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MATH3001: Project in Mathematics

Introducing and Using Flood Effective (FEV) Analysis to Quantify Flooding and Flood Mitigation Schemes Rivers in the North of the UK

Contents

1 Introduction

A flood is defined as a great flowing or overflowing of water, especially over land not usually submerged.[1] The frequency of extreme flooding in the UK has been predicted to increase with climate change. 17,000 properties were affected by flooding in the winter 2015-2016 in the North of the UK. December 2015 has been reported as the wettest month ever recorded.[2] In 2017, flooding was a natural hazard identified as a major threat to the UK on the UKs Risk Register.[3]

There are 4 main categories of flooding: fluvial (caused by a river bursting its banks), pluvial (caused by surface water run-off), coastal (caused by extreme tidal conditions) and reservoir (caused by dam failure).[4] This project studies river floods. Fluvial, pluvial and reservoir flooding are in scope of this project whilst coastal flooding is out of scope.

2 Flood Effective Volume (FEV)Analysis

2.1 Introduction

The FEV model aims to quantify flooding by approximating the volume of a flood. It can then be used to assess the cost effectiveness of mitigation solutions. This can assist policy makers in designing flood mitigation plans and allocating funding. The FEV model also acts a useful tool for comparing and contrasting different floods.

A flood mitigation plan aims to reduce the likelihood and impact of flooding [REF].There are 2 main categories of flood mitigation: **Structural** and **Non-structural**.

Structural solutions aim to reduce the volume of water discharged during a flood by using physical structures.[5] This can be split into manmade and natural solutions. Manmade solutions include dams, floodwalls and levees whilst natural solutions include leaky barriers and river restoration.[6, 7]

Non-structural solutions are those which can improve responsiveness to a flood event. These focus on the prediction, modelling, communication and preparation for flooding. Examples include residents having a personal flood plan prior to flooding and using sandbags in the event of flooding.[8]

The FEV model focuses on analysing Structural solutions.

2.2 Raw Data

The FEV model uses data obtained during a flood event to estimate the volume of the flood at a location along a river. In the UK, river levels are regularly checked by a network of monitoring stations.[9] At the monitoring stations, discharge and or stage measurements are typically taken every 15 minutes. Data of the discharge and stage during a flood event can be obtained upon request from the Environmental Agency (EA) under the Freedom of Information Act 2000 (FOIA).

2.3 Rating Curves

Where discharge is not measured directly, it can be calculated indirectly using a rating curve. A rating curve is the discharge of the river as a function of the stage. Rating curves can change with time due to changes in the stream channel. This could be a result of erosion, deposition or obstruction.[10]

For some monitoring stations in the UK, rating curve reports are available upon request from the EA under the FIOA 2000. For other stations these are not available as the relationship between stage and discharge is not deemed to consistent enough. [REF emails]

2.4 Quadrant Plots

The FEV model can be visualised using a quadrant plot which displays the relationships between stage and discharge, stage and time and discharge and time over the duration of a flood.

2.5 Threshold Values h_T,T_f,Q_T

h_T - the threshold height of a river at a given location is defined at the height above which flooding occurs. h_T is estimated in a variety of ways from interviews with eye witnesses to internet posts.

T_f - the flood duration can be estimated using h_t. The times at which the river rises above h_t and falls below h_t can be extrapolated from the graph of stage against time or by manual inspection of the raw data. This time interval can be defined as the duration of the flood T_f

Q_T - the threshold discharge can then be determined. If the discharge is directly measured, Q_T can be calculated by extrapolating the discharge at times when the stage equals h_T or through manual inspection of the data. If a rating curve is provided, Q can be calculated by inputting ht into the rating curve equation:

$$Q_t = Q(h_t) \tag{1}$$

2.6 FEV Calculations

There are 3 ways to estimate the volume of a flood.

2.6.1 Estimate 1 V_{e1}

$$V_e \approx V_{e1} = (Q_{max} - Q_t)T_f \tag{2}$$

This estimate is appropriate if stage h and discharge Q data are available, but the frequency of measurements is considered to be significant in comparison to T$_f$.

2.6.2 Estimate 2 V_{e2}

$$V_e \approx V_{e2} = \sum_{k}^{N} Q((h(t_k)) - Q_t \Delta t \tag{3}$$

Where the subscript k denotes the time interval at which $h(t_k)$ is recorded and $\Delta t = t_{(k+1)} - t_k$, ∀t=0,1,,N.

This estimate is appropriate if the frequency of measurements is considered to be less significant in comparison to T_f.

2.6.3 Estimate 3 V_{e3}

$$V_e \approx V_{e3} = T_f \frac{Q_{max}}{h_{max}}(h_m - h_T) \tag{4}$$

Where the time interval for h_m is T_f. This estimate is appropriate where automatic readings of river stage and rating curves are absent. T_f , Q_{max} , h_{max},h_m , h_T can all be estimated.

2.7 Square Lakes

Once FEV has been estimated, it can be visualised in the form of a 2m deep square lake viewed from above.[11] FEV is an estimate of the volume of water responsible for flooding and hence that which is intended to be mitigated. Square lakes can be generated for different mitigation schemes; each partitioned in relation to the component solutions e.g dams, flood walls, storage sites. A cost effective analysis can be conducted by weighting each partition to its cost and the percentage of FEV it mitigates.

Square lakes provide a way of visualising the volume of a flood and the effectiveness of different flood mitigation schemes. They are a visual tool which can be used by policy makers to quickly make evidence based decisions to optimise flood mitigation.
[REF Tom Onno's work on Square Lakes]

3 Familiarisation of the FEV Model

3.1 River Don, Hadfields, 2007

The River Don is a river in the north of the UK which rises approximately 460m in the Pennine Range. It flows 110 km in total past Sheffield in South Yorkshire and north-eastward past Doncaster before joining the River Ouse at Goole.[12] On the 25th June in 2007, the River Don experienced extreme flooding causing hundreds of people to evacuate their homes and the deaths of two people.[13] Extreme rainfall across the UK in the summer of 2007 caused widespread flooding and is estimated to have cost the economy between 2.5-3.8 billion.[14]

The Hadfields river monitoring station is located in city centre of Sheffield. In average weather conditions, the stage lies between 0.32m and 0.53m. On the 25th June 2007, the River Don reached its highest ever recorded stage of 4.68m at the Hadfields station[15].

Hydrological data for 25th-29th of June 2007 was analysed. Quadrant plots were reproduced using data from the Hadfield monitoring station for stage measured at 15 minute intervals and the corresponding flow, calculated using rating curve tables.

This is Rating F which is deemed valid for the period 01-MAR-1990 to 27-NOV-2014. [Ref Rating Curve Report]

Lower Stage Limit (m)	Upper Stage Limit (m)	c	b	a
0	0.52	78.4407	1.7742	0.223
0.52	0.931	77.2829	1.3803	0.3077
0.931	1.436	79.5956	1.2967	-0.34
1.436	3.58	41.3367	1.1066	-0.5767

Table 1: Table showing the coefficients for the rating curve function for different values of h for the River Don at Hadfields

h_T was estimated to be 2.90m. Shoothills Gaugemap states the most recent highest level recorded at the gauge as being 2.63m.[16]. Data for Shoothills Gaugemap is provided by EA. An increased estimate of 2.90m was used as Professor Bokhove and Dr Kent had experienced underestimations by the EA in other similar data.

Using Estimate 3, the FEV was approximated to be

$$V_{e2}(h_T = 2.9m) \approx 3.00Mm^3$$

This corresponds to a 2m-deep square lake of dimensions 1225m.

[REF Onno and Toms Paper]

Quadrant Plot

Flood Mitigation Plans

3.2 River Aire, Armley, 2015

The River Aire is a river in the north of the UK which drains the Pennine Range. It flows 114km in total southeastward through West Yorkshire and past the city of Leeds before joining the River Ouse on the border of East Riding in Yorkshire.[17, 18] In December 2015, the River Aire experienced extreme flooding. In Leeds alone,more than 3000 properties were affected, 20% of which were businesses. Leeds City Council estimates the cost of this flood to wider city region as being 500 million.[19]

The Armley river monitoring station is located approximately 2km upstream from the city centre of Leeds. In average weather conditions, the stage lies between 0.29m - 2.70m. On 27th December 2015, the River Aire reached its highest ever recorded stage of 5.21 m at the Armley station.[20]

Hydrological data from the 25th to the 30th of December 2015 was analysed. Quadrant plots were reproduced using the data from the Armley monitoring station for stage measured at 15 minute intervals and the corresponding flow was calculated using rating curve tables. This is "winter" Rating F published in 2016 in response to the 2015 floods. [Aire Rating Curve Report]

Lower Stage Limit (m)	**Upper Stage Limit (m)**	**c**	**b**	**a**
0	0.685	30.69	1.115	0.156
0.685	1.917	27.884	1.462	0.028
1.917	4.17	30.127	1.502	0.153

Table 2: Table showing the coefficients for the rating curve function for different values of h for the River Aire at Armley

h_T was estimated to be 3.9m. The time that flooding commenced at a nearby location was indicated by the time stamp of a photograph as 12:17:33 on 26th December 2015. At the Armley monitoring station, the recorded stage at 12:15:00 was 4.16m. In the evening of 12th December 2015, the River Aire was inspected at the location of the photograph and it was estimated that an additional 0.50m would cause flooding. At 00:00:00 on 13th December 2015 at Armley monitoring station a height of 3.70m was recorded. Hence it was estimated that $3.75m < h_T < 4.16m$. [REF Reference picture Tom and Onno's report]
Using Estimate 3, the FEV is approximated to be

$$V_{e3}(h_T = 3.9m) \approx 6.2Mm^3$$

This corresponds to a 2m-deep square lake of dimensions 1760m.

[REF Onno and Toms Paper]

Quadrant Plot

Flood Mitigation Plans

3.3 River Calder, Mytholmroyd, 2015

The River Calder is a river in the north of the UK in West Yorkshire. It flows 87km in total through the Calderdale valley; past the towns of Halifax, Huddersfield and Wakefield before joining the River Aire at Castleford.[21] In December 2015, the River Calder experienced extreme flooding. At least 2,000 homes and 200 businesses in the Calder Valley were estimated to have been affected by the Calderdale Council[22].

The Mytholmroyd river monitoring station is located in Mytholmroyd town centre. In average weather conditions the stage lies between 0.56m and 3.01m. On 26th December 2015, the River Calder reached its highest ever recorded stage of 5.65m at the Mytholmroyd station [23].

Hydrological data from the 25th-29th of December 2015 was analysed. Quadrant plots were reproduced using data from the Hadfields monitoring station for stage measured at 15 minute intervals and the corresponding flow was calculated using rating curve tables.

This is rating curve D which is referenced in the Rating Review report released in 2017.

Lower Stage Limit (m)	Upper Stage Limit (m)	c	b	a
0	2.107	8.459	2.239	0.342
2.107	3.088	21.5	1.37	0.826
3.088	5.8	2.086	2.515	-0.856

Table 3: Table showing the coefficients for the rating curve function for different values of h for the River Calder at Mytholmroyd

h_T was estimated to be 4.5m. Houses along the river are reported to start to flood at h=4.0m. According to local knowledge, a major flood alarm was historically issued at h=4.85m. Hence it was estimated that $4.0m < h_T < 4.85m$. [REF Tom and Onno's papers]
Using Estimate 3, the FEV is approximated to be:

$$V_{e3}(h_T = 4.5) \approx 1.6Mm^3$$

This corresponds to a 2m-deep square lake of dimensions 908m.
[REF Onno and Toms Paper]

Quadrant Plot

Flood Mitigation Plans

4 Application of FEV Model

4.1 River Ouse, York, 2000 & 2015

4.1.1 Introduction

The River Ouse is a river in the north of the UK. It flows 84km 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[24].

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[25].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[26].

FEV analysis of the River Ouse in York will increase the number of flood events studied. The River Ouse is connected to the River Don and the River Aire. The River Ouse, like the River Calder and River Aire, also experienced flooding in December 2015. This will provide an opportunity for comparison of different flood events.

FEV analysis of the River Ouse in York has the potential to inform the further design and implementation of Flood Mitigation plans in York. Quantifying flood events in relation to statistical returns periods and the effectiveness of different flood mitigation schemes could help local authorities make decisions which best protect citizens from flooding.[REF Tom Onno work]

4.1.2 Data Sampling Location

There are 17 river monitoring stations located on the River Ouse, 6 of which are located in the York area.[27, 28]. The Viking Recorder and Foss Barrier monitoring stations are located in central York whilst the Clifton Ings and Skelton monitoring stations are located within a 5 mile radius of the city centre.
The Skelton monitoring station (approximately 4 miles southwest from the city centre) records both stage and discharge whilst the Viking Recorder, Foss Barrier and Clifton Ings stations only record stage. No rating change reports are available for the Viking Recorder and Foss Barrier Stations because hydrologists deem the relationship between stage and flow to be too unreliable at these locations.

[REF Email on 05-FEB-2019]

4.1.3 December 2015

4.1.4 November 2000

5 Conclusion

6 Recommendations & Further Work

7 Appendix

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