A REPORT ON THE OBSERVED RAINFALL RUN-OFF ON THE DERRY HILL AND BINGLEY ROAD SITES DURING PROLONGED RAINFALL EVENTS

SUMMARY

Two rainfall events occurring on the 21-01-2008 and 24, 25-09-2012 have been analysed. Recorded data in the form of photographs and video clips were presented in a Witness Statement report for the Public Inquiry scheduled for 09-04-2013 and the Regulation and Appeals Committee of BMDC on 04-04-2013 (Reference 1) (Reference App/W4705/A/11/2167397). This new report adds further information but should be considered with the previous report to obtain a complete set of information.

The object of this report is to prove beyond any reasonable doubt that during these types of prolonged rainfall events the actual run-off from the sites is TEN times larger than that which is obtained from standard techniques, which assume that the run-off is only from rain falling on the ground on the direct surface water catchment area.

The probable sources of all this extra water are also considered.

1. Initially a standard computer analysis was performed covering an extended catchment area above the Derry Hill site for accepted 100-year return period rainfall depths estimated for storm durations of 1, 2, 3 and 6 hours as given in Appendix A. In Fig. 1 the position of the flow capture in the upper part of the watercourse on the Derry Hill site is shown, together with specific data in Table 1.3, which has been refined in Appendix F.

2. The particular event of September 2012 was simulated and the computed results are shown in Appendix B. An additional plot assuming a 100% run-off computed for 45 hours has been added. It should be noted that the peak flow in the watercourse between 4:00pm – 9:00pm on 24-09-2012 was less than 70 litres/second for the 40 per cent run-off assumption and less than 170 litres/second for the maximum 100 per cent run-off as expected. Eighteen hours later the peak was less than 45 litres/second and 120 litres/second respectively.

3. Two photographs in Appendix C show waterflow on the Derry Hill site in both the upper part and lower part, taken at about 6:00pm on 24-09-2012. The water flowing at the bottom right-hand side of the lower part of the watercourse flows into a well-defined open watercourse in the garden of 28 Moorfield Avenue. A photograph of the water flowing in this watercourse is also shown.

4. Two further photographs were taken at 10:30am on 25-09-2012 some 18 hours later (Appendix D). The first photograph clearly shows the water still leaving the watercourse in the lower part of the field and the second photograph shows the water flowing in the watercourse in 28 Moorfield Avenue.

5. It has been calculated that the capacity of the upper part of the watercourse passing through the Derry Hill site is between 1200 and 1400 litres/second (Ref. 1, Exhibit JDR3). From Appendix C it can be seen that the water is leaving the watercourse in the upper part and hence must be flowing at about 1250 litres/second as stated in Ref. 1. The capacity of the watercourse in 28 Moorfield Avenue has been calculated to be 330 litres/second and since the photograph in Appendix C shows water flowing to near capacity then this would imply that about 300 litres/second of water was flowing.

6. In Appendix D the water flowing in the watercourse in 28 Moorfield Avenue was about two-thirds full with 200 litres/second flowing. From the water flowing out of the lower part of the watercourse on the Derry Hill site it is likely that the flow was close to two-thirds of the flow 18 hours earlier ie 800 litres/second.

7. The ratio of the two flows in clauses 5 and 6 are similar to the ratio of the two flows in clause 2. Thus the average over the 18 hour period was around 1000 litres/second or a total volume of 65000m^3.

8. The flow of water in and around the Derry Hill watercourse was observed to be at a high level from 4:00pm to dark on 24-09-2012. Due to the physical constraints on the flow of water it was apparent that a conditional relationship between a rainfall event and the volume of waterflow in a watercourse could be derived independent of the details of the catchment area. Such a theorem is derived and proved in Appendix E.

9. To provide further validity to the theorem the analysis given in Appendix A was used, and the results given in Appendix F. Within the error involved in computing the volume of water flowing in any sliding time window, it can be seen that the theorem has been verified for these types of storms.

10. A more testing case is that of the actual storm of September 2012 with the very complex rainfall pattern. The plots plus the sliding time window values for the volume of water flow in the watercourse are given in Appendix B. The rainfall amounts in the similar time windows were also evaluated from Ref. 1, Exhibit JDR3. The peak flow for 1 hour was $428m^3$ and the additional flow beyond 63 hours was estimated to give a total volume of about $8500m^3$.

    Applying the theorem to these results produces the table in Appendix G. Again, within the error of the volume calculation, the total volume is predicted very accurately from observations of 3 hours and above. For one hour, as used in clause 16 of Ref. 1, the underestimate is 24 per cent.

11. The measured results give rise to the question ‘Where does all the extra water originate?’. To address this question one must first consider where the rain could have fallen and how long would it take for the water to reach the watercourse? This question is effectively answered in Appendix A where the flat topped peak of the waterflow in the watercourse lags behind the peak of the rainfall by 25 minutes for storms of all durations. From this fact it follows that the time delay for water falling at the very top of the direct catchment area must take about one hour to reach the watercourse. So any additional flow in the watercourse must be due to rain falling at least one hour earlier. The observed peak flow in the watercourse was around five hours later than the peak in the rainfall event and hence suggests that some of the water in the watercourse had fallen onto the ground some ten hours before it was observed in the watercourse. Furthermore, since the volume of water observed was an order of magnitude greater than that captured by simple surface flow, it suggests that an approximate model for the capture of water flowing in the watercourse is the summation of about ten contributions each delayed by one hour.

12. Appendix H shows a plot of a computed response from ten delayed versions of the flow in the watercourse from direct surface water capture with each delayed by one hour and it is assumed each of the summed flows have equal contributions. From this plot the high rate of flow of water is shown to last five hours covering the period where the high rate of flow was observed. Furthermore, 18 hours later, the flow is computed to be at about two-thirds of the peak flow as observed. The peak flow is 770 litres/second for the

assumed 40 per cent run-off rate. To meet the observed peak flow of 1250 litres/second then the equivalent run-off rate would be 65 per cent.

13. Appendix I gives the results from applying the basic theorem. Again the computed results confirm the validity of the basic theorem.

14. Taking the observed by photography and the computed responses then the total volume of water that flowed in the upper part of the watercourse on Derry Hill for the storm of September 2012 was well in excess of 100,000m^3. This figure is more than TEN times the amount obtained from direct surface water capture.

15. The question arises as to where all this extra water has come from. It obviously has come from the rain falling on the ground above the direct surface water capture area and has been channelled into this main area. How has this water been so channelled?

16. The first clue to answering this question comes from the Bedrock and Faults Map shown in Appendix J. The fault line starting to the south of Menston and moving in the north-easterly direction indicates that the bedrock layer above the Derry Hill Site and passing through the Bingley Road Site has slipped about 250 metres. The fault line to the south of Menston from the north-west to the south-east is a complex fault. Surface observations looking onto the moor in the west indicates that it is at least 100 metres wide and has obviously caused complex damage to the sandstone bedrock. By viewing the

Ordnance Survey Map of the same area (see Appendix K) it can be seen that these bedrock layers have collapsed by about 100 metres above Menston from the west towards the east and obviously the sandstone rock will be broken allowing water from the moor to the west to be channelled down towards the proposed development sites. For the bedrock layer, which passes above the Derry Hill Site and through the Bingley Road Site, there are at least six known permanent springs along the base of the bedrock from Dry Beck Delph in the west and including two on the Bingley Road Site itself. Many more permanent streams emerge below this level and they were culverted through Menston in the nineteenth century.

Above these permanent springs are where the seasonal springs emerge and become active during prolonged rainfall events such as those which occurred in January 2008 and September 2012. The photographs shown in Exhibits JDR7 and JDR8 in Ref. 1 show water emerging from the ground and flowing down the slope above the Derry Hill Site. A further very informative photograph was taken at dusk on 24-09-2012 and is shown in Appendix L. What is shown is the river of water that emerges from the fault line above Menston flowing down towards the Derry Hill Site. The water freely flows through a dry stone wall indicating the ease at which water will flow through the broken sandstone bedrock layer due to angle of the slopes in the area of the moor.

17. In Appendix M three maps, related to the Bingley Road Site, are shown. The first is from the late nineteenth century showing the location of several springs

and the deep lake to the east of the site. Also important to note is the ‘Trough’ along the south of Bingley Road, which conveyed overland water flow down the side of the road. The second map shows the two Bingley Road sites whilst the third map, in addition to the details proposed for the larger site, has details of the culverted watercourse to the north-east.

18. A photograph of the entrance into this culvert is shown in Appendix N and is about one metre wide and a depth of 46 cms to the underside of the stone slab. Further downstream as the 300mm culvert goes through Red House Gardens the velocity of the water has been measured to be about 1.5m/s. In addition, dye has been placed into the watercourse and detected downstream in Cleasby Road. This was in the 600mm culverted ordinary watercourse on the west side of Cleasby Road, about 4 metres below the surface, which carries a fast flowing stream from under Bingley Road. The surface water sewer that takes water along Bingley Road feeds into the combined sewer at the top of Cleasby Road, as shown in Appendix O. In this photograph the foul sewers from the houses on Bingley Road and Red House Gardens can also be clearly identified.

19. Initially standard 100 year return period storms were applied to a standard computer analysis of the Bingley Road sites using direct surface water capture without any culverted watercourses, surface water sewers or buildings. The large lake forms as shown in Appendix P and it was calculated to hold 450m^3 prior to flooding over towards Hawksworth Drive. The yellow lines show where the flow rates were captured. In particular the flow capture

point towards Cleasby Road is at the point where the watercourse is culverted as shown in Appendix N.

20. A table has been constructed, as shown in Appendix Q, and relates to the flow rates for the Cleasby Road capture on the Bingley Road sites, which is shown in Appendix P. For the computed 1, 2, 3, and 6 hour storms the ratios of the peak flows to peak rainfall in any 15 minute period gives very similar ratios, indicating that the system is very linear. The result may be applied directly to the September 2012 event giving a maximum flow of 15 litres/sec. From the information given in Clause 18 it follows that the culvert, which begins at this point, has a maximum capacity in excess of 100 litres/sec and hence will not allow overland flow to the east of this point. Similarly the surface water drainage on Bingley Road will not allow surface water from the September 2012 event to pass across the road.

21. As a consequence of Clause 20, the area blocked in Appendix P only receives water from rain directly falling on the site with possible additional amounts from groundwater emergence. The surface area for the blocked area is about 5450m^2.

22. In Appendix R there is a description of how this lake forms with observed timings of both its formation and rate of soak away. The soak away is likely to result from water passing into the ground where the original lake, which was about 4m deep, was infilled and on top of which the houses in Red House Gardens were built. During the September 2012 event the lake became fully

formed prior to the morning of September 25. To fill the lake in a similar time taken for the water to soak away then the volume of water from the rainfall must be at least twice the volume of the lake itself. Thus, from Clause 21, the minimum total equivalent rainfall, assuming the standard 40 per cent run-off rate is 425mm. The total amount of rainfall over the period when the lake formed was 40mm hence one can only deduce that at least 90 per cent of the water in the lake had originated from groundwater emergence.

23. The obvious source of all the extra water is from groundwater emergence from the broken bedrock layer as shown in Appendix J. This emerges from the land to the north of Bingley Road to form the lake. For the larger Bingley Road Site, as identified in the Geo-Environmental Appraisal Report by Sirius and confirmed by the British Geological Survey, the seasonal springs are both on and above the site and discharge across the site causing streams of water to flow between the houses on Hawksworth Drive. It has been shown that the amount of water emerging from the ground will, in certain circumstances, be an order of magnitude greater than that resulting from direct surface water capture. Placing ditches and swales to the south and west of the site will only have a marginal effect, as it is proposed to build the houses on seasonal springs. The effects of doing this was recently reported in a news item concerning the village of Bridge in Kent (see video obtainable from Dr Steve Ellam's email: s.ellams1@btinternet.com).

24. From detailed consideration of the September 2012 rainfall event it is clear that the amount of water flowing from the proposed development sites is at

least 10 times larger than that which can be attributed to direct surface water capture. More than 90 per cent therefore is due to ground water emergence from above the Derry Hill site and mainly out of the ground on both Bingley Road sites.

Appendix A

NOTE TO FILE

JBA Project Code	2014s0785
Contract	Bingley Road and Derry Hill Menston
Client	David Rhodes
Day, Date and Time	19 March 2014
Author	Guy Dixon. Checked: Mark Bentley
Subject	Derry Hill Menston – Design Events

1 Further Work – Derry Hill

1.1 Introduction

As part of the ongoing work in Menston additional information with regard to flow rates passing through the proposed development site at Derry Hill were required. No significant changes were made to the original model (developed in 2011) but the underlying LIDAR has been updated. In the original modelling study a combination of 5m and 1m LIDAR data was merged together to provide the topographic information required by the model; in the current study 1m resolution LIDAR data was available throughout the study area which should improve the representation of overland flow routes.

The rainfall inputs have also been revised as observations made from site videos and photographs suggest that the flow rate through the site may be higher than predicted by the model in the previous study. These were estimated using FEH depth-duration-frequency (DDF) parameters from which 100-year return period rainfall depths were estimated for storm durations of 1, 2, 3 and 6 hours. This approach follows the methodology set out in the National Surface Water Flood Mapping Study. Multiple storm durations were run for each return period because duration is strongly linked to topography. Therefore, simulating only one duration is unlikely to be representative across a catchment. On hill slopes for example the storm duration is generally short because the greatest flood flows arise from high intensity rainfall. In a low lying area a longer duration event would produce the greatest flooding as it will take some time for surface water to travel down the catchment.

DDF parameters are available in point form on 1km grid squares and in the previous study the closet DDF point to the study site was taken. As the study involves simulating overland flow on the surrounding hillside additional DDF points were also analysed to assess how the rainfall inputs may change. This showed that taking a point slightly to the south of Menston would generate slightly larger inflows for the lower storm durations so these were used for the current set of model runs.

1.2 Modelling Results

Analysis of the model results have shown that the increase in rainfall inputs, the higher resolution LIDAR data and the general improvements in the software's capability at simulating rainfall have increased the flow rates passing through the site. The results are now more in line with observations that were made during observed rainfall events. The location selected for extracting the flow can be seen in Figure 1.0 below (This is also available as a separate figure at the end of the note). The value of Standard Percentage Runoff (SPR) from the FEH catchment descriptors for Menston results is approximately 40%. Using this value of SPR resulted in runoff which resulted in peak flow rates ranging from 0.6m^3/s to 1.6m^3/s and corresponding volumes ranging from 7,210m^3 – 4,200m^3). This increases significantly should the SPR value be increased to represent possible antecedent conditions within the catchment. Please note that none of the watercourses in the model area have been formally represented which may affect the flow rates simulated at the Derry Hill site.

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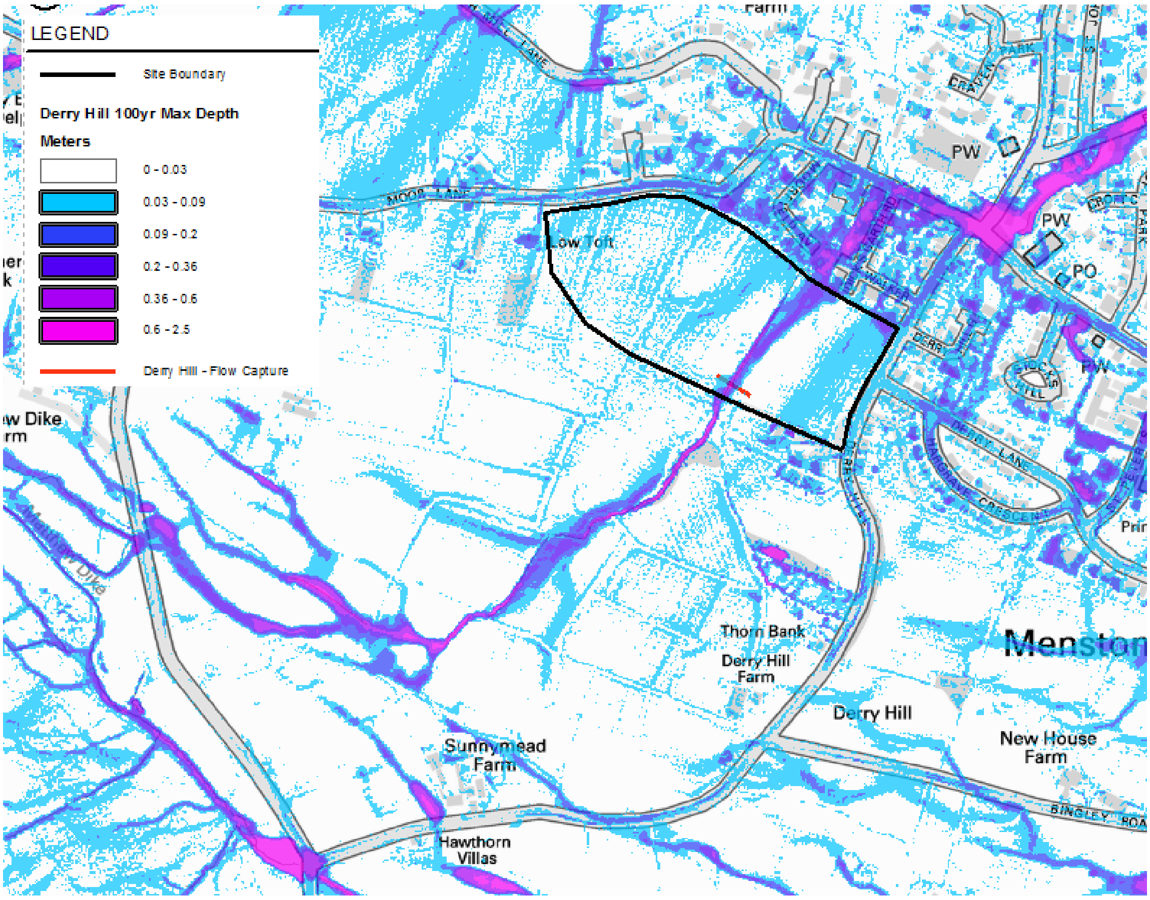
Fig 1.0 – 100-year Maximum Depth at Derry Hill



1.3 Volume Calculations

The table below summarises the depths of rainfall simulated by the model and the corresponding peak flow rates and volumes of water at the Derry Hill site.

Storm Duration (Hours)	Return Period (Years)	Total Rainfall Depth (mm)	Peak Rainfall (mm – 5min Interval)	Time of Peak Rainfall (Hours)	Model Run Time (Hours)	Max Flow Rate at Derry Hill (m^3/s)	Time of Peak Flow at Derry Hill (Hours)	Volume at Derry Hill (m^3)
1	100	45.26	12.46	0.67	2.5	1.60	1.08	4,200
2	100	53.84	9.20	1.16	3.5	1.55	1.57	5,206
3	100	59.61	7.57	1.66	4.5	1.40	2.05	5,888
6	100	70.89	5.31	3.16	7.5	1.00	3.59	7,210

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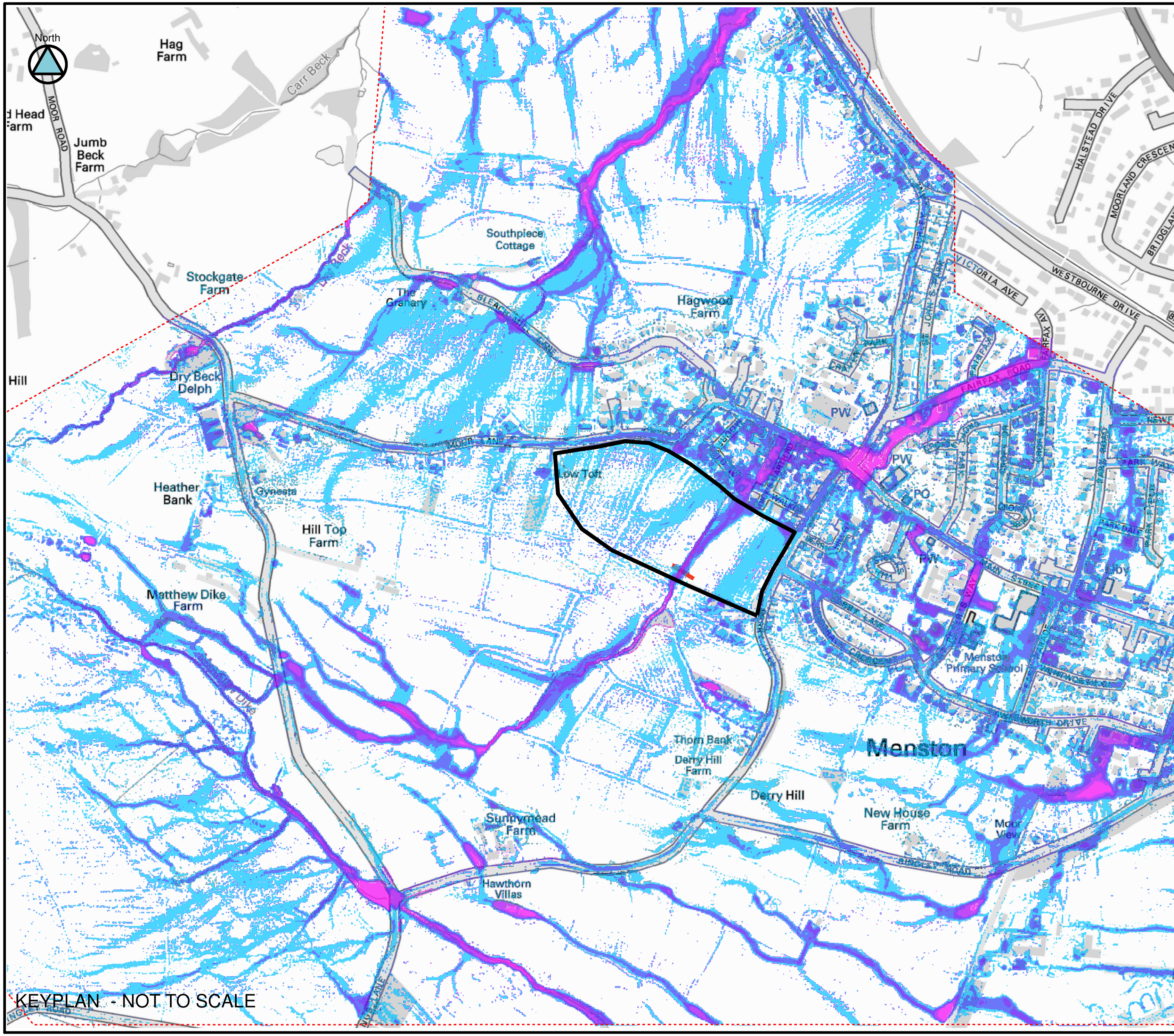

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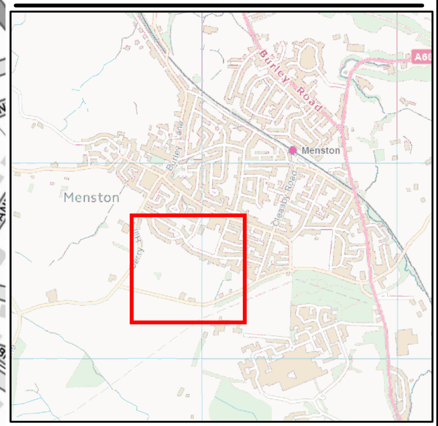

LEGEND

Site Boundary

Model Domain

Derry Hill 100yr Max Depth

Meters

- 0 - 0.03
- 0.03 - 0.09
- 0.09 - 0.2
- 0.2 - 0.36
- 0.36 - 0.6
- 0.6 - 2.5

Derry Hill - Flow Capture

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FIGURE 1.0

Derry Hill - 100yr Storm

Appendix B

NOTE TO FILE

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Author	Guy Dixon Checked: Mark Bentley
Subject	Derry Hill Menston – 2012 Observed Events

1 2012 Observed Event – Derry Hill

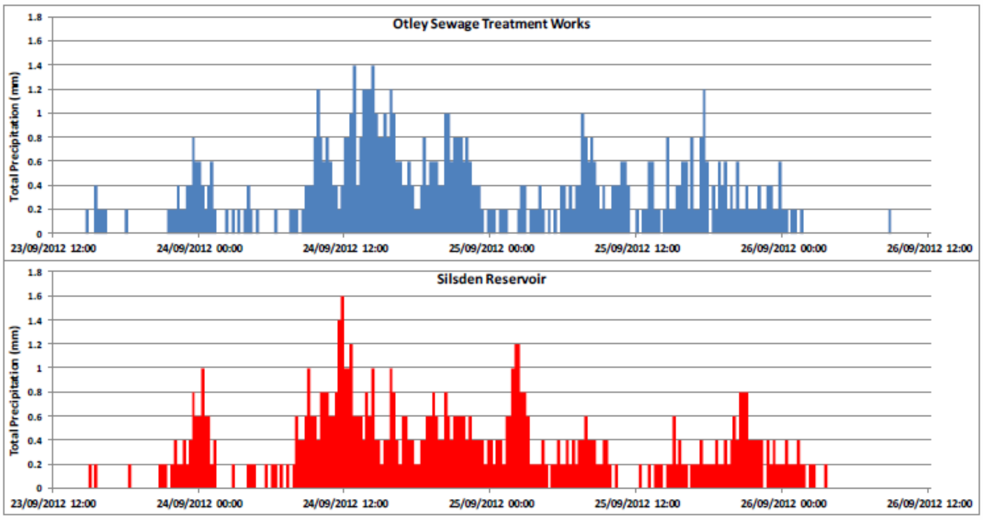
1.1 Introduction

This note summarises the results of a simulation of the September 2012 rainfall event in the Menston area. No rainfall data is directly available for Menston. Therefore, sub-daily data (15-minute resolution) from the following tipping bucket rain (TBR) gauges were obtained under license from the Environment Agency.

- Recording TBR gauge at Otley Sewage Treatment Works
- Record TBR gauge at Silsden Reservoir

The figure below illustrates the variations in rainfall which occurred over a 72-hour period between midday on the 23 September and midday on the 26 September. The event was prolonged but of low intensity, with 82.8mm recorded at the Otley and 80.4mm at the Silsden rain gauges respectively. Similar rainfall durations, onset and volume add confidence to the recorded values from these sites.

Fig 1.0 – 15-minute interval rainfall totals for gauges at Otley Sewage Treatment Works (top) and Silsden Reservoir (bottom)



Using the revised Derry Hill TUFLOW model and the observed rainfall from the Silsden rain gauge the period between 14:00 the 23 September and 05:00 on the 26 September was simulated.

1.2 Modelling Results

Comparisons between the photographic evidence available for the September 2012 event and the model results show that the model reproduced many of the observed flow routes and depths experienced in and around Menston during the event (As can be seen in Figure 2.0; which is also available as a separate figure at the end of the note). A volume of 8,357m^3 was simulated passing through the Derry Hill site over the 63-hour simulation. A maximum flow rate of 0.13m^3/s was simulated and flow was sustained above 0.1m^3/s for approximately 4-5hours. Observations during the event suggest that the flow rate through the site was significantly higher. However, these are based on photographic evidence and so precise flow estimates cannot be made.

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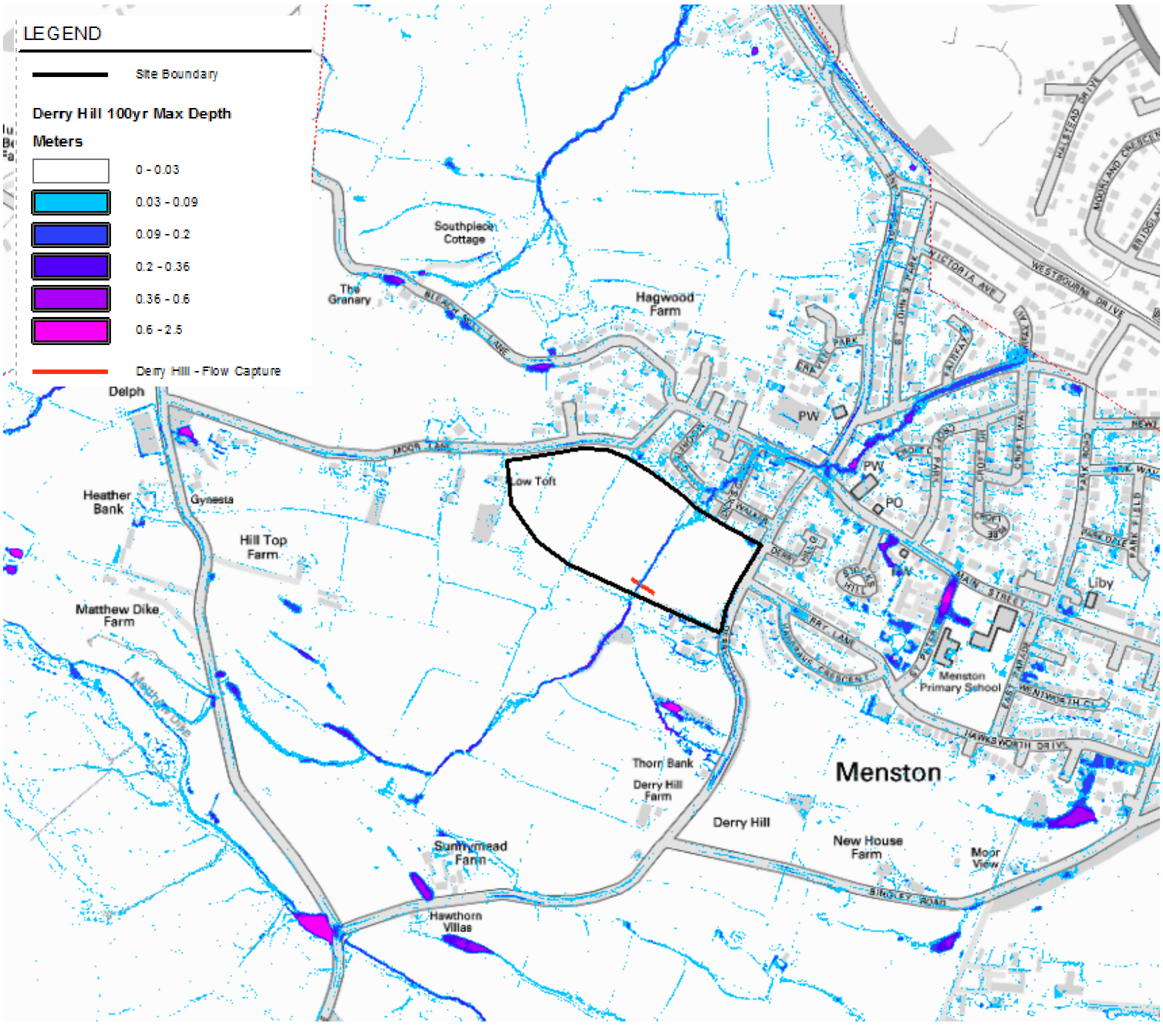
Fig 2.0 – 2012 Maximum Depth Grid

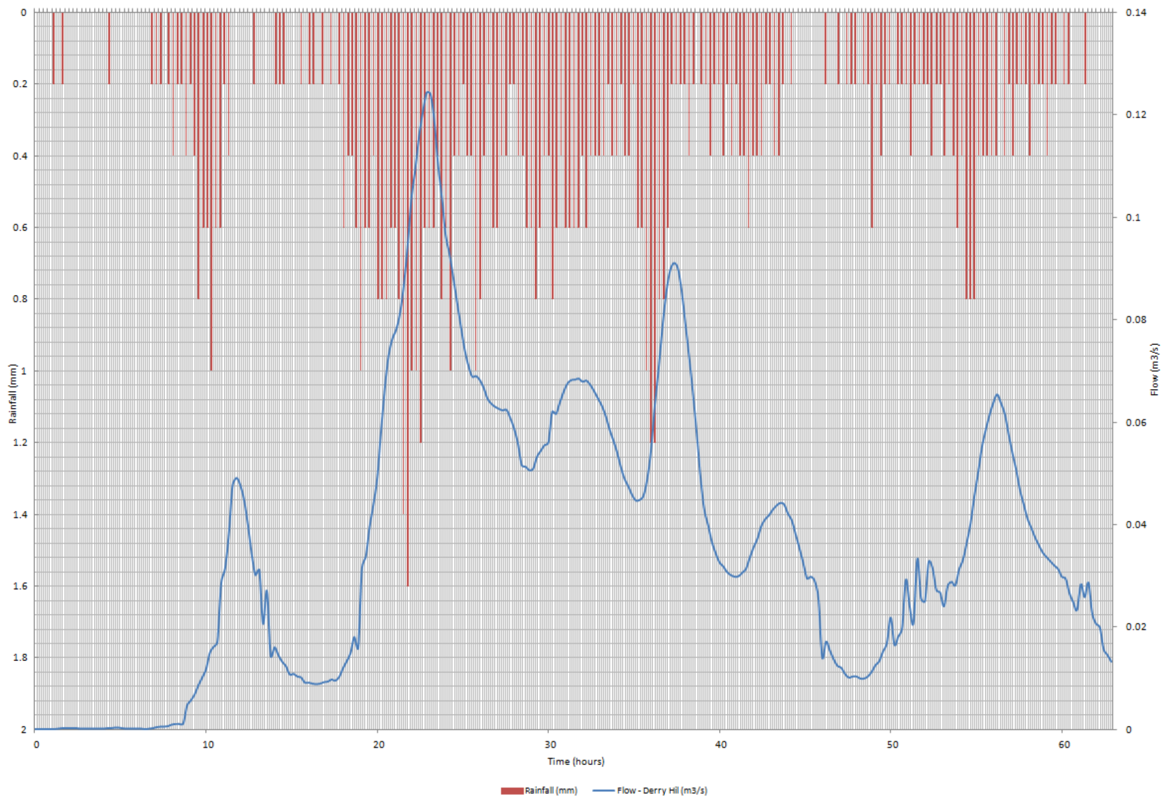


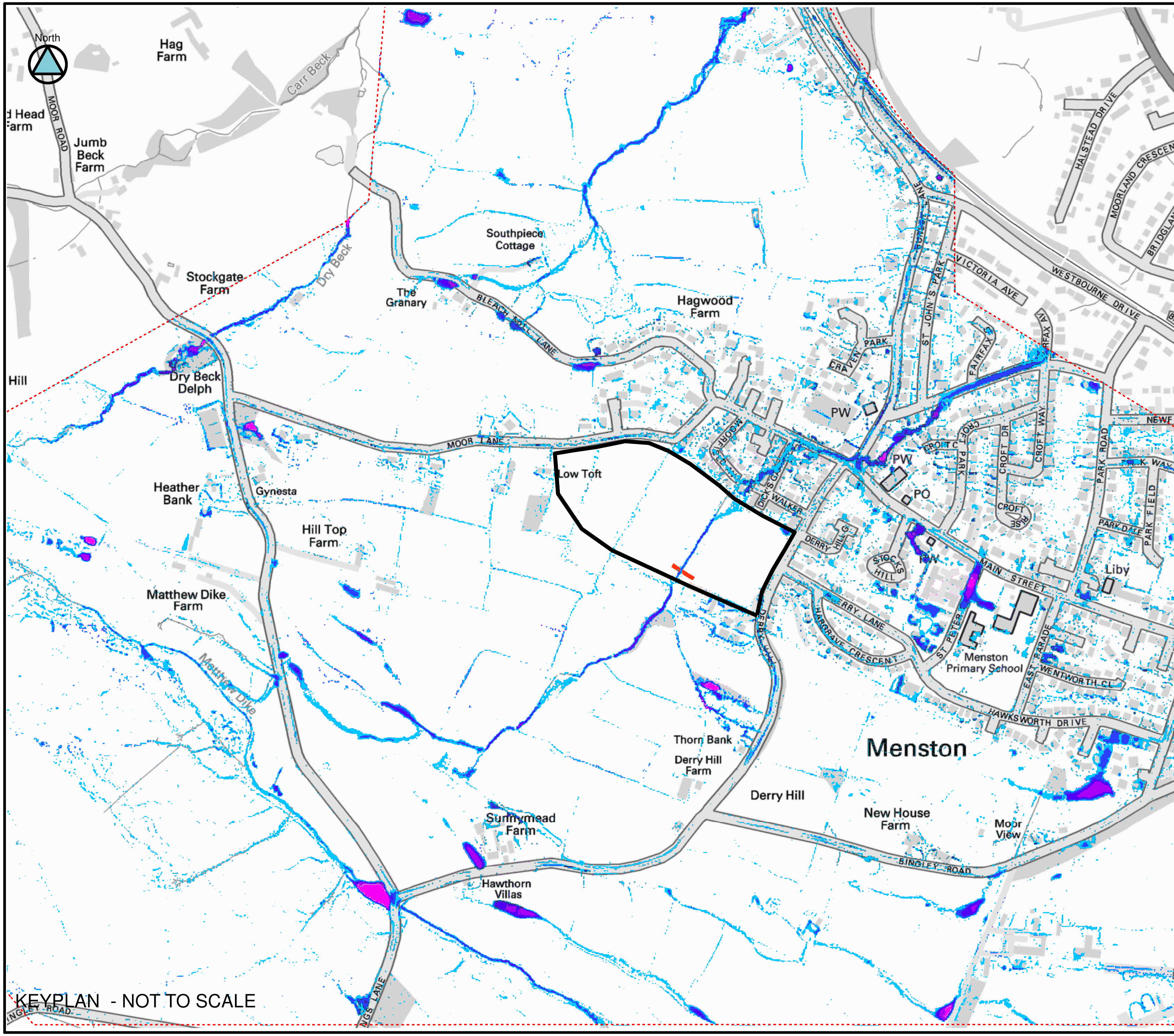
1.3 Volume Calculations

The table below summarises the flow rates and volumes at the Derry Hill Site for the 2012 observed event. The flow rate through the Derry Hill site has also be reproduced graphically in the plot below.

Storm Duration (hours)	Total Volume (m3)	Total Volume for a given time window (m3)					Maximum Flow Rate (m3/s)
		3hour	6hour	12hour	24hour	48hour	
2012 OBS	8,357	1,191	1,956	3,268	5,521	7,894	0.13

Plot 1.0 – Rainfall Model Input vs Flow Rate at Derry Hill





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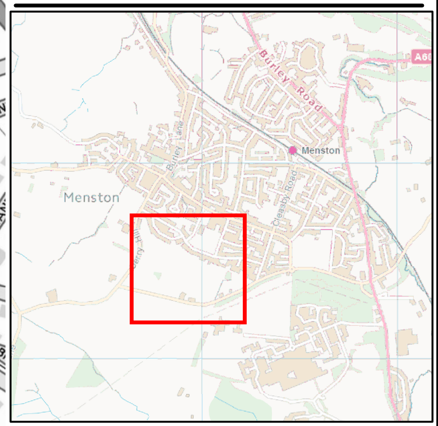


LEGEND

Site Boundary

Model Domain

Derry Hill 2012 Observed

Meters

0 - 0.03

0.03 - 0.09

0.09 - 0.2

0.2 - 0.36

0.36 - 0.6

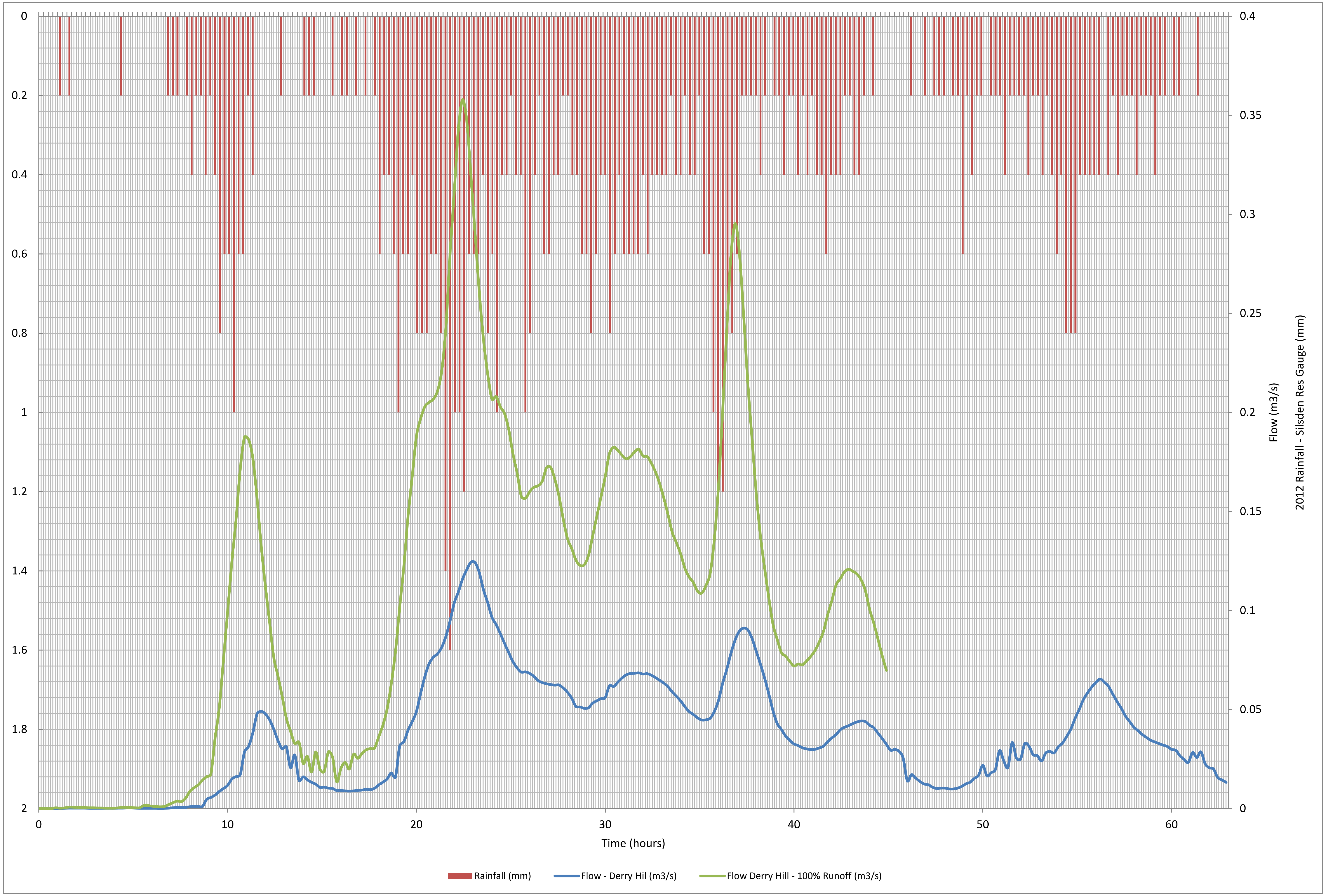
0.6 - 2.5

Derry Hill - Flow Capture

JBA consulting

FIGURE 2.0

Derry Hill - 2012 Observed



0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
10
20
30
40
50
60
Time (hours)
Flow (m3/s)
2012 Rainfall - Silsden Res Gauge (mm)
Rainfall (mm)
Flow - Derry Hil (m3/s)
Flow Derry Hill - 100% Runoff (m3/s)

Appendix C

Appendix D

Appendix E

A Fundamental Conditional Relationship between the Water Flow in any cross-section of a Catchment Area and a Storm Rainfall Event

Introduction:

For most catchment areas where there has been a significant rainfall event such that a meaningful measurement of water flow across any cross-section of the catchment can be made, then assuming a quasi linear behaviour over the rainfall event the flow can be determined using Linear System Theory.

From Linear System Theory and certain obvious physical constraints on rainfall and water flow the following theorem will be proved:-

For a rainfall event and a defined cross-section within an appropriate catchment area if the system is quasi linear for at least the time duration of the rainfall event then the following conditional relationship will always be valid.

$$VC >= PC.VR/PR$$

Where,

VC = the total volume of water flowing through the defined cross-section of the catchment in cubic meters due to the rainfall event.

PC = the maximum volume of water flowing through the defined cross-section of the catchment in any chosen sliding time window of arbitrary duration in cubic metres.

PR=the maximum rainfall per unit area in the same time duration as the sliding time window above (but not necessarily at the same time) in millimetres.

VR= the total rainfall per unit area for the whole of the rainfall event in millimetres

Hence if PC is only know for a small period of time, there is a minimum value for VC. Obviously, the larger the time interval over which the peak flow can be identified, the closer the condition becomes to the equality condition.

Detailed analysis has been done for water flows in the River Leven in Yarm during four storm events. If the baseline flow is removed the additional volume due to the rainfall event readily satisfies the above condition. The two different storms for Derry Hill in Menston in 2008 and 2012 give conditional values for the minimum total value, which are similar when normalised to the same return period, due to the antecedent conditions being similar.

The only case which will not abide by the condition is when a catastrophic event occurs during the rainfall event which would be readily identified. Note that the theorem is not stating that the catchment is always described by the same transfer function only that it is valid over the rainfall event and could be significantly different under various antecedent conditions.

Before proceeding to a formal proof, it is interesting to observe the consequences of this conditional relationship on a particular rainfall event. On the 24th and 25th September 2012 a prolonged rainfall event occurred in Menston, Ilkley and the recorded rainfall is shown in Fig.1 with a definition of the "sliding window" approach

The recorded results are from Otley Sewerage Treatment Works to the East of Menston and Silsden Reservoir to the West, and are taken from the exhibit JDR3 in the report Ref.1. The two sets of measurements are very similar, with a delay between the two due to the storm movement from West to East. The maximum rainfall in any one hour period is approximately 5mm for both measurements. The total rainfall is between 80-84mm with a mean value of 82mm. Further analysis of the rainfall event also is given in Fig.1.

In one part of Menston there is the Derry Hill Site which has a well-defined watercourse at the top of the field shown in Figs2 & Fig3. With water flowing at full depth, as it clearly is from the photographs, it can be estimated that the flow rate is approximately 1.25 m^3/sec or 4,500 m^3/hour. Thus from the conditional relationship for one hour peak flow the minimum value of water which flows in the watercourse during the storm period is:

$$VC \geq \frac{82}{5} X\ 4{,}500 = 73{,}800\ m^3$$

It is also of interest to note that the photographs were taken in the early evening of the 24th September when the rain was falling at only 2mm/hour. Hence, the water observed in the photograph is not only from the current rainfall in the area but from rainfall which occurred many hours earlier.

It was also noted from the photographs and video clips (Google-Schofield Youtube Menston) that were taken that the flow was close to the maximum for 4-5 hours between 4pm and 9pm.

From Fig.1 the mean values for the peak rainfall for 3 and 6 hour duration were 14.2mm and 19.5mm respectfully. From the unconditional relationship we have:-

3 hour peak:

$$VC \geq \frac{82}{14.2} X\ 3\ X\ 4{,}500 = 78{,}000\ m^3$$

6 hour peak:

$$VC \geq \frac{82}{19.5} X\ 6\ X\ 4{,}500 = 113{,}500\ m^3$$

Hence, for the peak lasting 4-5 hours the minimum value of VC is about 100,000 m^3.

A second rainfall event occurred on 21st January 2008 and the recorded rainfall is shown in Fig.4 with the appropriate analysis.

From the photographic evidence at the time the maximum flow in the top of the watercourse on this occasion was about 2 m^3/sec or 7,200 m^3/hour. The delay and duration of the peak was similar to the September 2012 event and the antecedent conditions were also similar. Hence for:

1 hour peak :

$$VC \geq \frac{42.6}{7.6}\ X\ 7{,}200 = 40{,}400\ m^3$$

3 hour peak:

$$VC \geq \frac{42.6}{18.7} X\ 3\ X\ 7{,}200 = 49200\ m^3$$

6 hour peak:

$$VC \geq \frac{42.6}{29.5} X\ 6\ X\ 7{,}200 = 62400\ m^3$$

From the analysis given in Figs1 and 4 the return periods for the two events were approximately 11years and 3 years respectively. An appropriate scaling factor on the January 2008 to the September 2012 event is approximately 1.6 giving very similar minimum values for VC for a return period of 11 years.

<u>Physical Constraints on Rainfall and Waterflow:</u>

There are three obvious constraints which can be identified and play a pivotal role in determining the constraints imposed on the Linear System analysis. These are:-

A. Rainfall in any period must be non-negative.
B. Since water can only flow downhill there is no mechanism which can feed the water back into the catchment area.
C. Any water observed in the catchment can only arise from the current rain falling and additional non-negative contributions from delayed versions of the rainfall event.

The mathematical implications of these constraints will now be applied to the Linear System Analysis.

Linear System Analysis:

As can be seen in Fig.1 rainfall records are in the form of a quantised values sampled over quantised time intervals and hence are in the form of a sampled data system. In particular, the amounts of rain water are typically quantised into 0.2mm increments and are sampled as the total amount of rainfall in typically every fifteen minute period. Additionally the rainfall will terminate after a finite number of sample periods.

Any finite sampled signal can be represented in the time domain as rainfall

$$r(t) = \sum_{q=0}^{m+1} a_q U(t - qT) \tag{1}$$

where u(t) is the unit step function defined by:

$$u(t) = 0 \qquad t < 0 \tag{2}$$

$$= 1 \qquad t > 0$$

T is the time delay between samples which for a typical rainfall event is 15 minutes and

$$a_q \qquad q = 0 \rightarrow m + 1 \tag{3}$$

are the values of the differences between the rainfall in the intervals *qT* and *(q-1)T.*

The coefficient a_q can be positive or negative depending upon whether or not there is an increase or decrease in the rainfall in consecutive periods. However, since the rainfall terminates after m sample periods we have:-

$$\sum_{q=0}^{m+1} a_q = 0 \tag{4}$$

For Linear systems the Laplace Transform is used and is defined by:-

$$R(p) = L\big(r(t)\big)$$

$$= \int_0^\infty r(t)e^{-pt}\,dt \qquad Re(p) > 0 \tag{5}$$

Where p is the complex frequency variable and the integral is evaluated for real part of p Re.(p) greater than zero.

Incorporating eqn.1 into eqn.5 gives:

$$R(p) = \frac{1}{p}\sum_{q=0}^{m+1} a_q\, z^q \qquad\qquad z = e^{-pT} \tag{6}$$

$$= \frac{1}{p} F_{m+1}(z)$$

where $F_{m+1}(z)$ is a polynomial of degree m+1 in z.

From equ.(4) we have the condition $F_{m+1}(1) = 0$ and hence $F_{m+1}(z)$ has a factor 1-z.

Hence,

$$F_{m+1}(z) = (1 - z)V_m(z) \tag{7}$$

With

$$V_m(z) = \sum_{q=0}^{m} b_q\, z^q \tag{8}$$

And

$$b_q = \sum_{k=0}^{q} a_k$$

which represents the total rainfall in the qth sample period. Hence from the first condition A

$$b_q \geq 0 \tag{9}$$

The total rainfall is therefore:

$$\sum_{q=0}^{m} b_q = V_m(1) \tag{10}$$

and the peak rainfall in any sliding time interval is given by the largest value of either b_q or the summation of consecutive samples of b_q in the sliding time window. Due to the fact that it is a sampled data system the transfer function between the rainfall event and water flow in any part of the catchment can be represented by a rational function in z thus:

$$H(z) = T(z)F_{m+1}(z) \tag{11}$$

where $\frac{1}{p}$H(z) is the Laplace Transform of the flow of water in the defined part of the catchment area and T(z) is the associated transfer function.

From condition B, since there cannot be any feedback then T(z) must be devoid of poles and be represented by a polynomial in z as:

$$T_n(z) = \sum_{r=0}^{n} C_r z^r \tag{12}$$

From condition C, since the delayed contributions from the rainfall event must be non-negative we have:

$$C_r \geq 0 \qquad r = 0 \rightarrow n \tag{13}$$

Substituting Eq.7 into Eq.11 we have:

$$\begin{aligned} H(z) &= T_n(z).(1-z)V_m(z) \\ &= (1-z)T_n(z)V_m(z) \\ &= (1-z)W_{n+m}(z) \end{aligned} \tag{14}$$

and hence, $\frac{1}{p}\, W_{n+m}(z)$ represents the Laplace Transform of the volume of water flowing with a total volume of $W_{n+m}(1)$ where:

$$W_{n+m}(1) = T_n(1)V_m(1) \tag{15}$$

Let

$$W_{n+m}(z) = T_n(z)V_m(z) \tag{16}$$

$$= \sum_{q=0}^{n+m} B_q\, z^q \tag{17}$$

and hence from (8) and (12)

$$B_q = \sum_{i=0}^{n} C_i b_{q-i} \tag{18}$$

with

$$b_l = 0 \qquad for\ 0 > l > m \tag{19}$$

Now

$$VC = \sum_{i=0}^{n} C_i . \sum_{i=0}^{m} b_i \tag{20}$$

$$VR = \sum_{i=0}^{m} b_i \tag{21}$$

therefore,

$$VC = \sum_{i=0}^{n} C_i . VR \tag{22}$$

and

$$PR = \sum_{l=r}^{r+k} b_l \tag{23}$$

where the summation of those $k+1$ terms from b_r to b_{r+k} represents the largest summation for any *k+1* consecutive terms from the rainfall event. Similarly PC is chosen as:

$$PC = \sum_{l=q}^{q+k} B_l \tag{24}$$

is the largest summation of any consecutive terms in the flow of water through the defined cross-section:

Define A as:

$$\sum_{i=0}^{n} C_i . \sum_{l=r}^{r+k} bl \ \ .A = \sum_{l=q}^{q+k} B_l \tag{25}$$

which from (18) becomes:

$$= \sum_{i=0}^{n} C_i . \sum_{l=q}^{q+k} b_{l-i} \tag{26}$$

Thus,

$$(1-A). \sum_{i=0}^{n} C_i \,. \sum_{l=r}^{r+k} b_l = \sum_{i=0}^{n} C_i \left[\sum_{l=r}^{r+k} b_l - \sum_{l=q}^{q+k} b_{l-i} \right]$$

And from (23) is therefore

$$= \sum_{i=0}^{n} C_i \ [PR - \sum_{l=q}^{q+k} b_{l-i}]$$

which is

$$\geq 0 \tag{27}$$

since PR is the largest summation of any k+1 consecutive terms of b_i and all the Ci are non-negative.

Thus since A≤1 from (24) and (25)

$$\sum_{i=0}^{n} C_i \sum_{l=r}^{r+k} b_l \geq PC \tag{28}$$

and substituting from (22) and (23)

$$VC \geq PC.VR/PR \tag{29}$$

Which establishes the validity of the basic theorem.

Conclusion:

A fundamental theorem has been established relating to the flow of water through a defined cross-section in a catchment area DUE to a rainfall event. The consequences of the conditional relationship related to storm events in September 2012 and January 2008 have been presented in detail. Fig.5 shows four storm events which were fully recorded for water flows in the River Leven at the bridge in Tarm, North Yorkshire. The factors by which the true flow was greater than the conditional requirement are shown as KF on the diagrams for taking a sliding time window of one hour. For the event on 17-3-80 if a sliding time window of 15 hours were taken then the appropriate Kf factor is less than 1.2 showing the convergence to unity as the sliding time window becomes larger.

The power of the conditional relationship can be appreciated from the Derry Hill results where a single photograph can provide a minimum volume of water flow for the whole of the rainfall event.

Reference:

Prof JD Rhodes "Witness Statement to the Public Enquiry on Land at Bingley Road, Menston" Ref. APP/W4705/A/11/2167397

FIG. 1

Figure 2 illustrates the temporal variations in rainfall for the longer duration event, which occurred within a 72 hour period centred on 25th September 2012. Rainfall between midday on September 23rd and midday on 26th September was prolonged but of low intensity, with 82.8mm recorded at Otley and 80.4mm at Silsden raingauge respectively. Similar rainfall durations, onset and volume add confidence to the recorded values from these sites.

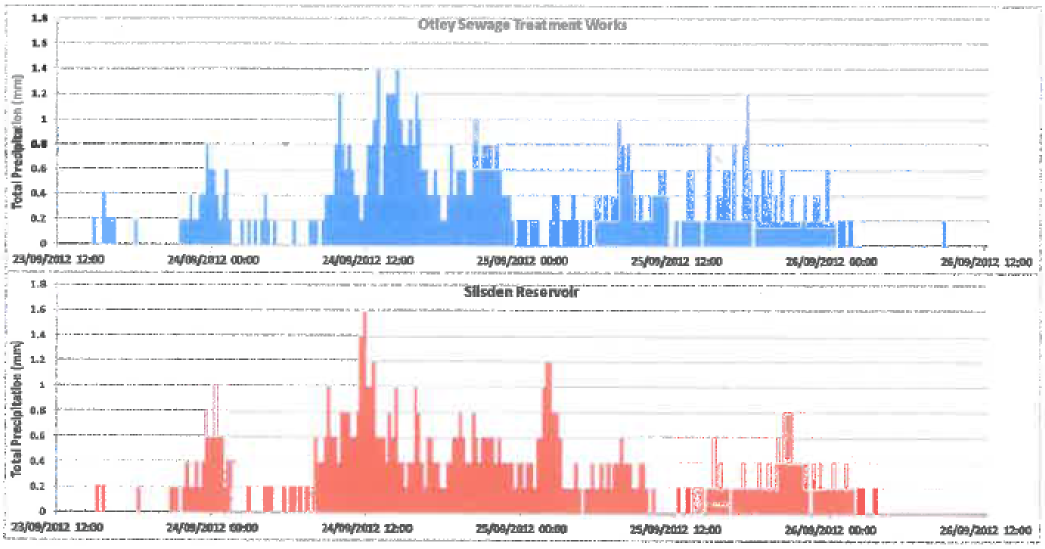


Figure 2: 15-minute interval rainfall totals for gauges at Otley Sewage Treatment Works (top) and Silsden Reservoir (bottom)

3.2 Depth-duration analysis

After checking the integrity of the rainfall data obtained from each TBR, a depth-duration analysis was carried out. This involved calculating the maximum depth of rainfall measured for durations ranging from 1 hour to 72 hours for the available data. A 'sliding window' approach was used; for example in the 1 hour duration case, the total rainfall between 09:00 and 10:00am, between 09:15 and 10:15am, between 09:30 and 10:30am and so forth is determined. The maximum depth for that duration is the largest of these rainfall totals.

The results of the analysis are summarised in **Table 1**.

Table 1: Rainfall Depth-duration-frequency analysis for storm event.

Otley Sewage Works								
Event start date	16th	16th	24th	24th	24th	24th	23rd	23rd
Duration (hours)	1	2	3	6	12	24	48	72
Maximum depth (mm)	10.4	12.2	12.4	20.2	34.8	50.2	77.4	84.4
Return period (years)	1.5	1.1	1.1	1.5	3.3	4.8	10.3	10.2
Rainfall Intensity (mm/hour)	10.4	6.1	4.1	3.4	2.9	2.1	1.6	1.2
Silsden Reservoir								
Event start date	12th	12th	12th	24th	24th	24th	23rd	23rd
Duration (hours)	1	2	3	6	12	24	48	72
Maximum depth (mm)	11.6	14.6	16.0	18.8	30.6	51.6	74.4	80.4
Return period (years)	1.9	1.3	1.6	1.3	2.3	6.4	11.5	9.4
Rainfall Intensity (mm/hour)	11.6	7.3	5.3	3.1	2.6	2.2	1.6	1.1

FIG2

Fig.3

FIG 4

NOTE TO FILE N003 (VERSION 3)

JBA Project Code	2011s5297
Contract	Drainage Advice on Planning Applications at Bingley Road & Derry Hill, Menston
Client	David Rhodes
Day, Date and Time	22 October 2012
Author	Maxine Zaidman & Andrew Peacock
Subject	Rainfall data analysis – January 2008

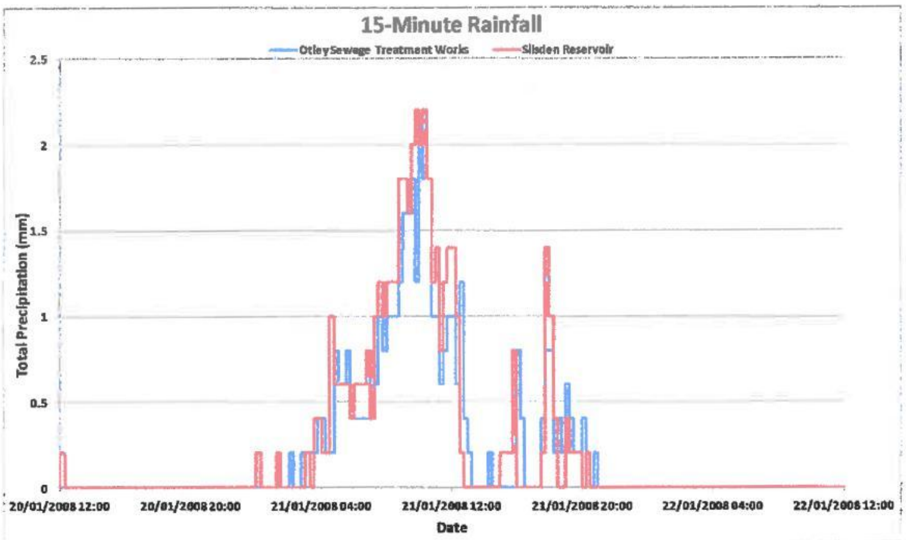
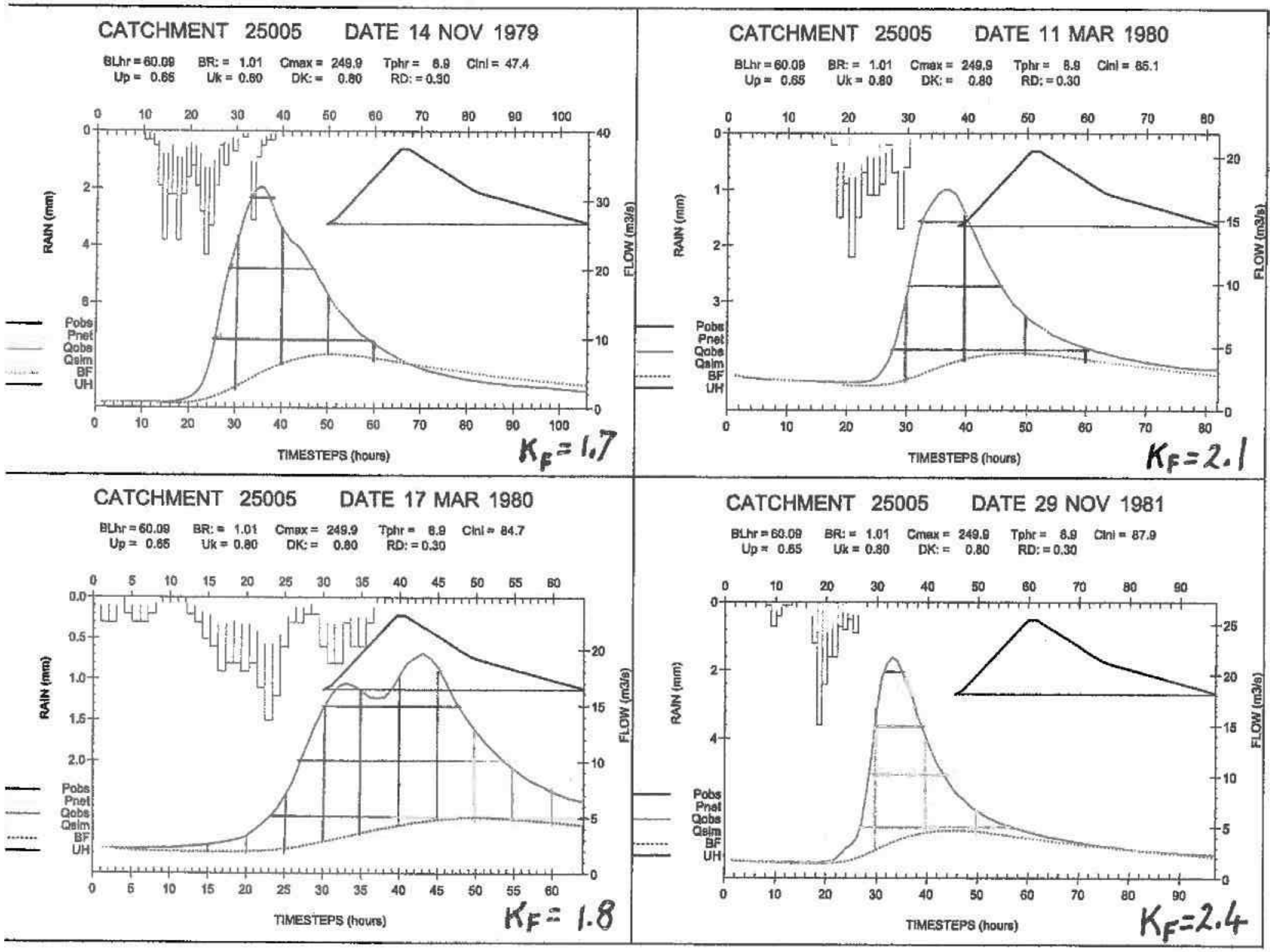


Figure 2: 15-minute interval rainfall totals for gauges at Otley Sewage Treatment Works and Silsden Reservoir

Table 1: Rainfall Depth-duration-frequency analysis for storm event

Otley Sewage Works								
Duration (hours)	1	2	3	6	12	18	24	36
Maximum depth (mm)	6.8	13.0	17.0	26.6	33.6	39.6	40.0	40.0
Return period (years)	1.0	1.1	1.8	3.0	2.9	3.0	2.1	1.3
Rainfall Intensity (mm/hour)	6.8	6.5	5.7	4.4	2.8	2.2	1.7	1.1
Silsden Reservoir								
Duration (hours)	1	2	3	6	12	18	24	36
Maximum depth (mm)	8.4	15.4	20.4	32.4	39.4	44.6	45	45.2
Return period (years)	1.1	1.5	3.00	6.3	5.7	5.3	3.70	2.2
Rainfall Intensity (mm/hour)	8.4	7.7	6.8	5.4	3.3	2.5	1.9	1.3

FIG 5



RIVER LEVEN AT LEVEN BRIDGE

Appendix F

Sliding Time Window for 100 Year Return Period Storms

Direct Surface Water Catchment Area

Storm Duration (Hours)	Time Window (Mins/Hours)	PR (mm)	PC (m^3)	Estimated VC (m^3)	$K_f = \frac{PR.VC}{PC.\ VR}$
1	5 mins	12.46	476	1729	2.52
	15 mins	29.02	1322	2062	2.11
	30 mins	37.76	2263	2712	1.61
	1 hour	45.26	3393	3393	1.20
	2.5 hours	VR=45.26	VC (Est)	4354	1.00
2	5 mins	9.20	469	2745	1.97
	15 mins	23.86	1342	3028	1.78
	30 mins	33.36	2394	3863	1.40
	1 hour	44.32	3745	4549	1.19
	2 hours	53.84	4898	4898	1.10
	3.5 hours	VR=53.84	VC (Est)	5396	1.00
3	5 mins	7.57	427	3362	1.81
	15 mins	20.53	1246	3618	1.69
	30mins	29.61	2303	4636	1.32
	1 hour	41.41	3766	5421	1.13
	2 hours	53.79	5173	5733	1.06
	3 hours	59.61	5752	5752	1.06
	4.5 hours	VR=59.61	VC (Est)	6102	1.00
6	5 min	5.31	327	4366	1.71
	15 mins	15.17	965	4509	1.66
	30 mins	22.75	1849	5762	1.30
	1 hour	33.99	3265	6810	1.10
	2 hours	48.67	5014	7303	1.02
	3 hours	57.81	6033	7398	1.01
	6 hours	70.89	7197	7197	1.04
	7.5 hours	VR=70.89	VC (Est)	7473	1.00

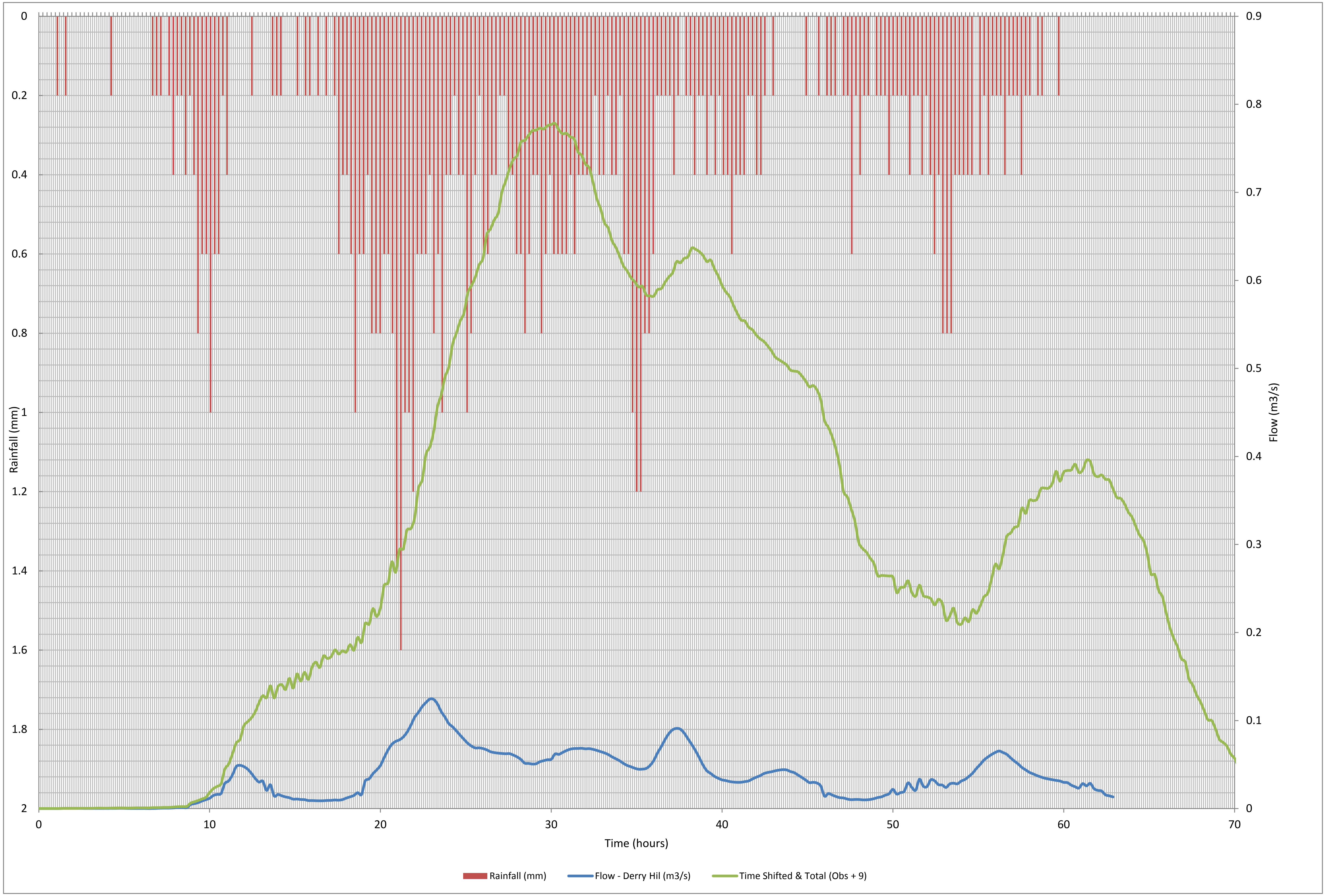
Appendix G

Sliding Time Window September 2012

Direct Surface Water Catchment Area

Storm Duration	Time Window (Hours)	PR (mm)	PC (m^3)	Estimated VC (m^3)	K_f = $\frac{PR.VC}{PC.\ VR}$
From 8:00pm on 23-09-2012 to 2:00am on 26-09-2012	1	5.0	428	6830	1.24
	3	11.0	1147	8321	1.02
	6	18.8	1956	8303	1.02
	12	30.6	3268	8522	1.00
	24	51.6	5520	8537	1.00
	48	74.4	7894	8467	1.00
	54	79.8			
	72	VR = 79.8	VC (Est)	8500	1.00

Appendix H



Rainfall (mm)
Flow (m3/s)
Time (hours)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10
20
30
40
50
60
70
Rainfall (mm)
Flow - Derry Hil (m3/s)
Time Shifted & Total (Obs + 9)

Appendix I

Sliding Time Window September 2012

Simulated Enlarged Catchment Area

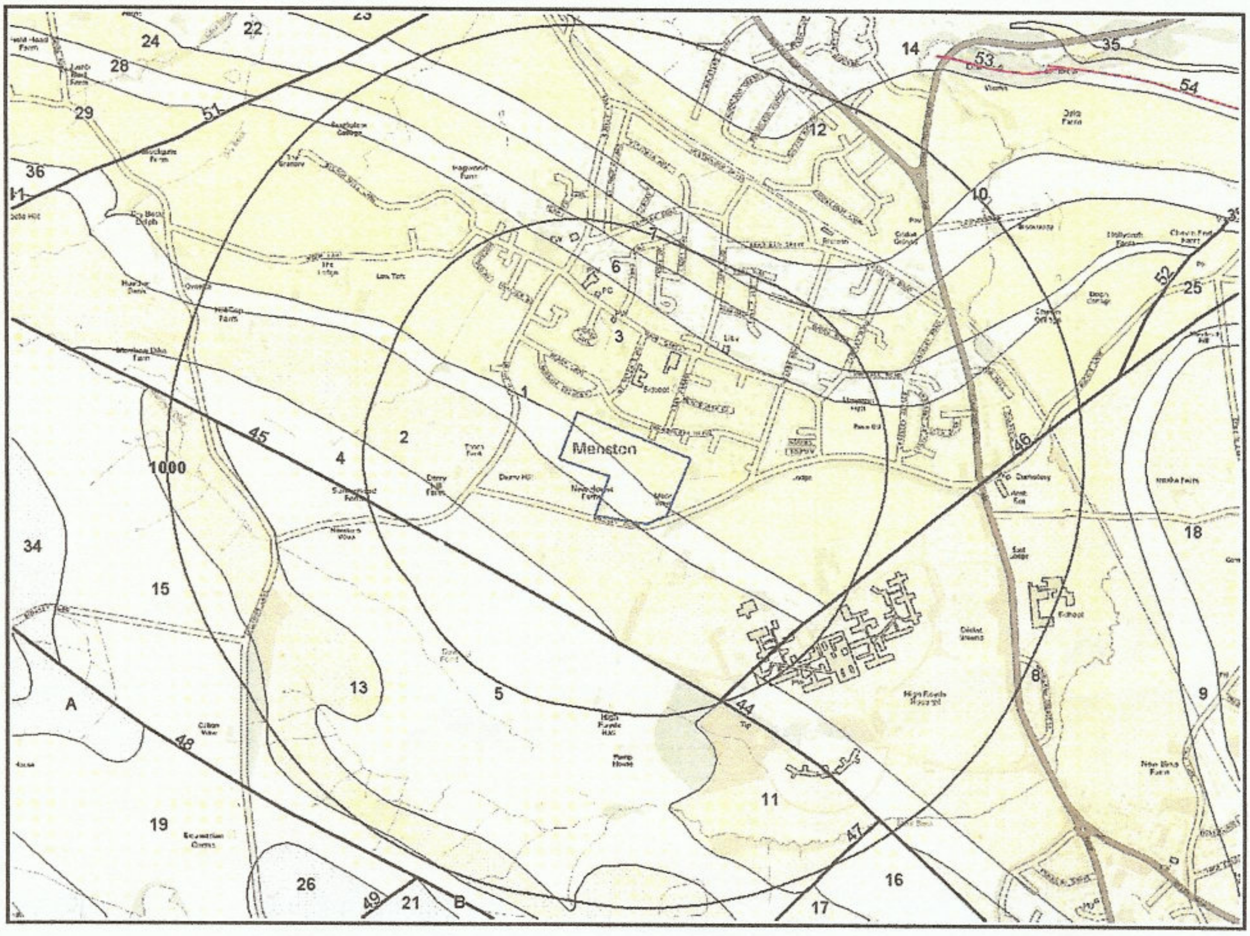
Storm Duration	Time Window (Hours)	PR (mm)	PC (m^3)	Estimated VC (m^3)	K_f = PR.VC / PC. VR
From 8:00pm on 23-09-2012 to 2:00am on 26-09-2012	1	5.0	2790	44528	1.91
	3	11.0	8306	60256	1.41
	6	18.8	16678	70793	1.20
	12	30.6	30035	78327	1.09
	24	51.6	52894	81801	1.04
	48	74.4	78203	83879	1.01
	54	79.8			
	72	VR = 79.8	VC (Est)	85000	1.00

Appendix J

GroundSure

1.3 Bedrock and Faults Map

N



S

Bedrock & Faults Deposits Legend

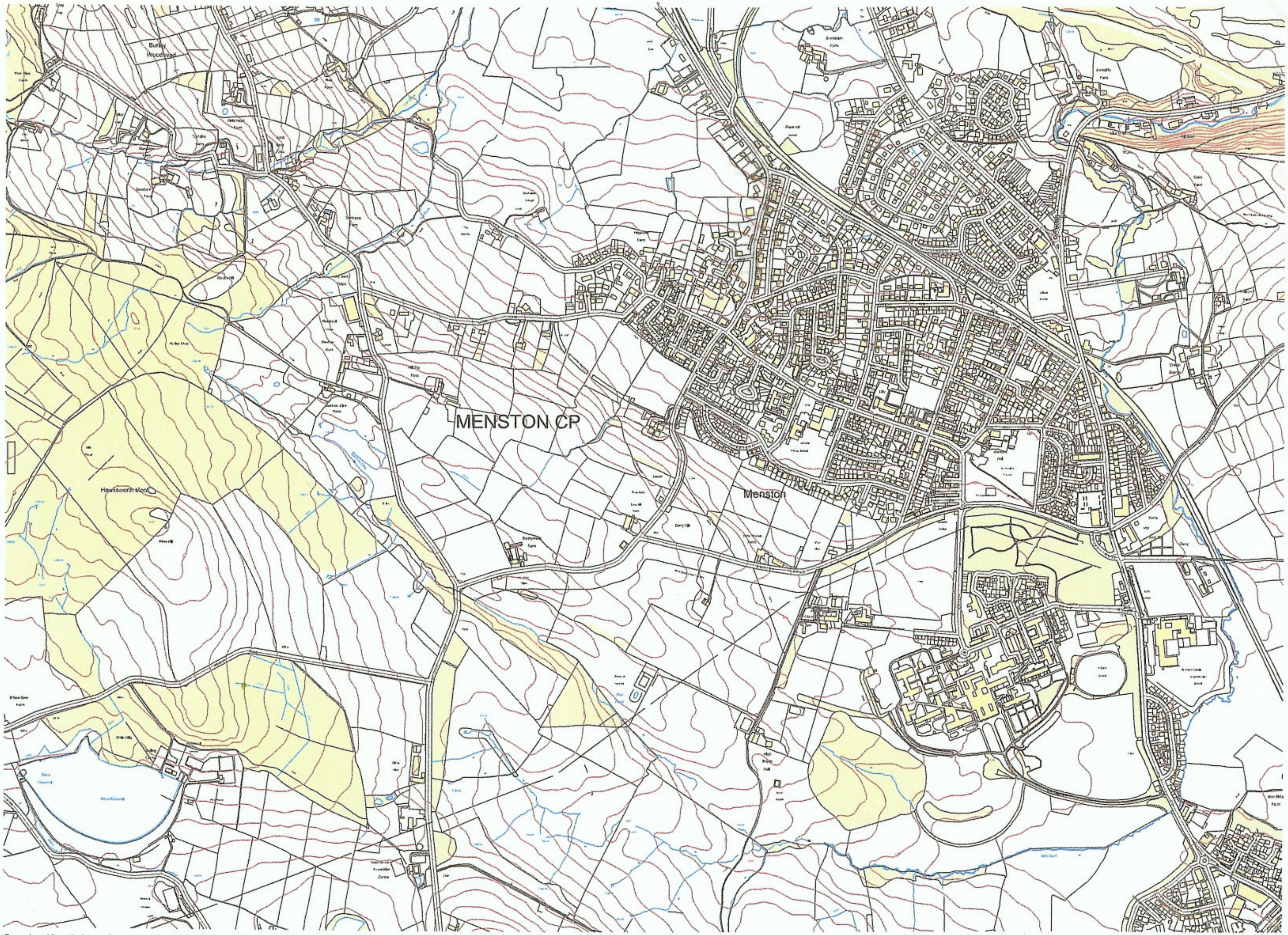
Enabled by Ordnance Survey

Site Outline

500 / 1000 Search Buffers (m)

Geological information represented on the mapping is derived from the BGS Digital Geological map of Great Britain at 1:50,000 scale.

Appendix K


MENSTON CP
Menston
Hawksworth Moor
Burley Woodhead