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EX 5160

Flooding in Boscastle and North Cornwall, August 2004

Phase 2 Studies Report

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Glossary

Annual probability of exceedence	The probability that a specified event will be equalled or exceeded in a given year
Avulsion	Sudden lateral river channel movement in which the river erodes a new channel away from the original channel
Backwater zones	Areas out of the main flow where the flow velocities are less than in the main flow
BHS	British Hydrological Society
BST	British Summer Time
CEH	Centre for Ecology and Hydrology, Wallingford
Channel avulsion	See Avulsion
CIRIA	Construction Industry Research and Information Association
Convective event (rainfall)	Rainfall caused by moist air being convected upwards through the troposphere
Convergence	Where two air masses moving in different directions meet forcing some of the air upwards
DTM	Digital Terrain Model – a representation of the land surface
FEH	Flood Estimation Handbook. A handbook that describes the analysis of rainfall and flow records in order to predict the magnitudes of floods with specified probabilities
FEH CD-ROM	A CD containing data on river catchments in England and Wales which forms part of the Flood Estimation handbook
FORGEX	Method to analyse rainfall data to determine the probability of rainfall events at specified locations. It is described in the Flood Estimation Handbook
FSR	Flood Studies Report. The forerunner of FEH
GEV	Generalised extreme value distribution, used to describe the probability of extreme events
GIS	Geographic Information Systems

GLO	Generalised logistic probability distribution, used to describe the probability of extreme events.
GMT	Greenwich Mean Time
Growth curve	The relationship between discharge and probability at a particular location
HR	HR Wallingford, a specialist hydraulics research company
Hydraulics	The study of the flow of water in channels and pipes
Hydrograph	The variation of discharge with time
Hydrology	Within the context of this report: The study of the relationship between rainfall and runoff into the river system. Note that in general hydrology has a wider meaning
HYFLOWS UK	Output from a project to up-date the database of flows that underpins the Flood Estimation Handbook
HYRAD	Software for rainfall estimation from weather radar produced by CEH Wallingford
Infoworks RS	Software for the numerical simulation of flow in rivers produced by Wallingford Software
ISIS	Software for the numerical simulation of flow in rivers
LIDAR	Light Detection and Ranging – a method of carrying out mapping remotely using a laser mounted on an aeroplane
Manning's n	A parameter to describe the hydraulic roughness of channels
MOSES-PDM model	Met Office Surface Exchange Scheme incorporating the Probability Distributed Model
NERC	Natural Environment Research Council
NIMROD	Nimrod is an automated system for weather analysis and nowcasting based around a network of C-band rainfall radars, which provides fine-resolution analyses and six-hour forecasts. It delivers routine predictions of: rainfall rate, rain accumulation, precipitation type, snow probability, cloud, visibility and wind gust speeds
Normal depth	The flow condition in which the water surface slope matches the bed slope of the channel
NWP model	National Weather Prediction model

PDM	Probability Distributed Model
Percentage runoff	The percentage of the rainfall that enters the river system
PMF	Probable Maximum Flood. An estimate of the extreme flood from a catchment used for the hydraulic design of dams.
Pooling group	A group of catchments from around the country which are hydrologically similar to the catchment under study. Data from the Pooling group can then be used predict the behaviour of the catchment being studied
Potential Vorticity	The product of measures of the spin of the air and its vertical density gradient. It is an atmospheric analogue to the angular momentum of a spinning body and provides a concise summary of atmospheric flow. A region of enhanced upper level PV has ascent ahead of it and descent behind, leading to an atmospheric 'vacuum cleaner' effect with increased likelihood of rain ahead."
PR	Percentage Runoff – the percentage of the rainfall that enters the river system
Precipitation anomaly	The difference between the actual rainfall and the long-term average rainfall
QMED:	Median annual maximum flood. The largest discharge each year is abstracted from a flow record for a given gauging station. QMED is the median value of the series, that is, the value for which half the flows are larger and half are smaller. In many, but not all, natural channels the QMED value approximates the bankfull discharge
Rainfall-runoff model	A model that converts rainfall into the corresponding runoff in the rivers
Return period	A method of expressing the probability of an event. An event with a T year return period can be expected to be equalled or exceeded on average once every T years
Roughness coefficient	The relationship between discharge and water level in a channel depends upon the hydraulic friction in the channel. The amount of friction is described using a roughness coefficient. A commonly used roughness coefficient is Manning's n, see above
Soil Moisture Deficit (SMD)	It measures the dryness of the soil and its ability to absorb water. The amount of water, in mm, that would have to be added to a soil to make is saturated. Thus a very wet soil has a low soil moisture deficit and a very dry soil has a high soil moisture deficit.
Synoptic	A general view of the overall conditions

TBR	Tipping bucket raingauge. The rainfall is collected and falls on a small bucket that tips when it is full. By recording the frequency of the 'tips', the rainfall intensity can be measured. TBRs thus provide data on how the rainfall intensity varied through a rainfall event. During very intense rainstorms the bucket sometimes cannot tip backwards and forwards fast enough and so the gauge may under record the rainfall
Thiessen polygons	A method for carrying out an analysis of spatial data
Tp	Time to peak of the unit hydrograph
Tropopause height	The height of the tropopause
Troposphere	The troposphere is where all weather takes place; it is the region of rising and falling packets of air. The air pressure at the top of the troposphere is only 10% of that at sea level (0.1 atmospheres). There is a thin buffer zone between the troposphere and the next layer (the stratosphere) called the tropopause.
UKMO	UK Met Office
Unit hydrograph	The river discharge that would result from a notional rainfall of 1 mm distributed uniformly over the catchment
WINFAP-FEH	Software for the statistical analysis of time series data produced by CEH Wallingford. This can be used to analyse annual maxima series of rainfall or river flow data
Wrack marks	Collections of trash left on buildings or trees after the flood that mark the highest water level during the flood

Summary

Flooding in Boscastle and North Cornwall, August 2004 Phase 2

On 16 August 2004 an extreme rainfall event took place near the north Cornwall coast when up to 200 mm of rain fell in a period of approximately 5 hours.. This rainfall led to severe flooding in the Valency and Crackington Stream catchments and serious flooding on the Rivers Ottery and Neet. This report describes the rainfall, and the flooding caused by the event. It was produced for the Environment Agency by HR Wallingford Ltd (HRW) with analyses of the meteorological, hydrological and hydraulic aspects of the event being undertaken by the UK Met Office (UKMO), the Centre for Ecology and Hydrology, Wallingford (CEH) and HR Wallingford, respectively. Field work and data collection for the Valency and Crackington Stream catchments were carried out by Halcrow and Royal Haskoning, respectively.

The August 2004 flood event in Boscastle must be one of the best recorded extreme flood events in the UK. Since the flood occurred during the day in the presence of many people, there is a good photographic record of the event. The prompt action by the Environment Agency in having the trash marks surveyed and in collecting eye-witness accounts following the event has added important qualitative and quantitative data. From the available data it has been possible to reconstruct the flood (see Tables 2.1 and 2.2 in the main report)

The evidence suggests that there were significant changes in flow paths during the event, as a result of bridges blocking with trash, walls falling down or water bursting through buildings.

A number of the eye-witnesses describe very rapid increases in water level over periods measured in minutes or seconds. These are reported at both Boscastle and Crackington Haven. A number of explanations have been offered for these rapid changes in water level. At Boscastle it has been suggested that these were due to trash dams developing and then breaking in the catchment upstream and hence causing flood waves downstream. The hydraulic modelling described in this report suggests that for the bursting of a trash dam to have a significant impact on flood levels in the centre of Boscastle, it would have had to retain a significant height of water, probably in excess of 3 metres. The hydraulic modelling suggests that changes in flow paths in Boscastle resulting from, for example, the bridge blocking, would lead to changes in water level of the magnitude of those observed. Though it is possible that the water levels at Boscastle and Crackington Haven were affected by trash dams upstream, it seems more likely that the observed rapid changes in water level arose from changes in flow paths caused by events such as a bridge blocking or a wall falling down in Boscastle.

Geomorphology

There was substantial morphological change during the flood along both the Valency and the Crackington Stream and also on their tributaries. Over most of the length of the Valency and the Crackington Stream, the main channel of the river increased in both width and depth. In places the vertical erosion was constrained by the presence of bed rock under and close to the bed of the original channel. Simultaneously with the increase in channel depth there was lateral channel movement. At a number of locations the river abandoned the pre-flood channel and cut a new channel through the floodplain (channel avulsion). In a number of cases the channel avulsion would have acted to reduce the length of the channel and hence increase the slope of the river channel. The erosion resulted in the release of large quantities of sediment into the flow. The size of sediment mobilised ranged from fine silts to large boulders. In a few limited locations there was sediment deposition. Where sediment deposition did take place it indicated that sediment sizes up to and including 1 metre were mobilised in the flood. These sediment deposits were on the floodplain and it is likely that larger sediment sizes would have been

mobilised in the main channel. The observed sediment deposition within the catchment represented a small fraction of the total sediment erosion.

A notable area of sediment deposition was the lower reach of the Valency and Boscastle harbour. The channel erosion and lateral movement of the channel in the upper catchment released large quantities of sediment which were then carried downstream by the flow. In any areas of slower moving flow sediment deposition took place. This resulted in large quantities of silt being deposited in the houses that were flooded in Boscastle. In addition the blockage of the bridges in Boscastle led to sediment deposition in the main channel upstream of them. A significant amount of the sand and gravel mobilised by the flood was deposited in the harbour though there was also scour around the nose of the southern breakwater as a result of the constriction of the flow. Finer sediment travelled further and was washed out to sea.

When the flows in the Valency and Crackington Stream were modelled using the post-flood river cross-section data, in general, the predicted peak water levels were significantly below the observed trash marks. When the river cross-sections were replaced with approximations to the pre-flood cross-sections, better agreement was obtained with the observed trash marks. Thus channel erosion during the flood event affected the observed flood levels. Sediment transport is a non-linear function of discharge so that much of the sediment erosion will have taken place during the peak of the flood.

Within the Jordan and Paradise Stream catchments there was significant erosion and downcutting. This released significant quantities of fine sediment into the flow. During the flood event the flow coming down the Jordan exceeded the flow through the culvert at the lower end of the catchment. As a result water began to pond upstream of the entrance to the culvert. This led to deposition of the sediment being carried by the Jordan in the area around the entrance to the culvert and eventually led to the blockage of the entry into the culvert. The water continued to pond upstream of the culvert until it broke through the Wellington Hotel and around the adjacent cottages.

Meteorology

Following a dry spring and a dry June, during which rainfall in the Valency cacthment was approximately 10% below average, the July rainfall for the Valency and adjacent catchments was close to the average. This led to a reduction in Soil Moisture Deficit in the North Cornwall area from the range 80 to 220 mm in June to the range 40 to 180 mm in July. The extreme rainfall accumulation in the North Cornwall area resulted from prolonged heavy rain over the four hour period 12:00 to 16:00 GMT on the 16 August 2004. The intensity of the rainfall was probably enhanced by large scale uplift associated with larger scale weather troughs. A large depression dominated the eastern Atlantic with a complex structure, reflecting a history of successive pulses of tropical air being absorbed into the circulation. The effect of the large scale processes would have been to create an environment of weak uplift and high moisture content which would favour heavier rainfall.

The extreme rainfall on the 16 August 2004 resulted from a sequence of convective storms that were channelled along the north Cornwall coast over several hours. The location of the storms was influenced by a strong convergence line along the north Cornwall coast, arising from the alignment of the prevailing wind with the coast. This may have been reinforced by an onshore pressure gradient resulting from solar heating over the land. As they developed in the convergence zone, each storm cell spread out into a line of storms, making the rain appear to be continuous. The extreme precipitation appears to have been related to the fact that while convection was strong enough to generate heavy precipitation, it was shallow enough to permit the development of closely packed storm cells with downdraughts weak enough not to distort the coastal convergence line.

Data on the temporal and spatial distribution of rainfall was derived from the network of rain gauges and the Cobbacombe and Predannack radars. This data shows that the spatial extent of the rainfall event was limited, and that the rainfall intensities had large spatial gradients.

Using the FORGEX method documented in the Flood Estimation Handbook (FEH), probabilities can be derived for the observed rainfall maxima:

	Annual probability of occurrence exceedence	Annual chance of exceedence
a) One hour rainfall at Lesnewth (82 mm)	0.25%	1 in 400
b) Three hour rainfall at Lesnewth (148 mm)	0.08%	1 in 1,250
c) Overall storm	0.05%	1 in 2,000

(Note: The annual probability of occurrence is the probability that the event under discussion will take place at least once during a given year. An event with an annual probability of occurrence of 1% means that there is a 1 in 100 chance of that event occurring in any year).

Given the shortness and sparseness of the instrumental record, the reliability of the estimates of the probability of such rare events is questionable, but the results can be safely taken to indicate an annual probability of occurrence less than 0.1%.

Inspection of the mechanisms involved in generating the rainfall indicates that the key features were the efficiency of the rainfall production and the length of time for which it remained over the same area. The FEH results suggest that the efficiency of the rainfall production meant that the annual probability for the maximum hourly rainfall was about 0.25%. As the high intensity rain remained over the same area for about 5 hours, the combined rainfall and duration reduced this annual probability to about 0.05%. As with other extreme storms that have been studied, the combination of factors that produced the event do not fit a pattern that has been observed before. Thus the event was caused by the combination of a number of factors, none of which are particularly rare but whose combination is. If one could assign a probability to all these events combining again it would not necessarily indicate the likelihood of recurrence as the next extreme event is likely to occur as a result of the combination of a different set of factors.

An alternative approach to estimating the probability of the event is to place the August 2004 storm in the context of historic extreme events. The characteristics of extreme rainfall events in the 20th Century have been studied by Hand et al (2004). The overall frequency of such events is one event every second year somewhere in the UK. If we consider only convective events we have something like a probability of 0.3 chance of an extreme convective event occurring somewhere in the UK each year. Most of these events have occurred during the summer months with none between November and April. The south west peninsula has been subjected to six extreme rainfall events in the last century, of which three occurred in the decade 1951-60. The point (1km^2) probability deduced from an examination of these events indicates a similar annual probability to that deduced using the FEH method. Allowing for the sparse observational network, the evidence indicates that an extreme event will occur somewhere in the south west region once every 20 years on average.

Hydrology

Neither the Valency nor the Crackington catchments are gauged and so there is no historic data on which to base a hydrological analysis. As a result ungauged catchment procedures have been used, which inevitably results in a relatively high degree of uncertainty. Estimates of the probability of the flood events were based on use of the Flood Estimation Handbook (FEH) and regional historical evidence. Two procedures were applied, the statistical approach and the rainfall-runoff model, using design rainfalls to derive full flood hydrographs.

FEH statistical procedures applied to the Valency and Crackington Stream give estimates of the floods with a 0.1% annual probability of exceedence of 16.6 and 14.9 m^3/s, respectively. It is apparent that these estimates are very small when compared to the estimated flood peaks of 16th August 2004, of approximately 180 m^3/s for the Valency/Jordan and approximately 90 m^3/s for Crackington Stream derived from the hydraulic modelling described below. This indicates that the 16th August 2004 floods were very rare events. Due caution ought, however, to be placed on probability estimates when FEH statistical procedures are applied to small, steep catchments. There seems to be greater variability between small catchments than between large catchments as the details of topography and geology become more important. In addition there is limited data from small catchments. This means that, in general, there are larger uncertainites associated with smaller catchments than larger ones.

The rainfall runoff method of the FEH uses the unit hydrograph-losses model to convert event rainfalls to flood runoff. The rainfall may be either a design storm of specified exceedence probability, or may be observed rainfall, in order to assess the resultant flood runoff. For the present study, both approaches have been adopted, the first in an attempt to establish the probable exceedence probability of the 16th August event, and the second, to determine the probable inflow hydrographs to the hydraulic modelling studies derived from the rainfall estimates described in Section 5.4.

The 0.1% annual probability flow estimates derived using the FEH rainfall-runoff method, at 34.8 m^3/s for the Valency/Jordan and 28.9 m^3/s for the Crackington Stream, are significantly higher than those derived using the statistical approach. The reliability of the FEH rainfall-runoff estimates for both streams is prejudiced by the dearth of good quality ‘donor’ catchments having the sort of flood regime typical of north Cornwall and Devon catchments, and by the fact that rainfall growth curves in this part of the UK are steep, and possibly steeper than flood growth curves.

The FEH rainfall-runoff modelling exercise was repeated using the radar-derived rainfall estimates produced by CEH using the HYRAD software. This produced discharge hydrographs at selected locations that were then used as inputs in the hydraulic modelling described in Chapter 6.

The current best estimates of the flood frequency relationship of the Valency/Jordan catchment, derived from a combination of the FEH statistical and rainfall-runoff methods, supported by historical evidence and considerable judgement, are shown in Figure 5.10. The act of ascribing exceedence estimates to floods generated by a rare combination of circumstances, in such small and steep catchments is inevitably uncertain, and the results are accordingly approximate. Notwithstanding, it is clear that the Boscastle flood of 16th August 2004 was unusual in origin, and very rare in occurrence - being rarer, certainly, than a 0.5% event. We believe, on balance, that the event had a 0.25% (1 in 400) chance of recurring in any one year.

It is extremely difficult to assess the annual probability for the flood at Crackington Stream, as we have been unable to trace any historic flood records. Thus we cannot use historic flood data, as a guide as was done for Boscastle. The magnitude of the peak flow and severity of the morphological change upstream of Crackington Haven would suggest that the event was extreme with an annual probably of occurrence smaller than 1%. The rainfall totals over the Crackington Stream cacthment were lower that those for the Velency catchment. This would suggest that the annual probability of exceedence was probably larger than 0.25%.

Hydraulics

The floods in the Valency and Crackington Stream catchments have been modelled using the numerical river modelling software, Infoworks RS. The models were based on post-flood survey and calibrated to the large range of wrack marks that were surveyed after the event.

The modelling suggested that the peak discharge on the Valency downstream of the confluence with the Jordan was of the order of 180 m^3/s and that at the time of the peak of the flood the bridges in Boscastle were virtually blocked.. The numerical model results under-predicted the levels of observed wrack marks upstream of Boscastle, probably due to the morphological changes that had taken place to the channel during the flood. The model results indicated that rapid blockage of the B3263 bridge could cause the water levels upstream to increase by between 1 and 2 metres in a time period measured in minutes or possible seconds, depending upon how quickly the bridge was blocked. The flow velocities in the Valency upstream of Boscastle were of the order of 3 m/s while the flow velocities in the centre of Boscastle were in some locations of the order 5 m/s. These are section averaged velocities and so the point velocities would have exceeded these values. At the time of the flood there was a tidal surge so that the tidal levels were approximately 0.3m higher than the astronomically predicted tide levels. The hydraulic modelling showed that, due to the steep nature of the river, the tidal influence extended a very short distance up the channel and did not affect flood levels in the centre of Boscastle.

The modelling of the Jordan River showed that the culvert at the downstream end of the catchment had limited capacity. When just flowing full the capacity of the culvert was approximately $2m^3/s$. This was insufficient to take the flow on the 16 August 2004 in which the peak discharge was estimated to be approximately $19m^3/s$ and as a result, flooding occurred upstream. As the water depth increased upstream of the culvert the discharge through the culvert increased. As the ponding effect upstream of the culvert increased, sediment was deposited, and the culvert was blocked. The flow which bypassed the culvert led to flooding of Marine Terrace downstream of the culvert.

The modelling suggests that the peak discharge at Crackington Haven downstream of the confluence with the Pengold Stream was of the order of 90 m^3/s. The peak discharges upstream of the confluence were of the order of 47 and 44 m^3/s for the Crackington Stream and Pengold Streams, respectively.

As for the Valency, the model results suggest that the morphological change that took place during the flood event had a significant impact on the discharge capacity of the channel in the upper part of the catchment.

The modelling results suggested that rapid blockage of the lowest bridge on the Crackington Stream would have resulted in a rapid rise in water level of approximately 3 metres.

Description of damages

During the flood, significant amounts of overland flow took place and there was flooding in many of the minor watercourses in the area as well as in the main rivers. This resulted in extensive damage to highways in the area of the rain storm event, see Appendix 5.1. Damage to bridges and severe damage to the road surface on some steep sections of road made some roads impassable or difficult to use.

In addition there was significant damage to properties adjacent to the major rivers and their tributaries. As Boscastle has the major concentration of properties adjacent to water courses in the area affected, much of the damage took place there and over 70 properties were flooded.

There was also significant damage however to properties in Crackington Haven and in the upstream catchments.

In addition to the damage to properties, there was also damage to local infra-structure. Damage to water supply, drainage and electricity supplies resulted in interruptions to these services for differing periods of time.

Contents

Contents continued

Contents continued

Tables

Contents continued

Contents continued

Contents continued

Plates

Contents continued

Contents continued

Appendices

1. Introduction

On the 16 August 2004, heavy rainfall centred over Otterham near the North Cornwall coast over a period of about 5 hours led to severe flooding in a number of river catchments. Those rivers most affected were the Valency and the Crackington Stream but flooding also occurred on the River Ottery and the River Neet. The flooding on the Valency and its tributary the River Jordan caused significant damage in Boscastle while the flooding on the Crackington Stream also caused damage in Crackington Haven. The damage caused by the event was not limited to these locations but also occurred throughout the area, see Figure 1.1. The numbers shown in Figure 1.1 refer to the table in Appendix 7.

The apparent magnitude of the flood flows and levels suggested that the event had been unusual with a very low annual probability of occurrence. As a result the Environment Agency commissioned HR Wallingford to carry out a brief study to assess the extent, magnitude and probability of the event. This study, as reported in October 2004, indicated that the event on the Valency and Crackington Stream had indeed been extreme. The upper parts of the River Ottery catchment and the River Neet had been subject to severe rainfall which caused flooding down to Canworthy Water on the River Ottery and down to Helebridge on the River Neet. As the rainfall event was limited in area, the severity of the event was less in the lower parts of these catchments. Thus the extreme event could be considered to be limited to the Valency and Crackington Stream catchments

On this basis the more detailed investigations into the meteorology, hydrology and hydraulics of the event, which the Environment Agency had planned to carry out from the outset, were confined to the Valency and Crackington Stream catchments.

The Environment Agency decided that it was important that the details of the events in these two catchments should be recorded and analysed. The scope of works for the study is given below. The Environment Agency commissioned HR Wallingford to carry out the study, with the direct support of Halcrow and Royal Haskoning (formally Posford Haskoning). HR was encouraged to secure support from other experts to ensure that best possible data, analysis and interpretations were incorporated. HR brought in the Met Office to provide expert work on the meteorology and CEH Wallingford to provide expert work on the hydrology of the event. This report is the account of that study.

Following the flood event, the Environment Agency collected information relating to the flood, including eye-witness accounts and photographs. This archive material has been used in the compilation of this report.

1.1 SCOPE OF WORK

The following is the scope of work for the study as specified by the Environment Agency.

Introduction

Early indications are that this flood ranks amongst the most extreme events recorded in Britain. The intensity and total amounts of rainfall, flows and consequent effects on the catchment, including the potential for loss of life, are all noteworthy. This study forms part of a comprehensive project to ensure that this event is thoroughly investigated, recorded, analysed and understood. The findings will inform the Environment Agency, particularly its management of flood risk, and also are likely to be of much wider interest and value.

Aim

The study will focus on hydrological aspects but will include consequential impact on the natural and built environment. The aim is to provide a comprehensive and definitive analysis of the event.

Requirements

The following are only intended to guide the requirements. The actual study will be agreed following discussion with the lead consultant. Whilst the emphasis is on Boscastle the extent is not confined to the village (to be defined)

Meteorology and Hydrometry

- Antecedent conditions
- Meteorological situation
- Forecast and actual rainfall, temporal and spatial over the whole area of the event (to be defined)
- Hydrological analysis including precipitation, evaporation, infiltration, percolation and underground storage, surface storage and surface run-off
- Reconciliation of rainfall and flow evidence
- Topography, geomorphology and land use
- Flows, volumes, velocities and stage, with timings at key points on the rivers and tributaries
- Restrictions and blockages
- Probabilities of rainfall and flows, with reference to other extreme events
- Site survey, records and other information gathering as necessary
- Modelling as necessary

Impact

- Record damage to structures including properties, roads and bridges. To distinguish between structural and flood damage and (where possible) identify the source and mechanism.
- Other infrastructure damage including services
- Other losses, including vehicles
- Impact on the natural catchment, including washouts and other erosion, deposition, regrading, and other regime changes.
- Analysis of the capacity and effect of artificial and manmade restrictions, including culverts, bridges and walls.

Excluded

- Event management
- Agency catchment management
- Lessons Learnt
- Appraisal of improvement options
- Multi-agency emergency response and management

1.2 APPROACH

Halcrow and Royal Haskoning are the consultants retained by the Environment Agency to work on the Valency and Crackington Stream catchments, respectively. They were responsible for data collection and field work within their respective catchments. The Met Office were responsible for the analysis of the rainfall, CEH were responsible for the hydrological analysis and HR Wallingford were responsible for the hydraulic analysis. In practise there was a significant interchange and discussions between the different organisations involved in the project.

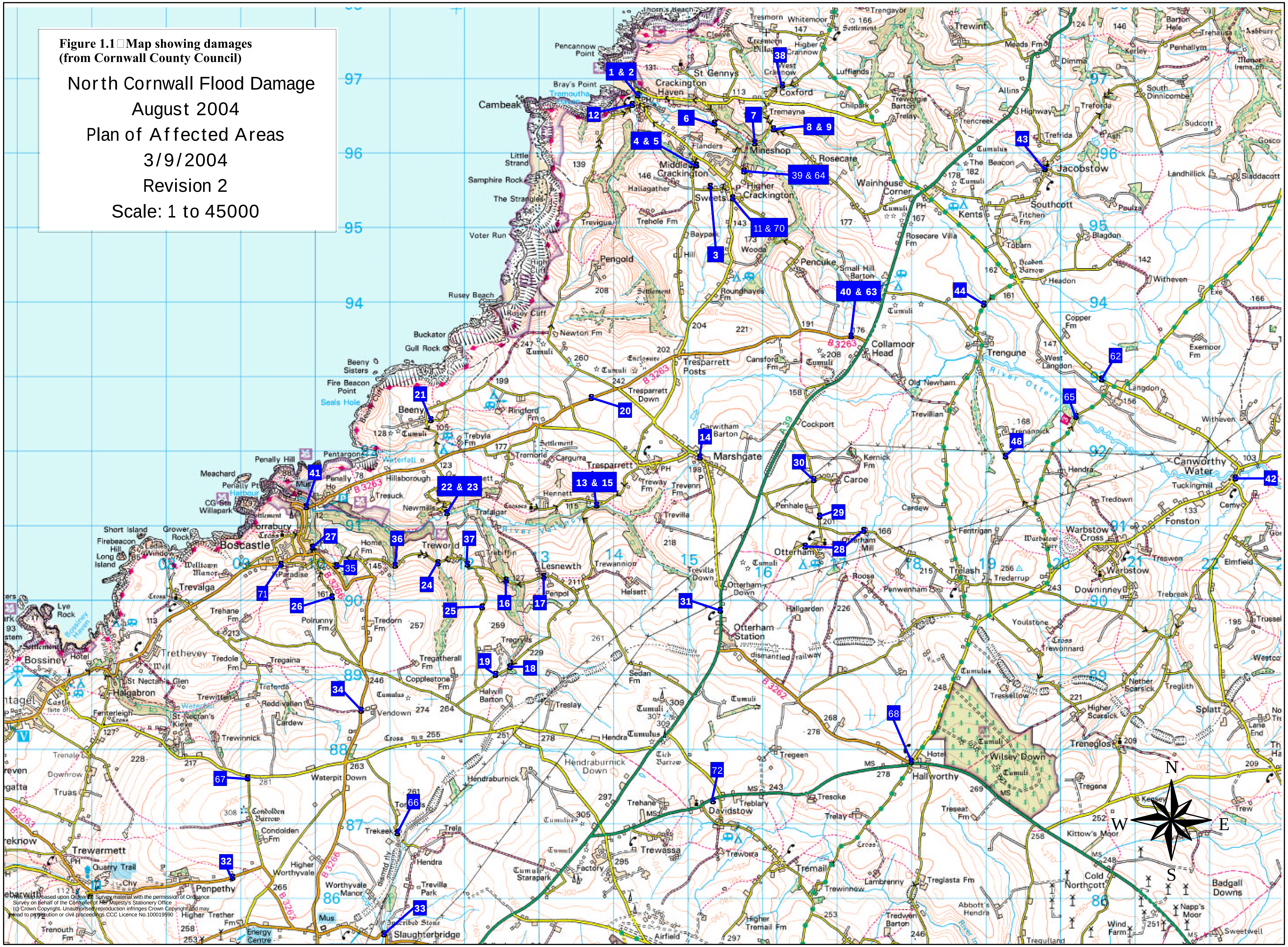


Figure 1.1 Map showing damages (from Cornwall County Council)

2. Description of the flood

2.1 DESCRIPTION OF THE FLOOD IN THE VALENCY CATCHMENT

2.1.1 The Valency River

Hydrology

When the rainfall began there was average soil moisture. During the initial phases of the rainfall event the rainwater would have infiltrated into the ground with limited surface run-off. As the rainfall continued the soils gradually became saturated. As some of the soils are thin and overlay impermeable bed rock the amount of rainfall required to saturate the soil is not large. As the soil became saturated the amount of the rainfall that infiltrated reduced and the amount of surface run-off increased, that is, the percentage run-off increased during the event. In many parts of the catchment the land slopes are large and so the movement of water towards the water courses is rapid.

Hydraulics

This account of the flooding is based on the eye-witness accounts summarised in Table 2.1. The flow in the Valency and its tributaries increased from approximately 13:00 BST onwards. By approximately 15:15 BST the flow in the Valency at Boscastle was approaching bankfull. At approximately 15:30 BST water began to spill out of the channel on the right bank between the two bridges (Plate 2.1). At 15.37 BST, the water in the river was touching the top of the arch of the underside of the small footbridge. At 15.43 BST, the water out of bank between the two bridges was a couple of inches deep on the footpath. Slightly later water begins to flood the Car Park. By 15:45 BST the cars were beginning to float in the Car Park. At 15.45 BST, water was a few inches deep on the B3263 (Plate 2.2), which shortly after, around 16:00 BST, became impassable as it was too deep and fast to wade through. Whilst the water at this time was deep and fast flowing down the B3263 towards Valency Row, it was still possible to stand on the B3263 road bridge as the bridge itself was dry.

At about 16:10 BST, the B3263 road bridge in Boscastle became blocked by debris (Plate 2.8). As a result the water level upstream of the bridge rose rapidly. It is likely that it is at this time that the water inundated the Spinning Wheel restaurant. This increase in water levels upstream of the B3263 bridge affected the river levels along by the Car Park. This rapidly increased water levels in the Car Park and increased the flow down the B3263. Thus at this time (16:10 BST) cars started to float out of the car park and be carried through the town by the flood water (Plates 2.5 and 2.6). The blockage of the B3623 road bridge increased the amount of water flowing down the B3263. Shortly after this the Clovelly Clothing shop was washed away at 16.15 BST (Plate 2.7).

In addition to this, the flooding on the River Jordan had worsened and water was pouring through the Wellington Hotel. It was at this time, with the blockage of the bridge and the flow of water from the grounds of the Wellington Hotel, that the water level on the bridge itself increased quickly and the bridge became impassable.

The amount of water pouring through the car park continued to increase and at 16.30 BST the 9 foot wall by the car park collapsed. This would have resulted in a surge of water going down the B3263. At about this time the visitors centre started to collapse as the depth and velocity of the flood water in the car park increased further. Between 16.30 BST and 17.00 BST there were cars and other larger debris passing by both sides of the Riverside Hotel in the flood water. At some time shortly after 16:30 BST the water from the Valency burst through the row of shops between the Car Park and the B3263 bridge, flowing from the river to the B3263 and then down to Valency Row.

At about 16:30 BST water from the River Jordan started to pour through the Wellington Hotel. This flowed down the road towards the Valency with some of the flow crossing the bridge and joining the flow down the right floodplain of the Valency.

The flood was at its peak shortly after 17.00 BST and had started to recede by 18.00 BST. Thus the total time between the river bursting its banks and the peak flow of the flood was just over 1.5 hours.

As described in Chapter 6, the blocking of the flow through the bridges in the centre of Boscastle had an impact on the flow distribution and flood levels. By the end of the flood there were substantial accumulations of debris upstream of both bridges. This had been cleared away before the project team had had an opportunity to examine it and so any comments have to be based on video and photographic evidence. The video evidence from the flood itself suggests that the flow through the lower bridge was running more or less freely until one of the first cars to be washed down the river became trapped against the upstream face of the bridge. This is described in the eyewitness account of DeCaux. It seems likely that this led to the subsequent substantial build up of trash at the bridge.

The opening in the B3263 road bridge is larger than that of the bridge downstream and there is video footage showing complete trees being washed under the bridge during the flood. Without having had the opportunity for detailed study of the debris one cannot be certain but it seems likely that some pieces of trash became caught on the upstream face of the bridge and these then trapped a number of the cars that were swept from the car park upstream.

For both bridges, once trash began to be caught at the bridge then the blockage of the bridge opening took place rapidly.

Figure 2.1 shows a reconstruction of the hydrograph shape at Boscastle based on the observations, this can be compared with the predicted hydrograph in Figure 6.30.

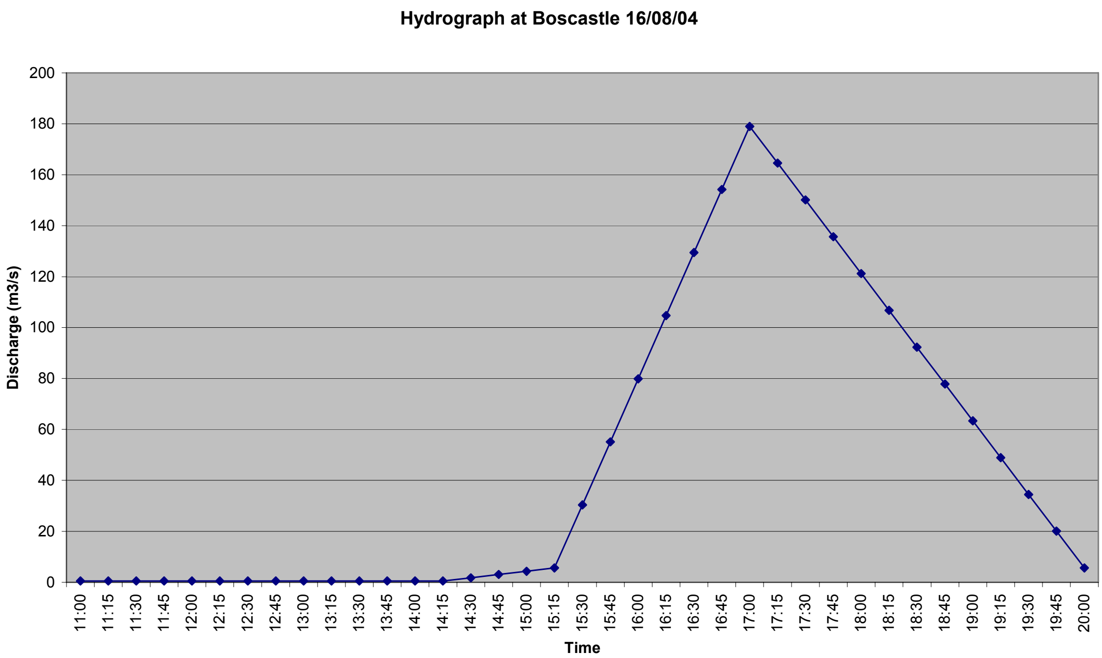


Figure 2.1 Reconstruction of the hydrograph shape at Boscastle

An important factor in the flooding of Boscastle was the changes in the flow paths during the flood. The blockage of the B3263 bridge occurred rapidly and this caused a sudden re-adjustment in the distribution of discharges. Simultaneously with these changes in flows, there were equally rapid changes in water level. The numerical modelling suggests that when the bridge blocked the water levels upstream rose by one to two metres in less than a minute. There were also other changes in flow paths that would have also caused rapid changes in water level, such as the collapse of the 9 foot wall and the flow coming through the shops between the Car Park and the B3263 bridge. These changes in flow paths resulting in rapid changes in water level are consistent with a number of accounts of people affected by the event.

There is a general issue of flood risk to people during flood events. In cases where the water on the floodplain is acting mostly as storage and consequently flow velocities are low, changes in water level as a result of changes in flow paths are likely to be slow. In cases where the water velocities on the floodplain are high and storage is small then changes in flow paths may result in rapid changes in water level.

Plate 2.1 Flooding on the Valency River at the small bridge. River comes out of bank. (Stollery, 15:43 BST)

Table 2.1 Eye witness accounts of flooding of the Valency River

Time BST	Observation	Photograph	Name of source	Time GMT
12:30 to 13:00	Loud bang and river rose by 6 feet with lots of debris		Yates	11:30 to 12:00
14:30	Flooding out of right bank		De Caux	13:30
15:00	Sudden rise in water level		De Caux	14:00
15:15	Cars floating in the car park		Steege	14:15
15:15	Things normal		Hancock	14:15
15:30	River bursting banks		Little	14:30
15:30	1 or 2 cars beginning to float		Little	14:30
15:30	Cars floating in Car Park		Hancock	14:30
15:30	Water coming in back of Newsagents		Hancock	14:30
15:30	Had to leave Harbour Lights due to flood warning		De Caux	14:30
15:36	Water coming out of bank at small bridge		Hooke Video	14:36
15:37	Water touch top of small bridge arch		Hooke Video	14:37
15:40	Water in Valency Row up to knees		Little	14:40
15:42	Water at Riverside thigh deep		Little	14:42
15:43	Water coming out of bank between bridges, a couple of inches deep on footpath	Plate 2.1	Hooke Video	14:43
15:45	Car Park begins flooding		Prescott	14:45
15:45	Car Park flooding		Arthan	14:45
15:45	Flooding of yard of Cornish Stores		Holland	14:45
15:45	Water coming over bank at bend in river		Sayer	14:45
15:46	Water a few inches deep on B3263	Plate 2.2	Hooke Video	14:46
15:45 to 16:15	Most rapid rise (in water level)		Sayer	14:45 to 15:15
15:45 to 16:00	Water started flooding Visitors Centre		David	14:45 to 15:00
15:50	One of last to cross bridge		Little	14:50
15:53	Car Park flooded up to wheel arches. Visitors Centre still standing		Hooke Video	14:53
15:55	Started flooding Cornish Stores		Holland	14:55
15:55	Cars floating in Car {arl		Holland	14:55
16:00	Collection of trees and debris came down in a wave		Scott	15:00
16:00	Crossed bridge in car		Rigby Jones	15:00
16:00	Crossed bridge – water knee deep		Arthan	15:00
16:00	Waded across bridge		Holland	15:00
16:00	Water drained away from Car Park		Prescott	15:00
16:00	Water up to 1 foot deep in Car Park		Rigby Jones	15:00
16:00	Cars and debris block bridge	Plate 2.8	Little	15:00
16:00	First car washed down river and under bridge and got stuck on downstream bridge		De Caux	15:00
16:00	Debris and large debris start passing		Sayer	15:00
16:05	Bridge blocked and impassable		Arthan	15:05
16:05	Water 3 feet deep outside shops		Sayer	15:05
16:07	Water is thigh deep at the side of the road on B3263		Hooke Video	15:07
16:10	First car passed – Red Mondeo		Sayer	15:10
16:14	Car drives out of top car park exit		Hooke Video	15:14
16:15	Large tree follows Red Mondeo		Sayer	15:15
16:15	Clovelly Clothing washed away	Plate 2.7	Arthan	15:15
Approx 16:15	Water rises rapidly in Visitors Centre		David	Approx 15:15
16:20	Old Bridge blocked with one car – New bridge clear		Ferret	15:20
16:20	Bridge blocked by trash and cars			15:20
16:30	9 food wall collapsed		Hooke	15:30
16:37	Several cars being washed down B3263	Plate 2.5 and 2.6	Hooke Video	15:37
Approx 16:30 to 16:45	Visitors Centre starts to collapse		David	Approx 15:30 to 15:45
16:30 to 17:00	Cars beginning to pass both sides of Riverside Hotel		Findley	15:30 to 16:00
16:30 to 17:00	Water level up to eaves of Crystal Cave and Rocking Shop		Findley	15:30 to 16:00
16:50	Watching cars being washed into harbour		Young	15:50
17:00	Flood near peak		Prescott	16:00
17:30	After main flood in harbour		Metcalfe	16:30
18:00	Flood reducing		Prescott	17:00

Plate 2.2 Flooding on the B3263 in Boscastle. (Stollery, 15:56 BST)

Plate 2.3 Flooding on the River Valency (Stollery, 16:05 BST)

Plate 2.4 Flooding on the River Valency. (Fire Brigade)

Plate 2.5 Flooding on the Valency at the B3263 bridge. (Fire Brigade).

Plate 2.6 Flooding on the Valency at the B3263 bridge. (Fire Brigade).

Plate 2.7 Flooding on the Valency, shortly after the collapse of Clovelly Clothing. (Fire Brigade).

Plate 2.8 **Flooding on the River Valency. B3263 bridge blocked. (Stollery, 18:13 BST)**

Plate 2.9 **Lower bridge blocked on the River Valency. (Mike Metcalfe, 21:14 BST)**

2.1.2 The River Jordan

Hydraulics

The following account is based on the eye-witness accounts summarised in Table 2.2. The flooding from the river Jordan started to be apparent from around 16.00 BST. The first locations to flood were Gunpool Lane and Fore Street (Plate 2.11, 2.12, 2.13, 2.14). The water built up steadily on Gunpool Lane and flowed down Fore Street towards the bend in the road as the road becomes Dunn Street. Initially, the water flowing down Fore Street continued in the same direction, through gardens, to reach the river Jordan, but as the flood water increased, Dunn Street became flooded between 16.00 BST and 17.00 BST (Plate 2.10) and water also flowed down Old Road. In addition the volume of water coming down the Paradise Stream exceeded the capacity of the culvert by the Post Office. Water then began to flow over the adjacent car park and into Dunn Street.

The majority of the flow, however, was through the gardens to join the river Jordan in its course parallel with Old Road. The stream normally flows through a culvert under the terraced row of cottages on Old Road, but the culvert capacity was exceeded and the water flowed directly through one cottage just upstream of the terrace and continued down through the valley above ground.

At around 16:30 BST, the Wellington Hotel was flooded; water was flowing directly through the building and out of the front door. The water then flowed through the neighbouring tourist shop and into the Valency at the Jordan-Valency confluence.

The flood peaked at around 17.45 BST and receded around 18.00 BST to 18.30 BST.

Plate 2.10 Flooding of the River Jordan on Dunn Street. (Mike Metcalfe, 16:17 BST).

Table 2.2 Eye witness accounts of flooding on the River Jordan

Time BST	Observation	Photograph	Name of Source	Time GMT
16:00	No flooding at Post Office		Turner	17:00
16:00	No flooding from Jordan		Ferrett	17:00
16:00 to 17:00	Flooding in Dunn Street	Plate 2.10	Lynnan	17:00 to 18:00
16:00	Car washed down Fore Street	Plate 2.13	Larratt	17:00
16:10	Water came out of Wellington Hotel		Arthan	17:10
16:15	Flooding in Gunpool Lane	Plate 2.12	Grant	17:15
16:30	Water bursts out of Wellington Hotel		Holland	17:30
16:30	Cars washed down Fore Street	Plate 2.13	Fletcher	17:30
16:30	Wellington Hotel flooded		Leeds	17:30
16:30 to 16:45	Orchard House on Gunpool Lane floods	Plate 2.12	Hunt	17:30 to 17:45
16:57	Jordan still rising but peaked shortly after		Howell	17:57
17:09	Flow down Old Road		Howell	18:09
17:15	Belmont on New Road flooding		Davson	18:15
17:30	Water had subsided		Bond	18:30
17:45	Flows down New Road peaked		Ferrett	18:45
18:00	Flooding in Paradise Road		Turner	19:00
18:00 to 18:30	Flooding in Gunpool Lane receded		Grant	19:00 to 19:30

Plate 2.11 Flooding of the River Jordan on Fore Street. (Colin Bond).

Plate 2.12 Flooding on Gunpool Lane. (Mr Grant)

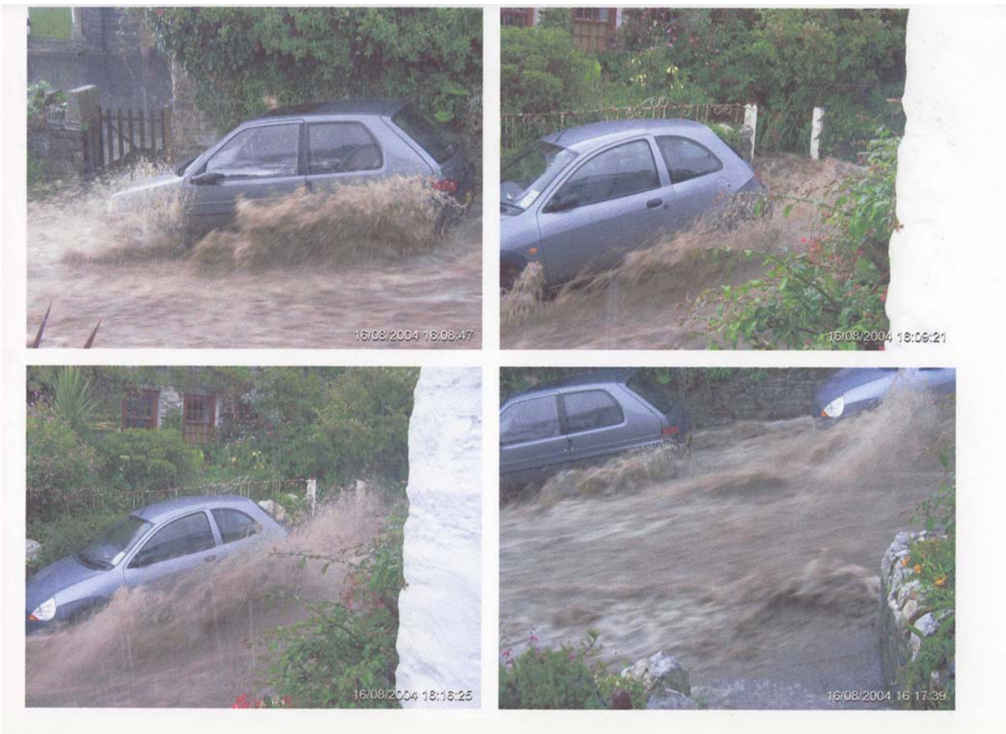


Plate 2.13 Flooding on Fore Street. (Mrs Laratt)

Plate 2.14 Flooding on Fore Street. (Mrs Laratt)

2.2 DESCRIPTION OF THE FLOOD IN THE CRACKINGTON STREAM CATCHMENT

HR Wallingford carried out a site visit to Crackington Haven on 19 August 2004, when the owner of the Haven Café was interviewed. From his account of the flood, it was noted that the water was approximately 2 metres deep at the shop as it nearly reached the ceiling of the one-storey building. The shop owner and his staff were trapped in the shop because the water rose so suddenly, as a “wall of water”, and a dramatic escape was made. His account was that the main bridge over the Crackington Stream was blocked (Plate 2.15).

Plate 2.15 Flooding on Crackington Stream. (Crackington Haven)

3. Geomorphological analysis and interpretation

3.1 INTRODUCTION

The following provides a description of the geomorphological impacts of the August 2004 floods and examines the geomorphological changes in the Valency and Crackington Stream catchments.

A reach scale geomorphological audit has been carried out by walking the length of the main rivers and the major tributaries and taking an inventory of the morphological features that have been created by the floods. Most of the length of the rivers have been surveyed in this way, but in places access was not possible due to dense vegetation or difficult terrain.

This report is accompanied by maps of the catchments identifying the geomorphological changes and a catalogue of photographs that are referenced to the maps. This material is held separately by the Environment Agency.

The Chapter is structured in two main sections; one for the Valency catchment and one for the Crackington stream catchment. Each section describes in detail the geomorphological impacts of the flood on the main rivers and their tributaries, described from downstream to upstream. The channels referred to are shown in Figures 3.1 and 3.2, which are located at the end of the sections for the Valency and Crackington Streams for convenience.

3.2 THE VALENCY CATCHMENT

3.2.1 General impacts

The geomorphological impacts of the flood on the River Valency are characterised by erosion of the banks, incision of the bed and lateral movement or avulsion in places. Where the tributaries join the main channel, there is typically a headcut on the tributary and deposition of an alluvial fan. The impacts of the flood are extensive throughout the catchment as there are similar changes observed on the tributaries, but in the headwaters of each river there are fewer impacts, if any, as the magnitude of the flood discharge reduces as the contributing catchment reduces.

3.2.2 The River Valency

A notable area of sediment deposition was the lower reach of the Valency and Boscastle harbour. The channel erosion and lateral movement of the channel in the upper catchment released large quantities of sediment which were then carried downstream by the flow. In any areas of slower moving flow sediment deposition took place. This resulted in large quantities of silt being deposited in the houses that were flooded in Boscastle. In addition the blockage of the bridges in Boscastle led to sediment deposition in the main channel upstream of them. A significant amount of the sand and gravel mobilised by the flood was deposited in the harbour though there was also scour around the nose of the southern breakwater as a result of the constriction of the flow. Finer sediment travelled further and was washed out to sea.

The downstream reaches of the River Valency flow through Boscastle and the morphology there has been highly modified since the flood by remedial works. The flood caused a large amount of deposition of sediment on the floodplain in Boscastle and in Boscastle harbour and there were trash dams and debris blockages at the bridges and on the floodplain. This was all cleared away shortly after the flood and the channel itself has been dredged so that there is now a large, rectangular channel through the town.

The post-flood modifications to the river channel cease approximately 150m upstream from the Boscastle car park. In the reach immediately upstream from the modified section, the channel has been widened during the rising limb and peak of the flood flow, from a pre-flood channel width of approximately 2 metres wide to a width of approximately 12 metres wide. In the recession of the flood, the discharge fell and the ability of the flow to transport sediment was reduced. Having eroded the channel banks during the rise and peak of the flood, the flow through this section has then deposited material in the channel during the recession. This has not caused significant aggradation because there was likely to be some incision during the flood event, so the resulting bed level has not significantly changed. The flow now is forming a sinuous channel through the shaly deposits that varies between 2 to 4 metres in width.

About 50 - 100 metres upstream of this reach there is a channel avulsion, with the new channel formed on the right floodplain. This is likely to have been caused by a build up of trash across the pre-flood main channel. The flow was displaced by the trash dam and eroded a new channel on the right floodplain, see Plate 3.1.

Plate 3.1 Channel avulsion caused by trash dam

There was channel widening and lateral movement towards the right bank in the reach immediately upstream from the avulsion. Where the water flowed over the right floodplain during the flood, there are patches of sediment deposition formed during the recession of the flood (Plate 3.3). There was no incision at this location. 100m upstream from here there was a build up of trash which induced avulsion at the location of the trash dam and lateral movement towards the right floodplain immediately downstream. There was an area of sediment deposition around the trash dam.

In the reaches immediately upstream and downstream from the tributary flowing from Minster Church (called Minster Stream in this account) there was an area of bank erosion, incision and lateral movement caused by the build up of trash. There were several trash dams, predominantly on the right bank, which had built up during the flood, causing a reduction in the velocity of the flood flow on the right bank and leading to deposition upstream of the trash dams. The channel had incised to bedrock. A headcut had been initiated on Minster Stream, just upstream from the confluence, occurring due to the difference in bed level resulting from the main channel incision, see Plate 3.2. There has been deposition on the alluvial fan of the tributary.

Plate 3.2 View from main channel looking towards Minster Stream showing deposition on the alluvial fan and a head cut where tributary enters main river channel

Plate 3.3 Deposition on right floodplain from flood recession

In the reach between Minster Stream confluence and Treworld Stream confluence there were trash dams which caused local areas of sediment deposition and incision (see Plate 3.5). Some sections of the bank have been stabilised by trees that line the bank, but other areas were subject to bank erosion. The channel has incised down to the bedrock and the reach is steep with steps in the bedrock, so the channel was able to efficiently convey large discharges which limited bank erosion.

The reach at the confluence with Treworld Stream and immediately upstream was characterised by avulsions, bank erosion, lateral movement to the right bank, and deposition due to reduced velocities located at field boundaries and in the pre-flood channel where avulsions had occurred. At one location there was a trash dam which had caused widening and incision.

At the reach at the trout farm the flooding caused incision to bedrock but there was limited channel widening as the channel banks are cohesive clay material. Water flowed over the floodplain during the flood.

At the reach at the Lesnewth Stream confluence there was a minor avulsion of the main channel immediately downstream of the confluence.

From 200m upstream from the Lesnewth Stream confluence there had been about 200m of bank erosion but no lateral movement. A paleo-channel is visible in this reach, indicating that the geomorphology of the river is an evolving and ever-changing dimension, see Plate 3.4.

Plate 3.4 View looking downstream with meander scar in foreground

Plate 3.5 Trash dams causing local deposition and incision

The next 700m (up to the confluence with Trewannion Stream) was characterised by channel widening and incision which in places had reached bedrock. There were several avulsions which in places had been caused by a build up of trash across the main channel, and elsewhere, by overland flow from the valley sides being prevented from entering the main channel due to dense trees and vegetation lining the banks and then flowing down the valley and cutting a channel adjacent to the tree lined bank. The pre-flood planform of these reaches was highly sinuous and in places where the flood had caused channel avulsion, the channel had become straighter but still with some sinuosity.

The reaches upstream from the confluence with Trewannion Stream that extend up to the confluence with Tresparrett Stream are characterised by incision and bank erosion to bedrock (see Plate 3.6). There is also significant widening up to 8m.

Immediately upstream of the confluence with Tresparrett Stream there was a large trash dam blocking the main channel (25m wide, 3m high). There were further trash dams upstream from this causing the formation of new channels and deposition (see Plate 3.6). Up to the confluence with the Helsett Stream, there had been channel incision and widening.

Plate 3.6 Incision and widening around Anderton Mill

Plate 3.7 Trash dam causing local deposition and new channel formation

Upstream from Helsett Stream to the source of the main river, there had been significantly less geomorphological impact from the flood. There was some widening and incision immediately upstream from the tributary, but after 300m there was no visible impact.

3.2.3 The River Jordan

The river Jordan joins the River Valency in Boscastle where its lower-most reach flows through a culvert under Marine Terrace. During the flood the flow exceeded the capacity of the culvert and flowed around and through the cottages of Marine Terrace and through the Wellington Hotel. There have been extensive post-flood modifications on the lower reach of the river Jordan with the construction of a new, significantly larger, culvert. The outfall to the Valency is downstream of the B3263 road bridge.

Plate 3.8 Incision and widening on the River Jordan

By the time of the inspection the Jordan had been modified since the flood throughout the downstream reaches. The modifications are likely to have ceased as the river draws parallel with Fore Street, but this was not observed since access to the stream is through private homes and gardens. The detailed survey of geomorphological changes starts at a footbridge just downstream from the first road crossing over the river, SX102906. In general, the observed impacts on geomorphology were pockets of bank erosion and incision to bedrock (see Plate 3.8).

There were few impacts on the 400 metre reach upstream from the footbridge, simply some minor bank erosion, indicating that the predominant process over this reach was transport of sediment during the flood. Around the B3266 crossing there is erosion of the bed and banks. About 50m upstream from the B3266 crossing there were areas of significant landslides on the valley sides which occurred as the saturated soil lost stability on the steep slope (see Plate 3.9). The sediment generated by the landslides caused deposition in the channel and due to the restricted culvert size under the B3266, the deposits remained upstream of the culvert during the flood. The flow is now cutting through these deposits.

Plate 3.9 Land slipping on the valley sides of the River Jordan

Paradise Stream

Paradise Stream is a tributary of the River Jordan that flows into the main channel near the downhill end of Fore Street. During the flood, flow left the Paradise Stream where Fore Street crosses the channel when the flow exceeded the culvert size and flowed over the road and through a resident's garden. Where the flow rejoined the river there was incision and widening of the channel.

At the B3266 crossing there were few observed geomorphological impacts, indicating that this was a transport section during the flood. In the 150m reach upstream from this road crossing to the next crossing, there was some channel widening and approximately 0.5m incision. Some erosion of the bank was caused from overland runoff from roads (see Plate 3.10). In the headwaters upstream from this second road crossing there was little or no observed changes in the geomorphology.

Plate 3.10 Overland runoff from roads causing erosion

3.2.4 Treworld Stream

Treworld Stream joins the River Valency just upstream of Peter's Wood. Like other tributaries of the Valency, there was a headcut at the confluence with the Valency (see Plate 3.11) and the flow is now cutting through an alluvial fan. There was aggradation upstream of the headcut where the water velocity reduced as the water spread out over the floodplain and a scour pool immediately downstream of the headcut.

There were several debris dams on Treworld Stream. The first, 150m upstream of the confluence caused deposition upstream from the blockage and widening immediately downstream to a channel width of about 3-4 metres. The eroded material from the channel widening had been deposited at the bank toe, so although there was enough energy in the flow to erode the banks, there was then not sufficient energy to transport the eroded material or incise the channel. About 100-150m upstream from the first debris dam, there were two further dams where there had been more bank erosion as well as incision, which had lowered the channel bed to the bedrock. There was sufficient energy for incision here as the channel slope is steeper than the reach downstream and so the flood flow velocities would have been greater.

There was increased incision in the next reach, just downstream from the road crossing, with the bed level approximately 2 metres below pre-flood level (see Plate 3.12). There was also evidence of trash dams causing avulsion and a headcut with associated deposition and erosion (see Plate 3.13). The severe incision was controlled by the bedrock but the non-cohesive bank material was readily erodible so widening up to 6m and some lateral movement had occurred.

Plate 3.11 Headcut on Treworld Stream

Plate 3.12 Incision on Treworld Stream

Plate 3.13 Headcut on Treworld Stream

For a further 600m upstream from the road crossing there was severe erosion and incision, with fewer trash dams than the downstream reaches. Upstream from this, the channel gradient reduces and there was a 100m reach of deposition with a channel avulsion as the flow cut a new channel through the deposits. Upstream from this there was channel widening and incision to bedrock but the impacts are fewer by comparison with the downstream reaches.

3.2.5 Lesnewth Stream

Geomorphological changes along this tributary of the Valency were characterised by incision and widening, with trash dams instigating many of the observed impacts, in common with the processes described above for the Valency.

At the confluence with the Valency there was a headcut on the Lesnewth Stream, as is common on the tributaries of the Valency caused by the difference in bed levels due to the incision on the Valency. There was aggradation on the alluvial fan and the floodplain where water has space to flow laterally causing velocities to decrease and deposition to occur.

There was incision to bedrock along much of the tributary, which was up to 2m deep in places (see Plate 3.12). There were local areas of deposition where the slope decreases and, conversely, there was significant bank erosion in places. There were also a few areas of avulsion.

Plate 3.14 Incision to bedrock on the Lesnewth Stream

3.2.6 Other Tributaries

Minster Stream

On Minster Stream there was a headcut at the confluence with a scour pool created from the flow cascading down the headcut. In the reach downstream from Minster Church there was severe incision of approximately 1.5-2m deep and channel widening. Along this reach two secondary channels formed during the flood (see Plate 3.15), which were initiated because the main channel did not have sufficient capacity for the flood flow and debris dams forced the water along side the main channel. There was evidence of trash dams further downstream.

Trewannion Stream

A spot survey on Trewannion Stream identified a headcut and deposition close to the confluence.

Tresparrett Stream

There was a headcut on the Tresparrett Stream at the confluence with the Valency, caused by the difference in bed level since the Valency incised during the flood. There was a further headcut on the Tresparrett Stream 50m upstream from the confluence. There were several trash dams along the full length of the stream. There were two avulsions approximately 100m and 250m upstream from the confluence that had formed meander cut-offs and one avulsion in the headwaters, about 700m upstream from the confluence, which was formed as the channel under the footbridge became blocked by sediment and a new channel formed around the footbridge (see Plate 3.16).

General impacts along Tresparrett Stream were channel widening and incision to bedrock as well as undercutting of banks causing widening.

Helsett Stream

A spot survey on the Helsett Stream identified a headcut just upstream from the confluence.

Plate 3.15 Secondary channel next to main channel formed during the flood

Plate 3.16 Avulsion at footbridge on Tresparrett Stream

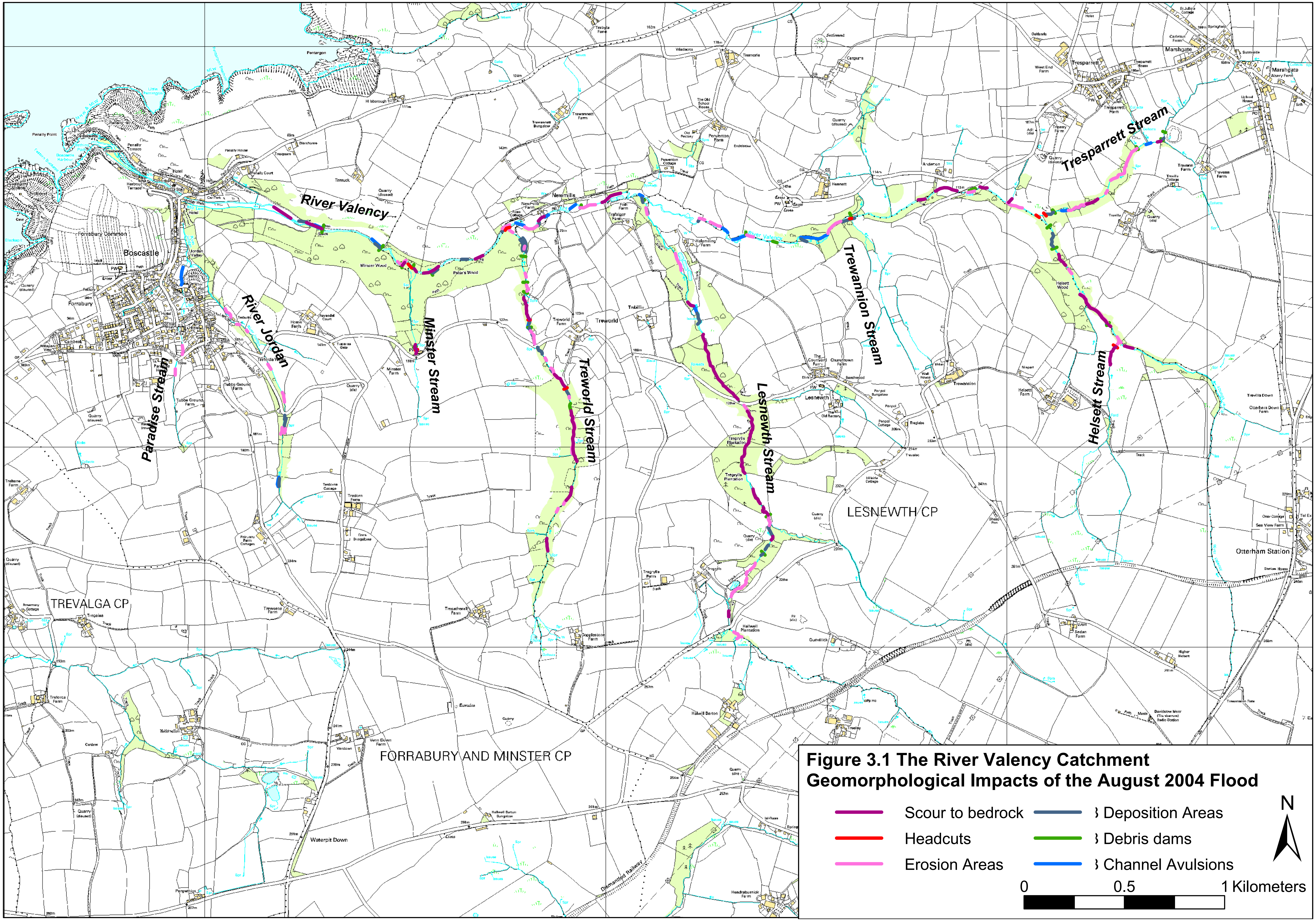


Figure 3.1 The River Valency Catchment Geomorphological Impacts of the August 2004 Flood

3.3 CRACKINGTON STREAM CATCHMENT

3.3.1 General impacts

The impacts of the flood on the geomorphology of the Crackington Stream catchment were mainly bank erosion and channel incision. As for the Valency catchment, the flooding led to the creation of a number of debris dams, which caused local areas of deposition and erosion. In contrast to the Valency, however, the flood did not cause any lasting channel avulsions or widespread lateral channel movement. This is due to a number of reasons including; a more constrained floodplain and a less extreme flood event. In addition, there were not as many headcuts on the Crackington tributaries as there were on the Valency tributaries, which reflects the fact that, in general, the incision and erosion of the main channel of Crackington Stream was not as severe as it was on the River Valency.

3.3.2 Crackington Stream

The downstream reaches of Crackington Stream flow through Crackington Haven which is a small harbour village. It is not possible to determine the impact of the flood on the geomorphology of the river for about 250m upstream from the estuary because at the time of the inspection there had been post flood remedial modifications of the channel and deposited material had been removed from the floodplain.

The first 350-400m reach of the river upstream from these remedial modifications were characterised by incision and erosion of the channel bed and banks. Bank erosion was generally most severe on the outside of meander bends, with some deposition on point bars and on the floodplains.

Plate 3.17 Pool caused by bedrock control

At The Nook, there was a debris dam with some deposition around the trees that had collected in the channel. Upstream of the debris dam there had been some channel widening, so that the channel was now around 10m in width. The widening continued upstream for another 200m where there was another debris dam and associated area of in-channel deposition. Upstream from this, to the weir at Congdons Bridge where there was another debris dam, there was some general bank erosion which was most severe at meander bends.

About 500m upstream from Congdons Bridge, there was a large pool that had formed in the channel as a result of a step bedrock control just upstream of the pool, shown in Plate 3.17. Just downstream from Mineshop Ford there was another trash dam, which pushed the flood water over the meander. This would have induced channel straightening, had there not been bedrock control on the left floodplain which prevented scour. Instead, there was enhanced erosion of the right bank and deposition on the left floodplain during the recession of the flood.

Moving 100m upstream from Mineshop Bridge, there was a trash dam which caused an avulsion, with the new channel cutting into the left floodplain. There was a headcut into the clay bed just upstream from the trash dam and pockets of deposition immediately upstream from the headcut. The predominant geomorphological impact though, was the severe incision that had occurred along this reach, in places down to the bedrock (see Plate 3.18).

Plate 3.18 Incision to bedrock

For another 500m upstream, the geomorphological impact was characterised by incision and some avulsion or lateral movement where there were trash dams. There is no detailed survey information for the headwaters of the main channel since the impacts were more homogeneous (general erosion) and less severe.

3.3.3 Ludon Stream and its tributaries

Ludon Stream is the largest tributary of the Crackington Stream and their confluence is within the estuary of the Crackington Stream. There was severe flooding on Ludon Stream on 16 August, as shown by the dramatic photographs showing the extent of the flooding on the hillside close to the confluence with Crackington Stream.

Immediately upstream from the confluence, Ludon Stream had been excavated to clear silt deposited in the recession of the flood. Around the road bridge at SX143967 there had been some local scour at the bridge invert and some bank erosion. The river upstream from this bridge for 400m upstream to just below the confluence with Lansweden Stream had been highly modified after the flood by the land owner, who had excavated the channel with diggers and created a large on-line pond.

At the confluence with Lansweden Stream, the geomorphological changes caused by the flood become more apparent. This was an area of incision to bedrock and bank erosion, which had caused undercutting of the wall of a stone building by the river (see Plate 3.19). Throughout the reaches in East Wood, the channel had widened and there were four trash dams that had exacerbated widening in those areas. Two of the trash dams had caused channel avulsions, as the main channel had become completely blocked with trees and the flood flow was able to find a path of lower resistance on the floodplain, cutting a new channel.

Plate 3.19 Erosion of bank under stone building wall

Over the reach between the Halgather Stream confluence and the Trevigue Stream confluence, the predominant impact on the geomorphology had been some widening of the channel (see Plate 3.20 which had been controlled in places by cohesive bank material as the soils are mostly clay. There were fewer trash dams than in the downstream reaches where the discharge would have been higher.

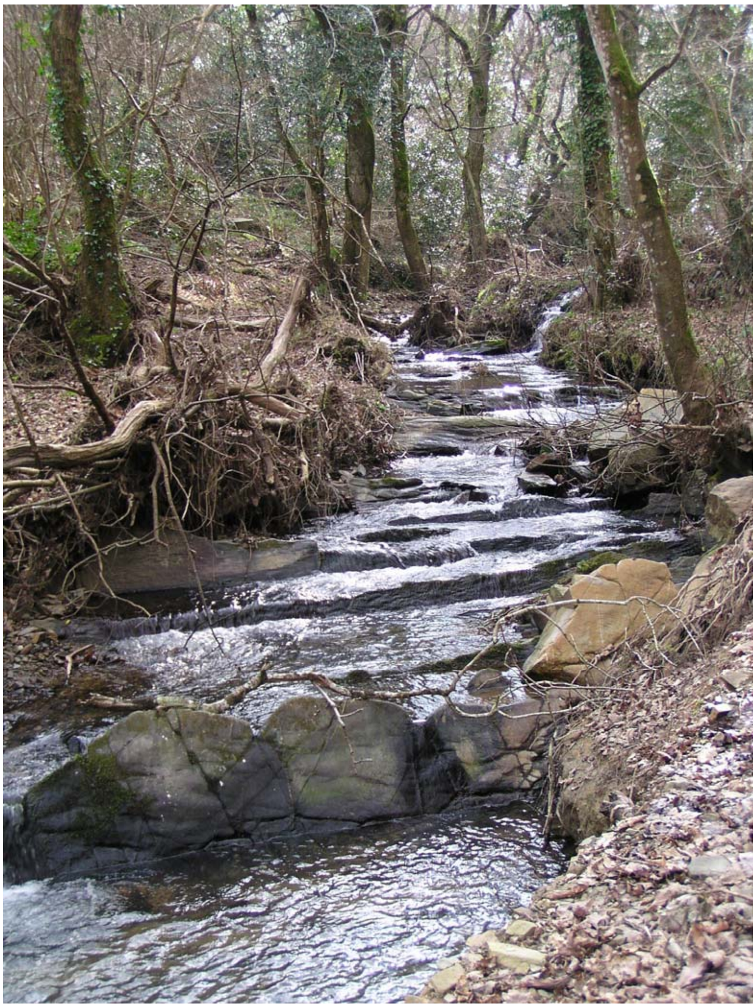


Plate 3.20 Channel widening

Lansweden Stream
There had been post-flood excavation on Lansweden Stream for 50m upstream of the confluence. Upstream from this there had been general incision to bedrock. In the reaches just downstream from Lansweden ford, the channel had incised to the bedrock and there was general bank erosion which was most severe at meander bends. At Lansweden ford there had been severe erosion of the bed and banks (see Plate 3.21) which continued in the reach upstream from the ford. A spot survey at the road crossing at Sweets found that the channel here had widened and slightly incised.

Halgather Stream
Not included in the survey.

Trevigue Stream
At the confluence with Ludon Stream, flood water from Trevigue Stream spilled on to the left floodplain, causing deposition of an alluvial fan. Due to the difference in bed level compared with the incised Ludon Stream, a headcut had initiated at the confluence.

Plate 3.21 Erosion at Lansweden ford

3.3.4 Other Tributaries of Crackington Stream

Mineshop Stream

For 100m to 200mm upstream from the confluence with Crackington Stream, there were pockets of bank erosion and widening on the Mineshop Stream. There was then a reach of severe incision to bedrock (see Plate 3.22). The incision and widening reduced further upstream.

Plate 3.22 Incised reach on Mineshop Stream

Wooda Stream
From a spot survey of Wooda Stream at Trewarden ford, the observed geomorphological changes caused by the flood included significant erosion of the reach downstream of the ford, which had been caused by a build up of trash. There had also been erosion causing widening upstream of the ford. Adjacent to this reach there was evidence of a moderate land slip on the right valley side; the instability caused by the saturation of soils on the steep valley side.

3.4 GENERAL MORPHOLOGICAL IMPACTS

3.4.1 Sediment budget for the flood event

On the available evidence it is difficult to estimate the total volume of sediment mobilised in the Valency catchment during the flood. As there is no pre-flood data on the channel dimensions it is difficult to estimate the amount of sediment removed from the channel by bed and bank erosion. An approximate estimate of the volume of channel erosion would suggest that the volume of material eroded might be of the order of 20,000 to 30,000 tonnes. One can put this in the context of the expected average volume of sediment that one could expect to be transported down the Valency. A typical catchment sediment yield in the UK might be in the order of 50 to 200 tonnes/km^2/year. This would imply an annual sediment yield in the range 1,000 to 4,000 tonnes per year. Thus the sediment released during the August 2004 flood event was comparable to the sediment that would normally be released over many years of more normal flows.

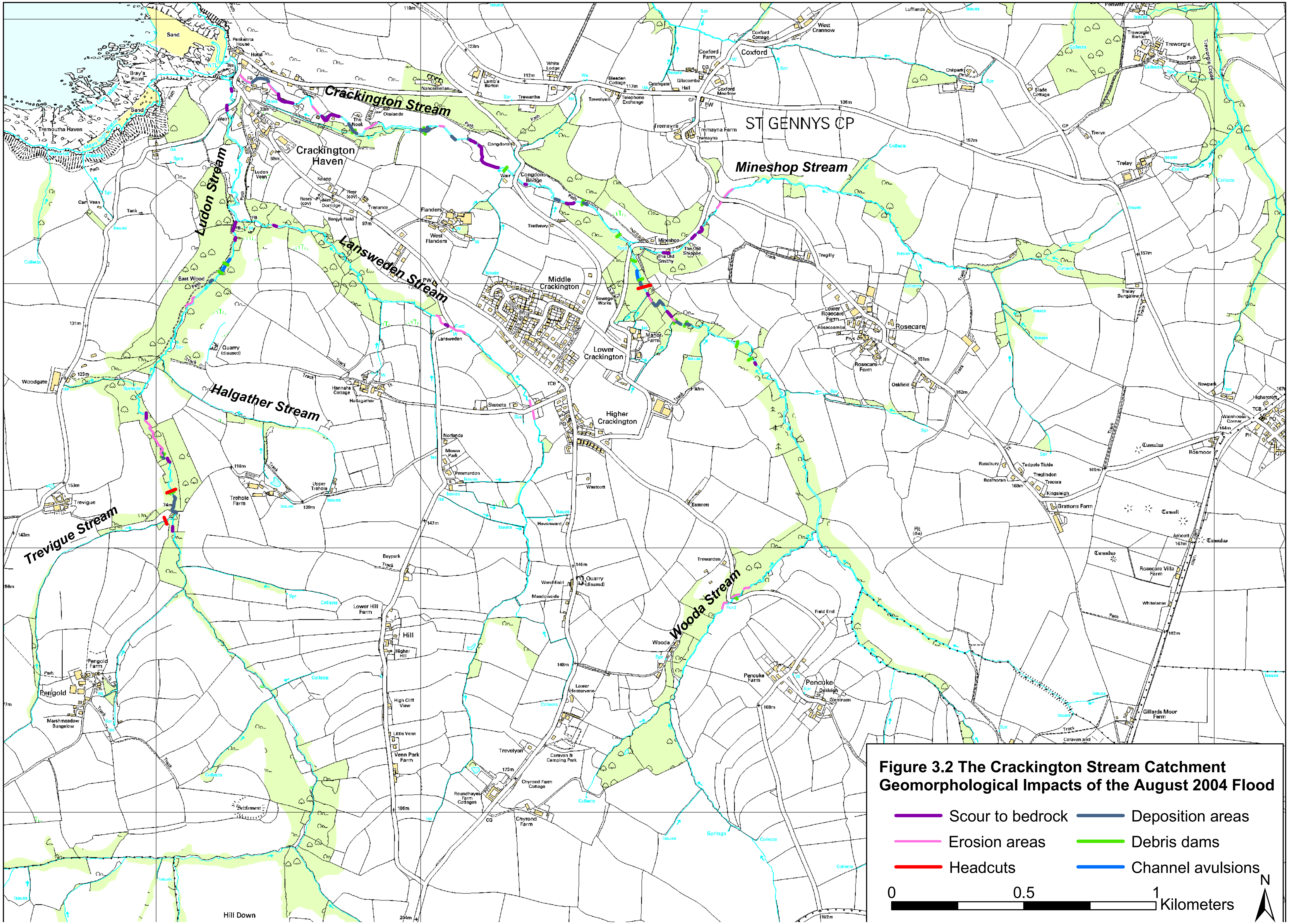


Figure 3.2 The Crackington Stream Catchment Geomorphological Impacts of the August 2004 Flood

3.4.2 Number of trash dams

The geomorphological survey took place sometime after the flood event by which time a number of the trash dams had been cleared away. It is thus difficult to be precise about the number of trash dams that occurred within the Valency catchment. During the flood trash dams were formed and then by-passed, overtopped or destroyed. At the end of the flood there was evidence of numerous trash dams but it is difficult to know how many were active at any one time. On the basis of the available evidence it would appear that there were of the order of 40 to 50 trash dams in the Valency catchment and 20 to 30 within the Crackington Stream catchment. The implication of the number of trash dams in the Valency catchment is that it is likely that trash did not move a substantial distance down the catchment during the flood event. Certainly it would seem that larger elements of trash such as trees would not have moved far before they would have been caught at one of the trash dams.

3.4.3 Summary of geomorphology

Erosion and down cutting were the dominant in-channel processes during the flood. The bed erosion was up to 1 to 2 metres in places while the channel widening was up to 3 to 4 metres. In places there was also channel avulsion and this was frequently associated with trash dams blocking the main channel. There was some sediment deposition in areas of reduced slope or where the floodplain widened but the amount of sediment deposition was slight. The event transported many times the average annual sediment load of the rivers and must be regarded as causing a major perturbation to the river system.

Where the channel has been deepened and widened during the flood it is expected that the natural sediment processes will lead to channel recovery whereby the channel dimensions tend to adjust towards the pre-flood conditions. The comparison of the amount of in-channel sediment erosion with the typical annual sediment yield for the catchment suggests that this process of re-adjustment will take many years. The recovery should not be seen as a steady progression towards a single well-defined state as the sequence of future flows may either speed up the process or cause further perturbations depending upon their magnitude.

There are now substantial amounts of exposed sediment throughout the catchment which will be vulnerable to re-erosion in subsequent floods. These may thus act as future sediment sources for a number of years until channel recovery and re-vegetation has taken place.

4. Meteorological Overview

This section looks at the soil moisture conditions prior to the event, at the meteorological conditions that generated the heavy rainfall, at the temporal and spatial characteristics of the rain and the likelihood of its recurrence. Additional information is given in Golding (2005).

All times are stated in Greenwich Mean Time (GMT) or British Summer Time (BST). Greenwich Mean Time (GMT) is one hour behind British Summer Time (i.e. 1500 GMT is 1600 BST).

4.1 ANTECEDENT CONDITIONS

Following a dry spring and a dry June, the ground was generally dry in north Cornwall at the end of June. July rainfall was above average in the region, but with marked spatial variability. Available observations indicate that the Valency catchment was in an area of about average rainfall, allowing the dryer than average conditions to persist.

Average August rainfall varies markedly across the north Cornwall region, with the driest areas in the vicinity of Padstow and Bude receiving less than half the rainfall observed on Bodmin moor. The coast at Boscastle is generally wetter than other parts of the coast, while the upper parts of the Valency catchment receive average amounts approaching those of the open moor.

The distribution of anomalies, relative to the 1961 to 1990 average, for the first half of August 2004 is shown in Figure 4.1, derived from all available daily reporting rain gauges. Most of north Cornwall had rainfall substantially higher than normal during this period, with the Valency receiving about 25% more than normal. As in July, the spatial variability is very marked, and so the accuracy of the resulting values is limited by the distribution of available rain gauges.

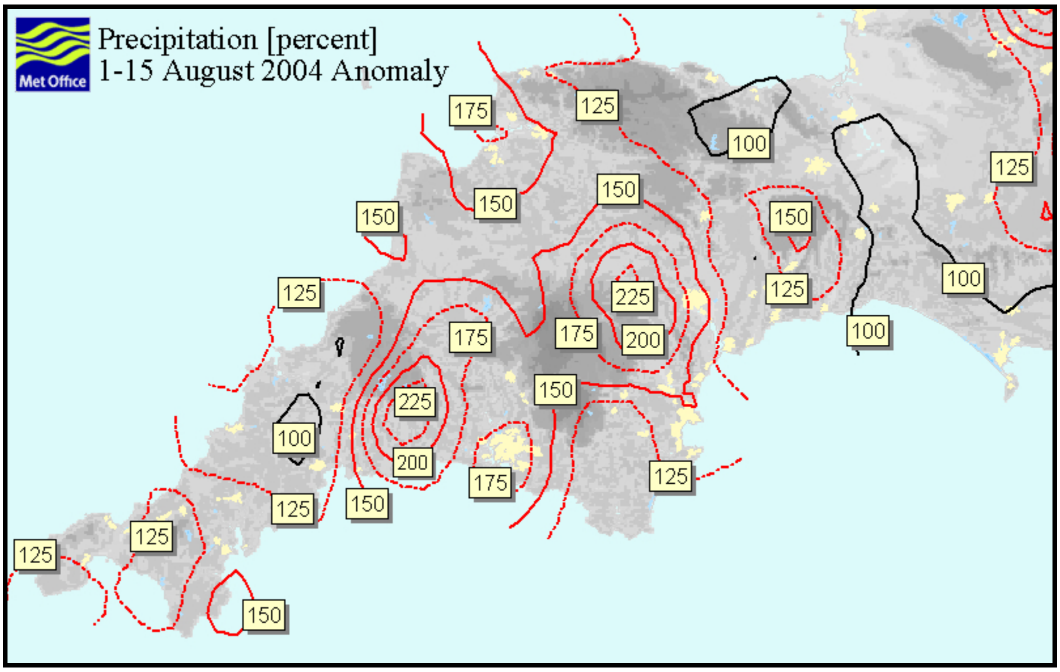


Figure 4.1 Precipitation anomaly map for South-west England, 1-15 August 2004, relative to 1961-90 averages

The Met Office's MOSES-PDM model (Met Office Surface Exchange Scheme incorporating the Probability Distributed Model) diagnoses the evolution of soil moisture using meteorological information, including radar rainfall and satellite cloud. The resulting soil moisture deficit (SMD) for Cornwall on the 16 August 2004 is depicted in Figure 4.2 and shows considerable spatial variability with values in the Valency catchment above Boscastle in excess of 100mm. The model diagnosed a reduction in SMD between 1st and 16th August consistent with the above average rainfall, the range of values around Boscastle dropping from 80-220mm SMD to 40-180mm SMD.

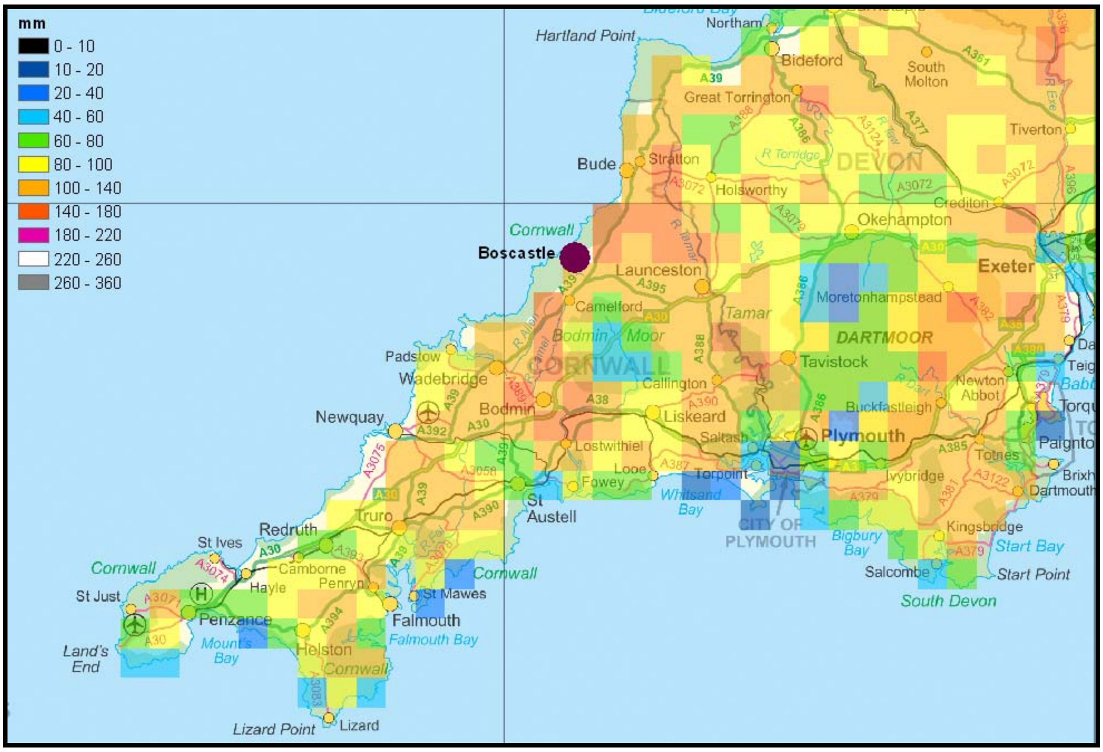


Figure 4.2 Diagnosed soil moisture deficit from MOSES-PDM for 0000GMT 16/8/2004

4.2 CAUSES OF THE STORM

The observed extreme rainfall accumulations resulted from prolonged very heavy rain over the four hour period 1200-1600GMT (13:00 to 17:00 BST) on the 16 August 2004. The exact track of the rainfall cells varied slightly during this period, but between the Camel Estuary and Bude the variation was sufficiently small to ensure that the heaviest rain fell into the same coast-facing catchments throughout the period. The intensity of the precipitation was probably enhanced by large scale uplift associated with larger scale weather troughs.

The large scale circulation is best illustrated by looking at the upper troposphere (Figure 4.3) in the Met Office Unified Model analysis for noon on the 16 August. A large depression dominated the eastern Atlantic with a complex structure of active development areas around it, shown by elevated values of potential vorticity. This structure reflects a history of successive pulses of tropical air being absorbed into the circulation, including former hurricane Alex. The variation in pressure is shown by contours of the height that corresponds to a given atmospheric pressure, in this case 300hPa.

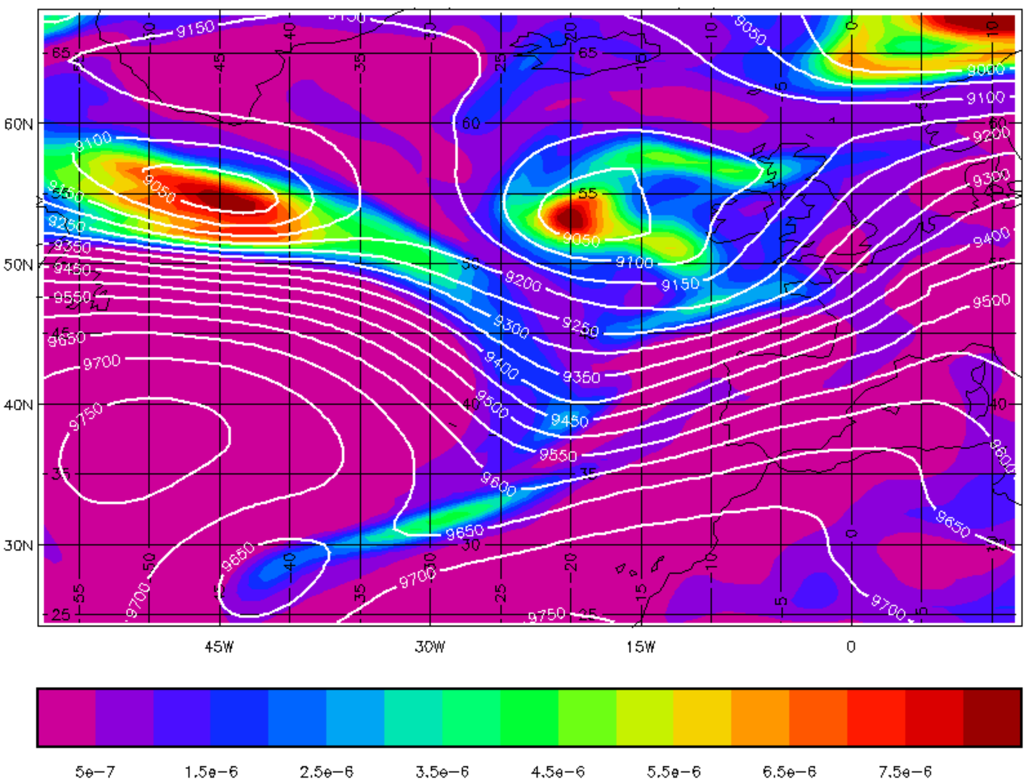


Figure 4.3 300hPa height (contours) and Potential Vorticity (colours) at 1200GMT 16/8/2004

The surface pressure pattern (Figure 4.4), analysed by the duty forecaster, reflects the upper air analysis. There is a complex set of low centres lying under the upper depression, with several troughs associated with the main bands of elevated potential vorticity.

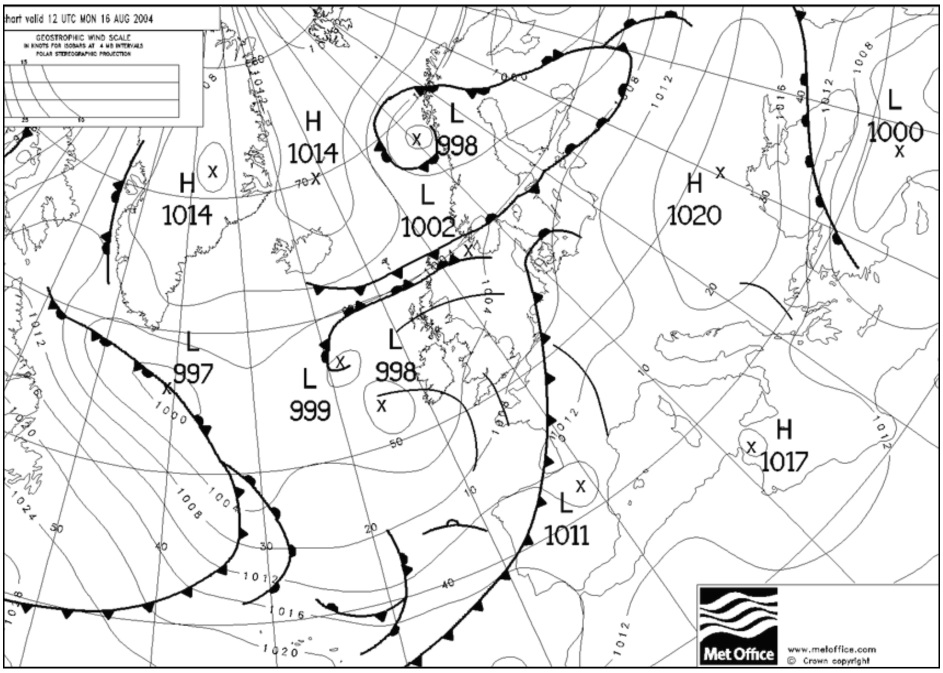


Figure 4.4 Surface analysis chart for 1200GMT on 16th August 2004

These troughs are difficult to trace in the surface weather, but can easily be identified as dry bands in the Meteosat-8 water vapour channel imagery (Figure 4.5) due to their association with a lowering of the tropopause height. Both features B and C may have influenced weather in the early afternoon in south west England. Feature B, in particular, shows cyclonic rotation and was probably the cause of the observed pressure falls in north Cornwall.

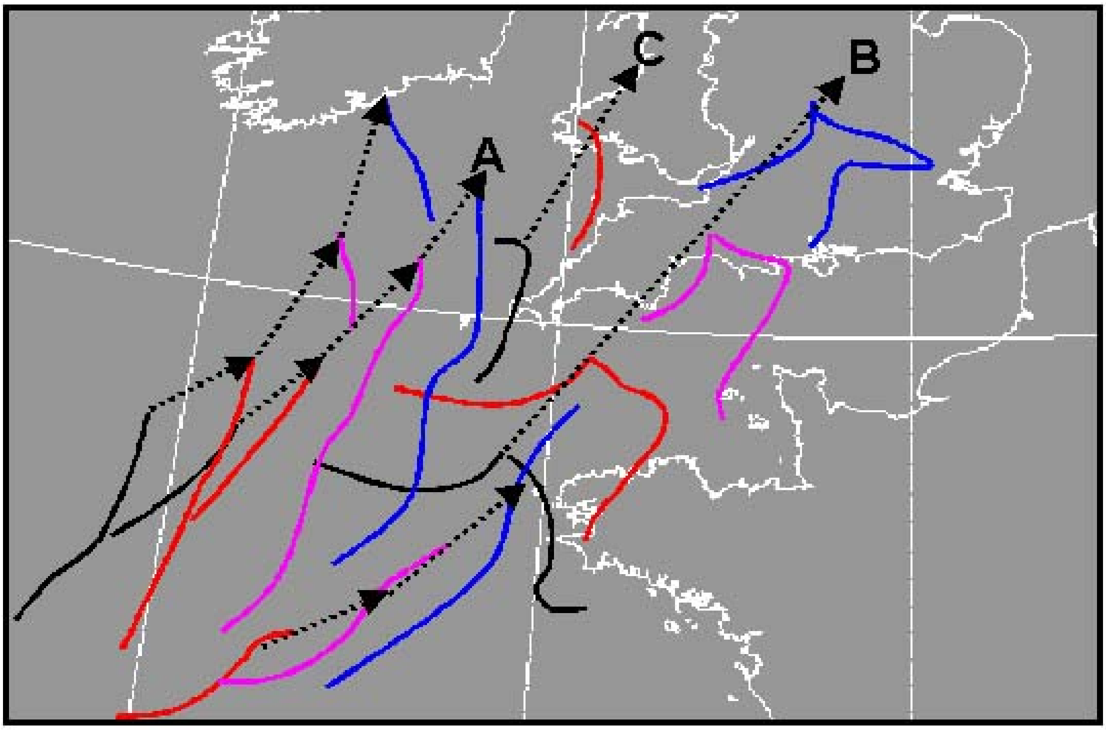


Figure 4.5 Tracks of dry features identified in the Meteosat-8 water vapour imagery. Colours show locations at 1030GMT (black), 1230GMT (red), 1430GMT (purple) & 1630GMT (blue).

The effect of these larger scale processes on the storm development would have been to create an environment of weak uplift and high moisture content, which would favour heavier rainfall.

Analysis of the radiosonde sounding from Camborne at 1200GMT on 16 August 2004 showed that the atmosphere was prone to storm development, with moist lower layers readily forming convective cloud above a base at about 900m. Above, strong instability in the lowest layers would produce a rapidly growing cloud. The equilibrium level where most clouds would stop was at 450hPa (6.5km), though the highest cloud tops would be at the tropopause at 350hPa (9.5km). The sounding supported fairly strong convection with a maximum vertical velocity of about 18m/s. Allowing for entrainment and averaging over the depth of the cloud, the mean vertical velocity is estimated to have been about 5m/s, supported by the absence of observed hail in the storm. At this speed it would take 15minutes for air from the boundary layer to reach cloud top. If we lift the observed 26mm of precipitable water to cloud top in 15 minutes we get a maximum rain rate of about 100mm.hr^{-1}. Much of this rainfall is normally evaporated into the surrounding air, giving an "efficiency" typically less than 50%. Maximum 15-minute rates observed by rain gauges and radar were 80-100mm.hr^{-1}, indicating an unusually high efficiency, while hourly accumulations of up to 60mm indicate that this high efficiency was being maintained over multiple cloud lifecycles without break.

The wind profile from the Camborne ascent showed a southerly near surface wind, veering to southwesterly 7.5 m/s (15kn) at the top of the boundary layer. Above this there was weak, unidirectional shear from there up to cloud top, the wind remaining southwesterly, increasing to 17.5 m/s (35kn) at 400hPa. Such a structure ensured that any downdraught would be down wind of the initiation point. It does not favour development of either multi-cell or supercell storms, which require directional shear of more than 20-30 degrees between cloud base and the height of origin of the downdraught (Pierce and Cooper, 2000). The wind at the middle of the storm layer (~500hPa), was southwest 12.5 m/s (25kn) consistent with the observed movement of the storms.

Estimates of probability and intensity of precipitation (see Hand, 2002), given the air mass characteristics represented in the model, indicated high (up to 70%) probabilities of showers with very variable rain rates up to 40mm.hr^{-1}, consistent with the analysis above. A set of predictors based on extreme events in the period 1900-2000 (Hand et al, 2004) suggested that the probability of a 1 in 100 year rainfall event in Cornwall was no larger than 10-15%. Both of these approaches are consistent with earlier evidence that the atmospheric structure supported heavy, but not extreme, individual thunderstorms.

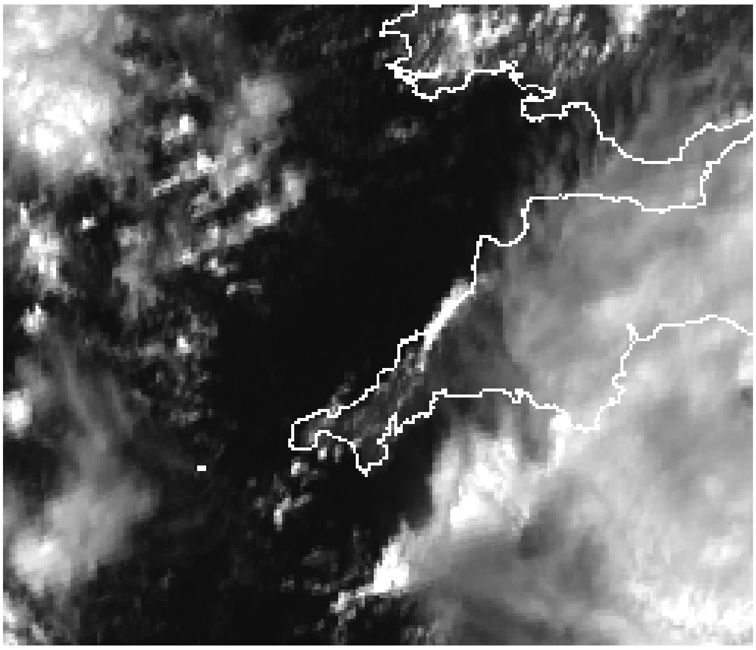


Figure 4.6 Meteosat-8 high resolution visible satellite image for 1130GMT

The extreme rainfall on the 16 August 2004 resulted from a sequence of convective storms that were channelled along the north Cornwall coast over several hours. This channelling is well illustrated by the satellite cloud image in Figure 4.6. Simulations carried out using 1km and 4km grid configurations of the Met Office NWP model all show a strong convergence line along the north Cornwall coast (Figure 4.7), providing 1-2m/s of uplift at cloud base. Its strength arises from alignment of the prevailing wind with the boundary between the rough land surface and the smooth surface of the sea. Over land the rough surface backs the surface wind from southwest to south-southwest. The subsequent acceleration over the sea results in a coastal jet that may be significantly stronger than the ambient wind (Hunt et al 2004). The boundary between the two is marked by strong convergence and uplift. This may be reinforced by an onshore pressure gradient resulting from solar heating over land. The synchronised initiation of showers along the whole coast at about 1100GMT is consistent with friction-induced coastal convergence as the primary cause. The exact position of the convergence relative to the coast varies with the ambient wind direction and the thermally induced pressure gradient. Initially the storms developed just offshore, consistent with pure frictionally driven convergence. The subsequent move inland and then back to the coast may be associated with a response to the late morning solar heating, followed by subsequent cooling due to heavy cloud cover in the afternoon, or it may merely reflect minor changes in the ambient wind direction.

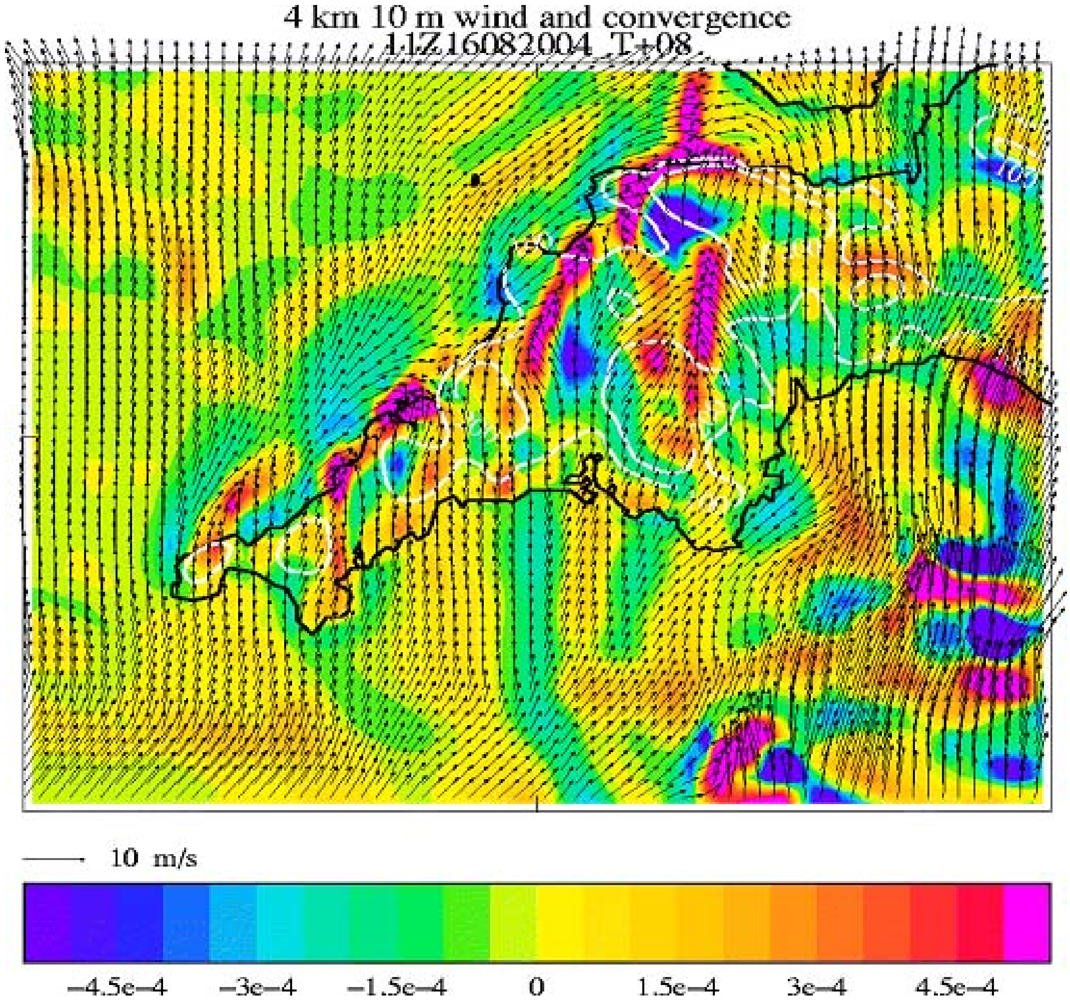


Figure 4.7 Surface wind and convergence at 1100GMT, 16th August 2004 from a 4km grid length integration of the Unified Model

The satellite image shown in Figure 4.6 indicates that convection developed upstream of Boscastle in the vicinity of the Fal estuary, but remained largely non-precipitating until it reached the convergence zone in the vicinity of the Camel estuary. Each storm cloud then developed rapidly to the equilibrium level (6.5km). This implies a cloud top temperature of around -15°C to -20°C which is only just cold enough to initiate ice processes in the cloud. However, the satellite images indicate that it is possible that the clouds were being adequately seeded with ice from the outflow cloud shields of earlier storms over Brittany.

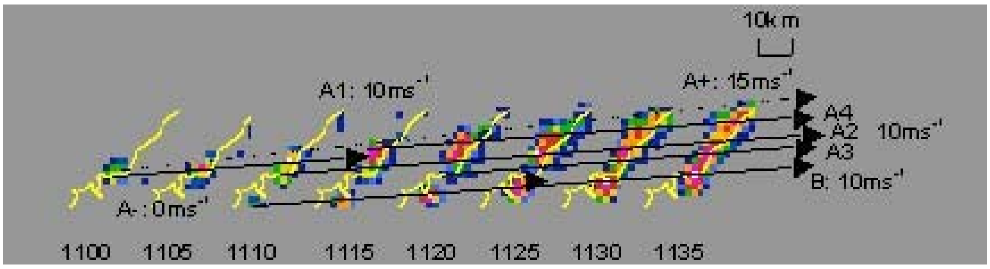


Figure 4.8 **Initial evolution of the 1st & 2nd storm cells, 1100-1135GMT. Each time is shifted right by an additional 25km for clarity. See Figure 2.9 for rain rate key.**

As it developed in the convergence zone, each storm spread out into a line of storms (Figure 4.8, Figure 4.9), spaced at intervals of about 5km, making the rain appear continuous. The recording rain gauge at Lesnewth confirmed the presence of variations in rain rate associated with these storms (Figure 4.10). The small size of the cells is consistent with the low altitude of the cloud tops. The secondary cells were characterised by very rapid growth, as observed by an eyewitness at St. Breward, and rapid development of intense precipitation. The extreme precipitation in the vicinity of Boscastle appears to have been related to the fact that while convection was strong enough to generate heavy precipitation, it was shallow enough to permit development of closely packed storm cells with downdraughts weak enough not to distort the coastal convergence line.

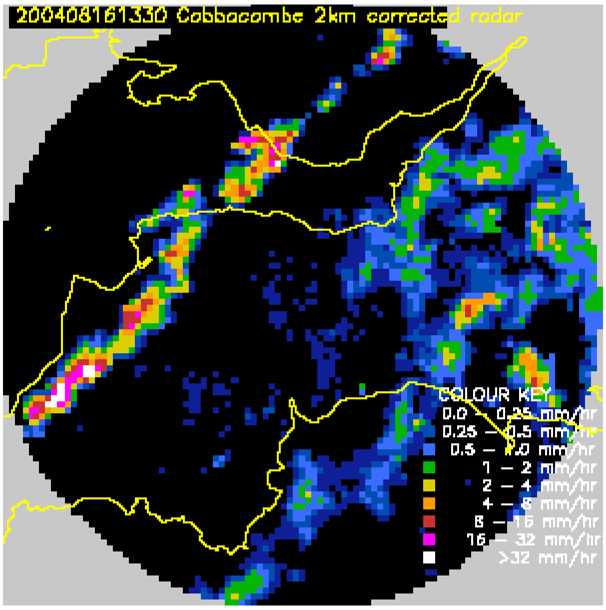


Figure 4.9 **Cobbacombe radar image for 1330GMT 16th August 2004**

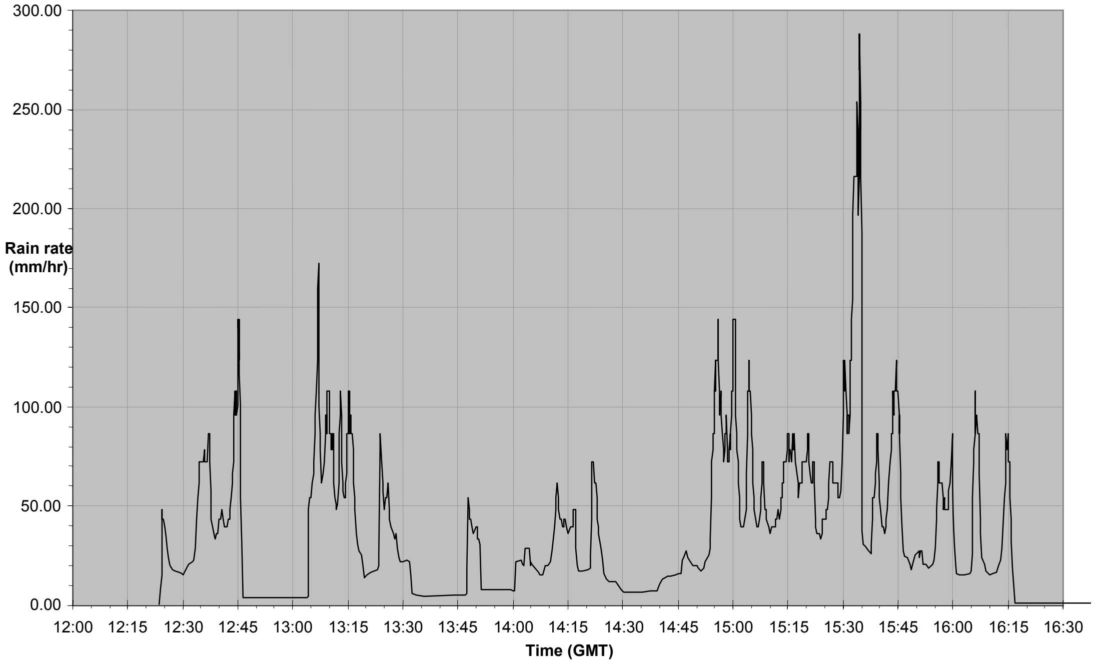


Figure 4.10 Smoothed rain rate profile from the Lesnewth Tipping Bucket Raingauge on 16th August 2004

At a later stage, some storms grew to the full depth of the troposphere at 250hPa (9.7km), developing large ice cloud shields and vigorous downdraughts, resulting in a gust front which distorted the convergence line, causing it to bow in an eastward arc to the north of Bude. A succession of such arcs is visible in the satellite and radar imagery, generating new rows of storm cells as they spread east into north Devon and across the Bristol Channel into south Wales (Figure 4.11, Figure 4.12).

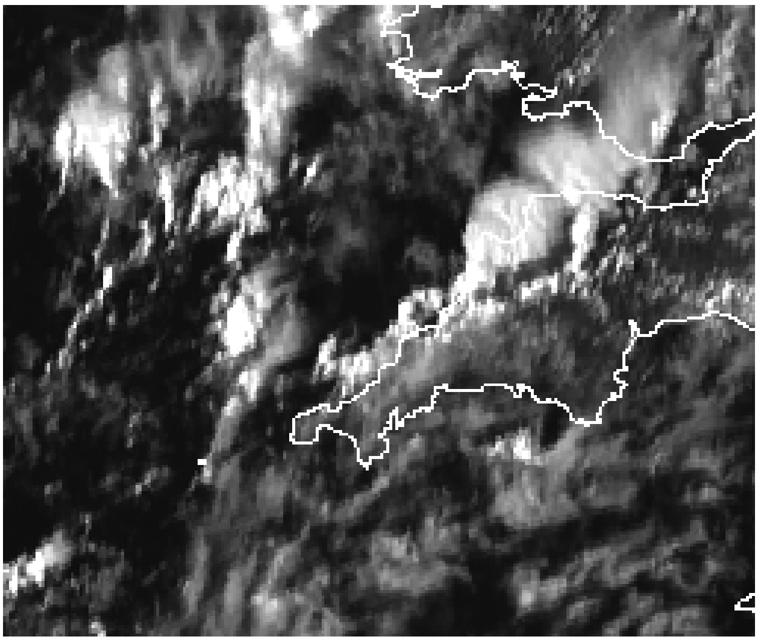


Figure 4.11 Meteosat-8 high resolution visible image for 1530 GMT 16th August 2004

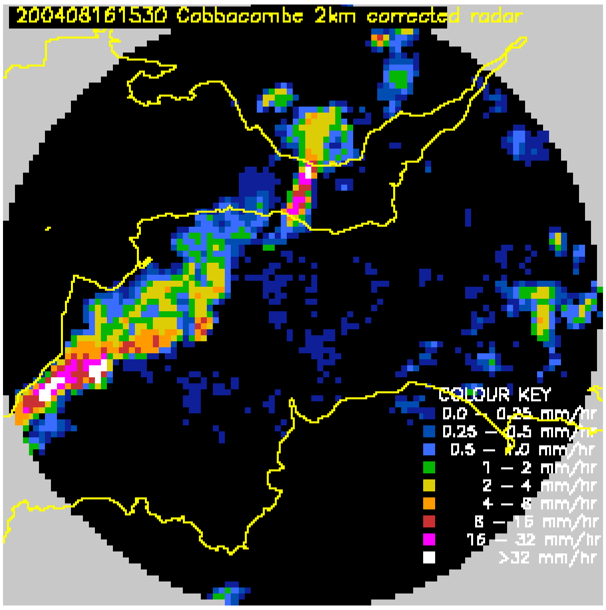


Figure 4.12 Cobbacombe radar image for 1530GMT 16th August 2004

4.3 RAINFALL DISTRIBUTION

The spatial distribution of total rainfall for the event is summarised in Figure 4.13 and Table 4.1. The area affected was very small with only three of the nearby daily rain gauges recording exceptional rain.

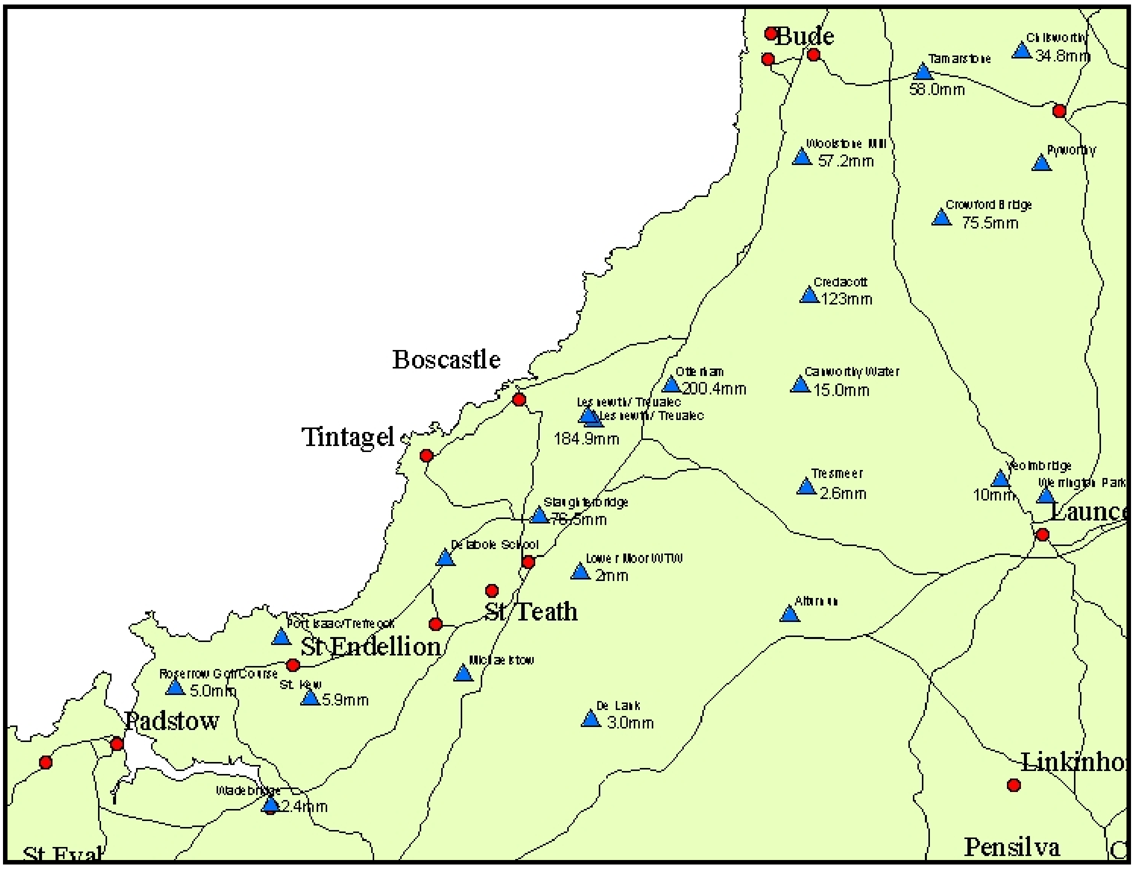


Figure 4.13 Available rain gauge locations, with 24 hour totals for 0900GMT 16/8/2004 – 0900GMT 17/8/2004, in relation to roads and settlements

Table 4.1 Quality controlled daily (24 hour) rainfall observations for 16/8/2004 from the ten nearest rain gauges to Boscastle

Station No.	Station Name	Operating Authority	Observed Value (mm)
371160	Otterham	EA Cornwall	200.4
371374	Creddacott	EA Cornwall	123.0
371899	Tresmeer	EA Cornwall	2.6
373165	Altarnun	EA Cornwall	11.8
384101	Lower Moor W.Wks.	EA Cornwall	2.0
384366	St Breward, Camperdown Farm	EA Cornwall	1.5
384901	Delabole P.Sch.	EA Cornwall	54.8
384966	Michaelstow	EA Cornwall	2.0
385589	Treknow	Met Office	31.3
385700	Lesnewth, Trevalec	EA Cornwall	184.9

The Tipping Bucket Rain gauge (TBR) at Lesnewth recorded maximum short period accumulations of 68mm in 1 hour, 123mm in 3 hours, and 152mm in 5 hours. Comparison with the quality controlled check gauge indicates that these should be increased by 20% to 82mm, 148mm & 183mm respectively to allow for under-reading by the TBR. The Lesnewth TBR also recorded a peak rain rate of nearly 300mm/hr at about 1535GMT (Figure 4.10). The temporal pattern is illustrated in Figure 4.14 for five TBRs and the highest overall radar total. Note that at Slaughterbridge and Crowford the storm peaked shortly after 1300GMT, whereas at Lesnewth the heaviest rain was around 1530GMT and at Woolstone and Tamarstone the peak was not until 1630GMT. These differences result from the slight changes in the position of the rain band.

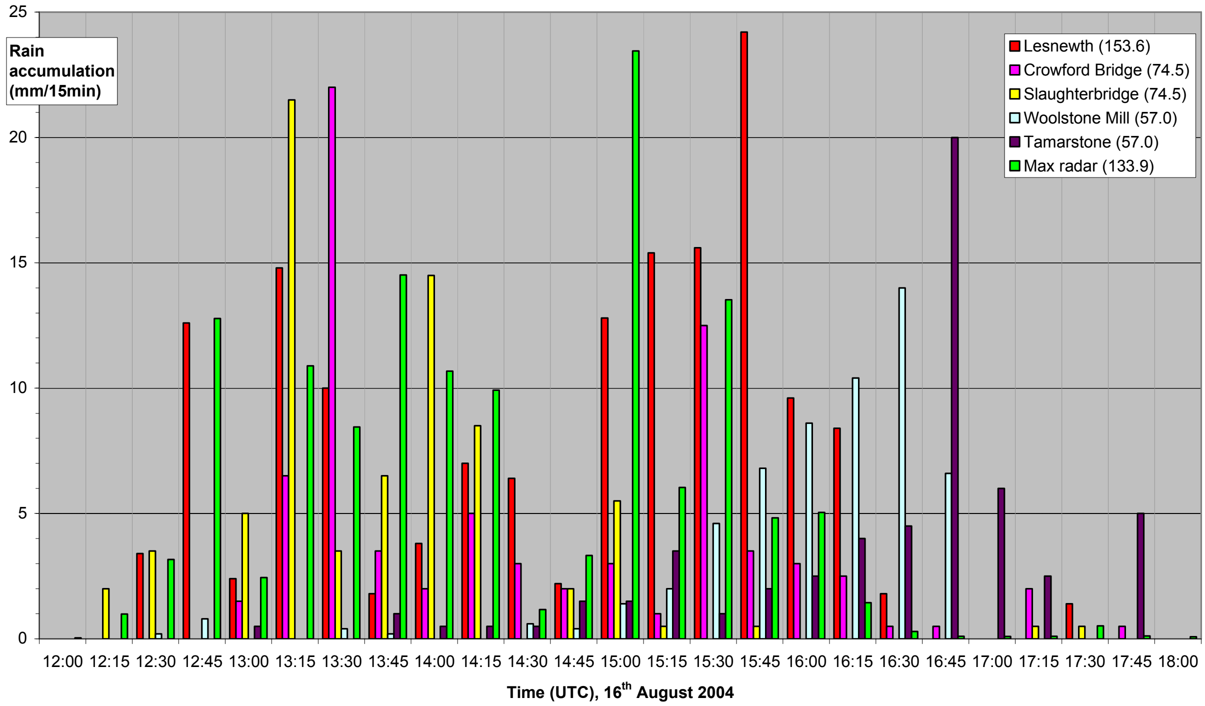


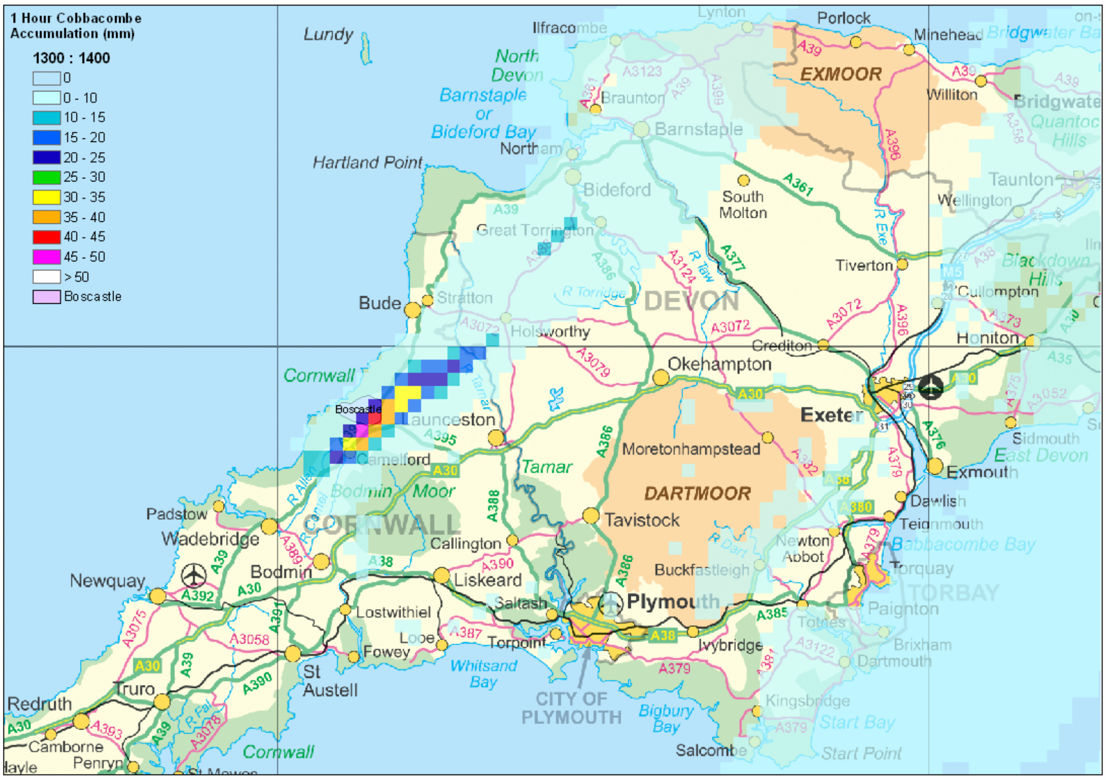
Figure 4.14 Comparisons between 15min rainfall accumulations at five tipping bucket raingauges (not quality controlled) and the 2km radar pixel having the highest total event accumulation

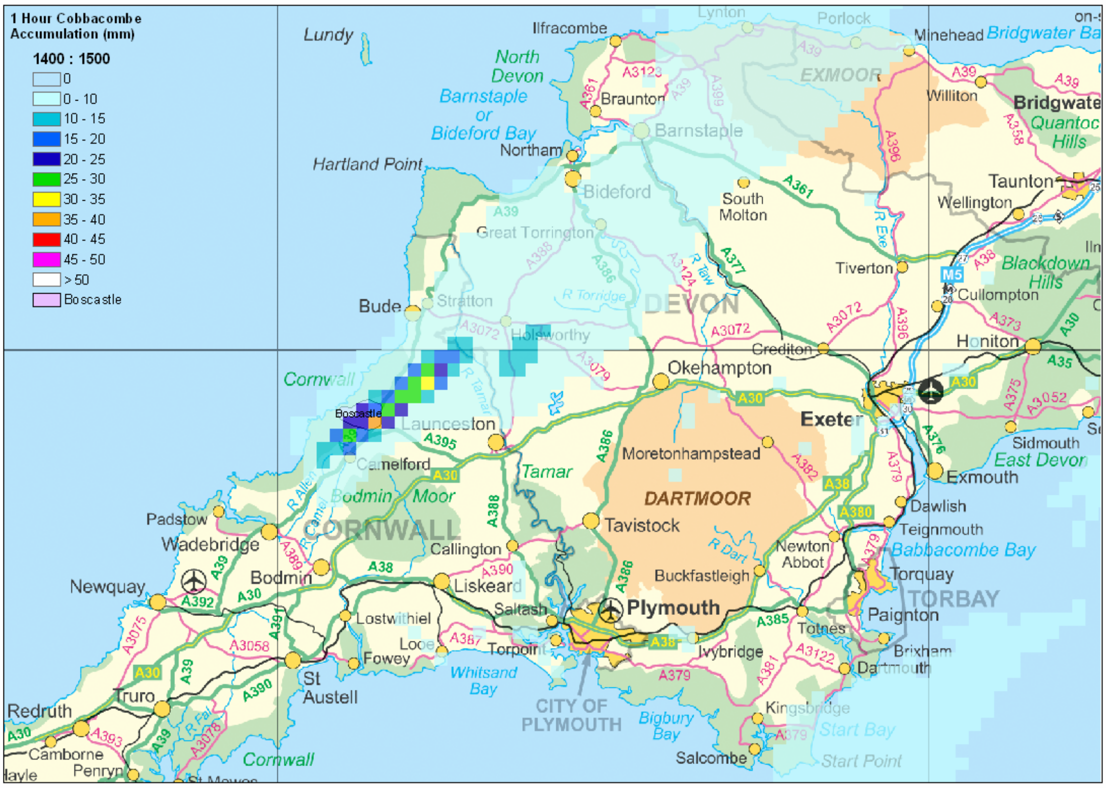
Observations of the spatial and temporal pattern of precipitation were well captured by the Cobbacombe and Predannack radars. Maximum values over 4km^2 pixels differed from those observed by the TBRs due to sampling differences, but the overall pattern was consistent.

Figure 4.15 summarises the radar information in a sequence of hourly rainfall accumulation maps obtained by summing 5-minute corrected radar rain rates at 2km resolution from the Cobbacombe Cross radar. The colour scheme emphasises the heavier rainfall amounts. The results have been displayed on a map background so that features can be geographically located. In the discussion below, the radar pattern is related to available TBR data, with TBR values given in brackets where available.

During the first hour, 1200-1300GMT, the axis of maximum rainfall was to the east of the Valency catchment, with three maxima of 15-20mm. Slaughterbridge (10mm) was between the 1st and 2nd of these and Lesnewth(17mm) was on the western edge of the 3rd, each having radar accumulations in the 10-15mm range. Otterham was on the axis of the maximum, with a radar estimate of 15-20mm.

During the period 1300-1400GMT, rainfall was much heavier, with the axis of maximum rainfall remaining along the east side of the Valency catchment and exceeding 30mm in a single 10km long, 4km wide plume from Slaughterbridge to Otterham. Maximum radar accumulations of 45-50mm occurred on the southeast edge of the Valency catchment, between Slaughterbridge (radar: 30-35mm; raingauge: 47mm) and Otterham (radar: 35-40mm). Again Lesnewth (29mm) was off the main axis of the rain with a radar pixel value of 20-25mm.


1 Hour Cobbacombe
Accumulation (mm)
1300 : 1400
0
0 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
> 50
Boscastle
Lundy
Ilfracombe
Porlock
Minehead
EXMOOR
Barnstaple
Bideford
Hartland Point
Bude
DEVON
Okehampton
Exeter
Cornwall
Launceston
Camelford
DARTMOOR
Tavistock
Padstow
Wadebridge
Newquay
Bodmin
Liskeard
Plymouth
Torquay
Paignton
St Austell
Truro
Redruth
CITY OF PLYMOUTH


1 Hour Cobbacombe
Accumulation (mm)
1400 : 1500
0
0 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
> 50
Boscastle
Lundy
Ilfracombe
Porlock
Minehead
EXMOOR
Barnstaple
Bideford
Hartland Point
Bude
DEVON
Okehampton
Exeter
Cornwall
Launceston
Camelford
DARTMOOR
Tavistock
Padstow
Wadebridge
Newquay
Bodmin
Liskeard
Plymouth
Torquay
Paignton
St Austell
Truro
Redruth
CITY OF PLYMOUTH

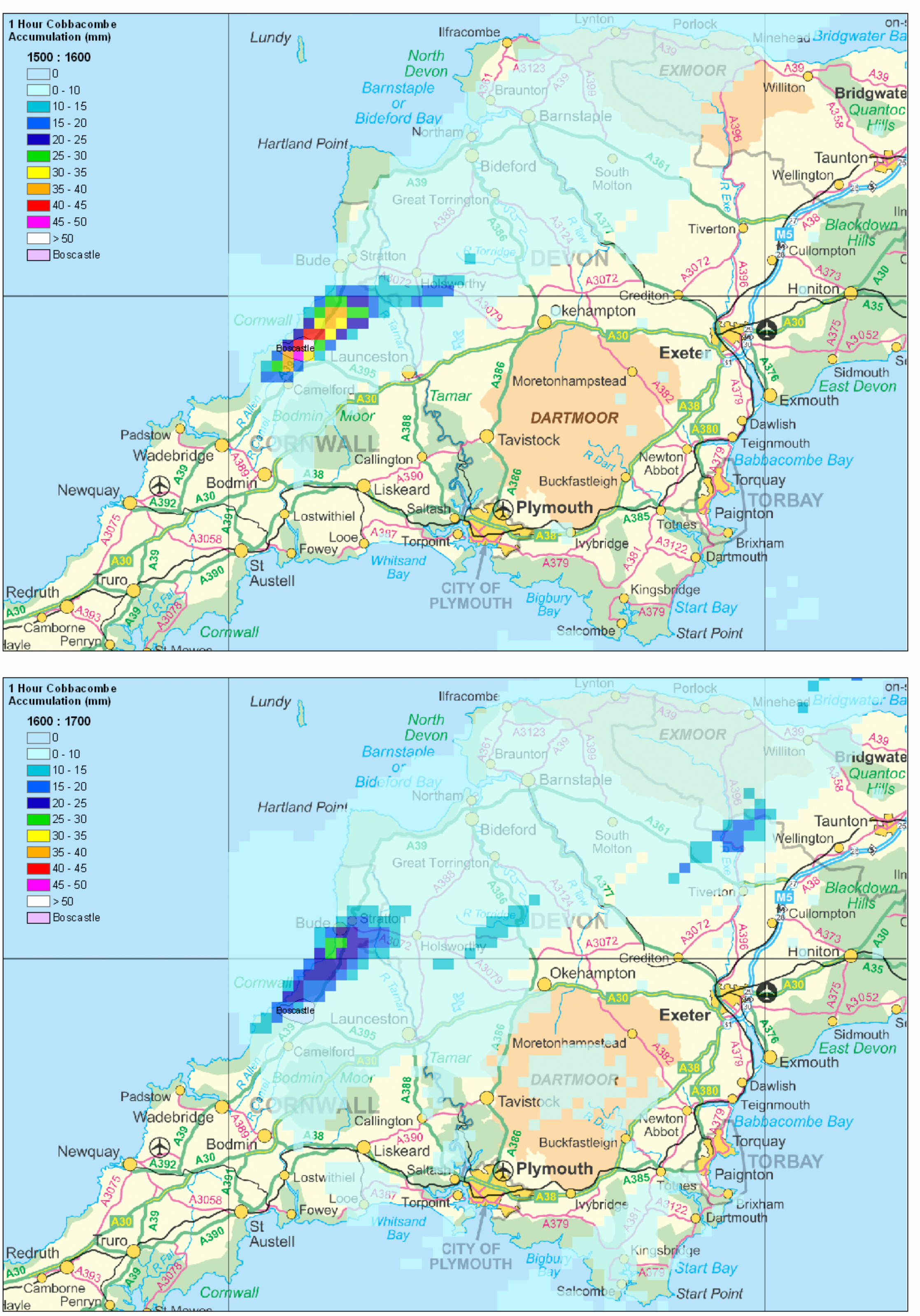


Figure 4.15 **Sequence of hourly accumulations of 2km corrected Cobbacombe radar data, 1200GMT-1700GMT.**

From 1400 to1500GMT, accumulations were lower than in the previous hour, with three local maxima, one of 25-30mm situated between Slaughterbridge and Boscastle, one of 35-40mm over the east part of the Valency catchment, and a more elongated one to the northeast reaching 30-35mm near Credacott. Slaughterbridge (8mm) was upwind of the first maximum, in a 15-20mm pixel; Otterham was downwind of the second maximum in a 25-30mm pixel; and Lesnewth (28mm) was on the western edge of the rain axis in a 15-20mm pixel.

Maximum rainfall was higher again in the hour from 1500-1600GMT, exceeding 35mm in a 12km long, 4km wide plume that runs right through the Valency catchment from near Slaughterbridge to beyond Otterham. The axis had shifted west by about 2km from the earlier position and Lesnewth (54mm) was in the heaviest pixel of >50mm. Slaughterbridge was upwind of the main maximum in a 15-20mm pixel, while Otterham (2mm) was on the eastern edge of the maximum in a 40-45mm pixel.

By 1600-1700GMT, the main rain area had moved away north and the remains of the plume had shifted west, putting Boscastle village under the maximum of 15-25mm, while the three local raingauges were all in pixels of less than 10mm. (Lesnewth TBR: 10mm, Slaughterbridge TBR: 0mm)

The temporal analysis is consistent with the gauge reports, with Slaughterbridge having its highest accumulation in the 1300-1400GMT period and reduced rates thereafter as the maximum shifts downwind, while Lesnewth was off the western axis of the rain maximum until later, receiving its maximum accumulation between 1500-1600GMT. From this analysis, Otterham would be expected to have peaked twice, with 35-40mm from 1300-1400GMT and again with 40-45mm in 1500-1600GMT.

The radar accumulation for the whole 5-hour period (Figure 4.16) indicates that the heaviest total rainfall accumulation probably occurred a few kilometres to the southwest of Otterham near the A39, with three consecutive hours in excess of 30mm.

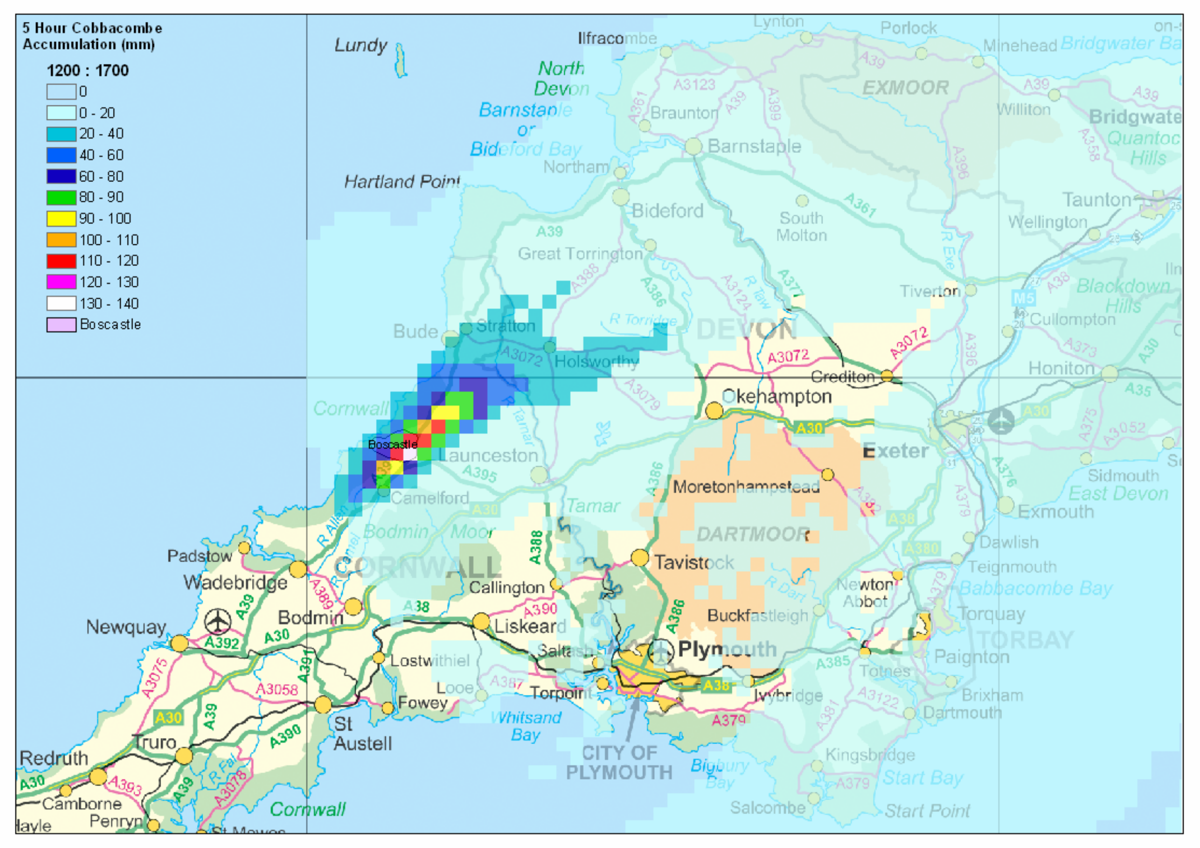


Figure 4.16 Five hour accumulated rainfall from 2km corrected Cobbacombe radar data, 1200-1700GMT 16th August 2004.

4.4 PROBABILITY OF RAINFALL EVENT

The probability of occurrence of the extreme rainfall observed in the vicinity of Boscastle has been studied in the context of climatology, meteorological phenomena, historical occurrence of storms, and historical occurrence of point rainfalls.

The standard technique for assessing probability of occurrence of floods in the UK is the FORGEX method documented in the Flood Estimation Handbook (FEH: Institute of Hydrology, 1999). This is based on analysis of historical values of the highest rain gauge record in each year, and represents the probability at a point. Table 4.2 is based on application of this method to values recorded during the August 2004 event. Note that the short periods are based on TBR records which are not quality controlled, and also that the FORGEX method is not designed for use with radar, which gives an area average rather than a point value.

The adjusted, observed maximum one hour fall at the Lesnewth TBR of 82 mm has an annual probability of occurrence around 0.13%. This is due to the very high precipitation efficiency, which has been associated with the large scale synoptic forcing and the close packing of small individual storms.

The three hour total, again at Lesnewth, is comparable with the Camelford flood in 1957, and with several events in other parts of the country, most of which were accompanied by large hail. The annual probability of occurrence is about 0.08%.

The overall storm has an annual probability of occurrence less than 0.05%. which is larger then that for the Lynmouth or Martinstown events. All cover very small areas, which contributes to the point rarity.

Table 4.2 Rolling peak rainfall accumulations and FEH point rainfall annual probability of occurrence

Duration (hrs)	1	2	3	4	5
Comp. QC 2km Radar (mm)	47	68	99	114	115
Annual probability of occurrence (%)	1	0.5	0.2	0.13	0.17-0.2
Cobb. QC 2 km Radar (mm)	48	83	117	132	133
Annual probability of occurrence (%)	~0.83	~0.25	~0.1	~0.08	~0.09
Lesnewth (mm)	68	94	123	150	152
Annual probability of occurrence (%)	~0.25	~0.14	~0.08	~0.045	~0.05
Slaughterbridge (mm)	46	63	73	74	74
Annual probability of occurrence (%)	1	0.5-0.67	0.5-0.67	0.67-1.0	1
Crowford Bridge (mm)	34	47	67	72	72
Annual probability of occurrence (%)	2-5	2	0.67-1.0	0.67-1.0	1-2
Woolstone Mill (mm)	48	70	72	73	74
Annual probability of occurrence (%)	1	0.5	0.5-0.67	0.67-1	1
Tamarstone (mm)	35	44	48	49	50
Annual probability of occurrence (%)	2-5	2-5	2-5	2-5	5

Given the shortness and sparseness of the instrumental record, the reliability of estimates of the annual probability for small probability events is questionable, but the results can be safely taken to indicate an annual probability of occurrence less than 0.1%.

Inspection of the mechanisms involved in generating the rainfall indicates that the key features were the efficiency of the rainfall production and the length of time for which it remained over the same area. The FEH results suggest that the efficiency of the rainfall production meant that the annual probability for the maximum hourly rainfall was about 0.25%. As the high intensity rain remained over the same area for about 5 hours the combined rainfall and duration reduced this annual probability to about 0.05%. As with other extreme storms that have been studied, the combination of factors that produced the event do not fit a pattern that has been observed before so it is not possible to deduce the likelihood of their recurrence.

An alternative approach is to place the August 2004 storm in the context of historic extreme events. The characteristics of extreme rainfall events in the 20th Century have been studied by Hand et al (2004). Figure 4.17 shows rainfall amounts and durations for these storms, broken down into rainfall mechanisms, with values for the August 2004 storm superimposed, based on the measurement at Otterham. The distribution per decade indicates a high degree of natural variability with no discernible trend. The overall frequency is one event every second year somewhere in the UK. If we select only convective events, we have something like a 30% chance of an extreme convective storm event occurring somewhere in the UK each year. Most of these events have occurred during the summer months with none between November and April. An explanation for this highly skewed distribution is that extreme events only occur when high sea temperatures generate high moisture content air in the vicinity of the UK. This is consistent with the expected relationship between the intensity of convective storms and their moisture content and is confirmed by noting that the observed rain rates in the August 2004 storm were modest compared with those observed in severe rain storms in more southerly latitudes.

The south west peninsula has been subjected to six extreme rainfall events in the last century, of which three occurred in the decade 1951-60. The point ($1km^2$) probability deduced from an examination of these events indicates a similar annual probability to that deduced using the FEH method. Allowing for the sparse observational network, the evidence indicates that an extreme event will occur somewhere in the south west region once every 20 years on average.

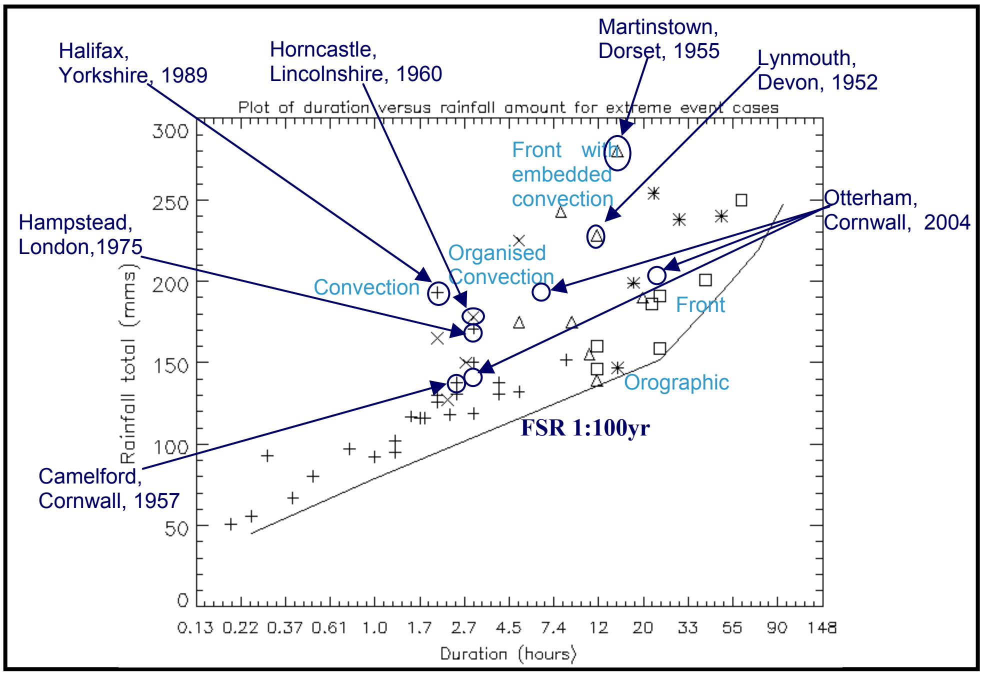


Figure 4.17 Extreme rainfall events of the 20th century with Boscastle superimposed. The dominant mechanism is convection (+), organised convection (x), frontal (□), frontal with embedded convection (△) or orographic (✱).

4.5 DATA QUALITY AND UNCERTAINTY

The main problems with records from well maintained gauges occur in high wind speeds (Robinson & Rodda, 1969). The daily rain gauges in the vicinity of Boscastle all have a good track record for accuracy and there was little wind on the day. The observations are consistent with each other and agree well with the known characteristics of the storm. The daily rain gauge totals are therefore accepted as accurate estimates of the rain that fell at specific locations, including a maximum daily accumulation at Otterham of 200.4mm.

Tipping Bucket Rain gauges (TBRs) suffer from known faults in intense rain events and those around Boscastle are not Met Office registered. The general pattern of rainfall amounts is consistent with that observed by radar and the daily rain gauges, but the amounts cannot be relied on, as is shown by comparison with the daily gauge at Lesnewth. The best estimate of short period totals is obtained by scaling the TBR amounts to the daily gauge total at the same site, where available.

Conditions for radar observation were good and the resulting data were fully quality controlled and calibrated using the methods described in Harrison et al (2000). The spatial and temporal distribution of rainfall was consistent between the two radars and with the available TBRs and there are no known faults in the data. Although Cobbacombe recorded a slightly higher maximum storm accumulation than Predannack in the Valency catchment, there is very little overall bias evident between the two sets of data. In the areas of common coverage at 2km resolution, Cobbacombe recorded 108 sq km with mean accumulations exceeding 64mm whereas Predannack recorded 132 sq km. Both Cobbacombe and Predannack radars recorded 9 pixels (36 sq km) with mean accumulations exceeding 96mm.

Due to the very high rainfall accumulation gradients, it is not possible to determine whether the differences between radar and rain gauge accumulations are solely due to sampling differences, or whether the radar has a low bias at high intensities.

For applications that are calibrated to point values from rain gauges, it is recommended that temporal information from the Lesnewth TBR, is adjusted to match the Otterham and Lesnewth gauges, with any spatial variation obtained using conventional approaches such as Thiessen polygons. Otherwise maximum point totals should be taken from the radar pattern, adjusted to the available daily gauges, and spatial averages should be taken directly from the radar.

5. Hydrological analysis and interpretation

5.1 INTRODUCTION

The hydrological studies described here aim to reproduce, as far as possible, the flood flows for the Valency and Jordan catchments flowing through Boscastle, and for the Crackington Stream catchment to the north, for the extreme flood event of 16th August 2004. The flooding at Boscastle from the Valency and Jordan catchments was very severe, and, in consequence, difficult to reproduce reliably given the currently accepted 'best UK methodology' provided in the Flood Estimation Handbook (Institute of Hydrology, 1999). The FEH methodology is directed primarily towards more commonplace floods than those that affected the north Cornwall coast in August 2004. The FEH approach is based on a large collection of UK flood data but inevitably the amount of data available from extreme floods is limited and so the reliability of the method applied to such extreme events is less than for more common flood events. It remains, however, the only practical tool for modelling flood events on small, ungauged catchments such as the Valency, Jordan and Crackington Stream.

For the hydraulic analysis flood estimates were required for a number of sub-catchments of the Rivers Valency and Jordan, and for the Crackington Stream catchment. The outflow points of the sub-catchments requiring modelling are shown in Table 5.1, and on Figure 5.1. These sub-catchment flows provided the upstream boundary conditions, or inputs to, the hydraulic modelling studies.

For each case, flood estimates were also derived for the whole catchment at its seaward limit, although these estimates were not used directly by the hydraulic modelling exercise, but were used as a simple check on the outcome of the overall modelling exercise.

Table 5.1 Points at which flood estimates required

1. Boscastle Catchment		
Sub-catchment	Grid Reference	Area (km^2)
B1	SX,09950,91200	2.4
B2	SX,11550,91050	1.88
B3	SX,12300,91100	4.47
B4	SX,14150,91150	5.5
B5N1	SX,13300,91250	0.58
B5S2	SX,13250,91100	0.66
	Total Sub-catchment area	15.49
	Undesignated lateral inflow area	4.53
Boscastle (whole Valency and Jordan catchment)	SX,09800,91350	20.02

Table 5.1 Points at which flood estimates required (continued)

2. Crackington Stream		
Sub-catchment	Grid Reference	Area (km^2)
C1	SX,14300,96450	6.25
C2	SX,15700,96200	6.35
Total sub-catchment area		12.60
Undesignated lateral inflow area		1. 28
Crackington (whole catchment)	SX,14300,96800	13.88
Additional Intermediate points		
C2A	SX,16150,96300	1.58
C2B	SX,16150,94750	1.06

Note: Areas computed using the DTM contained on the FEH CD-ROM

For both catchments, some areas drain directly into the main river channel either through very small streams or channels that do not appear as distinct sub-catchments on the FEH CD-ROM, and are not shown on the 1:25,000 scale maps. In some cases there does not appear to be a well defined stream channel from such areas, and rainfall probably runs off as lateral surface flow directly into the main Valency channel. These undifferentiated, or undesignated, lateral inflow areas are likely to have very rapid response times, that is sub-hour response times, and can be expected to contribute flow into the main river channels very quickly, which must be reflected in the modelling.

In the case of Crackington Stream, this undifferentiated area is relatively small at 1.28 km^2, or 9% of the total catchment area, and flows into the lower reaches of the catchment.

In the case of the Valency, however, these undifferentiated areas total 4.53 km^2, or almost 23% of the total catchment draining through the lower part of Boscastle near the Valency and Jordan confluence. Some of this lateral inflow enters the upper part of the catchment above sub-catchments B5N1 and B5S2, but a significant proportion of this undesignated lateral inflow enters the lower catchment, where the contribution to flow can be expected to be very rapid.

Flow estimates from these undesignated lateral inflow areas for both the Valency and Crackington Stream catchments were derived by scaling the computed flows from sub-catchment B5S2, which appears to the closest analogue catchment that might be representative of the response of these lateral inflows. This point is discussed in more detail later.

For both catchments, standard FEH approaches were initially applied to estimate flows for a range of probabilities of exceedence. Both the FEH statistical procedure (Volume 3) and rainfall-runoff method (Volume 4) were applied. These results were used to estimate the exceedence probability of the August 2004 flood.

The rainfall-runoff method was then applied to all of the sub-catchments using best estimates of actual storm rainfall, in an attempt to reproduce the observed levels and timing of the event.

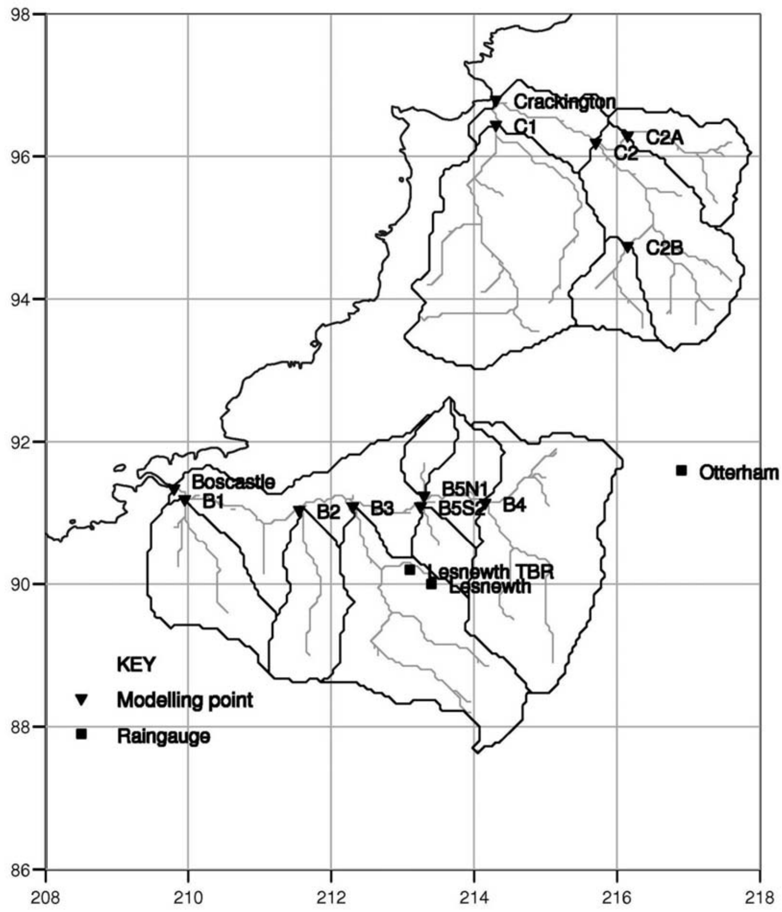


Figure 5.1 Sub-catchments modelled (shown with 2 km grid)

5.2 ESTIMATES OF PROBABILITY BASED ON FEH

Standard FEH procedures have been applied to both the Valency/Jordan and Crackington Stream catchments in an attempt to derive estimates of floods of varying probabilities of exceedence. It must be remembered that neither catchment is gauged, and hence FEH ungauged catchment procedures must be applied, which inevitably results in a relatively high degree of uncertainty associated with the derived flow estimates. Uncertainty will be considered later.

Two procedures have been applied, the statistical approach, and the rainfall-runoff model, using design rainfalls to derive full flood hydrographs.

5.2.1 Statistical analysis

The statistical procedures described in Volume 3 of the FEH (Institute of Hydrology 1999) include a methodology which allows a flood frequency curve to be produced for an ungauged site. This is a two-stage process; firstly an estimate of the median annual maximum flood (QMED) is required and secondly an estimate of the flood growth curve is needed. The statistical approach constructs the flood frequency curve as a product of the index flood QMED and the growth curve.

The subject sites considered relate to the entire Valency plus Jordan catchments to Boscastle (defined as 209800, 91350 by the FEH CD-ROM) and Crackington Stream to its outlet (214300, 96800).

5.2.2 Boscastle (Valency and Jordan catchments)

An initial estimate of QMED based on catchment descriptors provides a figure of 6.810 m^3/s. The FEH strongly recommends that this provisional estimate is adjusted by 'data transfer' from at least one gauged catchment judged to be hydrologically similar. Using five analogue catchments a multi-site adjustment procedure has been applied (see Appendix 1) giving a revised QMED estimate of 3.998 m^3/s. The fact that using data from analogue catchments led to a 40% reduction in QMED indicates the large degree of uncertainty in estimating QMED for ungauged catchments.

The growth curve has been estimated using the FEH pooling-group procedure for a target exceedence probability of 1% using the software WINFAP-FEH. A comprehensive review of the initial pooling-group was carried out in line with FEH recommendations. Both hydrological similarity and data quality were considered in making judgements that led to revision of the group. Reference was made to the provisional information (in advance of the official launch) provided by the EA web-based HiFlows-UK, both with respect to giving guidance on data quality and in providing updates to the annual maximum series for some pooling-group members. The final group membership is given in Appendix 1.

Growth curve factors and estimates of the peak flood flow for selected annual exceedence probabilities are given in Table 5.2.

Table 5.2 Peak flow estimates for selected annual exceedence probabilities for the Valency/Jordan (Boscastle) catchment FEH Statistical Method

Exceedence Probability (%)	Growth curve factor	Peak flow (m^3/s)
50	1.000	3.998
20	1.346	5.382
10	1.596	6.381
4	1.956	7.820
2	2.264	9.052
1	2.612	10.445
0.5	3.009	12.028
0.2	3.619	14.467
0.1	4.157	16.619

5.2.3 Crackington Stream

The initial estimate of QMED (5.650 m^3/s) provided by catchment descriptors was revised using a multi-site adjustment procedure to 3.317 m^3/s. In line with the approach taken above, the default pooling-group produced by WINFAP-FEH was subject to review and subsequently the growth curve was estimated using a much revised pooling-group (Appendix 1 gives details of the pooling-group membership used).

Growth curve factors and estimates of the peak flood flow for selected annual exceedence probabilities are given in Table 5.3 below.

Table 5.3 Peak flow estimates for selected annual exceedence probabilities for Crackington Haven

Exceedence Probability (%)	Growth curve factor	Peak flow (m^3/s)
50	1.000	3.317
20	1.368	4.538
10	1.637	5.430
4	2.028	6.728
2	2.367	7.850
1	2.752	9.128
0.5	3.194	10.593
0.2	3.880	12.870
0.1	4.491	14.897

It is apparent from Tables 5.2 and 5.3 that the FEH statistical procedure flood estimates for both catchments are small when compared to the estimated peaks that occurred on 16th August 2004 of 180 $m^3/s1$ for the Valency/Jordan and 90 m^3/s for Crackington Stream. This indicates that the observed flood peaks for the 16th August 2004 event were very rare events. Due caution ought, however, to be placed on probability estimates when FEH statistical procedures are applied to small, steep catchments. This matter is addressed later in the report.

5.3 RAINFALL-RUNOFF MODELLING

The rainfall runoff method of the FEH (Institute of Hydrology, 1999) uses the unit hydrograph-losses model to convert event rainfalls to flood runoff. The rainfall may be either a design storm of specified exceedence probability, or may be observed rainfall, in order to assess the resultant flood runoff. For the present study, both approaches have been adopted, the first in an attempt to establish the likely exceedence probability of the 16th August event, and the second, to determine the probable inflow hydrographs to the hydraulic modelling studies derived from the rainfall estimates described in Section 5.4.

5.3.1 FEH modelling to determine the annual probability of the 16th August event

As stated previously, there are no flow records for either the Valency River or its tributaries (the Boscastle catchment), nor for the Crackington Stream catchment. Thus flood estimates must be derived by using the ungauged site methods described in Chapter 2 of Volume 4 of the FEH. Catchment characteristics and rainfall descriptors for each of the required sub-catchments listed in Table 5.1 together with those for the entire Boscastle and Crackington catchments were abstracted from the FEH CD-ROM at the grid references specified in Table 5.1. From these catchment descriptors, all of the parameters required for derivation of the unit hydrograph, standard percentage runoff, baseflow and design rainfalls were exported.

These exported catchment descriptors were imported into a simple Microsoft Excel spreadsheet program to compute flood runoff using the methodology contained in

Volume 4 of the FEH. The details of this methodology is fully explained in Chapters 2 and 3 of Volume 4 of the FEH.

Within the standard FEH methodology, the design rainfall required to generate floods of specified Annual exceedence probability are given in Table 5.1, and extracts from this are reproduced in Table 5.4:

Table 5.4 FEH recommended storm exceedence probability to yield flood peak of required exceedence probability by design event method

Annual flood exceedence probability (%)	10	3.3	2	1	0.5	0.2	0.1
Annual rainfall exceedence probability (%)	5.88	2	1.23	0.714	0.417	0.192	0.1

Flood estimates for 1, 0.2 and 0.1% exceedence probability (100, 500 and 1000 years) were provided as input to the hydraulic modelling. The FEH methodology specifies the choice of design parameters for the calculation, and these are built into the spreadsheet methodology. It was decided, however, that it was more appropriate to adopt the slightly ‘peakier’ summer rainfall profile rather than the more normal winter profile.

The results of the analysis for the total Boscastle and Crackington catchments are presented in Table 5.5. The results for all of the required inflow points listed in Table 3.1 were provided for the hydraulic modelling, and are tabulated in Appendix 2.

Table 5.5 Results of FEH design case flood estimation exercise for Boscastle and Crackington Stream

Location	Flood Peaks (m^3/s) for specified annual exceedence probability (%)					
	2	1	0.5	0.2	0.1	0.02
Boscastle catchment	29.9	34.8	40.1	50.1	60.1	95.3
Crackington Stream catchment	24.7	28.9	33.5	42.1	50.1	81.7

The flow estimates derived using the FEH rainfall-runoff method are significantly higher than those derived using the statistical approach. This is probably due, in part, to a dearth of good quality ‘donor’ catchments having the sort of flood regime typical of north Cornwall and Devon catchments. In addition it also reflects the fact that rainfall growth curves in this part of the UK are steep, and possibly steeper than flood growth curves. The topic is discussed in the section on uncertainties.

5.4 SPATIAL RAINFALL ANALYSIS OF THE 16TH AUGUST 2004 STORM

The rainfall analyses undertaken have built upon the work that is presented in Chapter 4. For the hydrological studies the weather radar data was analysed to provide 15 minute rainfall estimates for each of the sub-catchments listed above. The HYRAD software was used to process the raw radar data to derive rainfall estimates for the specified sub-catchments.

The Boscastle and Crackington Stream catchments are covered by two weather radar systems, one at Cobbacombe Cross in north Devon, and the second at Predannack, at the tip of Cornwall, each of which is about 100 km from Boscastle. We have, therefore, produced two separate 2km grid rainfall estimates, one set derived using the Cobbacombe radar data, and a second set derived using the Predannack radar.

For the Boscastle catchment (Rivers Valency and Jordan), the rainfall totals derived from each radar are broadly similar, although both the spatial and temporal patterns show differences. For the Crackington Stream catchment, however, the Cobbacombe derived rainfall for the event is significantly lower than that using Predannack (see Figures 5.4(a) and 5.4(b)).

The accumulated rainfalls for each 2 km grid square using each of the two radars are shown on Figures 5.2(a) and 5.2(b). To clarify the figures, the total rainfall accumulation in mm for the event is shown for each grid square.

Although Cobbacombe recorded a slightly higher maximum storm accumulation than Predannack in the Valency catchment on Aug 20th, there is very little overall bias evident between the two sets of data. In the areas of common coverage at 2km resolution, Cobbacombe recorded 108 sq km with accumulations exceeding 64mm whereas Predannack recorded 132 sq km. Both Cobbacombe and Predannack radars recorded 9 pixels (36 sq km) with accumulations exceeding 96mm.

Comparison of the Cobbacombe and Predannack radar data suggests that the geo-location of the rainfall data was consistent to within the 2km data resolution. The best estimate by eye is that the rainfall recorded by Predannack is perhaps a few hundred metres North and/or West compared to the Cobbacombe data. Of the 9 pixels where Predannack recorded accumulations exceeding 96mm, 7 of these were common to pixels exceeding this threshold in the Cobbacombe data.

There is some evidence that the Predannack radar recorded significantly higher rainfall rates than Cobbacombe to the SW of Boscastle - around Tintagel. This is probably a manifestation of some attenuation of the Cobbacombe transmissions during passage through the heavy rainfall further to the East. The Predannack radar transmissions would not suffer this effect because the path-integrated rainfall to the SW of Tintagel would be much lower.

The 15 minute rainfalls and rainfall accumulations using both sets of radar data are shown on Figures 5.3(a) and 5.3(b) for the Valency and Jordan, and on Figures 5.4(a) and 5.4(b) for Crackington Stream.

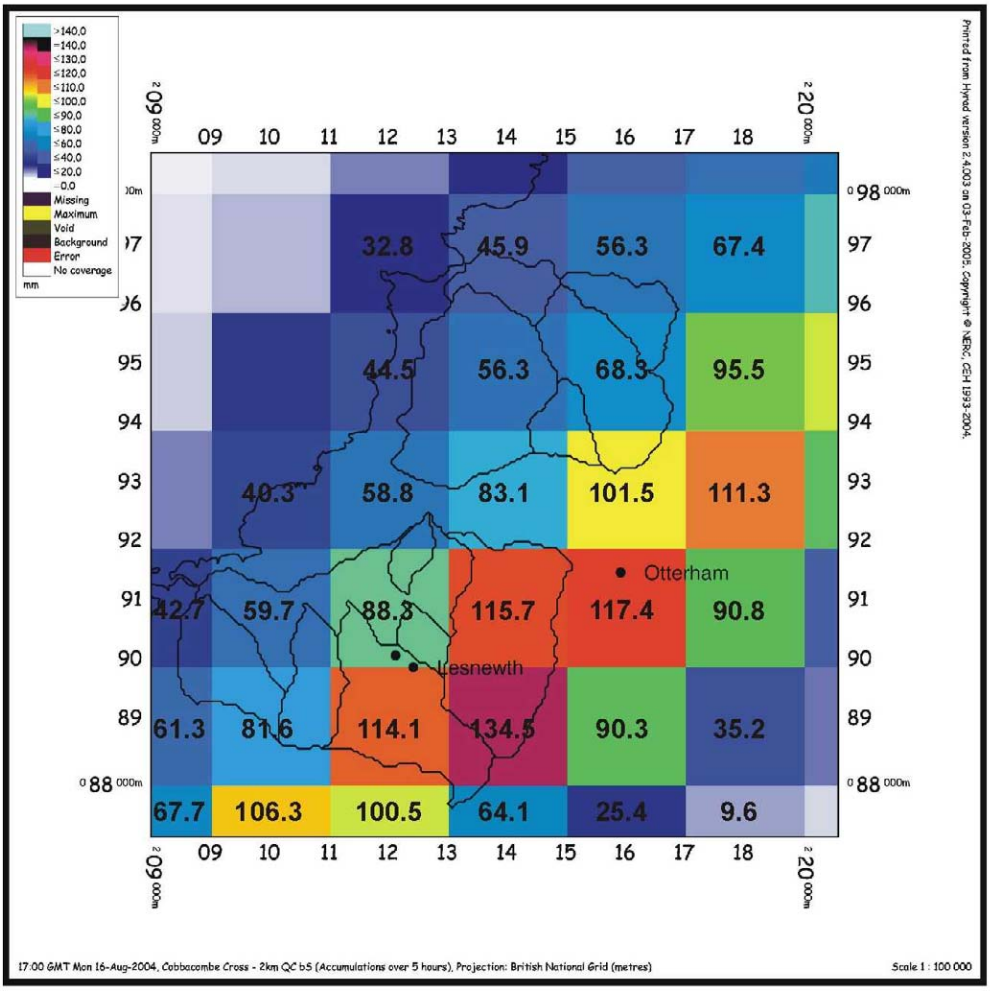


Figure 5.2(a) 2 km gridded rainfall estimates based on Cobbacombe Cross radar

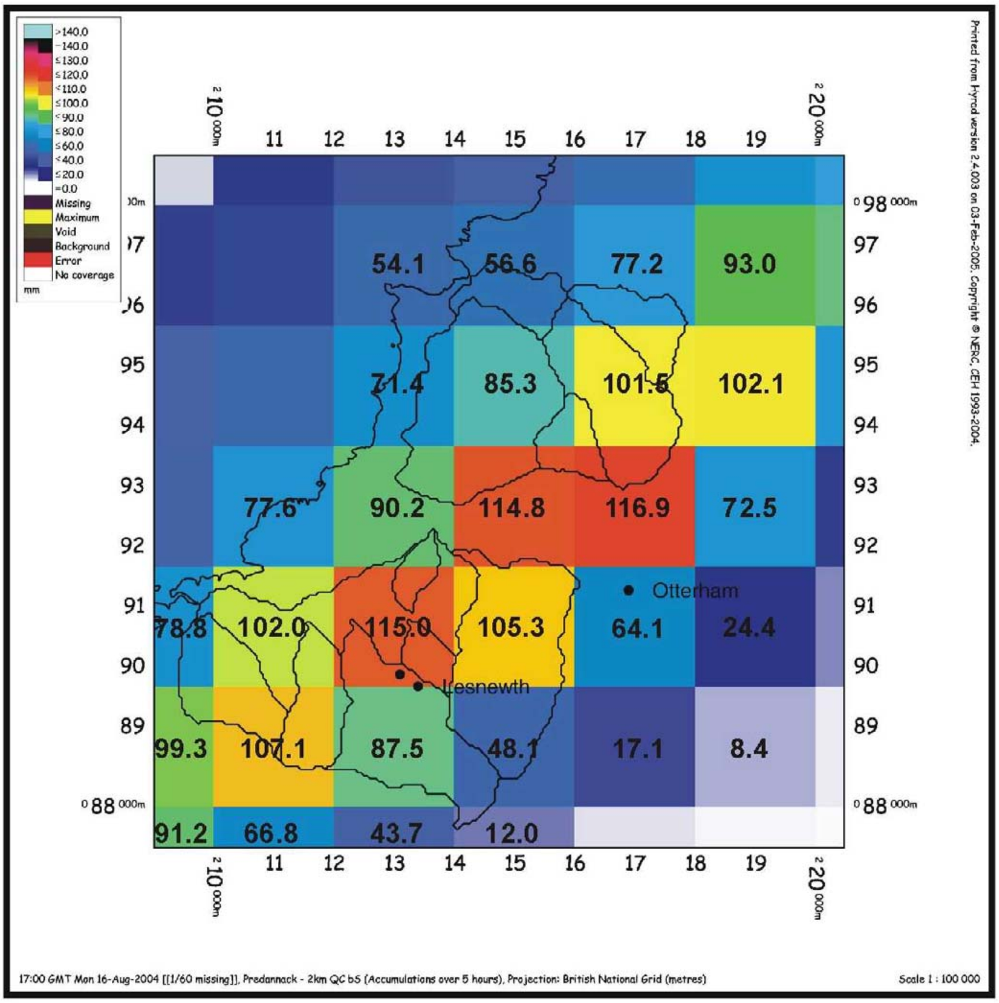


Figure 5.2(b) 2 km gridded rainfall estimates based on Predannack radar

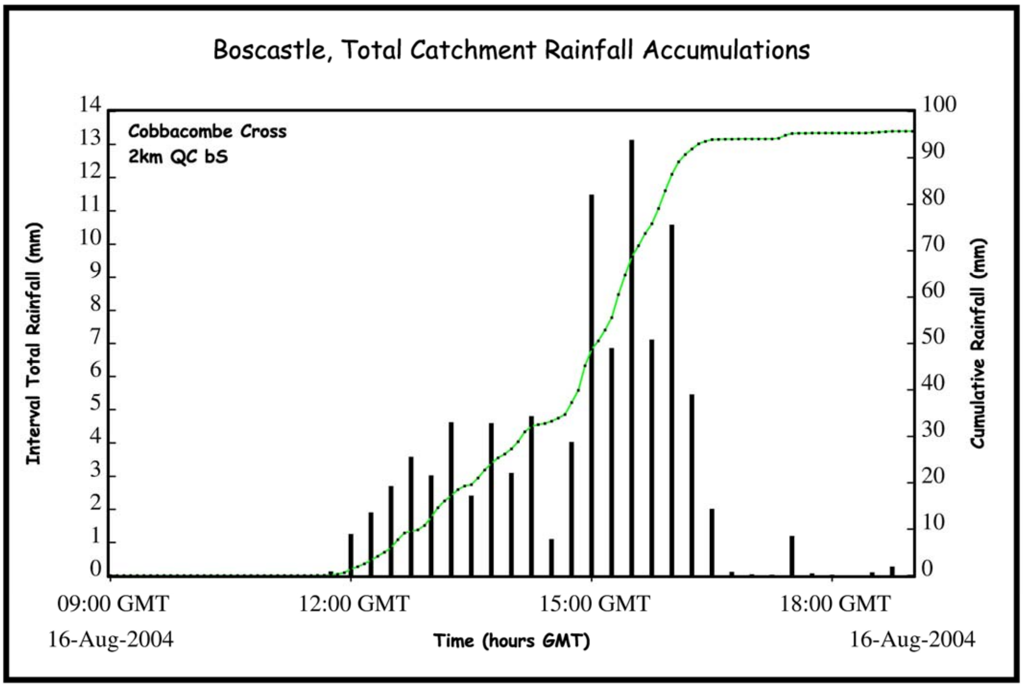


Figure 5.3(a) Cobbacombe rainfall over Valency/Jordan catchment

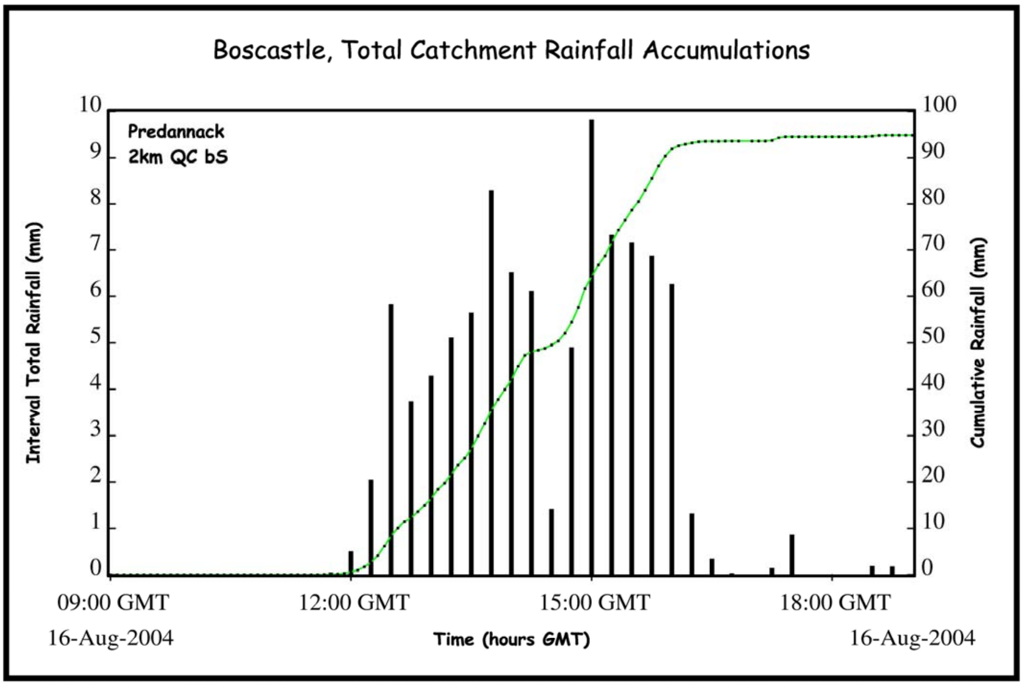


Figure 5.3(b) Predannack rainfall over Valency/Jordan catchment

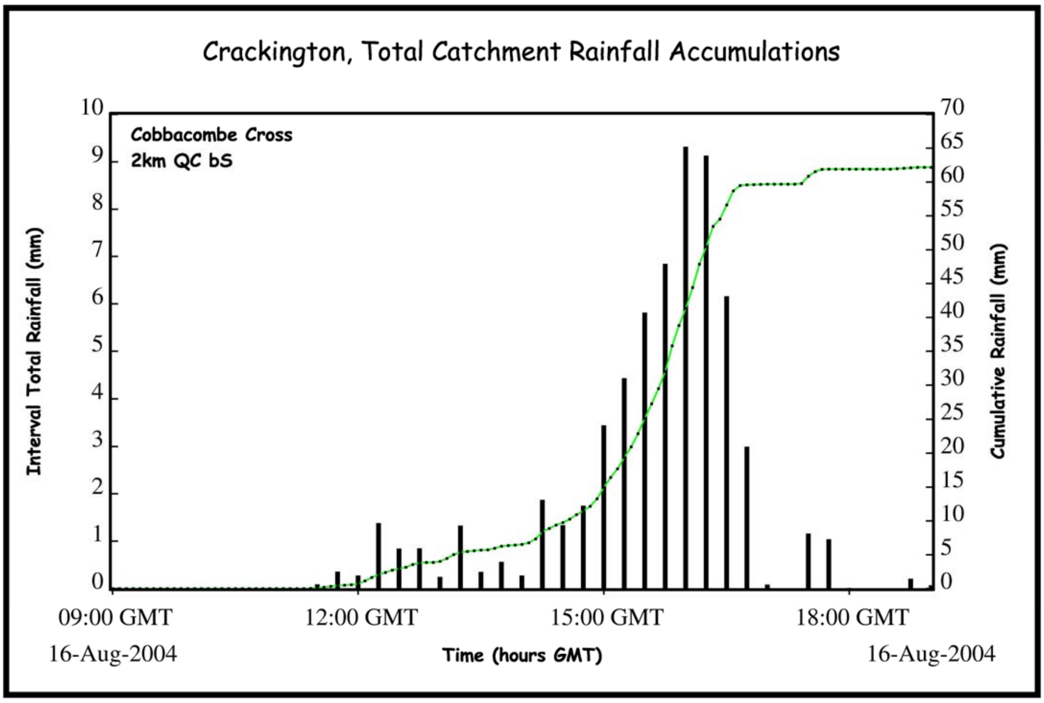


Figure 5.4(a) Cobbacombe rainfall over Crackington Stream catchment

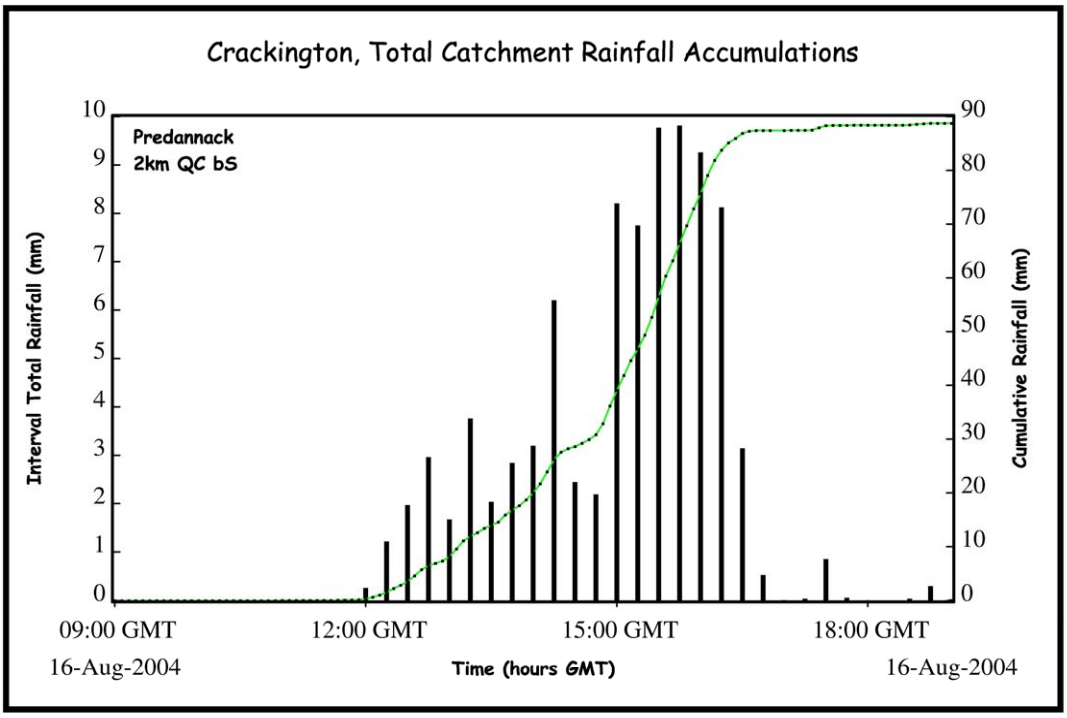


Figure 5.4(b) Predannack rainfall over Crackington Stream catchment

These rainfall accumulations can be compared against those from a range of recording raingauges located close to the storm centre for the 16th August event. This matter has been discussed in Section 4 of this report. For the hydrological analysis the most useful gauge is that at Lesnewth, situated within the headwaters of the Valency catchment. Figure 5.5 shows rainfall accumulations over time for a number of the tipping bucket gauges, and it is apparent that the Lesnewth gauge experienced much greater rainfall than any other gauge, which is consistent with the spatial rainfall information provided by the radar, as shown on Figures 5.2(a) and (b). Between 12:00 and 18:00 hrs GMT on 16th August, the Lesnewth gauge recorded 152.2 mm, but this must be compared with the 184.9 mm for the associated daily gauge. Whilst there was some rainfall at Lesnewth outside of the core storm period (12:00 to 18:00 GMT), almost all of the day's rainfall occurred during the core, and there is an argument for increasing the TBR record by 184.9/152.2, or by 21.5%, as shown on Figure 5.5.

No explicit attempt was made to correct the discrepancy between the Lesnewth TBR raingauge total of 153.6 mm and its associated check gauge total of 184.9, as the rainfall inputs used for rainfall-runoff modelling were derived from the Cobbacombe radar data. However, the radar estimates for each sub-catchment were believed to be rather low when compared to the Otterham and Lesnewth raingauge totals. Hence a series of simple rainfall factors (see Table 5.6) were used to increase the radar rainfall in an attempt to match the recorded rainfall totals better.

Table 5.6 Final parameters used in FEH modelling

Sub-catchment	Area (km^2)	Tp (hrs)	Rainfall Factor	Rainfall total (mm)*	Initial PR (%)	Final PR (%)**
1. Boscastle Catchment						
B1	2.4	0.81	1.4	89.1	52.0	93.6
B2	1.88	1.01	1.5	118.7	42.9	77.1
B3	4.47	1.40	1.35	150.5	46.3	83.3
B4	5.5	1.25	1.35	163.2	46.3	90.4
B5N1	0.58	0.82	1.35	103.6	40.1	72.1
B5S2	0.66	0.82	1.35	120.5	41.5	74.7
Whole Valency and Jordan catchment	20.02	1.64	1.35	129.3	44.7	80.5
2. Crackington Stream						
Sub-catchment						
C1	6.25	1.19	1.5	87.1	43.4	78.2
C2	6.35	1.19	1.5	104.2	45.5	81.9
Whole Crackington Stream catchment	13.88	1.35	1.5	93.3	44.0	79.3

* Rainfall total derived by applying rainfall factor to radar derived areal catchment rainfall
** Maximum final PR is that achieved at the end of the 16th August 2004 event

Figure 5.5 shows the rainfall accumulations for the TBR gauges and the Otterham collecting gauge. The figure shows that the TBRs recorded smaller rainfall accumulations than the collecting gauge. It also suggests that there are two families of curves which might indicate spatially distinct rainfall events.

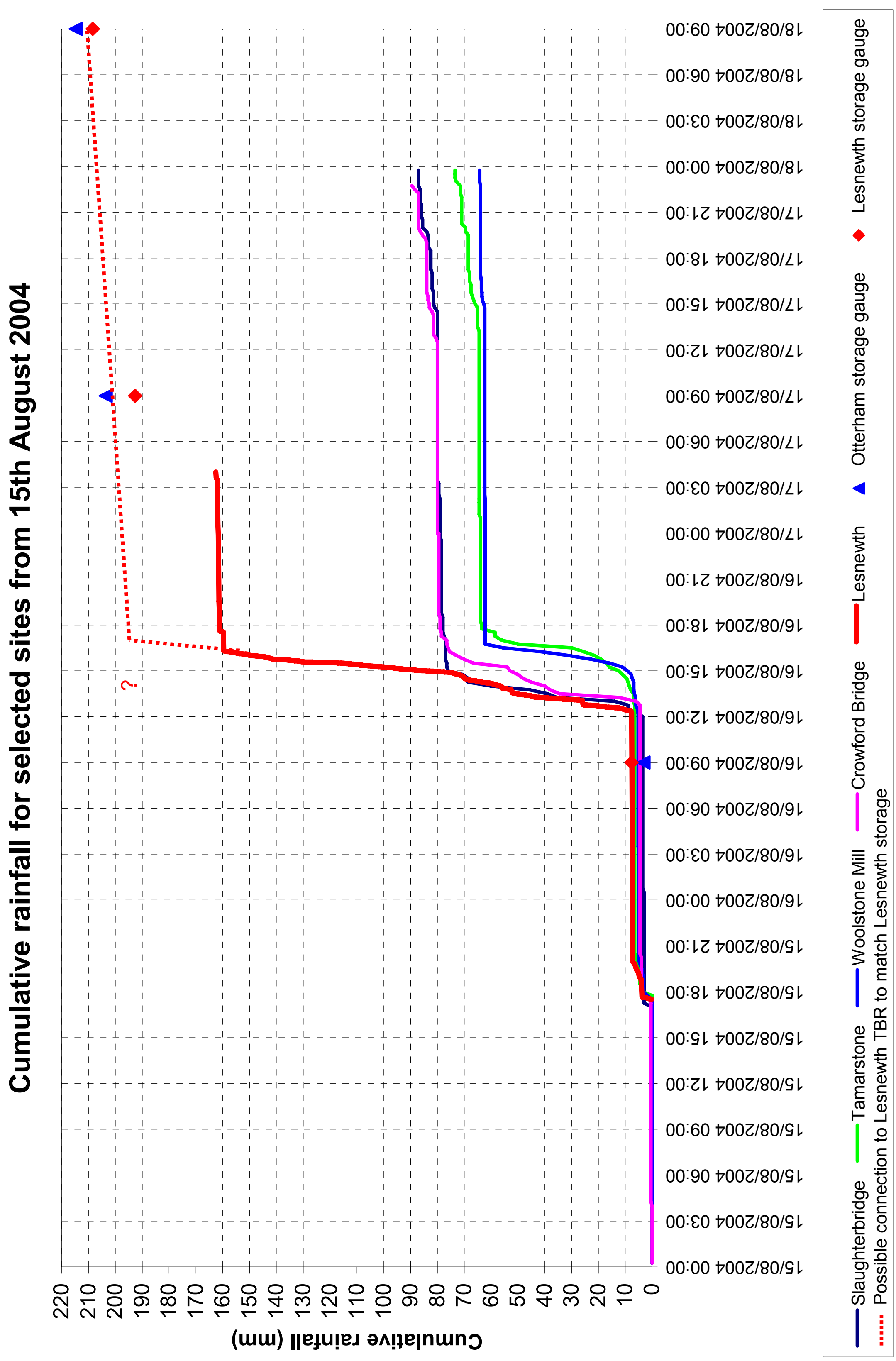


Figure 5.5 Rainfall accumulations at TBR gauges for 15th and 16th August

Figure 5.6 shows the hyetograph for the 1957 Camelford rainfall event in which the peak rainfall depth was comparable to the peak rainfall depth observed in the August 2004 event. This can be compared with Figure 5.2. It should be noted that the rainfall depths shown are derived in different ways. Figure 5.2 show average rainfall quantities over a 2km square grid so that each rainfall depth is the average rainfall over each grid square. Figure 5.6 shows contours of point rainfall depths. Comparison shows that the area of the two events was similar. Figure 5.7 shows the rainfall accumulation for the 1957 event. This can be compared with the data shown in Figure 5.3 for the August 2004 event. It can be seen that, in general, the most intense rainfall occurred later in the August 2004 event than in the 1957 event. This may have affected the hydrology of the event and the magnitude of the associated flood event. Due to the differences in location of the rainfall between the 1957 and the 2004 events, different catchments were affected. It would appear that in 1957 the flooding in Boscastle was not severe though other rivers were affected more by the 1957 event than that of August 2004.

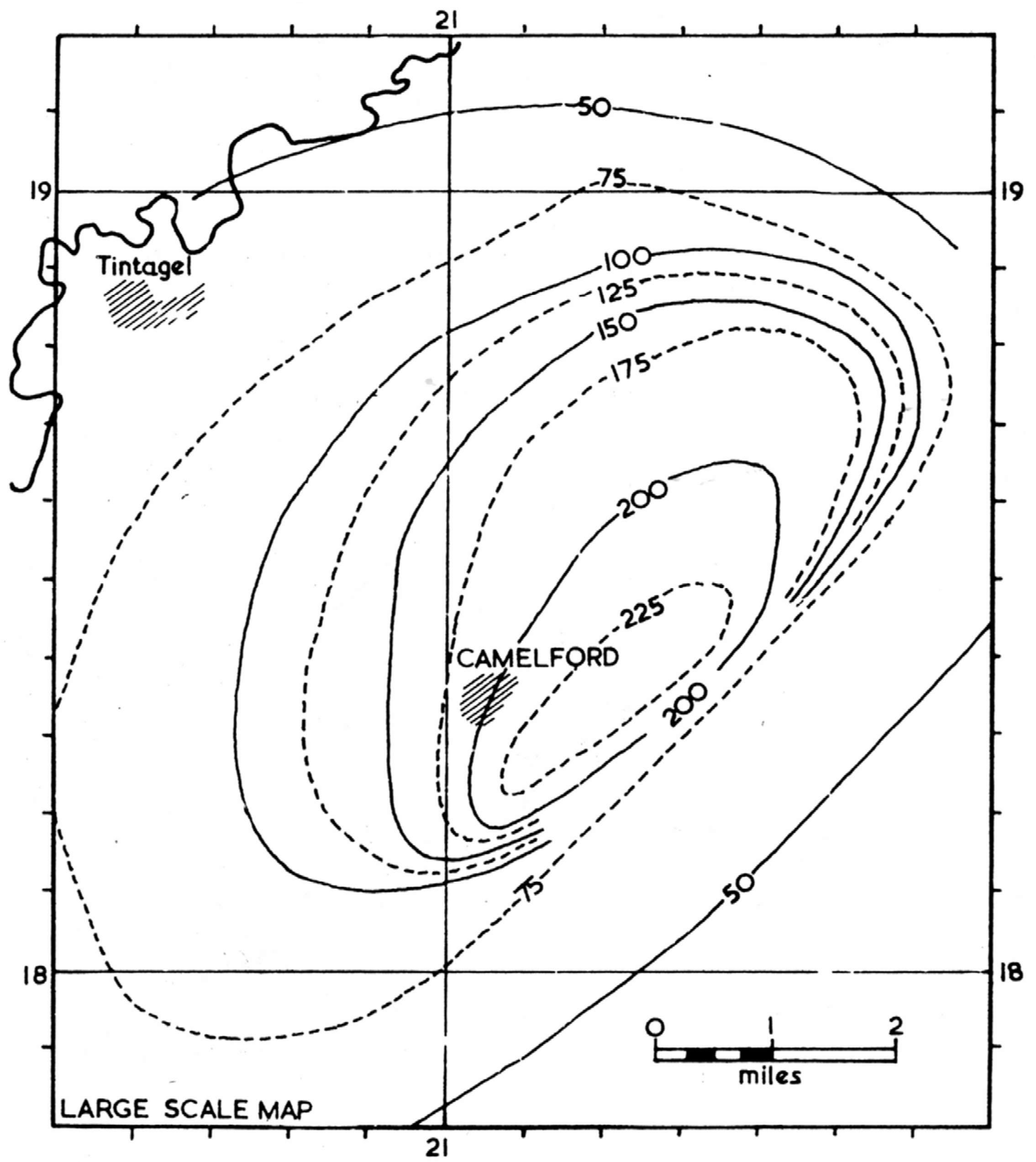


Figure 5.6 Rainfall for 1957 Camelford storm (after NERC, 1975)

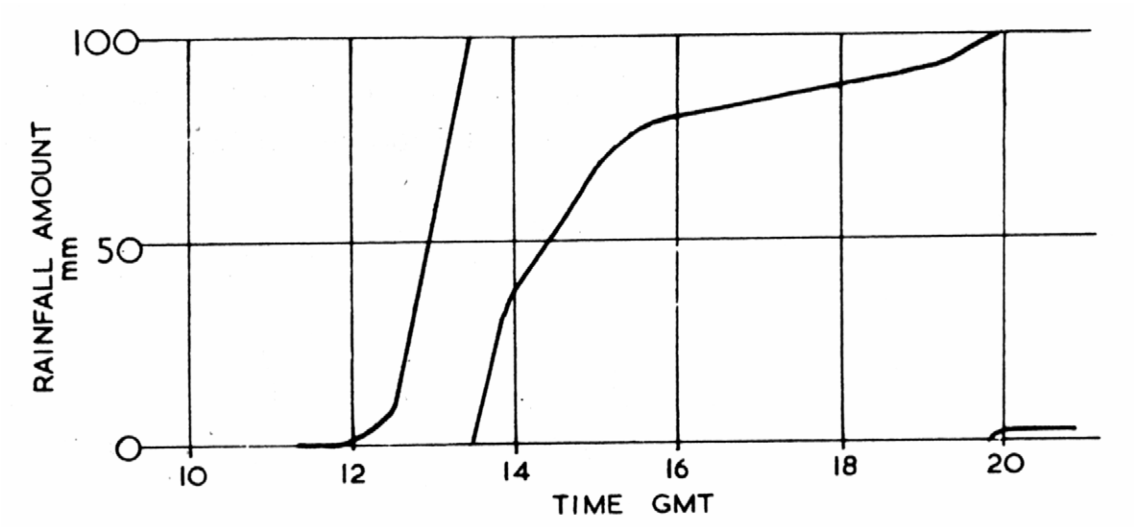


Figure 5.7 Rainfall accumulation for 1957 Camelford storm (after NERC, 1975)

The timing of the rainfall is the key factor driving flood response to the event, and a significant amount of time was devoted to considering this during the study. According to the eye-witness accounts of the time of the peak of the flood in the lower Valency at Boscastle seems to have occurred shortly after the time of the peak rainfall intensities. When comparing timings of rainfall and observed events it should be remembered that in general the rainfall data is expressed in GMT while the observations are often expressed in BST. The issue of timing of the flood at Boscastle is discussed in more detail later, but it is worth noting the timing of both the Lesnewth TBR rainfall, and the radar estimates. For the core storm period, the 15 minute rainfalls are shown on Figures 5.8(a) and 5.8(b), the first using sub-catchment rainfalls derived using the Cobbacombe radar, and the second derived using Predannack. It would appear that the Cobbacombe radar produces temporal rainfall patterns that are closer to the Lesnewth TBR trace, and hence it seems prudent to place greater credence in this rainfall series.

It can be seen from Figure 5.8(a) that for the upper Valency (sub-catchments B3, B4, B5N1 and B5S2), the heaviest rainfall occurred between 14:45 and 16:00 GMT, and the timing for the lower Valency (B2) was broadly similar, although intensities were lower. The Jordan catchment (B1), however, has a rather different time pattern, with the peak rainfall occurring during the period 15:45 and 16:15 GMT. The rainfall profile for the Lesnewth TBR gauge shows a similar time distribution, with the peak rainfall occurring at 14:45 and 16:15 GMT.

The temporal distribution of rainfall inputs to the rainfall-runoff modelling were derived from the radar data rather than from the single TBR record at Lesnewth. It is believed that the radar data provides a better estimate of the complex space and time variability of rainfall over the two catchments than can be derived from a single point value from the Lesnewth TBR record. However, Figures 5.8(a) and (b) show a reasonably good agreement between the time distribution of the radar data and that from Lesnewth TBR.

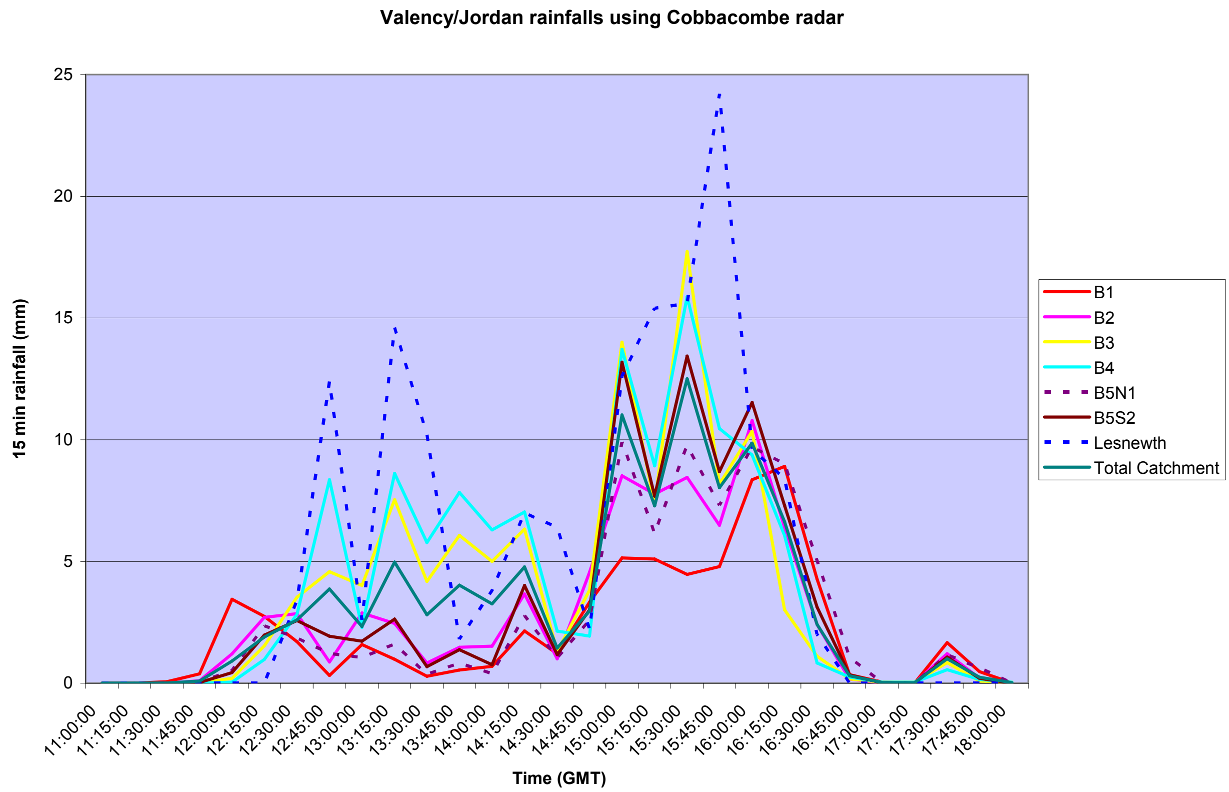


Figure 5.8(a) **Time distribution of Valency/Jordan rainfall on 16th August 2004 for various sub-catchments compared with Lesnewth TBR derived from Cobbacombe Cross radar**

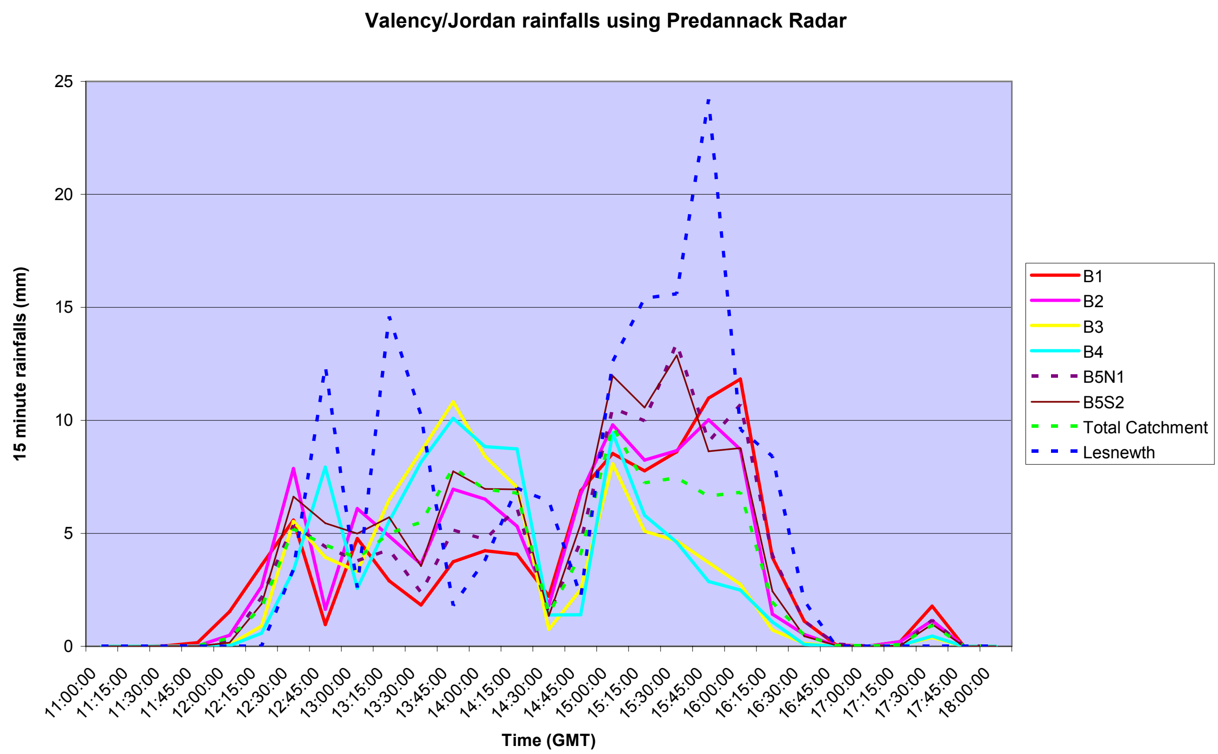


Figure 5.8(b) **Time distribution of Valency/Jordan rainfall on 16th August 2004 for various sub-catchments compared with Lesnewth TBR derived from Predannack radar**

5.5 HYDROLOGICAL MODELLING OF THE EVENT OF 16TH AUGUST 2004

5.5.1 Estimates based on basic FEH model parameters

The FEH rainfall-runoff modelling exercise described in Section 5.3 was repeated using the radar derived rainfall estimates produced using the HYRAD software, as described in Section 5.4. Flood estimates were made for all of the points listed in Table 5.1. Initially, two flood estimates are given, one using the Cobbacombe radar and the second using Predannack. Examination of peak flow rates and their timing suggested, however, that the Cobbacombe radar data was generally producing better estimates than the Predannack derived rainfall. In consequence, after the initial base run described below, only Cobbacombe derived rainfall has been used.

In Section 5.3.1, it was explained that unit hydrograph, percentage runoff rates and baseflow were derived from the FEH CD-ROM catchment descriptors. These ‘standard FEH’ model parameters were used to derive a set of ‘baseline’ flood estimates for each sub-catchment, using in this first case two rainfall series; that derived from the Cobbacombe Cross radar, and subsequently, that derived from Predannack. Results are given in Table 5.7

Table 5.7 Flood estimates derived using the 16th August 2004 radar rainfall estimates

Note all peaks occur on 16th August, and all times are GMT (= GMT)

Estimation point (Sub-catchment)	Flood estimates (m^3/s) and time of peak (GMT) derived from: Cobbacombe radar		Predannack radar	
	Peak flow	Time of Peak	Peak flow	Time of Peak
B1	7.70	17:00	7.65	17:00
B2	5.29	17:15	5.58	17:00
B3	10.75	18:00	9.37	16:45-17:00
B4	19.92	17:45	13.62	16:30-16:45
B5N1	1.52	17:15	1.97	17:00
B5S2	2.01	17:00	2.37	16:45
Whole Boscastle	41.12	18:45	40.01	18:30
C1	10.56	18:30	16.26	18:00
C2	13.65	18:15	18.68	17:45
Whole Crackington	23.17	18:45	33.78	18:15
C2A	3.60	17:45	4.85	17:30
C2B	3.55	17:30	4.09	16:45-17:00

5.5.2 Estimates based on modified parameters

Experience suggests that flood response from small, steep catchments such as the Valency, Jordan, Crackington and other tributaries is often more rapid than FEH predicts. In addition, observations of hydrograph response to the 16th August event for station 47005, the Ottery at Werrington Park, and 49001, the Camel at Denby showed very rapidly rising levels and flows in response to the event. In consequence, it seems that the catchment response derived using the FEH is not a realistic representation of the very short response times that seem to have occurred in this event.

The 1975 Flood Studies Report (FSR) (NERC, 1975) provides the best source of information on how flood response may change during notable events. In section 6.6.3 of Volume I of the FSR report, a number of significant historical flood events, including the 1952 Lynmouth flood, were studied to determine how effective standard FSR methods were in reproducing these notable past events. It should be noted that the current FEH methods are essentially the same as the 1975 methodology, with just one or two minor modifications.

The analysis suggested that the standard FSR rainfall-runoff approach consistently underestimated the flood peaks for all the historical notable events studied, and led to the recommendation that for reservoir spillway floods (i.e. the PMF), the unit hydrograph time to peak, Tp, be reduced by 33%. This 33% reduction was the average ratio of minimum observed Tp to mean Tp from all of the unit hydrograph catchments studied as part of the FSR analysis. It should be noted that this 33% reduction in Tp represents just over one standard error in the Tp prediction equation.

When the value of Tp is reduced, the overall time base of the unit hydrograph is reduced but the overall volume of the unit hydrograph remains the same. Thus the peak discharge of the unit hydrograph increases correspondingly.

It was felt that the FEH estimate of Tp should be reduced in an attempt to reproduce the 16^{th} August flood peaks better, and hence the analysis was repeated with FEH estimates of unit hydrograph time to peak, Tp, reduced by 33%. This reduction in Tp improved the reproduction of the 16^{th} August event, but estimated peak flows were still significantly lower than those required to reproduce observed levels during the event. Consequently, two further adjustments were introduced into the rainfall-runoff modelling exercise in an attempt to reproduce flood peaks more accurately.

The first adjustment was the introduction of a rainfall correction factor (RF), such that the sub-catchment radar derived rainfalls could be adjusted to fit better against the raingauge values. This rainfall factor simply scales the radar derived sub-catchment 15 minute rainfall values by a constant proportion.

The second adjustment was the replacement of the FEH constant percentage runoff (PR) with a time varying PR related to antecedent conditions. Thus the FEH predicted PR was used at the start of the storm, but percentage runoff was increased during the storm to reflect the wetting up of soil and increasing contributing area of the catchment. The percentage runoff was increased during the storm using the relationship:

$$PR_t = PR_{urb} * (1 + 0.8(\sum P_t/P_{TOTAL}))$$

where PR_t is the percentage runoff at time t during the storm, PR_{urb} is the FEH design percentage runoff derived from soil and storm rainfall total, $\sum P_t$ is cumulative rainfall from the start of the storm to time t, and P_{TOTAL} is the rainfall total for the entire storm. The factor of 0.8 was determined empirically in order to generate the necessary gearing factor to increase PR_{urb} from the FEH initial condition (42% for sub-catchments B5N1 and B5S2 to 49% for sub-catchment B4) to the 85 to 95% values that probably prevailed towards the end of the storm.

The rainfall-runoff model was re-run using a rainfall factor of 1.3, Tp reduced by 33%, and with an increasing percentage runoff throughout the event. The rainfall factor of 1.3 was chosen from comparison on the 2 km gridded rainfalls from Figures 5.2(a) and 5.2(b) with the Otterham and Lesnewth raingauge values. Results are shown in Table 5.8, where the marked difference between estimated flows on the Crackington Stream catchment between Cobbacombe and Predannack derived rainfalls is apparent. For the Valency and Jordan catchments, there is generally good agreement between the two sets of results, apart from on sub-catchment B4, where the Predannack rainfalls appear too low. This result seems to be a result of the differences in spatial positioning of the storm centres between the two separate radars. Referring back to Figures 5.2(a) and 5.2(b), it is apparent that, in general, the Predannack rainfall pattern has moved northwards one 2km grid square in comparison with the Cobbacombe data. Thus the maximum intensity rainfall derived from the Cobbacombe radar is located over the Otterham raingauge, whereas this cell has been located one grid square north by the Predannack radar. This apparent mislocation of the storm centre is one of the main reasons for disregarding the Predannack radar for future model runs. All subsequent modelling has been based solely upon Cobbacombe Cross radar products.

Table 5.8 Flood estimates derived using the 16th August 2004 radar rainfall estimates (Tp reduced by 33%, RF=1.3 and increasing PR throughout event)

N*ote all peaks occur on 16th August, and all times are GMT (= GMT)*

Estimation point (Sub-catchment)	Flood estimates (m^3/s) and time of peak derived from:			
	Cobbacombe radar		Predannack radar	
	Peak flow	Time of Peak	Peak flow	Time of Peak
B1	12.31	17:00	19.69	16:45
B2	13.48	17:00	13.55	16:45
B3	27.19	17:15	22.13	16:30
B4	49.31	17:00	31.50	16:00
B5N1	3.87	17:00	4.99	16:45
B5S2	5.09	16:45	5.92	16:30
Whole Boscastle	107.3	17:45	101.37	18:15
C1	27.50	17:45	41.92	17:45
C2	35.93	17:30	46.50	17:30
Whole Crackington	61.61	18:00	86.74	18:00
C2A	9.30	17:15	12.36	17:00
C2B	8.66	17:00	10.05	16:45

These hydrographs were used in the hydraulic model, but it was felt that the Valency and Jordan flows were still too low. Consequently, the runs were repeated with an even more extreme Tp adjustment to 50% of the FEH Tp estimates, and with a variable rainfall adjustment factor, RF. For sub-catchment B1 (the Jordan River) an RF value of 1.4 was applied, for B2, RF of 1.5 was used, and for all other sub-catchments, and RF of 1.35 was applied.

The reduction of the Tp value to 50% of the FEH Tp estimates was considered to be extreme. This reduction already exceeds that used when estimating Probable maximum Floods. A further reduction in Tp value would have led to larger peak discharges in the hydrographs but was not considered to be justifiable.

Table 5.9 Valency and Jordan flood estimates resulting from 16th August 2004 rainfall (Tp reduced by 50%, Variable RF, and increasing PR throughout event)

Note all peaks occur on 16th August, and all times are GMT (= GMT)

Estimation point (Sub-catchment)	Cobbacombe radar Peak flow	Time of Peak
B1	18.86	17:00
B2	15.09	16:45
B3	39.31	17:00
B4	58.62	16:45
B5N1	4.42	16:45
B5S2	6.19	16:30
Whole Boscastle	130.27	17:15

The flow estimates given in Table 5.9 are the best estimates using the methods applied of the likely flows that occurred from the subcatchments of the Valency and Jordan catchments during the 16th August 2004 event. The 15 minute flow values are listed in Appendix 3 and the hydrographs are shown on Figure 5.7. Despite the best efforts in the modelling, however, the predicted time of the peak is still later than that observed. It was considered that any further reduction in Tp in the unit hydrograph, which would have advanced the timing of the model results was not justifiable.

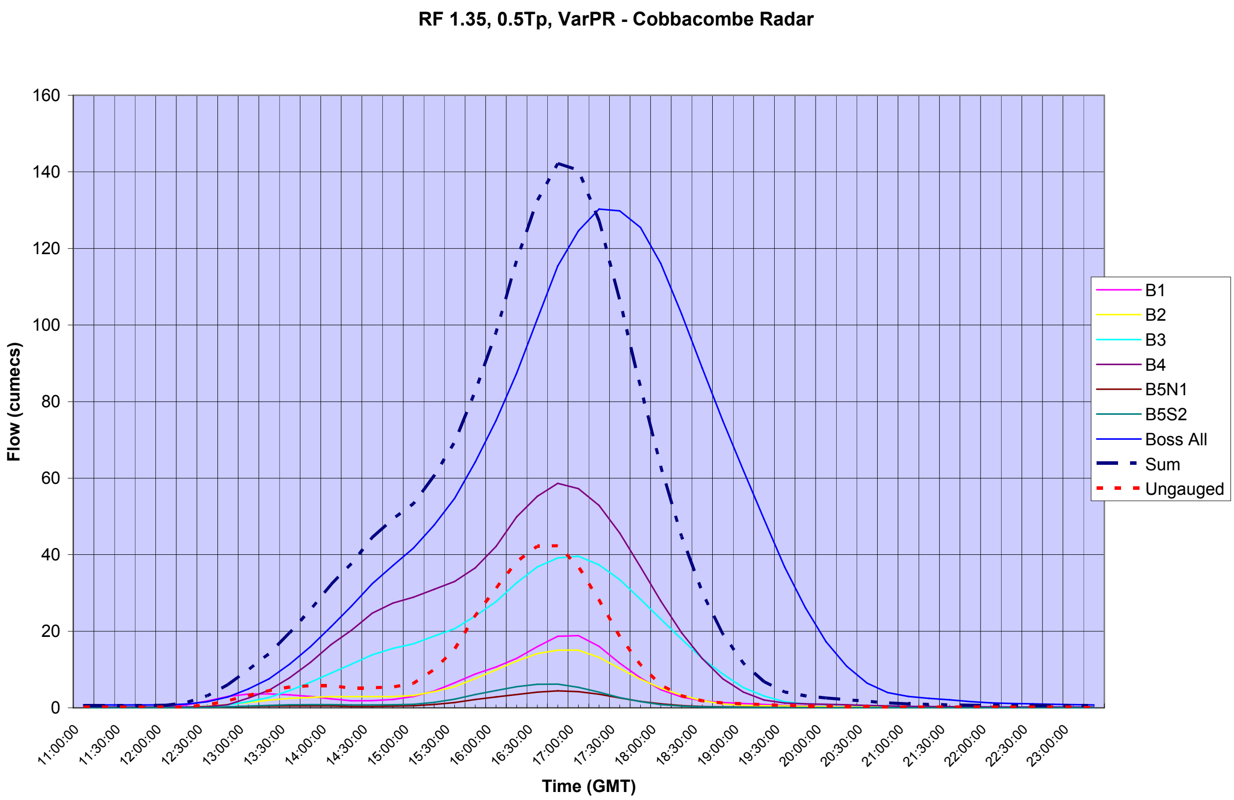


Figure 5.9 Best estimate of flows on 16th August 2004 for the Valency and Jordan

For the Crackington Stream catchment, a fixed RF factor of 1.5 was applied to the Cobbacombe derived rainfall estimates. This may be rather conservative, as it merely brings the rainfalls up to close to the Predannack derived rainfalls. The resultant flows look reasonable, however, when used in the hydraulic model and appear to reproduce observed levels reasonably well.

There is little or no hard evidence of the timing of the flood peak for Crackington Stream, so no discussion of the validity of timings is offered here.

Table 5.10 Crackington Stream estimates resulting from 16th August 2004 rainfall (Tp reduced by 50%, RF=1.5, and increasing PR throughout event)

Note all peaks occur on 16th August, and all times are GMT (= GMT)

Estimation point (Sub-catchment)	Cobbacombe radar Peak flow	Time of Peak
C1	37.80	17:00
C2	50.24	16:45
C2A	12.60	16:30
C2B	11.28	16:15
Whole Crackington	85.66	18:00

5.5.3 Discussion

One of the key outputs from the hydrological studies presented above has been derivation of a series of inflow hydrographs for the hydraulic modelling studies. Results were provided for a range of annual exceedence probabilities derived using FEH methods.

Of primary interest, however, were the estimated hydrographs derived using our current best estimates of catchment rainfalls during the 16th August 2004 event, using both the standard FEH estimate of Tp, and also estimates derived using modified FEH model parameters. A number of adjustments had to be made to standard FEH parameter values in order to achieve acceptable reproduction of the flood event, in terms of both its magnitude and timing. In some cases these adjustments were very significant indeed. For example, it was necessary to use a unit hydrograph time to peak parameter, Tp, reduced initially by 33 %, which is the recommendation for probable maximum flood estimates. However, the peak was ultimately reduced by 50% in order to derive peaks that got close to approaching the eye-witness statements that the Valency flows peaked at between 17:00 and 17:15 BST (16:00 to 16:15 GMT). Peak times shown in Table 5.9 show that the hydrological model consistently produces peaks significantly later than 16:00 GMT (17:00 BST),which is approximately the time of the peak in Boscastle as related by eye-witnesses, and there is no way of achieving a better fit as far as time of peak is concerned. The problem is that the radar derived rainfall estimates, either those derived from Cobbacombe or Predannack, clearly indicate heavy rainfall over the upper Valency catchment (sub-catchments B3 and B4) between 15:30 and 16:15 GMT, and sub-catchment B5S2, from which the undesignated lateral inflows are derived, received 30 mm of rain in the hour 15:30 to 16:30 GMT. Reconciling these late afternoon rainfalls over the upper catchment with the eye-witness claims of a 16:00 GMT (17:00 BST) peak level in the lower Valency is very difficult, and no further reduction in Tp can resolve this inconsistency.

The timing of the radar derived data agrees well with the Lesnewth TBR record, and, in fact, tends to precede it by 15 minutes at the peak, so we must have confidence in the timing of the rainfall. At the peak of the storm, the catchment was certainly saturated, and overland flow was widespread, as evidenced from post event photographs of flattened grass. Thus, the response to rainfall would certainly have been very rapid towards the end of the storm, nevertheless, rainfall takes a finite time to travel overland into a river channel and then further time for translation to the lower catchment.

The peak discharge was observed just over 30 minutes after the observed heavy rainfall in the upper catchment but this time does not seem to be long enough for the impact of the heavy rain to have reached Boscastle. The short time delay between the time of the intense rainfall and the time of the peak discharge in Boscastle remains one of the unresolved issues of the study.

5.6 HISTORICAL EVIDENCE

5.6.1 Introduction

This section collates the flood history compiled by Halcrow, CEH and evidence collected by HR Wallingford. The main sources of information were the Met Office archives, regional newspapers, the National River Flow Archive, Environment Agency rainfall archives, the BHS Chronology of Flood Events and other internet sources such as “WeatherOnline” and “Wiseweather.”

The summary includes some notable events from other parts of Devon and Cornwall. The North Cornwall coast is vulnerable to intense local summer storms, and, therefore, events that have occurred in other towns, such as Camelford and Wadebridge, do not indicate that there was flooding in the Valency or Jordan catchments. These events are of interest, however, and indicate the vulnerability of other catchments in the area to extreme summer rainfall events.

The flood history is summarised in Table 5.12. This has the following columns:-

- Date. Indicating the date of the flood according to newspaper reports
- Location. The Valency, Jordan, other nearby catchments.
- Rainfall. Twenty-four hour rainfall accumulation based on newspaper reports, meteorological reviews or a contemporary rain gauge record. Due to the local nature of summer rainfall, the point rainfall records do not provide appropriate information to estimate catchment accumulations. Further information on rainfall data is provided in Appendix 4
- Rank. The top 4 events on the Valency (inc. 2004) were ranked. There was insufficient evidence to rank several events (indicated by a X) and events in other catchment were not applicable (n/a).
- Level. An estimate of level is provided based on photos (Appendix 4) or the properties flooded.
- Flow. An estimate of flow was made using the ISIS hydraulic model. assuming the same river and floodplain geometry as in 2004.
- Properties flooded. A list of properties affected was collated from newspaper reports.
- Notes. Descriptions of events are provided from newspaper evidence and further comments are provided.

Further information is provided in Appendix4 (photos, rainfall data, newspaper reports).

5.6.2 Discussion

The flood history shows that Boscastle suffered an extreme flood in 1958 that caused extensive damage and loss of life. Other notable floods occurred in 1824, 1950 and 1963 and more local flooding occurred on the Jordan, affecting the Wellington Hotel, in 1968, 1981, 1987 and 1992. Some of the events on the Jordan appear to be associated with blockages to the adjacent culvert. and so are related to the combined probability of the hydrological event and blockage. The sensitivity of water levels to culvert and bridge blockages makes it difficult to estimate flows from anecdotal evidence on properties flooded. There is sketchy evidence on further floods in the historical records in 1770, 1780, 1797, 1847 and 1894 based on either well documented flooding elsewhere, such as Lynmouth in 1770, or entries in local archives. The catchment may have flooded in 1979 when the whole of Cornwall was affected by heavy rain but there are no local records of damage related to this event. Most of the events occurred in the summer months.

The August 2004 flooding was clearly the most severe event in at least 200 years. There is sufficient historical evidence to rank three events, 1958, 1963 and 1950 below the August 2004 flood. The levels for these events were estimated from photos and descriptions of the event (Table 5.11). The flows were estimated from level as approximately 90, 45 and 40 cumecs for the 1958, 1963 and 1950 events.

Table 5.11 Conversion of historical event levels into flows

Year	Rank	Evidence	Flow	Assumptions
1958	2	Level on bridge indicates of flow of ca. 90 cumecs. Extensive damage and descriptions of a 4.5 m wave of water. Loss of one life.	90	1958 conditions were hydraulically similar to existing conditions.
1963	4=	The two properties flooded are affected by flooding through the car-park from the Valency or by overland flow when the culvert below the Wellington Hotel is blocked. If the flooding was from the Valency peak flows would need to be ca. 60 cumecs. If this was the case there would have been more widespread damage. So this event is interpreted as a Jordan flood plus bankfull on Valency.	40	Cross-section and floodplain geometry as in 2004.
1950	4=	Photographic evidence shows flooding at the lower bridge in Boscastle. This indicates a flow of the order of 30 cumecs in the Valency. The descriptions suggest that there might have been flooding on the Jordan with water ponding in the Garage area and minor flooding on Valency. From my reading of the account the only reason for flooding on the Valency was that the lower bridge was blocked by trash.	40	Cross-section and floodplain geometry as in 2004.

Table 5.12 History of flooding at Boscastle

Date	Location	Rainfall Depth (24 hours)	Flood Magnitude Rank	Level	Flow	Properties flooded in Boscastle	Notes
Aug 1770	Lynmouth	N/a	N/a	N/a	N/a	Unknown	A precursor of the Lynmouth disaster of August 1952 (there is some evidence – e.g. the size of boulders moved in the two events – that the 1770 flood was of a higher magnitude). Spatial extent of the storm that caused the flood is not known but Boscastle may have been affected (Marsh, pers. comm.)
1797	?	?	×	×	×	Unknown	Mention of but no record. Information from Colin Clark
1780?	?	?	×	×	×	Unknown	Information from Halcrows
1824	Valency	?	×	×	×	Unknown	Information from the Boscastle archive.
8 July 1847	Camelford	Unknown	N/a	N/a	N/a	No flood?	No flood in Boscastle (Colin Clark, pers. comm.) Storm generated severe flooding in, and beyond, the Camel catchments – storm focus was believed to be Davidstow Moor. Many bridges were destroyed as a 'wall of water from 12 to 18 feet above the usual level swept down the River Camel'high. (Marsh, pers. comm.)
June 1932	Camelford	>125 mm (Dartmoor)	N/a	N/a	N/a	Unknown	Camelford. Observations that the river levels were high, almost at bankfull. Heavy rain in Callington on the 16th July 1932. (Source: East Cornwall Times) Flooding in Camelford. High flows likely on the Valency but limited rainfall intensity may have made for only a moderate peak (Marsh, pers. comm.)
1894	Unknown	N/a	N/a	N/a	N/a	Unknown	Information from Halcrows
30th August 1950	Valency	Unknown	4	Out of bank at	40 cumecs	Mr Beadon's house	"Torrential rain considered to be the heaviest in living memory". "remarkable sight…were the trees which the River Valency had

Date	Location	Rainfall Depth (24 hours)	Flood Magnitude Rank	Level	Flow	Properties flooded in Boscastle	Notes
				lower bridge in Boscastle		Mr N Webber's garage	uprooted from its banks in flooding further up the valley…they passed under the first bridge at the Harbour approach, but owing to the new sewage pipe-line at the second bridge, they piled up and blocked the bridge…water…was soon up to the roadway rendering it impassable." (source newspaper) "There was extensive damage at Boscastle where the River Valency overflowed its banks near the harbour. Whole trees were washed down by the flood, and a mass of debris jammed across the lower of Boscastle's two bridges pled up so that the flood water could not pass under it. The road on each side of the river was badly torn up." (Source Cornish Guardian 07/09/1950)
15th and 16th August 1952	Lynmouth	228 mm (Longstone Barrow) 93 mm (Bude)	N/a	N/a	N/a	None	Lynmouth, Devon. 229.5mm in 24 hours (internet). No rainfall event details in the Newspapers, which concentrated on the deaths and damage caused by the floods. River Torridge had the worst flood for 40 years. 9am on the 15th to 9am on the 16th of August 3.42 inches of rainfall fell. Measured at Jennets Reservoir Bideford. Source: Bideford and North Devon Gazette.
8th June 1957	Camelford, 1957	180 mm (Camelford) 24 mm (Bude)	N/a	N/a	N/a	None	Rainfall at Bude was only 24 mm so, like Boscastle in 2004, this was a very local event. Camelford, Cornwall. 203.2mm in 24 hours (internet). Rainfall of 7.06 inches in 12 hours from 9am to 9pm on the 8th. Earlier in the year it had taken 3 months to get 18.8 inches of rain. Camelford was flooded by the river Camel. 9am to 1pm 0.25 inches, 1pm to 4pm 5.5 inches, 4pm to 7pm 0.7

Date	Location	Rainfall Depth (24 hours)	Flood Magnitude: Rank	Flood Magnitude: Level	Flood Magnitude: Flow	Properties flooded in Boscastle	Notes
							inches, and 7pm to 9pm 0.6 inches. In 1938 Buttermere had 7.14 inches and in 1952 Longstone Barrow had 9 inches of rainfall in a similar time period. The record rainfall is Martinstown, Dorchester, which had 11 inches in 6 hours on the 18/07/1955. (Source: Cornish Guardian) Three 'very rare' rainfall events were observed in the Camelford area on the 8th of June 1958 and caused serious flooding. More detail in 'Heavy rainfall at Camelford, August 8, 1958' in *Meteorological Magazine*, Vol. **86**, pp. 339-343. There was also a heavy thunderstorm in Devonshire on the 18th of June 1957 which was classified as 'noteworthy' and caused Stokeinteignhead to flood to a depth of 4 ft and Teignmouth to flood to 2 ft.
Tuesday 3rd June 1958 (Evening) Also further flooding on 8th June	Valency	41 mm (Bude)	2	HR Wallingford	90	Mr Webber's garage (cars "submerged up to their radiators") and gift shop. Cars "swept across the floor". Mr S Burnard's general store near the bridge Mrs Beadon's nearby guesthouse and café ("river ran right through the	"A cloudburst on the high ground inland…roused the normally quiet little stream…into a roaring and raging torrent, smashing its way out of its normal bounds and doing much damage". "The…Valency rose many feet in a very short time, estimates putting it 15ft [4.5m] above its normal level". "The bridge which carries the road from Tintagel to Bude was partially destroyed, and the road completely closed to traffic, for not only was there flood water but also piles of debris blocking it". One man drowned after being "swept off his feet". "The whole of the lower part of Boscastle was in chaos afterwards and people said they had never seen such a flood in their lives". "There had been thunder and heavy rain at Boscastle in the

Date	Location	Rainfall Depth (24 hours)	Flood Magnitude Rank	Level	Flow	Properties flooded in Boscastle	Notes
						premises in at one side and out the other")	afternoon, but nothing like sufficient to cause such flooding as came down the Valency Valley. The water could be heard roaring through from a considerable distance before it reached Boscastle". "The road was torn up by the water and was completely blocked. There were piles of debris everywhere, as well as tables, chairs, pots and pans…The water rose at enormous speed, and it reached a tremendous volume". "It is thought that the water rose as much as 15ft [4.5m] in some 20 minutes".
						Island Cottages (Mr and Mrs Scott and Mrs Briscombe) ("flood water filled the lower rooms and the occupants were forced to take refuge in the bedrooms")	Mr Frederick aged 64, "This is the fourth serious flooding I have seen here in my lifetime and it is by far the worst."
						Mr Good's antique shop.	"The flooding was not widespread. There was some in Wadebridge, yet at Tintagel, practically next door to Boscastle there was little rain."
						"Many houses were coated in mud and slime as the water receded, their ground floor interiors a shambles"	Damages estimated at "many thousands of pounds".
							"20ft [6m] gap in the parapet of the ancient stone bridge across the river. Alongside a huge gash in the road 10ft deep [3m]".
							Evidence from the "time capsule" recovered from the Harbour Lights shop that was destroyed in the 2004 flood suggests a flood depth of 4 feet within the property. (Note that there was a step downwards into the property so this does not mean flood levels were 4 feet above ground level).
						Pixie Shop ("Mr. Webber's pixie shop was right in the path of the torrent. It swept through up-ending a large ice-cream refrigerator and a solid oak	"A torrent of water, presumably collected from a cloudburst in the Otterham district – there was no rain in Boscastle all day – rushed down the river course carrying with it trees, pieces of wooden bridges from further upstream, and all kinds of debris. The water rose 12 to 15 feet in a matter of seconds, and hit the solid stone

Date	Location	Rainfall Depth (24 hours)	Flood Magnitude: Rank	Flood Magnitude: Level	Flood Magnitude: Flow	Properties flooded in Boscastle	Notes
						counter.”	bridge with the force of a battering ram.”
						Riverside Cottages (“In some of the riverside cottages it was pouring in through the back doors and out through the front windows”).	“He saw part of the stone parapet of the bridge disappear and a raging torrent pour over the road inundating shops and houses. The force of the water not only broke down the massive parapet and lifted a huge piece of it yards into the middle of the road.” (source newspapers)
9 February 1963	Valency	23 mm (Bude) Snowmelt	3	~	60	Mr S Burnard’s grocery shop Mr F Turner’s garage.	“The combination of melting snow and torrential rainfall brought flooding to Boscastle” (source newspapers)
14th June 1965	Wadebridge	Unknown 30 mm (Bude)	N/a	N/a	N/a	Unknown	Wadebridge, Cornwall. 140mm in 220mins (internet). River Tavy flooded, heavy rain. Not as much rainfall as the event on the 17th July 1890 which affected the whole of Dartmoor, rivers Coswic, Walkham and Tavy. Source: East Cornwall Times.
1966	Valency?	Unknown 31 mm (Bude)	×	×	×	Unknown	Evidence from Cornwall River Authority letter
1968	Jordan	Unknown 30 mm (Bude)	×	×	>5	Major Flooding of the Wellington Hotel.	Major flooding occurred in which boulders were washed into the culvert. Substantial damage was caused at the Wellington Hotel as flood waters flowed through the split level Hotel, entering the ground floor and exiting the first floor.

			Flood Magnitude				
Date	**Location**	**Rainfall Depth (24 hours)**	**Rank**	**Level**	**Flow**	**Properties flooded in Boscastle**	**Notes**
December 1979	South West	62 mm (Bideford) 44 mm (Otterham)	N/a	N/a	N/a	Unknown	Widespread severe flooding in the South-West following abundant frontal rainfall) (Marsh, pers. comm.) 25^{th} to 27^{th} Truro, Cornwall. 3.5 inches of rainfall fell in 48 hours in West Cornwall. The Red River flooded Truro, Camborne and Brea. Considered worst flood for 20 years. (Source: The West Briton) 27^{th} to 28^{th} Kenwith Valley, Torridge and Bideford. Rainfall of 41mm (1.62 inches) on the 26^{th} December 1979 and 45mm (1.78 inches) on 27^{th} December 1979 onto already sodden ground. The flooding occurred on the 27^{th} and 28^{th} December effecting Torridge and Bideford in the Kenwith Valley. It was considered the worst flooding by residents and for some it was the first time they had been flooded in 40 years. The floods caused £375,000 worth of damage. (Source: Bideford and North Devon Gazette) 27^{th} Calstock. Torrential rain caused the river Tamar to flood. (Source: East Cornwall Times)
November 1981	Jordan	38 mm (Otterham)	×	×	> 5	Wellington Hotel	The depth of flooding in the Hotel reached 600mm to 900mm and structural damage was caused to the building. Note: Following the above incident SWW relayed a length of public sewer in the Wellington Hotel car park which previously passed through the culvert at an oblique angle just above the invert. Press reports of the time suggest this sewer was holding back “a tree, a bath and a car

			Flood Magnitude				
Date	Location	Rainfall Depth (24 hours)	Rank	Level	Flow	Properties flooded in Boscastle	Notes
							wheel".
12th July 1982	Lynmouth, Devon.	45 mm (Lundy)	N/a	N/a	N/a	No information	1 to 2 inches of rain fell in 2 hours starting at 5:30 am on 12th July 1982.
22nd July 1983	Penzance	32 mm (Otterham)	N/a	N/a	N/a	No information	Penzance, Cornwall. 1.79 inches of rain fell in a 2 hour period from 8am on the 22nd July 1983. Source: The Cornishman.
October 1987	Jordan	31 mm (Otterham)	×	×	> 5	Wellington Hotel	Hotel flooded under 200mm of fast flowing water, causing damage to the culvert at a cost of £22,500
1992	Jordan	91 mm (Otterham)	×	×	> 5	No information	Culvert Collapse immediately upstream of the Wellington Hotel
June 1993	Camel & Ottery	86 mm (Newspaper) 140-150 mm (Marsh)	N/a	N/a	N/a	Not known if any damage caused	Bodmin, Bude and Camelford flooded. 6.5 inches of rain fell in North Cornwall and Devon over a 30 hour period. 9 rivers had flood warnings including the river Tamar, Camel, Ottery and Caen. (Source: Cornish Guardian) Extreme flows recorded on both the Camel (remarkable runoff if the figures are to be believed) and the Ottery. Three-day rainfall totals of 140-150mm in headwaters (at total comparable to the Boscastle storm, but intensities were much lower in 1993 – thus impact on the Valency would have been moderated) (Marsh, *pers. comm.*)
Dec 1999	Camel & Ottery		N/a	N/a	N/a	No flood damage	Very high flows in Camel and Ottery headwaters –frontal rainfall? (therefore relatively low intensity, lesser impact on Boscastle) (Marsh, *pers. comm.*)

5.7 ESTIMATE OF RECURRENCE PROBABILITY OF THE 16TH AUGUST 2004 FLOOD

Another key output of the hydrological studies must be an assessment of the severity of the estimated peak flows for each catchment, and the main point of the statistical analyses presented in Section 3 was to attempt to ascribe an annual exceedence probability to the 16th August 2004 peak flows on the Valency/Jordan and Crackington Stream catchments.

The FEH recommends use of the statistical method for estimation of floods of a particular exceedence probability, and Section 5.2 estimated flood peaks of up to the 0.1% probability of exceedence for both the Valency/Jordan and Crackington Stream catchments. These estimates, derived using standard FEH procedures for ungauged catchments, however, yield low 0.1% probability estimates of only 16.6 m^3/s for the Valency/Jordan and 14.9 m^3/s for the Crackington Stream. In each case, best use has been made of data from gauged catchments having similar hydrological characteristics, and in both cases the median annual flood, QMED, estimated from the FEH CD-ROM has been significantly reduced. In the case of the Valency/Jordan catchment, QMED has been reduced by 41%, from 6.81 m^3/s to 4.0 m^3/s, whilst for the Crackington Stream catchment QMED has reduced by a similar amount from 5.65 m^3/s to 3.32 m^3/s.

This reduction in the QMED estimate derived from the catchment descriptors derived from the FEH CD-ROM arises since the FEH, in Table 7.1 of Volume 1, strongly recommends using data transfer from donor, or analogue, catchments for QMED estimation. This 41% reduction in the initial estimate of QMED, however, does not help to explain the extreme ratios of estimated peak flows for the 16th August event (Tables 5.8 and 5.9) to QMED, where growth factors of over 32 for the Valency/Jordan and almost 26 for Crackington Stream are suggested. Such implied growth factors are very extreme by UK standards, and indeed by world standards and throw doubts over the FEH statistical method's ability to estimate extreme events on this type of small, ungauged catchment. Even were the FEH CD-ROM estimates of QMED to be accepted, which the FEH recommends strongly that we should not do, growth factors of 19 for the Valency/Jordan and 15 for Crackington Stream are necessary to reproduce the flood peaks proposed in Tables 5.8 and 5.9.

The FEH statistical method implies that the flow estimates presented in Tables 5.8 and 5.9 are extremely rare events, having exceedence probabilities much less than 0.1%. The historical flood evidence presented in Section 5.5, however, clearly suggests that the Valency/Jordan catchment in particular has experienced a significant number of major floods that are several multiples of QMED. This seems to imply either that QMED may be higher than estimated in Section 5.2, or that flood frequency growth curves for small, steep catchments with shallow soils similar to the Valency/Jordan and Crackington Stream, may have steeper flood frequency curves than suggested by the pooling method.

The statistical method has not adequately estimated the severity of the flood, indicating as it has, that the flood apparently has a very low annual probability, a suggestion that we do not accept, partly at least because it is known that there were a number of significant floods on the Valency catchment over the past 50 years. It is suggested that the FEH rainfall-runoff approach may be giving more realistic estimates of flood severity than the statistical method but even here, the flood appears to have an annual exceedence risk of less than 0.1%.

In the light of the concerns about the predictions provided by the FEH rainfall-runoff approach, it was decided to combine an estimate of QMED with the historic data and use an extreme value distribution to fit the data. The detailed description of this process is given in Appendix 12. The derived flood frequency relationship is shown in Figure 5.10. The 16th august flood event was a very unusual event and was certainly rarer than the event with an annual probability of exceedence of 0.5%. We estimate that the event has an annual probability of exceedence of approximately 0.25%. There is, however, considerable uncertainty over this matter. The growth curve shown in Figure 5.10 is tabulated in Table 5.13.

Table 5.13 Growth curve based on GEV Type II probability distribution

Discharge (cumecs)	Annual probability of exceedence
6.65	0.5
10.2	0.2
15.0	0.1
25.8	0.04
40	0.02
63.4	0.01
102	0.005
193	0.002

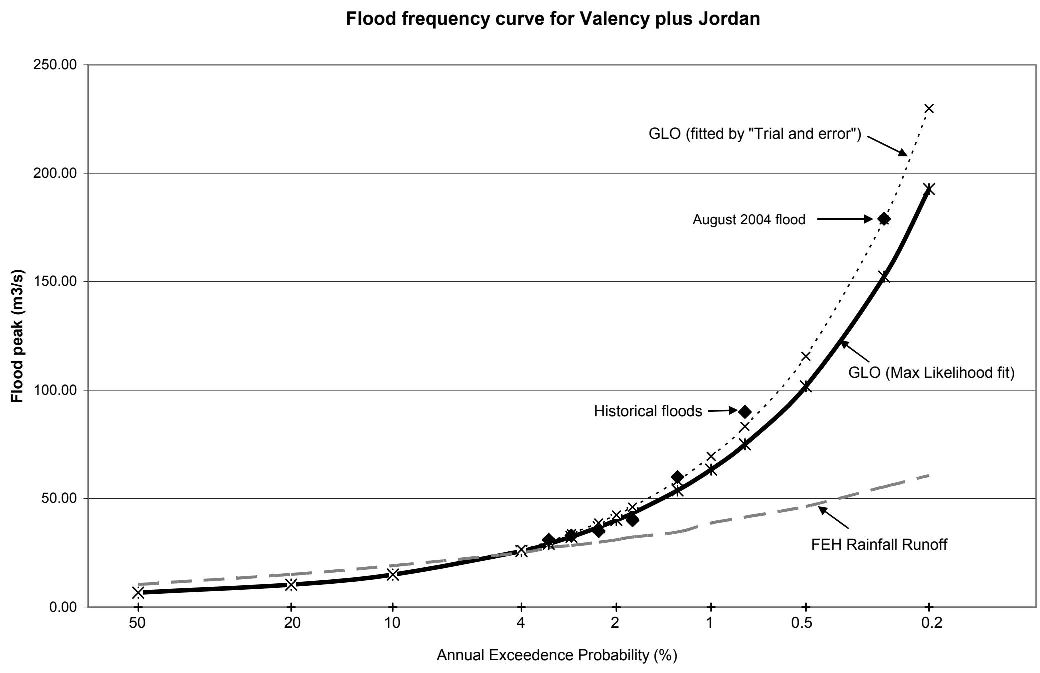


Figure 5.10 Estimated flood frequency curve for the Valency/Jordan catchment at Boscastle

It is extremely difficult to assess the annual probability for the flood at Crackington Haven as we have been unable to trace any historic flood records. Thus we cannot use historic flood data as a guide as was done for Boscastle. The magnitude of the peak flow and severity of the morphological change upstream of Crackington Haven would suggest that the event was extreme with an annual probably of occurrence probably smaller than 1%. The rainfall totals over the Crackington Stream catchment were lower than those for the Valency catchment. This would suggest that the annual probability of exceedence was probably larger than 0.25%.

5.8 MODEL ANALYSIS OF THE JORDAN CATCHMENT

This section reports on a conceptual rainfall-runoff model analysis of the Boscastle flood using hydrometric records for the River Jordan, prior to the flood, for model calibration and assessment. The River Jordan at Jordan Mill was gauged at SX 09910 90950, very close to the modelling point B1 at SX 09950 91200. The catchment area, derived from the CEH Digital Terrain Model, is 2.3 km^2. The gauging station was swept away during the Boscastle storm but stage records are available from 27 November 2002 to 27 July 2004.

A rating curve exists for the station up to a level of 0.464m (0.393 m^{3}s^{-1}), detailed in Table 5.14. The form of the rating equation is $Q = \alpha(h+d)^\beta$ for $h < h_T$, where Q is the flow in m^{3}s^{-1}, h is the stage in m with h_T the threshold stage for validity, and α, d and β are parameters of the relation.

Table 5.14 Rating equation for the River Jordan at Jordan Mill

h_T	α	d	β
0.296	4.31248	0.66282	0.0575129
0.465	4.66721	0	14.1626

Rainfall data in the vicinity of the catchment were available from raingauges at Lesnewth and Slaughterbridge. Data were only requested for 2004 to limit the amount received and to focus on the Boscastle event. Catchment average rainfall was estimated as a linear weighted combination of the two gauges, with the weights estimated as 0.85 and 0.15 for Lesnewth and Slaughterbridge respectively. These weights were arrived at by considering several different weighting algorithms, including Theissen weights and multiquadric surface fitting.

The PDM (Probability Distributed Model) rainfall-runoff model was used for catchment modelling purposes. An examination of the river level record for 2004 allowed periods for model calibration and evaluation to be selected: these are detailed in Table 5.15.

Table 5.15 Details of periods used for model calibration and evaluation

Period type	Period
Calibration	09:00 5 Jan 2004 – 09:00 26 Jan 2004
Evaluation	09:00 27 Jan 2004 – 09:00 11 Feb 2004

Due to its small size, the Jordan Mill catchment is very responsive with a very flashy and ‘spiky’ hydrograph as seen in Figure 5.11. After some manual calibration of the PDM parameters, automatic calibration was invoked to arrive at the final calibrated model. Reasonable agreement between the observed and modelled flow was achieved over the calibration event with an associated R^2 efficiency of 0.84. The simulated and observed flows shown in Figure 5.11 confirm that the model performs well, capturing both short- and long-term response characteristics of the Jordan catchment.

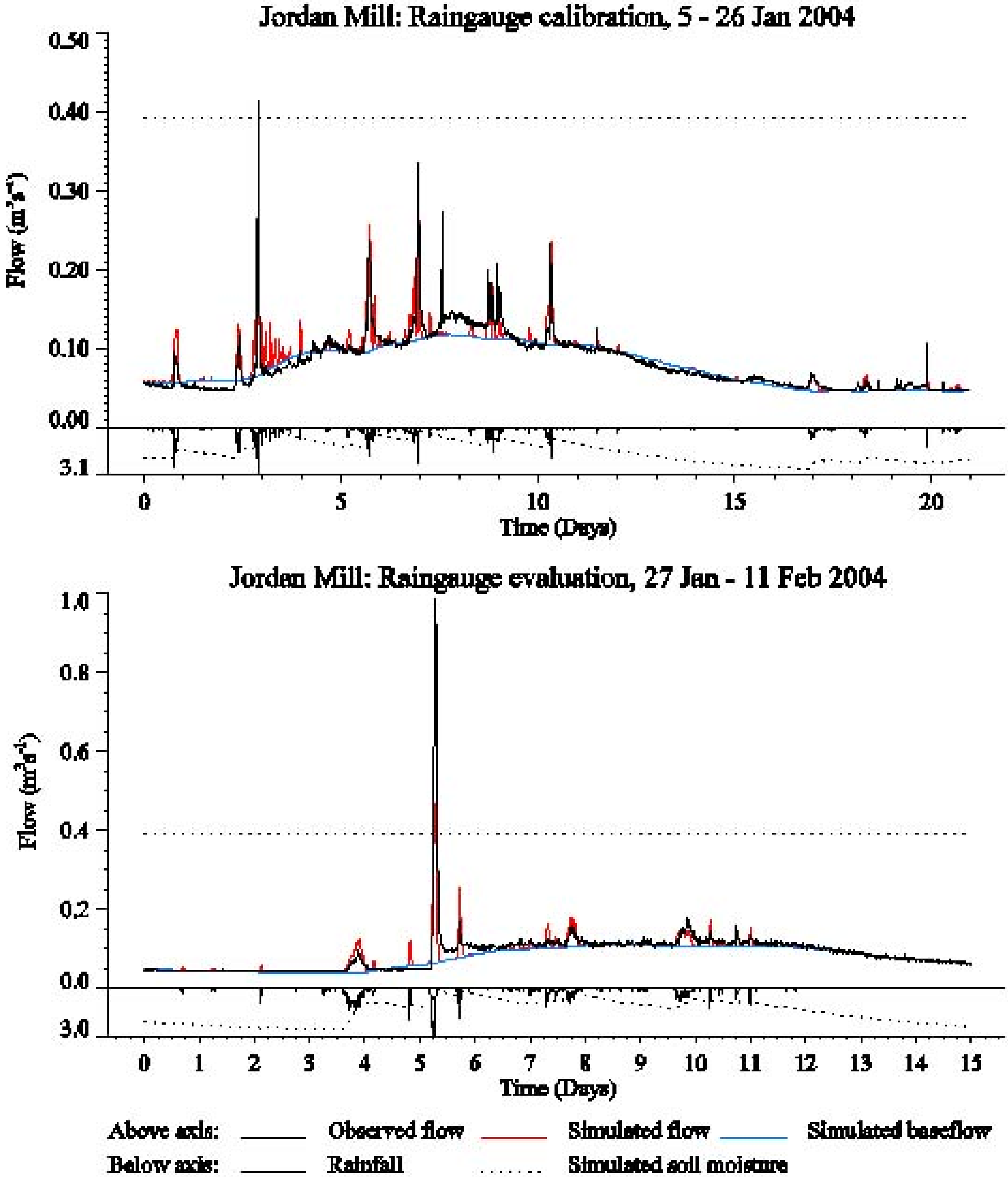


Figure 5.11 Hydrographs for calibration and evaluation periods for the Jordan catchment. The figure below the axis is the maximum 15 minute rainfall accumulation for the catchment. The horizontal dashed line indicates the upper threshold of the rating equation.

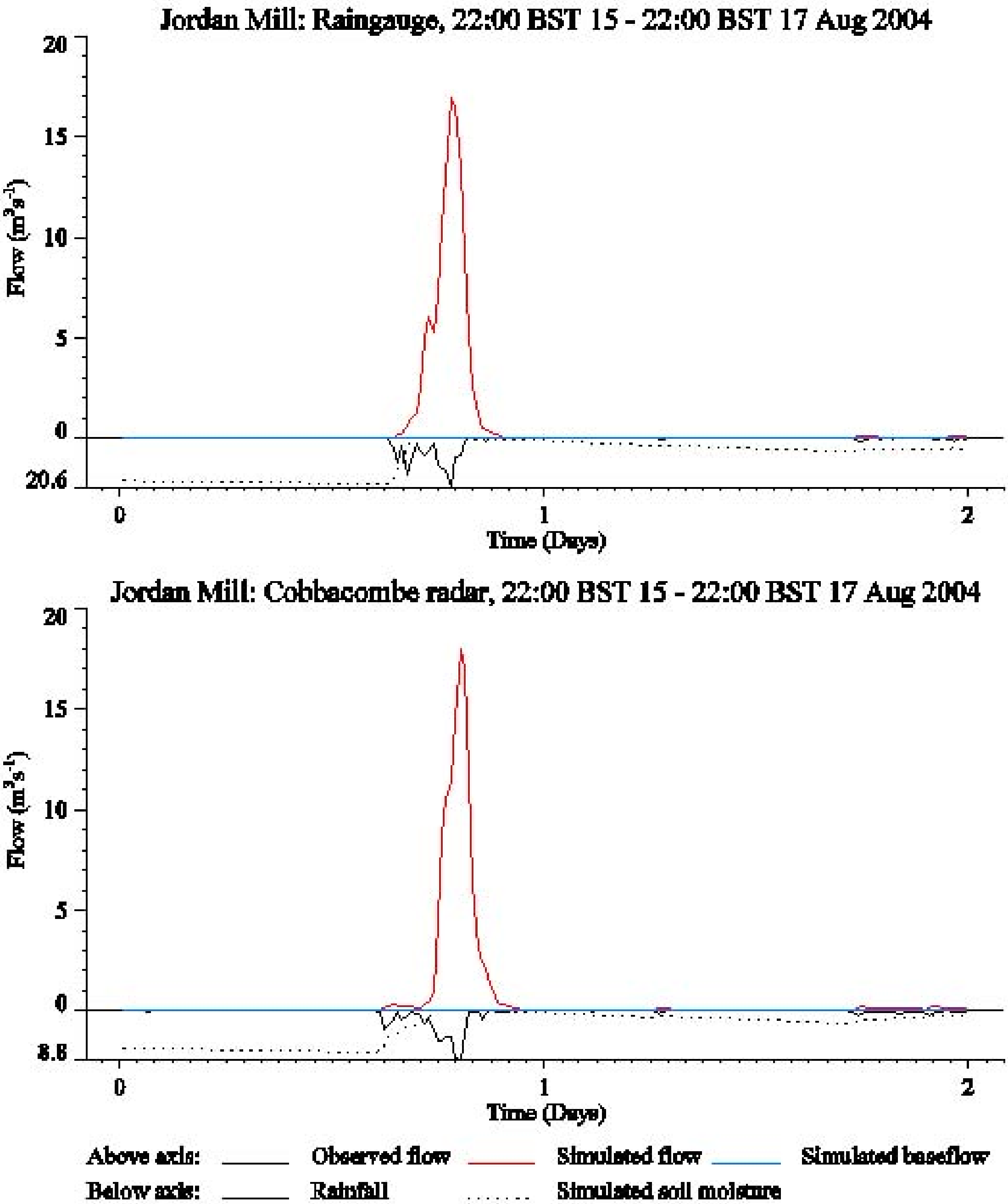


Figure 5.12 Hydrographs for the Boscastle event for the Jordan catchment using raingauge and Cobbacombe Cross radar data. The figure below the axis is the maximum 15 minute rainfall accumulation (for either raingauge or radar) for the catchment.

The calibrated PDM parameters are not listed here in detail. One parameter of particular significance, however, is the rainfall factor which simply multiplies the rainfall input to the model. The factor is normally considered to account for the representativeness of the weighted-raingauge estimate of catchment rainfall, but may include other causes requiring water volume adjustment. The calibrated rainfall factor for the Jordan catchment was low at 0.47.

The model also performed well over the period used for independent evaluation. Figure 5.11 shows good agreement except for the large peak. The latter seriously affects the R^2 efficiency, bringing it down to a still reasonable figure of 0.67. On closer examination this discrepancy between the observed and simulated flow is not surprising since it is beyond the upper limit of the rating equation.

Simulating the flow over the Boscastle event on 16 August 2004 using raingauge data as input gives a modelled peak flow of 16.9 m^3/s at 16:45 BST, as seen in Figure 5.12. Simulating the flow using Nimrod 2km radar rainfall data from the Cobbacombe radar as input gives a peak flow of 17.95 m^3/s at 17:15 BST, as seen in Figure 5.12. This compares with the FEH estimate (given in Table 5.8) of 18.86 m^3/s at 18:00 BST.

This result is obtained with a rainfall factor of 1. It has not been possible, within the constraints of the study, to assess an appropriate factor for use with radar data using historical records. Reassuringly the raingauge- and radar-derived simulated hydrographs give a consistent picture for the Boscastle flood event.

5.9 EFFECTS OF LAND USE CHANGES

There have been suggestions that recent land use changes within the Valency and Jordan catchments may have exacerbated the flooding during the August 2004 flood. Certainly there has been some increased urban development to the upper part of Boscastle within the Jordan catchment, and this might be expected to increase flood runoff and to reduce catchment response time to some extent. This might have slightly increased flood runoffs to some extent during commonplace floods, but for extreme events such as the 16th August 2004 flood, soils on rural portions of the catchment became waterlogged early on in the storm, and there would probably have been only small differences in flood runoff between rural and urban areas.

Similarly, there is a suggestion that removing some of the traditional Cornish banked hedges to increase field sizes might have increased flood runoff. It is difficult to prove or disprove this, as there is very limited scientific evidence on how various land use changes and farming practices might affect flood runoff. Defra commissioned a study in 2003 seeking to quantify these effects, but the consensus of the panel of experts involved was that considerably more research was needed before the impacts of such factors could be reliably quantified. CEH were involved in this study, which was led by the University of Newcastle. Whilst intuitively, removal of the sort of banked hedgerows typical of Cornwall might be expected to reduce natural storage within the catchment to some extent, the magnitude of such possible impacts cannot be reliably quantified. As with the case of increased urbanization, however, any impacts would probably have been small towards the end of storms such as occurred in August 2004 over the upper Valency catchment. For a catchment with fairly thin soils overlying predominantly impervious geology, towards the end of a storm of 150 to 200 mm in some 5 hours, soils would be saturated and overland surface runoff was obviously occurring. Whilst embanked field boundaries might have stored some of this runoff, the bulk of the flood response would probably have flowed downslope along the embankments and would probably have reached a road or water course fairly rapidly.

In our opinion, any impacts of recent land use changes within the catchments would have had little impact upon flood magnitude during the severe storm of August 2004.

5.10 LIMITATIONS OF ANALYSIS AND UNCERTAINTY ESTIMATES

There are many factors that will affect our confidence in these various estimates, but unfortunately it is very difficult to quantify most of them.

One uncertainty relates to the marked temporal and spatial differences between the 2 km radar derived rainfall estimates based upon either the Cobbacombe Cross or Predannack radars. This matter was discussed in Chapter 2, but no firm recommendation is given as to which set to use, as there is no real basis to believe that one set of derived data are better than the other. For the final flood estimates we have recommended using the Cobbacombe based radar product, as this appears to have a better spatial location, particularly for the Valency/Jordan catchment. The Cobbacombe radar, however, produces much lower catchment rainfall accumulations over the Crackington Stream catchment than does Predannack.

One of the limitations of the analysis is demonstrated by the fact that the models used were unable to reproduce the short delay between the intense rainfall in the upper part of the catchment and the time of the peak discharge in Boscastle.

There are numerous uncertainties within the unit hydrograph model used to reproduce the flood event. To an extent, however, these have been dealt with by 'calibration' of the model against the observed flood levels and times of peak. Thus, the unit hydrograph time to peak, Tp, has been dramatically reduced from the FEH derived value, in part to reflect the perception that such very rare events have much more rapid response times than more common floods, particularly towards the end of the storm. Ideally, a variable Tp might be used, but this cannot easily be achieved with current software. Similarly, a non-standard percentage runoff formulation has been developed and applied, again to reflect what appears to have occurred during the August event.

One major uncertainty remains over the risk of such an event occurring again. It is clear that current FEH methods find it difficult to reproduce such extreme specific flood runoffs (some 6 or 7 $m^3s^{-1}km^{-1}$). The 16th August 2004 floods were certainly a very rare event, but not unprecedented, as shown by the historical flood analysis. Much of the historical flooding, however, seems to relate primarily to the Jordan catchment, with frequent references to flooding of the Wellington Hotel. It is possible that this is not only related to the hydrology of the upstream catchment, but is also affected by issues such as the blockage of the culvert.

6. Hydraulic analysis and interpretation

6.1 BOSCASTLE CATCHMENT

6.1.1 Context

The overall objective of the hydraulic modelling is to describe the propagation of the flood throughout the catchment and to use, as far as possible, the eyewitness observations, the evidence left by the flood, the recorded rainfall and the hydrological processes in the catchment to assess the river flows.

The hydraulic modelling builds on the work on the rainfall and hydrology that is described above.

6.1.2 Model Overview

Modelling Approach

Three hydraulic models have been constructed using the InfoWorksRS (IWRS) software which uses the same hydraulic simulation "engine" as ISIS. IWRS was used because it is linked automatically to a GIS of the catchment, facilitating the use of geo-referenced data. IWRS also records the model versions as part of the run management facilities. The three models discussed below are for the

- River Valency using extended cross sections
- River Valency in the centre of Boscastle using a "quasi-two dimensional" model
- Jordan River using a "quasi-two dimensional" model

Unless specified otherwise, the results in this report derive from the quasi two dimensional approach to the River Valency.

Upstream flow conditions

The upstream limit of the hydraulic model is located approximately 5 km east of Boscastle, at point B4 on Figure 6.1 below. The runoff from the catchment is simulated in a distributed fashion from the Valency and its main tributaries. In all, HR Wallingford identified seven subcatchments, including the upper Valency catchment, and an inflow hydrograph has been calculated for each by CEH Wallingford. The locations of these inflow points are shown in Figure 6.1 below.

Inflows B1 to B4 are the principal tributaries, with B1 being the inflow to the Jordan River. The three contributions identified on Figure 6.1 as B5N, B5S1 and B5S2 represent the inflows at minor tributaries and the flow caused by direct lateral runoff from hill slopes into the River Valency. Two thirds of this lateral inflow is simulated as entering the model at inflow B5S1 and the remaining one third enters as lateral inflows to the reaches in the upper part of the model at B5S2

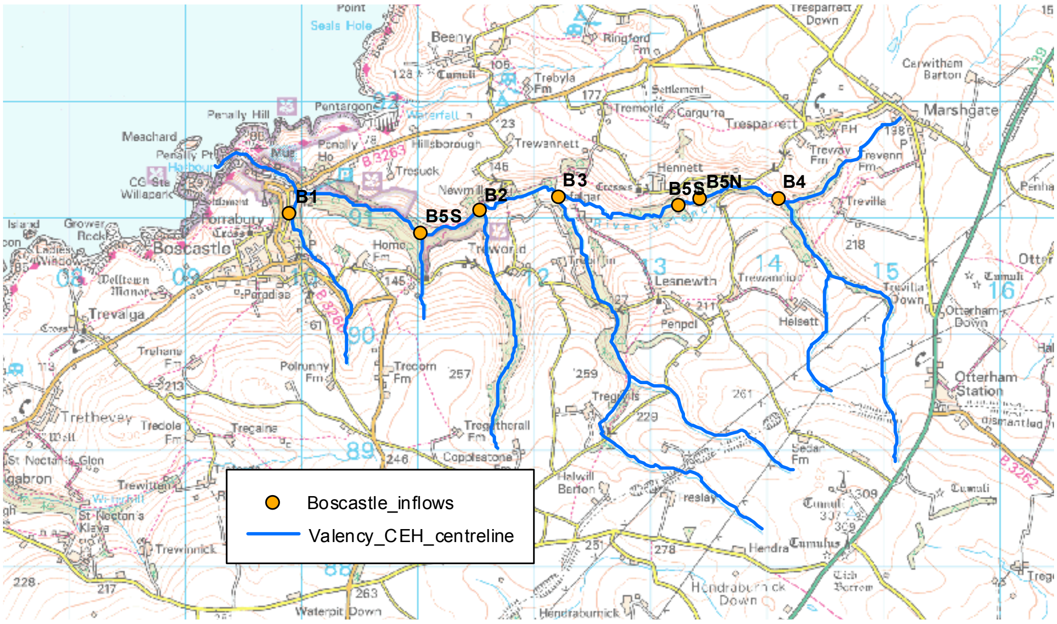


Figure 6.1 River Valency Catchment, showing locations of hydrological inputs

Downstream boundary

The downstream boundary of the hydraulic model was located downstream of Boscastle, where conditions in the River Valency are normally influenced by tides. The astronomic tidal water levels for Boscastle on the 16th of August 2004 were calculated from values and procedures in the relevant Admiralty Tide Tables. The reference station for Boscastle is Milford Haven in Wales; the data for this station was adjusted for time and water level using correction factors given in the Tide Tables for Boscastle, with no significant positive or negative surge. The calculated tide level at Boscastle at the time of the peak of the flood was 0.5 metres AOD. Data on actual tide levels during the event suggested that at the time of the flood there was a positive tidal surge of approximately 0.3 m. Thus the actual tide level at the peak of the flood was approximately 0.8 m AOD. Clearly this and the later high tide level of under 3.5 m AOD at approximately 18:10 GMT (19:10 BST) would not have affected the flood water levels recorded in the centre of Boscastle of 9 m AOD or more, see Figure 6.3. The downstream boundary condition used in the model, therefore, was a stage discharge relationship calculated assuming “normal” depth in the modelling at cross-section 1 in Figure 6.4.

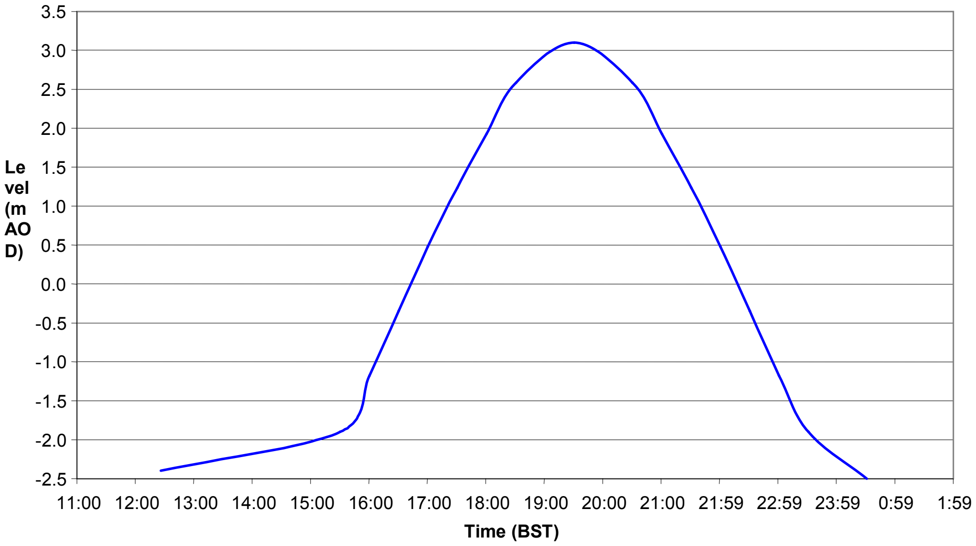


Figure 6.2 Tidal water level calculated for Boscastle from Milford Haven

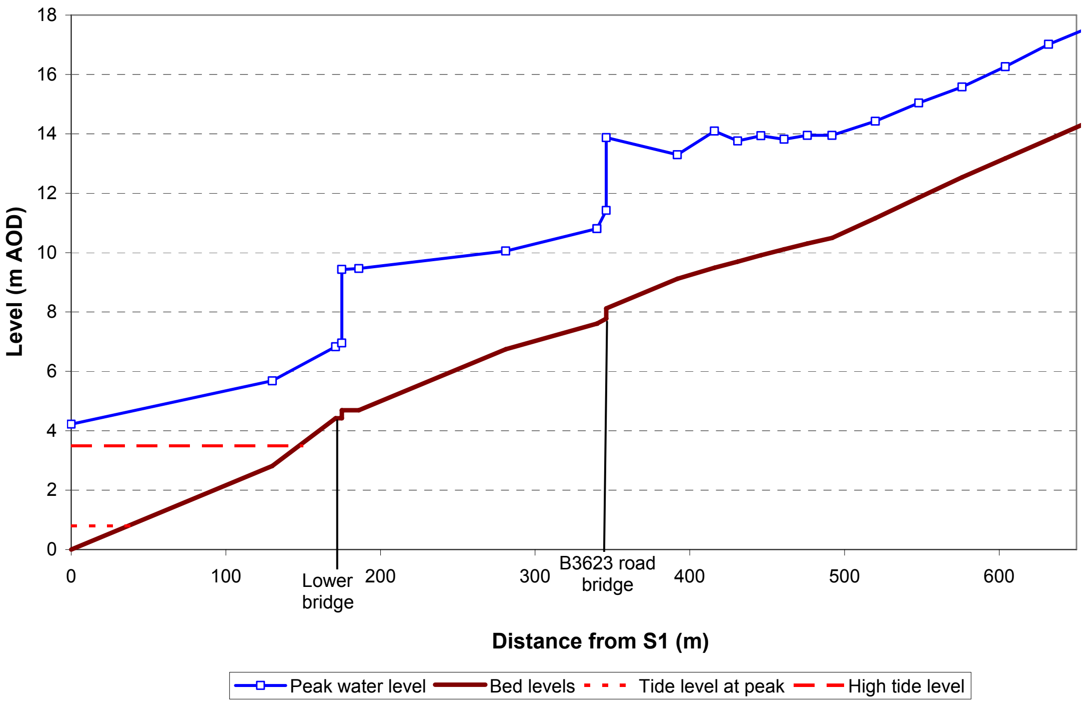


Figure 6.3 Comparison of tide levels with flood levels in Boscastle

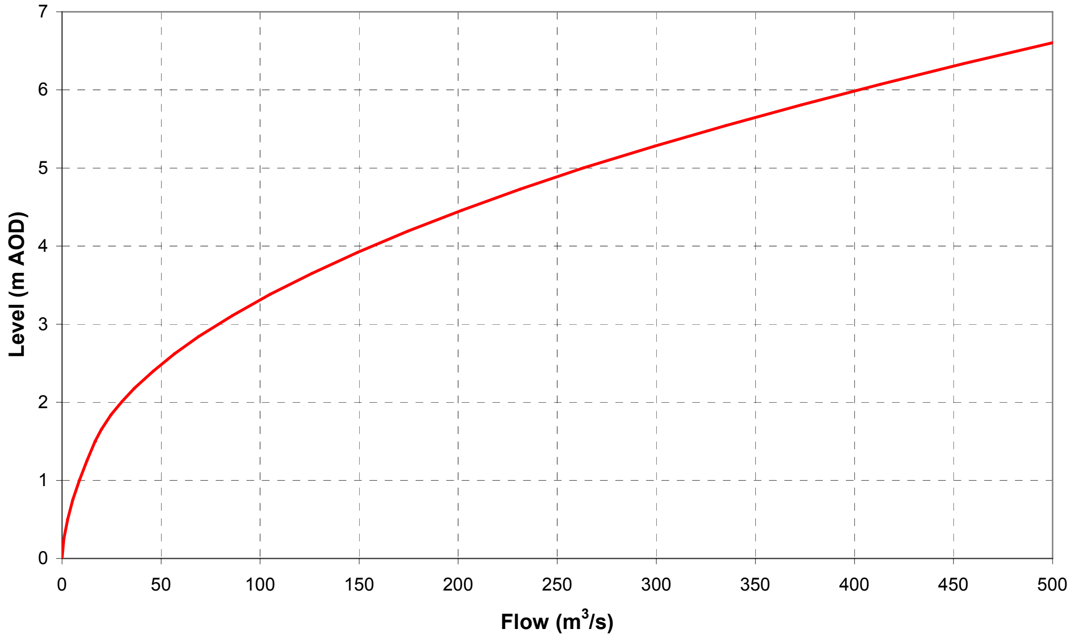


Figure 6.4 Stage discharge relationship at the downstream boundary of the Valency

Topographic Data

No detailed river survey of pre-flood conditions was available. The river and flood plain ground levels in the model were taken from the following sources:

- a river and flood plain cross-section survey by Halcrow, after the 2004 flood
- post-flood LIDAR data from the Environment Agency
- Wrack marks surveyed by Halcrow, after the 2004 flood

A sample of the LIDAR data for the centre of Boscastle is show in Figure 6.5. Note that structures such as houses have been removed so that the data reflects ground levels.

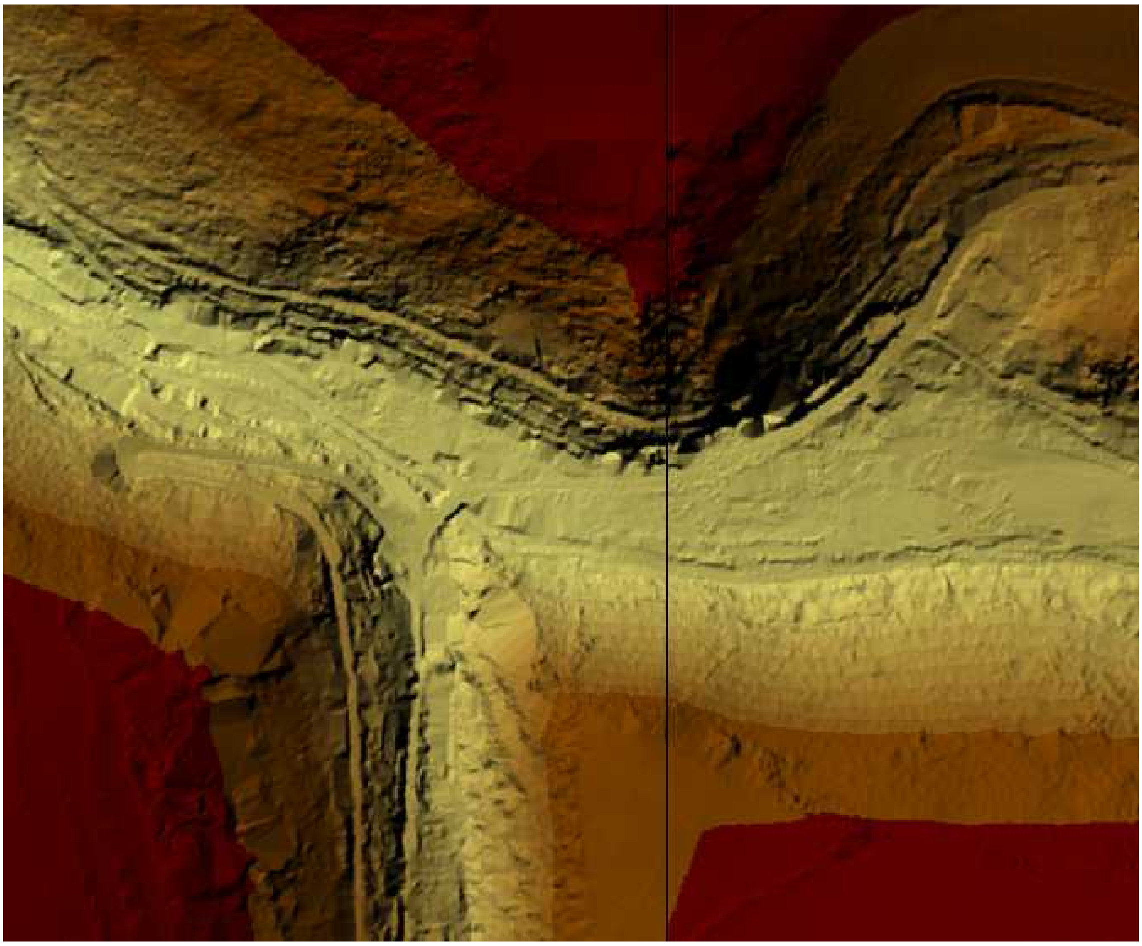


Figure 6.5 Example of post flood LIDAR data for Boscastle

Following a flood the peak water level is frequently marked by collections of floating branches or rubbish that has been carried by the flow. These are commonly referred to as 'wrack marks' and if they are surveyed after the event can be used to provide information on the maximum water levels during the flood event. The data from wrack marks, however, should be interpreted with care. If the wrack mark is in the branches of a tree then the tree may have been bent over by the flow at the height of the flood or they may reflect the height reached by some local temporary wave.

The wrack marks reflect the highest water level at a particular location but this may not correspond with the highest discharge. At a number of places significant morphological change took place during the flood. It may be that due to changes in the river channel during the flood that the highest water level occurred prior to the peak of the flood. In the numerical river modelling the geometry of the river is fixed and the only survey data available was measured after the flood. Where there are differences between the observed wrack marks and the predicted water levels it may be that these are due to morphological changes that took place during the flood. In the following analysis great use is made of wrack marks despite the reservations raised above, as the wrack marks provide the best indication of flood levels available.

Immediately following the flood work was done to clear accumulated sediment from the river channel upstream of the B3263 road bridge. The channel upstream was also excavated to ensure that it had an adequate capacity. The post-flood cross-section survey by Halcrows was carried out after this work was done and so the cross-sections used in the model reflected these changes.

During a site visit accompanied by Halcrow staff, HR Wallingford recommended a cross-section spacing every 20 to 50 metres in the village. Upstream of Boscastle, however, our requested cross-section spacing was much sparser, ranging from every 300 to 1500 metres. Since the survey by Halcrow was undertaken after the flood, in some locations channel size may be 20 to 30% larger than it was before the event, due to bed scour and bank erosion during the flood. The Halcrow survey also could not record the level of any bridge parapets, walls and banks that had been destroyed in the flood.

Features not modelled

The IWRS simulation model has fixed geometry except for certain types of gated structure. As the geometry is fixed in the model it cannot take account of changes in flow paths or channel morphology that might have taken place during the flood. The IWRS model does not take into account local standing waves caused by objects in the flow or local transient waves that can be produced by flows around debris such as trees or cars, of the sort that were observed in the floods of August 2004. In some sensitivity tests, however, we have reconfigured the model to approximate the effects of some assumed blockages by using gated structure options in the software.

6.1.3 Model Schematisation

River Valency using extended cross sections

In this model the floodplain is represented by extended river cross sections (i.e. using ground level cross sections of the river and floodplain, with a uniform water level across the whole) This approach is acceptable upstream of Boscastle, where the flow routes on the floodplain are not constrained by buildings.

The ground levels in these cross-sections have been taken directly from the Halcrow survey. In the upstream reaches IWRS has been used to interpolate extra cross-sections at the tributary inflow locations. In the cross-sections on the right hand floodplain through Boscastle, the locations of buildings were represented.

This approach was used in our initial testing as it was robust, fast to implement and provided an initial calibration of the whole catchment in a short time. The representation as extended cross-sections has been retained for calculation of water levels upstream of Boscastle village. There are some limitations, however, of this approach. The flow is not split into defined paths through the village streets; rather it is treated as a single unit for the whole cross-section. Consequently, a single water level is recorded for the cross-section and there is no lateral variation in water level across the flow path – contrary to the evidence of the wrack marks in Boscastle

River Valency in the centre of Boscastle using the "quasi-two dimensional" approach

Rationale

The complexity of the urban floodplain on the right floodplain through Boscastle means that the assumption of a uniform water level across the channel and flood plain is not appropriate for a detailed understanding of the flood movement. Consequently the flood plain flow has been separated from the main channel with flow paths defined down each street. These have been modelled with separate "river" units, representing the streets and car park, and they are connected to the main channel by "spill" units within the software. With this model, the flows and water levels in the streets are distinct in contrast to the "average" treatment of the model configured using extended cross sections. This provides a more realistic representation of flows on each flow path as water levels along each flow path may vary, leading to a potentially better reproduction of water levels through Boscastle. Figure 6.6 below indicates the general location of the surveyed sections and the represented flood flow routes through the village. Figure 6.7 shows the model schematisation.

The car park

The upstream and downstream ends of the car park were surveyed as sections 10 and 9 respectively, in the Halcrow survey. Flow between the channel and the car park is assumed to be over a small bank; at the upstream end of the car park this is 0.5 m above the ground level. This bank decreases in height downstream towards Section 9 where it is only 0.1m above the normal ground level.

Four additional cross sections have been interpolated in both the channel and the car park between cross-sections 10 and 9 to increase the accuracy of the calculation of the volume of water spilling into the car park. The ground levels in these interpolated cross-sections were checked against the LIDAR DTM of the car park. Upstream of the car park, four additional cross-sections have also been added between sections 11 and 10, using interpolation for the channel and LIDAR data for the right hand floodplain.

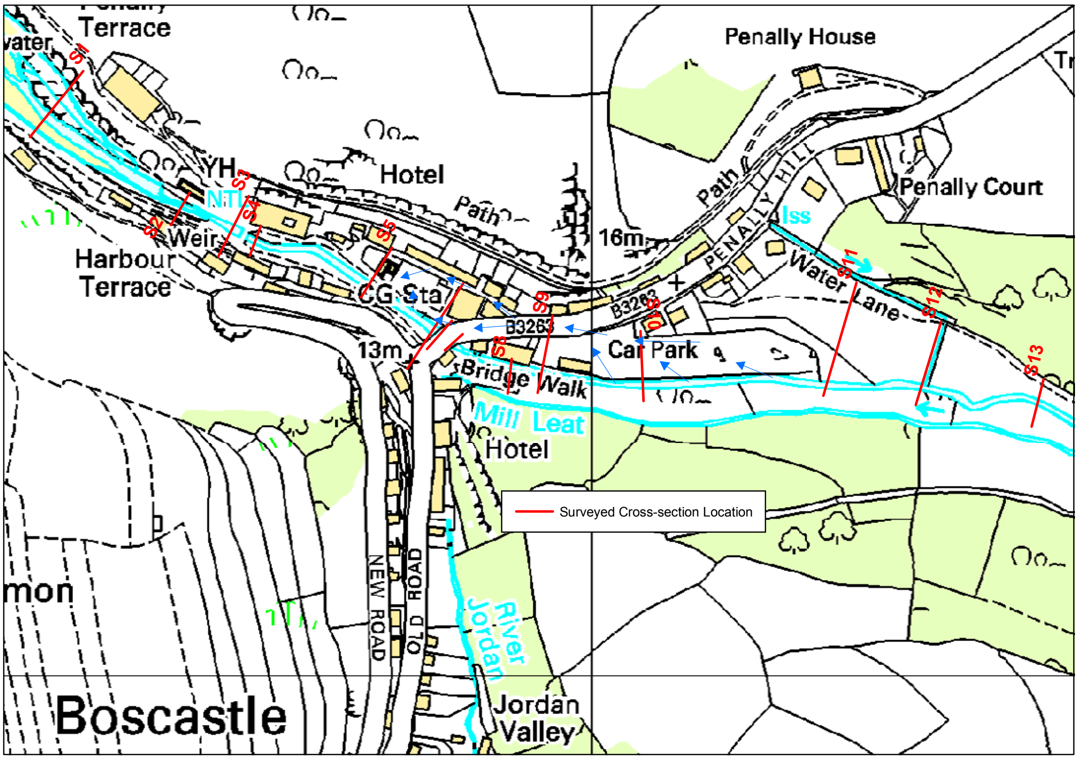


Figure 6.6 **Surveyed cross-section locations and flood flow routes in Boscastle, red lines show cross sections, blue arrows show flow lines during the flood**

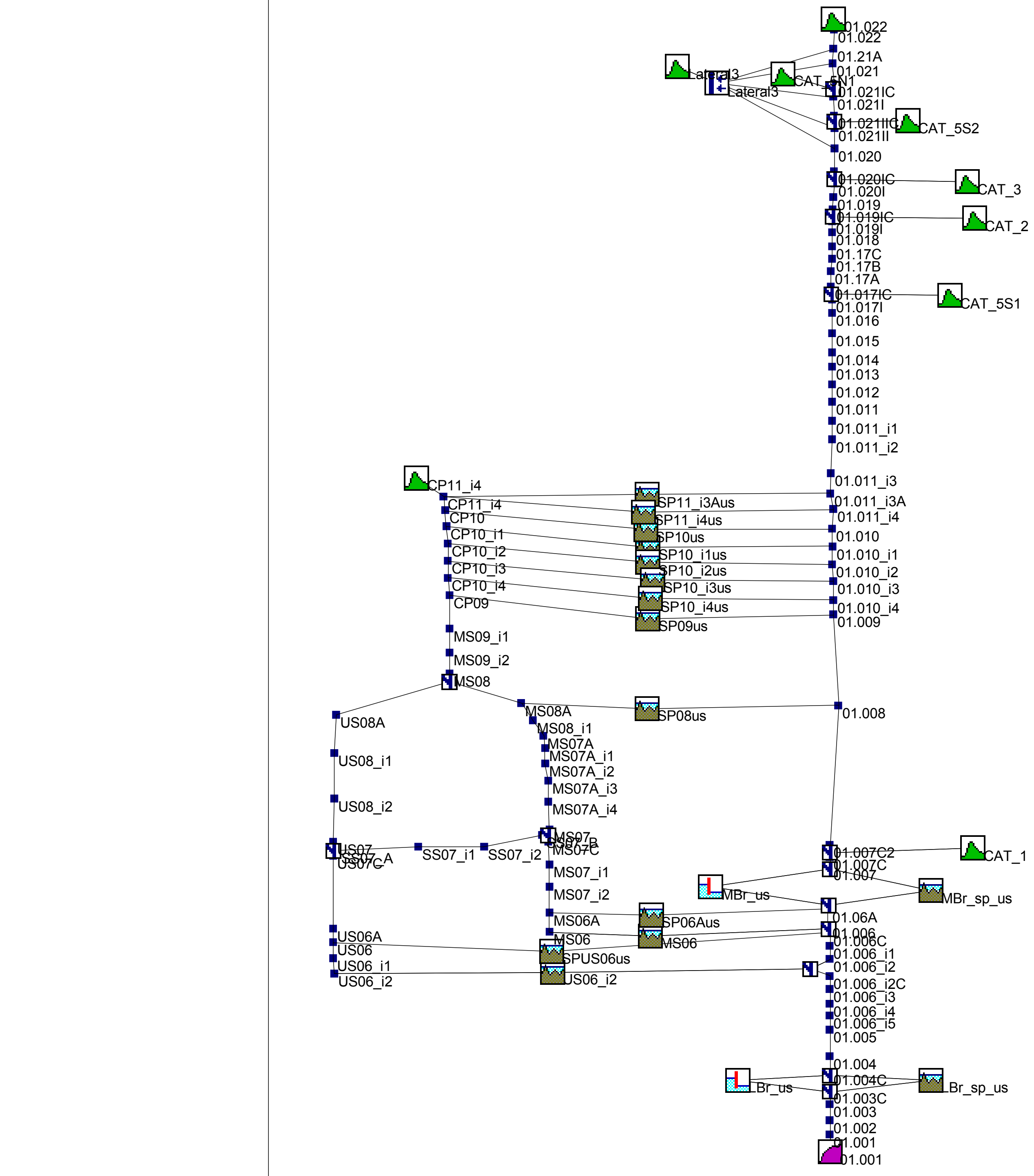


Figure 6.7 Valency model schematisation

The B3263 road

The observed flow path down the B3263 begins at the car park (upstream) and flows down past the B3263 Road Bridge where it re-enters the channel. The Halcrow survey includes the B3263 at 5 cross-sections. This data has been used to model the B3263 as separate river units in IWRS. Flow down the B3263 spills back over the flood plain into the main channel of the River Valency between sections 6A and 6, downstream of the B3263 Road Bridge.

During the 2004 flood, flow was observed through the doors and windows of the buildings on the right hand bank between the B3263 Road Bridge and the car park. Flow through these buildings has been represented in the model with a spill 20 metres in length at an elevation of 11.5 metres AOD.

Valency Row

The observed flow path along Valency Row begins at the junction with the B3263 downstream of the car park and runs down Valency Row to the open area between sections 5 and 6 where it spills over and through a wall to re-join the main flow path. Between sections 6 and 5 Valency Row is separated from the channel and floodplain by a wall and then by a building. Weir equations in IWRS have been used to model flow over the wall. Downstream of the building the flow from the street rejoins the main floodplain flow.

Jordan River

The Jordan River tributary joins the River Valency in the centre of Boscastle. The Jordan valley is steep (gradient approximately 0.05) and so the spatial extent of influence of the River Valency on flow conditions in the Jordan extends only approximately 50 m upstream from the confluence. Though the inflows from the Jordan were included in the model of the Valency, to understand better the hydraulic conditions in the Jordan, a separate numerical model of the Jordan was constructed. The outflow of the Jordan model provided an inflow to the model of the River Valency through the centre of Boscastle.

Halcrow surveyed cross-sections between the wrack marks on the left and right banks, extending 150 metres upstream of the Jordan culvert which commences at the southern end of Marine Terrace. The upstream dimensions of the culvert were also surveyed and the representation of the culvert was simplified in the model by using the dimensions at the upstream end throughout. During the peak of the event, the flow simulated through the culvert is only one third of the total flow assuming that the culvert remained clear of sediments. After the flood, however, a substantial accumulation of sediments was observed at the culvert entrance completely blocking the entrance to the culvert. There is no evidence as to the time during the event when the culvert became blocked, though it seems likely that the culvert was already blocked at the time of the peak discharge.

There is a flow route for flows bypassing the culvert which runs down the front of Marine Terrace, then through a building before reaching the River Valency. The LIDAR survey has been used to provide bed levels for this flow path and to derive the spill height (21.3 m AOD) for flow onto the street. The flow observed passing through the windows and doors of the Wellington Hotel has been represented using a spill unit.

6.1.4 Hydraulic structures

Lower Bridge

The Lower Bridge has been modelled using a vertical sluice gate unit in IWRS. This method allows representation of the bridge becoming blocked during the simulation. The sluice gate can be lowered during the peak of the event to simulate the blockage of the bridge.

The height of the sluice opening is taken from the lowest point on the channel bed to the soffit level of the bridge, and the width calculated so that the rectangular area of opening under the gate is equal to the flow area under the bridge. It has been assumed that the bridge became fully blocked at 16:10 hours BST (15:10 GMT).

Flow overtopping or bypassing the bridge has been modelled using weir equations in IWRS. The bridge shape has been taken from the survey by Halcrow after the 2004 flood. The parapets of the Lower Bridge were not destroyed in the flood.

B3263 Road Bridge

The River Valency is constricted upstream of this location by the buildings on either side of the channel, which force floodwaters to pass under or over the bridge. Thus blockage of this structure by debris can cause substantial increases in water level locally and the channel under the bridge is known to have been substantially blocked during the event. Furthermore the “spill” over the top of the bridge parapets was obstructed with debris, including a large tree.

Thus the B3263 Road Bridge was also modelled using a vertical sluice gate to simulate the bridge becoming blocked during the run, and the level spill over the parapet was also raised during one of the sensitivity tests reported below.

The height of the sluice opening is taken from the lowest point on the channel bed to the soffit level of the bridge, the width is calculated so that the rectangular opening area under the gate is equal to the flow area under the bridge. It has been assumed that the bridge became fully blocked at 16:20 hours BST (15:20 GMT).

Flow overtopping the bridge has been modelled using weir equations in IWRS of flow over the parapet. The bridge parapets were destroyed during the flood. The Halcrow survey gave the road level, which has been used to define the “spill” level over the bridge.

6.1.5 Choice of coefficients

Roughness values

The roughness coefficients used in the simulations are based upon estimates made during the visits to the site in the two weeks after the flood. The nature of the study involved a degree of iteration between the hydrological assessments by CEH Wallingford and the hydrodynamic simulations at HR Wallingford. The water levels are influenced by both the peak values of runoff from the catchment and the resistance of the channel and flood plain. At the end of the calibration we have recommended values of river resistance based upon our initial site visits since these, with a credible set of assumptions for rainfall and runoff, reproduced the observed water levels as described in Section 6 below.

Table 6.1 Assessed river roughness values for the River Valency at Boscastle

Location	Range of Manning's 'n'
Channel	0.040 to 0.050
Car park	0.040
Valency Row	0.030
B3263	0.025
Open areas/gardens	0.045
Side street	0.030
Left floodplain	0.050 to 0.125

In addition, some sensitivity testing was undertaken using higher resistance values. The higher values, however, still lie within "credible" bounds based upon our experience of modelling elsewhere, and information collected in the Environment Agency sponsored R&D project undertaken by HR Wallingford on *Reducing Uncertainty in Conveyance Estimation*(Defra/EA, 2002, Defra/EA 2003a, Defra/EA 2003b, Defra/EA 2004).

Other coefficients

In IWRS "spill" units calculate the flow of water over an irregular weir using a standard weir equation for dry, free and drowned flow, forward and reverse modes, and a weir coefficient. The default value of 1.7 was used for all the weir coefficients of the lateral spills between the channel and floodplain.

6.1.6 Calibration

Calibration data

The following data were available for calibration of the hydraulic model:

- Wrack levels surveyed by Halcrow shortly after the flood of the 16th August 2004
- Photographs taken during the 2004 flood from several sources
- Video footage of the 2004 flood from several sources
- Eye witness reports from the public of the 2004 flood

No observed river discharges or velocities were available for calibration; the information on discharge was derived from the hydrological studies. The water level data available for calibration were derived from the August 16 event. Ideally for model calibration, water levels and flows are sought for several events and the parameters in the model are adjusted to provide the best simulation of the historic events. In the case of the Valency there was no flow and water level data available from earlier flood events which could be used for calibration.

Calibration on the 16th August 2004 event

The model was calibrated against the observed wrack levels by varying the following parameters and inputs:

- The discharge hydrographs for the inflows (as determined by the CEH rainfall runoff modelling)
- The river roughness (Manning's 'n' values)
- The degree of blockage of the bridges

The downstream boundary condition (Section 6.1.2 above) was not adjusted during the model calibrations, and neither were the discharge coefficients for the spills and other structures.

The final model calibration uses discharge hydrographs from the iteration between the hydrological and hydrodynamic studies which have a combined peak flow of approximately 180 m^3/s at Boscastle, downstream of the confluence with the Jordan. The Manning's 'n' values are as tabulated in Table 6.1 above.

Figures 6.8 to 6.10 present the water levels calculated in the model calibration for the main river Valency channel through Boscastle and along two streets, the B363 and Valency Row, assuming that there is no blockage at the bridges. It is seen that the model under-estimates water levels with respect to the observed wrack levels through Boscastle. Water levels in the vicinity of the car park are up to 0.5 metres lower than the wrack levels taken on the left hand bank. Water levels simulated on the B3263 and on Valency Row are also 0.5 to 1 metre lower than the observed wrack levels. In the area between the two bridges the water levels are between the observed wrack levels.

In the reach extending 2 km upstream of the village of Boscastle (not shown here) the simulated water levels lie within the range of the observed wrack levels.

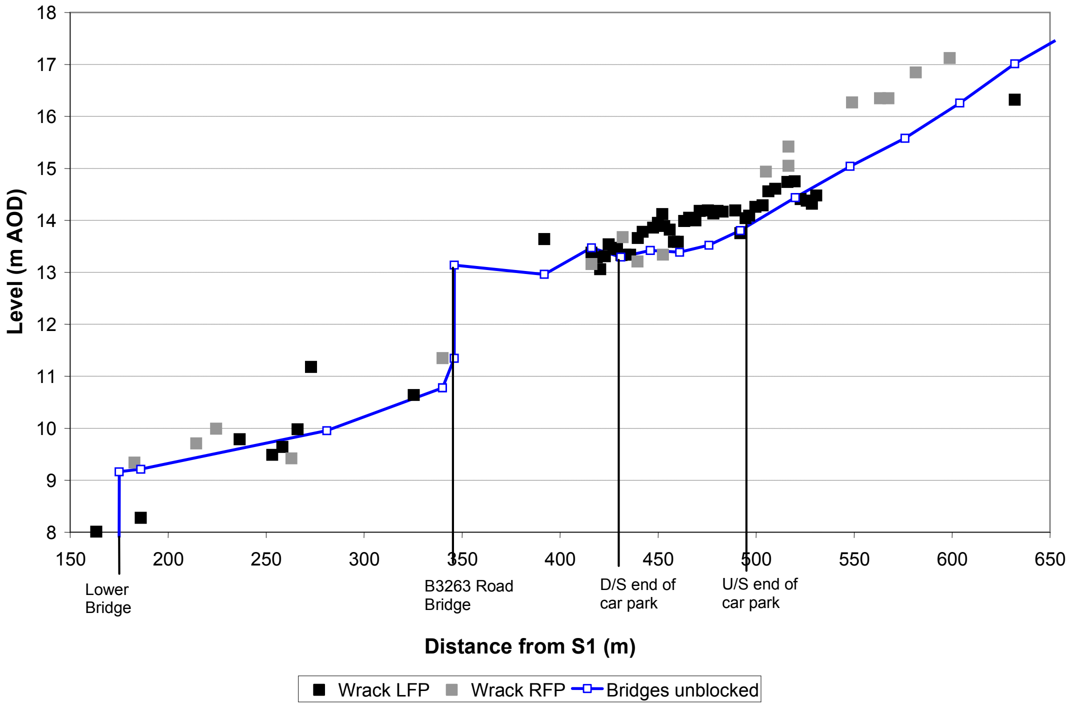


Figure 6.8 Flood levels in Boscastle with bridges unblocked. LFP and RFP are Left and Right Floodplains, respectively

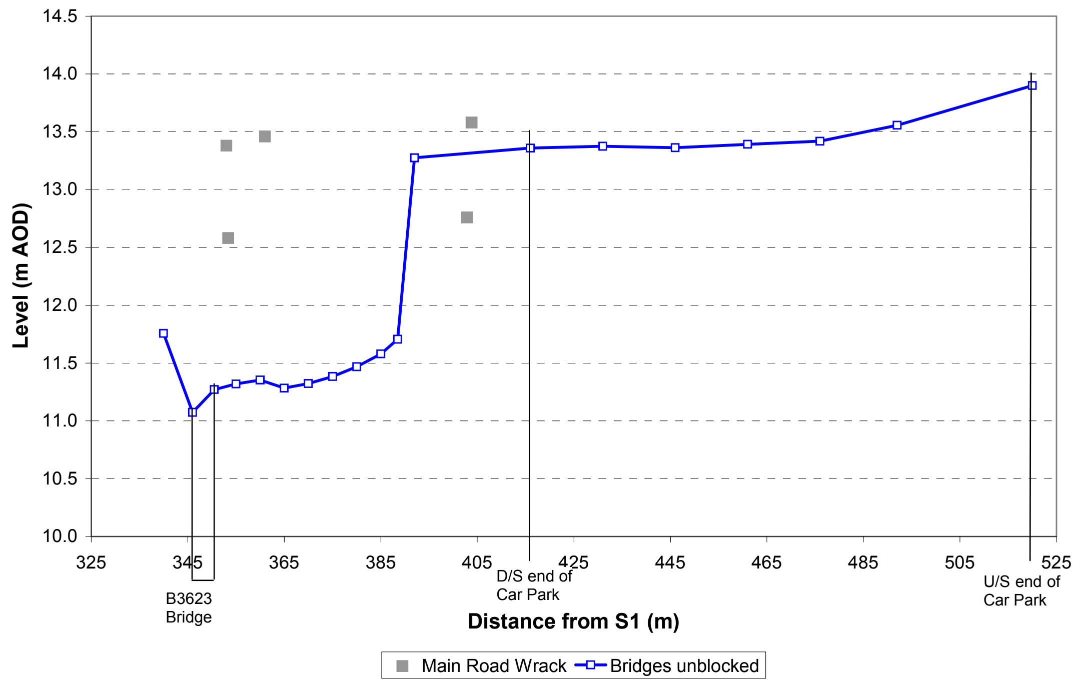


Figure 6.9 Flood Levels on the B3263 with bridges unblocked

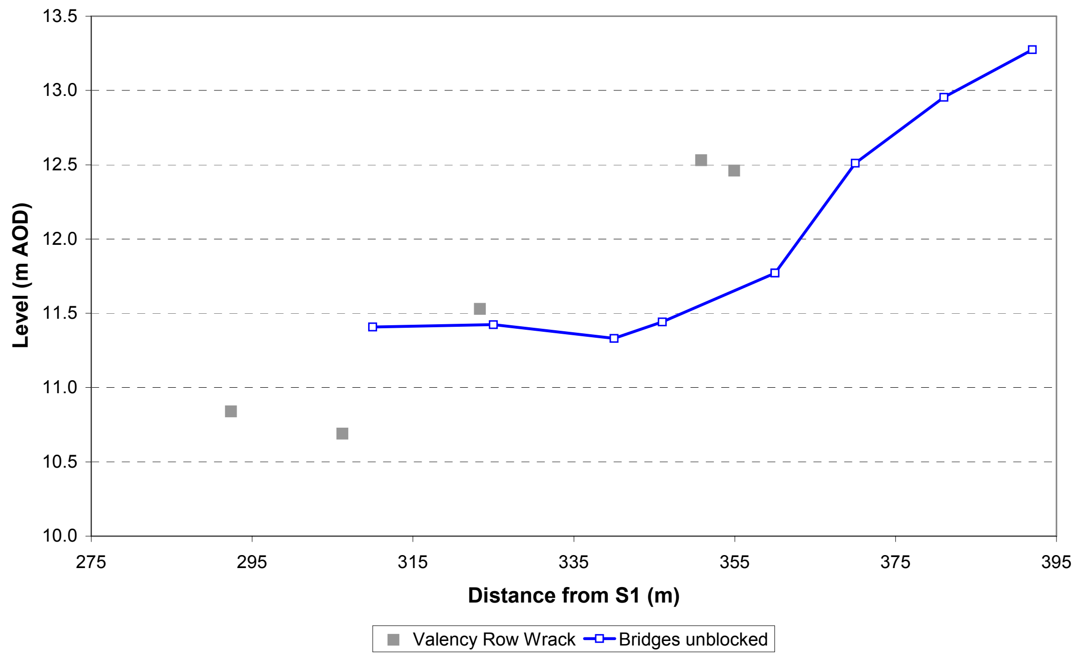


Figure 6.10 Flood levels on Valency Row with bridges unblocked

The Upstream reaches of the River Valency

In the reach extending 2 km upstream of the village of Boscastle, the simulated water level lies within the range of the observed wrack levels, see Figures 6.11 and 6.12 below.

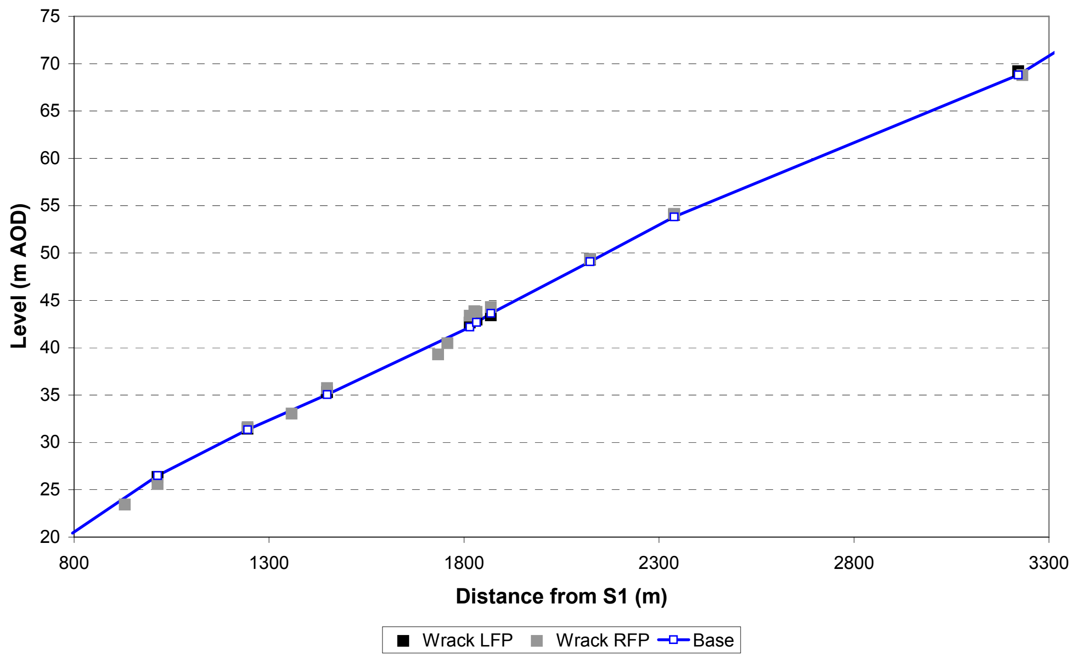


Figure 6.11 Flood levels in the middle reaches of the model

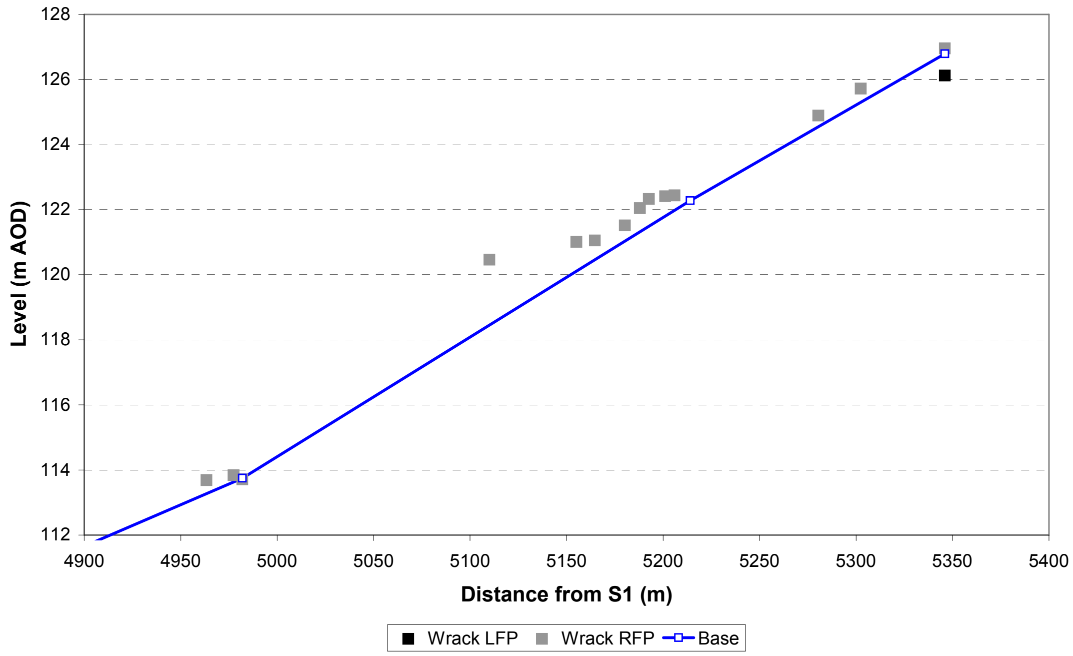


Figure 6.12 Flood levels in the upstream reaches of the model

Blockage of the Bridges

Photographic evidence

Photographs taken during and after the flood clearly show both bridges blocked with debris, (see Plates 6.1 to 6.3). Note the apparent jet of flow over the B3263 Bridge evident in Plate 6.3. Thus in the flow simulations, both bridges may be assumed to have been blocked with debris at some point during the flood; what is unclear is at what time during the flood these became blocked. On the basis of the eye-witness accounts, it has been assumed that the bridges where almost fully blocked from 16:20 hours BST (15:20 hours GMT) onwards during the peak of the event.

Plate 6.1 Photograph showing debris blocking the upstream face of Lower Bridge. Source: Mike Metcalfe. Flow is from R to L.

Plate 6.2 Cars and debris at the B3263 Road Bridge. Source: Fire Brigade

Plate 6.3 Cars and debris on the B3263 Road Bridge. Source: Fire Brigade

Figures 6.13 to 6.15 below show the maximum floodwater levels achieved in the simulations with the bridges blocked by debris.

Blockage of the Lower Bridge increases water level between Lower Bridge and B3263 Road Bridge by between 0.2 and 0.3 metres. This brings the modelled water levels closer to the observed wrack levels.

Blockage of the B3263 Road Bridge increases water levels by between 0.7 and 0.8 metres upstream of the bridge to level with the car park. These water levels agree with the wrack marks at the downstream end of the car park. At the upstream end of the car park the highest of the observed wrack marks are under predicted by 0.5 metres. Raised water levels due to the reduction in flow through the B3263 Road Bridge causes greater volumes of water to spill onto the car park, hence increasing water levels on Valency Row and the B3263 by 0.4 metres.

During the modelling it was assumed that the flow through the bridge was completely blocked, though in reality there would have been some flow under the bridge. It is unlikely that this flow through the bridge would have been significant.

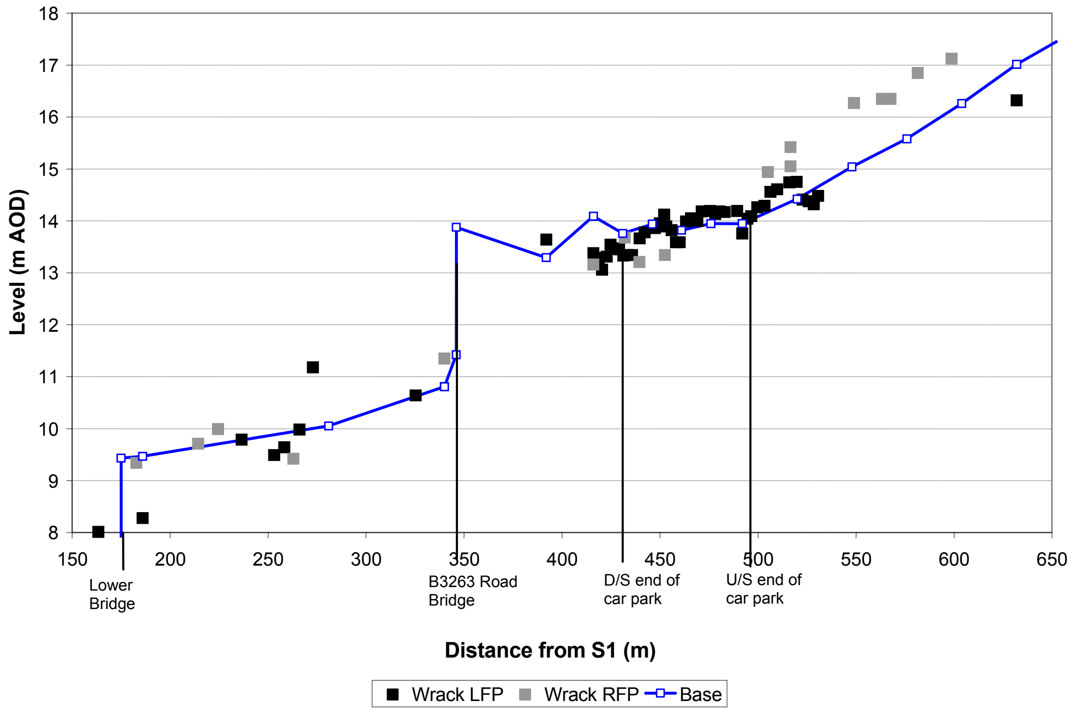


Figure 6.13 Flood levels in Boscastle with Bridges Blocked

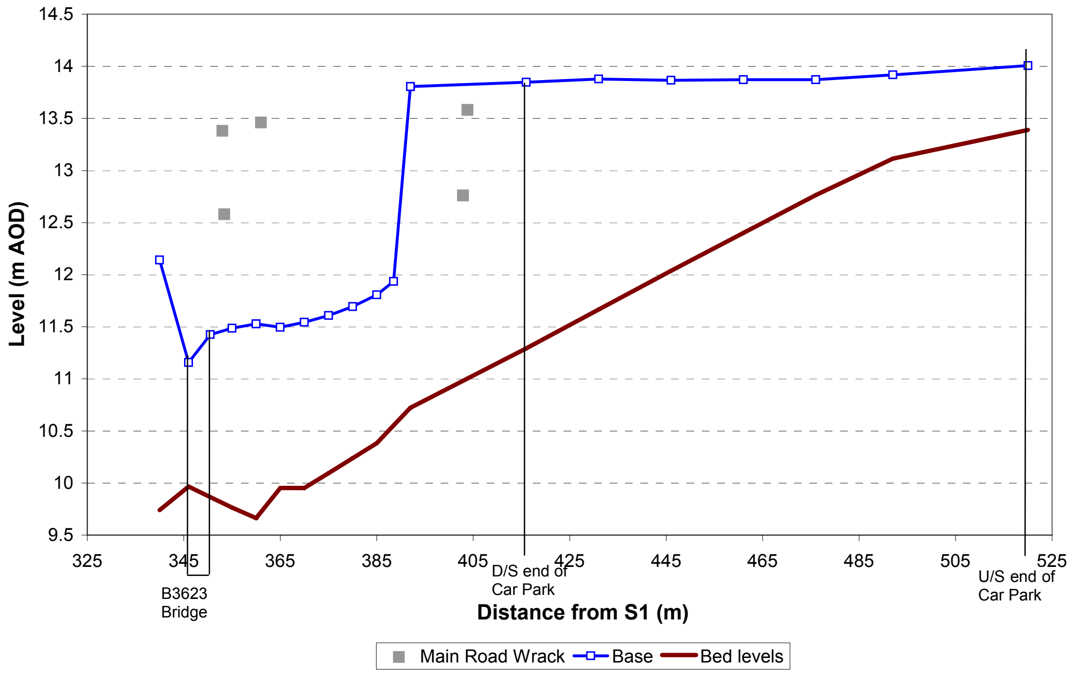


Figure 6.14 Flood Levels on the B3263 with bridges blocked

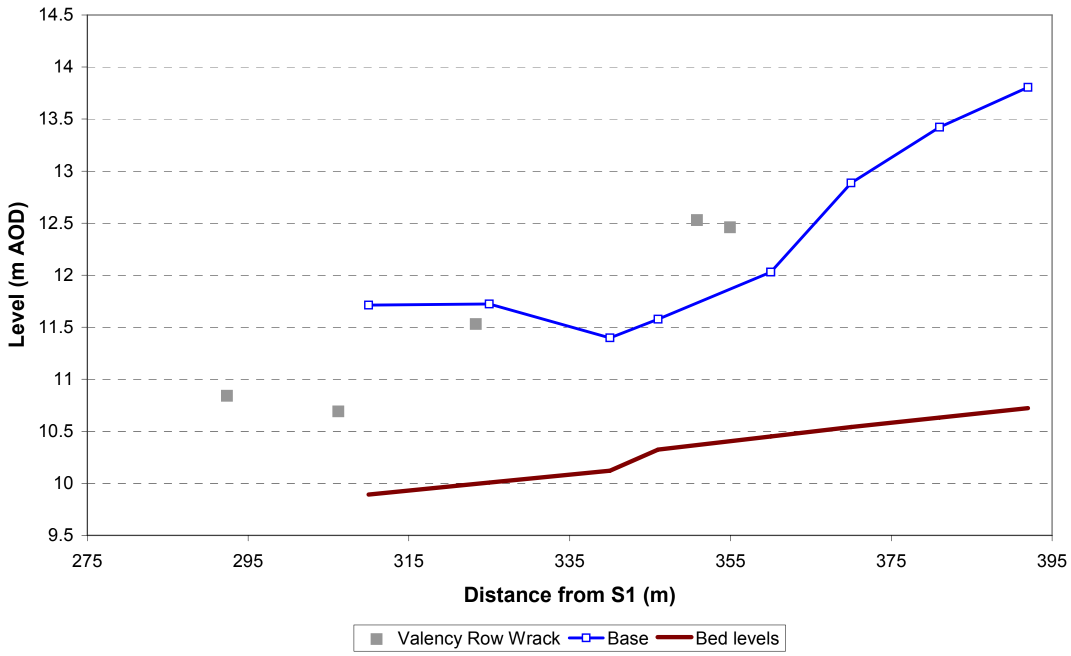


Figure 6.15 Flood levels on Valency Row with bridges blocked

Flow over the B3263 Bridge

Plate 6.4 taken after the flood of the 16th August 2004 shows that the flow route over the B3263 Road Bridge was also blocked by a large tree and other debris. The average height of this blockage has been estimated from the photographs as approximately 1.5 metres above the road level.

Plate 6.4 Photograph showing debris against the upstream parapet of the B3263 Road Bridge. Source: BBC

The effects of the blockage on top of the bridge, in conjunction with flow under the bridge being restricted, again increases the water level upstream of the bridge, resulting in closer agreement with the observed wrack levels taken from the left bank opposite the car park. This also increases water levels by 0.6 metres above the levels in the "unblocked" conditions on Valency Row and the B3263, see Figures 6.16 to 6.18.

It can be seen that the model over predicts the water levels in the reach from chainage 400 m to 500m. The water surface slope in the model appears to be significantly different to that observed from the wrack marks. This may be due to that the model is based on post flood channel cross-sections which are significantly different to those before and during the flood.

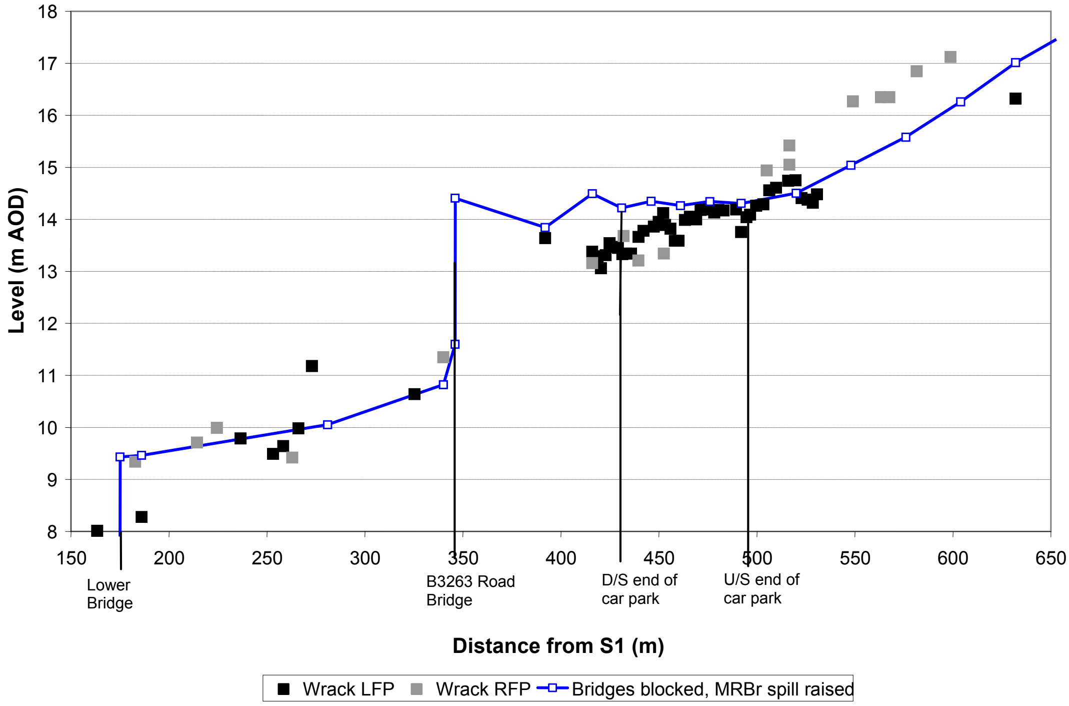


Figure 6.16 Flood levels in Boscastle with bridges blocked and B3263 road bridge spill blocked to 12.5 m AOD

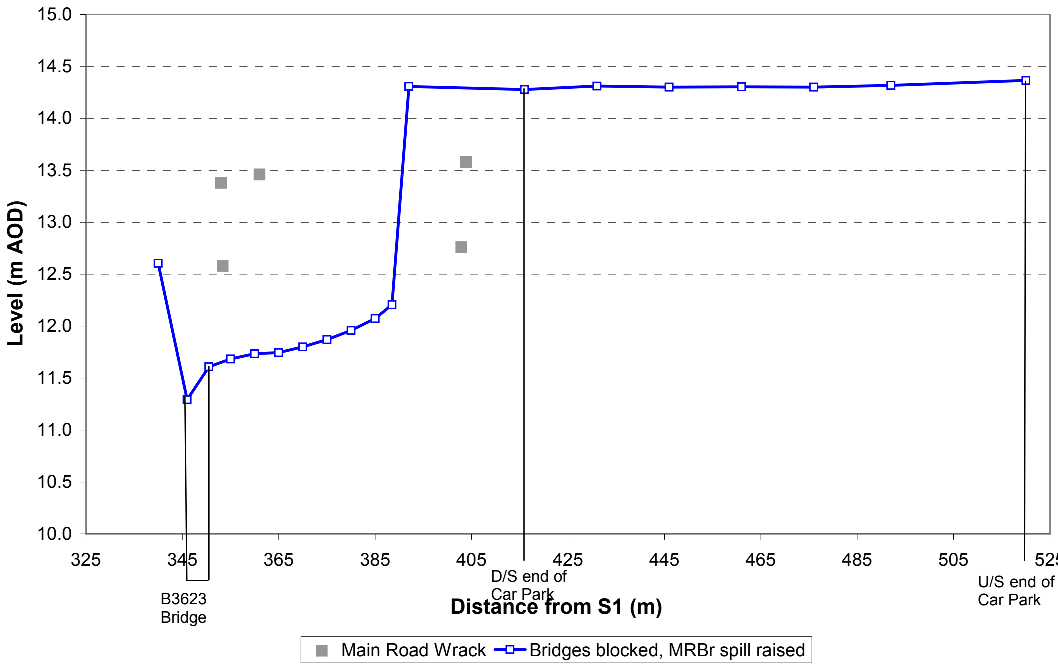


Figure 6.17 Flood Levels on the B3263 with bridges blocked and B3263 road bridge spill blocked to 12.5 m AOD

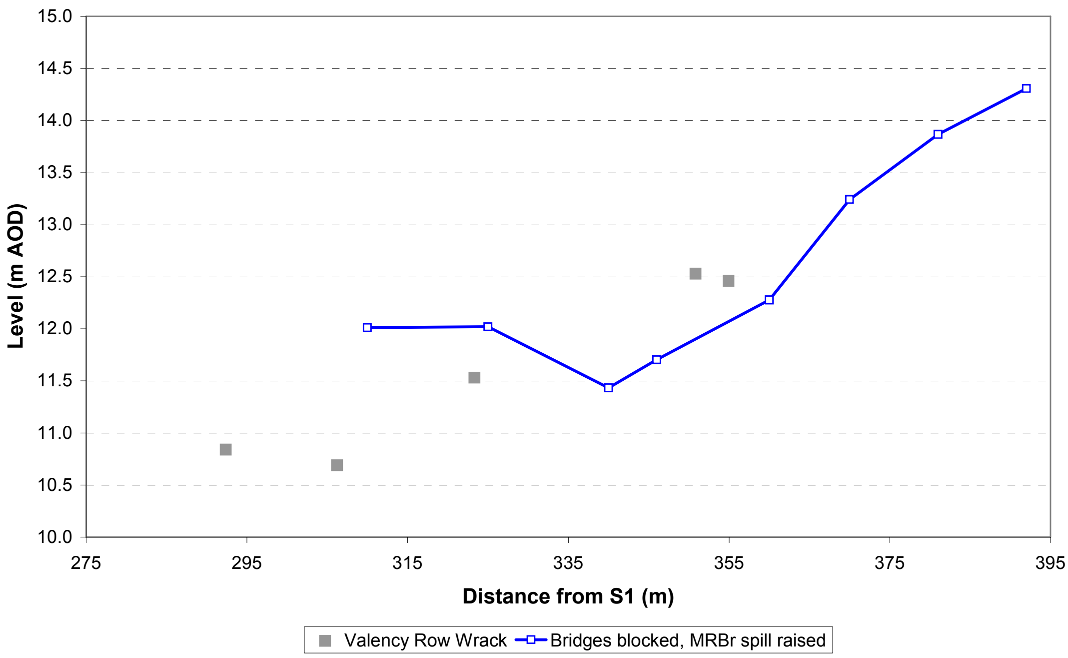


Figure 6.18 Flood levels on Valency Row with bridges blocked and B3263 road bridge spill blocked to 12.5 m AOD

Reproduction of wrack levels

Variability in the wrack levels of up to 1 metre in places may be related to standing waves and the build up of water behind transient, localised blockages, such as cars or other debris borne by the flood. The highly turbulent and surging nature of the flow is evident from Plates 6.2 and 6.3 taken during the event and can also be seen in video footage of the event. As IWRS does not represent such local transient features, it is not possible to replicate them within the constraints of the model and this may explain why the model could not replicate some of the highest wrack marks within in any realistic set of assumptions.

The water levels derived from the numerical model presented above represent the water level of the flowing water. In locations where the flow velocity approaches zero, for example, in backwaters adjacent to the bank, the water levels will rise to the total energy line. The difference between these water levels is given by the velocity head ($v^2/(2g)$). Some of the wrack marks will have come from such backwater zones and so may represent the higher total energy line rather than the water level of the flowing water as given in the above figures. As in the case of Boscastle the flow velocities were substantial, the difference between the two levels can be significant. For example, the velocity head associated with a flow velocity of 2 m/s is approximately 0.81 m. and the local flow velocities through the streets of Boscastle at the peak of the flood sometimes exceeded this value.

The wrack levels on the right hand bank upstream of the car park are remote from the river channel and are significantly higher (0.5 to 1 metre) than wrack levels on the left bank which were left in brush close to the river channel.

Sensitivity Analysis

River Resistance - Manning's 'n'

The Manning's 'n' values were increased by 25% which increased the maximum simulated water level by approximately 0.2 metres at all cross-sections. This change in water level, however, did not significantly improve the overall quality of fit to the range in observed wrack levels in Boscastle, see Figure 6.19.

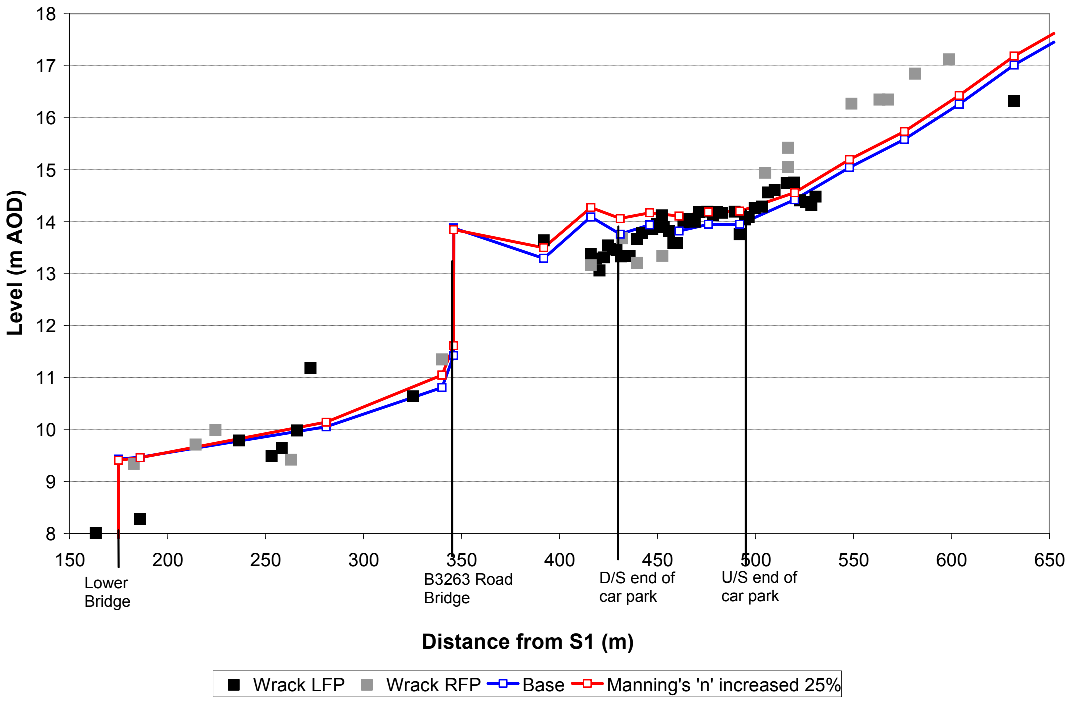


Figure 6.19 Flood levels in Boscastle for base case and increased roughness values

In the most upstream reach modelled, increasing the Manning's 'n' improves the degree of fit to the observed wrack marks, from 0.5 to 1 metre lower than the wracks to 0.25 to 0.5 metres lower than the wracks, see Figure 6.20. From chainage 400 to 500 m, however, there is still the discrepancy between the predicted water surface slope and the observed one determined from the wrack marks.

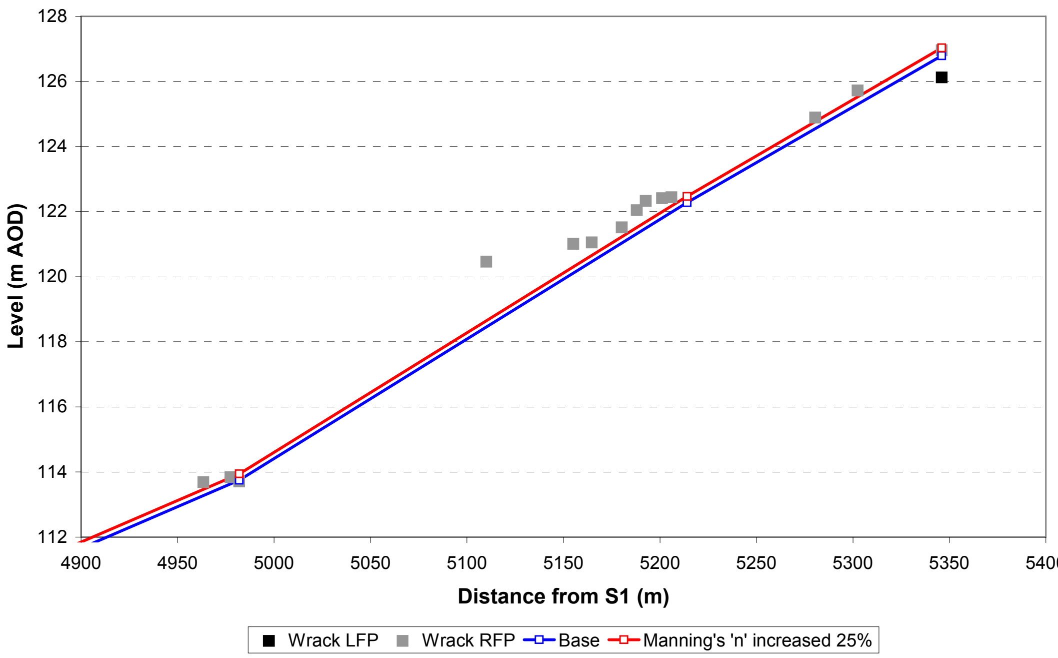


Figure 6.20 Flood levels in the upper reaches of the River Valency with base case and increased roughness values

Comparison of results for blockages at the bridges

As described in Section 6.4 above, the effects of blockage of the bridges were analysed using blockages of 0%, and 100%, and also the raising of the spill level over the parapet resulting from trapped debris.

Figures 6.21 to 6.23 below provide a comparison of the results for these three conditions.

The simulated blockage of the B3263 Road Bridge has a large effect on the water level (in excess of 1 m) in the channel upstream because of the constriction of the flow path by buildings on the right bank. The raised water levels around the car park increases the volume of water spilling into the car park and so down the streets raising water levels in the streets (Figures 6.22 and 6.23).

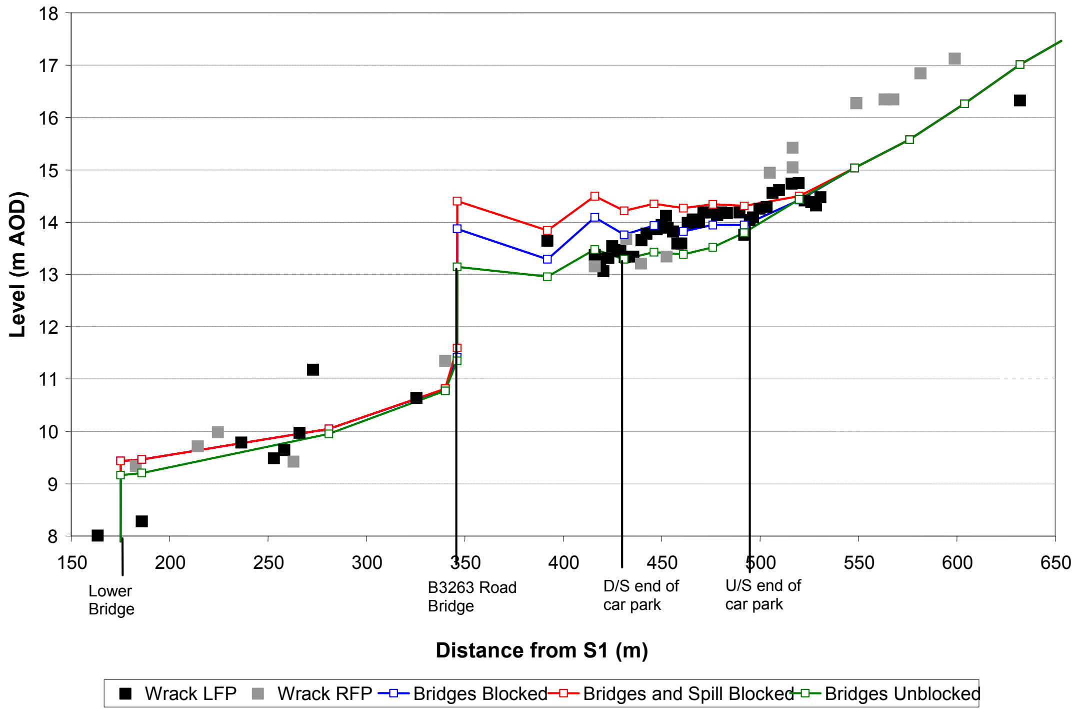


Figure 6.21 Effect of the degree of blockage of the two bridges on maximum water levels in the channel through Boscastle

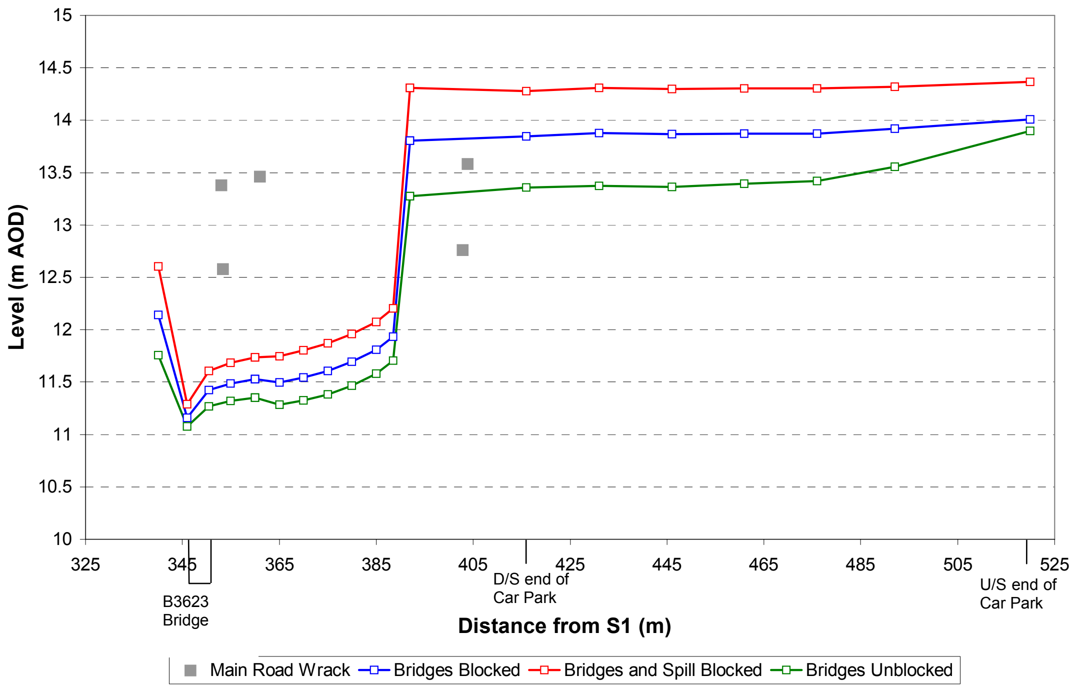


Figure 6.22 Effect of blockage of the two bridges, on maximum water levels in the car park and on the B3263

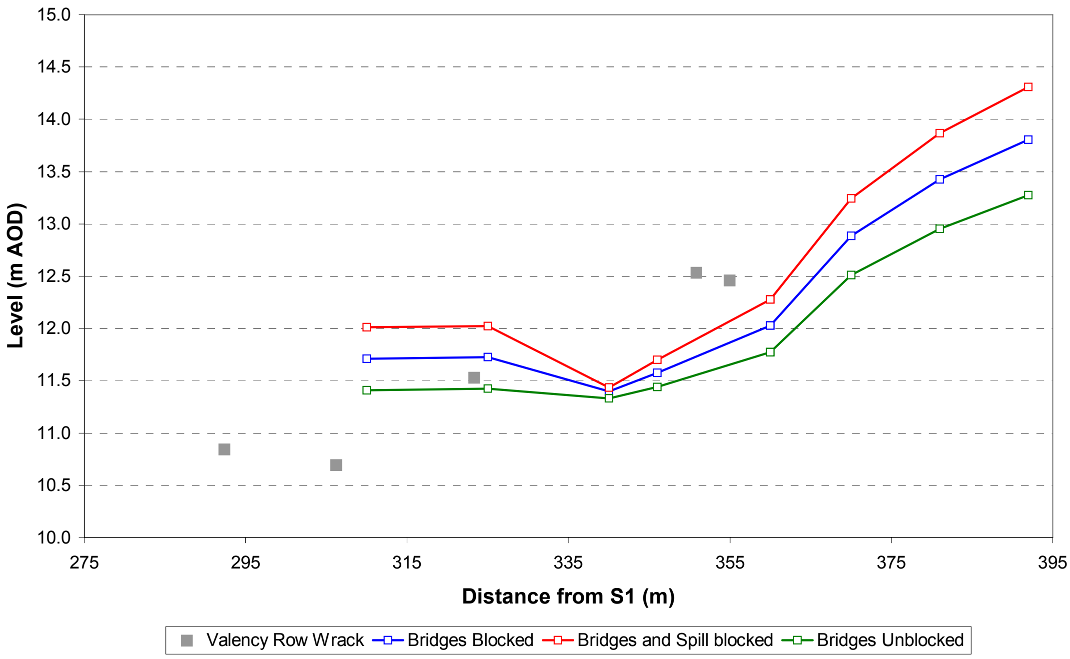


Figure 6.23 **Effect of blockage of the two bridges, on maximum water levels on Valency Row**

These Figures show that the simulated water levels are sensitive to the assumed degree of blockage of the bridges. The impact of debris blocking the B3263 Road Bridge is an increase of 0.4 to 0.5 metres in water level in the channel upstream of the bridge extending to opposite the car park, in the car park, on the B3263 and Valency Row. The impact of debris increasing the spill level over this bridge is a further increase of 0.4 to 0.5 metres at these locations. Blocking of the Lower Bridge has a much smaller impact, increasing water levels by 0.2 to 0.3 metres over a reach extending 100 metres upstream of the bridge. The smaller sensitivity arises because a substantial amount of the flow bypasses this bridge, particularly on the right floodplain.

Although there is evidence that the channel under both bridges was blocked with debris and debris was trapped on the parapet of the B3263 Bridge in the village centre, there is a large degree of uncertainty as to the extent of the blockage and the time at which it occurred. Thus uncertainty must remain in the modelled water levels. The peak water levels depend upon assumptions on the degree of blockage of the bridges, especially the B3263 Road Bridge but the "upper" and "lower" water profiles in Figures 6.21 to 6.23 above encompass most of the observed wrack levels in the channel.

Spill Elevations

The elevation of the spill representing flow through the buildings on the right bank upstream of the B3263 bridge and on to the B3263 has been varied from 11 m AOD to 12 m AOD. The crest level of the spill has been set to 11.5 m AOD in the calibrated model. Figures 6.24 to 6.26 below show that varying the level of this spill has a small (<0.1 metres) impact on the water level in the channel in the vicinity of the spill and on the car park and B3263. There is almost no impact on maximum water levels along Valency Row.

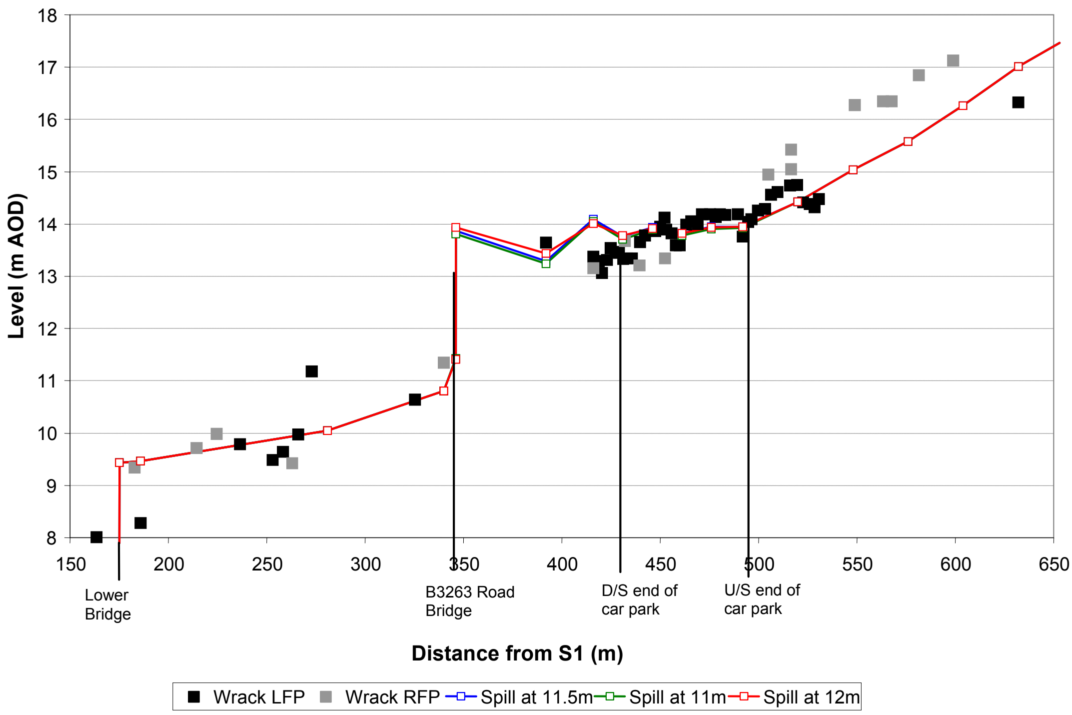


Figure 6.24 **Impact of altering the spill level for flow through buildings on to the B3263 on maximum water levels in the channel through Boscastle**

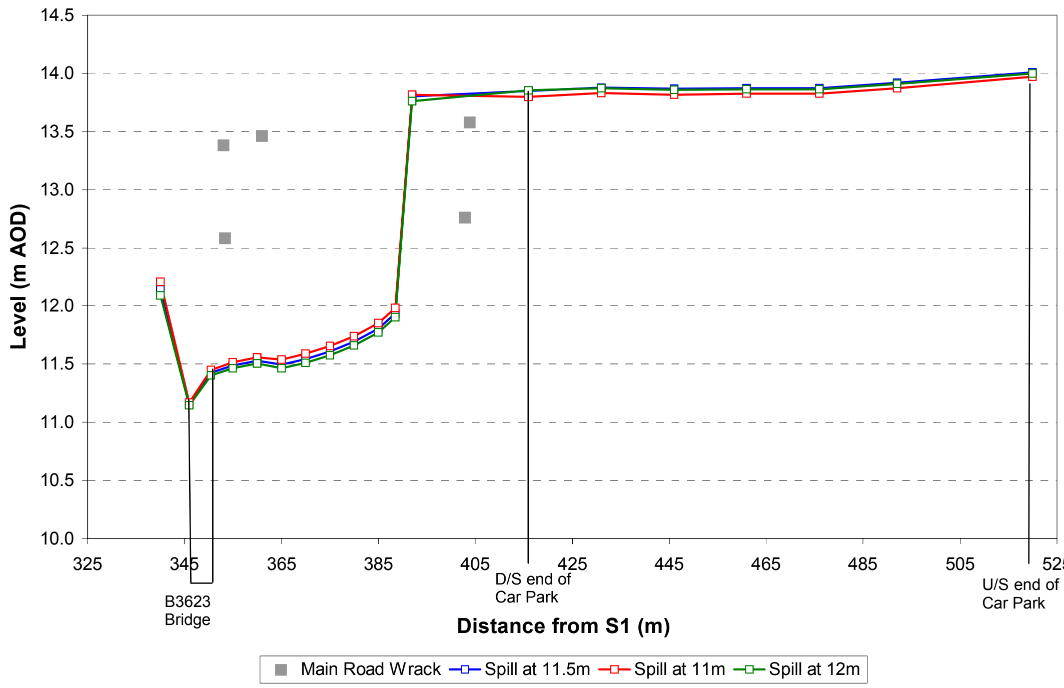


Figure 6.25 **Impact of altering the spill level for flow through buildings on to the B3263 on maximum water levels on the car park and B3263**

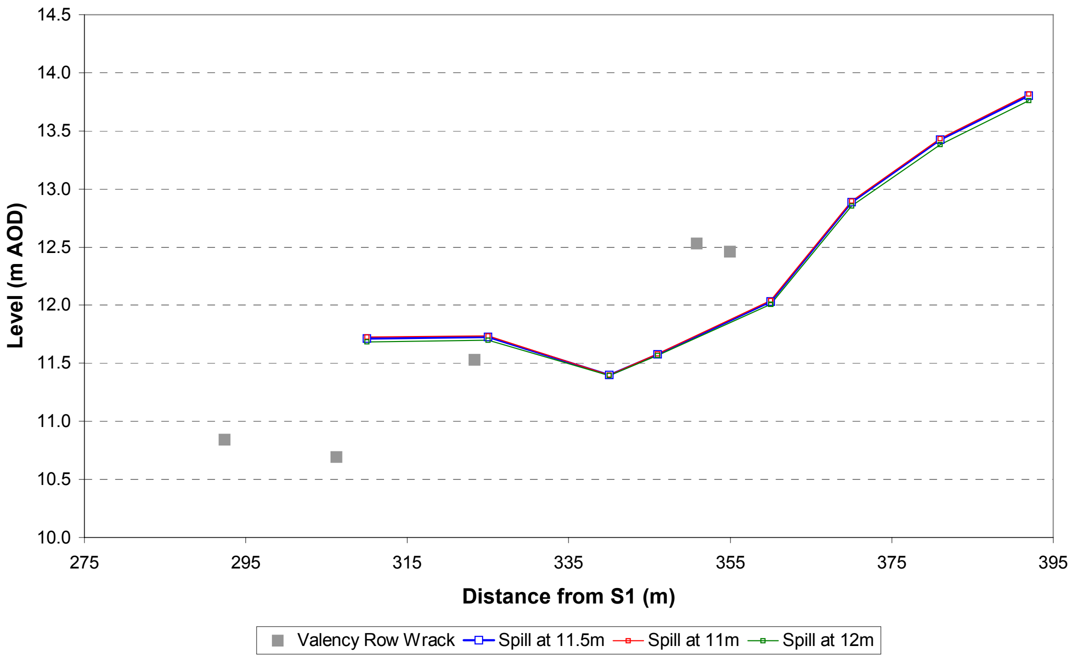


Figure 6.26 Impact of altering the spill level for flow through buildings on to the B3263 on maximum water levels on Valency Row

Car park wall

During the event it was observed that the 9 foot wall adjacent to the car park collapsed. Prior to its collapse this wall had been partially constricting flow from the Car Park down the B3263. An eyewitness account gives the time of the collapse as 16:30 BST and as this wall had collapsed prior to the flood peak, the model did not include this wall. The impact on water levels in the car park of assuming that the wall did not collapse until after the flood peak had passed was assessed. This increased peak water levels in the car park by approximately 0.25 metres.

Wall between Valency Row and gardens

The wall separating Valency Row from the open area between Clovelly Clothing and the Coastguard building was also known to have collapsed during the flood. Again it was assumed that this wall had collapsed prior to the flood peak.

The sensitivity of peak water levels in Valency Row assuming that the wall did not collapse until after the flood peak was assessed. This involved a change to the schematisation of the model; with the wall in place, Valency Row was modelled as a separate flow route, rejoining the main flow route downstream of the Coastguards building. The impact of this wall is to raise water levels from 11.35 to 11.45 metres AOD at the downstream end of Valency Row. The change affects water levels for 50 metres on Valency Row between the Coastguard building and adjacent to the B3263 Road Bridge, the new water levels being between 11.35 and 11.45 metres AOD on this section of Valency Row. There is a small reduction in water level of 0.1 metres on the main flow route due the extension of the Valency Row flow route.

Bank erosion

All the cross sections used in the model were surveyed after the 2004 flood. Geomorphological evidence indicates there was significant bed and bank erosion during the flood, see Section 3. The IWRS model has a fixed bed representation of the river channel and thus erosion is not taken into account. The channel size at some locations is likely to have been smaller during the rise of the flood than that used in the model. To test the sensitivity of channel size on the maximum flood levels, the cross-sectional area was reduced by an estimated 30% to represent the channel before the 2004 flood. The estimate of 30% was based upon our site visits to the area immediately after the event and applying standard regime theories for predicting the size and shape of stable alluvial channels.

In the upstream reach modelled, reducing the cross-sectional area increased the predicted water levels by approximately 1 metre and gave good agreement with the observed wrack levels, see Figure 6.27. In the middle reaches this over-predicted some of the wrack levels but gave good agreement with others. Upstream of the B3263 Road Bridge, reducing the width of the channel and increasing the bed had a relatively small impact on water levels compared to the upstream reaches. The effect on maximum flood level is approximately similar to that of increasing Manning's 'n' by 25%.

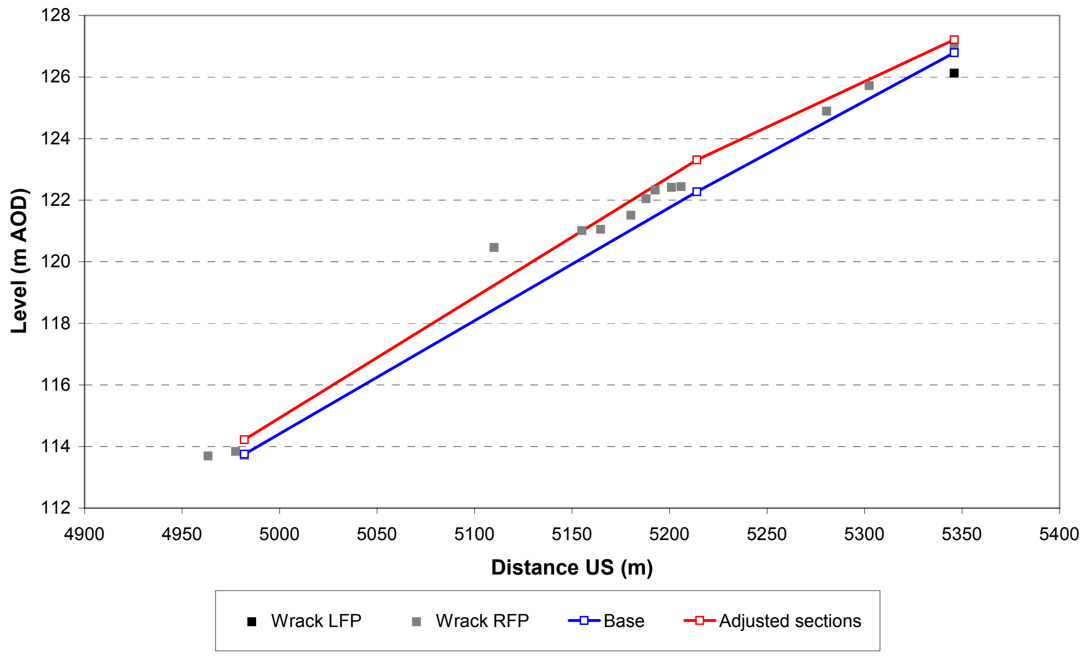


Figure 6.27 Effect of channel size on water levels on the most upstream reach modelled

Jordan River

The simulation of flood conditions in the Jordan River model has been calibrated against the observed wrack levels. The model could only be calibrated for the cross-sections upstream of the culvert for which data was available. Water is known to have ponded upstream of the culvert by Marine Terrace once the culvert capacity was reached before spilling onto the street. Upstream of section 5 the simulated water levels tend to be within 0 to 0.5 meters of the observed wrack levels. The few wrack levels available on the street correlate well with the simulated water levels in two locations, but not at the third, upstream of the building.

Figures 6.28 and 6.29 show the variation of water levels simulated along the Jordan River compared with the wrack marks.

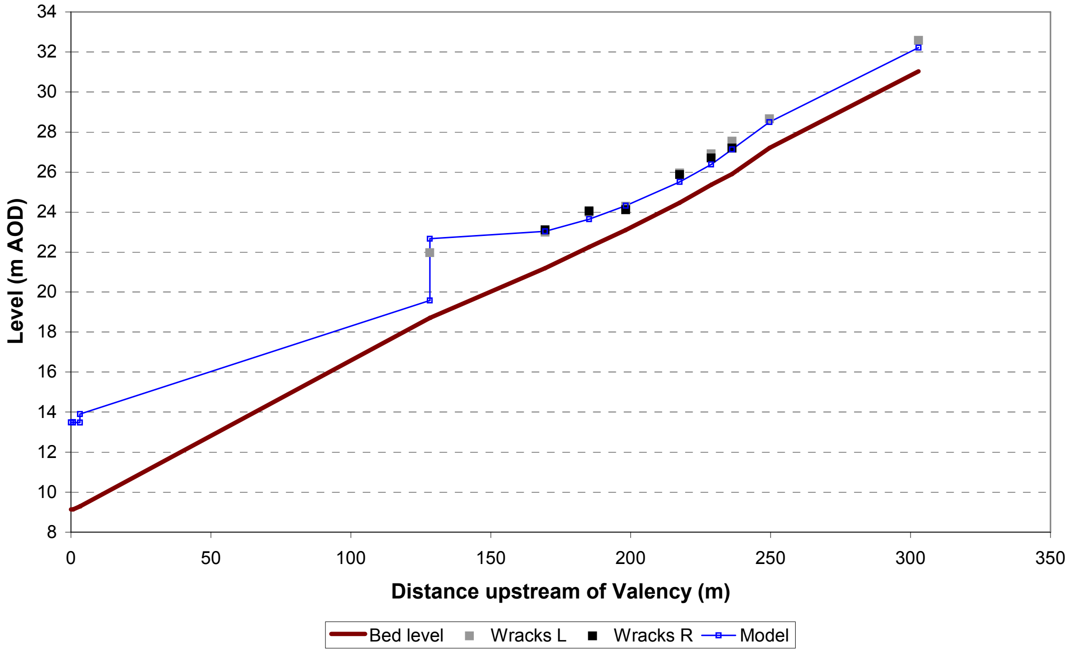


Figure 6.28 Water levels in the Jordan River channel

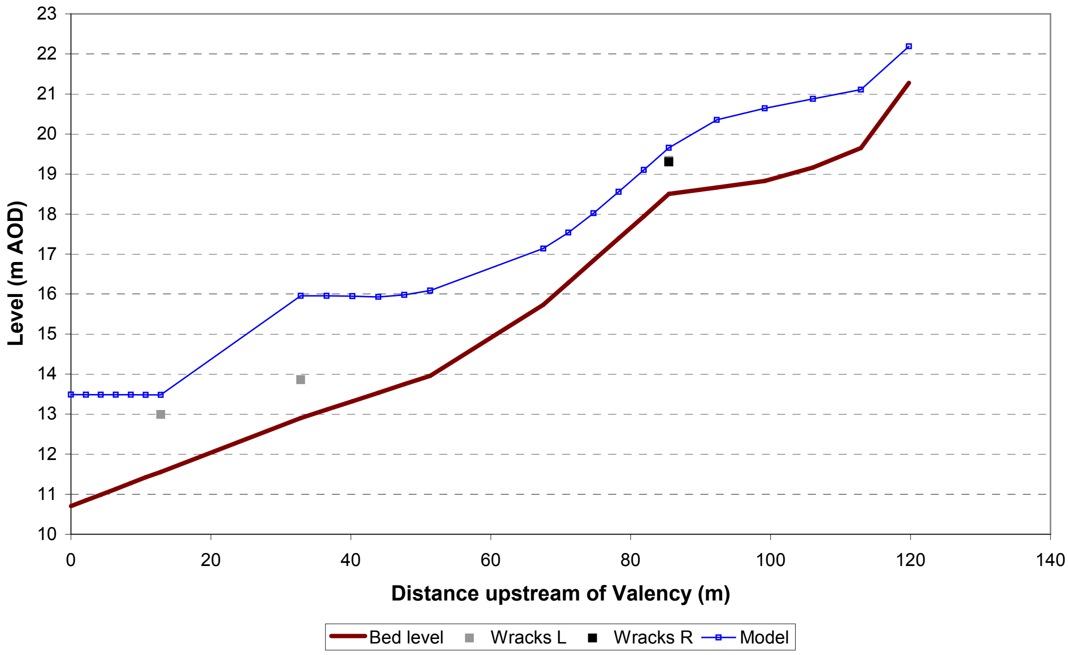


Figure 6.29 Water levels adjacent to Marine Terrace

River Discharge Hydrographs

Discharge hydrographs have been produced at the upstream extent of the Valency model, at Newmills in the middle and upstream and downstream of the confluence with Jordan River. The hydrographs are tabulated in Appendix 11.

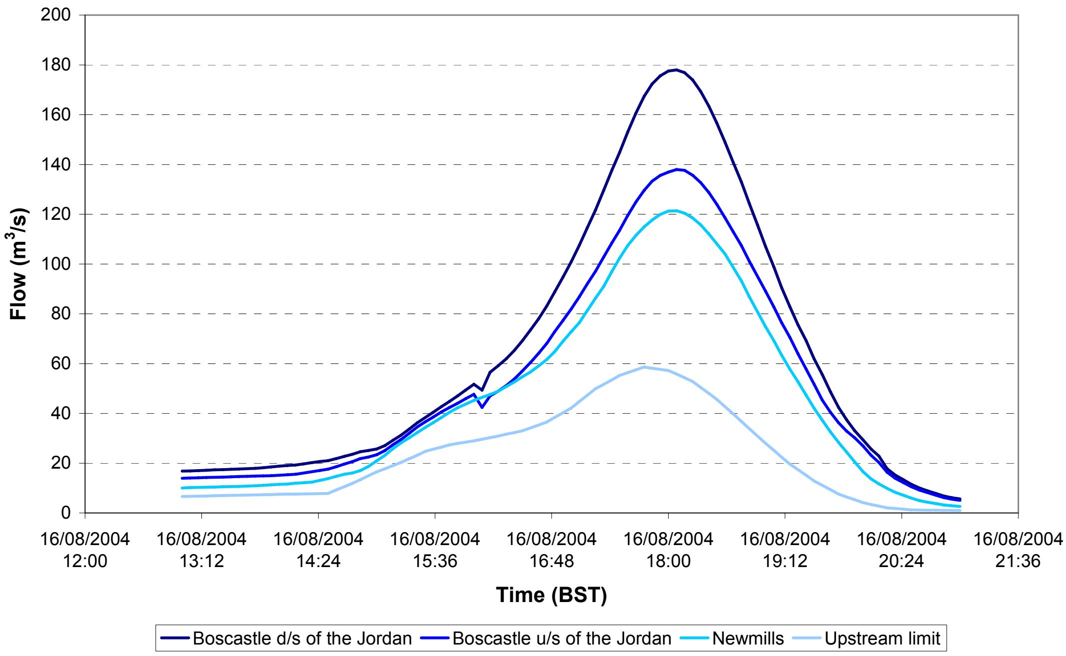


Figure 6.30 Discharge hydrographs at sites on the River Valency

The difference in timing of the peak discharge over the 5.5 kilometres of the River Valency modelled is limited to approximately 20 minutes. The difference in time of the hydrograph peak from the upstream input (B4 in Fig 6.1) to Newmills is approximately 20 minutes but from Newmills to Boscastle upstream of the Jordan is less than 5 minutes. The peak flow from the River Jordan occurs earlier than the peak on the Valency which means the peak flow on the Valency downstream of the confluence with the Jordan is earlier than on the Valency upstream of the confluence.

The difference in timing of the peaks at locations on the valley are not necessarily the actual transit time of the flood wave along the reach. The difference in time of peak occurrence is also influenced by the relative timings of the flood peak transmitted along the River Valency and the time of the runoff peaks from the various tributaries, which contribute the majority of the flow at Boscastle.

Water Velocity

The maximum flow velocity has been plotted for each cross section against the distance from the upstream limit of the model. Because IWRS is a one-dimensional hydraulic model the velocity is the average for the whole cross-section. Representing the streets as separate channels, however, means that in the centre of Boscastle velocities are available for the channel, car park, B3263 Road and Valency Road.

The maximum values of the simulated velocities are shown in Figures 6.31 to 6.33. The velocities are high but are generally consistent with the speed which might be inferred from the videos of the debris transported of the event. No direct mesurements of velocities are available for comparison. It should also be noted that the maximum water velocity may not occur at the same time as either the maximum discharge or the maximum flood level. It should be noted that the peak velocities in Boscastle are very high and would have represented a significant risk to people.

It should be noted that the velocity in the main river channel is approximately 3 m/s. The kinematic wave speed of a flood wave in a natural channel is approximately 1.3 times the water velocity and so will be about 4 m/s. This gives a transit time of about 1400 seconds (or about 23 minutes) for the 5.5 km length of river modelled.

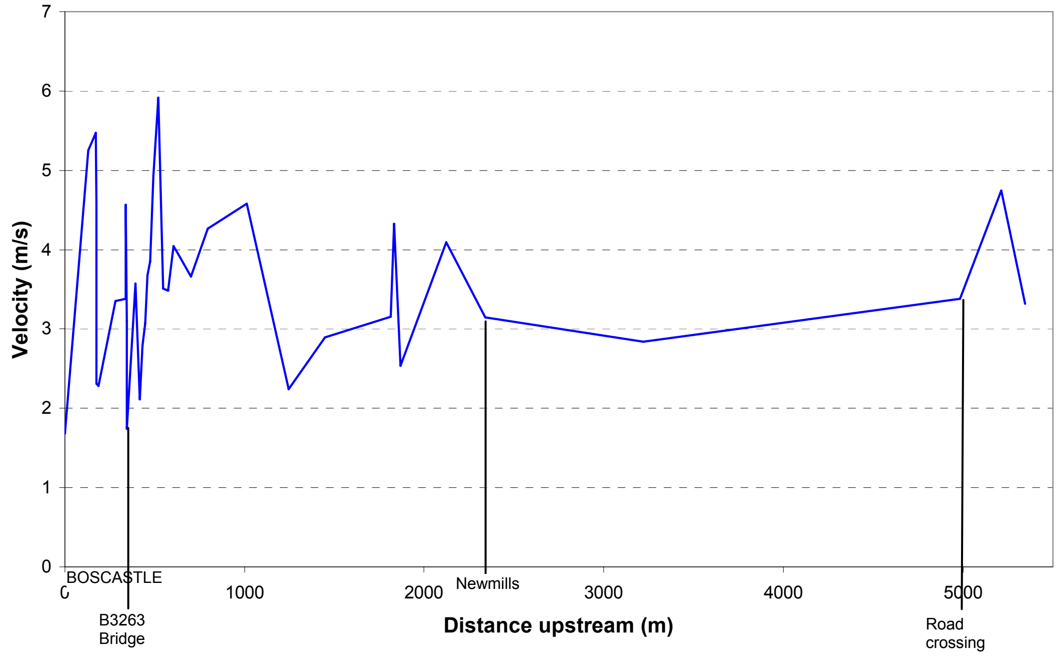


Figure 6.31 Maximum velocity at each section in the channel

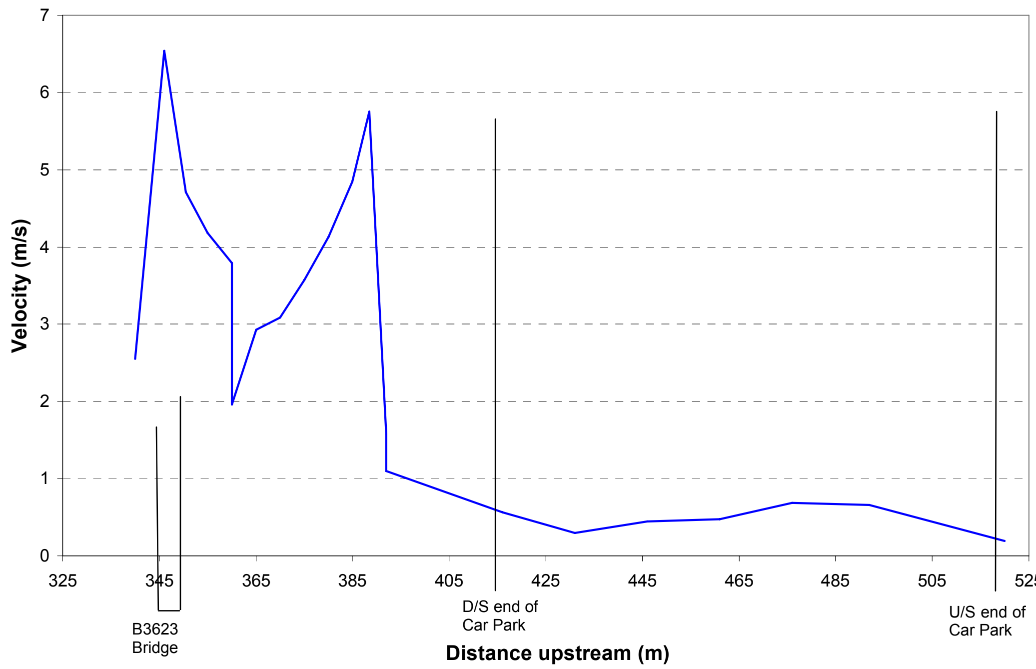


Figure 6.32 Maximum velocity on the car park and B3263

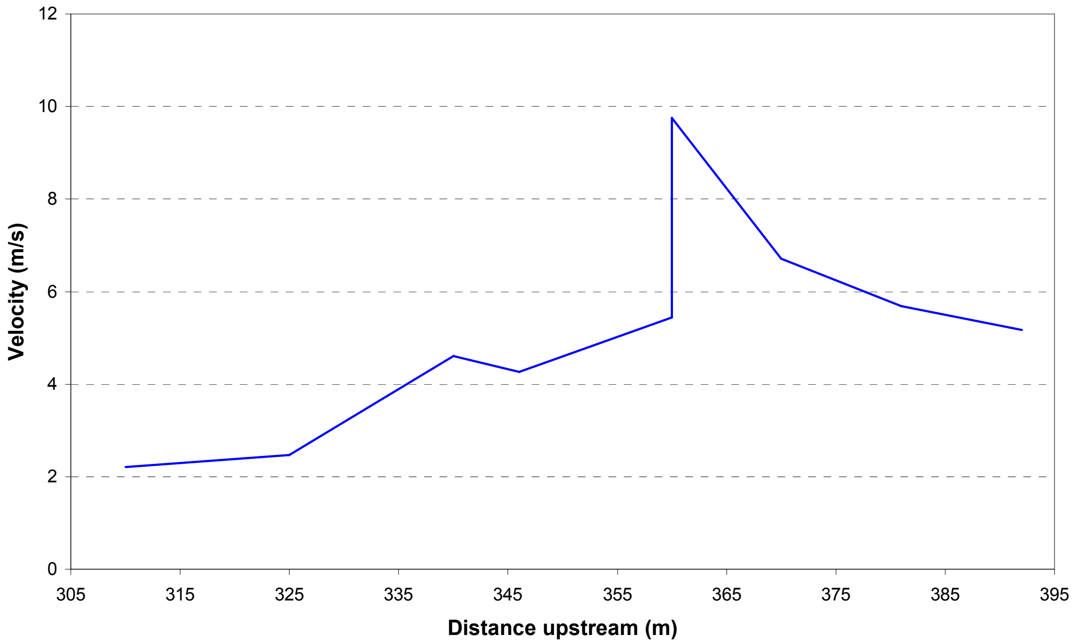


Figure 6.33 Maximum velocity in Valency Row

6.1.7 Debris dams

There is evidence that during the floods a large number of trash dams formed throughout the Valency and Crackington Stream catchments. Many of these were either broken or overtopped during the flood. The rapid failure of a trash dam has the potential to release a flood of water downstream and it has been suggested that this may have been the cause of the rapid increases in water level observed in Boscastle.

The impact of a dam failure depends upon a number of factors including; the volume of stored water, the speed of failure of the dam and the location. The main factors that control the peak discharge that is released are the height of the dam and the speed of failure. The volume of water that is stored in the dam affects the duration of the increase in discharge. In general, once a dam breaches releasing water downstream, the flood peak tends to attenuate as it goes downstream, that is, the peak discharge reduces.

To investigate the potential impact of trash dams on discharges and water levels in Boscastle a number of tests were carried out using the numerical river model. Discharge hydrographs resulting from the failure of trash dams of different heights were calculated using equations from CIRIA report Risk Management for UK Reservoirs (CIRIA C542(2000)) relating to the failure of dams.

These equations indicated that the peak discharge released from the failure of a trash dam 25 m wide and 1 metre high is 16 m^3/s. The outflow would be released as a triangular shaped hydrograph with a time base of 1 minute with the peak discharge occurring at 30 seconds.

The peak discharge released from the failure of a trash dam 2 metres high is predicted to be 45 m^3/s. The outflow hydrograph would be trapezoidal with a time base of 1 minute

15 seconds; the peak discharge occurring at 30 seconds and staying constant for 15 seconds.

As the flood wave from a dam breach attenuates as it travels downstream, the location of the dam is an important factor in determining the potential impact downstream. Thus the same dam breach occurring at different locations in the Valency catchment would have different impacts at Boscastle depending upon its location. If it occurred in the upper part of the catchment then the peak would have reduced more by the time it reached Boscastle than if it occurred much closer to Boscastle.

For exploratory purposes only, it was been assumed that a trash dam was located at section 13, approximately 200 metres upstream of the car park, although there was no evidence of a trash dam at this location. The impact of the trash dams on water levels has been assessed upstream of the car park and downstream of the car park, upstream of the B3263 Road Bridge. The discharge hydrograph due to the dam breach was added to the numerical model at the assumed location during the rise of the flood. Comparison of the water levels at these sections with and without the dam breach discharge hydrograph allows the impact of attenuation over a short reach to be assessed.

Table 6.2 Effect of hypothetical trash dams on the flood

Cross-section	Location	Level (m AOD)					Level increase (m)			
		No dam	1m Dam	2m Dam	5m dam	10m dam	1m Dam	2m Dam	5m dam	10m dam
12	Upstream of car park	17.501	17.556	17.660	18.197	19.478	0.055	0.159	0.696	1.977
8	Between car park and B3263 road bridge	12.230	12.263	12.323	12.667	14.192	0.033	0.092	0.437	1.962

Failure of a 1 metre high trash dam causes an increase of water level of 0.055 metres compared to 0.159 metres for a trash dam 2 metres high. This increase in water level declines in magnitude with distance downstream of the trash dam as the “dam-break” flow is attenuated.

Figure 6.34 shows how the discharge and the height of the flood wave reduces as one progresses downstream. The variation in the curves in Boscastle reflect the impact of the features on the floodplain confining the flow and impact of the different flow paths. The figure indicates that a 5 m high dam at the assumed location would result in a flood wave in the centre of Boscastle less than a metre high.

The modelling suggests that any trash dam would need to be of a substantial size to cause a rapid surge of water noticeably larger than the many generated by other turbulent processes. There are historic reports of significant trash dams developing in the catchment in the past. Following the August 2004 floods there were substantial log dams on the floodplain upstream of Boscastle. These are likely to have developed and then broken up during the flood. There was no visual evidence however, that any of these log dams were sufficiently large and located across the whole river and floodplain as to retain the substantial volume of water required to significantly affect flood levels in Boscastle itself.

Thus, though it may have been possible that the formation and bursting of trash dams had a significant impact on flood levels in Boscastle, it seems unlikely that such events were indeed responsible for the fluctuations of water level (“walls of water”) observed during the event; the modelling work described above indicates that dam bursts provide neither a necessary nor a sufficient explanation for the water level variations observed.. There were rapid rises in water level reported but it is probable that these were due to other causes, such as, for example, the blocking of the B3262 bridge.

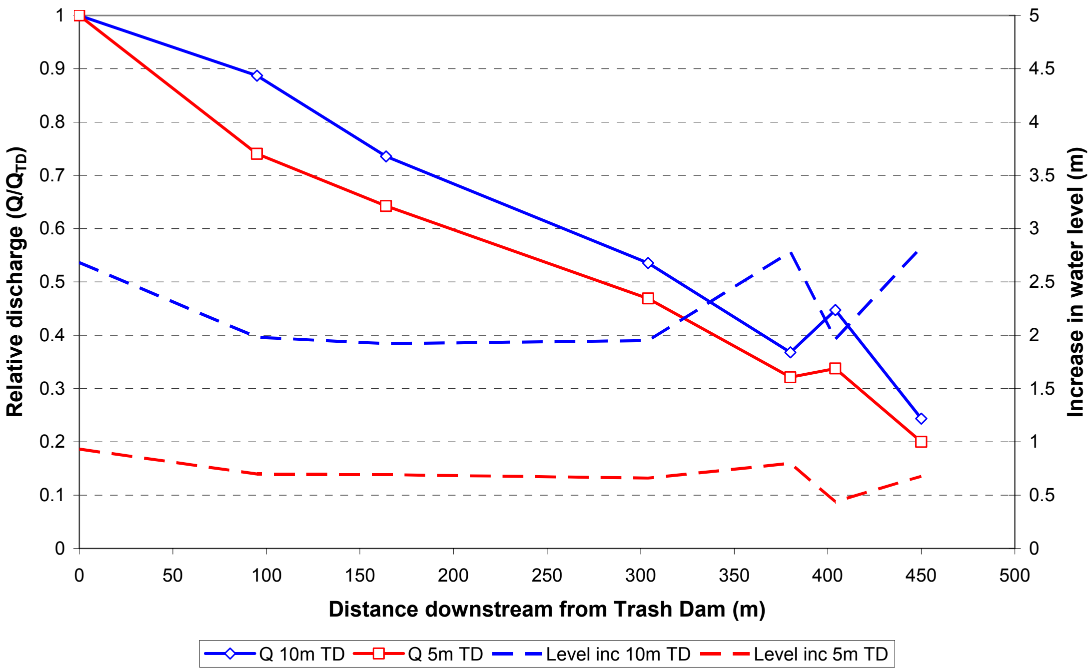


Figure 6.34 Attenuation of flood wave downstream of a trash dam

6.1.8 Discussion

Quality of Calibration

Water Levels

The hydrodynamic models of the River Valency and the Jordan River have been calibrated against the wrack levels recorded after the flood. The maximum water levels generally lie within the range of the wrack levels in Boscastle and are consistent with the overall gradient of the wrack lines. There is, however, considerable scatter in the wrack levels locally about the overall trend and it has been impossible to fit the model to each observed level

Simulated water levels under predict the wrack levels on the B3263 downstream of the car park. Upstream of the B3263, however, the model tends to over predict the observed wrack marks. The simulation of the flow down the various streets of Boscastle is difficult within the context of a one-dimensional model as the division of the flow between the various flow paths may depend upon local features. In addition the representation of bridges significantly blocked by trash is also difficult to represent with any confidence. This means that the confidence that one can place in the predicted water levels is less than one might otherwise have. It is clear that the simulation of water levels through urban areas is subject to uncertainty.

Timing

The time of concentration of the runoff from the subcatchments between the peak incident rainfall and the peak outflow is discussed in the hydrological studies. This should be added to the transit time for flows along the main river (of the order of 20 minutes over the 5.5 km upstream of Boscastle).

The key determinants of the timing of the flood peak in Boscastle arise from the hydrological modelling assumptions.

Capacity of Structures

Lower Bridge

The soffit level of the Lower Bridge is 6.490 metres AOD which is the bankfull level. The flow capacity of the unblocked bridge is 12.8 m^3/s. It should be noted that this is significantly smaller than the peak flood discharge. The implication is that there would have been extensive flooding in this area even if the bridge had not been blocked by trash during the flood.

B3263 Road Bridge

The soffit level of the B3263 Road Bridge is 10.320 metres AOD, which is below the bankfull level. The flow capacity of the unblocked bridge is 31.8 m^3/s. It should be noted that this is significantly smaller than the peak flood discharge. The implication is that there would have been extensive flooding in this area even if the bridge had not been blocked by trash during the flood.

Jordan Culvert

The flow capacity of the unblocked Jordan culvert when the culvert is just flowing full is of the order of 2 m^3/s. The maximum flow passed by the culvert during the event, assuming that it had not been blocked by the peak was of the order of 5.3 m^3/s. This compares with peak discharge in the Jordan at this location during the event of approximately 19m^3/s.

Assessment of bankfull discharge at selected cross-sections on the Valency

The assessments of bankfull discharges are based on post-flood cross-section surveys. Due to the extensive morphological changes, particularly in width and depth of the main channel this means that the pre-flood bankfull discharges may have been significantly different.

Upstream of the Lower Bridge and downstream of the B3263 Road Bridge the bankfull capacity of the channel has been assessed as approximately 53 m^3/s. Upstream of the B3263 Road Bridge where the channel is constrained by buildings the capacity of the channel is approximately 21 m^3/s, however at the upstream end of the car park the capacity of the channel to the top of the flood bank is approximately 116 m^3/s. This figure reflects the post flood channel widening and deepening that were carried out. The results show that the channel capacity of the Valency through Boscastle is highly variable which reflects the large amount of human interference with the river channel in this area.

At the upstream end of the Valency at New Mills the bankfull capacity of the channel was assessed to be approximately 23 m^3/s and at the most upstream cross-section in the model to be approximately 17 m^3/s. This reduction in bank full capacity as one progresses upstream reflects the reducing flows as one progresses up the main stem of the river.

Assessment of bankfull discharge at selected cross-sections on Crackington Stream

Upstream of the Crackington Haven bridge the bankfull capacity of the channel has been assessed as approximately 30 m^3/s. At two locations between Crackington Haven and Congdons Bridge the channel capacity is approximately 12 and 26 m^3/s, while at Congdons Bridge the bankfull capacity is approximately 32 m^3/s. At Mineshop at the upstream end of the modelled reach the bankfull discharge is approximately 10 m^3/s.

Effects of blockages and failures

The numerical model results show that blockage of the B3263 bridge had a significant effect on water levels and flow distribution between the river and streets, see for example Figure 6.21. The greatest sensitivity to this lay in the reach between the B3263 Bridge and the Car Park where levels between the scenarios differed by over 1 m. It should be noted, however, that the capacity of the bridge was so much smaller than the peak flood discharge that the depth of flooding in this area would still have been substantial even if the bridge had not been blocked.

If the bridge became blocked nearly instantaneously, it would have led to a rapid increase in water levels upstream, towards the car park, and a corresponding increase of flow along the streets in Boscastle.

The effects of failure of walls in the flood depend upon the timing of failure and their location. For example if the car park wall had not failed, the maximum levels would have been locally about a quarter of a metre higher.

Summary of the modelled conditions

Discharge peak

The model calibration discussed in this report relates to a peak river flow in the Valency downstream of the confluence with the Jordan of 178 m^3/s from the hydrological modelling of the catchment. The choice of rainfall depths and runoff parameters which produce this rate of flow are described in the account of the hydrological studies in Chapter 5.

River resistance

Our approach to the selection of river resistance is based upon expert assessment during site visits in the fortnight or so following the flood. This assessment produced a gradation of resistance along the river according to the bed and bank conditions. The ranges of values selected are as given in Table 6.1 above. Generally the Manning's n for the river channel lies between 0.04 in the straight reaches towards the downstream end of the model rising to 0.05 in the more natural channel upstream of the car park.

Configuration of structures

Our final modelled simulation of the flood assumed that the main river channel was effectively blocked under the arch of both bridges but that the flow path was effectively "clear" above the bridge.

Water surface profiles

The water surface profiles under these conditions for the 2004 flood are given in Figures 6.12, 6.13 and 6.14 above.

Sensitivities and uncertainties

The uncertainties introduced by several modelling assumptions have been studied, see Section 6.5 above.

Uncertainty in assumptions made on the degree of blockage to the B3263 Road Bridge has significant impact on simulated water levels upstream of the bridge, in the car park, on the B3263 and Valency Row.

The assumptions on water flowing through the buildings on the right bank upstream of the B3263 bridge have a low impact on water levels.

In the upper kilometre of the modelled River Valency water levels are significantly (1 metre) lower than observed wrack levels. This can be explained if it is assumed that the cross-sections surveyed post flood had been eroded during the flood.

The sensitivity to river resistance is such that a uniform 25 percent increase in all Manning's 'n' roughness coefficients increases water levels by up to 0.25 metres.

Local standing waves which cannot be modelled in IWRS and the impact of the velocity head may explain the variability in the observed wrack marks, and the under or over prediction of some of these.

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6.2 CRACKINGTON STREAM

6.2.1 Model Overview

Modelling Approach

The hydraulic model of the Crackington Stream catchment has been constructed using the InfoWorksRS (IWRS) software which uses the same hydraulic simulation "engine" as ISIS. IWRS was used because it is linked automatically to a GIS of the catchment, facilitating the use of geo-referenced data. It also records the model versions as part of the run management facilities.

Crackington Stream Model Area

The Crackington Stream catchment has two main rivers, the Crackington Stream and the Pengold Stream, the confluence of which is located at the downstream end of the catchment, downstream of the Road Bridge. The majority of properties flooded were upstream of the bridge on both the Crackington and Pengold Streams.

The modelled reach of Crackington Stream extends from Mineshop, where there is a confluence of two tributaries forming Crackington Stream, to the estuary at the downstream end. The modelled extent of Pengold Stream is a short 200m reach extending to the confluence with Crackington Stream.

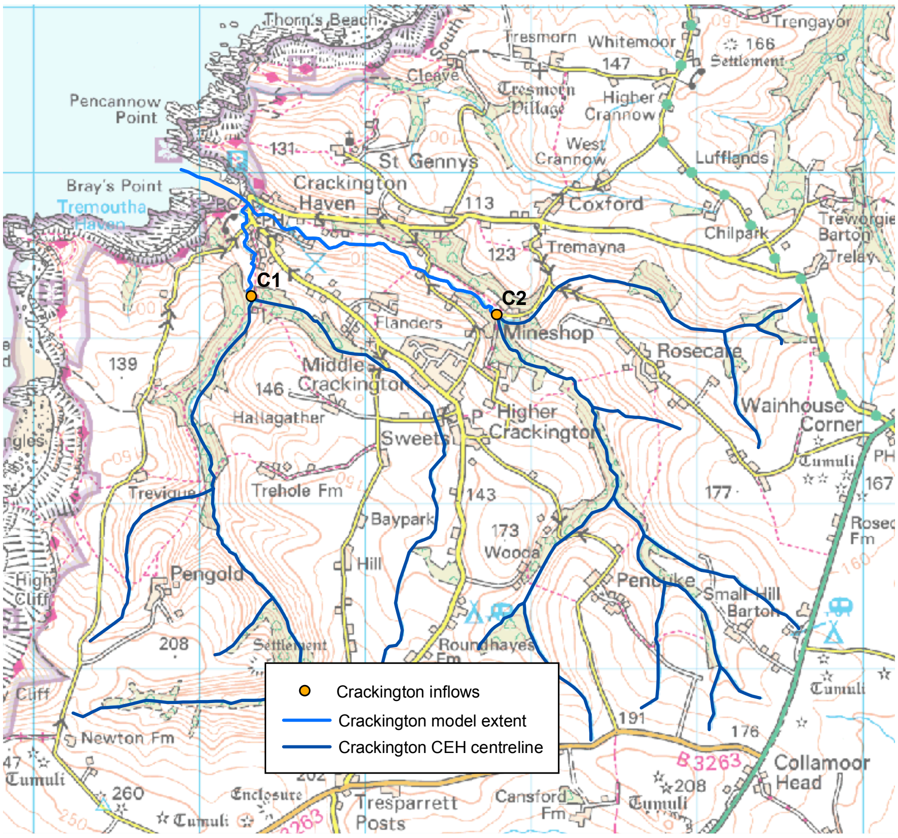

Figure 6.34 Crackington Stream catchment, showing locations of hydrological inputs

Upstream flow conditions

The upstream limit of the hydraulic model is located approximately 2 km east of Crackington Haven, at point C2 on Figure 6.34. The runoff from the catchment is simulated in a distributed fashion from Crackington and Pengold Streams. In all, HR Wallingford identified two subcatchments and an inflow hydrograph has been calculated for each by CEH Wallingford. The locations of these inflow points are shown in the Figure 6.34 above. Boundary C1 is the upstream boundary of Pengold Stream and boundary C2 the upstream boundary of Crackington Stream.

Downstream boundary

The downstream boundary is located at the point where the river widens into the estuary and is far enough downstream so as not too influence the water levels in Crackington Haven. The tidal water levels for Boscastle and Crackington Haven on the 16th of August 2004 have been calculated from Admiralty Tide Tables; the nearest tide station is Milford Haven in Wales. The data for this station has been adjusted for time and water level using correction factors given in the Tide Tables for Boscastle and the calculated tide level of 0.5 metres AOD at Boscastle at the time of the peak of the flood. Data on actual tide levels during the event suggested that at the time of the flood there was a positive tidal surge of approximately 0.3 m. Thus the actual tide level at the peak of the flood was approximately 0.8 m AOD. Study of the site concluded that the tidal levels had no impact on the peak flood water level in the village of Crackington Haven and, therefore, the downstream boundary condition used in the hydraulic modelling was a discharge stage relationship. This was derived using the normal depth method at the downstream cross section.

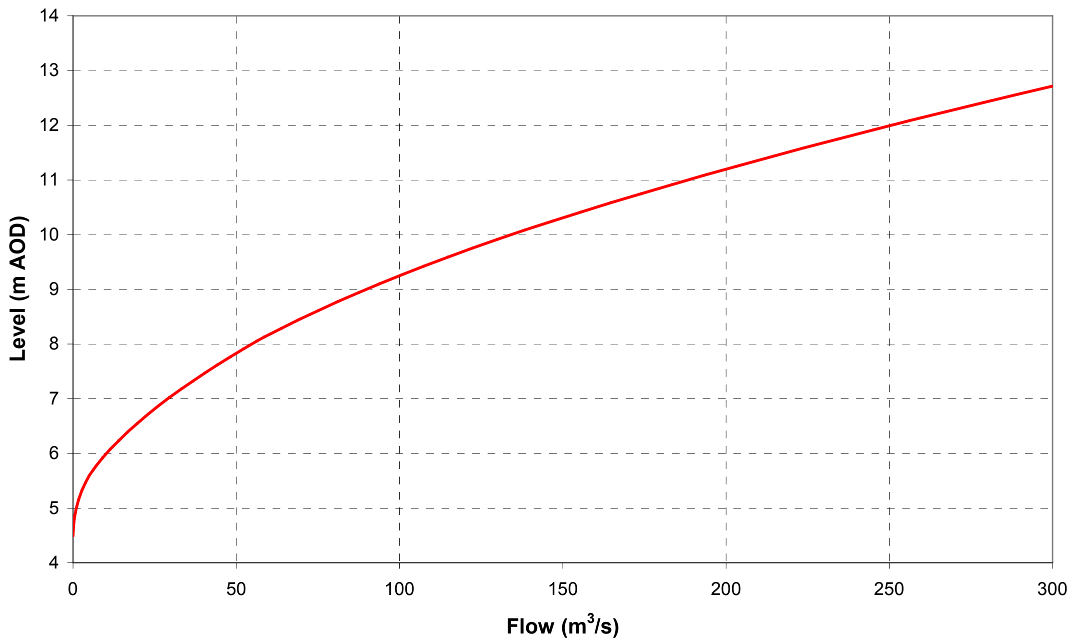

Figure 6.35 Stage discharge relationship at the downstream boundary of Crackington Stream

Floodplain representation

The hydraulic model for Crackington Stream represents the floodplain as extended cross-sections. This is because for the most part flow routes on the floodplain are not separated from the channel. The floodplain complexity also tends to be simple, for example, fields. In Crackington Haven buildings are generally at the edge of the floodplain, and, unlike Boscastle, there is not the presence of significant separate flow routes down streets.

Topographic data used to construct the model cross-sections came from two sources:

- Survey of Crackington Stream and Pengold Stream undertaken by Royal Haskoning, after the event
- pre-event LIDAR data from the Environment Agency

The LIDAR data was used to extend the surveyed cross-sections in certain areas of the model where the surveyed cross-sections did not cover the full width of the floodplain but it was only used in locations where it had good agreement with the surveyed cross-section elevations.

The river has large meanders: to ensure the flow chainage and slope is correct on the floodplain relative to the channel, the "Relative Path Length" is used in IWRS. Relative Path Length (RPL) is a factor relating the distance of the flow path on the floodplain to the chainage along the channel. The length of the flow path on the floodplain at the inside of a bend can be reduced and the length of flow path on the floodplain at the outside of the bend increased; this influences the effective local water surface gradients and velocities.

Features not modelled

The IWRS simulation model has fixed geometry except for certain types of gated structure. The IWRS model does not take into account local standing waves caused by objects in the flow or local transient waves that can be produced by flows around debris such as trees or cars. In some sensitivity tests, however, we have reconfigured the model to approximate the effects of some assumed blockages by using gated structure options in the software.

6.2.2 Hydraulic Structures

There are four key hydraulic structures on Crackington Stream.

Bridge Structure 1

Bridge Structure 1, the road bridge in Crackington Haven, has been modelled with three vertical sluice units in IWRS. The left hand arch (when looking downstream) has been modelled using two vertical sluice units to represent the change in ground levels within this arch. The right hand arch has been modelled using a single sluice gate. The representation as sluices was chosen to account for the weir under the bridge, which it is not possible to model using an arch bridge unit. The sluice gates within the model are of such a size as not to allow flow over the top of the gate. Weir flow overtopping the bridge parapets has been modelled with an in-line spill unit in parallel with the sluice gates.

An advantage of the vertical sluice unit is that the impact of blockage of the bridge can be represented by lowering the sluice gate during the run. Simulations have been run with the sluice gates open representing the unblocked bridge and with the gates closed from 18:00 hours GMT (19:00 BST) during the peak of the event representing the bridge when blocked.

Bridge Structure 2

Bridge Structure 2, an access bridge located upstream of Crackington Haven, has been modelled with an arch bridge unit in IWRS. Bridge structure 2 is a small bridge with no parapets. Weir flow overtopping the bridge has been modelled with an in-line spill unit in parallel with the arch bridge. The bridge shape and spill elevations have been taken from the Royal Haskoning survey.

Bridge Structure 3 (Congdons Bridge)

Congdons Bridge, labelled as Bridge Structure 3, has been modelled in IWRS as a two arch bridge with an overflow weir. The bridge shape has been taken from the Royal Haskoning survey.

Weir downstream of Congdons Bridge

The survey photographs show the presence of a small weir downstream of Congdons Bridge. However this weir was not surveyed. The weir has been modelled using an in-line spill unit taking the ground levels from section CH1305 as the weir crest.

There are three key hydraulic structures on Pengold Stream.

Bridge Structure 0

Bridge structure 0 is a single arch road bridge upstream of the confluence with Crackington Stream. The bridge shape has been taken from the Royal Haskoning survey. Weir flow overtopping the bridge has been modelled with an in-line spill unit in parallel with the arch bridge. The Royal Haskoning survey did not include parapet levels for this bridge but the road elevation was included and this was used in the spill unit.

Bridge Structure 4

Bridge structure 4 is a single arch road bridge located towards the upstream end of the modelled reach of the Pengold Stream. This has been modelled as an arch bridge unit in IWRS. The Royal Haskoning survey did not include parapet levels for this bridge since this had been demolished in the flood; the road elevation was included and this was used in the spill unit.

Weir downstream of Bridge structure 4

There is a weir at the downstream end of Bridge Structure 4. However this weir was not surveyed. This has been modelled using an in-line spill unit taking the ground levels from section PS184 as the weir crest.

6.2.3 Calibration

Calibration data

The following data were available for calibration of the hydraulic model:

- Wrack levels surveyed by Royal Haskoning following the flood of the 16th August 2004
- Eye witness reports from the public of the August 2004 flood

No observed river discharges or velocities were available for calibration; the information on discharge was derived from the hydrological studies. The water level data for calibration were derived for the August 16 event only; ideally for model calibration water levels and flows are sought for several events but in this case this has not been possible.

Calibration on the 16th August 2004 event

The model can be calibrated against the observed wrack levels by varying the following parameters and inputs:

- The discharge hydrographs
- The river roughness (Manning's 'n' values)
- The degree of blockage of the bridges
- The "Spill" levels for the hydraulic connection between different parts of the network through the village
- The discharge coefficients for the spills and other structures

The calibrated model predicts a peak flow of 91 m^3/s in the village of Crackington Haven, downstream of the confluence with the Pengold Stream. The peak flows on Crackington Stream upstream of the confluence with Pengold Stream and the Pengold Stream itself are 47 m^3/s and 44 m^3/s, respectively. In IWRS, "spill" units calculate the flow of water over an irregular weir using a standard weir equation for dry, free and drowned flow, forward and reverse modes, and a weir coefficient. The default value of 1.7 was used for the weir coefficients of the in-line spills for flow overtopping the bridges and for flow over the weirs. The calibrated model has a Manning's 'n' of 0.075 in the channel and 0.15 on the floodplains.

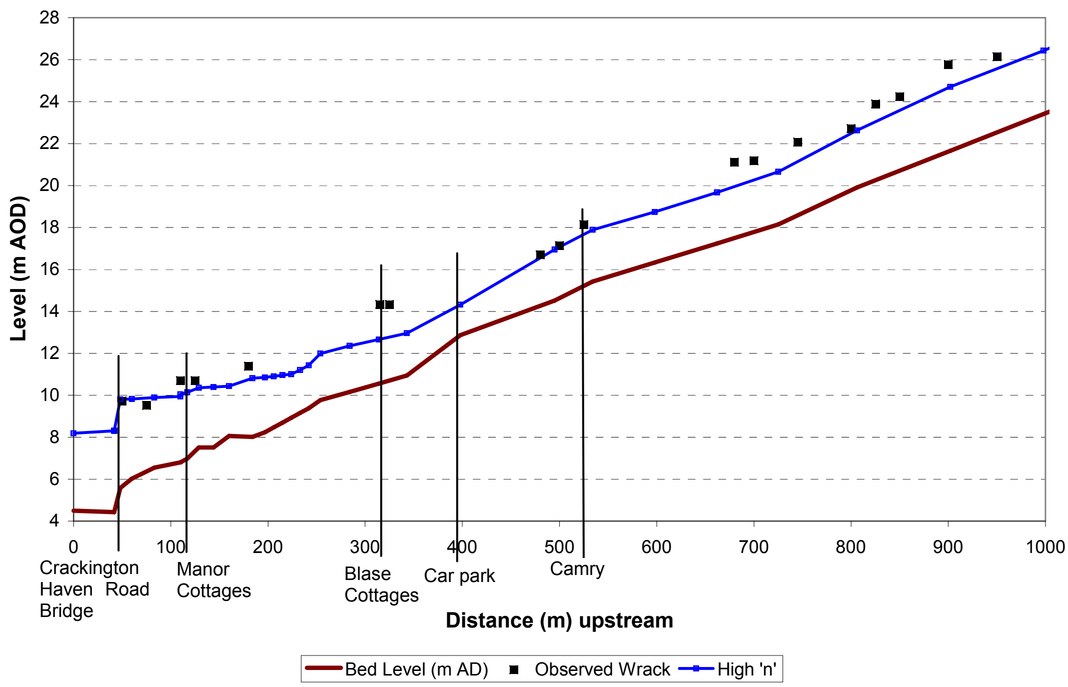

Figure 6.36 Water level compared to observed wrack levels in the downstream km of Crackington Stream modelled

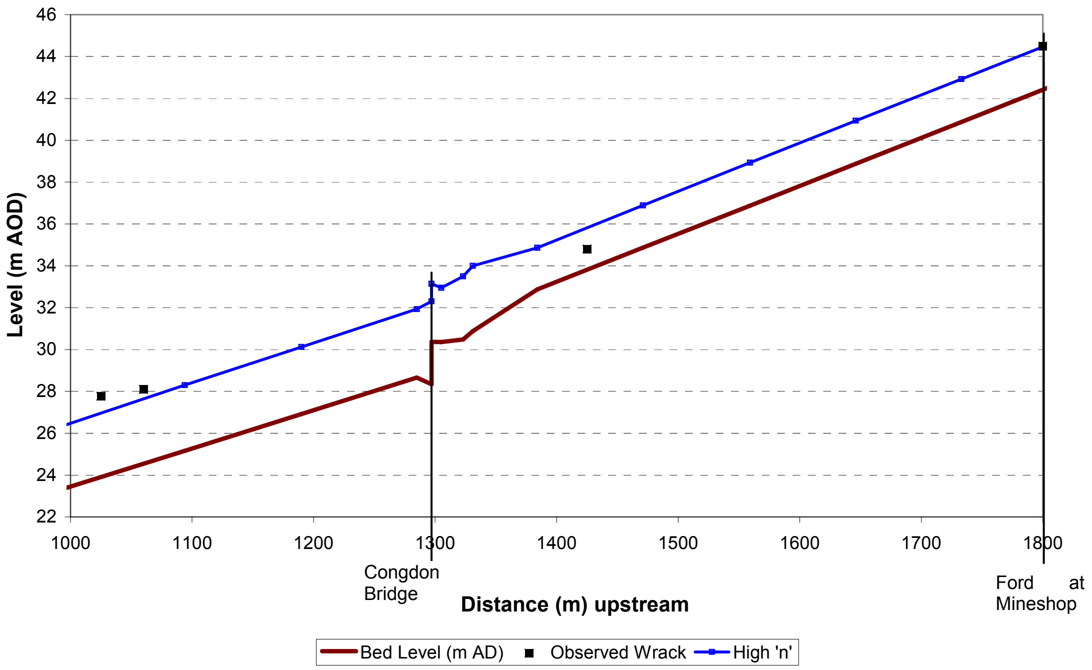

Figure 6.37 Water level compared to observed wrack levels in the upstream km of Crackington Stream

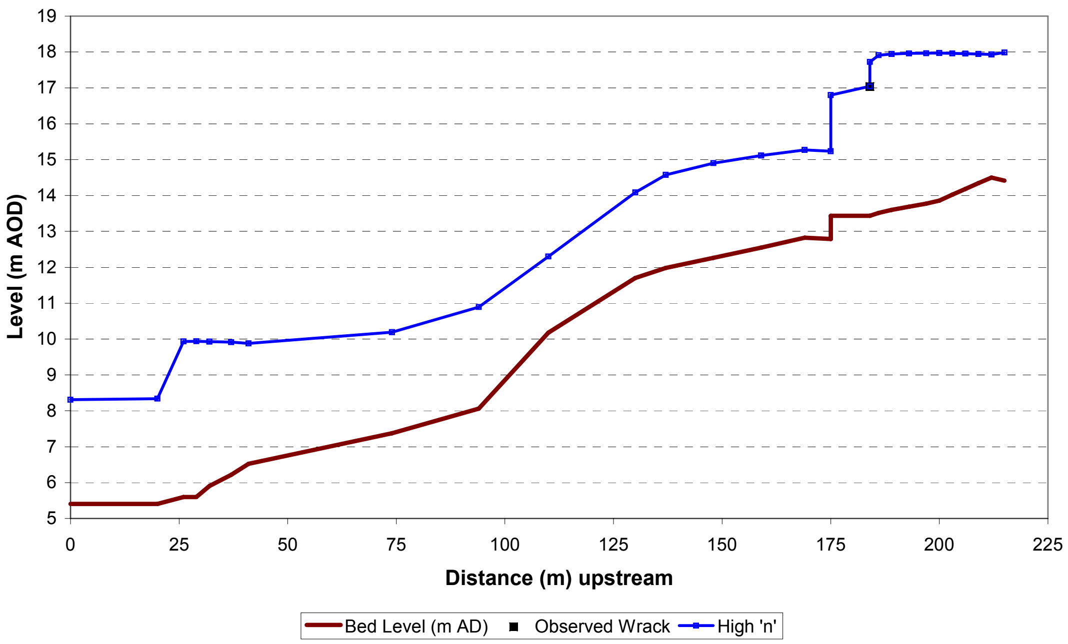

Figure 6.38 Water level compared to observed wrack levels on Pengold Stream

Figures 6.36 and 6.37 show the comparison between the maximum water levels from the calibrated model and the observed wrack levels. Immediately upstream of the Crackington Haven Road Bridge (Bridge structure 1), water levels are the same as the observed levels, however, 100 metres upstream of the bridge simulated water levels are lower than the wrack levels by 0.5 to 1 metres. Upstream of Crackington Haven the simulated water levels plot on or between the wrack levels at some locations, however, the majority of the wrack marks are 0.5 to 1 metre higher than the model results.

There is one notable exception, 300 to 350 metres upstream of Crackington Haven the observed wrack marks are 1.5 to 1.75 metres above the modelled water levels. At this location the channel meanders and the bed elevations fall so that the majority of flows are contained at the downstream end. During the event, flow was observed to bypass the meander over the floodplain from the upstream of the bend. This is likely to be the explanation of the differences between the model results and the observed wrack marks.

Figure 6.38 shows that for the only wrack level observed on Pengold stream the modelled water level is 1 metre higher than the wrack mark. It was also observed that the bridge upstream of the confluence with Crackington Stream was overtopped during the flood, in the Royal Haskoning August 2004 Floods Preliminary Report for Crackington Haven. The road level of this bridge is 9.15 metres AOD, upstream of the bridge the modelled water level is approximately 10 metres AOD.

6.2.4 *Sensitivity Analysis*

River Resistance - Manning's 'n'

The model has been run for two roughness scenarios. The first has low Manning's 'n' values of 0.04 in the channel and 0.08 on the floodplains, similar to those used for the base analysis at Boscastle, the second has high Manning's 'n' values of 0.075 in the channel and 0.15 on the floodplain.

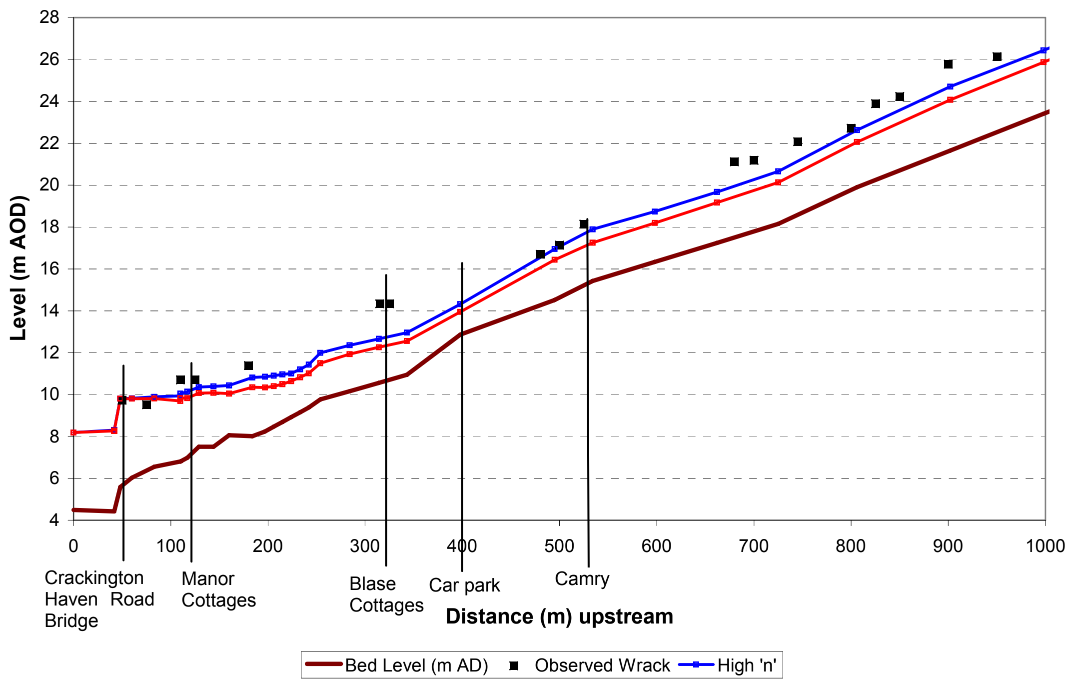

Figure 6.39 Water levels at the downstream end of Crackington Stream for the two roughness scenarios

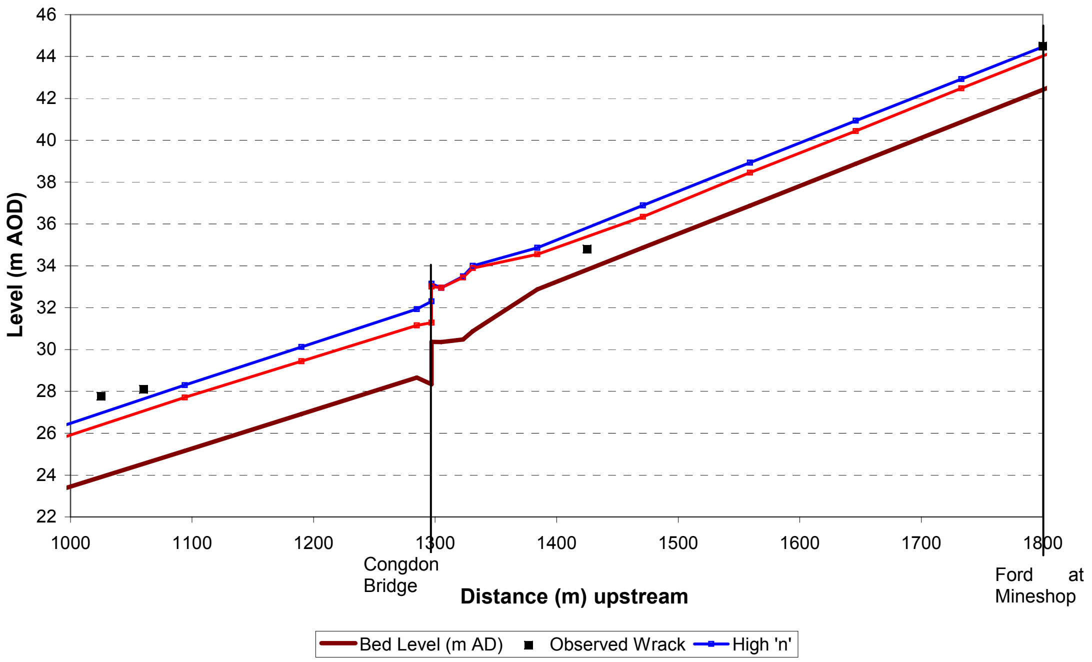

Figure 6.40 Water levels at the upstream end of the Crackington Stream model for the two roughness scenarios

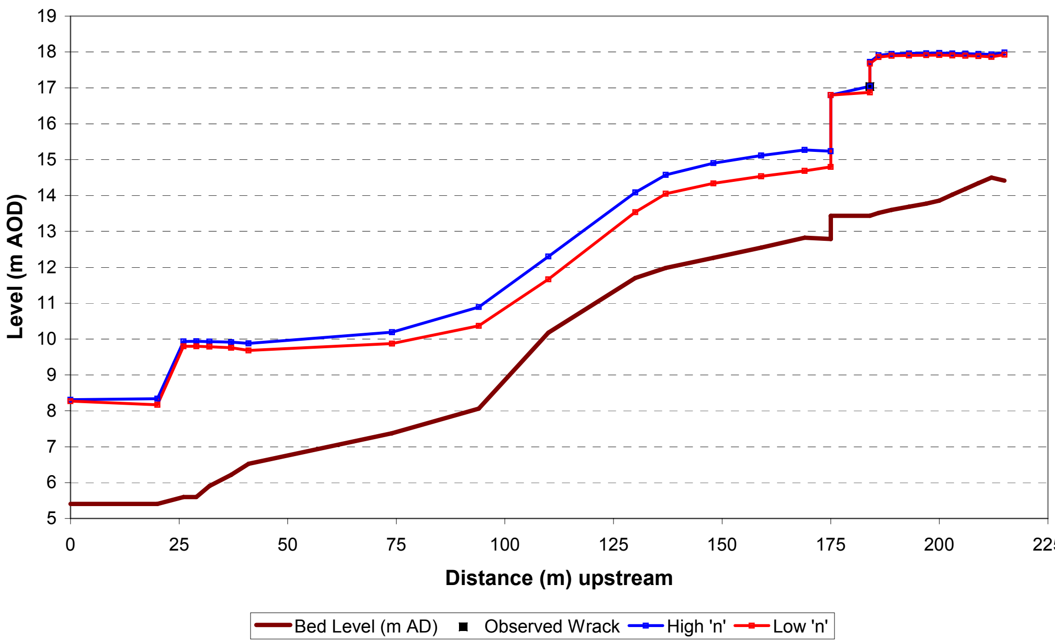

Figure 6.41 Water levels on Pengold Stream for the two roughness scenarios

Figures 6.39 and 6.40 show that for the peak discharge of 47 m^3/s on the Crackington Stream, water levels simulated with the higher Manning's 'n' are a better fit to the observed wrack levels than those with the lower Manning's 'n', at almost all wrack marks.

The value of Manning's 'n' of 0.075 in the channel is higher than we had expected for the channel conditions observed at the downstream reach of the Crackington Stream. There is evidence of substantial channel change, however, during the event which might explain this higher than expected resistance value. Plate 6.5 below indicates conditions approximately 500m upstream of Bridge 1.

Uncertainty remains in the final choice of river resistance in the situation where extensive channel change has occurred. The same overall capacity and water level may be produced by an "oversized" geometry from the post-event survey and a high resistance factor or by a smaller cross-section and a lower resistance.

Plate 6.5 Conditions 500 metres upstream of bridge 1

In the upper, steeper reaches of the Crackington Stream, the channel conditions are consistent with a high value of Manning's n, as indicated in Plate 6.6 which shows the conditions upstream of Mineshop.. Here the channel is very irregular and is obstructed by fallen trees and boulders.

Plate 6.6 Conditions upstream of Mineshop

Bridges

The impact of blockage to the bridge in Crackington Haven (Bridge Structure 1) has been analysed, using blockages of 0 and 100% during the peak of the event. In the simulation the bridge was assumed to be blocked at 17:10 hours BST during the peak of the flood event. Blocking the bridge during the peak of the event over predicts the wrack marks observed immediately upstream of the bridge. This increases water levels by 0.7 to 0.8 metres upstream of the bridge (Figure 6.42). Thus from the hydraulic modelling it seems unlikely that the bridge was fully blocked during the peak of the flood event.

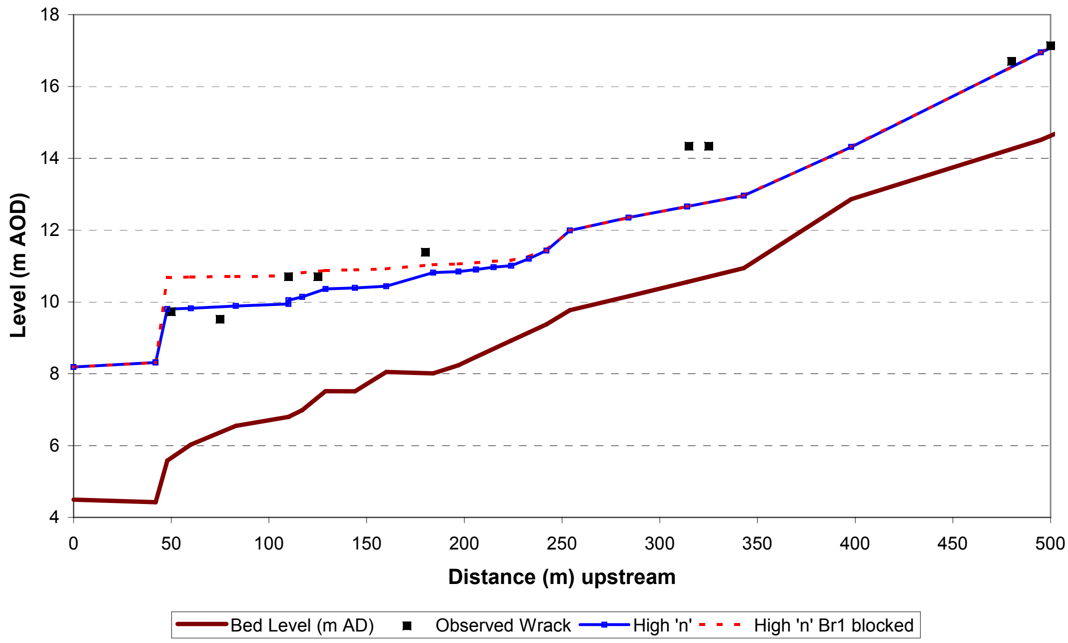

Figure 6.42 Impact of blockage to bridge 1 on maximum water levels

There is evidence to suggest, however, that the bridge may have become blocked to some extent when the flow reached bankfull. The Royal Haskoning August 2004 Floods Preliminary Report for Crackington Haven states that the road bridge became blocked within 1 hour of the commencement of the flood, and contains photographs of the blockage. Eye witness reports indicate that water levels rapidly rose 2 metres upstream of the bridge, and the water went from in-bank to flooding properties in a short period of time. In the model the bridge has been blocked in the hydraulic model at 17:10 hours BST (the time of bankfull) to investigate whether this observation was due to the bridge becoming blocked with debris, see Figure 6.43.

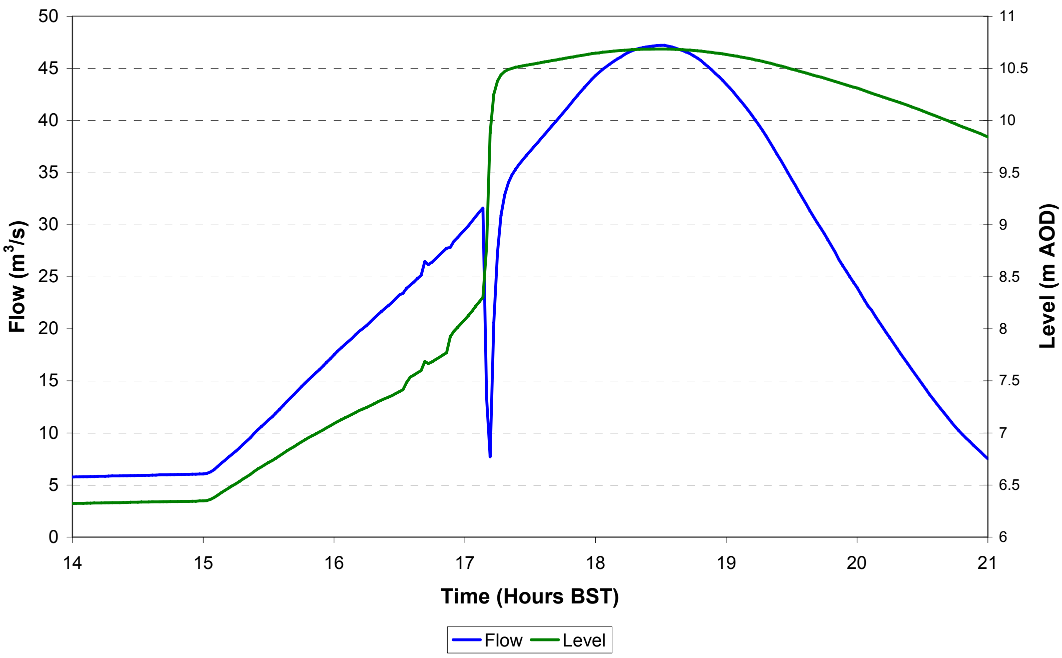

Figure 6.43 Impact of blockage to the Crackington Haven Bridge at bankfull

The model simulates an increase in water level of 2.25 metres assuming that the bridge became fully blocked in the space of a minute. Thus it is feasible that the observed rapid rise in water levels may be attributed to rapid partial blockage of the bridge.

River discharge hydrographs

Flow hydrographs have been produced at Mineshop in the upstream of Crackington Stream, Congdons Bridge in the middle and the Bridge at the downstream end of the river in Crackington Haven, see Figure 6.44.

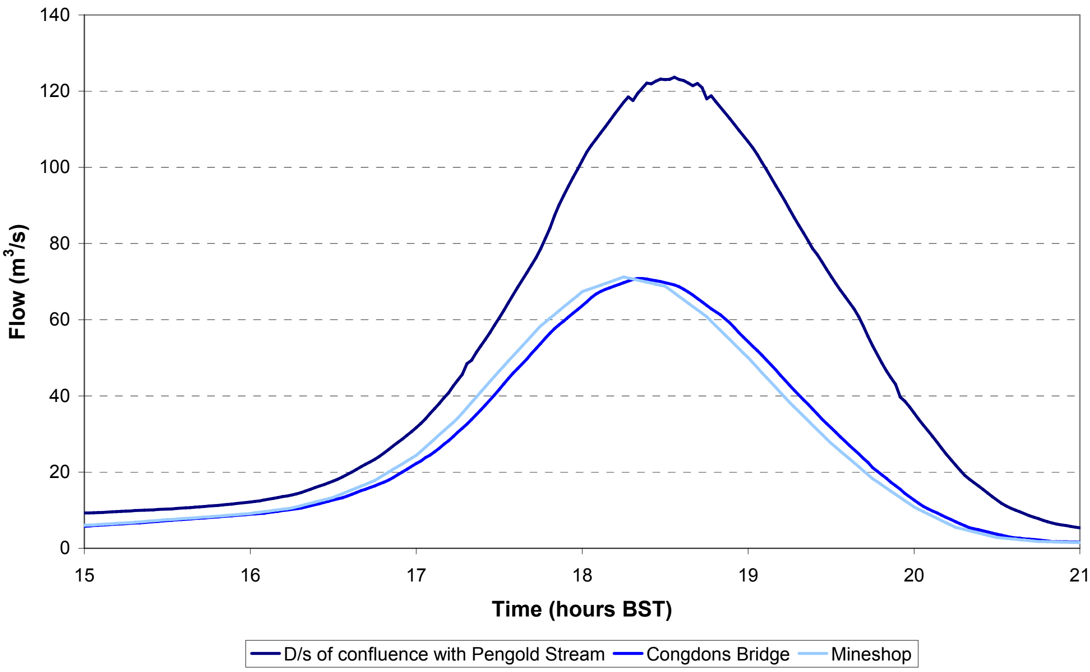

Figure 6.44 Modelled flow hydrographs at three locations on Crackington Stream

The travel time of the peak flow over the 2 kilometres of Crackington Stream modelled is approximately 15 minutes. The travel time from Mineshop to Congdons bridge is short, approximately 9 minutes. The peak flow is significantly larger at the downstream end of Crackington Stream because it has been taken below the confluence with Pengold Stream. The flow from Pengold Stream may also affect the timing of the peak flow downstream of the bridge in Crackington Haven.

Water velocity

Maximum velocity has been plotted for each cross section against the distance from the upstream limit of the model. Because IWRS is a one-dimensional hydraulic model the velocity is the average for the whole cross-section.

The maximum values of velocity simulated are shown in Figures 6.45 and 6.46. The velocities are high but are generally consistent with observations during the event. No actual observations of velocities are available for comparison. It should also be noted that the maximum water velocity may not occur at the same time as either the maximum discharge or the maximum flood level.

It should be noted that the velocity in the Crackington Stream main river channel is approximately 2 m/s. The kinematic wave speed of a flood wave in a natural channel is approximately 1.3 times the water velocity and so will be about 3 m/s. This gives a transit time of about 670 seconds, or about 11 minutes, for the 2 km length of river modelled.

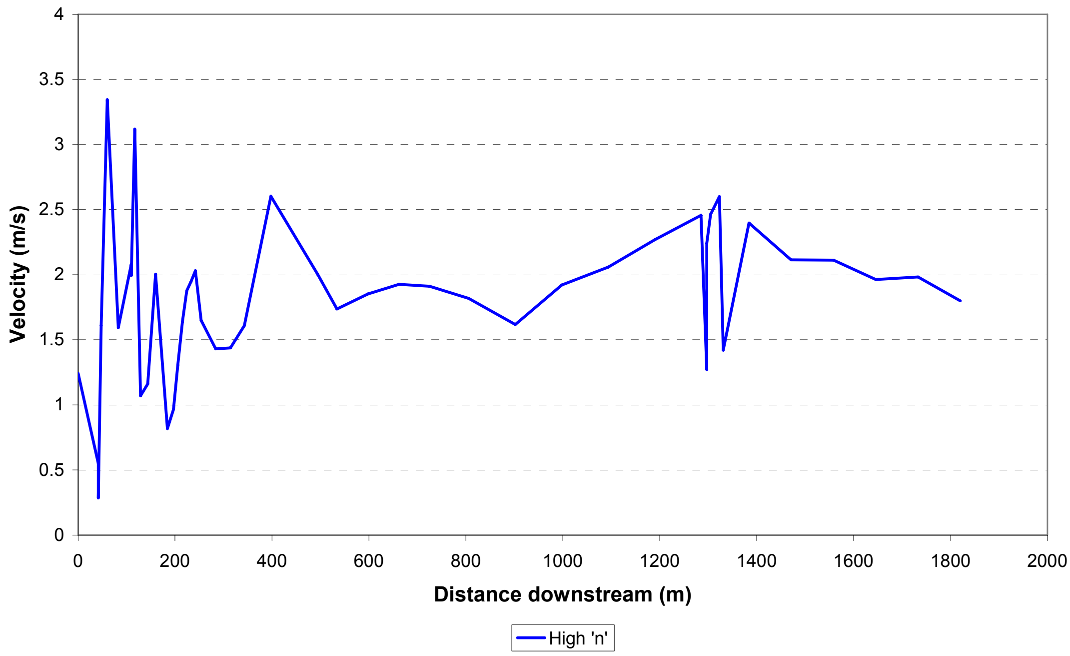

Figure 6.45 Maximum velocity plotted against distance downstream on Crackington Stream

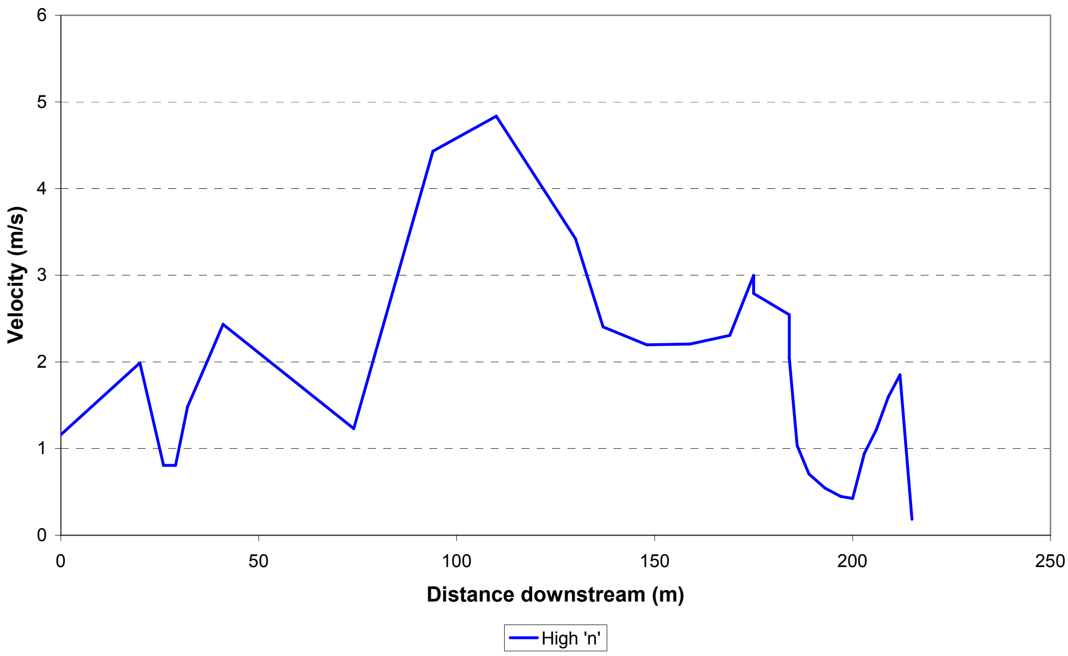

Figure 6.46 Maximum velocity plotted against distance downstream on Pengold Stream

Water level hydrographs

Water level has been plotted against time at Mineshop, Congdons Bridge, and at Crackington Haven, see Figures 6.47 to 6.49.

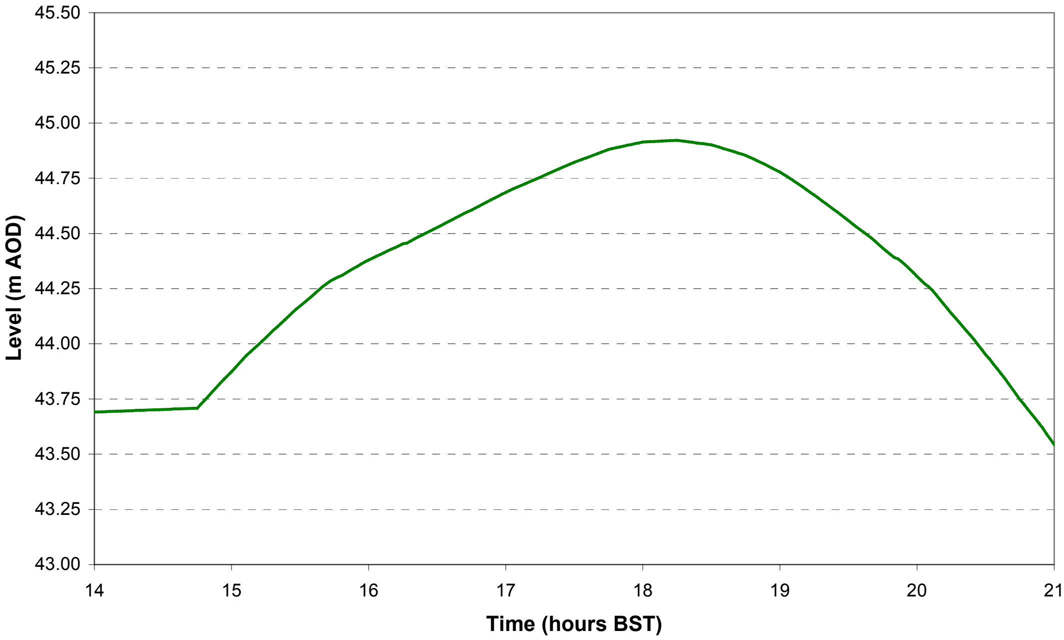

Figure 6.47 Water level against time at Mineshop

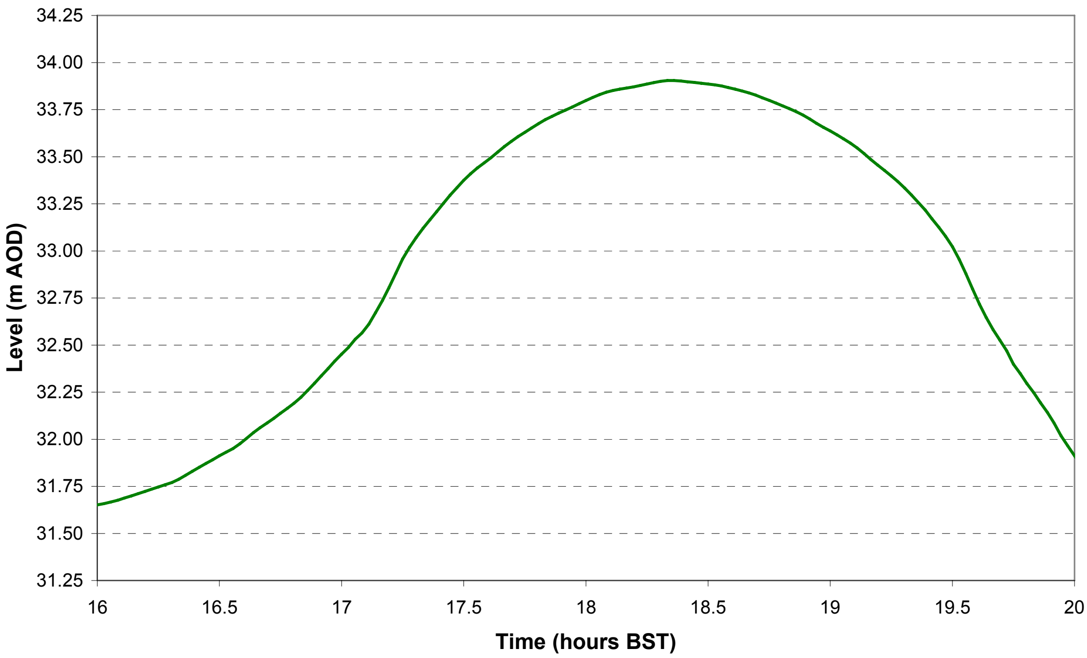

Figure 6.48 Water level against time at Congdons Bridge

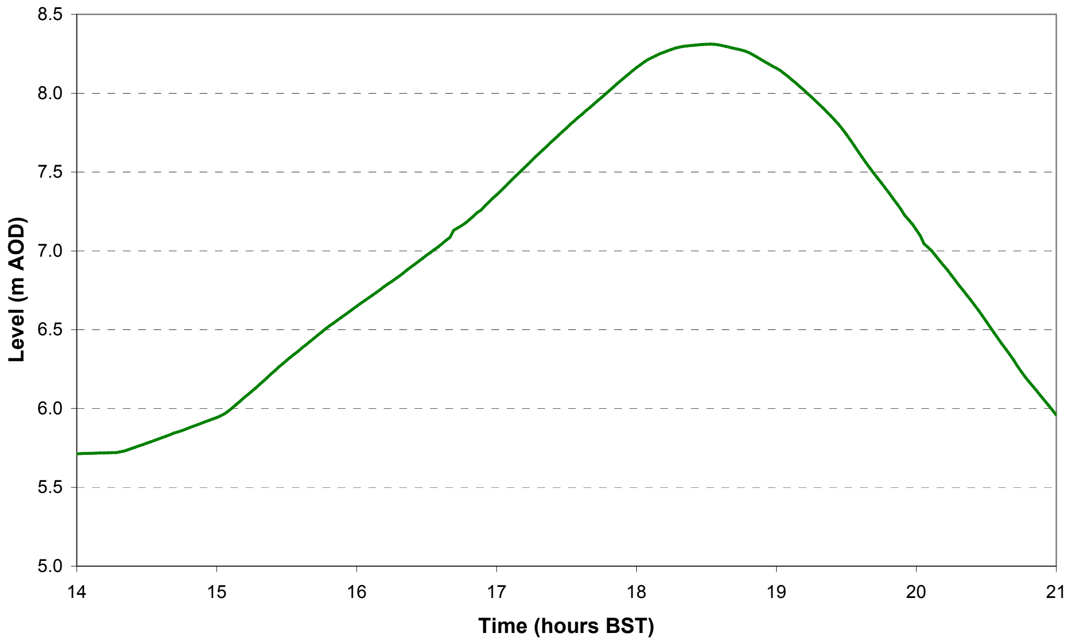

Figure 6.49 Water level against time at Crackington Haven downstream of the confluence with Pengold Stream

6.2.5 Discussion

Quality of Calibration

Water Levels

The hydrodynamic model of the Crackington and Pengold Streams has been calibrated against the wrack levels recorded after the flood. The maximum water levels generally lie within the range of the wrack levels in Crackington Haven and are consistent with the overall gradient of the wrack lines. There is however considerable scatter in the wrack levels locally about the overall trend and it has been impossible to fit the model to each observed level.

Timing

The time of concentration of the runoff from the subcatchments between the peak incident rainfall and the peak outflow is discussed in the hydrological studies. This should be added to the transit time for flows along the main river (of the order of 11 minutes over the 2 km upstream of Crackington Haven).

The key determinants of the timing of the flood peak in Crackington Haven arise from the hydrological modelling assumptions.

Capacity of Structures

Bridge structure 1

The soffit level of the Crackington Road Bridge (Bridge 1) is 7.363 metres AOD for arch 1 and 7.326 metres AOD for arch 2, which is below the bankfull level. The flow capacity of the unblocked bridge is 22.6 m^3/s.

Bridge structure 2

The soffit level of the Access Bridge (Bridge 2) is 9.901 metres AOD, which is above the bankfull level. The flow capacity of the unblocked bridge is 46 m^3/s.

Bridge structure 3

The soffit level of the Congdons Bridge (Bridge 3) is 32.4 metres AOD for both arch 1 and arch 2, which is below the bankfull level. The flow capacity of the unblocked bridge is 22 m^3/s.

Pengold Stream Bridge structure 0

The soffit level of the Bridge upstream of the confluence with Crackington Stream (Bridge 0) is 8.491 metres AOD which is below the bankfull level. The flow capacity of the unblocked bridge is 20.8 m^3/s.

Pengold Stream Bridge structure 4

The soffit level of the Bridge at the upstream of the modelled Pengold Stream (Bridge 4) is 15.08 metres AOD, which is at the bankfull level. The flow capacity of the unblocked bridge is 8.5 m^3/s.

Effects of blockages and failures

Blockage of the Crackington Road Bridge (Bridge 1) had a significant effect on water levels and flow distribution between the river and streets see for example Figure 6.42. The greatest sensitivity to assumptions lay in the reach upstream of the Bridge where levels between the scenarios differed by over 0.5 m.

If the bridge became blocked nearly instantaneously then this would lead to a rapid increase in water level upstream of the bridge.

Summary of the modelled conditions

Discharge peak

The model calibration discussed in this report relates to a peak river flow downstream of the confluence with the Pengold Stream of 91 m^3/s. The choice of rainfall depths and runoff parameters which produce this rate of flow are described in the Section 3 above.

River resistance

Our approach to the selection of river resistance is based upon expert assessment during site visits in the fortnight or so following the flood. This assessment produced a gradation of resistance along the river according to the bed and bank conditions.

Water surface profiles

The water surface profiles under these conditions for the 2004 flood are given in Figures 7.1, 7.2 and 7.3 above.

Sensitivities and uncertainties

The uncertainties introduced by several modelling assumptions have been studied (see Section 4 above).

Uncertainty in assumptions made on the degree of blockage to the Crackington Road Bridge (Bridge 1) has a significant impact on the simulated water levels upstream of the bridge.

In the upper 1.5 kilometres of the modelled Crackington Stream, water levels are significantly (1 metre) lower than the observed wrack levels. This can be explained if it is assumed that these cross-sections surveyed post flood had been eroded during the flood.

The sensitivity to river resistance is such that a uniform 25 percent increase in all Manning's 'n' roughness coefficients increases water levels by up to 0.25 metres.

Local standing waves caused by flow obstructions, which can not be modelled in IWRS, and the impact of velocity head may explain the variability between the model results and the observed wrack marks.

7. Description of flood damages

7.1 DAMAGE IN THE AREA AFFECTED BY THE FLOOD

Cornwall County Council reported that infrastructure had been badly affected by the flood, with bridges and culverts damaged and some parts of the road network completely washed away. Shortly after the flood Highways Officers drew up a programme of works and estimated that repairs would cost more than £1 million. The reported road damage is given in Appendix 7.

7.2 VALENCY CATCHMENT

7.2.1 Introduction

The bulk of the flood damage in the Valency catchment occurred in Boscastle, though there was also significant damage in the catchment upstream. Though the main source of flooding was from the Valency itself there was also substantial damage caused by flooding of the Jordan Stream and from surface run-off. Much of the damage resulted from inundation by water but in places this was exacerbated either by the velocity of flow or by fast flowing water carrying trash. High velocity flow down some of the side streets resulted in damage to the road surfaces. The combination of high flow velocities in both the main channel and on the floodplain carrying trees and cars led to severe impact forces on buildings and structures through the centre of Boscastle.

7.2.2 Damage to buildings

Figure 1.1 shows the distribution of flood damage as a result of the flood. A large proportion of the damage occurred in Boscastle as a result of flooding from the Valency, the Jordan and the Paradise Stream. The flooded properties and their locations are given in Appendices 5 and 6.

7.2.3 Damage to infrastructure

In addition to the damage to properties there was extensive damage to infrastructure as described below.

South West Water

As a result of the flooding in Boscastle, water supply to a number of properties was cut-off but the majority of customers did not lose water supply at any time. Following the flooding South West Water worked to repair and restore water and sewerage services to those parts of the village affected.

The sewerage network in the village which had been damaged by the floodwater has also been restored and blockages cleared.

Water supply

Supply was lost to the harbour area with significant damage to the supply to some 25 properties. As a result the supply had to be turned off to the lower part of the village which meant that properties without damage to their supply were also affected. Within 3 to 4 days an overland pipe was laid and water quality samples taken. This made available supply to stop cocks. A permanent underground main was then laid.

Sewerage

Damage to the sewage system occurred at the following locations:

- Main river, main outfall
- Two main sewers leading to outfall either side of the main river
- Main sewer behind Marine Terrace
- Sewer adjacent to Post Office in Dunn Street
- Tourist information area in main car park
- Main sewer adjacent to the North Cornwall District Council car park
- Main sewer under Wellington Hotel

As a goodwill gesture, South West Water also carried out work on sections of private sewers at the following sites:

- Frogapit
- 1-6 Marine Terrace
- Wellington Hotel

There are no records of the number of people affected. During the repair work it was found that some of the sewers were silted up with debris as a result of the flood.

North Cornwall District Council

An initial assessment following the floods suggested that:

- approximately 80 cars had been recovered
- 1000s of tons of waste removed (trees, rubble, buildings, silt, household, commercial, food)

Information provided by NCDC building services indicates that:

- 5 nr. buildings required total demolition
- 1 nr. building required demolition in part
- 7 nr. buildings suffered structural damage, and
- 2 nr. suffered structural damage and required partial demolition.

Electricity supplies - Western Power Distribution

The electricity supply went down briefly on Monday 16 August at 14:05, 14:14, 14:28, 16:09 and 16:26 BST as the circuit breaker tripped and then closed again after 30 seconds. Supply to 843 properties was finally lost at 16:46 BST into Boscastle..

Part of the underground network by harbour was removed by the flooding. and the Boscastle harbour substation destroyed.

The following work was carried out:

network rebuilt
entire new HV network (underground) installed
LV in harbour area installed ,
new transformer and switch gear installed and
some OH replaced by underground cabling.

Environment Agency

There was damage to and blockage of the culvert under the Wellington Hotel.

The bridges in Boscastle were blocked by debris which had to be removed. The river banks through Boscastle were damaged and had to be repaired or re-instated. Sediment had been deposited in the river channel upstream of the B3263 road bridge in Boscastle which had to be removed.

National Trust

There were significant quantities of sediment deposited in Boscastle harbour. There were significant quantities of log dams on the floodplain throughout the catchment.

7.2.4 Post-flood survey

Following the flood event cross-sections of the Valency and Jordan rivers were surveyed and the level of trash marks recorded. The details of the trash marks are given in Appendix 6.

7.3 CRACKINGTON STREAM

7.3.1 Introduction

During the flood event a rapid rise in water levels was experienced and the road bridge across the Crackington Stream became quickly blocked by large trees and debris carried from upstream. It is reported that within 1 hour of the commencement of the flood the road bridge was overtopped, prohibiting the passage of pedestrian and vehicles (Plate 7.1).

Plate 7.1 View from Coombe Barton Hotel toward the substantially blocked road bridge

Twelve properties were affected by the flood waters from the Crackington Stream, some to significant flood depths. Two properties were destroyed by the fast flowing flood waters and numerous cars, a caravan, footbridges and fences were carried downstream by the flood water.

A tributary to the Crackington Stream, the Pengold Stream, also rose quickly and bypassed and overtopped the masonry bridge immediately upstream of it's confluence with the Crackington Stream. Three properties were affected by flooding from this watercourse, again to significant flood depths.

The flood flows in both watercourses were extremely fast and this resulted in significant areas of sediment and bank erosion and deposition. The bridge across the Pengold Stream was substantially eroded and undermining of the foundations of the main road bridge also occurred (Plate 7.2). The Pengold Stream footbridge has been partially repaired to allow access to the beach but it is no longer able to serve as a vehicular access.

Plate 7.2 Erosion and undermining of Pengold Stream and the main road brides

There were no reports of injury or loss of life associated with the flood event although there were anecdotal reports of incidents that would be classed as life threatening.

7.3.2 Flow Routes

The majority of the flood water associated with the Crackington Stream was contained within the flood plain. Significant flood depths across the flood plain were recorded and properties that would have appeared to be outside of a normal flood envelope were affected by overland flows. This is particularly the case for the Blase properties, which are some 3m above the bed of the stream immediately downstream yet still experienced internal flooding (Plate 7.3).

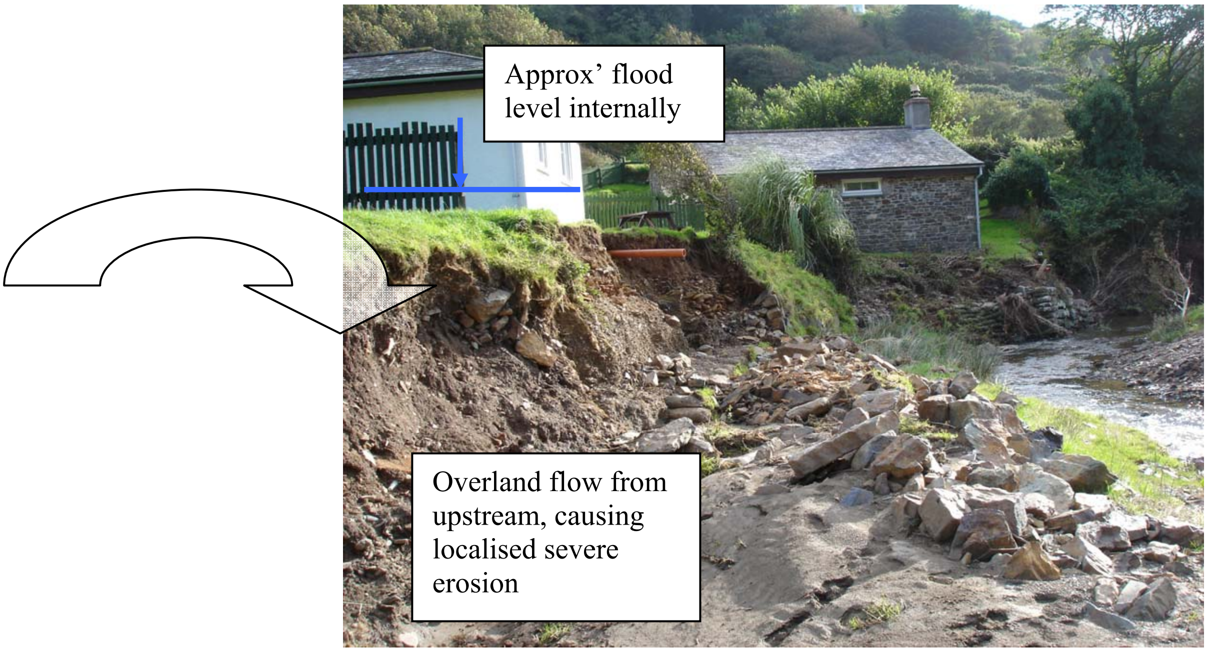

Plate 7.3 The Blase properties.

The capacity of the Pengold Stream was also quickly exceed and high velocity out of bank flows were experienced. This not only caused damage to numerous fences and three properties but lifted the tarmacadam surface of a minor road.

The extent of flooding is indicated on the Flooded Outline in Appendix 8.

7.3.3 Buildings Affected

A total of 15 properties were affected by the flooding, two of which were destroyed by the flood (Tremar and Camry). A selection of the properties' threshold and flood levels are indicated in Table 7.1.

The majority of properties experienced flood depths in excess of 1m which has caused significant loss and disruption. The safe exit from a number of properties could have been an issue as several properties were completely surrounded by fast flowing floodwater. Plate 7.3 shows two of the properties flooded and is typical of the majority of affected properties. In all the instances of flooding, deep layers of sediments were deposited within the properties.

7.3.4 Summary of Damages

The tables below summarise the details of damages accrued. Further information is contained in Appendix 9.

Table 7.1 Residential Properties affected

Properties	Notes	Flood Depth (m)
Little Bridge Cottage	Cottage opposite Coombe Barton Hotel towards sea.	
Crackington Manor Apartments	Three apartments were affected on the ground floor. The fourth Apartment was on slightly higher ground and was not internally flooded	1.138 0.642 0.755
Manor Cottage	Holiday Home	1.298
Stable End		0.752
Blasé No 1		0.488
Blasé No 2		1.001
Chy-an-Pont	Flooded by Pengold Stream	1.888
Tremar	Completely destroyed by floods – no records exist for planning permission at the Environment Agency.	Unknown
Camryn	Completely destroyed by floods – no records exist for planning permission at the environment agency	Unknown

Table 7.2 Commercial Properties Affected

Properties	Notes	Flood Depth (m)
The Cabin Cafe	Although the café itself was only flooded to a depth of 0.109m, it had a basement that was completely submerged	0.109 1.889
Coombe Barton Hotel Shop		1.818

Table 7.3 Other Buildings Affected

Building	Notes	Flood Depth (m)
Public Toilets	None	Unknown
Lifesaving Club	None	Unknown

Table 7.4 Roads affected

Road	Notes	Flood Depth (m)
Road across Crackington Stream	Road was impassable during flood	Unknown
Minor road past Chy-an-Pont	Impassable during flood. Possible removal of tarmac upstream of Chy-an-Pont	Unknown
Private Car Park adjacent to Coombe Barton hotel	Totally submerged by flood water resulting in loss of hardstand and significant clearance.	Unknown

Table 7.5 Bridges affected

Bridge	Notes	Flood Depth (m)
Main road bridge over Crackington Stream	Severe erosion and undermining	Unknown
Foot Bridge over Pengold Stream	Severe erosion and undermining	Unknown
Footbridge next to manor cottage	Damage to railings and erosion	Unknown
Unconsented footbridge next to Blase	Washed away	Unknown
Footbridge next to Camryn	Damaged	Unknown

Table 7.6 Vehicles Affected

Vehicle	Notes	Flood Depth (m)
	A number of cars were washed away.	N/a

Table 7.7 Mobile Homes Affected

Mobile Home	Notes	Flood Depth (m)
Caravan	Caravan washed from vicinity of Tremar to garden of Stable End.	Unknown

Following reconnaissance visits to Crackington Haven, subsequent to the flooding event, an in-undated area plan was developed using flood levels and anecdotal evidence. A copy of this drawing is included as Appendix 7 of this report.

Wrack Marks

A preliminary site visit was conducted by Royal Haskoning and HR Wallingford to establish the location of wrack marks. These were then surveyed by Royal Haskoning and levels established. The details of the wrack marks are included in Appendix 10.

8. *Implications of North Cornwall floods*

8.1 INTRODUCTION

The study of the August 2004 North Cornwall floods has raised a number of issues that have wider implications both for the simulation of what happened in adjacent catchments during the same event and the prediction of flood characteristics in similar catchments in the future. It should be emphasised that there is a great risk in trying to draw too definite conclusions from just one event. The methods underlying the FEH are based on thousands of station-year records. These cannot be discarded on the basis of a single flood event but the analysis of the flood has raised a number of issues that deserve further consideration and analysis.

8.2 ESTIMATE OF ANNUAL PROBABILITY OF RAINFALL EVENT

An area of concern that this study has highlighted but has been unable to resolve is the issue of reconciling the assessment of the probability of the rainfall event and the probability of the flood event. Analysis of the rainfall based on use of the FORGEX method and rainfall records suggests an annual probability of exceedence for the rainfall event of the order of 0.05%. Analysis of the flow data from the event and data from historic floods suggested that the flood might have an annual probability of exceedence of the order of 0.25%. Though, in general, one would not necessarily expect the probability of the flood event to match the probability of the rainfall, one would normally expect a greater correspondence between the two. It should be noted that very different approaches have been used to derive the two probabilities and that there are significant uncertainties associated with both. It may be that in this study significant errors have been made in assessing the magnitude and occurrence of historic floods or it may be that Boscastle has been unfortunate in having a number of extreme flood events in the last 200 years. It is also possible that the FORGEX analysis underestimates the probability of extreme events. Rainfall records are only included in the FORGEX method if 15 minute data is available. The appropriate data in the South-west is sparse and does not include a number of historic extreme events. It is thus possible that the FORGEX method under estimates the probability of extreme events in the South-west. It is impossible to draw firm conclusions from just one flood event but it would seem to be prudent, therefore, for those concerned with flooding issues to consider this possibility when assessing the probabilities of extreme rainfall events.

8.3 APPLICATION OF FEH METHODOLOGY TO SIMULATE THE AUGUST 2004 ON OTHER CATCHMENTS

When the FEH methodology was applied to the Valency and Crackington Stream catchments, empirical adjustments had to be made to the Time to Peak, Tp, of the Unit hydrograph and adjusting the Percentage Runoff, PR. These adjustments were purely empirical and were made to improve the agreement between the modelling and the observations. It was considered that these adjustments had to be made because the depth of rainfall and the intensity combined with shallow soils and steep catchment slopes meant that the amount of run-off and speed of run-off were both increased.

One needs to consider whether, if one were simulating the same rainfall event in other catchments, such as the River Ottery or River Neet, the same adjustments would be appropriate. As the rainfall was spatially restricted, in general, the rainfall over the catchments of the Ottery and the Neet was less than over the Valency. In addition, in general, the catchment slopes of the Ottery and the Neet are not as steep for the Valency. The implication would seem to be that, in this case, the same adjustments to Tp and PR are unlikely to be appropriate. It would seem likely, however, that some adjustment to both Tp and PR would be appropriate. It also seems likely that the magnitude of any adjustment would depend upon exactly which catchment or sub-catchment was being considered. If a small sub-catchment at the head of either the Ottery or the Neet were being considered then the magnitude of any adjustment would likely have to be larger than if a larger catchment were being considered.

8.4 APPLICATION OF FEH TO OTHER SMALL, STEEP CATCHMENTS

As discussed above, when simulating the August 2004 event in the Valency and Crackington Stream catchments, it was necessary to adjust the values of Tp and PR in the FEH methodology. One needs to consider the implications for estimating extreme events on small steep catchments in the future. As discussed earlier in the report, smaller catchments tend to exhibit greater variability in hydrological behaviour than larger ones. In addition, there is a shortage of data from small, steep catchments. The simulation of the Valency and Crackington Stream catchments for the August 2004 event suggests that the use of the FEH methodology for small, steep catchments contains a high degree of uncertainty. It would be inappropriate to suggest that the FEH methodology should be modified on the basis of one flood event but it has highlighted the need for further data and study in this area. In the meantime it would be prudent for those concerned with flooding issues to take account of the potential uncertainties that study of the August 2004 flood has revealed.

In the simulation of the August 2004 event the Time to peak of the unit hydrograph was reduced by a larger proportion (50%) than is recommended when carrying out studies for reservoir safety where the recommended proportion is 30%. It may be, therefore, that for small, steep catchments the current recommendation of a 30% reduction may not take fully into account the potential reduction of the Time to peak of the unit hydrograph during extreme events. This implication needs to be addressed when considering the assessment of floods for dam safety.

9. Conclusions

9.1 DESCRIPTION OF FLOOD

The August 2004 flood event in Boscastle must be one of the best recorded extreme flood events in the UK. Since the flood occurred during the day in the presence of many people, there is a good photographic record of the event. The prompt action by the Environment Agency in having the trash marks surveyed and in collecting eye-witness accounts following the event has added important qualitative and quantitative data. Inevitably there are gaps and inconsistencies in the accounts but for the most part we have extremely good information of the flood. The photographic record of the flooding in Crackington Haven is not as copious but there is good wrack mark data collected on behalf of the Environment Agency. From this data it has been possible to reconstruct the flood, see Tables 2.1 and 2.2.

The evidence suggests that during the flood event there were significant changes in flow paths during the event, either as a result of bridges blocking with trash, walls falling down or water bursting through buildings.

A number of the eye-witness describe very rapid increases in water level over periods measured in minutes or seconds. These are reported at both Boscastle and Crackington Haven. A number of explanations have been offered for these rapid changes in water level. At Boscastle it has been suggested that these were due to trash dams developing and then breaking in the catchment upstream and hence causing flood waves downstream. The hydraulic modelling has suggested that for the bursting of a trash dam to have a significant impact on flood levels in the centre of Boscastle it would have had retain a significant height of water, probably in excess of 3m. The hydraulic modelling has suggested that changes in flow path resulting from, for example, a bridge blocking, would lead to changes in water level of the magnitude of those observed. Though it is possible that the water levels at Boscastle and Crackington Haven were affected by trash dams upstream, it seems more likely that the observed rapid changes in water level arose from changes in flow paths caused by events such as a bridge blocking or a wall falling down.

9.2 GEOMORPHOLOGICAL ANALYSIS

There was substantial morphological change during the flood along both the main stem of the Valency and also on the tributaries. Over most of the length of the Valency the main channel of the river increased in both width and depth. In places the vertical erosion was constrained by the presence of bed rock close under the bed of the original channel. In some locations it would appear that the bed rock was eroded during the flood event. When morphological change takes place during floods in rivers flowing through erodible sediments then the width and depth adjust to a size that depends upon the magnitude of the flow and the nature of the sediment. If erosion is constrained either horizontally or vertically then the area of the cross-section tends towards the value that would occur in erodible sediment. Thus where vertical erosion was constrained by the presence of bed rock then additional lateral erosion took place. Simultaneously with the increase in channel size there was lateral channel movement. At a number of locations the river abandoned the pre-flood channel and cut a new channel through the floodplain (channel avulsion). In a number of cases the channel avulsion would have acted to reduce the length of the channel and hence increase the slope of the river channel. The erosion resulted in the release of large quantities of sediment into the flow. The size of sediment mobilised ranged from fine silts to large boulders. In a few limited locations such as at Newmills the floodplain of the river widens and there was sediment deposition. At Newmills the sediment deposition tended to be limited to the larger sediment fractions. The sediment deposition on the floodplain indicated that sediment sizes up to and including 1 m were mobilised in the flood. These sediment deposits were on the floodplain and it is likely that larger sediment sizes would have been mobilised in the main channel. The observed sediment deposition within the catchment represented a small fraction of the total sediment erosion.

A notable area of sediment deposition was the lower reach of the Valency and Boscastle harbour. The channel erosion and lateral movement of the channel in the upper catchment released large quantities of sediment which were then carried downstream by the flow. In any areas of slower moving flow sediment deposition took place. This resulted in large quantities of silt being deposited in the houses that were flooded in Boscastle. In addition the blockage of the bridges in Boscastle led to sediment deposition in the main channel upstream of them. A significant amount of the sand and gravel mobilised by the flood was deposited in the harbour though there was also scour around the nose of the southern breakwater as a result of the constriction of the flow. Finer sediment travelled further and was washed out to sea.

When the flows in the Valency and Crackington Stream was modelled using the post-flood river cross-section data, in general, the predicted peak water levels were significantly below the observed trash marks. When the river cross-sections were replaced with approximations to the pre-flood cross-sections then better agreement was obtained with the observed trash marks. Thus channel erosion during the flood event affected the observed flood levels. Sediment transport is a non-linear function of discharge so that much of the sediment erosion will have taken place during the peak of the flood.

Within the Jordan and Paradise Stream catchments there was significant erosion and downcutting. This released significant quantities of fine sediment into the flow. During the flood event the flow coming down the Jordan exceeded the flow through the culvert at the lower end of the catchment. As a result water began to pond upstream of the entrance to the culvert. This led to deposition of the sediment being carried by the Jordan in the area around the entrance to the culvert and eventually led to the blockage of the entry into the culvert. The water continued to pond upstream of the culvert until it broke through the Wellington Hotel and around the adjacent cottages.

9.3 METEOROLOGY

Following a dry spring and a dry June, July rainfall was above average. This led to a reduction in Soil Moisture Deficit in the North Cornwall area from the range 80 to 220 mm in June to the range 40 to 180 mm in July. The extreme rainfall accumulation in the North Cornwall area resulted from prolonged heavy rain over the four hour period 12:00 to 16:00 GMT on the 16 August 2004. The intensity of the rainfall was probably enhanced by large scale uplift associated with larger scale weather troughs. A large depression dominated the eastern Atlantic with a complex structure, reflecting a history of successive pulses of tropical air being absorbed into the circulation. The effect of the large scale processes would have been to create an environment of weak uplift and high moisture content which would favour heavier rainfall.

The extreme rainfall on the 16 August resulted from a sequence of convective storms that were channelled along the north Cornwall coast over several hours. The location of the storms was influenced by a strong convergence line along the north Cornwall coast, arising from the alignment of the prevailing wind with the coast. This may have been reinforced by an onshore pressure gradient resulting from solar heating over the land. As they developed in the convergence zone, each storm cell spread out into a line of storms, making the rain appear to be continuous. The extreme precipitation appears to have been related to the fact that while convection was strong enough to generate heavy precipitation, it was shallow enough to permit the development of closely packed storm cells with downdraughts weak enough not to distort the coastal convergence line.

The spatial distribution of rainfall is summarised in Figure 4.13 and Table 4.1. The Tipping Bucket Rain Gauge (TBR) at Lesnewth recorded maximum short period accumulations of 68 mm in 1 hour, 123 mm in 3 hours and 152 mm in 5 hours. Comparison with the quality controlled check gauge indicates that these should be increased by 20% to 82 mm, 148 mm and 183 mm, respectively, to allow for under-reading by the TBR

The temporal and spatial patterns of rainfall are provided by the Cobbacombe and Predannack radars. Figure 4.15 summarises the radar information in a sequence of hourly rainfall accumulation maps obtained by summing 5-minute corrected radar rainfall rates at 2 km resolution from the Cobbacombe Cross radar. The radar accumulations for the whole 5-hour period indicates that the heaviest total rainfall accumulation probably occurred a few kilometres to the south west of Otterham near the A39, with three consecutive hours in excess of 30 mm.

The spatial gradients of the rainfall totals are large in comparison with the 2 km radar pixels. In addition there are spatial differences in the pixels used by Cobbacombe and Predannock radars. This lends uncertainty in resolving the spatial variability of the rainfall and in comparing the two sets of radar data.

Using the FORGEX method documented in the Flood Estimation Handbook, probabilities for the observed rainfall maxima were derived:

	Annual probability of occurrence
a) One hour rainfall at Lesnewth (82 mm)	0.25%
b) Three hour rainfall at Lesnewth (128mm)	0.08%
c) Overall storm	0.05%

Given the shortness and sparseness of the instrumental record, the reliability of the estimates of the probability of such rare events is questionable, but the results can be taken to indicate an annual probability of occurrence less than 0.1%.

Inspection of the mechanisms involved in generating the rainfall indicates that the key features were the efficiency of the rainfall production and the length of time for which it remained over the same area. The FEH results suggest that the efficiency of the rainfall production meant that the annual probability for the maximum hourly rainfall was about 0.25%. As the high intensity rain remained over the same area for about 5 hours the combined rainfall and duration reduced this annual probability to about 0.05%. As with other extreme storms that have been studied, the combination of factors that produced the event do not fit a pattern that has been observed before so it is not possible to deduce the likelihood of their recurrence.

An alternative approach to estimating the probability of the event is to place the August 2004 storm in the context of historic extreme events. The characteristics of extreme rainfall events in the 20th Century have been studied by Hand et al (2004). The overall frequency of such events is one event every second year somewhere in the UK. If we consider only convective events we have something like a 30% chance of an extreme convective event occurring somewhere in the UK each year. Most of these events have occurred during the summer months with none between November and April.

The south west peninsula has been subjected to six extreme rainfall events in the last century, of which three occurred in the decade 1951-60. The point (1km^2) probability deduced from an examination of these events indicates a similar annual probability to that deduced using the FEH method. Allowing for the sparse observational network, the evidence indicates that an extreme event will occur somewhere in the south west region once every 20 years on average.

9.4 HYDROLOGY

Neither the Valency nor the Crackington Stream catchments are gauged and so there is no historic data on which to base a hydrological analysis. As a result ungauged catchment procedures have had to be used, which inevitably results in a relatively high degree of uncertainty. Estimates of the probability of the flood events were based on the use of the Flood Estimation Handbook (FEH) and regional historical evidence. Two procedures were applied, the statistical approach and the rainfall-runoff model, using design rainfalls to derive full flood hydrographs.

The statistical procedures described in Volume 3 of the FEH (Institute of Hydrology, 1999) include a methodology which allows a flood frequency curve to be produced for an ungauged site. This is a two-stage process; firstly an estimate of the median annual maximum flood (QMED) is required and secondly an estimate of the flood growth curve is needed. The statistical approach constructs the flood frequency curve as a product of the index flood QMED and the growth curve. When applied to the Valency and Crackington Stream this method gave estimates of the floods with a 0.1% annual probability of exceedence of 16.6 and 14.9 m^3/s, respectively. It is apparent that the FEH statistical procedure flood estimates for both catchments are small when compared to the estimated peaks that occurred on 16th August 2004 of approximately 180 m^3/s for the Valency/Jordan and approximately 90 m^3/s for Crackington Stream. This indicates that the observed flood peaks for the 16th August 2004 event were very rare events. Due caution ought, however, to be placed on probability estimates when FEH statistical procedures are applied to small, steep catchments.

The rainfall runoff method of the FEH uses the unit hydrograph-losses model to convert event rainfalls to flood runoff. The rainfall may be either a design storm of specified exceedence probability, or may be observed rainfall, in order to assess the resultant flood runoff. For the present study, both approaches have been adopted, the first in an attempt to establish the probable exceedence probability of the 16th August event, and the second, to determine the probable inflow hydrographs to the hydraulic modelling studies derived from the rainfall estimates described in Section 5.4.

Table 5.5 shows the results using design rainfall events. The 0.1% annual probability flow estimates derived using the FEH rainfall-runoff method are significantly higher than those derived using the statistical approach. This is probably due, in part, to a dearth of good quality ‘donor’ catchments, having the sort of flood regime typical of north Cornwall and Devon catchments. It also reflects the fact that rainfall growth curves in this part of the UK are steep, and possibly steeper than flood growth curves.

The FEH rainfall-runoff modelling exercise was repeated using the radar derived rainfall estimates produced using the HYRAD software. This produced discharge hydrographs at selected locations that were then used as inputs in the hydraulic modelling described in Chapter 6.

It would appear that the FEH statistical method does not adequately estimate the severity of the flood, indicating as it has, that the flood apparently has a very low annual probability. This suggestion is difficult to accept because of the known significant historic flood events that have occurred in the Valency catchment. It is suggested that the FEH rainfall-runoff approach may be giving more realistic estimates of flood severity, but even here, the flood appears to have an annual exceedence risk of less than 0.1%.

The current best estimates of the flood frequency relationship of the Valency/Jordan catchment, derive from a combination of the FEH statistical and rainfall-runoff methods, supported by historical evidence and considerable judgement are shown on Figure 5.10. The 16th August flood event was clearly a very unusual event and was certainly rarer than the 0.5% event. We estimate that the event has a 0.25% chance of recurring in any year, a probability of 0.0025. There is, however, considerable uncertainty over this matter.

It is extremely difficult to assess the annual probability for the flood at Crackington Haven as we have been unable to trace any historic flood records. Thus we cannot use historic flood data as a guide as was done for Boscastle. The magnitude of the peak flow and severity of the morphological change upstream of Crackington Haven would suggest that the event was extreme with an annual probably of occurrence probably smaller than 1%. The rainfall totals over the Crackington Stream catchment were lower than those for the Valency catchment. This would suggest that the annual probability of exceedence was probably larger than 0.25%.

9.5 HYDRAULICS

9.5.1 Introduction

The floods in the Valency and Crackington Stream catchments have been modelled using the numerical river modelling software, Infoworks RS. The models were based on post-flood survey and calibrated to the large range of wrack marks that were surveyed after the event. The flow inputs to the models were provided by the hydrological analysis.

9.5.2 Valency River

The modelling suggested that at the time of the peak of the flood the bridges where virtually blocked. Assuming that this is the case then the modelling suggests that the peak discharge on the Valency downstream of the confluence with the Jordan was of the order of 180 m^3/s. The water level hydrograph produced by the model reproduced the account of the events derived from eye-witnesses but the timing of the peak discharge appears to be a little later than that observed.

The model results show the development of the flood wave down the catchment. and demonstrate the very rapid movement of the peak down the main river, Figure 6.30. The Figure also shows that the slope of the hydrograph increases as one progresses downstream.

The numerical model results under-predicted the observed wrack marks upstream of Boascastle. To match the wrack marks it would have been necessary to increase the peak discharge or the hydraulic roughness to unrealistic values. The model was based on post-flood cross- sections which are larger than the pre-flood ones. When estimated pre-flood cross-sections were included in the model then there was significantly better agreement between the model results and the wrack marks. This suggests that the morphological change that took place during the flood event had a significant impact on the discharge capacity of the channel in the upper part of the catchment.

The model results indicated that rapid blockage of the B3263 bridge causes rapid changes in water and in particular the water level immediately upstream of the bridge. These can rise between 1 and 2 metres in a time period measured in minutes or possible seconds, depending upon how quickly the bridge blocks. The model results also showed that failure of the 9 foot wall would also result in rapid changes in water level.

9.5.3 Jordan Stream

The modelling of the Jordan Stream showed that the culvert at the downstream end of the catchment had a limited capacity. When just flowing full, the capacity of the culvert was approximately 2m^3/s. This was insufficient to take the flow on the 16th August in which the peak discharge was estimated to be 19m^3/s. Due to the lack of capacity flooding occurred upstream of the culvert. As the water depth increased upstream of the culvert the discharge through the culvert increased. As the ponding effect upstream of the culvert increased, sediment was deposited that led to the culvert being blocked. The blockage of the culvert during the event was not simulated.

9.5.4 Crackington Stream

The modelling suggests that the peak discharge at Crackington Haven downstream of the confluence with the Pengold Stream was of the order of 90 m^3/s. The peak discharges upstream of the confluence were of the order of 47 and 44 m^3/s for the Crackington Stream and Pengold Streams, respectively.

As for the Valency, the model results suggest that the morphological change that took place during the flood event had a significant impact on the discharge capacity of the channel in the upper part of the catchment.

The modelling results suggested that rapid blockage of the lowest bridge on the Crackington Stream would have resulted in a rapid rise in water level of approximately 3 m.

9.6 DESCRIPTION OF FLOOD DAMAGES

During the flood, significant amounts of overland flow took place and there was flooding in many of the minor watercourses in the area as well as in the main rivers. This resulted in extensive damage to highways in the area of the rain storm event, see Appendix 5.1. Damage to bridges and severe damage to the road surface on some steep sections of road made some roads impassable or difficult to use.

In addition there was significant damage to properties adjacent to the major rivers and their tributaries. As Boscastle has the major concentration of properties adjacent to water courses in the area affected, much of the damage took place there but there was also significant damage to properties in Crackington Haven and in the upstream catchments. This damage is described in Chapter 7.

In addition to the damage to properties, there was also damage to local infra-structure. Damage to water supply, drainage and electricity supplies resulted in interruptions to these services for differing periods of time.

10. Acknowledgements

The project team would like to thank those who provided eye-witness accounts, photographs or other material describing the event, and their experiences. We would particularly like to thank all those who attended the drop-in centres organised by the Environment Agency, gave accounts of the event and also those who provided photographs or video or the event.

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Appendices

Appendix 1 FEH Procedure

Table A.1 Adjustment of FEH Statistical estimates of Qmed for the Valency/Jordan and Crackington Haven catchments

Site	QMED OBS	QMED CDS	QMED AF	QMED S,ADJ	Adj. weghting	Weighted geometrically QMED S,ADJ
Boscastle (total catchment)		**6.81**				
Cornwall North-Coast analogues						
49003 - De Lank at De Lank	12.885	17.471	0.738	5.02578	0.2	1.3811495
49002 - Hayle at St.Erth	4.398	9.081	0.484	3.298	0.2	1.2695615
49004 - Ganel at Gwills	14.126	8.453	1.671	*Comment:*	*Uncertainty over high flow measurment.*	
					Adj. factor at odds with others - do not use as an analogue.	
Other analogues (from top of PG)						
48010 - Seaton at Trebrownbridge	6.958	12.723	0.547	3.724	0.2	1.3007936
47009 - Tiddy at Tideford	6.206	11.966	0.519	3.532	0.2	1.2870694
51003 - Washford at Begearn Huish	6.8	9.889	0.688	4.683	0.2	1.3617605
					1	
		Mean	0.595	4.053		
					User defined QMED S,ADJ	**3.998**
Crackington Haven		**5.65**	0.587		**User defined QMED S,ADJ**	**3.317**

KEY: Qmed Obs	Median flood from data
Qmed CDS	Median flood derived from FEH CD
Qmed AF	Adjustment factor = Qmed Obs / Qmed CDS
Qmed S.Adj	Boscastle or Crackinton adjusted Qmed from single site
Weighted Geometrically Qmed, S,Adj	Geometrically weighted Qmed adjustment factor
User defined Qmed S,Adj	Finally user-defined adjusted Qmed

Table A.2 Selection of Pooling Group members

Gauging station	Area (sq km)	Record Length	L-CV	L-Skewnes	L-Kurtosis	Discordar	Sim Dist	Comments	Inlcude in PG?
55015 (Honddu @ Tafolog)	25.1	30	0.229	0.286	0.228	0.128	0.165	HiFlows-UK says unsuitable for QMED and PG	N
52801 (Tone @ Wadhams Farm)	?	6	0.207	-0.012	-0.196	1.958	0.313	FARL is 0.887 and short record	N
47009 (Tiddy @ Tideford)	37.2	34	0.161	0.13	0.194	0.501	0.351	HiFlows-UK says OK - use update	Y
48010 (Seaton @ Trebrownbridge)	39.1	31	0.208	0.238	0.231	0.123	0.387	HiFlows-UK says OK - use update	Y
51003 (Washford @ Beggearn Huish)	36.3	36	0.311	0.422	0.433	1.438	0.397	HiFlows-UK says OK - use update	Y
51002 (Horner Water @ West Luccombe)	20.8	15	0.235	0.058	0.083	0.82	0.492	HiFlows-UK says flood rating doubtfull	N
15004 (Inzion @ Loch of Lintrathen)	24.7	44	0.192	0.038	0.11	0.791	0.51	Not on HiFlows-UK - Period of record unique	Y
45006 (Quarme @ Enterwell)	20.4	9	0.206	0.289	0.298	0.395	0.513	Not on HiFlows-UK - short record	N
60004 (Dewi Fawr @ Glasfryn Ford)	36.7	15	0.122	0.043	-0.138	1.683	0.532	HiFlows-UK says unsuitable for QMED and PG	N
73803 (Winster @ Lobby Bridge)	?	12	0.095	0.265	0.151	2.21	0.536	Not on HiFlows-UK - looks OK	Y
75010 (Marron @ Ullock)	27.7	8	0.229	0.329	0.241	0.315	0.561	Not on HiFlows-UK - short record	N
48004 (Warleggan @ Trengoffe)	25.3	24	0.271	0.197	0.135	0.378	0.627	HiFlows-UK says OK	Y
47007 (Yealm @ Puslinch)	54.9	32	0.1	-0.015	0.119	1.704	0.662	HiFlows-UK says OK	Y
52014 (Tone @ Greenham)	57.2	13	0.19	0.146	0.118	0.063	0.67	HiFlows-UK says unsuitable for PG - FARL is 0.937	N
49004 (Gannel @ Gwills)	41	23	0.26	0.085	0.025	0.864	0.677	HiFlows-UK says OK	Y
15809 (Muckle Burn @ Eastmill)	?	20	0.242	0.034	-0.005	1.018	0.692	Not on HiFlows-UK - FARL at least 0.96	N
56003 (Honddu @ the Forge Brecon)	62.1	21	0.263	0.32	0.314	0.452	0.7	HiFlows-UK says uncertain > QMED but use	Y
48006 (Cober @ Helston)	40.1	20	0.23	0.427	0.371	1.072	0.757	HiFlows-UK says unsuitable for PG	N
49002 (Hayle @ st Erth)	47.6	46	0.235	0.364	0.163	0.996	0.774	HiFlows-UK says OK - Promote to rank 5 - use update	Y
15002 (Newton Burn @ Newton)	15.4	24	0.202	0.274	0.11	0.558	0.776	Not on HiFlows-UK but use	Y
64006 (Leri @ Dolybont)	47.2	11	0.152	0.071	-0.087	1.014	0.793	HiFlows-UK says probably OK	Y
52016 (Currypool Stream @ Currypool Farm)	15.7	23	0.32	0.328	0.066	1.871	0.796	HiFlows-UK says unsuitable for PG - SAAR 25% lower	N
61003 (Gwaun @ Cilrhedyn Bridge)	31.3	15	0.151	0.25	0.22	0.639	0.798	HiFlows-UK says unsuitable for QMED and PG	N
63003 (Wyre @ Llanrhystyd)	40.6	11	0.375	0.403	0.354	2.108	0.798	HiFlows-UK says unsuitable for QMED and PG	N
15005 (Melgan @ Loch of Lintrathen)	40.9	38	0.132	0.042	0.228	1.901	0.813	Not on HiFlows-UK - FARL is 0.8	N
Total		518							
Weighted means			0.209	0.183	0.163				
New PG members following first review									
56013 (Yscir @ Pontaryscir)	62.8	22	0.241	0.371	0.337	0.445	0.813	HiFlows-UK says OK	Y
48003 (Fal @ Tregony)	87	29	0.311	0.458	0.374	1.094	0.815	HiFlows-UK says OK	Y
47014 (Walkham @ Horrabridge)	44.6	22	0.203	0.258	0.306	0.449	0.852	HiFlows-UK says OK	Y
21019 (Manor Water @ Cademuir)	61.6	25	0.132	-0.191	0.153	3.908	0.863	HiFlows-UK says OK - discordant but looks OK	Y
50007 (Taw @ Taw Bridge)	71.4	21	0.312	0.388	0.27	0.743	0.881	HiFlows-UK says OK	Y
End of 100 year pooling-group									
48009 (st Neot @ Craigshill Wood)	22.7	12	0.249	0.363	0.234	0.328	0.888	FARL is 0.635	N
52017 (Congresbury Yeo @ Iwood)	66.6	19	0.232	0.063	0.076	0.41	0.89	HiFlows-UK says unsuitable for PG - FARL is 0.89	N
56012 (Grwyne @ Millbrook)	82.2	13	0.245	0.56	0.435	1.582	0.892	HiFlows-UK says unsuitable for QMED and PG	N
72014 (Conder @ Galgate)	28.5	9	0.35	0.088	-0.057	3.177	0.912	HiFlows-UK says OK -discordant but due to short record	Y
66003 (Aled @ Bryn Aled)	70	26	0.236	0.14	0.087	0.227	0.952	HiFlows-UK says unsuitable for QMED and PG - FARL is 0.951	N
60005 (Bran @ Llandovery)	66.8	15	0.204	0.057	0.049	0.36	0.962	HiFlows-UK says OK	Y
59002 (Loughor @ Tir-y-dail)	46.4	16	0.21	0.285	0.285	0.243	0.968	HiFlows-UK says unsuitable for PG	N
73011 (Mint @ Mint Bridge)		24	0.144	0.274	0.22	0.866	0.979	HiFlows-UK says OK	Y
Force into pooling-group as Rank 4 site									
49003 De Lank at De Lank	21.5	36						HiFlows-UK says OK - use update	Y
		Exclude from PG							
		Move pos. in PG - HiFlows-UK record used							
		HiFlows-UK record used							

Table A.3 Final pooling group station details

Gauging station	Station No. on Fig A.1	Record yrs	L-CV	L-Skewne	L-Kurtosis	Discordan	Sim Dist
47009 (Tiddy @ Tideford)	1	34	0.17	0.112	0.11	0.192	0.351
48010 (Seaton @ Trebrownbridge)	2	31	0.231	0.22	0.126	0.195	0.387
51003 (Washford @ Beggearn Huish)	3	36	0.237	0.287	0.416	1.372	0.397
49003 (de Lank @ de Lank)	4	37	0.226	0.267	0.163	0.145	1.467
49002 (Hayle @ st Erth)	5	46	0.249	0.253	0.176	0.16	0.774
15004 (Inzion @ Loch of Lintrathen)	6	44	0.192	0.038	0.11	0.492	0.51
73803 (Winster @ Lobby Bridge)	7	12	0.095	0.265	0.151	3.077	0.536
48004 (Warleggan @ Trengoffe)	8	24	0.271	0.197	0.135	0.71	0.627
47007 (Yealm @ Puslinch)	9	32	0.1	-0.015	0.119	1.244	0.662
49004 (Gannel @ Gwills)	10	34	0.25	0.116	0.018	1.356	0.677
56003 (Honddu @ the Forge Brecon)	11	21	0.263	0.32	0.314	0.405	0.7
15002 (Newton Burn @ Newton)	12	24	0.202	0.274	0.11	0.579	0.776
64006 (Leri @ Dolybont)	13	11	0.152	0.071	-0.087	1.718	0.793
56013 (Yscir @ Pontaryscir)	14	22	0.241	0.371	0.337	0.622	0.813
48003 (Fal @ Tregony)	15	29	0.311	0.458	0.374	1.134	0.815
47014 (Walkham @ Horrabridge)	16	22	0.203	0.258	0.306	0.496	0.852
21019 (Manor Water @ Cademuir)	17	25	0.132	-0.191	0.153	3.252	0.863
50007 (Taw @ Taw Bridge)	18	21	0.312	0.388	0.27	0.852	0.881
Total		505				Mean	0.715611
Weighted means			0.214	0.194	0.176		

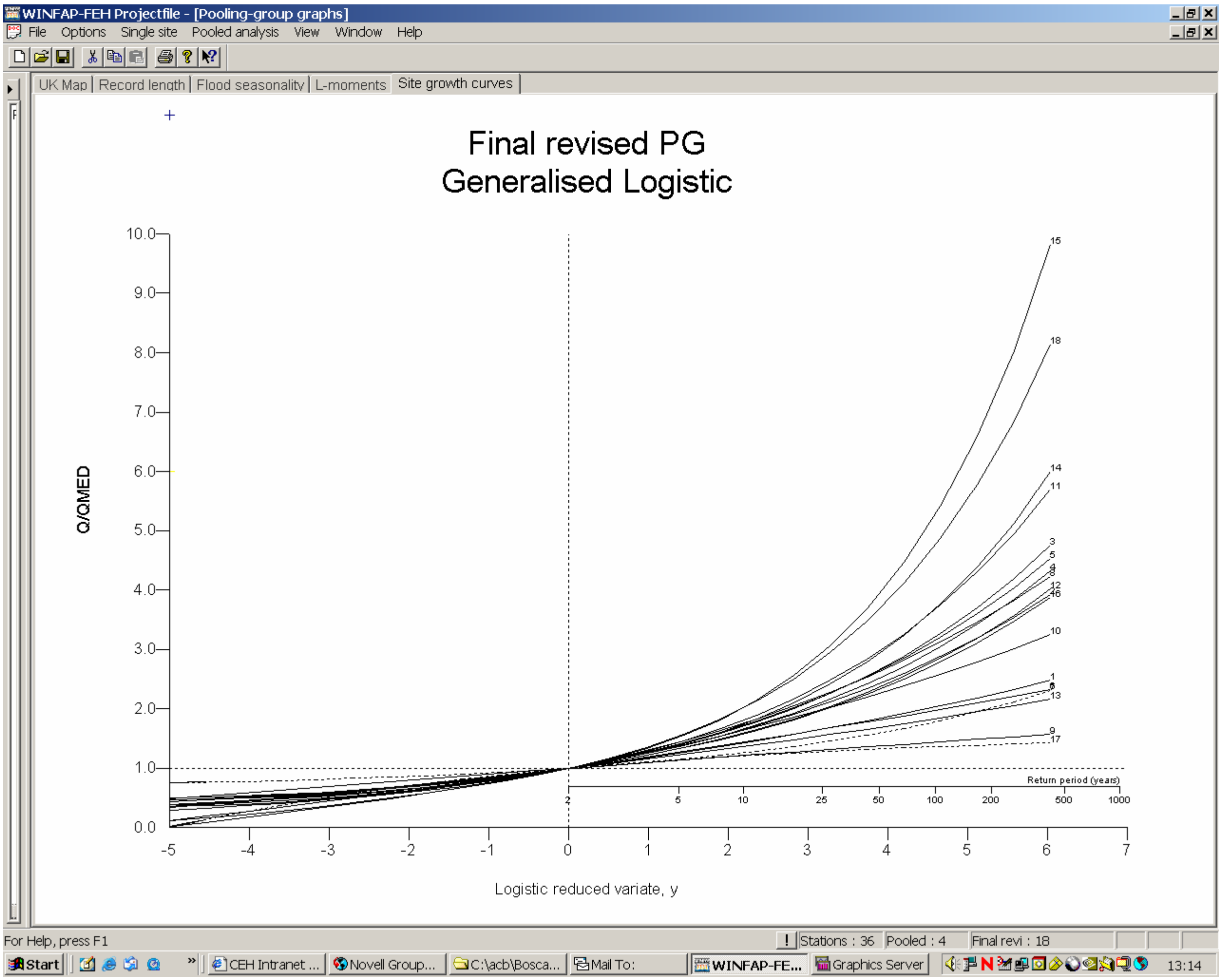


Figure A.1 Final flood frequency analysis using Pooling Group stations

Appendix 2 Table of flow at input points for hydraulic model

Time (hours)	Boscastle FEH derived 1 in 100 year inflows (m^3/s)							
	B1	B2	B3	B4	B5N1	B5S2	B5S1	Lateral 3
0	0.08	0.07	0.18	0.22	0.02	0.02	0.82	0.41
0.25	0.12	0.09	0.20	0.25	0.03	0.04	0.90	0.45
0.5	0.21	0.12	0.23	0.30	0.05	0.06	1.05	0.52
0.75	0.35	0.18	0.28	0.39	0.08	0.09	1.28	0.64
1	0.57	0.25	0.35	0.50	0.12	0.15	1.59	0.80
1.25	0.90	0.36	0.44	0.66	0.19	0.23	2.00	1.00
1.5	1.48	0.50	0.55	0.85	0.31	0.38	2.51	1.25
1.75	2.41	0.71	0.69	1.10	0.50	0.61	3.14	1.57
2	3.51	1.03	0.86	1.41	0.73	0.89	3.92	1.96
2.25	4.63	1.49	1.07	1.82	0.97	1.18	4.90	2.45
2.5	5.71	2.05	1.34	2.34	1.20	1.45	6.15	3.07
2.75	6.63	2.63	1.70	3.05	1.40	1.69	7.77	3.88
3	7.17	3.21	2.16	4.01	1.52	1.84	9.90	4.95
3.25	7.08	3.76	2.78	5.14	1.52	1.83	12.71	6.36
3.5	6.58	4.26	3.50	6.36	1.43	1.71	16.02	8.01
3.75	5.89	4.63	4.29	7.61	1.29	1.54	19.61	9.81
4	5.11	4.78	5.09	8.85	1.13	1.35	23.30	11.65
4.25	4.27	4.70	5.90	10.05	0.95	1.14	27.01	13.50
4.5	3.39	4.45	6.70	11.15	0.77	0.92	30.64	15.32
4.75	2.50	4.12	7.46	12.11	0.58	0.69	34.13	17.07
5	1.67	3.74	8.17	12.79	0.41	0.48	37.36	18.68
5.25	1.02	3.33	8.78	13.07	0.26	0.30	40.17	20.09
5.5	0.63	2.89	9.23	12.94	0.16	0.19	42.25	21.13
5.75	0.41	2.44	9.46	12.52	0.10	0.12	43.27	21.64
6	0.26	1.98	9.42	11.91	0.07	0.08	43.12	21.56
6.25	0.17	1.52	9.20	11.18	0.04	0.05	42.11	21.06
6.5	0.11	1.10	8.85	10.37	0.03	0.04	40.49	20.25
6.75	0.08	0.76	8.41	9.50	0.02	0.03	38.47	19.24
7	0.08	0.53	7.91	8.59	0.02	0.02	36.20	18.10
7.25	0.08	0.38	7.37	7.65	0.02	0.02	33.74	16.87
7.5	0.08	0.27	6.81	6.69	0.02	0.02	31.15	15.57
7.75	0.08	0.20	6.21	5.70	0.02	0.02	28.44	14.22
8	0.08	0.15	5.60	4.72	0.02	0.02	25.64	12.82
8.25	0.08	0.11	4.98	3.77	0.02	0.02	22.78	11.39
8.5	0.08	0.09	4.34	2.90	0.02	0.02	19.86	9.93
8.75	0.08	0.07	3.70	2.19	0.02	0.02	16.92	8.46
9	0.08	0.07	3.07	1.66	0.02	0.02	14.03	7.02
9.25	0.08	0.07	2.47	1.29	0.02	0.02	11.32	5.66
9.5	0.08	0.07	1.94	1.02	0.02	0.02	8.88	4.44
9.75	0.08	0.07	1.50	0.81	0.02	0.02	6.86	3.43
10	0.08	0.07	1.17	0.65	0.02	0.02	5.37	2.68
10.25	0.08	0.07	0.94	0.52	0.02	0.02	4.29	2.14
10.5	0.08	0.07	0.76	0.41	0.02	0.02	3.48	1.74
10.75	0.08	0.07	0.62	0.33	0.02	0.02	2.84	1.42

Time (hours)	Boscastle FEH derived 1 in 100 year inflows (m^3/s)							
	B1	B2	B3	B4	B5N1	B5S2	B5S1	Lateral 3
11	0.08	0.07	0.51	0.28	0.02	0.02	2.33	1.17
11.25	0.08	0.07	0.42	0.24	0.02	0.02	1.92	0.96
11.5	0.08	0.07	0.35	0.22	0.02	0.02	1.59	0.79
11.75	0.08	0.07	0.29	0.22	0.02	0.02	1.32	0.66
12	0.08	0.07	0.24	0.22	0.02	0.02	1.12	0.56
12.25	0.08	0.07	0.21	0.22	0.02	0.02	0.97	0.48
12.5	0.08	0.07	0.19	0.22	0.02	0.02	0.87	0.44

The locations of the inputs B1 to B5S are shown in Figure 6.1. Lateral 3 represents the inflow from areas with no defined tributary.

Time (hours)	Boscastle FEH derived 1 in 500 year inflows (m^3/s)							
	B1	B2	B3	B4	B5N1	B5S2	B5S1	Lateral 3
0	0.08	0.07	0.18	0.22	0.22	0.02	0.82	0.41
0.25	0.15	0.10	0.20	0.26	0.26	0.04	0.93	0.47
0.5	0.28	0.15	0.25	0.34	0.34	0.07	1.15	0.58
0.75	0.49	0.23	0.33	0.46	0.46	0.13	1.49	0.74
1	0.81	0.34	0.43	0.64	0.64	0.21	1.95	0.97
1.25	1.31	0.50	0.56	0.86	0.86	0.34	2.54	1.27
1.5	2.18	0.71	0.72	1.15	1.15	0.56	3.29	1.64
1.75	3.57	1.02	0.92	1.51	1.51	0.91	4.22	2.11
2	5.23	1.49	1.17	1.96	1.96	1.33	5.36	2.68
2.25	6.92	2.18	1.48	2.55	2.55	1.77	6.79	3.40
2.5	8.54	3.01	1.88	3.32	3.32	2.18	8.61	4.30
2.75	9.92	3.88	2.40	4.35	4.35	2.54	10.98	5.49
3	10.73	4.74	3.08	5.75	5.75	2.77	14.10	7.05
3.25	10.60	5.57	3.98	7.41	7.41	2.75	18.21	9.11
3.5	9.85	6.30	5.04	9.19	9.19	2.57	23.06	11.53
3.75	8.81	6.86	6.19	11.02	11.02	2.32	28.31	14.15
4	7.64	7.08	7.37	12.83	12.83	2.02	33.71	16.85
4.25	6.38	6.96	8.55	14.57	14.57	1.70	39.13	19.56
4.5	5.06	6.59	9.71	16.19	16.19	1.37	44.45	22.23
4.75	3.71	6.10	10.83	17.58	17.58	1.02	49.56	24.78
5	2.48	5.53	11.86	18.58	18.58	0.70	54.28	27.14
5.25	1.49	4.92	12.76	18.98	18.98	0.44	58.39	29.19
5.5	0.90	4.27	13.43	18.79	18.79	0.27	61.43	30.72
5.75	0.57	3.59	13.75	18.18	18.18	0.17	62.92	31.46
6	0.35	2.90	13.70	17.29	17.29	0.11	62.71	31.35
6.25	0.21	2.23	13.38	16.22	16.22	0.07	61.23	30.61
6.5	0.13	1.61	12.86	15.04	15.04	0.04	58.86	29.43
6.75	0.08	1.10	12.22	13.78	13.78	0.03	55.90	27.95
7	0.08	0.75	11.49	12.45	12.45	0.02	52.57	26.29
7.25	0.08	0.53	10.70	11.07	11.07	0.02	48.98	24.49
7.5	0.08	0.37	9.87	9.66	9.66	0.02	45.18	22.59
7.75	0.08	0.27	9.01	8.23	8.23	0.02	41.22	20.61
8	0.08	0.19	8.11	6.79	6.79	0.02	37.13	18.56
8.25	0.08	0.13	7.20	5.40	5.40	0.02	32.94	16.47
8.5	0.08	0.09	6.27	4.14	4.14	0.02	28.68	14.34

Time (hours)	Boscastle FEH derived 1 in 500 year inflows (m^3/s)							
	B1	B2	B3	B4	B5N1	B5S2	B5S1	Lateral 3
8.75	0.08	0.07	5.33	3.10	3.10	0.02	24.38	12.19
9	0.08	0.07	4.40	2.33	2.33	0.02	20.15	10.07
9.25	0.08	0.07	3.54	1.79	1.79	0.02	16.18	8.09
9.5	0.08	0.07	2.76	1.39	1.39	0.02	12.61	6.31
9.75	0.08	0.07	2.11	1.09	1.09	0.02	9.66	4.83
10	0.08	0.07	1.63	0.85	0.85	0.02	7.47	3.74
10.25	0.08	0.07	1.29	0.65	0.65	0.02	5.89	2.95
10.5	0.08	0.07	1.03	0.50	0.50	0.02	4.71	2.35
10.75	0.08	0.07	0.82	0.39	0.39	0.02	3.77	1.89
11	0.08	0.07	0.66	0.30	0.30	0.02	3.03	1.51
11.25	0.08	0.07	0.53	0.25	0.25	0.02	2.43	1.21
11.5	0.08	0.07	0.42	0.22	0.22	0.02	1.94	0.97
11.75	0.08	0.07	0.34	0.22	0.22	0.02	1.55	0.78
12	0.08	0.07	0.27	0.22	0.22	0.02	1.25	0.63
12.25	0.08	0.07	0.23	0.22	0.22	0.02	1.04	0.52
12.5	0.08	0.07	0.20	0.22	0.22	0.02	0.89	0.45

The locations of the inputs B1 to B5S are shown in Figure 6.1. Lateral 3 represents the inflow from areas with no defined tributary.

Time (hours)	Crackington Haven FEH derived sub-catchment inflows			
	1 in 100 year flow (m^3/s)		1 in 500 year flow (m^3/s)	
	C1	C2	C1	C2
0	0.20	0.21	0.20	0.21
0.25	0.24	0.25	0.25	0.26
0.5	0.31	0.32	0.37	0.38
0.75	0.43	0.44	0.54	0.55
1	0.60	0.61	0.79	0.80
1.25	0.82	0.84	1.12	1.13
1.5	1.12	1.13	1.55	1.57
1.75	1.51	1.53	2.13	2.16
2	2.07	2.09	2.95	2.98
2.25	2.91	2.94	4.19	4.23
2.5	4.09	4.13	5.92	5.97
2.75	5.50	5.55	7.99	8.06
3	6.99	7.05	10.18	10.26
3.25	8.51	8.58	12.41	12.51
3.5	10.00	10.09	14.61	14.72
3.75	11.43	11.53	16.72	16.85
4	12.75	12.86	18.65	18.80
4.25	13.85	13.97	20.27	20.43
4.5	14.52	14.65	21.25	21.43
4.75	14.58	14.72	21.34	21.53
5	14.15	14.28	20.71	20.89
5.25	13.45	13.59	19.68	19.86
5.5	12.58	12.71	18.40	18.58
5.75	11.59	11.71	16.95	17.12

Time (hours)	**Crackington Haven FEH derived sub-catchment inflows**			
	1 in 100 year flow (m^3/s)		**1 in 500 year flow (m^3/s)**	
	C1	**C2**	**C1**	**C2**
6	10.53	10.65	15.39	15.55
6.25	9.42	9.53	13.76	13.91
6.5	8.27	8.37	12.07	12.20
6.75	7.08	7.18	10.32	10.45
7	5.88	5.96	8.55	8.65
7.25	4.71	4.78	6.84	6.93
7.5	3.63	3.68	5.24	5.32
7.75	2.65	2.70	3.81	3.87
8	1.88	1.92	2.68	2.72
8.25	1.36	1.39	1.91	1.94
8.5	1.02	1.04	1.40	1.43
8.75	0.77	0.79	1.04	1.06
9	0.58	0.60	0.76	0.78
9.25	0.44	0.46	0.56	0.57
9.5	0.34	0.35	0.40	0.42
9.75	0.26	0.28	0.30	0.31
10	0.22	0.23	0.23	0.24
10.25	0.20	0.21	0.20	0.21

The locations of the inputs C1 and C2 are shown in Figure 6.34.

Appendix 3 15 Minute Flow for the Valency and Crackington Catchments

Valency Catchment

Time (BST)	Sub-catchment Inflows (m^3/s)							
	B1	**B2**	**B3**	**B4**	**B5N1**	**B5S2**	**B5S1**	**Lateral 3**
12:00:00	0.08	0.07	0.18	0.22	0.02	0.02	0.11	0.06
12:15:00	0.08	0.07	0.18	0.22	0.02	0.02	0.11	0.06
12:30:00	0.08	0.07	0.18	0.22	0.02	0.02	0.11	0.06
12:45:00	0.09	0.07	0.18	0.22	0.02	0.02	0.11	0.06
13:00:00	0.16	0.08	0.18	0.22	0.02	0.03	0.12	0.06
13:15:00	0.76	0.16	0.20	0.22	0.04	0.04	0.18	0.09
13:30:00	1.79	0.43	0.34	0.36	0.11	0.12	0.53	0.26
13:45:00	3.02	0.90	0.76	0.87	0.24	0.27	1.24	0.62
14:00:00	3.59	1.42	1.58	2.56	0.38	0.47	2.17	1.09
14:15:00	3.67	2.02	2.73	4.57	0.47	0.65	2.99	1.49
14:30:00	3.39	2.50	4.57	7.88	0.52	0.79	3.63	1.82
14:45:00	3.00	2.72	6.69	11.87	0.51	0.84	3.87	1.93
15:00:00	2.37	2.94	9.08	16.51	0.48	0.85	3.88	1.94
15:15:00	1.85	2.94	11.43	20.28	0.40	0.75	3.44	1.72
15:30:00	1.89	2.94	13.81	24.71	0.40	0.76	3.48	1.74
15:45:00	2.20	2.94	15.53	27.39	0.43	0.80	3.65	1.82
16:00:00	2.99	3.24	16.72	28.92	0.54	0.93	4.27	2.14
16:15:00	4.40	4.23	18.72	30.95	0.89	1.45	6.65	3.33
16:30:00	6.55	5.53	20.68	33.02	1.40	2.24	10.24	5.12
16:45:00	8.82	7.64	23.99	36.54	2.18	3.51	16.07	8.03
17:00:00	10.69	9.93	27.73	42.14	2.85	4.54	20.79	10.39
17:15:00	12.92	12.26	32.67	49.89	3.51	5.56	25.44	12.72
17:30:00	16.01	14.18	36.80	55.24	4.09	6.15	28.14	14.07
17:45:00	18.67	15.09	39.18	58.62	4.42	6.17	28.24	14.12
18:00:00	18.86	15.07	39.61	57.25	4.24	5.37	24.57	12.29
18:15:00	16.06	13.21	37.38	52.84	3.56	4.11	18.80	9.40
18:30:00	11.68	10.31	33.50	45.64	2.59	2.72	12.42	6.21
18:45:00	7.83	7.49	28.38	36.82	1.71	1.64	7.49	3.74
19:00:00	4.74	5.13	23.17	27.93	1.03	0.87	3.97	1.99
19:15:00	2.85	3.29	17.93	19.65	0.59	0.46	2.10	1.05
19:30:00	1.85	1.91	12.90	12.88	0.35	0.27	1.22	0.61
19:45:00	1.40	1.02	8.83	7.59	0.23	0.19	0.85	0.42
20:00:00	1.14	0.66	5.32	4.12	0.18	0.15	0.69	0.34
20:15:00	0.92	0.55	3.07	2.06	0.14	0.12	0.55	0.28
20:30:00	0.64	0.49	1.61	1.23	0.10	0.09	0.42	0.21
20:45:00	0.48	0.42	1.05	1.06	0.07	0.08	0.34	0.17
21:00:00	0.37	0.29	0.84	0.97	0.06	0.06	0.29	0.15
21:15:00	0.27	0.22	0.73	0.81	0.05	0.05	0.24	0.12
21:30:00	0.18	0.18	0.60	0.64	0.04	0.04	0.19	0.09
21:45:00	0.10	0.15	0.48	0.50	0.03	0.03	0.14	0.07
22:00:00	0.09	0.11	0.36	0.42	0.02	0.03	0.12	0.06
22:15:00	0.08	0.08	0.31	0.37	0.02	0.02	0.11	0.06
22:30:00	0.08	0.07	0.27	0.31	0.02	0.02	0.11	0.06
22:45:00	0.08	0.07	0.24	0.26	0.02	0.02	0.11	0.06
23:00:00	0.08	0.07	0.21	0.23	0.02	0.02	0.11	0.06
23:15:00	0.08	0.07	0.19	0.22	0.02	0.02	0.11	0.06
23:30:00	0.08	0.07	0.18	0.22	0.02	0.02	0.11	0.06

The locations of the inputs B1 to B5S are shown in Figure 6.1.

Crackington Catchment

Time (BST)	Crackington Haven Inflows (m^3/s)	
	C1	C2
12:30:00	0.20	0.21
12:45:00	0.21	0.21
13:00:00	0.24	0.22
13:15:00	0.31	0.24
13:30:00	0.52	0.33
13:45:00	0.81	0.53
14:00:00	1.16	0.85
14:15:00	1.51	1.21
14:30:00	1.89	1.76
14:45:00	2.24	2.37
15:00:00	2.39	2.96
15:15:00	2.41	3.43
15:30:00	2.43	3.93
15:45:00	2.52	4.59
16:00:00	2.70	5.12
16:15:00	3.14	5.83
16:30:00	3.96	7.05
16:45:00	5.27	9.06
17:00:00	7.10	11.88
17:15:00	9.82	15.81
17:30:00	13.49	21.01
17:45:00	17.72	26.63
18:00:00	21.91	31.77
18:15:00	25.35	35.55
18:30:00	27.79	37.62
18:45:00	28.80	37.42
19:00:00	28.23	34.88
19:15:00	26.00	30.86
19:30:00	22.76	26.17
19:45:00	19.46	21.49
20:00:00	16.33	16.99
20:15:00	13.24	12.77
20:30:00	9.98	8.87
20:45:00	7.03	5.60
21:00:00	4.63	3.18
21:15:00	2.94	1.75
21:30:00	1.91	1.06
21:45:00	1.38	0.77
22:00:00	1.04	0.63
22:15:00	0.72	0.50
22:30:00	0.44	0.38
22:45:00	0.31	0.31
23:00:00	0.28	0.28
23:15:00	0.25	0.26
23:30:00	0.22	0.23
23:45:00	0.20	0.21
00:00:00	0.20	0.21

The locations of the inputs C1 and C2 are shown in Figure 6.34.

Appendix 4 Historic Evidence

1950 flood – lower bridge

1950 flood

1958 flood (written as 1957)

BOSCASTLE FLOODS 1957: The first warning was given by Mrs. Elizabeth Whitehouse who was riding her horse up the valley, saw the rivers coming and galloped down to give advance warning. It came with such a rush, like a huge wave, that no one had a chance to get furniture out of their rooms.

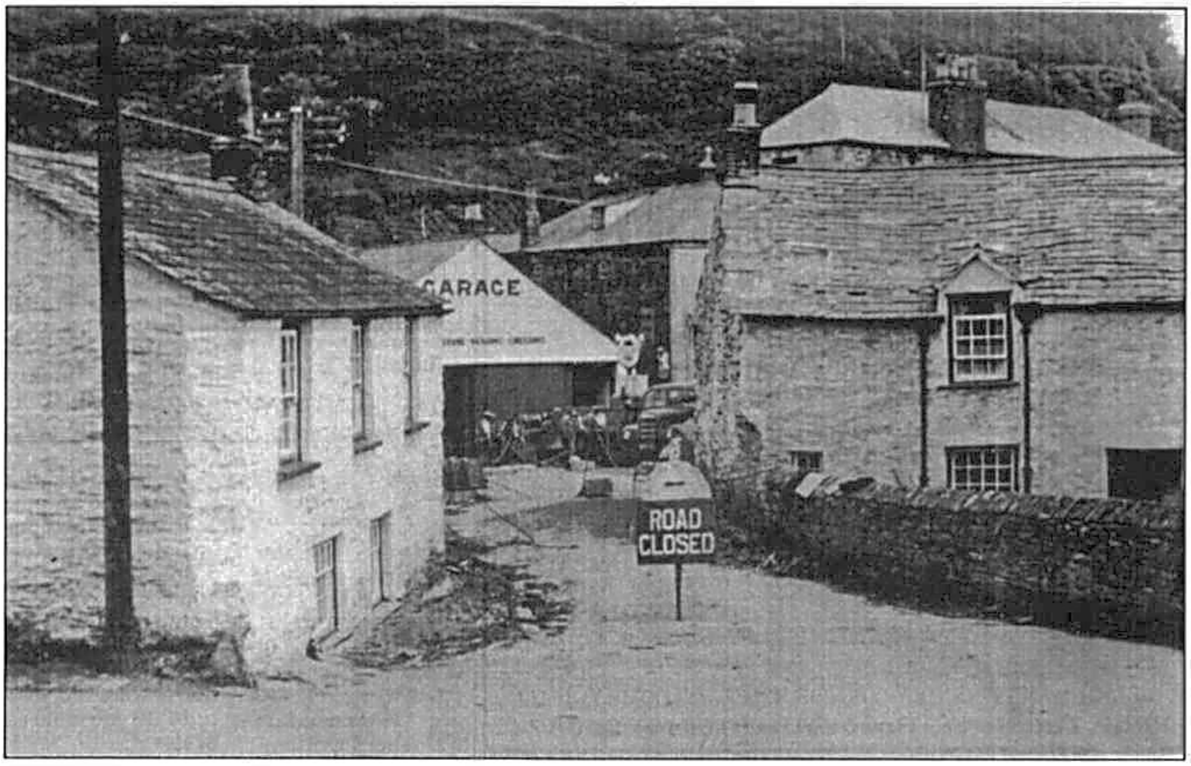
Miss Rachel Beadon was in the call box at the end of the bridge ringing Norman Webber to ask for help, the flood came on so fast that she could not get out of the telephone box and two of the young fishermen crawled across on the parapet of the bridge with a rope and rescued her. The river overflowed into the whole of the Valency Valley, over the lawns and into the cottages, shops and garage, many household items and furniture were washed into the sea.

1958 flood (written as 1957)

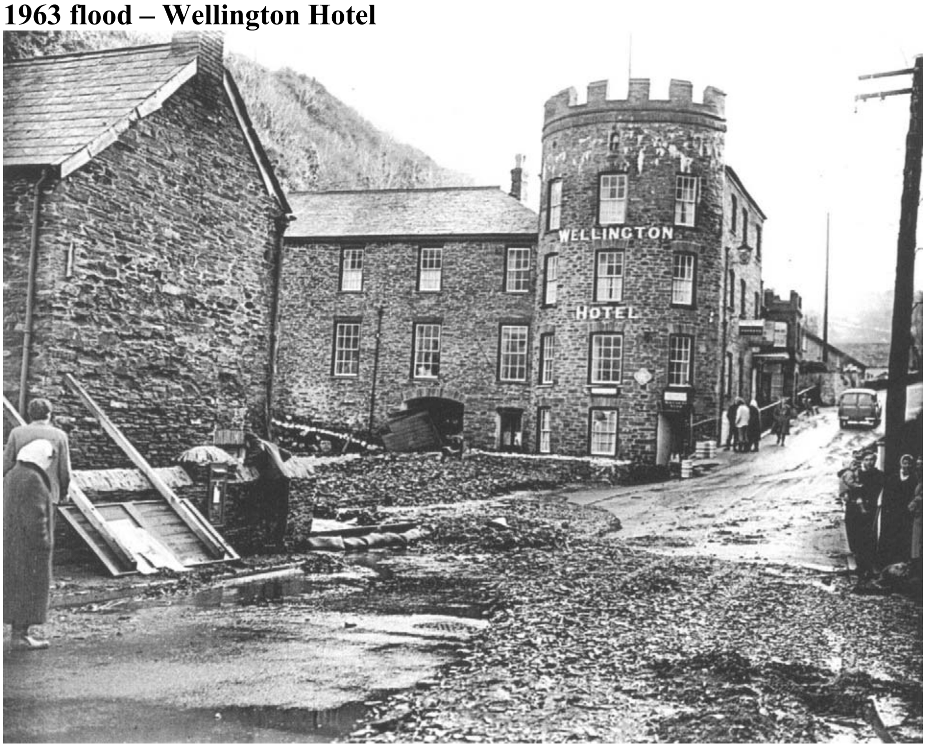
THE FLOODS: In 1957 there was a terrible flood. There had been continuous torrential rain which came down the Valency River from the moors and hills. The power of the water damaged the top bridge and flooded surrounding cottages and shops. People were trapped and had to be rescued from their homes. Charlie Berryman, the local bandsmaster drowned when he fell in trying to retrieve a chair. Mrs Beadon and her daughters Rachel, Edith and Millicent lost their furniture from the Riverside Hotel.

1958 flood

The building on the left in the picture below belonged to Mr. Pearn and was demolished when the bridge was rebuilt and the road widened following the floods.



1963 flood – Wellington Hotel



1963 flood

1993

Summary of Rainfall data

30th June 1932 event
Daily rainfall for 1932 at a Camelford gauge and a gauge at Callington.

15th August 1952 event (Lynmouth Flood)
Daily rainfall for 1952 at a Lynmouth gauge.
Summary information on the event including a list of gauges which had high rainfall on the 15th and 16th of August 1952.

8th June 1957 event (Camelford flood)
Daily rainfall for 1957 at 2 gauges near Boscastle, 3 gauges at Camelford and summary information containing the amount, duration, rate and start of the event for selected gauges.

June 1958 event (Boscastle flood)
Daily rainfall for 1958 at 2 gauges near Boscastle, and 3 gauges at Camelford and summary information describing the areas affected.

August 1958 event
Daily rainfall for 1958 at a gauge in Bude and a gauge in St Austell, and summary information describing the areas affected.

27th December 1979 event
Daily rainfall for December 1979 at 2 gauges in Bideford, 2 gauges in the Hayle catchment and a gauge at Truro and summary information of the monthly rainfall, and the amount and date of the highest daily rainfall in 1979 for all gauges in the Cornwall and Devon area.

12th July 1982 event
Daily rainfall for July 1982 in Lynmouth, and summary data showing the monthly rainfall and the highest daily rainfall and the date it occurred in 1982.

12th June 1993 event
Daily rainfall for June 1993 for a gauge at Bude, 2 gauges at Bodmin, and 2 gauges at Camelford.

Note that the Otterham/Lesnewth series starts in 1971.

Flood event information from newspapers

16**th July 1847 (Rivers Camel and Inney)**
Heavy rainfalls on Davidstow Moor. The rivers Camel and Inney rose between 12 and 18 feet.

30th June 1932 (Camel)
Camelford. Observations that the river levels were high, almost at bankfull.
Heavy rain in Callington on the 16th July 1932.
Source: East Cornwall Times.

Gauge	Date	Rainfall (inch)	Rainfall (mm)
1893 @ Camelford	30/06/1932	1.34	34.04
1892 @ Camelford	30/061932	1.35	34.29
1944 @ Callington	17/07/1932	1.53	38.86

15th and 16th August 1952 (Lynmouth flood)
Lynmouth, Devon. 229.5mm in 24 hours (internet). No rainfall event details in the newspapers, which concentrated on the deaths and damage caused by the floods.
River Torridge had the worst flood for 40 years. 9am on the 15th to 9am on the 16th of August 3.42 inches of rainfall fell. Measured at Jennets Reservoir Bideford.
Source: Bideford and North Devon Gazette.

Gauge	Date	Rainfall (inch)	Rainfall (mm)
1830 @ Ilfracombe	15/08/1952	3.49	88.50
1861 @ Bideford	15/08/1952	3.42	86.87
Longstow Barrow	15/08/1952	9.00	228.60
Torrington	15/08/1952	4.45	113.03
Okehampton	15/08/1952	4.42	112.27

8th June 1957 (Camelford flood) ~
Camelford, Cornwall. 203.2mm in 24 hours (internet).
Rainfall of 7.06 inches in 12 hours from 9am to 9pm on the 8th. Earlier in the year it had taken 3 months to get 18.8 inches of rain. Camelford was flooded by the river Camel. 9am to 1pm 0.25 inches, 1pm to 4pm 5.5 inches, 4pm to 7pm 0.7 inches, and 7pm to 9pm 0.6 inches.
In 1938 Buttermere had 7.14 inches and in 1952 Longsone Barrow had 9 inches of rainfall in a similar time period. The record rainfall is Martinstown, Dorchester, which had 11 inches in 6 hours on the 18/07/1955.
Source: Cornish Guardian.

Three 'very rare' rainfall events were observed in the Camelford area on the 8th of June 1957 and caused serious flooding. More detail in 'Heavy rainfall at Camelford, August 8, 1957' in *Meteorological Magazine*, Vol. **86**, pp. 339-343. There was also a heavy thunderstorm in Devonshire on the 18th of June 1957 which was classified as 'noteworthy' and caused Stokeinteignhead to flood to a depth of 4 ft and Teignmouth to flood to 2 ft.
Source: British Rainfall 1957.

Gauge	Date	Rainfall (inch)	Rainfall (mm)	Short Period rainfall (mm)	Duration of short period (hrs)
1893/9 @ Bossing	09/06/1957	2.69	68.33	N/a	N/a
1893/3 @ Delabole	08/06/1957	6.00	152.40	101.60	3
1893 @ Camelford	08/06/1957	2.13	54.10	N/a	N/a
1894 @ Bude	08/06/1957	0.96	24.50	N/a	N/a
1893/1 @ Camelford	08/06/1957	6.33	160.78	127.00	3
1893/2 @ Camelford	08/06/1957	7.09	180.09	139.19	3

3rd June 1958 (Boscastle)
There was heavy rainfall in Cornwall on the 3rd of June 1958, where the River Valency rose 15 ft in 20 minutes and flooded Boscastle damaging property. The river Camel also rose rapidly and flooded Camelford and Wadebridge to a depth of 3 ft.
Source: British Rainfall 1958.

Gauge	Date	Rainfall (inch)	Rainfall (mm)
1893/9 @ Bossing	04/06/1958	1.05	26.67
1893/3 @ Delabole	03/06/1958	1.69	42.93
1893 @ Camelford	03/06/1958	0.85	21.59
1893/1 @ Camelford	03/06/1958	1.26	32.00
1893/2 @ Camelford	03/06/1958	1.28	32.51

August 1958
Flooding occurred in St Austell (internet).

Gauge	Date	Rainfall (inch)	Rainfall (mm)
1894 @ Bude	19/08/1958	1.32	33.50
1928/2 @ St Austell	27/07/1958	1.22	30.99
1928/5 @ St Austell	07/08/1958	1.59	40.39

14th June 1965
Wadebridge, Cornwall. 140mm in 220mins (internet).
River Tavy flooded, heavy rain. Not as much rainfall as the event on the 17th July 1890 which affected the whole of Dartmoor, rivers Coswic, Walkham and Tavy.
Source: East Cornwall Times.

25th to 27th December 1979
Truro, Cornwall.
3.5 inches of rainfall fell in 48 hours in West Cornwall. The Red River flooded Truro, Camborne and Brea. Considered worst flood for 20 years.
Source: The West Briton.

27th to 28th December 1979
Kenwith Valley, Torridge and Bideford.

Rainfall of 41mm (1.62 inches) on the 26th December 1979 and 45mm (1.78 inches) on 27th December 1979 onto already sodden ground. The flooding occurred on the 27th and 28th December effecting Torridge and Bideford in the Kenwith Valley. It was considered the worst flooding by residents and for some it was the first time they had been flooded in 40 years. The floods caused £375,000 worth of damage.
Source: Bideford and North Devon Gazette.

27th December 1979
Calstock. Torrential rain caused the river Tamar to flood.
Source: East Cornwall Times.

Gauge	Date	Rainfall (inch)	Rainfall (mm)
390388 @ Bideford	26/12/1979	1.15	29.20
390388 @ Bideford	27/12/1979	2.44	61.90
390480 @ Bideford	26/12/1979	1.33	33.90
390480 @ Bideford	27/12/1979	2.20	55.90
381899 @ Bossow	26/12/1979	2.03	51.60
381899 @ Bossow	27/12/1979	2.19	55.50
382035 @ Townshend	26/12/1979	1.19	30.20
382035 @ Townshend	27/12/1979	1.70	43.20
379134 @ Truro	26/12/1979	1.66	42.10
379134 @ Truro	27/12/1979	1.97	50.00

12th July 1982
Lynmouth, Devon. 1 to 2 inches of rain fell in 2 hours starting at 5:30 am on 12th July 1982.
Source:

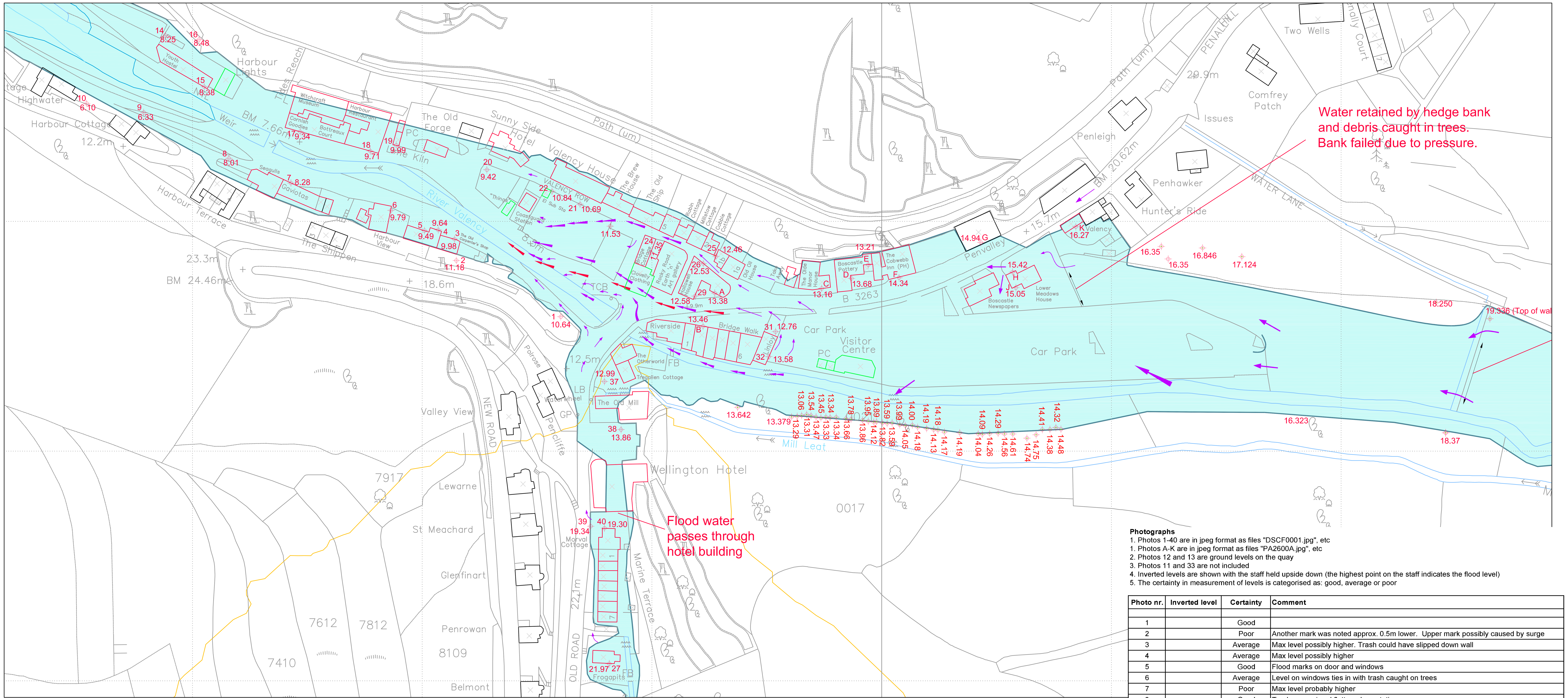
Gauge	Date	Rainfall (inch)	Rainfall (mm)
396384 @ Lundy	11/07/1982	0.67	17.10
396384 @ Lundy	12/07/1982	1.77	44.90
396384 @ Lundy	13/07/1982	1.12	28.50

22nd July 1983
Penzance, Cornwall.
1.79 inches of rain fell in a 2 hour period from 8am on the 22nd July 1983.
Source: The Cornishman.

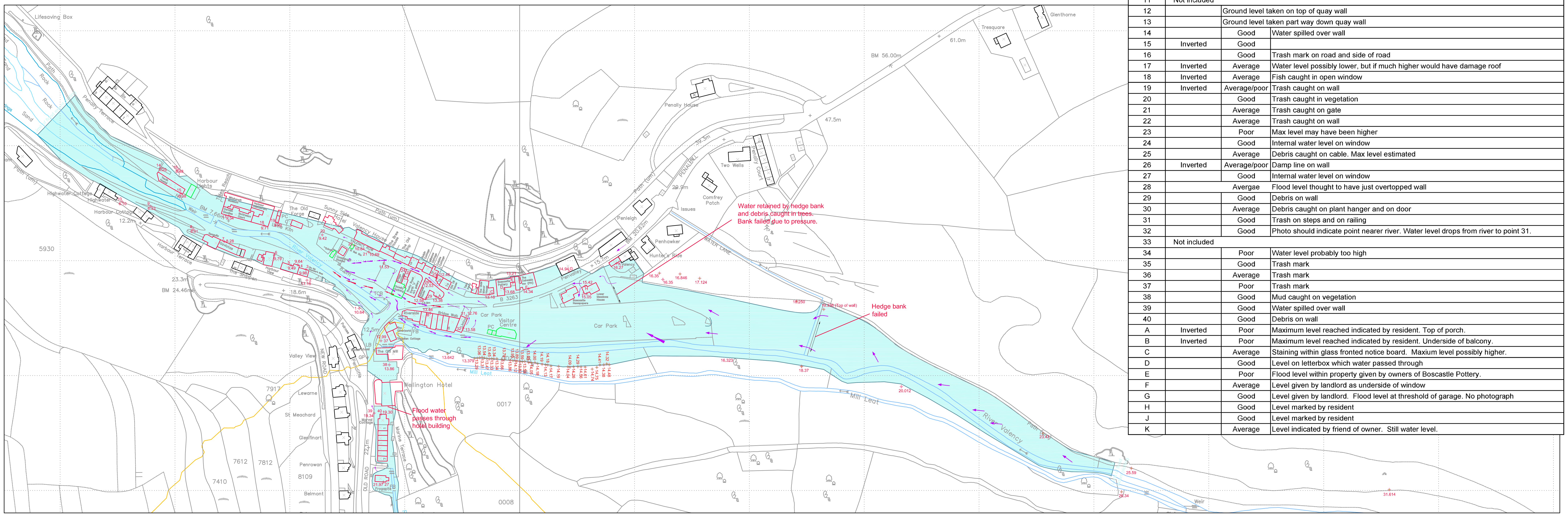
12th and 13th June 1993
Bodmin, Bude and Camelford flooded.
6.5 inches of rain fell in North Cornwall and Devon over a 30 hour period. 9 rivers had flood warnings including the river Tamar, Camel, Ottery and Caen.
Source: Cornish Guardian.

Gauge	Date	Rainfall (inch)	Rainfall (mm)
386255 @ Bude	11/06/1993	2.27	57.70
Bodmin	11/06/1993	1.51	38.40
384539 @ Bodmin	11/06/1993	1.14	29.00
Camelford	11/06/1993	3.41	86.50
384101 @ Camelford	11/06/1993	1.58	40.10

Appendix 5 Maps of flooded area in Boscastle



Scale 1:1000 @ A1

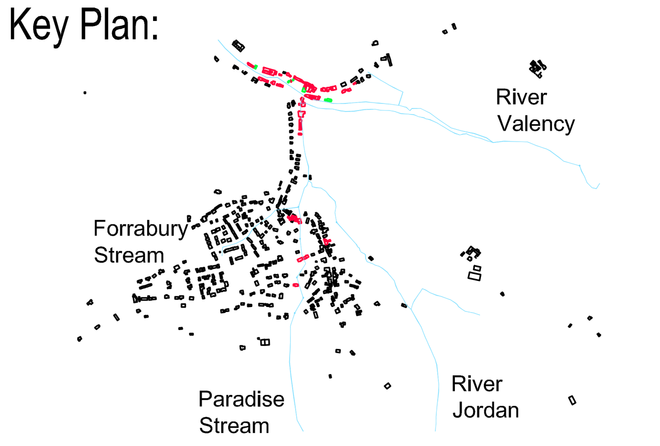


Scale 1:2000 @ A1

Photographs
1. Photos 1-40 are in jpeg format as files "DSCF0001.jpg", etc
1. Photos A-K are in jpeg format as files "PA2600A.jpg", etc
2. Photos 12 and 13 are ground levels on the quay
3. Photos 11 and 33 are not included
4. Inverted levels are shown with the staff held upside down (the highest point on the staff indicates the flood level)
5. The certainty in measurement of levels is categorised as: good, average or poor

Photo nr.	Inverted level	Certainty	Comment
1		Good	
2		Poor	Another mark was noted approx. 0.5m lower. Upper mark possibly caused by surge
3		Average	Max level possibly higher. Trash could have slipped down wall
4		Average	Max level possibly higher
5		Good	Flood marks on door and windows
6		Average	Level on windows ties in with trash caught on trees
7		Poor	Max level probably higher
8		Good	Trash on road and flattened vegetation
9		Average	Vegetation marked and flattened
10		Good	Gravel washed away and trash mark
11	Not included		
12		Ground level taken on top of quay wall	
13		Ground level taken part way down quay wall	
14		Good	Water spilled over wall
15	Inverted	Good	
16		Good	Trash mark on road and side of road
17	Inverted	Average	Water level possibly lower, but if much higher would have damage roof
18	Inverted	Average	Fish caught in open window
19	Inverted	Average/poor	Trash caught on wall
20		Good	Trash caught in vegetation
21		Average	Trash caught on gate
22		Average	Trash caught on wall
23		Poor	Max level may have been higher
24		Good	Internal water level on window
25		Average	Debris caught on cable. Max level estimated
26	Inverted	Average/poor	Damp line on wall
27		Good	Internal water level on window
28		Avergae	Flood level thought to have just overtopped wall
29		Good	Debris on wall
30		Average	Debris caught on plant hanger and on door
31		Good	Trash on steps and on railing
32		Good	Photo should indicate point nearer river. Water level drops from river to point 31.
33	Not included		
34		Poor	Water level probably too high
35		Good	Trash mark
36		Average	Trash mark
37		Poor	Trash mark
38		Good	Mud caught on vegetation
39		Good	Water spilled over wall
40		Good	Debris on wall
A	Inverted	Poor	Maximum level reached indicated by resident. Top of porch.
B	Inverted	Poor	Maximum level reached indicated by resident. Underside of balcony.
C		Average	Staining within glass fronted notice board. Maxium level possibly higher.
D		Good	Level on letterbox which water passed through
E		Poor	Flood level within property given by owners of Boscastle Pottery.
F		Average	Level given by landlord as underside of window
G		Good	Level given by landlord. Flood level at threshold of garage. No photograph
H		Good	Level marked by resident
J		Good	Level marked by resident
K		Average	Level indicated by friend of owner. Still water level.

Key Plan:



Notes:

Key

- Trash/wrack mark level
- Flooded property
- Demolished building
- Flow direction (mid-range flows)
- Flow direction (high-range flows)
- Sub-catchment boundary derived from 1m resolution Lidar data

1. Flood levels are shown to ??? datum Newlyn.
2. Benchmark and OS Landline spot levels are to the old ??? datum. These levels should be adjusted by +???mm to bring them to the ??? datum
3. Positions of some trash marks may not tie in with OS baseplan due to inaccuracies in baseplan

FLOODED PROPERTY NOT ON THIS PLAN

1. Minster Church, Polsarna, Green Lane, PL35 0DP (flooding approx. depth 1.5m within church)

Rev	By	Chkd	Apprvd	Date	Description

Client

ENVIRONMENT AGENCY

Halcrow Group Limited
Ambassador House, Ambassador Drive, Exeter Business Park, Exeter, EX1 3QN
Tel. +44 (0) 1392 444252 Fax. +44 (0) 1392 444301
Exeter@halcrow.com
www.halcrow.com

Halcrow

Project

BOSCASTLE FLOOD EVENT ANALYSIS

Drawing

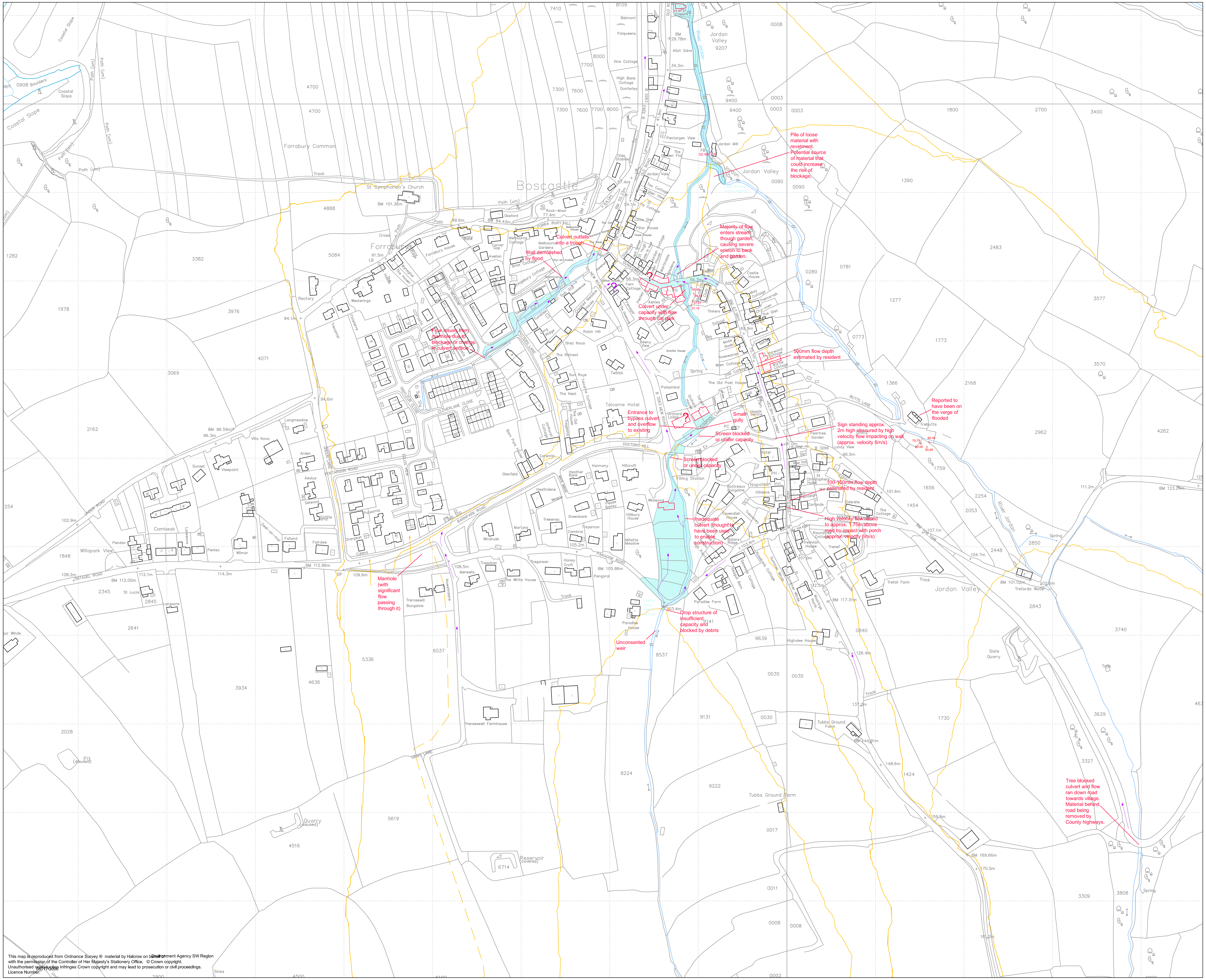
16 August 2004 Flood Event
Flood Record
North Sheet

Drawn by: TW Date: Nov 04
Checked by: TW Date: Nov 04
Approved by: TW Date: Nov 04

Drawing No. WB/BOSF/003
Revision -

Drawing Scale: 1:2,000 at A1

Drawing file path & name :
Xreference file path
User and Plot Date



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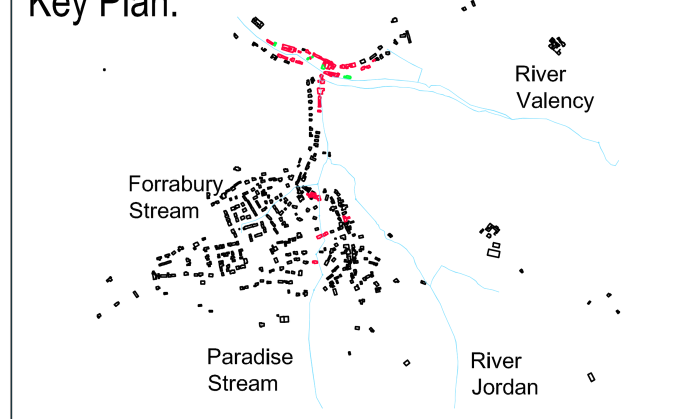
Key Plan:



Notes:

Key

- Trash/wrack mark level
- Flooded property
- Flow direction (mid-range flows)
- Flow direction (high-range flows)
- Sub-catchment boundary derived from 1m resolution Lidar data
- Sub-catchment boundary from site investigation

1. Flood levels are shown to ??? datum Newlyn.
2. Benchmark and OS Landline spot levels are to the old ??? datum. These levels should be adjusted by +???mm to bring them to the ??? datum
3. Positions of some trash marks may not tie in with OS baseplan due to inaccuracies in baseplan

Rev	By	Chkd	Apprvd	Date	Description

Client

ENVIRONMENT AGENCY

Halcrow Group Limited
Ambassador House, Ambassador Drive, Exeter Business Park, Exeter, EX1 3QN
Tel. +44 (0) 1392 444252 Fax. +44 (0) 1392 444301
Exeter@halcrow.com
www.halcrow.com

Halcrow

Project

BOSCASTLE FLOOD EVENT ANALYSIS

Drawing

16 August 2004 Flood Event
Flood Record
South Sheet

Drawn by: TW Date: Nov 04
Checked by: TW Date: Nov 04
Approved by: TW Date: Nov 04

Drawing No. WB/BOSF/002 Revision -

Drawing Scale: 1:2,000 at A1

Appendix 6 Flooded properties in Boscastle

Boscastle Flooded Properties 16 August 2004

(Rev 1, 27 April 2005)

Notes

1. The properties listed in the following table are unlikely to be entirely comprehensive due to unreported flooding and the difficulty in differentiating nearly flooded properties (e.g. with precautionary sandbags) and those flooded (with no signs of flooding)
2. Property names are taken partly from Ordnance Survey plans and partly from site survey
3. Properties are categorised broadly as: R - Residential; C - Commercial; and, P - Public
4. Source of flooding: F - Fluvial; S - Surface
5. This table should be read in conjunction with the north and south flood extent plans
6. Levels are measured above OS GB36 datum.
7. Floor levels are estimated from 1m Lidar and cross sections and are potentially +-0.5m
8. Flood levels are approximated from nearest good quality post-event trash marks. Ranges of flood depth are estimated where no information is available.

Ref	Name	Street	Postcode	Type	Source	Flood level (m)	Floor level (m)	Flood depth (m)	Notes
	River Valency - right bank (north of river)								
1	Youth Hostel, Palace Stables	The Harbour	PL35 0HD	C	F	8.4	4.7	3.7	Flooded to 5 feet (1.5m) according to YHA
2	Harbour Lights	The Harbour	PL35 0HD	C	F	8.4	5.6	2.8	Demolished
3	Cornish Goodies	The Harbour	PL35 0HD	C	F	9.3	6.5	2.8	
4	Botreaux Court	The Harbour	PL35 0HD	C	F	9.3	6.5	2.8	
5	Witchcraft Museum	The Harbour	PL35 0HD	C	F	9.3	6.5	2.8	
6	Harbour Restaurant	The Harbour	PL35 0HD	C	F	9.7	7.5	2.2	
7	Public toilets	The Harbour	PL35 0HD	P	F	10.0	7.5	2.5	
8	Sunnyside Hotel	The Harbour	PL35 0HD	C	F	9.4	9.1	0.3	
9	Things	The Harbour	PL35 0HD	C	F	9.4	9.3	0.1	Demolished
10	Coastguard Station	The Harbour	PL35 0HD	P	F	10.8	9.5	1.3	
11	Valency House	Valency Row	PL35 0HB	R	F	10.8	9.6	1.2	
12	Electrical sub-station	Valency Row	PL35 0HB	C	F	10.8	9.8	1.0	Demolished
13	The Brew House	Valency Row	PL35 0HB	R	F	11.5	10.0	1.5	
14	The Old Ship	Valency Row	PL35 0HB	R	F	11.5	10.3	1.2	

Ref	Name	Street	Postcode	Type	Source	Flood level (m)	Floor level (m)	Flood depth (m)	Notes
15	5	Valency Row	PL35 0HB	R	F	11.4	10.4	0.9	
16	Robin Cottage	Valency Row	PL35 0HB	R	F	11.4	10.4	0.9	
17	Millstow Cottage	Valency Row	PL35 0HB	R	F	12.5	10.4	2.1	
18	2, Cobble Cottage	Valency Row	PL35 0HB	R	F	12.5	10.5	2.0	
19	1b	Valency Row	PL35 0HB	R	F	12.5	10.5	2.0	
20	1a, Old Oil House	Valency Row	PL35 0HB	R	F	12.5	10.5	2.0	
21	Bridge Cottage	The Bridge	PL35 0HE	R	F	11.4	10.2	1.2	
22	Clovelly Clothing	B3263	PL35 0HE	C	F	12.6	10.0	2.6	Demolished
23a	Rocky Road Earth 'n' Art Gallery	B3263	PL35 0HE	C	F	12.6	10.0	2.6	
23c	Boscastle Gallery	B3263	PL35 0HE	C	F	12.6	10.0	2.6	
23b	Gift shop	B3263	PL35 0HE	C	F	12.6	10.0	2.6	
24a	Flat 1, Hollowell House	B3263	PL35 0HE	R	F	12.6	10.4	2.2	
24b	Flat 2, Hollowell House	B3263	PL35 0HE	R	F	12.6	10.4	2.2	
24c	Bridge House	B3263	PL35 0HE	C	F	13.3	10.4	2.9	
25	Take away	B3263	PL35 0HE	C	F	13.2	11.5	1.7	
26	The Olde Manor House	B3263	PL35 0HE	C	F	13.2	11.5	1.7	
27	Boscastle Pottery	B3263	PL35 0HE	C	F	13.7	12.5	1.2	
28	The Cobweb Inn	B3263	PL35 0HE	C	F	14.3	12.9	1.4	
29	Boscastle Newspapers	B3263	PL35 0HF	C	F	15.4	13.9	1.5	
30	Lower Meadows House	B3263	PL35 0HF	R	F	15.4	14.8	0.6	
31	Valency (annex)	B3263	PL35 0HF	R	F	16.3	15.7	0.6	
32	The Riverside	The Bridge	PL35 0HE	C	F	13.5	10.7	2.8	
33	The Picture Parlour	Bridge Walk	PL35 0HE	C	F	13.5	10.7	2.8	
34	Craftly	Bridge Walk	PL35 0HE	C	F	13.5	10.7	2.8	
35	Treasure Chest	Bridge Walk	PL35 0HE	C	F	13.5	10.7	2.8	
36	Ye Olde Rock Shop	Bridge Walk	PL35 0HE	C	F	13.5	10.7	2.8	
37	Boscastle Bakery	Bridge Walk	PL35 0HE	C	F	13.5	10.7	2.8	
37a	Flat 3, first floor flat	Bridge Walk	PL35 0HE	R	F	13.5	10.7	2.8	
38	The Spinning Wheel	Bridge Walk	PL35 0HE	C	F	13.5	10.7	2.8	

Ref	Name	Street	Postcode	Type	Source	Flood level (m)	Floor level (m)	Flood depth (m)	Notes
38a	Flat 4, first floor flat	Bridge Walk	PL35 0HE	R	F	13.5	10.7	2.8	
39	Linloy	B3263	PL35 0HE	C	F	13.6	10.7	2.8	
40	Visitor Centre and toilets	Car Park		P	F	13.6	12.3	1.3	Demolished
	River Valency - left bank (south of river)								
41	Seagulls	The Harbour	PL35 0AG	R	F	8.3	6.7	1.6	
42	Gaviotas	The Harbour	PL35 0AG	R	F	8.3	6.7	1.6	
43	Harbour View	The Harbour	PL35 0AG	R	F	9.8	7.7	2.1	
44	Carpenters Cottage	The Harbour	PL35 0BQ	R	F	9.6	8.5	1.1	
45	The Old Carpenters Shop	The Harbour	PL35 0BQ	C?	F	10.0	8.9	1.1	
	River Jordan								
46	The Otherworld	B3263	PL35 0AQ	C	F			1-2	
47	Tregallan	B3263	PL35 0AQ	R	F			1-2	
48a	Miller's Pantry, The Old Mill	Old Road	Pl35 0AQ	C	F			1-2	
48b	The Leather Shop, The Old Mill	Old Road	PL35 0AQ	C	F			1-2	
49	The Wellington Hotel	Old Road	PL35 0AQ	C	F	Flooding on multiple levels			
50	Morval Cottage	Old Road	PL35 0AQ	R	F			1-2	
51	1	Marine Terrace, Old Road	PL35 0AH	R	F			1-2	
52	2	Marine Terrace, Old Road	PL35 0AH	R	F			1-2	
53	3	Marine Terrace, Old Road	PL35 0AH	R	F			1-2	
54	4	Marine Terrace, Old Road	PL35 0AH	R	F			1-2	
55	5	Marine Terrace, Old Road	PL35 0AH	R	F			1-2	
56	6	Marine Terrace, Old Road	PL35 0AH	R	F			1-2	
57	7	Marine Terrace, Old Road	PL35 0AH	R	F			1-2	
58	Frogapits	Old Road	PL35 0AJ	R	F			1-2	

Ref	Name	Street	Postcode	Type	Source	Flood level (m)	Floor level (m)	Flood depth (m)	Notes
	Paradise Stream - Dunn Street								
59	Post Office	Dunn Street	PL35 0AA	C	F/S			1-2	
60	Highcroft	Dunn Street	PL35 0AU	R	F/S			1-2	
61	Rivers Brink	Dunn Street	PL35 0AA	R	F/S			<1	
62	Rivers Bank	Dunn Street	PL35 0AU	R	F/S			<1	
63	Penlea	Dunn Street	PL35 0AA	R	F/S			<1	
64	No. 2 Penlea	Dunn Street	PL35 0AA	R	F/S			<1	
65	Ingeldene	Dunn Street	PL35 0AA	R	F/S			<1	
	Paradise Stream - Fore Street								
66	Harwood Cottage	Fore Street	PL35 0AX	R	S			<1	Flooded from water running down road
67	Myrtle Cottage	Fore Street	PL35 0AX	R	S			<1	Flooded from water running down road
68	Tanglewood	Fore Street	PL35 0AX	R	S			<1	Flooded from water running down road
	Paradise Stream - Gunpool Lane								
69	Orchard House	Gunpool Lane	PL35 0AT	R	F			<1	
70	Targan	Gunpool Lane	PL35 0AT	R	F			<1	
	Paradise Stream - Between Gunpool Lane and Paradise Road								
71	Wildwood	Doctors Hill	PL35 0BA	R	F			<1	
	Left bank tributary of River Valency upstream of Boscastle								
72	Minster Church		PL35 0BN	P	F			1.5	Approx. 1.5m flooding within church

Appendix 7 Damage to Highways relating to flooding on 16 August 2004

SUMMARY OF DAMAGE TO HIGHWAYS RELATING TO FLOODING ON 16th AUGUST 2004

No	SITE	DAMAGE	WORK TYPE	COMMENTS
1)	Crackington Bridge	Bridge / Retaining wall	Structures	Rebuild parapet / spandrel wall.
2)	Crackington Sea Wall	Retaining wall structure damage	Structures	Retaining wall repairs.
3)	Sweets Bridge	Parapet Damage	Structures	None
4)	Lansweden - Footbridge (Brockhill)	Bridge washed away	Structures	Replace Footbridge.
5)	Lansweden - Ford	Minor Ford Damage	Maintenance	None
6)	Congdons Bridge	Bridge Damage / ditches need clearance underneath	Structures	None
7)	Minesshop Bridge	Footbridge gone	Structures	Replace footbridge.
8)	Tremayna Bridge	Footbridge gone	Structures	Replace footbridge.
9)	Tremayna Ford	Minor Ford Damage	Maintenance	None
10)	Minesshop Ford	Pipe ford damage	Maintenance	None
11)	Higher Crackington - Pencuke	Landslide - Road blocked	Structures & Maintenance	None
12)	Tremoutha Bridge / Trevigue	D/S Parapet & Wing walls	Structures	None
13)	Anderton Ford	Footbridge gone	Structures	Replace footbridge
14)	Marshgate	Blocked Culvert / minor carriageway damage	Structures & Maintenance	None
15)	Tresparret - Anderton Ford	1) West Rd 2) Ford 3) East Rd	Maintenance / Surfacing / Structures	Total Rebuild required.

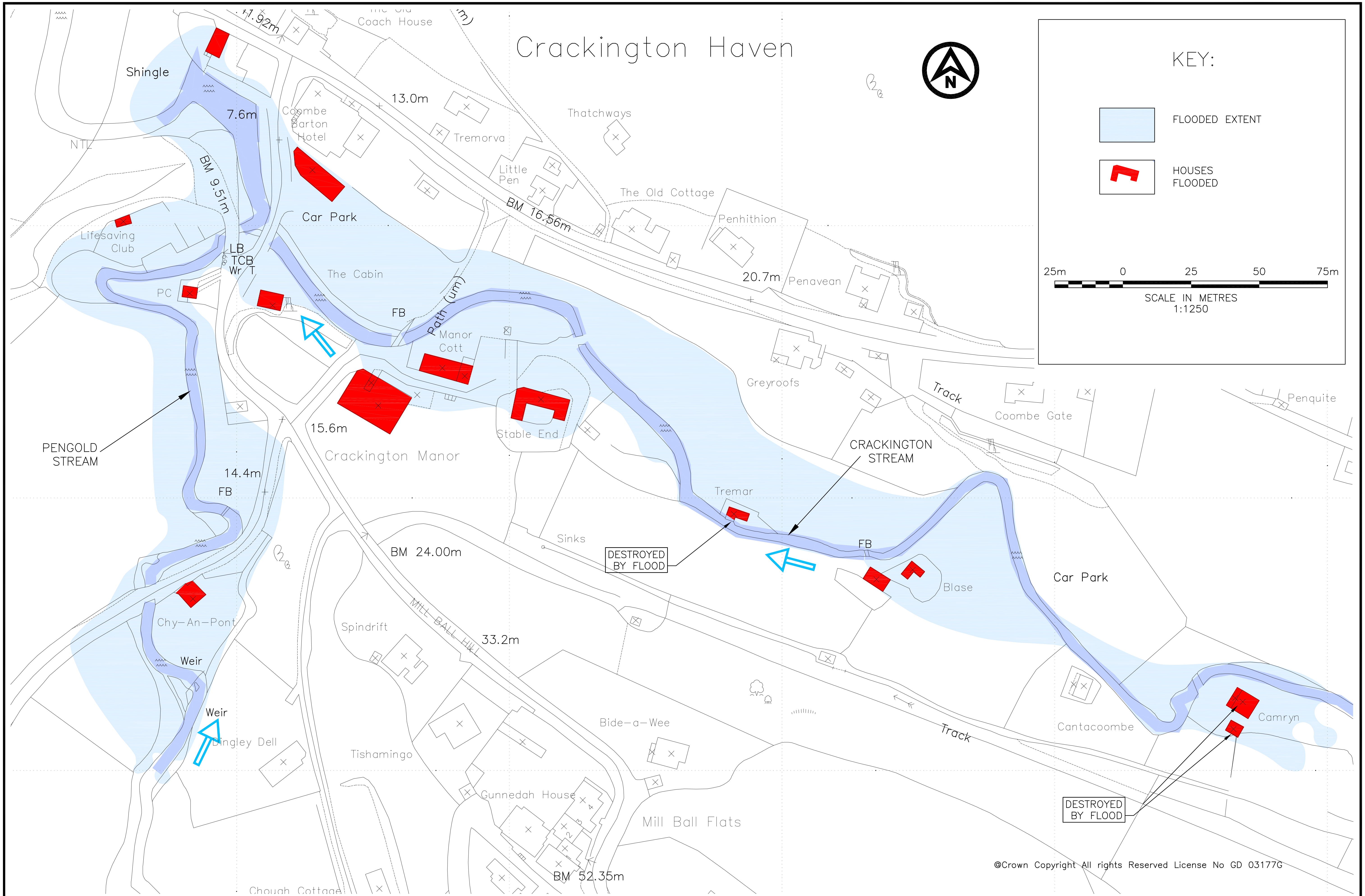
No	SITE	DAMAGE	WORK TYPE	COMMENTS
16)	Lesnewth - Treworld Churchabridge	1) Channel parapet wall 2) Retaining wall	Surfacing / Maintenance	None
17)	Lesnewth Cottages	Debris in road / patching dmg	Surfacing / Maintenance	None
18)	Hallwell Plantation	Minor ford damage	Maintenance	None
19)	Tregrylls Farm/Bridge	D/S parapet gone	Structures	Rebuild D/S masonry parapet
20)	B3263 Boscastle - A39	Road repairs needed on entire length	Maintenance / Structures	None
21)	Middle - Higher Beeny	Hedge/ Road Dmg & Culvert	Maintenance	None
22)	New Mills Ford (Treworld)	Ford out. Major damage	Maintenance / Surfacing	None
23)	New Mills Ford (Footbridge)	Footbridge out	Structures	Replace footbridge
24)	Treworld Bridge	Dmg to abutments / w/walls	Structures	Repair wingwall and retaining wall.
25)	Treworld - Hallwell Barton	Patching work needed	Surfacing	None
26)	Boscastle - Polrunny Farm	Road Damaged	Surfacing	Edge repairs, drainage & surfacing.
27)	Old Hill - Boscastle	Carriageway / Channel damage	Surfacing	None
28)	Otterham / Otterham Mill	Road washed out.	Surfacing	Saface Dressing & Gabions. Surfacing Done.
29)	Otterham - Penhale	Road damaged	Surfacing	None
30)	Penhale - Caroe	Drainage damaged	Maintenance	None
31)	A39 @ Otterham	French Drains work	Maintenance	None
32)	B3263 - Higher Penpethy Farm	Dmg to rd surface / drainage	Surfacing / Maintenance	Drains & Patching.
33)	B3314 Slaughtersbridge	Damage to parapet, piers & abutments	Structures	Repair scour damage to pier & abutment. Build concrete toe.

No	SITE	DAMAGE	WORK TYPE	COMMENTS
34)	Vendown - Boscastle B3266	Road damage	Surfacing	None
35)	Treforda Water	Debris on road. Road damage	Surfacing	Drainage, Clearance & Patching
36)	Minster Church	Debris & road damage	Maintenance & Surfacing	None
37)	Treworld - Trebiffen	Debris on road. Road damage	Maintenance & Surfacing	None
38)	Coxford	Debris on road	Maintenance	None
39)	Lower Crackington	Carriageway damage	Surfacing / Maintenance	None
40)	B3263 Collamoor Head	Carriageway damage	Surfacing / Maintenance	None
41)	Boscastle Bridge	Parapets, wing walls, abutments & training walls	Structures	None
42)	Canworthy Water	Dmg to Carriageway / Ditches	Surfacing / Maintenance	New drainage outfall required
43)	Jacobstow - Orchard Cottages	Portion of barrel collapsed and partial blocking of bridge. Repairs On-going	Structures	Demolish existing arch bridge and replace with RC slab on mass concrete abutments.
44)	Tregune (Vosswater Bridge)	Parapets collapsed	Structures / Surfacing	Patching needed.
45)	Woolstone Mill	Collapsed hedge. Blocked ditches	Maintenance	Hedge collapse and drainage repairs
46)	Tregune - Warbstow	Hedge Collapsed / Drainage	Maintenance	None
47)	B3254 Whitstone	Blockage / Flooding	Maintenance	None
48)	A39 Helebridge	Flooding	Maintenance	Jetting
49)	Stratton	Floodi	Maintenance	Jetting
50)	Millook	Some debris on road	Maintenance	Jetting
51)	Widemouth Bay	Flooding	Maintenance	Jetting
52)	Kings Hill	Flooding	Maintenance	Jetting
53)	Kilkhampton	Flooding	Maintenance	Jetting
54)	Newmills - Poundstock	Damaged Bridge	Maintenance	None

No	SITE	DAMAGE	WORK TYPE	COMMENTS
55)	Pethericks Mill	Flooding	Maintenance	Jetting
56)	Rodds Bridge	Debris under bridge	Maintenance	None
57)	The Strand/Crescent - Bude	Flooding	Maintenance	None
58)	Week St Mary - Broad Langdon	Hedges/ditches/verges washed out	Maintenance	None
59)	Flexbury, Bude	Flooding	Maintenance	Jetting
60)	Diddies, Stratton	Flooding	Maintenance	Jetting
61)	B3263 Collamoor Head	Road surface damaged	Surfacing / Maintenance	None
62)	Jacobstow - Canworthy Water	Flooding	Maintenance	Jetting
63)	Treforda	Bridge damage and debris	Maintenance	None
64)	Lower Crackington	Flooding	Maintenance	None
65)	Bowater Ford / Bridge	Damage to training walls	Structures	None
66)	Trekeek, Nr Waterpit Down (B3266)	Road damage	Surfacing	Patching work needed.
67)	Condolden, Nr Waterpit down (B3266)	Road damage	Surfacing	None
68)	Hallworthy	Flooding	Maintenance	None
69)	Penpednick	Road damage	Surfacing	None
70)	Higher Crackington	Flooding	Maintenance	Outlet headwall & piperun.
71)	Paradise	Gabions repairs	Maintenance	None
72)	Davidstow A395	Blocked Culvert	Maintenance	None

Note: table modified from data provided by CCC

Appendix 8 Flooded area Crackington



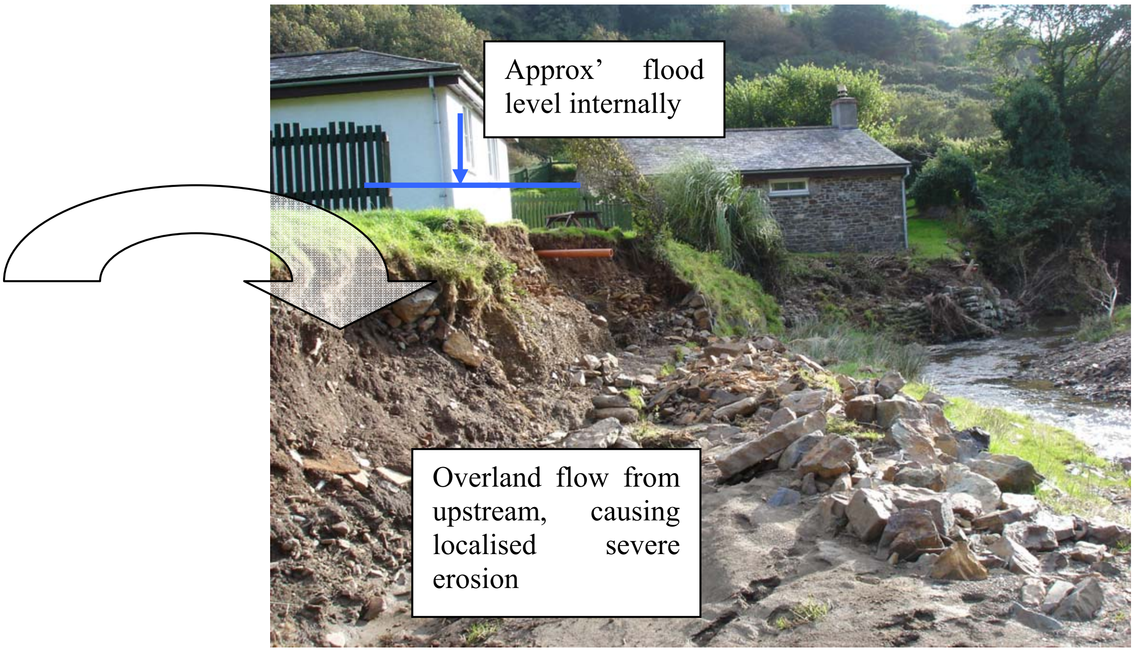
TITLE	PROJECT				
FLOODED AREA OUTLINE	CRACKINGTON HAVEN	ROYAL HASKONING	Job No. 9P8516	DATE 25.01.05	SCALE AS SHOWN
			ACAD Ref.	CHECKED MA	PASSED HMH
			DRAWN TDL	DRG No. 9P8516–1000	REV _

HASKONING UK Ltd.
ELIZABETH HOUSE
EMPEROR WAY
EXETER, EX1 3QS
Telephone +44 (0)1392 447999
Fax +44 (0)1392 446148
E-mail mail.exeter@royalhaskoning.com
Internet www.royalhaskoning.com

Appendix 9 Details of flood damage for Crackington Stream

Flow Routes

The majority of the flood water associated with the Crackington Stream was contained within the flood plain. Significant flood depths across the flood plain were recorded and properties that would have appeared to be outside of a normal flood envelope were affected by overland flows. This is particularly the case for the Blase properties, which are some 3m above the bed of the stream immediately downstream yet still experienced internal flooding (Photograph 1).



Photograph 1 The Blase properties

The capacity of the Pengold Stream was also quickly exceeded and high velocity out of bank flows were experienced. This not only caused damage to numerous fences and three properties but lifted the tarmacadam surface of a minor road.

Buildings Affected

A total of 15 properties were affected by the flooding, two of which were destroyed by the flood (Tremar and Camry). A selection of the properties' threshold and flood levels are indicated in Table 2.1.

The majority of properties experienced flood depths in excess of 1m which caused significant loss and disruption. The safe exit form a number of properties could have been an issue as several properties were completely surrounded by fast flowing floodwater. Photograph 2 shows two of the properties flooded and is typical of the majority of affected properties. In all the instances of flooding, deep layers of sediments were deposited within the properties.

Table A5.2.1 Recorded Flood Levels from the 16 August 2004 Event at Crackington Haven

Location	Threshold Level (mOD)	Flood Level (mOD)	Flood Depth (m)
The Cabin Café	9.410	9.519	0.109
Basement	7.630	9.519	1.889
Coombe Barton Hotel Shop	7.918	9.730	1.818
Crackington Manor Apartments	9.567	10.705	1.138
	10.063	10.705	0.642
	9.95	10.705	0.755
Manor Cottage	9.407	10.705	1.298
Stable End	10.633	11.385	0.752
Blase No.1	13.849	14.337	0.488
Blase No. 2	13.326	14.337	1.011
Chy-an-Pont	15.150	17.038	1.888

Photograph 2 – Flood levels at Manor Cottage and Chy-An-Pont

Roads Affected

The road across the Crackington Stream was impassable due to flood waters as was the minor road past the Chy-An-Pont residential property. There were reports of numerous localised incidences of road flooding throughout the area due to the heavy rainfall. The village was not cut-off during the flood and emergency vehicles were able to attend the site.

People Rescued

A number of people had to be rescued during the event but none by helicopter.

Structural Damage

Aside from the two properties that were destroyed there were no external signs of structural damage to properties. In view, however, of the high velocity of flood flows, the erosion and the risk of longer term rotting to structural timbers it is likely that some renovations will be necessary.

Appendix 10 Wrack mark data on Crackington Stream

Wrack Marks

A preliminary site visit was conducted by Royal Haskoning and HR Wallingford to establish the location of wrack marks. These were then surveyed by Royal Haskoning and levels established. Table 7.2.8 contains a list of established wrack marks and their locations. Please refer to drawings showing the location of wrack marks.

Table 7.2.8: Wrack Marks

	Level (mOD)	Grid Reference
Wrack Mark 1	16.695	SX 14660 96650
Wrack Mark 2	17.136	SX 14680 96645
Wrack Mark 3	18.138	SX 14720 96640
Wrack Mark 4	21.117	SX 14845 96625
Wrack Mark 5	21.186	SX 14875 96620
Wrack Mark 6	22.08	SX 14903 96620
Wrack Mark 7	22.718	SX 14952 96624
Wrack Mark 8	23.891	SX 14980 96604
Wrack Mark 9	24.241	SX 15013 96600
Wrack Mark 10	25.777	SX 15047 96622
Wrack Mark 11	26.14	SX 15105 96605
Wrack Mark 12	27.765	SX 15165 96560
Wrack Mark 13	28.098	SX 15203 96560
Wrack Mark 14	32.696	SX 15350 96390
Wrack Mark 15	34.431	SX 15400 96400
Wrack Mark 16	34.798	SX 15482 96388
Wrack Mark 17	44.491	SX 15778 96175
Wrack Mark 18	45.284	SX 15780 96150
Wrack Mark 19	45.911	SX 15805 96155
Wrack Mark 20	47.962	SX 15800 96100
Wrack Mark 21	48.433	SX 15820 96120
Wrack Mark 22	67.259	SX 16140 96330
Wrack Mark 23	62.644	SX 16240 95720

Appendix 11 Predicted discharge hydrographs at Valency and Crackington Stream

Time (BST)	Flow (m^3/s) at four locations on the River Valency			
	Boscastle d/s of B3263 Road Bridge (Cross-section 5)	Boscastle u/s of B3263 Road Bridge (Cross-section 8)	Newmills (Cross-section 19)	Upstream limit (Cross-section 22)
16/08/2004 11:30	14.53	12.25	8.43	5.41
16/08/2004 11:45	14.85	12.49	8.69	5.62
16/08/2004 12:00	15.23	12.78	8.98	5.82
16/08/2004 12:15	15.62	13.08	9.26	6.03
16/08/2004 12:30	16.01	13.37	9.53	6.23
16/08/2004 12:45	16.38	13.65	9.80	6.44
16/08/2004 13:00	16.78	13.96	10.08	6.64
16/08/2004 13:15	17.16	14.24	10.35	6.85
16/08/2004 13:30	17.54	14.53	10.62	7.05
16/08/2004 13:45	17.92	14.82	10.92	7.26
16/08/2004 14:00	18.81	15.17	11.47	7.47
16/08/2004 14:15	19.75	16.06	12.17	7.67
16/08/2004 14:30	21.02	17.60	13.84	7.88
16/08/2004 14:45	23.57	20.61	16.05	11.87
16/08/2004 15:00	25.69	23.36	20.93	16.51
16/08/2004 15:15	31.19	29.49	28.19	20.28
16/08/2004 15:30	38.35	36.59	34.31	24.71
16/08/2004 15:45	44.83	42.40	40.44	27.39
16/08/2004 16:00	51.75	47.65	45.26	28.92
16/08/2004 16:15	59.13	48.98	48.92	30.95
16/08/2004 16:30	69.22	57.06	54.73	33.02
16/08/2004 16:45	83.19	68.19	61.69	36.54
16/08/2004 17:00	100.81	81.92	72.78	42.14
16/08/2004 17:15	121.61	97.07	86.31	49.89
16/08/2004 17:30	144.83	113.56	102.38	55.24
16/08/2004 17:45	167.32	129.58	114.86	58.62
16/08/2004 18:00	177.49	136.90	121.32	57.25
16/08/2004 18:15	173.95	135.68	118.51	52.84
16/08/2004 18:30	156.60	123.94	108.13	45.64
16/08/2004 18:45	132.99	107.48	93.25	36.82
16/08/2004 19:00	106.96	89.03	74.82	27.93
16/08/2004 19:15	82.93	70.54	57.87	19.65
16/08/2004 19:30	61.90	51.74	42.04	12.88
16/08/2004 19:45	42.45	36.20	28.31	7.59
16/08/2004 20:00	29.38	27.02	16.66	4.12
16/08/2004 20:15	17.80	16.36	9.90	2.06
16/08/2004 20:30	11.51	10.55	5.97	1.23
16/08/2004 20:45	7.89	7.13	3.76	1.06
16/08/2004 21:00	5.67	5.12	2.62	0.97

Flow on Crackington Stream

Time (BST)	Flow (m^3/s) at three locations on Crackington Stream		
	Crackington Haven d/s Pengold Stream (Cross-section CH0042C)	Congdons Bridge (Cross-section CH0725)	Mineshop (Cross-section CH1820)
16/08/2004 14:00	8.37	5.80	5.85
16/08/2004 14:15	8.51	5.88	5.92
16/08/2004 14:30	9.65	5.95	6.00
16/08/2004 14:45	11.09	6.02	6.08
16/08/2004 15:00	12.73	6.88	8.57
16/08/2004 15:15	16.41	9.62	11.44
16/08/2004 15:30	21.02	12.73	14.73
16/08/2004 15:45	25.62	15.86	17.93
16/08/2004 16:00	30.06	18.86	20.76
16/08/2004 16:15	34.64	21.66	23.50
16/08/2004 16:30	39.87	24.49	26.73
16/08/2004 16:45	45.94	27.74	30.28
16/08/2004 17:00	52.90	31.40	34.14
16/08/2004 17:15	60.84	35.16	37.66
16/08/2004 17:30	68.84	38.74	41.37
16/08/2004 17:45	76.58	42.43	44.81
16/08/2004 18:00	84.44	45.43	46.91
16/08/2004 18:15	89.60	47.01	47.34
16/08/2004 18:30	91.01	46.98	46.07
16/08/2004 18:45	89.05	45.19	43.15
16/08/2004 19:00	83.67	41.83	38.85
16/08/2004 19:15	75.91	37.27	33.41
16/08/2004 19:30	66.21	31.83	27.94
16/08/2004 19:45	54.69	26.48	22.91
16/08/2004 20:00	44.45	21.23	18.31
16/08/2004 20:15	35.10	16.75	13.88
16/08/2004 20:30	26.51	12.32	9.87
16/08/2004 20:45	18.52	8.70	6.57
16/08/2004 21:00	12.46	5.83	4.01

Appendix 12 Valency catchment: Estimation of floods of specified exceedence probabilities

Introduction

As part of the work, the project team were asked to estimate the magnitude of floods of specified exceedence probabilities for both the Valency and Jordan catchments.

As stated in the main report, there are no recorded measurements of flood flows on either the Valency or Jordan rivers. Some water level data has been collected in recent years for the Jordan, but no rating curve is available to determine the corresponding discharges. Hence estimation of flood probabilities must be undertaken using a combination of the FEH methodology combined with the use of historical evidence of flood levels converted to discharges through hydraulic modelling.

The estimates presented below are the best estimates that can be produced given the available data, although there still remains considerable uncertainty over these estimates as a result of the uncertainties in the data. Discussion on these uncertainties is presented below.

Historical evidence

A discussion of the evidence of historical flooding is given in Section 5.6 of the main report. Where possible, some of these historical events were simulated in the hydraulic model to derive an estimated peak discharge, matching the modeled peak water levels to photographic records and eyewitness accounts of maximum levels at key locations. There are a number of potential uncertainties in this approach which affects the confidence that can be placed in the estimates of the discharges.

To summarise the historical evidence, it appears that the August 2004 flood is the largest since at least 1824, and possible for a much longer timespan, on both the Valency and Jordan catchments. There are accounts of earlier flooding in 1770, when a major flood affected Lynmouth, and some evidence of flooding at Boscastle in 1780 and 1797, although in none of these cases can reliable level or flow estimates be derived. Thus, what can be said for the Valency is that the August 2004 event was probably the largest in the past 200 years (or possibly somewhat longer), that the flood of 3rd June 1958 was probably the second largest event, that February 1963 was the third largest, and August 1950 the fourth largest. The next largest floods were probably those of 1952, 1932, 1847, and possibly 1770, but it is not possible to quantify these with any confidence, or to place them in rank-order.

There are frequent references to historical flooding on the Jordan, much of it at the culvert beneath the Wellington Hotel, which has suffered flooding on many occasions, possibly exacerbated by debris blocking the culvert during flooding. It is difficult to draw firm conclusions from this historical data because of uncertainties over the degree of blockage in any particular event, the imprecise nature of many of the historical evidence, and the fact that the channel and culvert have been modified in the past. The most useful historical evidence, therefore, is that from records in Boscastle itself, which of course are the result of a variable combination of flows from the Valency and Jordan.

Potential flood estimation methods

For catchments such as the Valency and Jordan, where no flow data are available, the most commonly applied method of flood estimation are those presented in the FEH. Two methods are presented in the FEH; a statistical method based upon the use of an index flood, QMED, the median flood of the annual maximum series; and a rainfall-runoff approach where flood magnitude is derived from conversion of rainfall to flow using a unit hydrograph and losses model. The rainfall-runoff model presented in Volume 4 of the FEH is currently being updated, and a revised model, referred to as the ReFEH method, is expected to be published in July 2005.

Results of application of both the statistical model and the original rainfall-runoff model for the whole Valency plus Jordan catchment are presented in Sections 5.2 and 5.3 of the main report. These previous results, however, were only for the Valency and Jordan combined, and no division was presented for the separate catchments.

For this work, the statistical model has been not been applied separately to the Valency and Jordan catchments, because of the uncertainty over the accuracy of the methods for small catchments such as the Jordan, which has a catchment area of only 2.4 km^2. The best source of 'donor' data for statistical flood estimation on ungauged catchments is the new HiFlows-UK data set available from the EA hosted website: http://www.environment-agency.gov.uk/hiflowsuk/ where quality-controlled annual maximum flood data is available to replace the original FEH CD-ROM. On the new HiFlows-UK website, there are only 10 stations having catchment areas of less that 5 km^2, but two of these are in dry, eastern parts of the country, and of the remaining 8, only 5 are suitable for estimation of QMED, and only 2 for pooling (source: HiFlows-UK website). There are a further 3 stations suitable for pooling having an area of between 5 and 10 km^2, but only one of these is suitable for QMED estimation, and for larger stations of between 10 and 30 km^2, there are a further 15 suitable for pooling, and 17 for estimation of QMED. This relatively small number of donor catchments led us to believe that there was only sufficient information to allow the estimation of the combined Valency and Jordan flows, rather than to estimate each separately. Were the two catchments to be modeled separately, the same source data from a limited number of donor catchments would be used for each; thus no 'new' information would be brought in by treating the two catchments separately.

The key results from the statistical method were presented in the main report, where it was shown that the QMED estimate from catchment descriptors alone was 6.8 m^3/s, but that the adjusted QMED based on data from five hydrologically similar catchments was only 4 m^3/s.

For the rainfall-runoff method, however, the Valency and Jordan catchments were treated separately, and both rainfall-runoff methods, the original FEH model and the new ReFEH model, were applied. For comparison with the statistical method, however, the combined catchment to its outfall was also modeled.

Proposed methodology

As is shown in Figure 5.10 of the main report, neither the statistical model nor the rainfall-runoff model of the FEH was able to derive a flood frequency curve that matched the historical data for the Valency and Jordan combined. Each method was believed, however, to produce good flood estimates for exceedence probabilities in excess of 5 to 10 percent, with the apparent flood frequency curve having to deviate from the FEH estimates for more extreme floods in order to match the historical data discussed above.

Consequently, a novel approach has been adopted to fit a distribution to a limited number of *m* historical floods out of a historical period of *M* years, using an estimate of the median discharge, QMED. The estimate of QMED adopted is a weighted mean of the range of FEH estimates available as shown in Table A12.1. It should be noted that as described in the main report when an estimate QMED was made from the data on the FEH CD-ROM then a value of 6.81 m^3/s was obtained. Using data from donor catchments the estimate of QMED was approximately 4 m^3/s. In this part of the work, therefore, it was decided to adopt a weighted average of a number of different estimates of QMED.

Table A12.1 Estimation of QMED for the combined Valency and Jordan catchments

Method	QMED Estimate (m^3/s)	Weighting
Statistical estimate from catchment descriptors (FEH CD-ROM)	6.81	1
Adjusted statistical estimate using data transfer	4.0	3
FEH rainfall-runoff estimate	10.45	1
Revised FEH rainfall-runoff estimate (using ReFEH methodology)	10.61	1
Weighted Mean	6.65	

Estimation of the parameters of either the Generalised Logistic (GLO) or General Extreme Value (GEV) distribution may be fitted to the best estimate of QMED, 6.65 m^3/s, and a series of estimated historical floods as follows.

If G is the distribution function of annual maximum values, and g is its density, then the distribution function of the largest annual maximum in M years is

$$F_M(x) = \{G(x)\}^M$$

and the density is

$$f_M(x) = Mg(x)\{G(x)\}^{M-1}.$$

So the relevant contribution to the log.likelihood of the observation $X_M = x_M$ is

$$l_M(x_M) = \log g(x_M) + (M-1)\log G(x_M).$$

For the second largest, the contribution is based on the conditional distribution of X_{M-1} given X_M. The conditional distribution function of the second largest in M years is

$$F_{M-1}(x;x_M)=\left\{\frac{G(x)}{G(x_M)}\right\}^{M-1}$$

and the density is

$$f_{M-1}(x;x_M)=(M-1)g(x)\frac{\{G(x)\}^{M-2}}{\{G(x_M)\}^{M-1}}.$$

So the relevant contribution to the log.likelihood of the observation $X_{M-1}=x_{M-1}$ is

$$l_{M-1}(x_{M-1};x_M)=\log g(x_{M-1})+(M-2)\log G(x_{M-1})-(M-1)\log G(x_M).$$

and so forth.

The required log likelihood is, therefore,

$$L=\left\{\sum_{j=1}^{m}\log g(x_{M-j+1})\right\}+(M-m)\log G(x_{M-m+1})$$

The historical data used in the fitting method are shown in Table A12.2.

Table A12.2 Historical flood data used in distribution fitting

Date of flood	Rank	Estimated peak flow (m^3/s)
16 Aug 2004	1	179
3 June 1958	2	90
9 Feb 1963	3	60
30 Aug 1950	4	40
16 Aug 1952	5	35
June 1932	6	33
1824	7	30

It has been assumed that the August 2004 flood has been the largest since at least 1824, when historical records indicate property damage. There is mention of flooding in Boscastle in 1797, but no details of damage caused. Hence it has been assumed that there were no significant historical floods during the 20 or more years preceding the 1824 flood on the Valency between the rather sketchy account of the 1797 flood and the 1824 event. Hence we estimate that the August 2004 flood was the largest in 200 years. It should be noted that the historical flood records are based upon accounts of flood damage to various points within the village of Boscastle and are essentially accounts of combined Valency and Jordan river flows. Thus all of the following results are for the combined catchment at its outlet to the harbour.

Using the methods outlined above, a QMED value of 6.65 m^3/s, the historical flow estimates given above, and an assumed record length, M, of 200 years, the parameters of the Generalised Logistic (GLO) and General Extreme Value (GEV) distributions have been computed through a simple maximum likelihood fitting procedure (ML) as:

$\alpha=2.309$, $k=-0.5975$ are found for the GLO
$\alpha=2.46$, $k=-0.583$, $\xi=5.6454$ are found for the GEV

To compute the flood Q(T) of any return period, T years using the GLO distribution, equation 15.6 of Volume 3 of the FEH, gives:

$$Q(T) = QMED * \{ 1 + \beta/k *(1 - (T\text{-}1)^{-k}) \}$$

where $\beta = \alpha/QMED$

For the GEV case, Q(T) can be found from :

$$Q(T) = \xi + \{ \alpha/k *(1 - e^{-kT}) \}$$

Using the parameter values given above, flood estimates for a range of exceedence probabilities may be derived, and are shown below for the combined Valency and Jordan catchments.

Table A12.3 Design flood estimates for the combined Valency and Jordan catchments

Exceedence probability (%)	GLO estimate (all data used) (m^3/s)	GEV estimate (all data used) (m^3/s)	GLO estimate (3 years removed) (m^3/s)
20	11.6	11.5	10.4
10	17.2	17.1	15.0
4	28.6	28.7	25.8
2	42.3	42.4	40.0
1	63.0	63.1	63.4
0.5	94.1	94.2	101.8

It is clear that the GLO and GEV methods give essentially identical results when fitted using ML, and because the GLO is the recommended distribution in the FEH, all further work concentrates solely on fitting this one single distribution. Figure A12.1 shows the historical data used to fit the distributions together with the fitted GLO curve.

The results presented above have been derived using the seven historical flood estimates presented in Table A12.2 above. There is less confidence, however, in the estimates of the peak discharges of the floods in 1952, 1932 and 1847 than the other events as these floods are documented less well than the others. The analysis was repeated using the GLO distribution only with these three floods excluded, but the results changed very little. The results are shown in the final column of Table A12.33 where it appears that a slightly improved fit to the more extreme historical data can be achieved.

In view of the uncertainty over the magnitude of the floods of 1952, 1932 and 1847, it is recommended that the GLO estimates presented in the final column of Table A12.3 provide the best estimates of the combined Valency and Jordan flows. However, it should be noted, that the apparent improvement in fit to the more extreme floods (1 and 0.5% exceedence) is achieved through a small reduction in the more common flood estimates.

One final check undertaken was to attempt to fit the GLO by a “trial-and-error” hand search through possible parameters. A reasonably successful fit to the historical data was achieved using parameter values of:

$$\alpha = 1.45\,,\ k = -0.77$$

This fitted curve is shown on Figure A12.1 together with the recommended curve fitted objectively using ML. Although this curve is a good fit to the three largest floods, however, it was fitted purely by trial-and-error, and it would not be wise to adopt such a curve. It is suggested that the GLO fitted objectively by the ML methods described above provides the best estimates of design floods for all exceedences.

The form of the curves shown in Figure A12.1 are very dependent upon the historical data that has been used. As discussed above there are large uncertainties in the estimates of the peak flows for all the floods prior to 2004. This results in uncertainties in the derivation of the growth curve shown in Figure A12.1 and in the estimates of the magnitudes of floods with different probabilities shown in Tables A12.3 and A12.5.

Design flood estimates for Valency and Jordan catchments

The analyses presented above have provided design flood estimates for the combined Valency and Jordan catchment, but the requirement is for estimates for each catchment separately. As stated earlier, the FEH statistical flood method cannot readily deliver such estimates. The FEH rainfall-runoff method, and the new ReFEH model can be used, however, to derive suitable estimates for each catchment separately. While the work described in the main report has shown that these methods appear to significantly under-estimate the magnitude of low probability events on the Valency they are being used here only to proportion flows between the Valency and Jordan catchments. This is based on the expectation that while these methods may under-estimate the peak flows the relative contributions of the two catchments should be estimated more reliably.

Using catchment descriptor data from the FEH CD-ROM, suitable unit hydrograph, losses and baseflow estimates can be derived for each catchment. Computed flow peaks for the 1% (100 year) event for each catchment are show in Table A12.4.

Table A12.4 Estimated 1% flood peaks for the Valency and Jordan catchments derived using the FEH and ReFEH models

Catchment	FEH model peak (m^3/s)	FEH model peak (m^3/s)
Valency	29.8	28.6
Jordan	6.79	6.54
Jordan peak as percentage of combined Valency plus Jordan	18.6%	18.6%

In general, one would expect the Jordan peak to occur one or more hours before the Valency peak due to the shorter stream length and hence shorter response time of this catchment. For simplicity, however, the derived flood peaks given in Table X.3 above may be apportioned between the Valency and Jordan catchments using the ratio of peaks derived using the FEH rainfall-runoff model. In the case of the 1% (100 year) flood, the Jordan catchment generates 18.6 percent of the total Valency plus Jordan peak flow. This proportion should be compared with the fact that the Jordan catchment represents only 12 percent of the total combined catchment area. The disproportionately high peak flow contribution reflects the somewhat flashier natures of this small tributary.

Thus, design flow estimates from Table A12.3 can be apportioned between the Jordan and Valency catchments using this factor of 18.6 percent. These estimates, derived using the GLO distribution estimates given in the final column of Table A12.3, are shown in Table A12.5.

Table A12.5 Computed flows for the Valency and Jordan catchments with the specified probabilities of exceedence

Exceedence probability (%)	Valency peak (m^3/s)	Jordan Peak (m^3/s)
20	8.47	1.93
10	12.2	2.80
4	21.0	4.80
2	32.6.	7.40
1	51.6	11.8
0.5	82.9	18.9

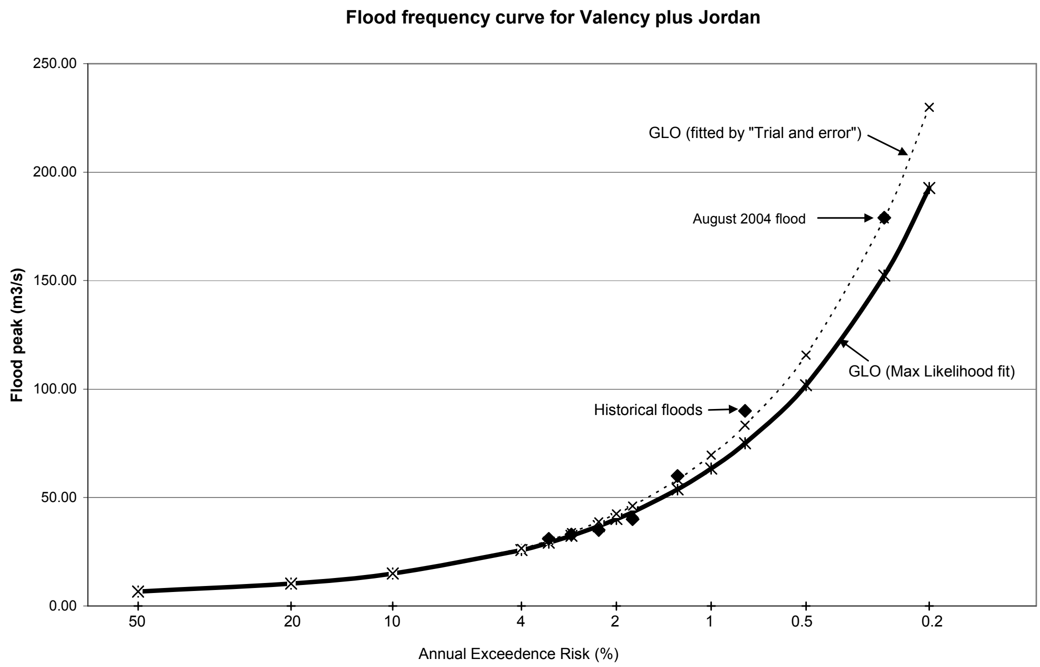


Figure A12.1 Fitted flood frequency curves to combined Valency and Jordan flows