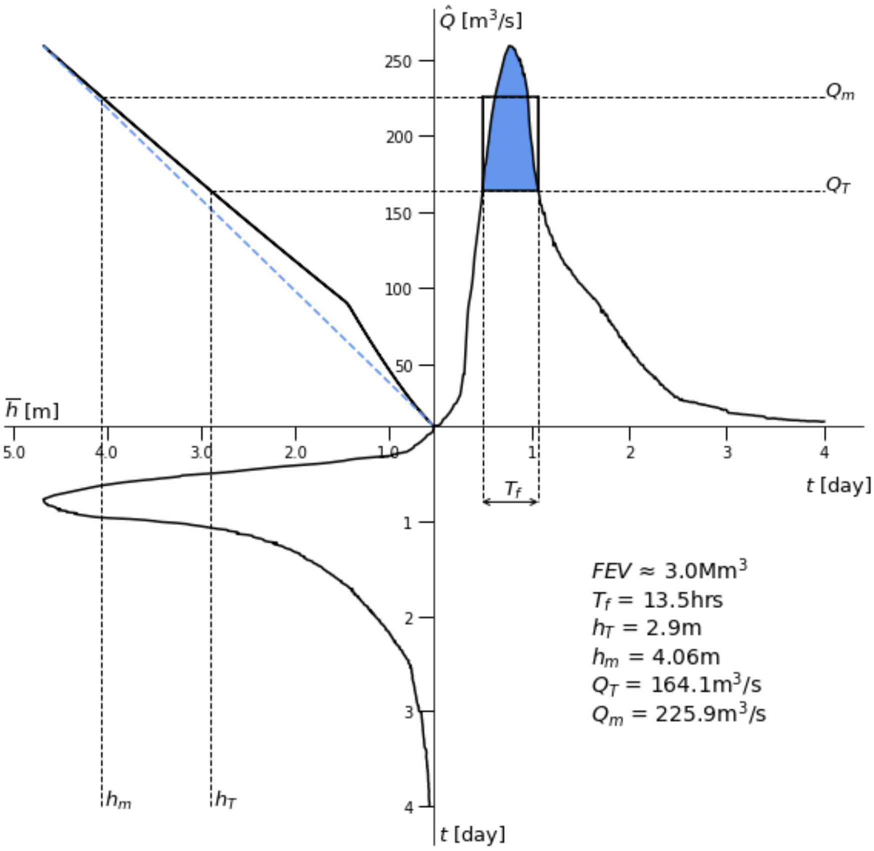
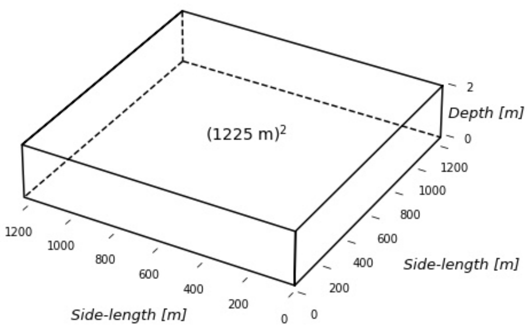


Figure 2: A reproduction of the integrated hydrograph for the River Don at Sheffield Hadfields river monitoring station for the flood from 25th-29th June 2007 found in [10] It shows the relationship between time t, recorded river level $\overline{h}$ and the predicted discharge $\hat{Q}$ calculated using the rating curve limbs and coefficients (2.1.a)(**Table 1**). The black line in the *bottom-left* quandrant shows the relationship between time t and the recorded river level $\overline{h}$. The black line in the *top-left* quandrant shows the relationship between the recorded river level $\overline{h}$ and predicted flow $\hat{Q}$ using the rating curve (2.1.a)(**Table 1**) whilst the blue dashed line shows their approximate linear relationship. The black line in the *upper-right* quandrant shows the relationship between time t and the predicted discharge $\hat{Q}$. The threshold height h_T and threshold discharge Q_T and the flood duration T_f are labeled on the hydrograph. The blue shaded region in the *upper-right* quandrant shows the FEV calculated using the first estimate V_{e_1} and the black box represents this same volume reshaped to determine average river level h_m and discharge Q_m during the flood duration T_f. This visual was generated using the automated code [41] developed as part of this project. Other similar graphs are also in this report (See **Appendix**).

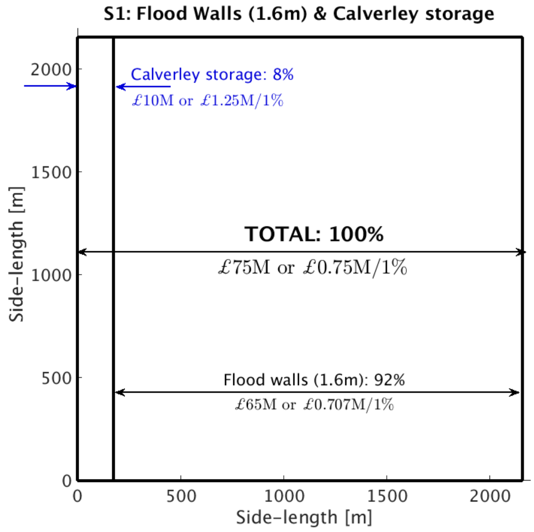
2.3 Communication & Cost-Effective Analysis

Once the volume of the flood has been quantified using the estimates in section 2.2 or through the use of hydrological river modelling, it is important to to understand its statistical significance. The term *return period* represents its Average Recurrence Interval (ARI) [40] of the studied flood happening e.g a flood of with return period 1:100 has a probability of occurrence of 1% [7]. This is a commonly misunderstood term when communicating natural hazards and is being replaced by the term Annual Exceedance Probability (AEP). This represents the "*percentage of a particular storm event being exceeded in any one year*"[39].

It is important to visualise magnitude of water when designing flood mitigation schemes. The concept of a two meter square lake is introduced in [7][10]. The flood-excess volume can be visualised as a lake of 2m depth and equal side lengths (**Figure 3(a)**).



(a) A visual representative of the FEV in **Figure 2** in the form of a square lake with a depth of 2 m corresponding to side lengths of 1225m. *(Figure is not drawn to scale).*



(b) A partitioned square lake for the FEV calculated for 2015 Boxing Day floods on the River Aire at the Armely monitoring station. The area partitioned represents the volume proportion of the FEV mitigated by different flood mitigation solutions and the the labels relate to cost estimates and cost per % of FEV mitigated [42].

Figure 3

The 2D view of the square lake from above also provides a tool for communicating the cost-effectiveness of different flood mitigation schemes (**Figure 3(b)**). Designing and implementing flood mitigation schemes is often the responsibility of local authorities with limited budgets and sometimes technical expertise. Flood mitigation schemes are composed of an array of different mitigation solutions e.g raings flood walls, contructing a dam or reservoir. Understanding how effective they are collectively and in relation to their cost can be challenging. Partitioning the square lakes to represent the volume of water mitigated by each solution and when combined along with their costs can be used as an evidence based visual to facilitate decision making .

3 FEV Analysis: River Ouse

3.1 Background

The Rivers Swale, Ure, Nidd and Ouse form the SUNO catchment upstream of York which has an estimated area of 3,300km^2 [11]. The River Ouse flows 99km in total through the city of York and the towns of Selby and Goole before joining the River Trent to form the Humber Estuary on the east coast of the UK. The River Aire, Don, Wharfe and Foss are all tributaries which flow into the River Ouse[27].

York is a historical walled city with a population of approximately 200,000 people, located at the confluence of the River Ouse and the River Foss[28].York has a history of extreme flooding and was recently devastated by the 2015 Boxing day floods where one of the city's major flood defences (the Foss Barrier)experienced an electrical problem and failed[11].

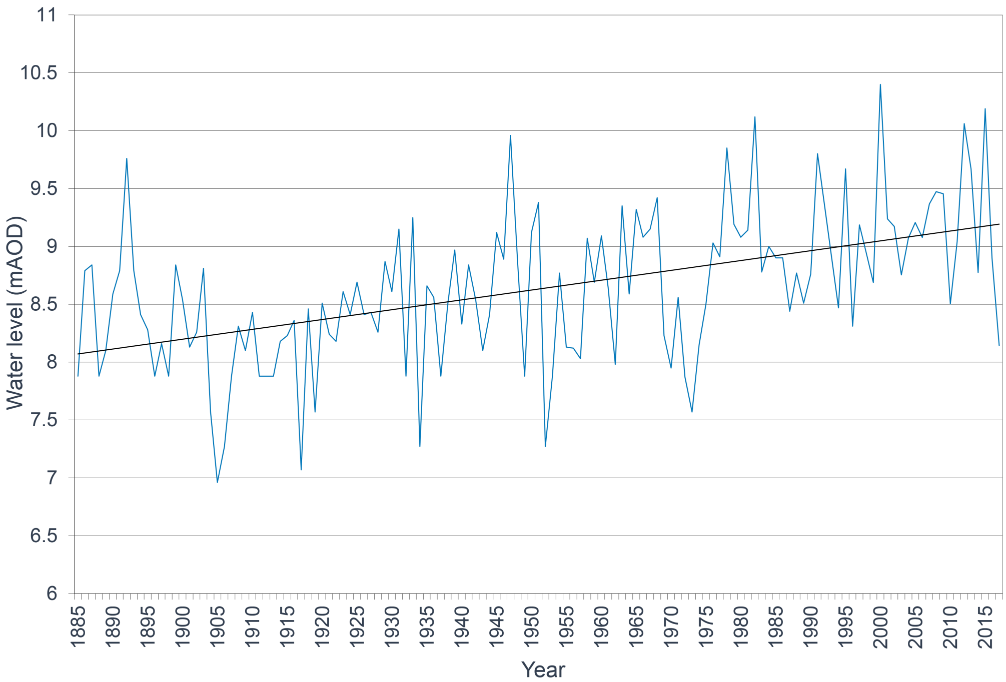


Figure 5: Recorded river levels for centre York from 1885 to 2015 indicating an increase in river levels each year. The units on the y axis are mAOD (meters Above Ordinance Datum) which is a relative scale in meter to a set height [32].

3.2 Data

There are 3 river monitoring stations on the River Ouse upstream of centre of York : Skelton , Clifton Ings and the Viking Recorder which are approximately 6 km, 3km and 0.5km respectively from the confluence with the River Foss [29][30]. Skelton records both river level $\overline{h}$ and discharge Q directly whilst the Clifton Ings and the Viking Recorder only record river level. No rating curves are available for for Clifton Ings and the Viking Recorder, hence FEV analysis was performed on data collected at the Skelton Station using the raw discharge data [31].

For Skelton, the threshold level h_T was estimated to be 6.17m According the Environment Agency in York [22], a river level $\overline{h} = 4.55$m at the Viking Recorder river monitoring station (approximately 5.5km downstream of Skelton) was observed to cause flooding. At the Viking Recorder, a river level $\overline{h} = 4.444$ m was reached on 27th December at 00:15 which corresponded to a river level of Skelton of 6.169m. Hence h_T was estimated as being 6.17m.

A rating curve was provided by the Environment Agency of the form in (2.1.a) however it is not authorised to be used for this project [22]. Instead, a function $\hat{Q} = \hat{Q}(\overline{h})$ was generated by fitting a polynomial of degree 4 to the raw discharge Q and river level $\overline{h}$ data for each flood event.

$$\hat{Q}(\overline{h}) = a_0 + a_1(\overline{h}) + a_2(\overline{h})^2 + a_3(\overline{h})^3 + a_4(\overline{h})^4 \tag{4.1.a}$$

The coefficients $[a_0, a_1, a_2, a_3, a_4]$ were determined automatically by minimising the squared error E between the predicted value for the the flow $\hat{Q} = \hat{Q}(\overline{h})$ evaluated at $\overline{h}(t_k)$ and the recorded flow $Q = Q(t)$ evaluated at time t_k

$$E = \sum_{k}^{N_m} \left| \hat{Q}\big(\overline{h}(t_k)\big) - Q\big(t_k\big) \right| \tag{4.1.b}$$

3.3 November 2000

In November 2000, York experienced extreme flooding with an return period of approximately 1:50 years [22]. The Skelton monitoring station recorded its highest ever level of 6.79m (10% greater than $h_T = 6.17$m) on 4th November 2000 during this flood [30]. More than 3,000 people were left homeless and in response the government promised £51M to be spent on improving flood defences[35]. The FEV was calculated to be the following.

$$\begin{aligned} V_e \approx V_{e_1}\big(h_T = 6.17\text{m}\big) &= 24.32\text{Mm}^3 \\ V_{e_2}\big(h_T = 6.17\text{m}\big) &= 25.15\text{Mm}^3 \end{aligned} \tag{4.2.c}$$

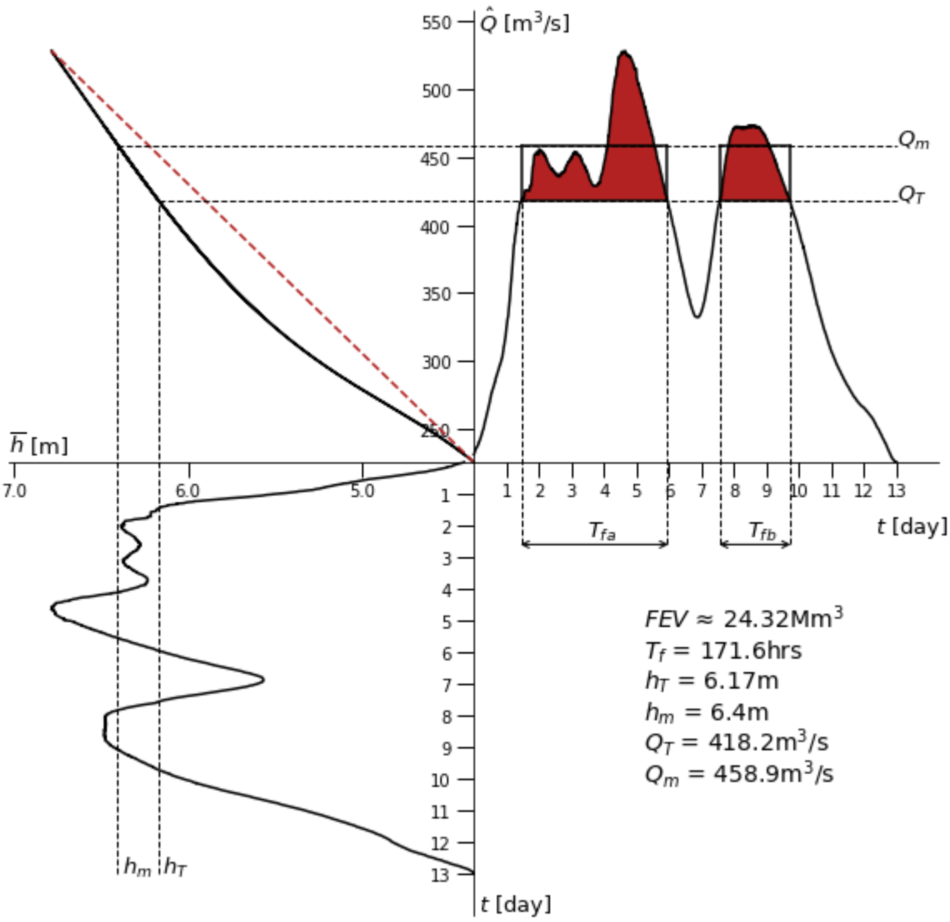


Figure 6: The FEV estimated was $V_{e_1} = 24.32\text{Mm}^3$ and V_{e_2}=25.15Mm^3 with h_T=6.17m. Hence V_{e_2} overestimates V_{e_1} by 3.41 %. Hydrological data from the 30th October 2000 to the 13th November 2000 has been analysed here from the Skelton monitoring station. A rating curve $\hat{Q} = \hat{Q}(\overline{h})$ was generated by automatically fitting a polynomial of degree 4 of the form (4.1.a) to the raw discharge data $Q = Q(t_k)$ measured at times t_k. The symbol h_m denotes the average river level during the flood duration T_f when the river level exceeds h_T such that $\overline{h} \geq h_T$. Calculations of the FEV were performed using automatic code generated as part of this project which was modified to include the polynomial fitted rating curve. At the time of writing, the automatic code generated cannot calculate the flood duration T_f for multiple flood peaks which each have an associated flood duration of T_a and T_b in the graph above. In this instance T_f was calculated by manually determining T_a and T_b by reviewing the raw level data $\overline{h}$. This does not affect the calculation of the first estimate V_{e_1}, only the second estimate V_{e_2}.

	a_0	a_1	a_2	a_3	a_4
	-9539.05	7056.26	-1909.17	227.97	-9.97

Table 2: Automatically generated coefficients for the rating curve of the form (4.1.a). Coefficients were found using the polyfit function of order 4 using raw height $\overline{h}$ and flow Q data.

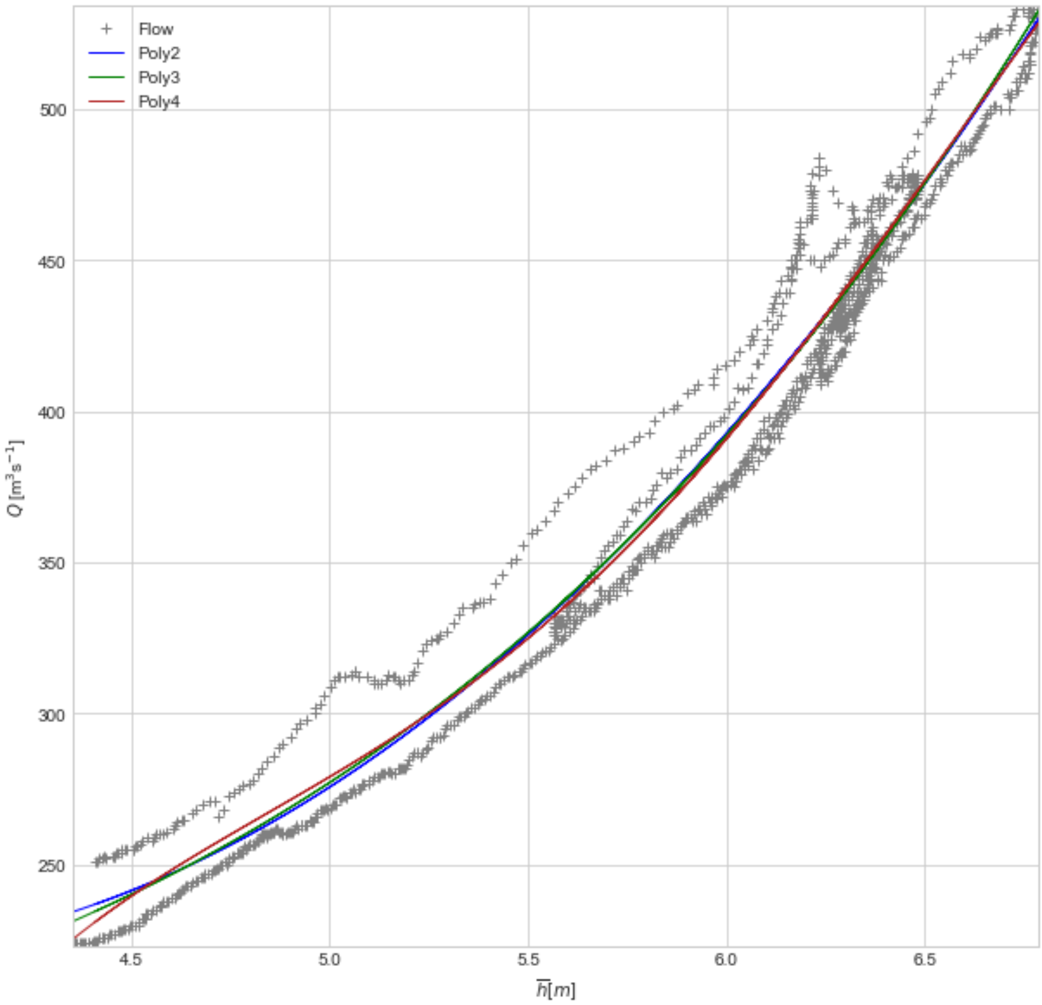


Figure 7: A graph showing the relationship (grey crosses) between raw flow data Q and river level data $\overline{h}$ for the flood event on the River Ouse at the Skelton monitoring station from 30th October to the 13th November 2000. Polynomials of degrees 2 (blue), 3 (green) and 4 (red) were fitted using the polyfit. function in Python.

3.4 December 2015

In December 2015, York experienced extreme flooding with an estimated return period of 1:40 years. The peak discharge on the River Foss had a return period in excess of 1:200 years and this is believed to be reason why the centre of York experienced such severe flooding [22]. 250 people were evacuated from their homes and 115 people used temporary accommodation provided by the Council [36]. Using the most accurate estimate, the FEV was calculated to be the following.

$$\begin{aligned} V_e \approx V_{e_1}\big(h_T = 6.17\text{m}\big) &= 10.34\text{Mm}^3 \\ V_{e_2}\big(h_T = 6.17m\big) &= 10.49\text{Mm}^3 \end{aligned} \tag{4.2.d}$$

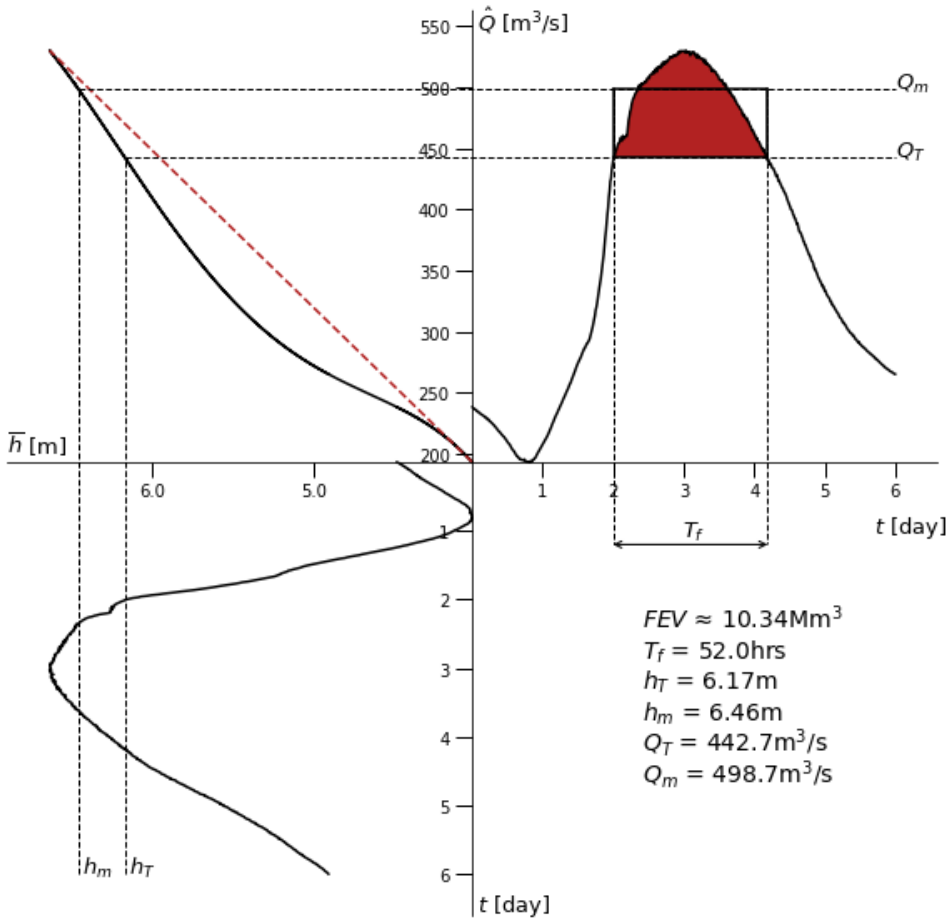


Figure 8: The FEV estimated was $V_{e_1} = 10.34\text{Mm}^3$ and V_{e_2}=10.49Mm^3 with h_T=6.17m. Hence V_{e_2} overestimates V_{e_1} by 1.50%. Hydrological data from the 25th December 2015 to the 31st December 2015 has been analysed here from the Skelton monitoring station. A rating curve $\hat{Q} = \hat{Q}(\overline{h})$ was generated by automatically fitting a polynomial of degree 4 of the form (4.1.a) to the raw discharge data $Q = Q(t_k)$ measured at times t_k. The symbol h_m denotes the average river level during the flood duration T_f when the river level exceeds h_T such that $\overline{h} \geq h_T$. Calculations of the FEV were performed using automatic code generated as part of this project which was modified to include the polynomial fitted rating curve.

	a_0	a_1	a_2	a_3	a_4
	-13986.32	1086.04	-3095.80	388.13	-17.87

Table 3: Automatically generated coefficients for the rating curve of the form (4.1.a). Coefficients were found using the polyfit function of order 4 using raw height $\overline{h}$ and flow Q data.

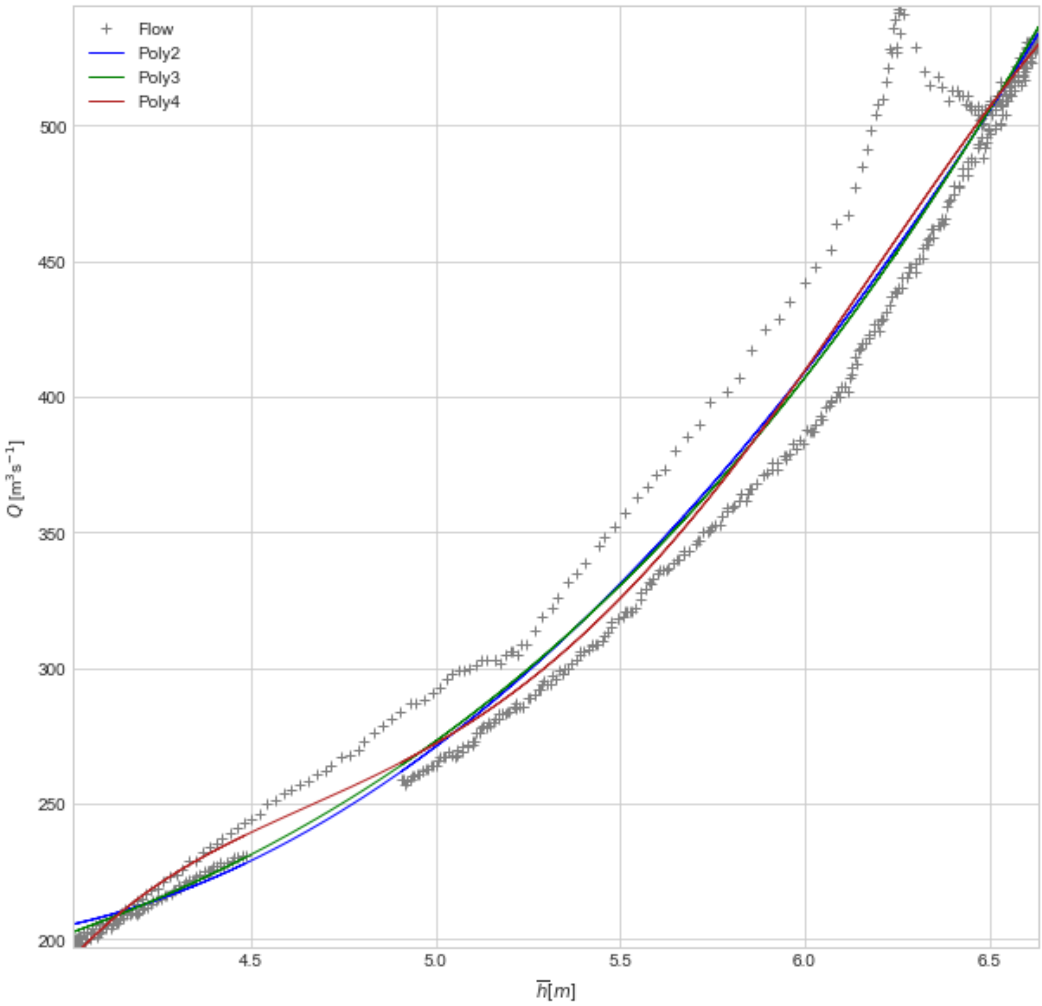


Figure 9: A graph showing the relationship (grey crosses) between raw flow data Q and river level data $\overline{h}$ for the flood event on the River Ouse at the Skelton monitoring station from 25th December to the 31st December 2015. Polynomials of degrees 2 (blue), 3 (green) and 4 (red) were fitted using the polyfit. function in Python.

3.5 Mitigation Plans

In March 2016, York received £45.2 million in response to the December 2015 floods to improve the Standard of Protection (SoP) against flooding[12]. In November 2016, the Environment Agency published the York Five Year Plan which divided York into 10 communities and outlined potential flood mitigations for each of these[33]. Further assessments identified 29-30 "*flood cells*" where flooding occurs in a specific way [32]. Only 19 of these flood cells are being considered for investment in flood mitigation as the remaining do no meet the DEFRA cost-benefit ruling. The aim of the York Five Year Plan is to better protect 2,000 properties in York by implementing measures from 2015-2021.

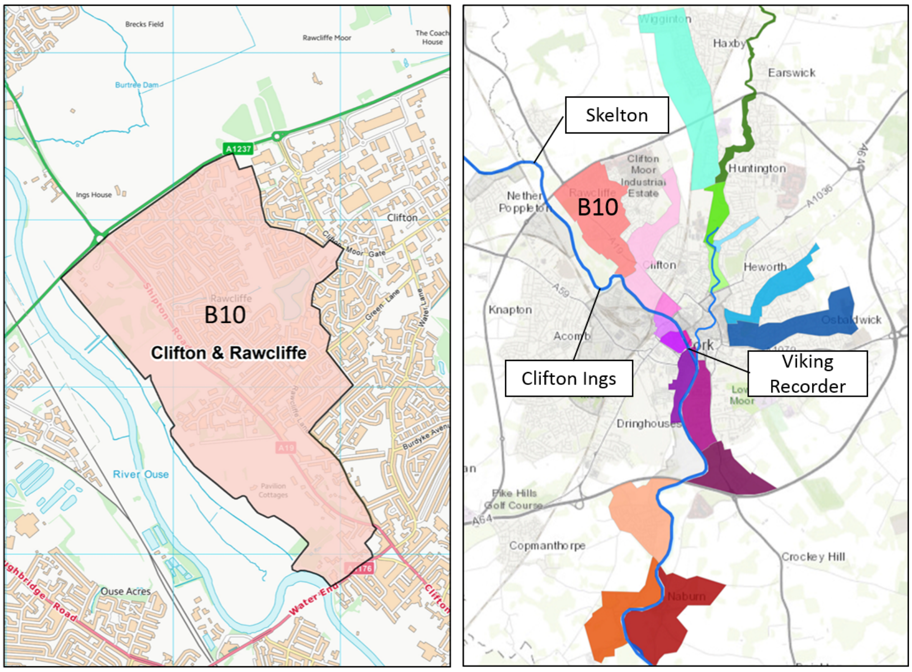


Figure 10: The picture on the left shows the Clifton and Rawcliffe flood cell (B10) [18] and the picture on the right shows the other flood cells (indicated by coloured and grey shaded regions) in York [32]. The coloured regions are flood cells where investment in flood mitigation is being considered and grey shaded regions are flood cells where investment is not being considered due to a failure to meet cost-benefit ruling. The labels on picture on the right show the locations of the 3 river monitoring stations upstream of the confluence between the River Ouse and River Foss.

A cost-effectiveness analysis is performed on one of these flood cells located upstream of the city of York in the following sub sections. The flood cell *Clifton & Rawcliffe* , (reference B10) has been selected for analysis due to its location and the availability of data. It is located upstream from the confluence of the River Foss and hence fluvial flooding is assumed to be caused only by the River Ouse and downstream from the Skelton Monitoring station. The planned work and more than 100 associated documents are available online for the public to view [12].

3.6 Clifton & Rawcliffe (B10)

The Clifton and Rawcliffe (B10) flood cell contains the existing flood defence Clifton Ings. Clifton Ings is an off-line flood-attenuation reservoir which is operated to fill with water from the River Ouse during a flood event [11]. During a flood, the Clifton Ings Inlet opens and diverts water into an area which is enclosed by embankments(raised land). Part of the Clifton Ings is a Site of Special Scientific Interest (SSSI); home to rare meadow grassland species such as the Tansy Beetle [32].

As part of York's Flood Alleviation Scheme for the Clifton and Rawcliffe community, improvements to the existing flood defences in this flood cells are planned with the purpose of further protecting 140 properties in this area [18]. The planned work for this flood cell is complex and and not all projects are motivated by directly reducing flood risk.

An outlet pump station is planned to be installed at Blue Beck to increase the rate flood water can be released and hence minimise the time rare habitat is submerged with water.Existing embankments are planned to have their angle of incline reduced and foot print increased in order to improve structural stability. Culverts are planned to be extended due to modifications to the incline of embankments. Drainage works and creation of compensatory SSSI grassland are also planned however exact details have not been confirmed [12] and hence will not be considered subsequently.The the installation of the Blue Beck pump station and the extension of culverts are not expected to increase the volume of water stored by Clifton Ings. Modifications to the angle of incline to embankments are predicted to reduce the storage volume of Clifton Ings by a maximum of 52,900m^3[34].

A southern extension of existing embankments is planned in the form of a concrete flood wall. A northern extension of existing embankments in planned in the form of grass embankments. All existing embankments are planned to be raised. These projects are predicted to increase the volume of water stored by Clifton Ings. Estimations of changes to storage volume and costs for this project are detailed in the following subsection.

3.6.1 Effectiveness Calculations

The effectiveness of this investment can be quantified by the additional storage volume of water it affords. In the absence of hydraulic modelling, this can be calculated by approximating the shape of the storage area to a cuboid and calculating the change in volume as a result of raising existing embankments. Information on the increased surface area as a result of the southern and northern extensions could not be found. It is assumed that the increase in surface area and hence the storage volume of Clifton Ings gained through the southern and northern extensions is equal to the storage volume lost as result of modifications to the incline of existing embankments.

Where a range of 2 values $[x_i, x_{ii}]$ is quoted, the mean $\overline{x}$ has been taken to the true value and half the difference Δx between x_i and x_{ii} is taken to be error. Values are written in the following form.

$$x = \overline{x} \pm \frac{\Delta x}{2} \quad \text{where} \quad \Delta x = (x_{ii} - x_i) \tag{4.5.1aa}$$

The current storage volume of Clifton Ings V_c is quoted as $V_c \in [2.30, 2.45]$ Mm^3 in [11][12].

$$V_c = (2.38 \pm 0.08)\text{Mm}^3 \tag{4.5.1a}$$

The current height z_c of existing embankments is quoted as $z_c \in [10.95, 11.80]$ mAOD in [12], where mAOD (meters Above Ordnance Datum) is measuring scale in meters relative to a defined height.

$$z_c = (11.38 \pm 0.43)\text{mAOD} \tag{4.5.1b}$$

The planned height z_p of embankments after the land has settled is quoted to be the following [12]

$$z_p = 11.86\text{mAOD} \tag{4.5.1c}$$

The representative surface area of the S_c of the defence can be calculated by dividing the current volume V_c by its current height z_c. This can then be multiplied by the planned height z_p to find the planned volume V_p. The difference in the planned volume V_p and the current storage V_c is the additional storage volume V_{B10} afforded for mitigation.

$$S_c = \frac{V_c}{z_c} \quad , \quad V_p = z_p S_c \quad , \quad V_{B10} = \big(V_p - V_c\big) \tag{4.5.1d}$$

Combining the equations above, the additonal storage volume V_{B10} can be expressed in the following way.

$$V_{B10} \approx V_c\left(\frac{z_p}{z_c} - 1\right) \tag{4.5.1e}$$

Letting δ denote the error in variables e.g the error of the current volume V_c is $\delta V_c = 0.08$ Mm^3. The additional storage volume $V_{B10} = V_{B10}(V_c, z_c)$ is a function of V_c and z_c which both have associated errors. By error proprogation rules, the error in additional storage volume δV_{B10} can be estimated.

$$\begin{aligned} \delta V_{B10} &\approx \sqrt{\left(\frac{\partial V_{B10}}{\partial V_c}\right)^2 \delta {V_c}^2 + \left(\frac{\partial V_{B10}}{\partial z_c}\right)^2 \delta {z_c}^2} \\ &= \sqrt{\left(\frac{z_p}{z_c} - 1\right)^2 \delta V_c^2 + \left(-\frac{V_c z_p}{z_c^2}\right)^2 \delta z_c^2} \end{aligned} \tag{4.5.1f}$$

Inputting values into the equations (4.5.1e)(4.5.1f) above, the additional storage volume V_{B10} and its error δV_{B10} can be calculated.

$$V_{B10} \approx (0.10 \pm 0.09)\text{Mm}^3 \tag{4.5.1g}$$

3.6.2 Cost Calculations

A high-level cost prediction has been performed which estimates the total of capital costs and operation and maintenance costs for a period of 5 years (the timescale of the York's Plan) and 50 years (the typical design time of flood defences [34].These do not include enabling costs (e.g design),decommissioning costs(e.g destruction), optimism bias or considerations of inflation. Cost estimations are taken from the evidence directories provided by the Enviromental Agency [13][16][14][17][15].

Where a range of target conditions grades are presented, target grade 3 is chosen. Where a range of mechanical and manual clearance operation and maintenance costs are presented for embankments and walls, the manual costs are considered. Where exact dimensions (e.g cross-sectional areas σ, diameters and lengths) are not explicitly stated, these have been estimated using information available in planning documents. Where a broad range of costs £$[c_{min}, c_{max}]$ are presented, a weighting and scoring methodology is applied, as directed by the evidence directories aforementioned. Factors are presented with different weights(typically 1-2) and scored (typically 0-2). For each factor, the weight and score are multiplied together to give a weighted score s. A total weighted score s_{total} is found by the summation of the weighted scores for each factor. The ratio between the total weighted score s_c and the maximum possible weighted score s_{max} is multiplied by the difference between the maximum cost c_{max} and the minimum cost c_{min} to estimate a representative cost c_{rep}.

$$c_{rep} = c_{min} + \left(\frac{s_{total}}{s_{max}}\right)\big(c_{max} - c_{min}\big) \tag{4.5.2a}$$

<u>**Blue Beck Pump Station**</u>

Limited information on the pump capacity could be found in the general planning documents [12] and hence it is assumed that a medium pump with a capacity ranging from 50-200 l/s will be installed. The capital cost is estimated as £227,000 [13]. The annual operation and maintenance costs are estimated at £11,000 for running and maintenance and £8,000 for refurbishments, totalling £19,000 [13]. Hence operation and maintenance costs are estimated as £95,000 and £950,000 for 5 and 50 years respectively. The high-level cost estimates of this project is thus £322,000 and £1,177,000.

	Capital	O&M *(5 years)*	O&M *(50 years)*
Cost	£227,000	£95,000	£950,000
Total	-	£322,000	£1,177,000

Table 4: A table showing the high-level cost-estimation breakdown for the installation of a pump station at Blue Beck. The final row is the total of the capital costs and the operation and maintenance costs for 5 years and 50 years. Capital costs came from Table 1.2 in [13] and operation and maintenance costs (abbreviated to O&M in the table) came from Table 1.3 in[13]

Culverts

According to submitted planning documents [19] the culvert is planned to be 10m long with a diameter of 1.2 m and hence a cross-sectional area $\sigma = 1.13\text{m}^2$. The capital cost of a target condition grade 3 culvert of length 10m and cross-sectional area $\sigma = 1.0\text{m}^3$ is quoted as £10,600 per metre length [14]. Hence the capital costs for this project is estimated as £106,000. The operation and maintenance cost for a target condition grade 3 culvert of diameter 0-1.2 m and length 0-20 m ranges from $£340 - 3,600$ per annum per culvert [14]. A weighted scoring system was performed to obtain a representative cost c_{rep} as detailed in (4.5.2a).

$$\begin{aligned} £[c_{min}, c_{max}] &= £[340, 3,600] \qquad s_{total} = 5 \qquad s_{max} = 10 \\ c_{rep} &= £340 + \left(\frac{5}{10} \times (£3,600 - £340)\right) \\ &= £1,970 \end{aligned} \tag{4.5.2.b}$$

Hence the operation and maintenance costs are estimated as £9,850 and £98,500 for 5 and 50 years respectively.The high-level cost estimates for this project is thus £115,850 and £204,500.

	Capital	O&M *(5 years)*	O&M *(50 years)*
Cost	£106,000	£9,850	£98,500
Total	-	£115,850	£204,500

Table 5: A table showing the high-level cost-estimation breakdown for extending existing culverts. The final row is the total of the capital costs and the operation and maintenance costs for 5 years and 50 years. Capital costs came from Table 1.1 in [14] and operation and maintenance costs (abbreviated to O&M in the table) came from Table 1.5 in[14]. A weighted score was obtained using Table 1.7 in [14]

Southern Extension

According to submitted planning documents [12], a wall of height 1.0-1.2m and length 55m is planned to be built. The capital cost of a target condition grade 3 concrete wall in the height band 0-1.2m is £1,419 per metre length[17]. Hence the capital cost can be estimated as £78,045. The operation and maintenance cost for the manual clearance for target condition grade 3 concrete walls ranges from £125-£565 per year per kilometer[17]. A weighted scoring system was performed to obtain a representative cost c_{rep} as detailed in (4.5.2a).

$$\begin{aligned} £[c_{min}, c_{max}] &= £[125, 565] \qquad s_{total} = 8 \qquad s_{max} = 12 \\ c_{rep} &= £125 + \left(\frac{8}{12} \times (£565 - £125)\right) \\ &= £418 \end{aligned} \tag{4.5.2.c}$$

The distance of the wall is 0.055 km. Hence the operation and maintenance costs are estimated as £115 and £1,150 for 5 and 50 years respectively. The high-level cost estimate of this project is thus £78,160 and £79,195.

	Capital	O&M *(5 years)*	O&M *(50 years)*
Cost	£78,045	£115	£1,150
Total	-	£78,160	£79,195

Table 6: A table showing the high-level cost-estimation breakdown for the southern extension of the existing embankments by the construction of a wall. The final row is the total of the capital costs and the operation and maintenance costs for 5 years and 50 years. Capital costs came from Table 1.1 in [17] and operation and maintenance costs (abbreviated to O&M in the table) came from Table 1.11 in[17]. A weighted score was obtained using Table 1.15 in [17].

Northern Extension

According to submitted planning documents [20] an embankment of approximate cross-sectional area $\sigma = 10.55\text{m}^2$ and a length of 550m. Multiplying these dimensions together, the embankment is planned to have a volume of 5,803m^3. The capital cost for an embankment in volume band $5,000 - 15,000\text{m}^3$ is £64 per m^3[17]. Hence the capital cost can be estimated as £371,360. The operation and maintenance cost for the manual clearance of a target grade 3 embankment is £1385-£17,225 per year per kilometer [17].A weighted scoring system was performed to obtain a representative cost c_{rep} as detailed in (4.5.2a).

$$\begin{aligned}
\pounds[c_{min}, c_{max}] &= \pounds[1,385, 17,225] \qquad s_{total} = 5 \qquad s_{max} = 10 \\
c_{rep} &= \pounds 1,385 + \left(\frac{5}{10} \times (\pounds 17,225 - \pounds 1,385)\right) \\
&= \pounds 9,305
\end{aligned} \tag{4.5.2.c}$$

The distance required to be travelled is estimated as 2.2km. Hence the operation and maintenance costs are estimated as £102,355 and £1,023,550. The high-level cost estimates for this project are thus £473,715 and £1,394,910.

	Capital	O&M *(5 years)*	O&M *(50 years)*
Cost	£371,360	£102,355	£1,023,550
Total	-	£473,715	£1,394,910

Table 7: A table showing the high-level cost-estimation breakdown for the northern extension of the existing embankments by the construction of grass embankments. The final row is the total of the capital costs and the operation and maintenance costs for 5 years and 50 years. Capital costs came from Table 1.4 in [17] and operation and maintenance costs (abbreviated to O&M in the table) came from Table 1.10 in[17]. A weighted score was obtained using Table 1.14 in [14].

Embankment Modifications

According to submitted planning documents,modifications to the embankment will have a cross-sectional area $\sigma = 52.27\text{m}^2$ (See **A.5,Appendices**)[21] and a length of 1210m. Multiplying these dimensions together, modifications to the embankment will have a volume of $63,246\text{m}^3$. No information on embankment raising is detailed in [17][15], hence the costings for new embankments are used. The capital cost for an embankment in volume band $> 15,000$ m^3 is £33 per m^3 [17]. Hence the capital cost is estimated as £2,087,105. The current maintenance and operation activities are expected to cover modifications to the embankments hence no operation and maintenance costs are calculated. The high-level cost estimate of this project is thus £2,087,105

	Capital	O&M *(5 years)*	O&M *(50 years)*
Cost	£2,087,105	-	-
Total	-	£2,087,105	£2,087,105

Table 8: A table showing the high-level cost-estimation breakdown for the modifications to existing embankments.The final row is the total of the capital costs and the operation and maintenance costs for 5 years and 50 years. Capital costs came from Table 1.4 in [17]. Operation and maintenance activities are assumed to be covered by existing costs (abbreviated to O&M in the table).

4 Results and Discussion

4.1 2000 & 2015 FEV calculations

	Return Period [years]	V_{e_1} [Mm^3]	V_{e2} [Mm^3]	Difference
November 2000	1:50	24.32	25.15	(+3.41 %)
December 2015	1:40	10.34	10.49	(+1.50 %)
Ratio	-	2.35	2.40	2.27

Table 9: A table summarising the estimates of the FEV using the first estimate V_{e_1} (2.2.a) and the second estimate V_{e_2} (2.2.b) calculated for the floods in November 2000 and December 2015. The difference in the second estimate to the first estimate is calculated in the final column. The ratio between the estimates and their differences between both

For the flood in November 2000 with an return period of 1:50 years [22], the FEV was estimated as $V_{e_1} = 24.32\text{Mm}^3$ and for the flood in December 2015 with an approximate return period of 1:40 years, the FEV estimated was $V_{e_1} = 10.34\text{Mm}^3$. Using the York Detailed Hydraulic Model, the volume of water required to keep water levels of the River Ouse below existing flood defences is 9.47Mm^3 and 19.22Mm^3 for Annual Exceedance Probabilities (AEP) of 1%(+20% climate change) and 0.1 % respectively [11]. In the same report, the AEP for December 2015 flood is quoted as 1% and hence a comparison of the FEV and modelled volume can be made [11]. For the December 2015 floods, FEV calculated using the first estimate $V_{e_1} = 10.34\text{Mm}^3$ was 9.15% greater than the modelled value of 9.47Mm^3. This suggests that the analysis of hydrological to quantify the volume of a flood event is a good estimate, however more floods need to be assessed and compared to validated models to test this hypothesis. The volume generated by the York Hydraulic Model could then be used to determine the threshold height h_T. The calculated FEV using the first estimate $V_{e_1} \in [9.25, 9.61]\text{Mm}^3$ using $h_T \in [6.19, 6.20]$m hence implying that a better estimate of h_T lies within this range.

The FEV estimates for the flood in November 2000 are almost double those for the floods December 2015. This is expected as the associated return period of 1:50 years corresponds to a more extreme flood event than the associated return period. The difference between the first estimate V_{e_1} and V_{e2} for the flood in November 2000 is 3.4% and for the flood in December 2015 is 1.5%. Comparing (**Figure 6**) and (**Figure 8**), the flood in November 2000 has multiple flood peaks (periods of time where $\overline{h} \geq h_T$) whereas the flood in December 2015 only has one, suggesting that the second estimate V_{e_2} performs worse for the FEV analysis of multiple flood peaks. More flood events need to be assessed to test this hypothesis. For the flood in 2000, the second estimate V_{e_2} was calculated by manually extrapolating T_f from the raw data, instead of automatically via computation. This is a potential source of error can could contribute to the differing performance of the second estimate V_{e_2} for the floods in November 2000 and December 2015.

The rating curves $\hat{Q} = \hat{Q}(\overline{h})$ used to calculate the first estimate V_{e_1} were generated automatically using a polynomial of degree 4. A polynomial fit was was used due to the parabolic nature of raw flow Q and river level $\overline{h}$ data. Degree 4 was used as this minimised E in (4.1.b). Lower order polynomials had higher associated values of E implying a worst fit of the model. Higher order polynomials experienced over-fitting where the generated function $\hat{Q}$ oscillated and was not deemed representative. A rating curve is available for the Skelton monitoring station and has been valid since August 1992 hence could be used to predict the relationship between $\hat{Q}$ and the river level $\overline{h}$, however this function is not permitted to be published [22].

4.2 Effectiveness Calculation

The volume addition storage volume of Clifton Ings afforded by the raising the embankments is estimated as

$$V_{B10} \approx (0.10 \pm 0.09)\text{Mm}^3 \quad (4.5.1\text{g})$$

This is equivalent to 0.41% and 0.97% of FEVs estimated for the November 2000 and December 2015 floods respectively, which are very small proportion.

The error associated with this estimate is substantial, being 90% of the calculated vale. A large error is expected as the calculation is very empirical; using ranges and estimated geometries in place of exact values. The additional storage afforded by raising the embankments exclusively is not quoted [34].

The calculation for the the additional storage volume gained by raising the embankments V_{B10} assumes that the volume lost by reducing the angle of incline of embankments (approximated as 52,900 m^3 [34]) is equal the additional storage gained by the southern and northern extensions of the existing embankments.

Another metric used to quantify effectiveness could be the number of properties an investment is predicted to protect. The investment in Clifton and Rawcliffe flood cell in predicted to provide protection to 140 properties. The York Five Year Plan aims to improve protection to 2,000 properties. Hence 7% of the target number of properties could be protected.

4.3 Cost Calculations

	Cost Estimate *(5 years)*	Cost Estimate *(50 years)*
Blue Beck Pump Station	£322,000	£1,177,000
Culverts	£115,850	£204,500
Southern Extension	£78,160	£79,195
Northern Extension	£473,715	£1,394,910
Embankment Modifications	£2,087,105	£2,087,105
Total	£3,076,830	£4,942,710

Table 10: A table summarising the high-level cost estimates for the the investment in flood mitigation activities planned for the Clifton and Rawcliffe flood cell (reference B10). The first and second columns of costs show the scenarios where 5 and 50 years of operation and maintenance costs are considered respectively.

For the high-level cost estimates which includes 5 years and 50 years of operational and maintenance costs, the total cost estimate equates to £3.01M and £4.94M respectively. This amounts to an expenditure of 6.81% and 10.9% of the budget of £45.2M allocated by the Government in March 2016.

Embankment modifications are the most expensive project, costing almost 70% and 40% of the total cost estimates for the 5 year and 50 years operation and maintenance cost scenario. This is attributed to the large volume being added ($\approx 63,246\text{m}^3$) to existing embankments in-order to reduce their angle of incline. The motivation for reducing the angle of incline can be traced to 2013, before the December 2015 floods [12].This is reported as potentially reducing the storage capacity of Clifton Ings by a maximum of 52,900m^3, equivalent to less than 2.3% [34], however the volume gained through raising the existing embankments is not quoted.

The Blue Beck Pump Station and installation of Culverts are predicted to not increase the storage capacity of Clifton Ings and hence its effectiveness as a flood defence. However the total of these projects is almost 30% of the total cost estimate for the 50 year operation and maintenance scenario. This is due to the the annualised operation and maintenance costs of pump stations of £1,970.

Cost estimates were calculated using the Evidence Directories provided by the Environment Agency [13][16][14][17][15] which were published 4-5 years ago.With limited information available in the public domain, a number of assumptions have been made. Cost estimates for the drainage works and the SSSI compensatory grassland have not been included as not enough information about the projects in known at present. The scoring methodology leads to variability in cost-estimates when performed by different individuals as the scoring of factors in subjective. A high-level cost estimate has been performed by the author using the afore referenced evidence directories and planning documents in the public domain. These include capital costs and operation and maintenance costs, however have not included enabling costs (e.g preliminary design, investigations) which are expected to be significant provided there are more than 100 documents attached to the planning application [38].

4.4 Cost-Effective Assessment

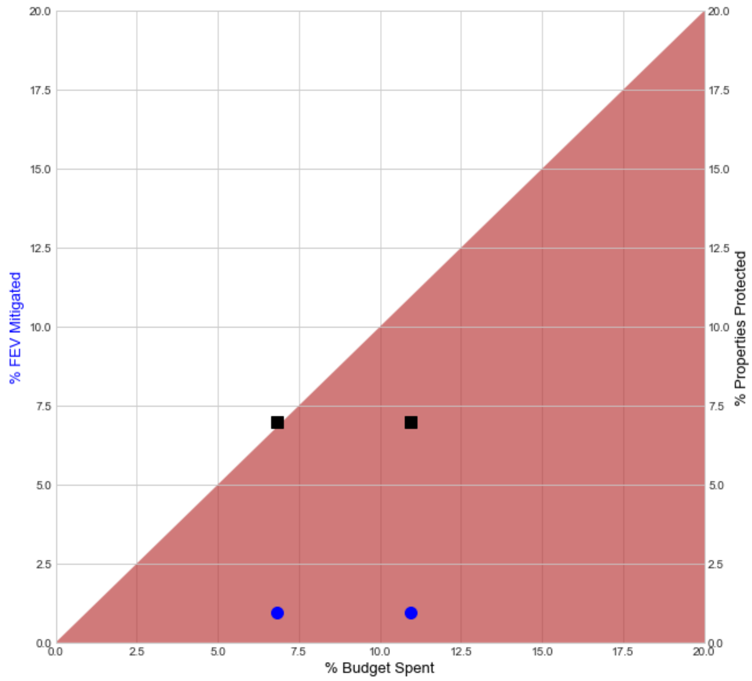


Figure 11: A graph comparing the estimated % of FEV mitigated, % properties protected and the estimated % of the £45.2 M budget spent for the flood mitigation planned for the Clifton and Rawcliffe flood cell B10. The blue dots relate to the FEV mitigated and the black squares relate to the properties protected. Two scenarios for the % budget are considered based on different timescales for operation and maintenance activities. The scenario for 5 years translates to 6.81% of the budget whilst the 50 year scenario translates to 10.9% of the budget. The red region represents investments which for 1% of the budget invested, less than 1% effectiveness is observed where effectiveness is defined by mitigation of the FEV or properties protected.

The generation of a partitioned square lake for analysis of the Clifton and Rawcliffe flood mitigation scheme is deemed appropriate as the flood volume is mitigated by only via improvements to existing flood defences and not a suite of separate ones.

Instead, comparison of the estimated cost of the this project, the volume of water it mitigates and the the properties it protects can be undertaken to determine the cost-effectiveness. Cost-effectiveness can be defined as 1% of the budget being spent delivering $\geq$ 1% of the the effectiveness criteria (represented by the white region in **Figure 5**). The budget is taken to be £45.2 M.

Effectiveness can be defined as the % of FEV mitigated by the investment (represented by the blue dots in **Figure 5**). Planned work for the Clifton and Rawcliffe flood cell is estimated to only mitigate 0.97%

of the FEV calculated using the first estimate for the flood in December 2015 and is estimated to cost 6.81% and 10.90% for the 5 year and 50 year operation and maintenance cost estimate scenarios. This corresponds to 1% of the budget delivering $\leq$ 1% of FEV mitigation in both scenarios. Hence, this investment is not deemed cost-effective for mitigating the FEV.

Effectiveness can be defined as the % of properties protected by the investment (represented by the black squares in **Figure 5**). Planned work for the Clifton and Rawcliffe flood cell is estimated to protect 7% of the target of 2,000 properties[33] and is estimated to cost 6.81% and 10.90% for the 5 year and 50 year operation and maintenance cost estimate scenarios. This corresponds to 1% of the budget delivering $\geq$ 1% for the 5 year scenario and $\leq$ 1% for the 50 year scenario. Hence, this investment is only deemed cost-effective for protecting properties for the 5 year scenario and not the 50 year scenario.

Cost-effectiveness for the protection to properties is only observed when operation and maintenance costs are considered for only 5 years. Overall, this investment is not predicted to be cost-effective when comparing the % of the allocated budget spent to the %FEV mitigated and % of properties protected.

4.5 Other Observations

There is no standardised way of choosing of h_T and, through the research of the author, it is not provided by the Environment Agency. One member of the the research group was told they would have to pay inorder to obtain this value. Questions are surrounded around why the threshold level h_T (i.e the level at which flooding occurs) is not known for river monitoring stations in the UK.

The evidence directories provided by the Environment Agency are not easy to use and do not connect cost with effectiveness. They require alot of information about planned mitigation work and technical and local expertise to perform the scoring methodology as part of the cost estimates. A comparison between and cost and effectiveness is also not made in them.

The on-going flood mitigation activities planned for York are complex to understand and rely on the York Detailed Hydraulic Model which is reported to only extend as far as Skelton [11].The reliance of the design of flood mitigation activities on this model, which has its own limitations, has the potential to result in ineffective flood mitigation.

The Environment Agency in York bid for money from the government in response to the December 2015 floods and then have invested it in private consultation with specialists such as AECOM [11], Mott MacDonald and Jacobs [34] who then all contributed to the design of current work. Questions remain around why private consultation was required and why the subject matter expertise was not available by the Environment Agency.

Of the 29-30 flood cells identified [32][34], the ones which have been dismissed for investment are predominantly rural and less populated than those in the city-centre. Questions are surrounded by the cost-benefit ruling system used to Environment Agency to determine where money will be invested in flood defences in York.

5 Conclusion

Flood-excess volume analysis of hydrological data can provide a quick way of quantifying the magnitude of a flood which can inform the design of flood mitigation. There is evidence, supported by hydraulic modelling in case of the December 2015 floods on the River Ouse, that the estimate generated can representative of the predicted volume of a flood [11].

York has a history of extreme flooding and is currently working on flood mitigation schemes to protect 2,000 properties affected by flooding using the 45.2M budget allocated by the government in March 2016. Their current strategy, which differs to the one outlined in the initial York Five Year Plan [33], divides York into 29-30 regions termed flood cells[32][12] which flood in different ways and hence require different solutions.

An assessment of the Clifton and Rawcliffe flood cell (B10) implies that it is only cost-effective in meeting the objective of protecting properties when 5 years of maintenance activities are considered. However it is not deemed to be cost-effective in mitigating the FEV for all cost estimates. Overall, the planned work for this area is not considered to be cost-effective.

6 Recommendations & Further Work

This is an ongoing project. All code generated can be found on GitHub[41] and links to the work of other members of this research group can also be found.

The validity of estimating the volume of a flood by analysing hydrological data needs to be tested. This could be performed by comparison with validated hydraulic models, however these also have limitations. Understanding the performance of the estimates for FEV is challenging as the exact volume of a flood event is not physically measured.

The validity of generating a rating curve using data from one flood event requires exploration. The morphology of rivers changes with time and hence so could the relationship between the flow and river level. Rating curves are typically generated using long time series of data and hence temporal changes in the relationship between the river level $\overline{h}$ could be lost. With the permission of the Environment Agency, the rating curve for Skelton could be compared to those generated for the floods in November 2000 and December 2015 could to assess their fit.

The arbitrary form of rating curves provided by the Environment Agency for many rivers requires investigating. The rating curves provided by the Environment Agency typically all have the same form (2.1.a). There are many different equations appropriate [8] and different monitoring stations may require different forms of ratings curves. A phenomena observed for at the Skelton monitoring station in November 2000 and December 2015 floodis *hysteresis*- where the relationship between raw discharge Q and river level $\overline{h}$ data is non-symmetrical during a flood. This is observable in a plot of the raw data for discharge Q and river level $\overline{h}$ where there appears to be two separate relations above and below fitted rating curves. A rating curve form has been established which fits both these individual relationships separately called the *Jones Formula* [37].

The cost-estimation evidence directories required alot of information about planned mitigation work and technical and local expertise (especially for the scoring methodology).It was observed that information about the effectiveness of mitigation solutions were also not in the same document.This requires escalation to the Environment Agency inorder to generate user-friendly resources which compare the cost and effectiveness of different flood mitigation solutions.

Hydrological data for the river levels of the River Ouse at Clifton Ings and the Viking Recorder monitoring stations for the flood events in November 2000 and December 2015 were also provided by the Environment Agency. These could be analysed to investigate relationships between the river level at these locations.

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A Appendices

A.1 FEV Analysis: River Aire, Armley 2015

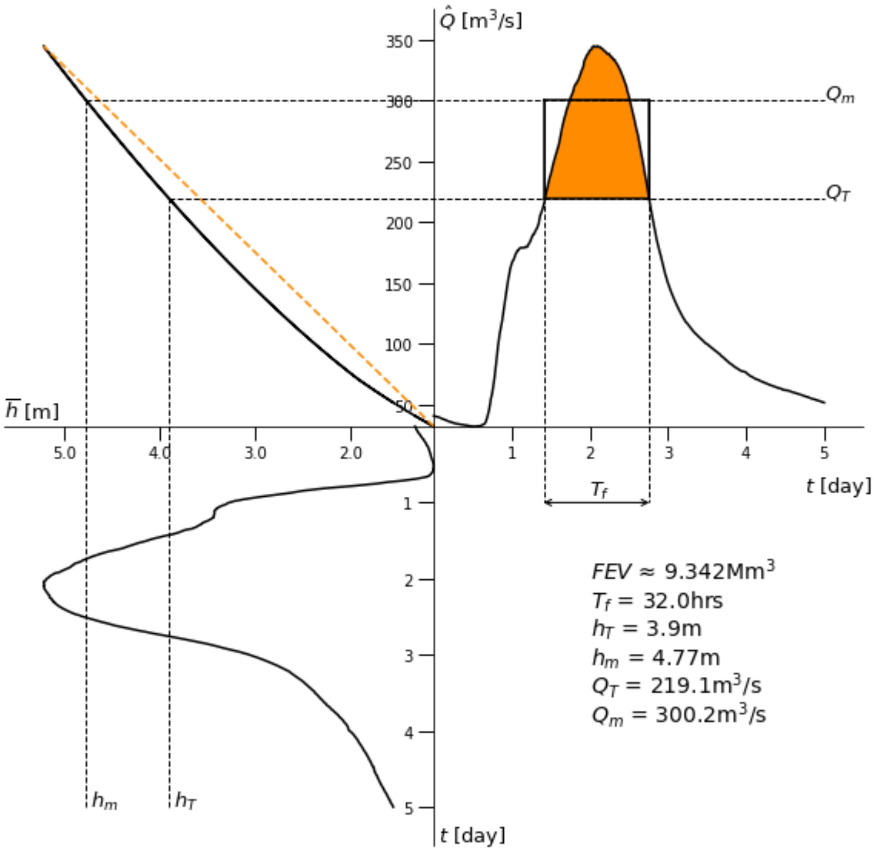
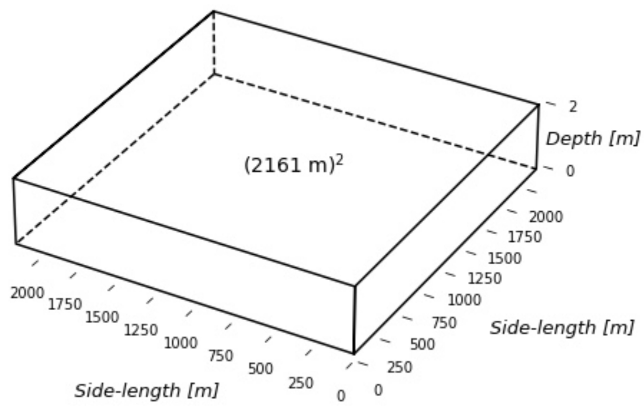


Figure 12: i)Above is a reproduction of the integrated hydrograph [7] for the River Aire at the Armley monitoring station for the flood event from 25th December to the 30th December 2015. The threshold level h_T was determined to be 3.9m through a review of eye-witness and hydrological data. The discharge was predicted using a rating curve [41] and the FEV was calculated automatically using the first estimate (2.2.a).An explanation of the regions of the graph can be found in **Figure 2**. ii)Below is the associated square lake for the calculated FEV with side lengths 2161m^2.



A.2 FEV Analysis: River Calder, Mytholmroyd, 2015

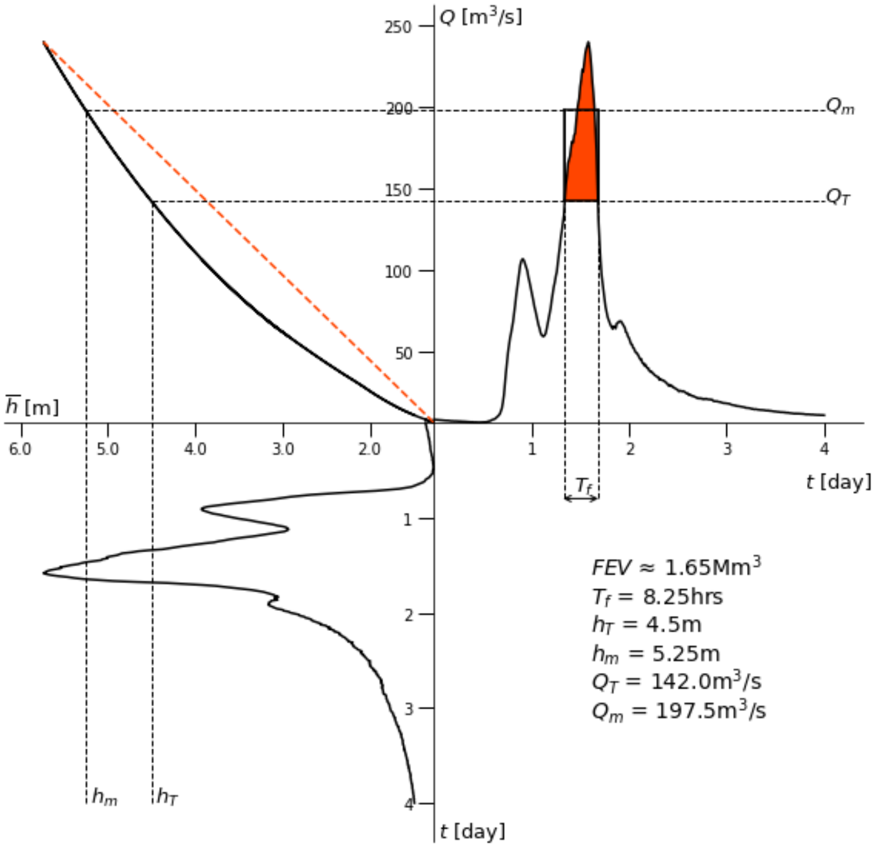
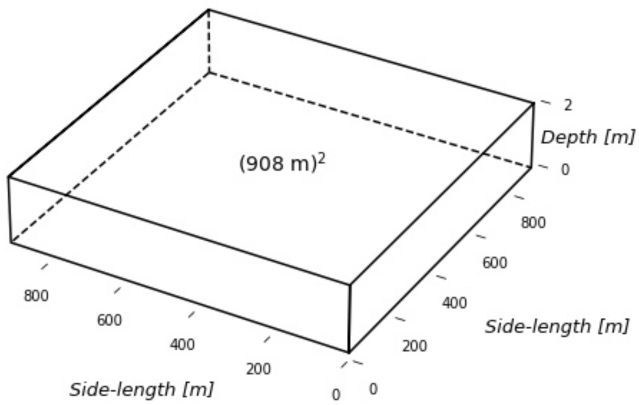


Figure 13: i)Above is a reproduction of ther integrated hydrograph [7] for the River Calder at the Mytholmroyd monitoring station for the flood event from 25th December to the 29th December 2015. The threshold level h_T was determined to be 4.5m through a review of flood warnings and eye-witness accounts. The discharge was predicted using a rating curve [41] and the FEV was calculated automatically using the first estimate (2.2.a).An explanation of the regions of the graph can be found in **Figure 2**. ii)Below is the associated square lake for the calculated FEV with side lengths 908m^2.



A.3 FEV Analysis: River Don, Hadfields, 2007

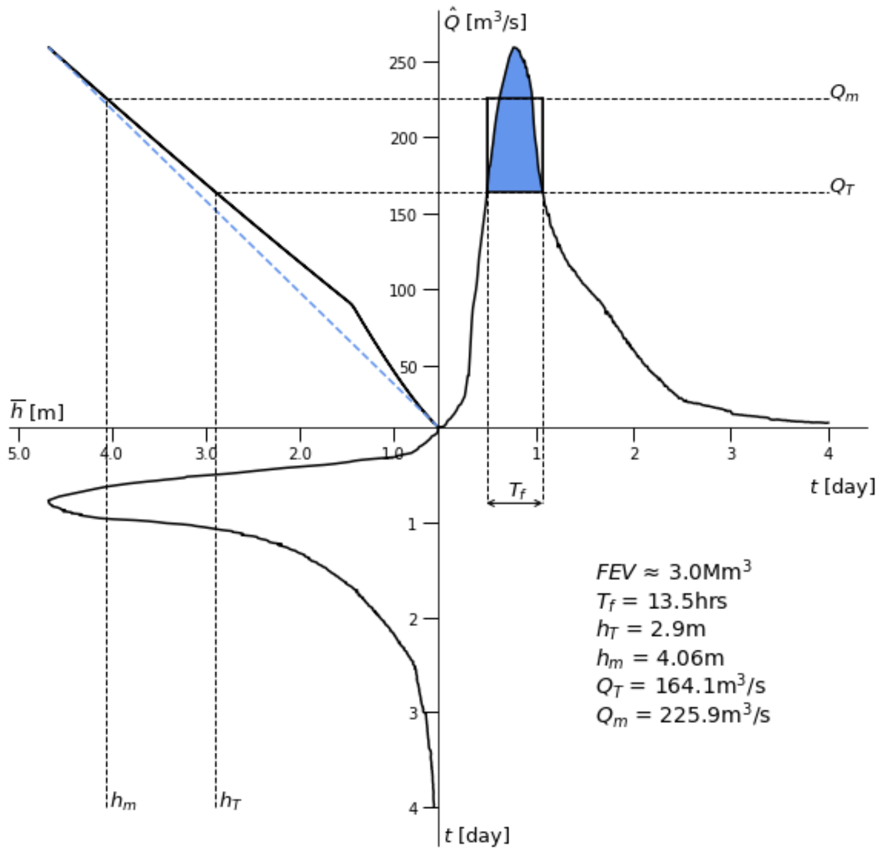
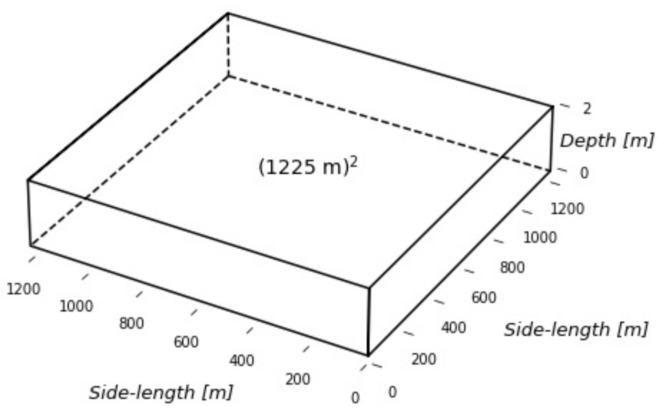


Figure 14: i)Above is a reproduction of the integrated hydrograph [7] for the River Don at the Sheffield Hadfields monitoring station for the flood event from 25th June to the 29th June 2007. The threshold level h_T was determined to be 2.90m through a review of historical data. The discharge was predicted using a rating curve [41] and the FEV was calculated automatically using the first estimate (2.2.a).An explanation of the regions of the graph can be found in **Figure 2**. ii)Below is the associated square lake for the calculated FEV with side lengths 1225m^2.



A.4 Comparison of Square Lakes

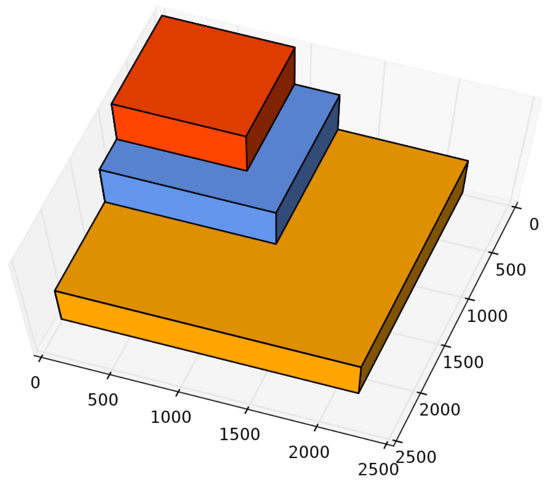


Figure 15: A 3D visual comparing the size of the 2m square lakes of the FEVs calculated using the first estimate (2.2.a) for the flood event in December 2015 on the River Aire (orange), in June 2007 on the River Don (blue) and in December 2015 on the River Calder.

A.5 Embankment Cross-section estimation

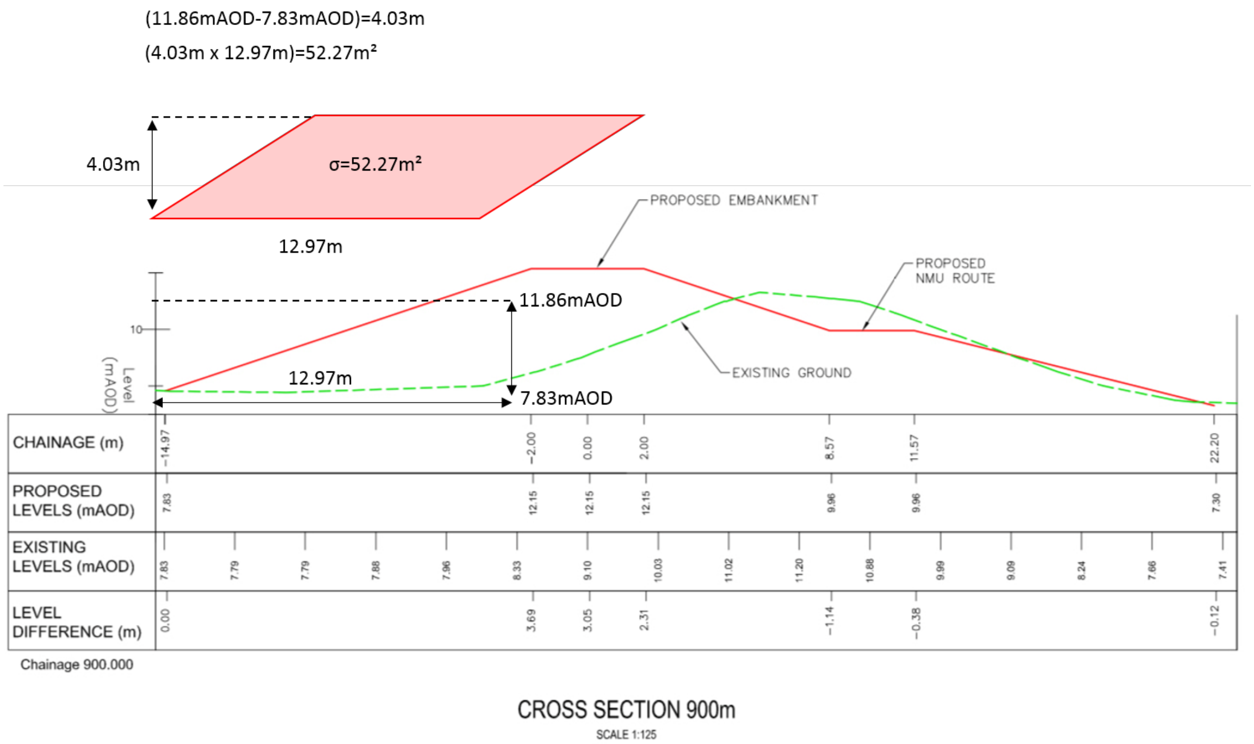


Figure 16: Picture taken from the planning documents [21] for planned modifications to embankments and annotations and workings used to estimate the cross sectional area σ for cost estimation calculations.