UNIVERSITY OF LEEDS

MATH3001: Project in Mathematics

Flood Analysis:Assessing and communicating mitigation of river floods to policy makers and the general public

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Contents

1 Introduction

This project aims to use the analysis of flood data for multiple floods of a range of rivers as provided under the Freedom of Information Act by the Environment Agency and subsequently analyse the cost benefits of various proposed flood mitigation plans.
Should I reference Toms' Github or the EA for Aire, Calder and Don data?
Specifically we will explore:

- The possible flood mitigation plans that could be used.
- The 2015 Boxing Day floods of the Rivers Aire, Calder and Don. This analysis will be done by the entire group.
- The cost benefits of proposed flood mitigation plans to prevent any future floods along these rivers.
- The 2012 November floods of the River Avon in both Warwick and Stratford-upon-Avon. This analysis will be done individually.
- The cost benefits of proposed flood mitigation plans to prevent any future floods along the River Avon and specifically in these locales

How do I attach graphs, code, excel spreadsheets e.t.c.
"It is estimated that flood damages in England have risen by around 60% over the past 25 years and already exceed 1 billion per year in direct costs to communities and business".[2]

2 Flood Mitigation

2.1 The Meaning of Flood Mitigation

First of all, it should be made clear what Flood Mitigation actually is. To mitigate a flood is to reduce the amount of flooding, and thereby the damage as a result of such flooding, caused when a river breaks its banks.
This has been attempted since the very origins of non-nomadic humanity as the negative financial and social repercussions of a large flood (such as loss of property, crops, infrastructure and even life) are severe. Early examples of attempts to mitigate floods include the construction of stilt-houses by the Yue people in Ancient China around 7000 years ago.[1]
In the modern world, we now have access to a vast array of possible flood mitigation schemes due to factors such as improvements in engineering and the implementation of a centralised government with access to large sums of money with wich to implement flood mitigation schemes as well as the legal authority with which to do so.
In the course of this report, we will be investigating the effectiveness of such schemes at realistically reducing the volume of water discharged during a flood and thereby the cost effectiveness also, in the hopes that policy makers could make use of such analysis when implementing flood mitigation proposals.

2.2 Possible Methods of Flood Mitigation

Examples of possible Flood Mitigation strategies include, but are not limited to:
want to reference Onno here, can I?

- High Flood Walls: increases the total volume of water a river can hold before it starts to flood.
- River-Bed wWdening: similar to high flood walls, it increases the capacity of the river itself.
- Flood Plain Enhancement: increases the water retention of the ground itself within places at risk of flooding.
- Natural Flood Management. This method includes examples such as:
  - Tree Planting: improves the water retention of the ground as trees 'drink' water.
  - Peat Restoration: improves the water retention of the ground.
  - Flow Attenuation Features: includes examples such as 'leaky dams' (like the ones that a beaver colony would build) that slow the flow of the river.
- Sustainable Drainage Systems. This includes: [3]
  - Source Control:
    - Green Roofs: roofs that are comprised of vegetation on top of a drainage system.
    - Rainwater Harvesting: collects rainwater from roofs and thereby prevents the rainwater from contributing to any possible flooding. One such way of harvesting rainwater is the use of water butts, which collects rainwater running off roofs.
    - Permeable Pavements: pavements that allow rainwater to pass through the hard surface (preventing it from gathering and causing any potential flooding) where it will be stored to either be released into the ground at a sustainable rate (i.e. a rate that will not cause the ground to become waterlogged and thereby cause flooding) or into a drainage system that will transport the rainwater away from the immediate vacinity.
    - Soakways: similar to permeable pavements, there aim is to store rainwater run off from a development so it can then be fed into the ground.

- Site Control:
  - Filter Strips: used in order to transport rainwater run off to systems such as soakways or streams.
  - Trenches: similar to filter strips but with the aim of storing rainwater to gradually be released into the ground as opposed to transporting the rainwater to an alternative storage entity.
  - Swales: akin to trenches but whereas trenches are filled with material like rubble, Swales are filled with vegetation and can be used both to store and release water as well as transport it.
  - Bioretention: also known as rain gardens, are shallow bowls in the ground that capture, and more significantly, treat rainwater.
  - Geocellular/Modular Systems: situated below the ground, these, much like permeable pavements, can either infiltrate rainwater run off into the ground or store said run off until it can be transported to a drainage system.
- Regional Control:
  - Infiltration Basins: comparable to bioretention methods, infiltration basins store run off for it to then be released into the ground but do not treat the water.
  - Detention Basins: temporarily store rainwater run off and, through a controlled flow, mitigates the force of the flow.
  - Ponds: unlike infiltration basins, detention basins and bioretention methods, ponds are permanent bodies of water. Ponds mitigate floods if they are low-lying, i.e. they can accept an addition of a high volume of water before they break their banks.
  - Wetlands: marshland, these works by helping to store water before it slowly enters the ground and also by reducing water flow.

- The drawing down of drinking water reservoirs before predicted heavy rainfall: reduces the total volume of fluid stored in reservoirs thereby allowing said reservoir to accomodate a larger volume of rain fall before it fills up and begins to flood.

3 Analysis of the 2015 Boxing Day floods

Here, we will be analysing flood data, provided by the **Environment Agency** from the Boxing Day 2015 floods with specific focus give to the Rivers Aire, Calder and Don.
Below is Figure 1. In the next section we will be using Figure 1 to explain the features of the graph as our analysis of the flood at different locations uses the same graph but with different inputted data.

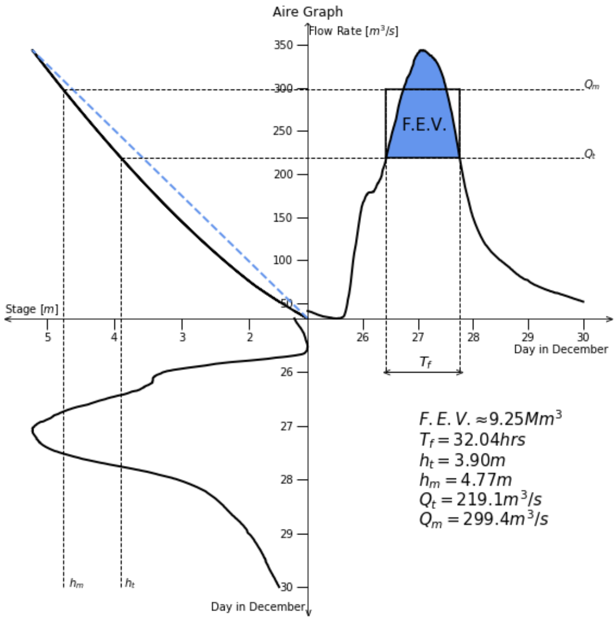

Figure 1: Graph detailing the relationship between the Height and Flow Rate of the River Aire during the 2015 Boxing Day floods using data provided by the Environment Agency from the monitoring station 'Armley'.

3.1 Explanation of the Graph

In order to plot this graph, we used data showing the stage (stage means height) in metres of the River Aire from the beginning of the 25th until the end of the 30th of December 2015 in 15 minute increments.

3.1.1 h_t and h_m

The lower left quadrant shows a plot of stage values against their corresponding time values, which are the only two raw data sets used in this graph.
Here, h_t is the threshold stage, i.e. the height at which the river burst its banks and began to flood. h_t can be approximated through a variety of approaches, including using online resources such as gaugemap.co.uk to estimate the height at which a river could begin to flood and social media to find pictures of the river beginning to flood and using the time at which these photos were posted to find the corresponding stage value for the estimated time at which the river began flooding. In this case, Professor Onno Bokhove witnessed the River Aire begin to flood around 10:00 on the 26th of Decmber 2015 at Armley in Leeds.
h_m is the mean stage of the river after it has begun to flood. We calculated this by taking all the stage values that are numerically larger than h_t, adding up all these values and dividing that sum by the number of said values:

$$\frac{\Sigma_{i=1}^{n} h_i}{n}, \forall h_i \geq h_t$$

3.1.2 Rating Curve

For each different gauging station, the environment agency can provide rating information which can be used to define a function Q with which the flow rate of the river can be calculated from a given stage. The general function is defined as:

$$\mathbf{Q}(h) = c(h-a)^b$$

where c, a and b are provided by the Environment Agency and vary for each gauging station and for different stage intervals. For example, the rating information for the River Aire's Armley station is:

Lower Stage Limit [m]	Upper Stage Limit [m]	c	b	a
0.2	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

By running each of our stage values through $\mathbf{Q}$(h) as defined for the desired time segment, we compiled a set of time values, their corresponding stage values and their corresponding flow rate values also. This allowed us to plot the rating curve (in the upper right quadrant) and also to plot the flow rate against the time values (in the upper left quadrant).
As the provided final upper stage of the rating curve is said to be 4.17 but our maximum stage value is clearly above this, we have had to extrapolate this total upper stage limit to include stage values larger than 4.17.

3.1.3 $\mathbf{Q_t}$ and $\mathbf{Q_m}$

We have now defined the meaning of $\mathbf{Q}$(h) and so it is very simple to derive Q_t as being $\mathbf{Q}(h_t)$ and, simlarly, Q_m as being $\mathbf{Q}(h_m)$. As h_t is 3.90, we use the c, b and a values as defined in the last row of our rating information table.

3.1.4 $\mathbf{T_f}$ and F.E.V.

As we have deduced the time, stage and flow rate at which the river begins to flood, it is logical to think that the time from which the flow rate increases above Q_t to when the flow rate decreases back below Q_t is the length of time for which the river is actively flooding. This is said to be T_f.
It is therefore sensible to assume that the excess flow rate (i.e. the collective flow rate values above our threshold flow rate (Q_t)) multiplied by the length of the flood (T_f) gives the Flood Excess Volume (F.E.V). This is the excess volume of water above that maximal capacity of the river that is actually causing the flood and can be seen on our graph as the shaded area between $\mathbf{Q}$(h) and Q_t for the duration of the flood.
A good approximation of the F.E.V. can be found using our mean excess flow rate (Q_m) and multiplying this by T_f:

$$\mathbf{F.E.V.} \approx T_f(Q_m - Q_t)$$

This constitutes the area of the bold box connecting Q_m, Q_t and T_f on our graph.

3.2 River Aire

Having thoroughly explained the various elements of our graph and how they are derived, we can now begin to analyse the data.

3.3 The River Calder

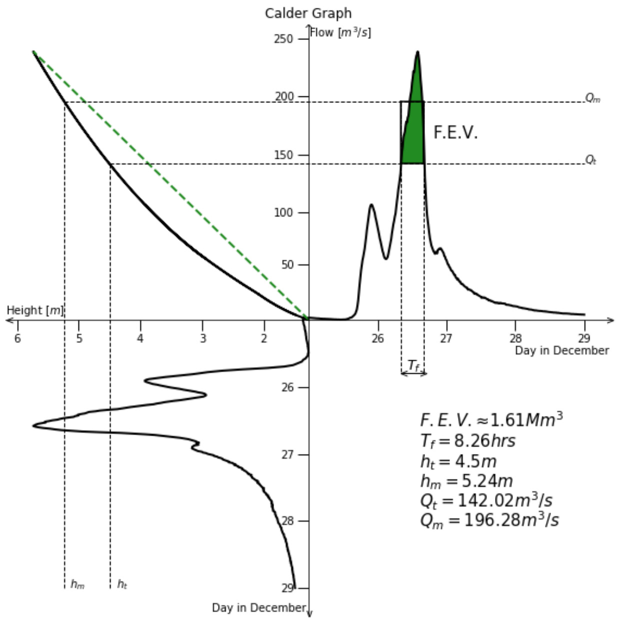

Figure 2: Graph detailing the relationship between the Height and Flow Rate of the River Calder during the 2015 Boxing Day floods using data provided by the Environment Agency from the monitoring station 'Mytholmroyd'.

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

3.4 The River Don

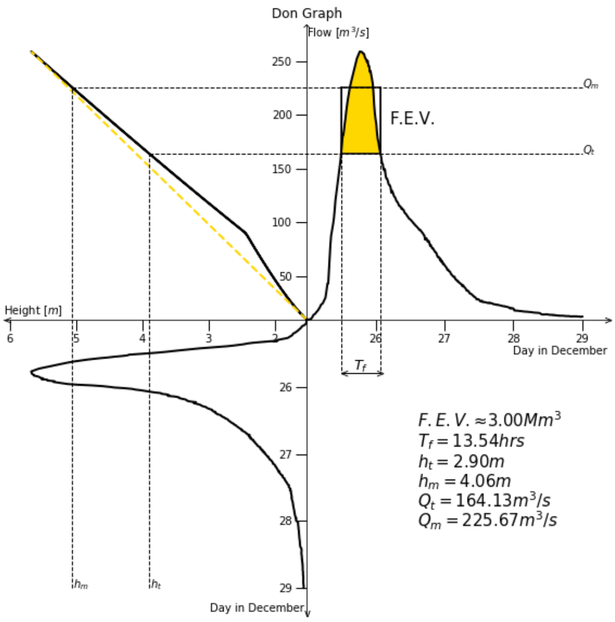

Figure 3: Graph detailing the relationship between the Height and Flow Rate of the River Don during the 2015 Boxing Day floods using data provided by the Environment Agency from the monitoring station 'Sheffield Hadfields'.

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

4 Analysis of the 2012 November floods

4.1 The River Avon at Stratford-upon-Avon

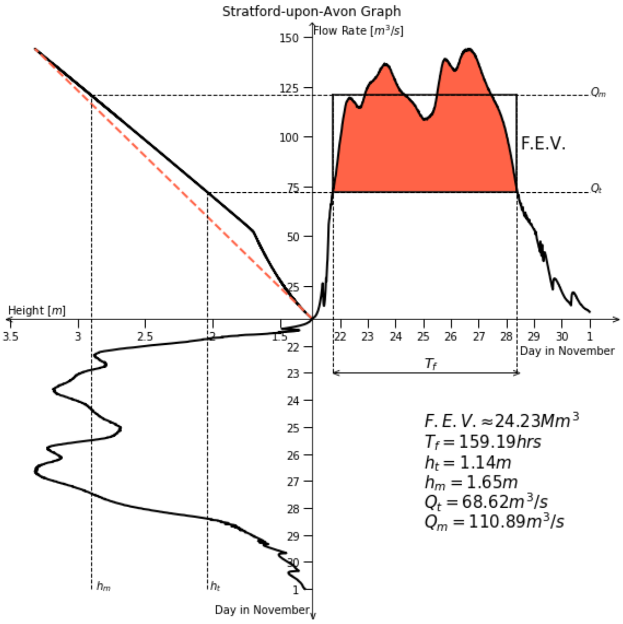

Figure 4: Graph detailing the relationship between the Height and Flow Rate of the River Avon during the 2012 November floods using data provided by the Environment Agency from the monitoring station at 'Cox's Yard'.

Lower Stage Limit [m]	Upper Stage Limit [m]	c	b	a
0.136	0.938	158.04	2.85438	0.262919
0.938	1.427	87.0362	0.962129	0.358741

4.2 The River Avon at Warwick

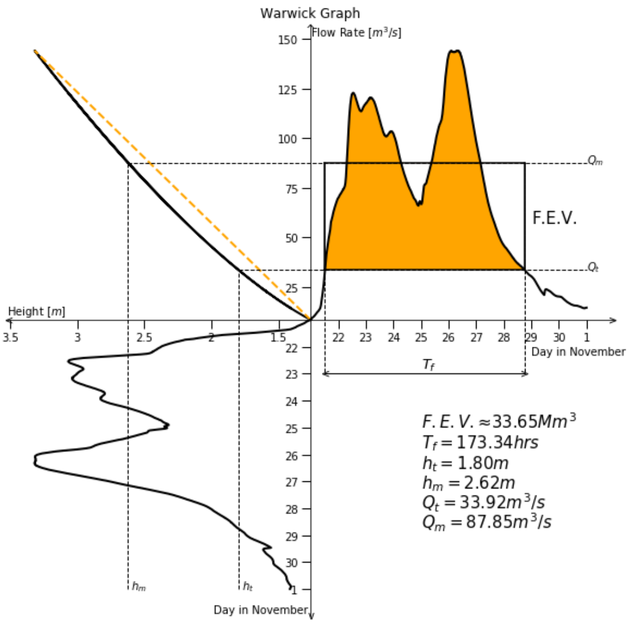

Figure 5: Graph detailing the relationship between the Height and Flow Rate of the River Avon during the 2012 November floods using data provided by the Environment Agency from the monitoring station at 'Warwick'.

Lower Stage Limit [m]	Upper Stage Limit [m]	c	b	a
0.960	3.000	40.6178	1.44854	0.917837

5 References

References

[1] http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.383.1610

[2] https://apps.warwickshire.gov.uk/api/documents/WCCC-1039-29

[3] https://apps.warwickshire.gov.uk/api/documents/WCCC-1039-45

A Appendix

The Aire Quadrant Graph - Python Code:
Should I include all data sets and code for each graph?

```
import matplotlib.pyplot as plt
import pandas as pd
import numpy as np

plt.rcParams["figure.figsize"] = [10,10]
plt.rcParams['axes.edgecolor']='white'
fig, ax = plt.subplots()

#Import the Data
armley=pd.read_csv('Aire Data.csv')
day = armley['Day in December']
flow = armley['Flow Rate (m^3/s)']
height = armley['Height (m)']

#Scale our Data
def scale(x):
    return ((x-min(x))/(max(x)-min(x)))
scaledday = scale(day)
scaledheight = scale(height)

#finding and using ht from the hm.
ht=3.9
HM = []
for i in height:
    if i>=ht:
        HM.append(i)
hm=sum(HM)/len(HM)

#Finding qt and qm.
def Q(x):
    if x<=0.685 and x>=0.165:
        y = (30.69*((x-0.156)**1.115))
    elif x<=1.917 and x>0.685:
        y = (27.884*((x-0.028)**1.462))
    elif x<=max(height) and x>1.917:
        y = (30.127*((x-0.153)**1.502))
    return(y)
qt = Q(ht)
qm = Q(hm)

#Rating Curve
Flow = []
for i in height:
    if i<=0.685 and i>=0.165:
        Flow.append(30.69*((i-0.156)**1.115))
    elif i<=1.917 and i>0.685:
        Flow.append(27.884*((i-0.028)**1.462))
    elif i<=max(height) and i>1.917:
        Flow.append(30.127*((i-0.153)**1.502))
```

```
scaledFlow = []
for i in Flow:
    scaledFlow.append((i-min(Flow))/(max(Flow)-min(Flow)))


#Plot the Rating Curve using Q NOT the Flow Rate.
negheight = -scaledheight
ax.plot(negheight,scaledFlow,'black',linewidth=2)
ax.plot([0,-1],[0,1],'cornflowerblue',linestyle='--', marker='', linewidth=2)
#Originally the dotted line was wrong because it went to the positional origin
#and not the actual origin.

#Plot the Flow Rate and Height against the Date.
negday = -(scaledday)
ax.plot(scaledday, scaledFlow, 'black', linewidth=2)
ax.plot(negheight, negday, 'black', linewidth=2)

#Plot the lines illustrating ht,hm,qt,qm
#Scaling ht,hm,qt and qm.
scaledht = (ht-min(height))/(max(height)-min(height))
scaledhm = (hm-min(height))/(max(height)-min(height))
scaledqt = (qt-min(Flow))/(max(Flow)-min(Flow))
scaledqm = (qm-min(Flow))/(max(Flow)-min(Flow))
ax.plot([-scaledht,-scaledht],[-1,scaledqt], 'black', linestyle='--', linewidth=1)
ax.plot([-scaledhm,-scaledhm],[-1,scaledqm], 'black', linestyle='--', linewidth=1)
ax.plot([-scaledht,1],[scaledqt,scaledqt], 'black', linestyle='--', linewidth=1)
ax.plot([-scaledhm,1],[scaledqm,scaledqm], 'black', linestyle='--', linewidth=1)

#Fiddly plot to plot the box around the F.E.V. and the Tf line.
ax.plot([71/250,71/250,71/250],[scaledqt,scaledqm,-1/5], 'black', linestyle='--',
ax.plot([69/125,69/125,69/125],[scaledqt,scaledqm,-1/5], 'black', linestyle='--',
ax.plot([71/250,69/125],[-1/5,-1/5], 'black', linewidth=1)
ax.plot([71/250,71/250],[scaledqm,scaledqt], 'black',linewidth=1.5)
ax.plot([71/250,69/125],[scaledqm,scaledqm], 'black',linewidth=1.5)
ax.plot([71/250,69/125],[scaledqt,scaledqt], 'black',linewidth=1.5)
ax.plot([69/125,69/125],[scaledqm,scaledqt], 'black',linewidth=1.5)

#Formatting the ticks and the Axis.
ticks_x = [-3874/4091,-2874/4091,-1874/4091,-874/4091,1/5,2/5,3/5,4/5,1]
#This describes the position I want each tick to be on a graph with x axis
#from -1 to 1. Done by doing (2-min(height))/(max(height)-min(height))
#to find where 2 should be positioned on the axis.
ticks_y = [-1,-4/5,-3/5,-2/5,-1/5,3/52,17/78,59/156,7/13,109/156,67/78,53/52]
ax.set_xticks(ticks_x)
ax.set_yticks(ticks_y)
Ticks_x = [5,4,3,2,26,27,28,29,30]
Ticks_y = [30,29,28,27,26,50,100,150,200,250,300,350]
ax.set_xticklabels(Ticks_x)
ax.set_yticklabels(Ticks_y)
ax.spines['left'].set_position(('center'))
ax.spines['bottom'].set_position(('center'))
ax.spines['left'].set_color('black')
```

```
ax.spines['bottom'].set_color('black')
ax.tick_params(axis='x', colors='black', direction='out', length=10, width=1)
ax.tick_params(axis='y', colors='black', direction='out', length=10, width=1)

#Graph Title.
plt.title('Aire Graph')

#Graph labels.
plt.text(-4/6, -1,'$h_t$')
plt.text(-13/15, -1,'$h_m$')
plt.text(1, scaledqm, '$Q_m$')
plt.text(1, scaledqt, '$Q_t$')
plt.text(0.34,0.70, 'F.E.V.', size=15)
plt.text(0.4,-0.18,'$T_f$',size=13)
plt.text(0.27,-0.213,'<')
plt.text(0.535,-0.213,'>')

#Axis Labels.
plt.text(0, 1.05,'Flow Rate $[m^3/s]$', size=10)
plt.text(0.75, -0.13,'Day in December', size=10)
plt.text(-0.35, -1.09,'Day in December', size=10)
plt.text(-1.1, 0.02,'Stage $[m]$', size=10)

#Arrows at end of Axis.
plt.text(-0.015,1.07,'^')
plt.text(-0.011,-1.11,'v')
plt.text(1.08,-0.013,'>')
plt.text(-1.105,-0.013,'<')

#Text on Graph.
plt.text(0.4,-0.4,'$F.E.V.   9.25Mm^3$', size=15)
plt.text(0.4,-0.475,'$T_f=32.04hrs$', size=15)
plt.text(0.4,-0.55,'$h_t=3.90m$', size=15)
plt.text(0.4,-0.625,'$h_m=4.77m$', size=15)
plt.text(0.4,-0.7,'$Q_t=219.1m^3/s$', size=15)
plt.text(0.4,-0.775,'$Q_m=299.4m^3/s$', size=15)

#Fill in the F.E.V.
QT=[]
for i in scaledFlow:
    i = scaledqt
    QT.append(i)
#Because I have to make qt into a list otherwise I get an error because I'm
#comparing a list with a float.
a=np.array(scaledFlow)
b=np.array(QT)
#Puts lists into an array as opposed to a list. Means that Python finds it easier
#compare the 2.
ax.fill_between(scaledday,a,b,where=a>=b,facecolor='cornflowerblue')

#Find the Tf
idx = np.argwhere(np.diff(np.sign(b - a))).flatten()
print(scaledday[idx])
```

```
def unscaleday(x):
    return (((max(day)-min(day))*x)+min(day))
c=unscaleday(0.283)
d=unscaleday(0.55)
Tf=(d-c)*24
print(Tf)
#find Tf in seconds
Tfs=Tf*(60**2)

#Find F.E.V
FEV=(qm-qt)*Tfs
print(FEV)
```