Dissertation for Bachelor of Science

Analysing the 2009 River Derwent flood event in Cumbria and investigating the most cost-effective flood-mitigation scheme

Yi Wang
201333389

Supervised by Onno Bokhove
Mathematics and Statistics

School of Mathematics, Leeds University

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Chapter 1

River Derwent Flooding

1.1 Introduction

Over the past century, sea levels in the UK have risen by an average of three millimetres per year. This is strong evidence that rainfall patterns in the UK are changing [15]. The World Health Organisation claims that floods are usually caused by heavy rainfall, rapid snowmelt, storm surges caused by tropical cyclones and coastal tsunamis [26]. This has meant that the UK has been suffering from severe flooding in recent years. And this was confirmed in reality. For example, the 2007 flooding of the River Trent, where 50,000 Gloucestershire homes were left without electricity, means that extreme disasters can cause huge costs and damage to the UK.
The aim of this report is to study site-specific flooding events, establish the concept of Flood-excess volume (FEV) and visualise FEV using code. We will analyse and learn from the measures that the government has proposed to manage flooding, develop our own scenarios and find the most cost effective methods of flood mitigation.

1.2 Derwent Flooding

2009 was the year with the fewest meteorological disasters in recent years, but a highly destructive flood in Cumbria in November still holds the UK record for 72 and 96 hours of rainfall.Cumbria recorded 372mm of rain between Wednesday 18 November and Friday 20 November 2009. Seathwaite received 314 mm of rain in the 24 hours ending at 00:45 on Friday. This was the daily rainfall record for Britain at the time.

I have used this flood as a case study for my research. I chose the Derwent River because Cokermouth, the most damaged area of the floods, was most affected by the Derwent River and I felt that studying the Derwent River would give the best estimate of the serious damage caused by the floods. I chose to focus on the data from the Lodore monitoring station because it is just downstream of Seathwaite where the most rainfall had occurred and it thus gives a more realistic picture of the damage.

1.3 Causes of flooding

1.3.1 Precondition

Before the Derwent floods, Cumbria had already received close to the whole-month November average rainfall before this event occurred. The very wet ground exacerbated high river flows and the extreme flood event of November 18th occurred. In addition, urbanisation also has a significant impact on flooding. Spaces such as Cokermouth have increased a mount of impermeable surfaces which means water gets to the river more quickly due increasing discharge [11].

1.3.2 Weather

As can be seen in Figure 1.1, between Wednesday 18th and Friday 20th a warm, moist south-westerly airstream was associated with a very deep Atlantic depression tracking slowly north-eastwards between Scotland and Iceland. A weather front within this airstream brought exceptionally prolonged and heavy rainfall for around 36 hours. This heavy precipitation was so severe that the rainwater spilled out of the ground as surface runoff before it could infiltrate further into the ground. This flow soon joined the Derwent. Bad weather and other antecedent causes were causing the river to increase in flow at a rapid rate.

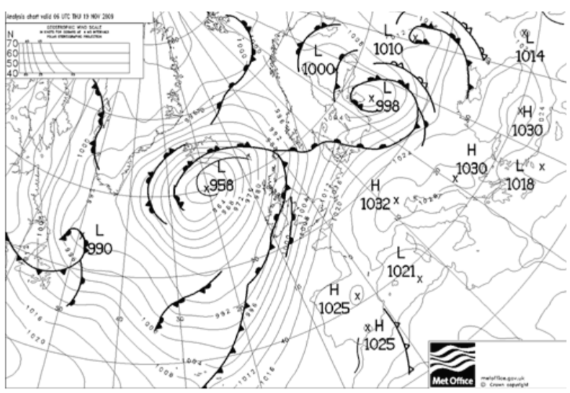
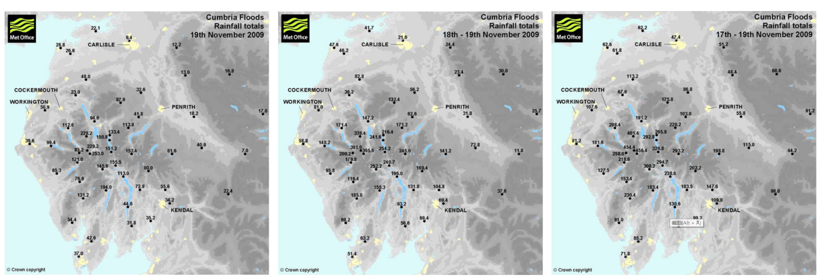


Figure 1.1: The synoptic situation at 0600 GMT on Thursday 19 November 2009. The air pressure at the centre of the cyclone is low, while the surrounding air pressure is high. The air flows in an anticlockwise direction towards the centre, creating a low-pressure state. The airflow rises vertically, cooling and condensing the water vapour contained in it, resulting in rainfall.

1.4 Total Rainfall

As is shown in Figure 1.2, the highest rainfall occurred at Seathwaite in Borrowdale, which was 316.4 mm in 24 hours – a UK record for any 24-hour period at that time. The rainfall during this event still holds the 72-hour record and the 96-hour record.

According to documents provided by the UK national weather service, these rainfall data indicates a return period exceeding 200 years for the 48- and 72-hour durations [7]. Return period refers to the mean time or estimated mean time between events such as floods. The estimates are based on the Flood Estimation Handbook (FEH) methodology. The Handbook introduces the concept of of Annual Exceedance Probability (AEP), which indicates the probability that a given rainfall total accumulated over a given period of time will be exceeded in any one year [12]. For example, if the return period is 1:100, the AEP=1%, which means, that regardless of when it last occurred, there is a 1% probability that this event will occur in a given location in any given year. The return period of the Derwent flood is 200 years, which means that the probability of a flood of the same magnitude occurring in the Derwent in any given year is 0.5%. This is a very small number, which means that flooding in the Derwent is very extreme.



(a) 24-hour rainfall totals 0900 19th to 0900 20th

(b) 48-hour rainfall totals 0900 18th to 0900 20th

(c) 72-hour rainfall totals 0900 17th to 0900 20th

Figure 1.2: Rainfall totals (mm) recorded by rain gauges during the 2009 Derwent flood. The rainfall is concentrated in the central part of the area, mainly in Seathwaite. It rises rapidly on the first two days and slows on the third.

Chapter 2

Methodology

2.1 Flood-Excess Volume (FEV)

2.1.1 Flood-Excess Volume

FEV is the river discharge at a certain time at which the river height $\bar{h}$ exceeds a chosen threshold h_T for that river in that area (Bokhove et al., 2020). T_f represents the duration of time from when the river height exceeds the threshold value to when it returns below the threshold value. The determination of the threshold is very important as it will determine the size of the FEV. This implies that as the threshold increases, T_f gradually shortens and FEV gradually decreases. The thresholds are different for each monitoring station on each river. When the Environment Agency cannot provide thresholds, we need to gather information from multiple sources to choose them ourselves.

2.1.2 Rating Curve

Before introducing FEV approximation, the concept of the rating curve must be understood. Usually monitoring stations are used to measure the height of a water surface cross-section (Bokhove et al., 2018). For rating curve $Q(\mathrm{m}/s^3)$, this can be written as

$$Q = Q(\bar{h}) \ or \ Q = Q(\bar{h}(t)). \tag{2.1}$$

Because some stations do not have the capacity to measure discharge, the Environment Agency (EA) usually uses the coefficient of fit for river discharge Q as a function of river height h. The formula is written as

$$Q = a_j \left(\bar{h} - b_j\right)^{c_j}, j = 1, ..., N. \tag{2.2}$$

We divide the measured river into different upper and lower bounds, also called stages or limbs, and for each $h_{j-1} < \bar{h} < h_j$ for j=1,...,N, the EA gives different coefficients (Bokhove et al., 2020). Using different coefficients for different water levels allows for a better fit of the flow Q.

2.1.3 FEV Approximation

With equation 2.2 we have mastered the approximation of the river discharge Q. If we have the frequently record of level $\bar{h}$ and a rating curve Q, the first equation for FEV can be obtained,

$$V_{e1} \approx \sum_{k=1}^{N_m} \left(Q\left(\bar{h}_k\right) - Q_T\right) \Delta t. \tag{2.3}$$

N_m represents the number of times the flow $Q(h)$ exceeds the threshold flow $Q(h_T)$, so $Q(h)$ in the equation must be greater than $Q(h_T)$. Δt is the time interval of the measurement, and we can write $\Delta t = T_f/n$ when we know the flood duration T_f. And as Δt decreases, the accuracy of V_{e1} increases. By increasing N_m infinitely and decreasing Δt infinitely, we set $N_m \to \infty$ and $\Delta t \to 0$, an integral equation can be obtained,

$$\lim V_{e1} = \int_{t_f}^{t_f+T_f} (Q(t) - Q_T)dt. \tag{2.4}$$

This equation can be shown as blue shading in the upper right quadrant on Figure 2.1. Then further we get rectangle area,

$$Q_{bar} = \left(\bar{Q}(h_T) - Q_T\right) T_f. \tag{2.5}$$

Q_m represents the average water flow rate above the threshold, where

$$Q_m = \bar{Q}(h_T) = Q(h_m), \tag{2.6}$$

which can be presented as a visualization in the upper right quadrant of Figure 2.1 in the form of a rectangle. This implies that equation 2.5 can be written as

$$Q_{bar} = (Q_m - Q_T)\, T_f. \tag{2.7}$$

The second method is used when only a small amount of information is known; for example, the water level and rating curve might not be known, but we still need to know the threshold h_T, the duration of the flood T_f, the maximum water flow Q_{max} and the corresponding maximum water level h_{max}. From this, we can calculate the average river discharge Q_m and the river discharge Q_T when the water level is at the threshold,

$$Q_m \approx \frac{h_m}{h_{max}} Q_{max}, \quad Q_T \approx \frac{h_T}{h_{max}} Q_{max}. \tag{2.8}$$

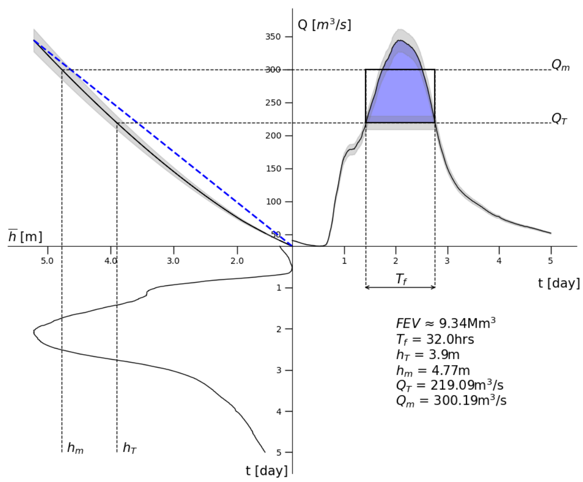


Figure 2.1: The quadrant plot for December 2015 flood of River Aire at Armley. The blue part in the upper right corner represents the FEV, which is not a regular graph so we can only estimate it. The top left corner represents the rating curve fitted by equation 2.2 and the coefficients provided by the EA. The bottom left corner represents the relationship between time and height. The error bar for this water level graph is 0.055.

Equation 2.8 and equation 2.7 can be used to obtain equation 2.9. As is shown in Figure 2.1, the part of the upper right-hand corner framed by the rectangular box column is trapezoidal, and the peak duration is approximately $T_f/2$. If the corresponding hydrograph is triangular with extremely short peak duration, equation 2.10 is more suitable, if the hydrograph is rectangular and peak duration is similar to T_f, equation 2.11 is more appropriate.

$$h_m \approx \frac{(3h_{max} + h_T)}{4}, \tag{2.9}$$

$$h_m \approx \frac{(h_{max} + h_T)}{2}, \tag{2.10}$$

$$h_m \approx h_{max}. \tag{2.11}$$

We then obtain an alternative form of the second estimation method,

$$V_{e3} = T_f \frac{Q_{max}}{h_{max}}(h_m - h_T) \tag{2.12}$$

It is clear and straightforward to see that V_e for the second method depends entirely on the setting of the threshold h_T. In other words, if the threshold is set to 0, then any flow above the lowest point of the river will be considered as a volume of water that will cause a flood hazard, which indicates the poor flood protection. Conversely, if the threshold is set to a very high point such as h_T=h_{max}, V_e=0, this is a flood mitigation measure which similar to the creation of a flood wall. Therefore, implementing flood mitigation measures to increase h_T can improve flood protection.

Chapter 3

Verification

To analyse the 2009 Derwent River flood, the authenticity of the existing code must first be verified. The existing data can be run with the previous code to reproduce the integrated hydrographs and square lake maps from previous research papers. If the resulting graphs are the same as in the respective paper, then the code is considered reliable. Another aim of this chapter is to add error bar .

To reproduce the integrated hydrographs and square lake maps, data sets were selected of the River Irwell flood in 2015 with error 0.1 and the River Calder flood in 2020 with error 0.14. Square lake map is a virtual two-metre deep square lake in which the FEV is collected. This allows a better visualisation of the size of the huge volume of water in the flood.

3.1 River Irwell Flood in 2015

The first integrated hydrograph and square lake of the River Irwell to be recreated is from Zhu (2020). Figure 3.1 shows the hydrograph successfully reproduced through Table 3.1.

k	$h_{k-1}\,[m]$	$h_k\,[m]$	$c_k\,\left[m^{3-b_k}/s\right]$	$b_k\,[-]$	$a_k\,[m]$
1	0.158	0.851	75.298	1.5728	0
2	0.851	2.1	75.224	1.8282	-0.024

Table 3.1: The coefficients a_k, b_k and c_k of upper and lower bounds for rating curve provided by Environment Agency.

As can be seen from the table, the three coefficients vary with increasing height. This is because the coefficients have corresponding limits. Thus for heights 0.158 to 0.815, the coefficients a_k, b_k and c_k are 0, 1.5728 and 75.298 respectively and for heights 0.815 to 2.1, the three coefficients become -0.024, 1.8282 and 75.224.

Therefore, the rating curve can be written as equation 2.2 in Chapter 2.

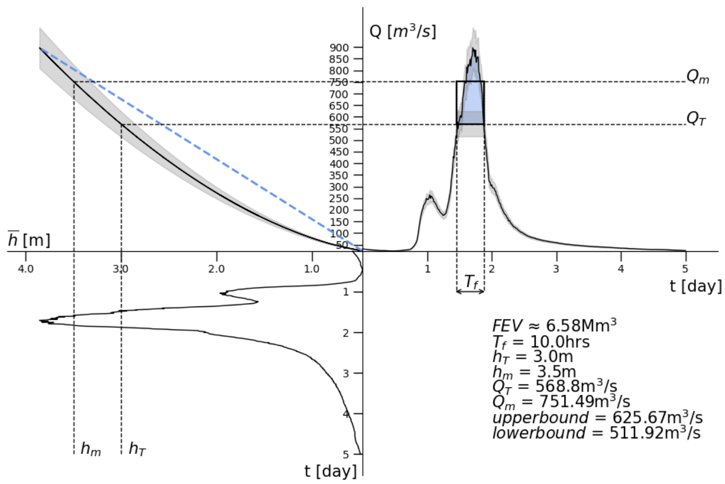


Figure 3.1: The quadrant plot for 2015 flood of River Irwell in Salford. The error rate is 0.1.

The blue dashed line in the upper left quadrant of Figure 3.1 shows the rating curve calculated from Table 3.1 and equation 2.2, and the solid black line next to it is its linear approximation. the lower left quadrant shows height versus time. The upper right quadrant shows the FEV versus time obtained by Q_m-Q_t. The blue shaded part is the FEV.

After calculating the FEV, to facilitate observation, we moved FEV to a two-meter-deep square lake, the length of which can be written as

$$side = \sqrt{\frac{FEV}{2}}. \tag{3.1}$$

Figure 3.2 shows a two metre deep square lake with a side length of 1,813 metres. The lake can hold approximately 5.95 billion cubic metres of water, which is the FEV of the 2015 flood of River Irwell in Salford.

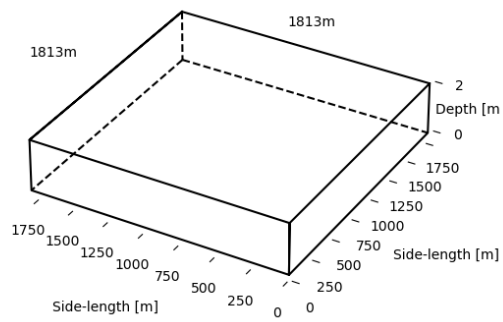


Figure 3.2: Two metre deep square lake for December 2015 flood of River Irwell in Salford.

3.2 River Calder Flood in 2020

The integrated hydrograph and square lake of river Calder we are going to recreate comes from Zhu (2020). Figure 3.3 below shows the hydrograph successfully reproduced through Table 3.2. Similarly to those of the River Irwell, the co-

k	$h_{k-1}\ [m]$	$h_k\ [m]$	$c_k\ \left[m^{3-b_k}/s\right]$	$b_k\ [-]$	$a_k\ [m]$
1	0	2.107	8.459	2.239	0.342
2	2.107	3.088	21.5	1.37	0.826
3	3.088	5.8	2.086	2.515	-0.856

Table 3.2: The coefficient a_k, b_k and c_k of upper and lower bounds for rating curve provided by Environment Agency.

efficients for the River Calder vary with height. However, it is worth noting that there are three bounds on the height of the River Calder.Thus for heights 0 to 2.107 the three coefficients a_k, b_k and c_k are 0.342 , 2.239 and 8.459 respectively, for heights 2.107 to 3.088 the coefficients become 0.826, 1.37 and 21.5, and when the height goes from 3.088 to 5.8 the coefficients become -0.856, 2.515 and 2.086, respectively. We can then substitute the data into equation 2.2 to obtain the rating curve. The blue dashed line in the upper left quadrant of this graph shows the rating curve calculated from Table 3.2 and equation 2.2, and the solid black line next to it is its linear approximation. the lower left quadrant shows height versus time. The upper right quadrant shows the FEV versus time

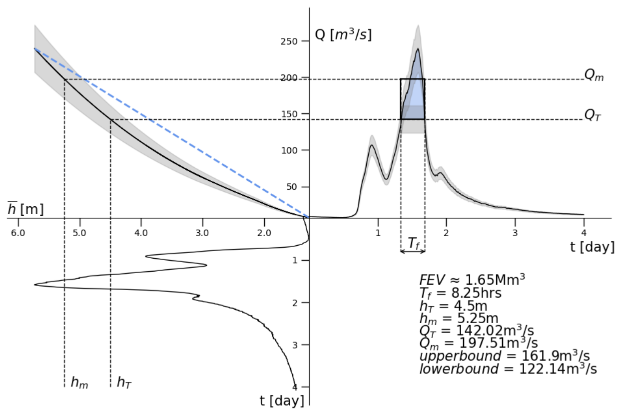


Figure 3.3: The quadrant plot for 2020 flood of River Calder. The error rate is 0.14.

obtained by Q_m-Q_t.The blue shaded section is the FEV.

As in the previous analysis for the River Calder, the FEV was calculated and then placed in a two metre deep square lake.

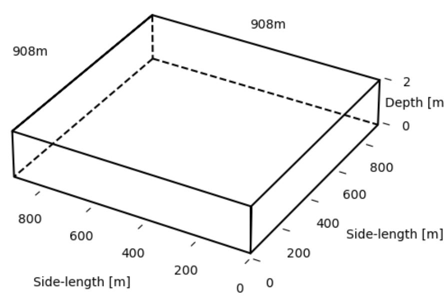


Figure 3.4: Two metre deep square lake for 2020 flood of River Calder. It shows a two metre deep square lake with a side length of 908 metres. The lake can hold approximately 1.65 million m_3 water.

Chapter 4

Application of FEV

4.1 Overview

As shown in Figure 4.1, the River Derwent is located in Cumbria and it starts in Borrowdale and runs north through Derwent Water and Bassenthwaite Lake before flowing into the sea at Workington [1]. There have been two extreme events related to flooding in the history of the Derwent River, one in December 2015 and another one in November 2009, which is we explored.

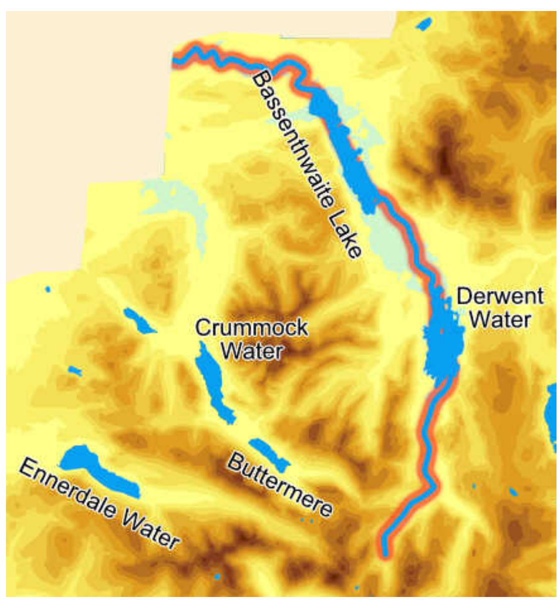


Figure 4.1: River Derwent starts in Borrowdale and flows from south to north before flowing into the sea from the west. The river is represented by the orange line in the image.

In the 2009 Cumbria flooding, the worst-hit areas were affected by flooding from the River Derwent, draining an area of the southern fells and flowing to the coast at Workington. In Workington, a police officer died (Met Office, 2009). 3,057 businesses were affected. The cost of damage to each household was on average £28,000. Insurance claims from the flood totalled £100 million (Government,2009).

4.2 Analysis

4.2.1 FEV Analysis

Cumbria was hit by severe flooding in November 2009. The worst affected area, Seathwaite, received 316mm of rainfall in 24h (Met Office, 2009). And Seathwaite received 456.4 mm of rainfall from the 17th to the 19th and 495 mm from the 16th to the 19th, setting British rainfall records of 72 and 96 hours respectively. I have therefore chosen data from Portinscale monitoring station, which is the nearest monitoring station to Seathwaite. The river height and flow required is from the Environment Agency. The code is from Yiting Zhu [3].

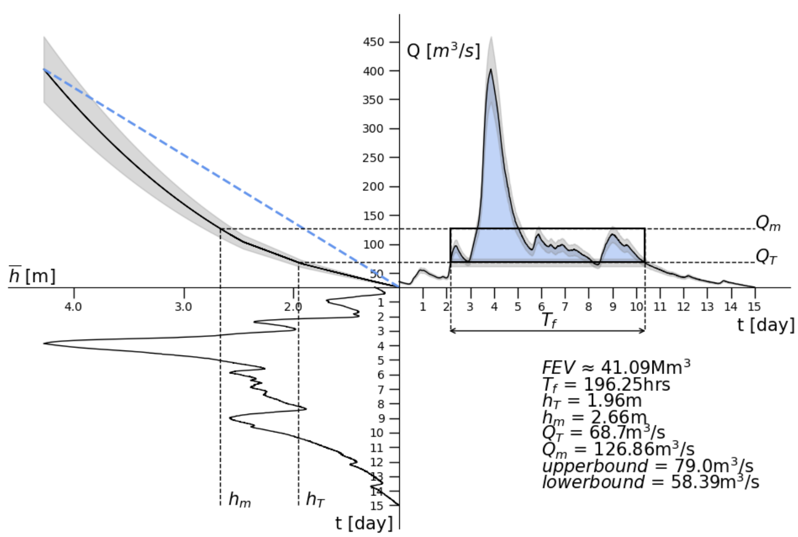


Figure 4.2: The quadrant plot for 2009 flood of River Derwent at Portinscale monitoring station. The grey shaded area is calculated with error rate of 0.15.

It can be shown that the threshold we have chosen is 1.96m. According to the rating curve on the upper left, the threshold discharge is 68.7 m^3/s. The solid black line next to the rating curve is its linear approximation. The long flood duration is 196.25 hrs. The lower left quadrant shows height versus time. The upper right quadrant shows the FEV versus. The blue shaded part is the FEV, which is 41.09 Mm^3.

It is worth noting that between the second and third day and the eighth and ninth day, we find a small period of time when the flows are rather vague. It is difficult to judge whether they are below average flows. Here we have chosen an error rate of 0.15, and with an FEV of 41 million m^3 for this flood, this part of the flow could well be covered by the error. For the purposes of calculation and analysis, therefore, they are treated here as above average flows, which means that there is only one peak for the entire flood period.

The possibility of a threshold is not unique. After checking the Portinscale monitoring station on GaugeMap, I found that the threshold for water levels around this station was around 1.36m [4]. On further searching, however, I found that, at Portinscale, the River Derwent had been recorded for at least 150 days in the last 12 months between 0.26 m and 1.96 m [5]. In 2021 Cumbria was flooded from 28 to 30 October. Compared to 150 days, 3 days is a very short period of time. We therefore think it would be more reasonable to raise the threshold to 1.96m and ensure that this value is sufficiently safe.

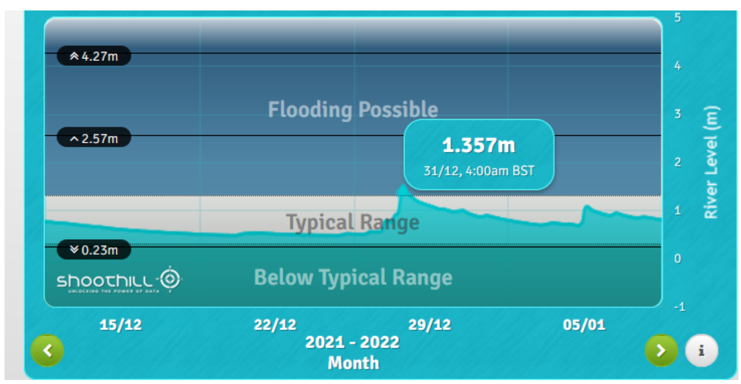


Figure 4.3: The river height of River Derwent from 26 December 2021 to 1 January 2022 at Portinscale monitoring station.

Figure 4.2 shows that the average discharge is 126.86m^3/s, the discharge at threshold is 68.768.7m^3/s, and the duration is 196.25hrs. Hence, equation 2.5 can be used to obtain a first approximation of FEV,

$$V_{e1} = T_f\left(Q_m - Q_T\right) = 196.25 * 3600 * (126.86 - 68.7) \approx 41.090Mm^3 \tag{4.1}$$

According to data provided by Environment Agency, the maximum river height h_{max} and maximum discharge Q_{max} are 4.271m and $402.30 m^3/s$ respectively. We have threshold, average height and flood duration already. Then we can use equation 2.10 get the second approximations of FEV,

$$V_{e2} = T_f \frac{Q_{max}}{h_{max}} (h_m - h_T) = 196.25 \cdot 3600 \cdot 402.30/4.271 \cdot (2.66 - 1.96) \approx 46.58 Mm^3 \tag{4.2}$$

4.2.2 Square Lake Analysis

The corresponding Square Lake is shown on Figure 4.4.

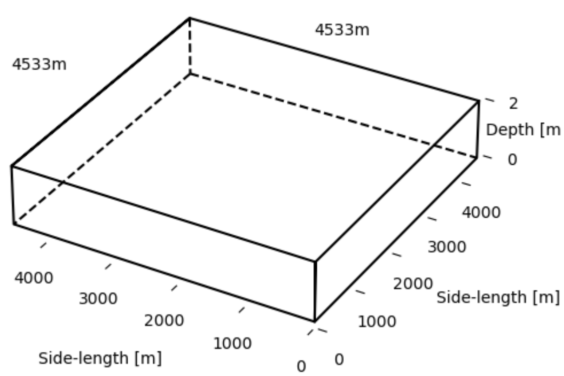


Figure 4.4: The 2m square lake of 2009 flood of River Derwent at Portinscale monitoring station. We can then obtain as a 4533 metre side according to the equation 3.1 for the side length and the volume is 41.09Mm^3.

To visualise the FEV, the FEV was moved into this 2-metre-deep square lake. Later in Chapter 5, we will look at this square as a plane and simulate the different flood mitigation scenarios.

Chapter 5

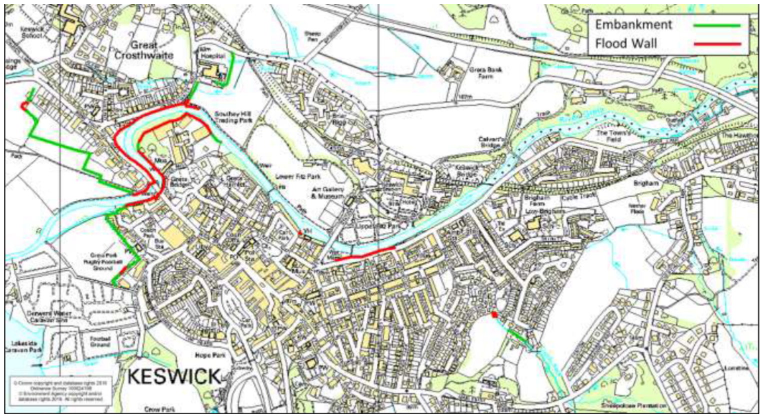
Flood Mitigation

5.1 Keswick

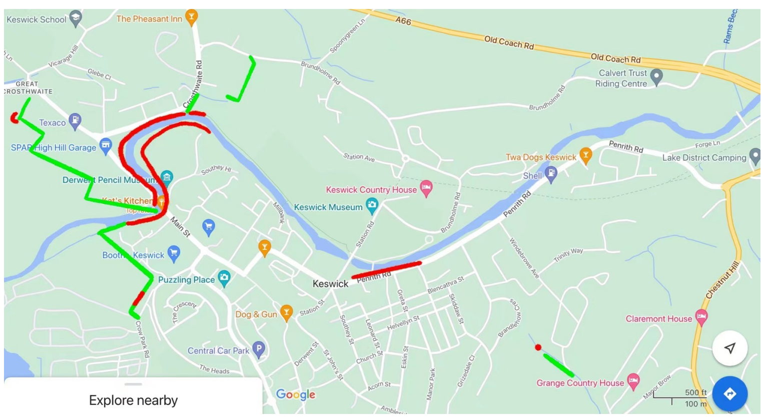
Cumbria has been hit by several severe floods in recent years. In 2009, the Environment Agency published the River Derwent Catchment Flood Management Plan (CFMP). In the CFMP, the Environment Agency divided the Cumbria area into sub-areas according to flood resources and flood risk levels, such as Keswick, Cockermouth, Wigton etc. [6]. The Keswick area is about two kilometres from the Portinscale monitoring station. The government has developed a flood-mitigation schemes for Keswick. We will analyse the government's proposed mitigation schemes and propose our own hypothetical scheme to find the most effective one in the following section.

5.2 Keswick Flood Risk Management Scheme

The Keswick Flood Risk Management Scheme was proposed after the 2005 and 2009 floods and work began in May 2011. The defences include flood walls, embankments and three flood gates [9].



(a) Map of the Keswick Flood Risk Management Scheme flood defences without scale published by the Environment Agency



(b) An equivalent-scale reproduction on Google Maps.

Figure 5.1: A map of the Keswick Flood Risk Management Scheme flood defences published by the Environment Agency and my equivalent scale reproduction on Google Maps. The scale is at the bottom right. The red line shows where the floodwall is located and the green line shows where the embankment is located.

Figure 5.1(a) does not include information on the length of the flood-protection defences, and so a map was created on Google Maps at equal scale from which the length of the embankments and the flood walls could be estimated.

Embankment

A road embankment is now a common method of flood protection. It protects against flooding by raising the slope from the original land. The shape of the embankment resembles a trapezoid with a wide bottom and a narrow top, and its footprint can be 15 metres wide, which gives it more space than is needed for a flood wall. For this reason, embankments are often built in the countryside. Relatively low costs is an advantage of the embankment, but in order to maintain the proper function of the embankment people need to inspect and maintain it regularly, including removal of unwanted weeds and dealing with nests holes by burrowing animals.

Embankments are typically between 1 m and 3 m high. Given the data references provided by the Environment Agency, we have assumed that the embankment in the Keswick Flood Risk Management Scheme is 2.5 metres high and that a footprint of 15 metres is required at its widest point [17]. The crest width of the Porto Tolle experimental embankment is 30 metres and the bottom 65 metres wide [35], which allows us to estimate the crest width of the embankment at Keswick to be 7 metres. The cross-sectional area of the embankment is therefore estimated to be 27.5 m^2. When measured on the reproduction map, the length of the embankment measured on the map was 23.3 cm, and when scaled up, the actual length of the embankment was 2330 m. We obtained a volume of 64,075 m^3 for the embankment.

Embankment unit costs

Volume band	Average (£/m^3)	Number of projects
< 500 m3	188	9
500 - 5,000 m3	94	28
5,000 - 1,5000 m3	64	11
> 15,000 m3	33	18

Figure 5.2: Cost per metre for the construction of different volumes of embankment provided by the Environment Agency [18].

Based on the data provided by the Environment Agency, we obtained an amount of approximately £2.8 million for the construction of the embankment. The embankment is approximately 2.5 m high and the river threshold rises from 1.9 m to 4.4 m. The River Greta near the Keiswick area is a tributary of the River Derwent and is approximately 30 m wide. This section of the river can therefore safely carry a volume of water of approximately 175,000 m^3. This represents approximately 4.3% of the total FEV of the River Derwent at the portinscale monitoring station in November 2009. Therefore, the embankment cost of mitigating 1% of the FEV is £0.65 million.

Flood Wall
A flood wall is usually a barrier constructed of vertical concrete elements. It is mostly erected in areas where space is limited. Floodwalls are more expensive than road embankments. Moreover, when the wall is built on permeable soil, it is likely that an additional impermeable barrier will be required [17].

In the UK, flood defences rarely exceed 5 metres, and those of 1 to 3 metres are more common [17], so we pick the average. Let us assume that the height of the new flood wall is 2 m. The red line in Figure 5.1(b) is approximately 24.2cm. In reality, then, the flood wall is approximately 2.42 km long.

Environment Agency Unit Cost Database wall raising and wall construction mean costs per m length

Height band	Wall raising (£/m)	All wall types (£/m)
<1.2m	1,029	1,419
1.2–2.1m	2,177	2,905
2.1–5.3m	–	3,577
>5.3m	–	11,168
All heights	1,526	2,984

Figure 5.3: Costs per metre for the construction of floodwalls of different heights according to the Environment Agency [19].

With the assumption that the wall is 2 m high, the cost of the flood wall is approximately £7 million. This section of flood wall would raise the threshold of the river derwent in the Keswick area from 1.9m to 3.9 m. This represents approximately 3.5% of the total FEV of the River Derwent at the Portinscale monitoring station in 2009. In other words, it would cost £2 million to manage every 1% of the FEV with flood walls.

It is worth noting that the River Derwent does not have an overall major flood alleviation scheme to date. The flood mitigation schemes discussed in this paper are local, and a major scheme of floodwalls tends to increase the percentage of protection to a higher level.

Figure 5.4: Photos of Keswick Flood Risk Management Scheme. The photograph on the left shows the flood wall along High Hill, with the steel and concrete wall encased in stone. The picture on the right also shows a reinforced concrete wall in Penrith Road with a flood gate below.

The aim of this scheme is to reduce the risk of damage to 182 properties from flooding at an APE = 1.3% [10]. However, the flood levels in December 2015 exceeded the Keswick Flood Risk Management Scheme's defences could withstand, so they were flooded but still provided time for people to respond to the flooding.

5.3 Hypothetical Flood Mitigation Schemes

GRR

The next hypothetical method we will explore is GRR, also known as living-room-to-the-river. This method mitigates flooding by widening the width of the river and increasing its cross-section. Firstly, we have to introduce the concept of Manning's formula. Manning's formula is a formula for calculating the flow rate of liquids in open pipes and channels [27]. The formula is

$$Q = \frac{K}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}, \tag{5.1}$$

where n is the Manning coefficient, K=1.0 for SI units, R is the hydraulic radius and S is the gradient of the river [28]. Different coefficients of friction n need to be selected depending on the surface materials. Further simplifying this equation by defining A to be the cross sectional area and P to be the wetted perimeter, we can obtain the equation

$$Q = \frac{\sqrt{S}}{n} \frac{A^{\frac{5}{3}}}{P^{\frac{2}{3}}}. \tag{5.2}$$

We can use this equation as a basis for discussing the widening of the river. We define a widening of the river by w_{GRR} metres, with the widened portion being z_{GRR} metres from the riverbed and b is the transverse bank slope. Thus, the cross-sectional area A and the wetted perimeter P can be represented respectively as

$$A = w_{GRR}\left(h_T - z_{GRR}\right), P = \left(w_{GRR} + \left(h_T - z_{GRR}\right)\sqrt{1+b^2}\right). \tag{5.3}$$

Substituting A and P, we get

$$\Delta Q = \frac{\sqrt{S}}{n}\frac{w_{GRR}\left(h_T - z_{GRR}\right)^{\frac{5}{3}}}{\left(w_{GRR} + \left(h_T - z_{GRR}\right)\sqrt{1+b^2}\right)^{\frac{2}{3}}}, \tag{5.4}$$

which is discussed by Bokhove et al. [13]. Lastly, the original flow and the increased portion are added up to the flow after flood mitigation using GRR

$$Q_{GRR} = Q + \Delta Q. \tag{5.5}$$

Note that ΔQ is the formula for widening a river on one side, if both sides of the river are widened together twice the ΔQ is required.

The Derwent River is 60 miles long [29] and it would be highly unrealistic to widen the entire length of the river. We therefore selected the section of the river from the Portinsclae monitoring station to Bassenthwaite Lake National Nature Reserve. This section of the river is surrounded by flat land, with few villages and few roads, which would reduce the problem of compensating for houses and trees during the expansion of the river.

Figure 5.6 demonstrates the extension scenario for the Derwent River, where the solid line shows the present river cross-section and the dashed line shows the extended river cross-section. channel is 0.46 m from the river bed, 1.5 m high and extends 12 m towards the bank on each side. Thus, the cross-sectional area of the river is increased by 18 m^2 on each side of the river, giving a total of 36 m^2.

As stated earlier, the Derwent River begins at Borrowdale and ends at Workington, which are respectively $106m$ and $10m$ in elevation [30], and the river is 60 miles long. The river therefore has a gradient S of 0.001. The area of the river we are expanding is mostly agricultural land, so we have chosen a Manning coefficient of n of 0.035 [31]. The slope of the new river bank is similar to the original bank, which we denote by $sin^{-1}(1.5/b)$. b is estimated to give 1.7 based on the cross section. We can therefore calculate the river flow after GRR mitigation

$$Q_{GRR} = Q + \frac{\sqrt{0.001}}{0.035}\frac{\left(12\left(1.96-0.46\right)\right)^{\frac{5}{3}}}{\left(12+\left(1.96-0.46\right)\sqrt{1+1.7^2}\right)^{\frac{2}{3}}} = 68.9 + 17.45 * 2 = 103.6 \tag{5.6}$$

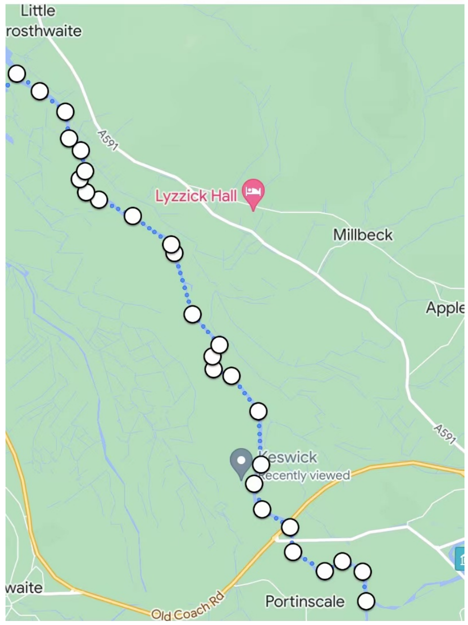


Figure 5.5: The section of the Derwent River from Portinscale monitoring station to Bassenthwaite Lake National Nature Reserve. The total length is 5 km.

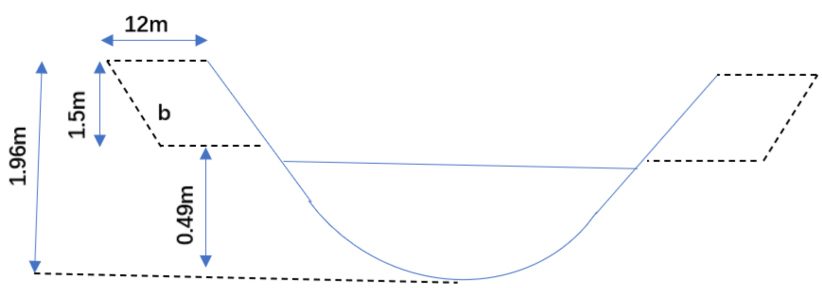


Figure 5.6: Cross section of derwent river extension.

Cost considerations for the GRR mitigation scheme need to be made in a variety of ways, such as excavation costs, bank reinforcement, maintenance costs etc. This cost estimate is rough and is only considered as a preliminary cost, more specific costs need to be analysed in further detail [32]. According to the Environment Agency's 2015 cost estimate, it would take £1,510 to create an open channel with a cross-sectional area of 30 m^2 [32]. As shown in Figure

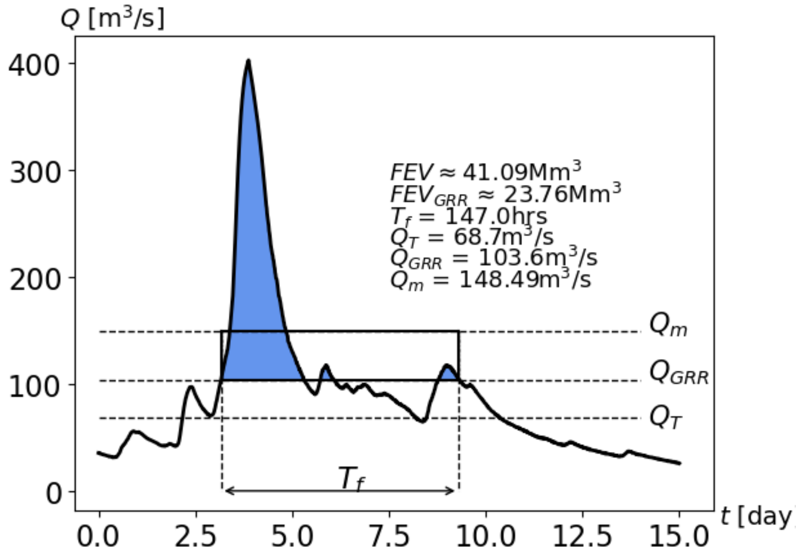


Figure 5.7: FEV of Derwent River after GRR is 23.76 Mm^3. 17.33 Mm^3 of flood water was mitigated, representing approximately 42% of the FEV. There are three peaks in the graph, the two on the right have very small values, while the total amount of FEV is sufficiently large that we allow for the existence of error rates. Therefore, for ease of calculation and analysis, we see the FEV as one peak here.

5.6, the extension has a cross-sectional area of 36 m^2, so we can estimate the cost of excavation requiring £1,812 per metre. £1,812 in 2015 is approximately £2,174 in 2022 due to inflation. The construction of hard bank reinforcemen is necessary to protect the riverbed from erosion. We considere the use of stone gabions to create hard bank reinforcemen. Each metre of stone gabions would have cost £250 in 2007, as it is now equivalent to approximately £343 through expansion. The annual cost of maintenance of the open channel using the machines is between £830 and £8,445 per kilometre, we take the middle number of £4,638. Stone gabions have a useful life of about 75 years in the suburban [34], so we calculate the maintenance cost to be about £348 per metre, which is about £452 because of inflation. The total length of the section we are widening is 5km and the cost of using the GRR is approximately £14.8 million. This mitigation scheme would manage approximately 42% of the FEV at Portinscale station, which means that it would cost £0.36 million for each percent of FEV.

Higher Embankments

As shown in Figure 5.8, the monitoring station at Portinscale is about 24,223 m from Cockermouth, the largest nearby city. To prevent the city suffering damage from flooding, it is necessary to build flood defences along this stretch of road. As mentioned in Section 5.2, since a large part of the flood-protection works are built in a rural area, it is preferable to build embankments with a larger footprint.

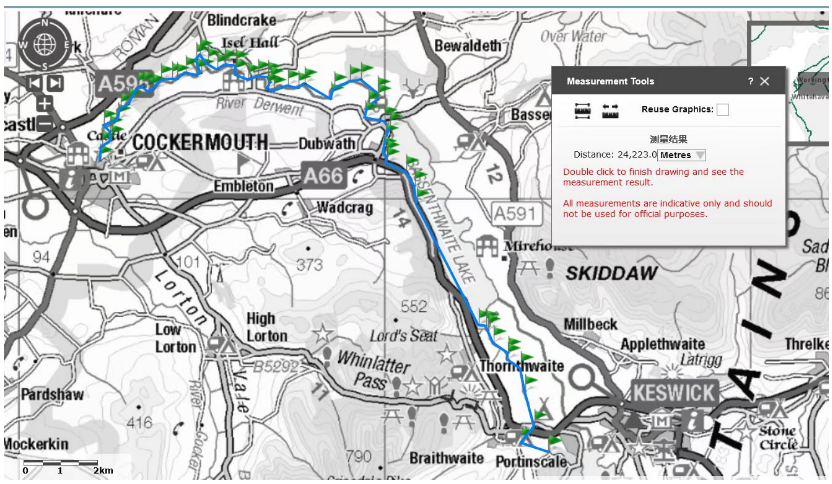


Figure 5.8: Distance of River Derwnet from Portinscale to Cockermouth as marked on Magic Map [24].

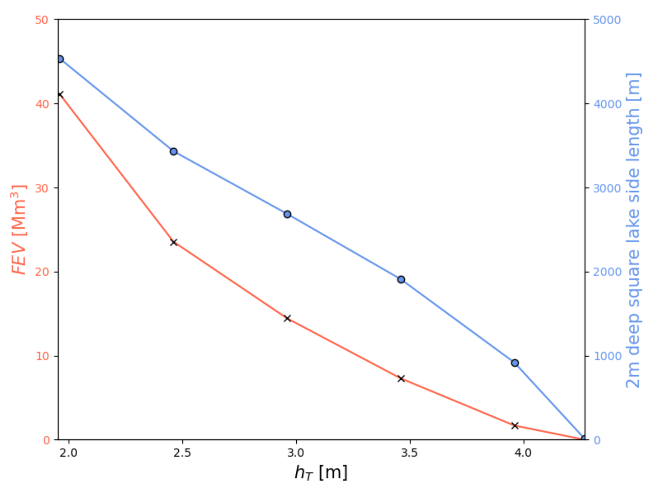


Figure 5.9: Relationship between threshold h_T and FEV and side length.

As shown in Figure 5.9, if we increase the threshold to 2.96 m, which means creating a 1 m high embankment, 26.5 Mm^3 of flood water will be managed, accounting for approximately 64% of the FEV of the Portinscale monitoring station. Referring to figure 5.2, the cost of constructing this section of embankment would be £94.5 million. This means that it would cost £1.48 million to mitigate one per cent of the FEV. However, if we choose to build a 2.31 m high embankment, which increases the threshold to 4.27 m, the entire flood can be managed. The construction cost is £209 million, which means that for every one per cent of the FEV, it would cost £2.09 million, which is £0.61 million more per metre than building a 1 metre embankment.

5.4 Mitigation Schemes Scenarios

5.4.1 First Scenario

In the first scenario, two methods were used to mitigate a total of 100% of the FEV. The GRR mitigating 42% of the FEV and the creation of higher embankments mitigating 64% of the FEV. The two methods mitigate more flooding than the entire FEV, so that the embankment scheme accounts for only 58% of the Figure 5.10.

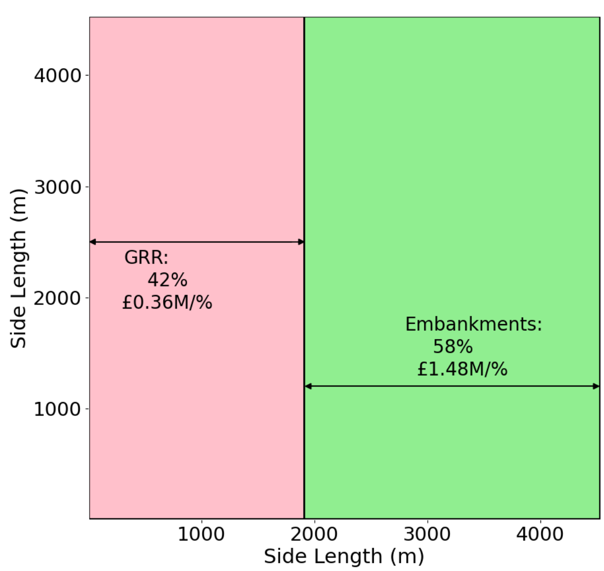


Figure 5.10: The first scenario contains a total of two mitigation methods. The pink part of the figure represents GRR and the green part represents the higher embankments.

5.4.2 Second Scenario

The second scenario has already been mentioned in Section 5.3. If a 2.31 m embankment is built along the river bank, the entire flood can be mitigated. Therefore we only use this type of treatment in the second scenario.

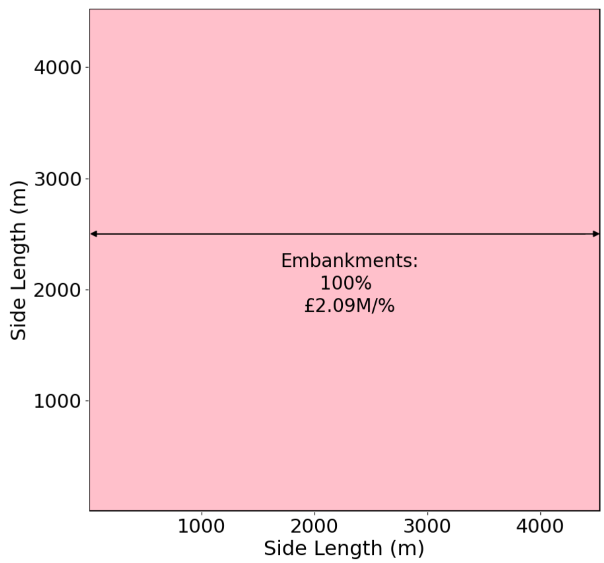


Figure 5.11: The second scenario includes only one method of building embankments and costs £3.63 million per 1% of FEV managed. This scenario relies on only one method.

Chapter 6

Conclusion and Limitation

This report has introduced the concept of FEV and explored the most cost-effective flood-mitigation schemes. There are still some shortcomings, however, that we have not addressed or have not mentioned in the report. Firstly, several months were spent waiting for the data, once a bottleneck is encountered during the subsequent analysis, it is difficult to have enough time to change the object of analysis. Secondly, the choice of threshold h_T has a very subjective element. We need to combine multiple sources of information to estimate the thresholds, so the FEV estimates based on the thresholds are inaccurate.

Two options have been given for the scenario of a mitigation plan. The first consists of two methods and the second consists of only one method, namely building embankments. The second scenario is ineffective, however, because relying on only one method of flood management is dangerous: once the method fails, there are no fall-back methods to contain the situation. It is worth noting that the calculations for the first scenario are not entirely accurate and that some social factors are not taken into account. For example, relocation costs and losses due to the termination of the plan due to objective factors. In addition, the wishes of the local people should be fully respected during the relocation.

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