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Multiscale experimentation, monitoring
and analysis of long-term land use
changes and flood risk

Report – SC060092/R1

Flood and Coastal Erosion Risk Management Research and Development Programme

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Miranda Kavanagh
Director of Evidence

Executive summary

This is the final report for Environment Agency project SC060092 'Multiscale experimentation, monitoring and analysis of long-term land use changes and flood risk'. The PhD studentship (Josie Geris) funded under the project runs until January 2011.

A detailed review in Defra/Environment Agency Project FD2114 on the impact that changes in rural land use/management have on downstream flooding concluded that very little is known about this subject and that new data sets, models and methods are required. An opportunity arose to monitor the impact of extensive upland restoration works being carried out in the Hodder catchment in north-west England under the United Utilities' Sustainable Catchment Management Plan (SCaMP). Project SC060092 was set up to instrument the Hodder catchment and to monitor these impacts. The resulting data has been used in the development of new models and methods in the Natural Environment Research Council's Flood Risk from Extreme Events (FREE) and the Engineering and Physical Sciences Research Council's Flood Risk Management Research Consortium 2 (FRMRC2) programmes.

In the SCaMP, the upper part of the Hodder catchment is undergoing works including blocking of grips (drains) in peatland, tree planting, and reducing sheep and cattle stocking densities. The main aims of the SCaMP are to improve the colour of water abstracted for public supply and the condition of Sites of Special Scientific Interest.

When working on problems such as analysing flood generation or predicting flood levels, obtaining good hydrological data for a catchment can be a time-consuming and frustrating process that involves approaching several data holders and trying to piece together fragmented, disjointed and degraded information. To make the Hodder and SCaMP data more generally available to researchers in this field, a detailed Electronic Project Record (EPR) has been compiled that contains all the data and background information on the catchment and the SCaMP works. A large fraction of these data and information would probably be lost within 10 years if it were not recorded in the EPR. It is estimated that the effort involved in creating the EPR amounted to approximately 15% of the total effort on data collection and archiving. However, the potential benefits to the research community are significant. Access to the EPR is available through the Environment Agency.

It was challenging to draw general conclusions from this work primarily because:

- the pre-SCaMP and post-SCaMP hydrology cannot be fully characterised because the monitoring period was short
- the accurate measurement of differences is inherently difficult, and the impact of a change in land use/management is essentially the difference between the behaviour that did happen and the behaviour that would have happened if there had been no change
- there are no existing data sets for use in testing or comparisons
- there was a limited budget for field work
- the FD2114 review showed that existing models are inadequate as a basis for analysing the hydrological behaviour
- statistical approaches are inadequate because the records are short and there is large natural variability

- despite FD2114, many researchers and hydrologists have fixed ideas about the impact of changes in land use and management, so any conclusions are likely to face resistance

When estimating the impact of the SCaMP works on flood hazard, ideally it would be possible to use the EPR and the new models and methods to estimate the impact on the Flood Frequency Curve (FFC) at the flow gauge at Hodder Place (261 km²), which lies just upstream of where the Hodder joins the River Ribble.

To help place the SCaMP works and the monitoring in Project SC060092 within their proper context, the report discusses some of the problems of estimating impacts in FFCs and summarises results from a wide survey of the information available on the nature and properties of the catchment including its geology, soils, water abstraction system and rainfall/run-off history.

The context is one of complexity and detail, because the various data for the catchment have a huge range of space and time scales (<1 ha to 261 km²; five minutes to >100 years). Part of the problem when estimating the impact on the FFC is that the SCaMP works and data have relatively small space scales and short time scales, but the FFC intrinsically applies at 261 km² and long timescales (flood return periods are measured in years or decades).

Little can be done about timescale or the FFC, so the work focused on short-term impacts and the poorly understood problem of the scale dependence and downstream propagation of impact. Arguably, understanding scale dependence and downstream propagation is the key to fully understanding the link between upland changes and downstream impact. Taking all the limitations into account, an unusual experimental design was chosen that neglects local variables such as phreatic surface levels and concentrated instead on multiscale nested flow monitoring. The multiscale nested network allows the propagation of flood peaks through the catchment to be monitored. In total there are 31 gauges, nested up to five deep (for example, 0.0014, 1.7, 11, 25 and 261 km² in the nested catchments of Sapling Clough, Brennand, Dunsop and Hodder). To complement the flow network, rain gauges and an automatic weather station were installed.

The results in this report seem to show the following:

- The Hodder response is simple and flashy (that is, simple in that it can be modelled accurately using a simple model).
- There is strong inherent scaling with area. Using a scale equation that depends solely on the total land area drained to the various flow gauges, it was found that if the peak discharge for a storm event is known at one gauge then good estimates can immediately be made for the peak discharges at all the other gauges.
- Peak discharge depends strongly on rainfall and drained area.
- There are complex time-varying spatial patterns associated with the impact that changes in land use/management have on the flood response.

The results imply that the Hodder flood response will show strong, simple sensitivity to variability in the weather but weak, complex sensitivity to changes in land use/management.

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Acknowledgements list correct as of January 2011. Please note that some of the people mentioned may not work for the organisation currently listed.

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1 Introduction

The upper part of the River Hodder catchment in north-west England is undergoing major changes in land use/management under the United Utilities Sustainable Catchment Management Plan (SCaMP). Rainfall, evaporation and channel network flow were monitored in this project to record the impact that these changes on downstream flooding. The ultimate aim is to solve an important problem in the field of engineering hydrology, that is, predicting the effects of upstream changes in land use/management on downstream flooding.

The inception report for the project noted the scarcity of data for use in modelling and predicting the impact of changes in rural land use/management on downstream flooding. The report used the term 'change-effects database' when referring to the available data and listed three objectives for the project:

5. Analyse the requirements and value of the change-effects database, and create a database that defines and stores the data required for analysing and modelling change effects. This will be a template for use in future field and modelling programmes.
6. Contribute to, and widen, the change-effects database.
7. Run preliminary analyses of the link between land use/management change and flood impact, using the new data collected during the project.

This report describes:

- the Hodder catchment
- the SCaMP works
- the instrument network
- the Hodder data
- the analyses performed to date
- future work

To address the first two objectives, all the Hodder data have been installed in a comprehensive, user-friendly, Electronic Project Record (EPR), which is the main output from this work. The EPR is designed to be useful in future research, especially to those interested in the impact of SCaMP works on downstream flooding, but also more generally to those studying the links between rural land use/management and downstream flooding.

In the EPR, the field instruments are allocated codes such as BRE_sap (for the flow gauge at Sapling Clough in the Brennand catchment). For consistency with the EPR, these codes are used in maps in the body of this report. Full lists and details for the codes are given in Section 6.

The main work on the analysis of the Hodder data is being carried out in projects that form part of two research programmes:

- Engineering and Physical Sciences Research Council's Flood Risk Management Research Consortium 2 (EPSRC-FRMRC2)
- Natural Environment Research Council's Flood Risk from Extreme Events (NERC-FREE)

Details of both programmes are given in Section 1.3.

To give a full picture of the analysis and so that analysis of the short-term impact of the SCaMP works carried out in Project SC060092 (addressing Objective 3) can be seen in its proper context, some results are given in this report from the FREE project.

1.1 Statement on use of this research by the Environment Agency

Both the Defra strategy, *Making Space for Water*, and Sir Michael Pitt's review of the summer 2007 floods recommend using land use to reduce flooding. The Environment Agency intends to use this research to inform the development of evidence-based practice to deliver flood and coastal risk management. Given that this project covers only a small area of the UK, the findings of this study will be used alongside other research to inform national plans.

The Environment Agency sees this project (SC060092) as an example of good practice that should be used as a template to inform a range of complementary catchment studies. These catchment studies should provide the foundation for detailed modelling and data analysis on which decisions will be based.

1.2 PhD studentship

The proposal on which this project is based made provision for a three-year funded PhD studentship. This studentship represents a major component of the project, and following the project's launch in October 2007, it was advertised online. Following interviews at the beginning of November 2007, Miss Josie Geris from the Netherlands was awarded the studentship. Through her undergraduate and postgraduate (MSc) studies at the Vrije University of Amsterdam, she had acquired an excellent background for a predominantly field-based project. She commenced work on 2 January 2008. The title of her PhD project is 'Multiscale experimentation, monitoring and analysis of the impacts of local scale, upstream, land use management changes on downstream flooding'.

A chapter outline for her PhD thesis is given in Appendix A. The PhD project will take three years and so the work will continue beyond the formal end of the project in February 2010. At the time of writing this report (November 2010), it was expected that the thesis would be submitted in January 2011.

1.3 Links to FREE and FRMRC2

This project forms part of a larger programme of work funded from a number of sources. This larger programme of work is using the data from this and a number of other monitoring projects within a modelling framework that allows the results to be scaled up and used to demonstrate the potential of land use/management interventions to mitigate downstream flooding.

A schematic representation is given in Figure 1.1 of the various elements of the integrated monitoring and modelling research programme assembled to address the following priorities:

- detection of land use management impacts in catchment flood response data – followed up in Project FD2120 (Beven et al. 2008)

- multiscale experiments that cover a range of land use/management interventions and provide high quality data across a range of scales for model validation
- new distributed modelling approaches that allow impacts to be tracked from local to catchment scales
- field trials of mitigation measures to determine their performance
- tools to support decision-making such as source–pathway–receptor (SPR) modelling and vulnerability mapping

These priorities were identified as an outcome of the FD2114 review commissioned by the Department for Environment, Food and Rural Affairs (Defra) and the Environment Agency (O'Connell et al. 2005).

Four field experiments (SCaMP, CHASM, Pontbren and Belford) are supplying data in support of new modelling developments:

- The initial scoping study (Project EIT36-05-017) that led to this project (SC060092) was funded by English Nature.
- The Catchment Hydrology and Sustainable Management (CHASM) multiscale monitoring programme was funded under the NERC Joint Investment Framework and established in the Eden in the Lake District in 2002.
- The ongoing Pontbren multiscale experiment in mid-Wales is being funded under FRMRC2.
- The ongoing Belford study in Northumbria, funded under the Environment Agency Flood Levy, was set up to provide a full operational assessment of the extent to which flooding at local scale can be mitigated to provide flood protection for a small community.

New modelling developments are taking place within both the NERC-FREE and EPSRC-FRMRC2 programmes. Ultimately, these developments will feed through into the next generation of catchment-scale flood risk management planning tools, such as SPR modelling and vulnerability mapping tools.

One of the goals in the FREE programme (<http://www.nerc.ac.uk/research/funded/programmes/free/>) is to:

'research what causes and propagates floods, so helping to forecast and quantify flood risk, and inform our society about the likely effects of climate change'

FREE is quite a wide-ranging programme; the relevant part for this project is being run by Newcastle University (with Imperial College) and is entitled 'Land use management effects in extreme floods'. In this project, the data for the Hodder catchment are being used in the development and testing of models for the generation of floods. One element of the work is to look at the 1967 flood in the Dunsop subcatchment of the Hodder, which was caused by the largest 90-minute rainfall ever recorded in the UK (117 mm).

The overarching aim in FRMRC2 (<http://www.floodrisk.org.uk>) is to:

'enhance our understanding of flooding and improve our ability to reduce flood risk through the development of sustainable flood management strategies'

Imperial College is leading Super Work Package 5 (SWP5: Land Use Management) and Newcastle University is involved in modelling the spatial patterns of flood generation and the spatial sensitivity to changes in land use/management. The main work is on three test catchments:

- the Hodder
- the Eden, which drains to, and floods, Carlisle
- the Upper Severn, where Imperial College has been conducting local-scale impact experiments at Pontbren, involving manipulating land use/management and monitoring the effect on run-off

One of the goals in SWP5 is to extrapolate from the work on the test catchments so that the modelling developed by Newcastle University and Imperial College in the FREE and FRMRC2 programmes can ultimately be applied throughout the UK.

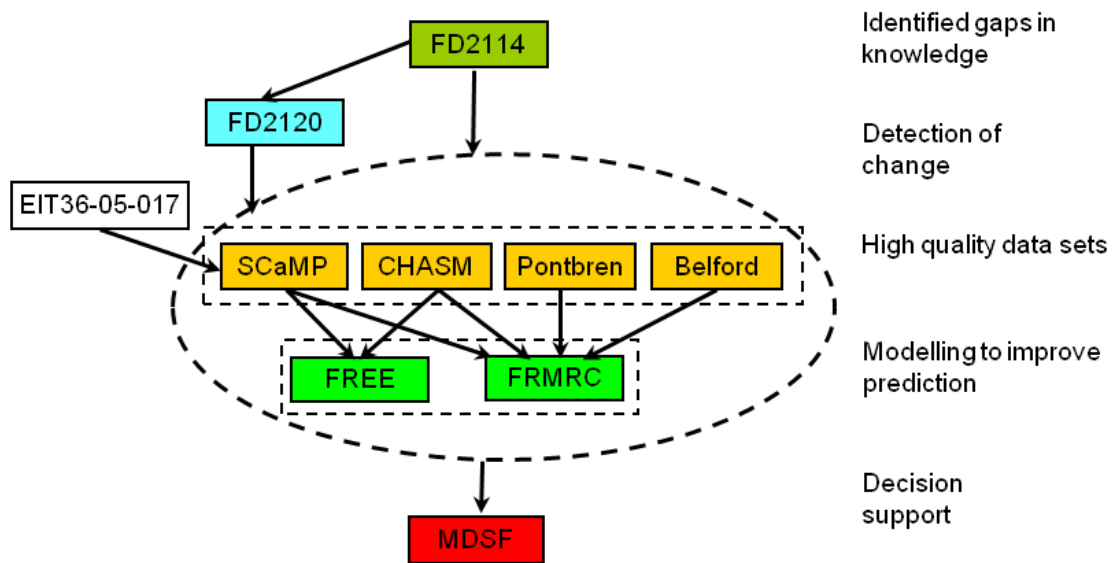


Figure 1.1 Integrated land use/management research programme

Notes: MDSF = Modelling and Decision Support Framework

1.4 Modelling the impact of changes in rural land use/management

It is not within the scope of this report to describe in detail all the modelling being conducted to estimate the impact of the SCaMP works on downstream flooding.

The roles of seven models being used at Newcastle University are described briefly below, but no attempt is made to place the models or modelling work within a wider context. Floodplains and urban and coastal areas are not represented – only the supply of water they receive from upstream rural areas. The models simulate the generation of flood waters in rural areas and their routing downstream.

1.4.1 SHETRAN

The Physically Based Distributed (PBD) model SHETRAN (Ewen et al. 2000) was used in the early stages of this project as a starting point for modelling the Hodder and testing the data sets.

The standard approach to estimating downstream impact using PBD models is to alter the local parameters to reflect the local effects of change and then let the model propagate the impacts downstream through the catchment. This has been criticised heavily (for example, O'Connell et al. 2005, Ewen et al. 2006a) on the grounds that the mathematical structure of PBD models is inadequate.

1.4.2 SHETRAN adjoint model

The adjoint version of SHETRAN developed by John Ewen gives sensitivity maps for catchments (for example, showing the sensitivity of downstream flow rates to changes in upstream infiltration properties) and uses algorithmic differentiation (Griewank 2000).

In the FREE and FRMRC2 projects, adjoint modelling is being used when generating sensitivity and vulnerability maps that show the link between rural land use/management change and the downstream impact on flooding. The work with SHETRAN demonstrated the power and generality of this approach, showing that it can be applied successfully to large complex pieces of software.

1.4.3 Dense Network Routing Model (DNRM) model

The Dense Network Routing Model (DNRM) was designed and developed by John Ewen as a basis for tracking information as it moves through the catchment. It solves the non-inertia Saint Venant equations on a dense dendritic drainage network. Greg O'Donnell designed and developed software to work with DNRM that tracks the movement of water through the drainage network. He used this in his PhD work to create maps that show the source of the water in flood hydrographs (O'Donnell 2008). A full Saint Venant version of DNRM exists but is not currently being used.

1.4.4 DNRM adjoint model

In the FREE and FRMRC2 projects, DNRM has been coupled to metamodels for run-off generation (developed by Imperial College) and the adjoint version of this coupled model is being run using long-term synthetic rainfall series created using RainSim (Burton et al. 2008). The main outcomes, which are all based on the idea of tracking flood peaks (that is, tracking the propagation of head rather than the movement of water), are:

- plots showing the impact on the Flood Frequency Curves
- maps showing sensitivities and vulnerabilities to changes in land use/management

1.4.5 Evolution model

A coupled land-surface/drainage-network model called Evolution has been designed by John Ewen and is being developed with Greg O'Donnell. It considerably extends the capabilities of DNRM to make the maximum use of the detailed field information available for the Hodder (for example, cross-sections and small-scale inundation). Its name derives from the way that the model structure evolves as new information from the field is added to the catchment data set. If time allows, the central elements of the Evolution model (in particular the treatment of the network geometry) will be used in the FREE and FRMRC2 projects.

1.4.6 Juke model

The Juke model was designed and developed by John Ewen and used in Project FD2120 (Beven et al. 2008) for the specialised task of adjusting observed hydrographs to simulate the impacts of hypothetical historical changes in land use/management. Juke contains several useful and powerful modules, and is being used in this project and the FREE and FRMRC2 projects to generate grids and flow networks for the Hodder, Eden and Pontbren.

1.4.7 Storage–discharge (SDD) model

In this project, a simple storage/discharge (SDD) model is being used to detect short-term early impacts in the various hydrographs observed at a range of scales in the Hodder. This very simple SDD model is based on the lumped hysteretic model developed by Ewen and Birkinshaw (2007). The SDD model and its use in detection are described in Section 10.

1.5 Errors and limitations

This is very much work in progress and fuller analysis will be possible using the data collected during the autumn and winter of 2009 to 2010.

The methods used were designed to make an assessment of the value of different data possible, which will be addressed in the PhD thesis by Jose Geris. In addition, the entire work was designed such that it can be used in sensitivity analyses (an example is given of how maps of sensitivity to changes in land use/management can be derived for the Hodder). This will be used in the FREE project to estimate the overall sensitivity to errors, so that the error analyses can focus on the particular data and modelling that are crucial in producing the overall results.

The monitoring period (two years) is very short, so the collected data are not representative of the full range of hydrological variability experienced in the catchment (for example, droughts, wet autumns, cold winters, dry winters). This weakness in the work is discussed in Section 13.

2 Hodder catchment

The River Hodder drains an area of 261 km². It joins the River Ribble just downstream of the Environment Agency flow gauge at Hodder Place, approximately 4 km south-west of the town of Clitheroe in north-west England (Figure 2.1).

Elevations in the catchment vary between 40 metres above Ordnance Datum (mOD) at the catchment outlet and 544 mOD at the summit of White Hill in the north of the catchment. The catchment is largely rural, with land use dominated by livestock farming and game rearing. The headwater areas are characterised by steeply incised valleys and plateaux covered with rough moorland and blanket peat mire.

In the headwaters, the Dunsop, Langden and upper Hodder (upstream of Stocks Reservoir) catchments have been used for surface water abstraction since the early 20th century. There is some minor groundwater abstraction. Within the Dunsop catchment (25 km²) are the Brennand (11.0 km²) and Whitendale (13.6 km²) catchments.

The United Utilities SCaMP restoration works (described in Section 4) are taking place in the Dunsop, Langden, Croasdale and upper Hodder catchments.

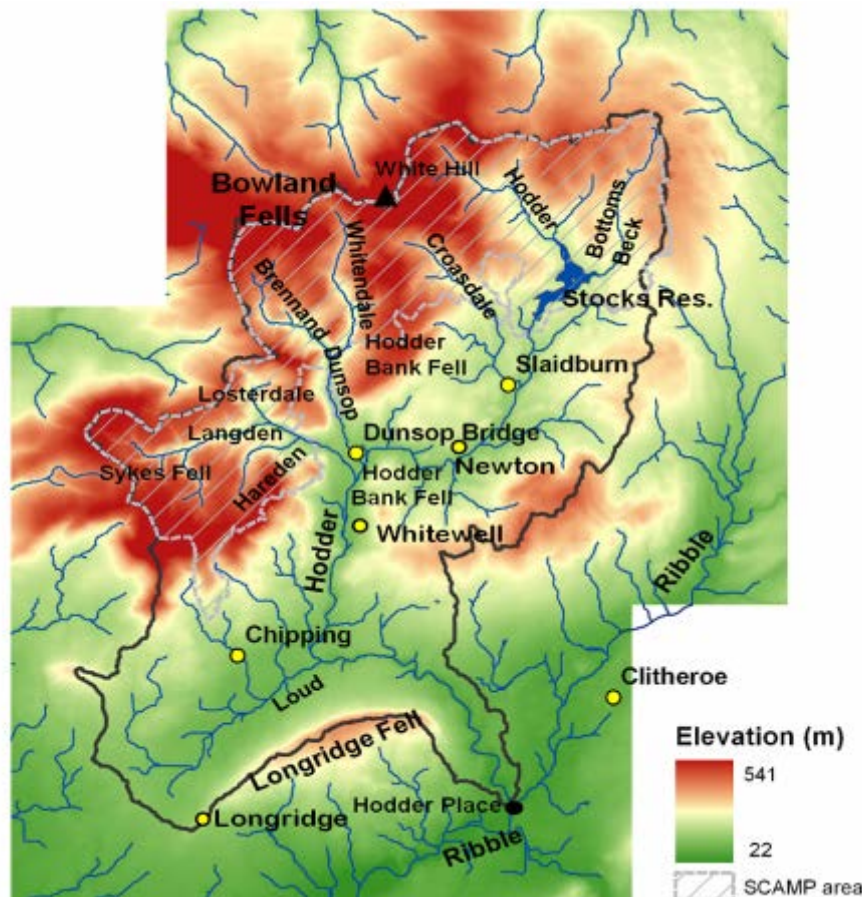


Figure 2.1 Hodder catchment

The upland areas have rich organic soils supporting grassland and moorland vegetation, and receive high annual rainfall totals in excess of 1,500 mm. At lower elevations, in the main Hodder valley and the River Loud catchment, there are mineral soils supporting improved grassland, making the area more favourable for agriculture. The annual rainfall total in these areas is around 1,100 mm.

2.1 Land use

Table 2.1 gives Defra 2003 Agricultural Census data for the Chipping Ward, which covers the upper Croasdale, Dunsop, Langden and Loud catchments, and the Bowland Newton and Slaidburn Ward, which covers the remainder of the Hodder.

Table 2.1 Land use data for the Hodder catchment

Category	Chipping Ward	Bowland Newton and Slaidburn Ward	% area
Total farmed area (ha)	5,465	15,894	
Temporary grassland (ha)	622.2	103.6	3.4
Permanent grassland (ha)	3,643	6,003	45.2
Rough grazing (ha)	1,071.4	9,554	49.7
Woodland (ha)	74.9	159.2	1.1
Dairy cattle	2,099	1,534	NA
Sheep (<1 year)	14,440	32,379	NA

Source: Defra 2002 Agricultural Census

Land use in the Hodder catchment is predominantly permanent grassland (45.2%), which has been improved in lower lying areas by drainage and fertiliser/lime application, and rough grazing (49.7%) at higher elevations, which is also used for game rearing.

There are some small areas of arable farming, predominantly wheat, maize and horticulture, mainly in the Loud catchment and in the main Hodder valley downstream of Stocks Reservoir.

Areas of commercial coniferous forest were planted in about 1950 in the Dunsop Valley (2 km²) and at Gisburn Forest (12 km²) upstream of Stocks Reservoir in the Bottoms Beck catchment. There is an additional area of coniferous forest, mixed with some native woodland, along the slopes of Longridge Fell. Pockets of native woodland are scattered throughout the lower Hodder Valley.

2.2 Soils/superficial deposits

2.2.1 Soils and peat

The soils associations of the Hodder catchment are shown in Figure 2.2 and their properties summarised in Table 2.2.

The Winter Hill association (Figure 2.2; association 1011b) is present in the north of the catchment on the low gradient plateaux of the Bowland Fells. This association consists of deep, wet, organic blanket (*Eriophorum-Sphagnum*) peat, with a typical depth of 1–3 m, but the depth exceptionally exceeds 6 m (see, for example, Aitkenhead et al. 1992). These soils are perennially waterlogged (Aitkenhead et al. 1992). Extensive erosion of the peat is taking place in numerous areas, notably on the summits of Sykes Fell, the adjacent Fair Snape's Fell, and the headwaters of the Brennand, where remnant peat hags are dissected by drainage gullies.

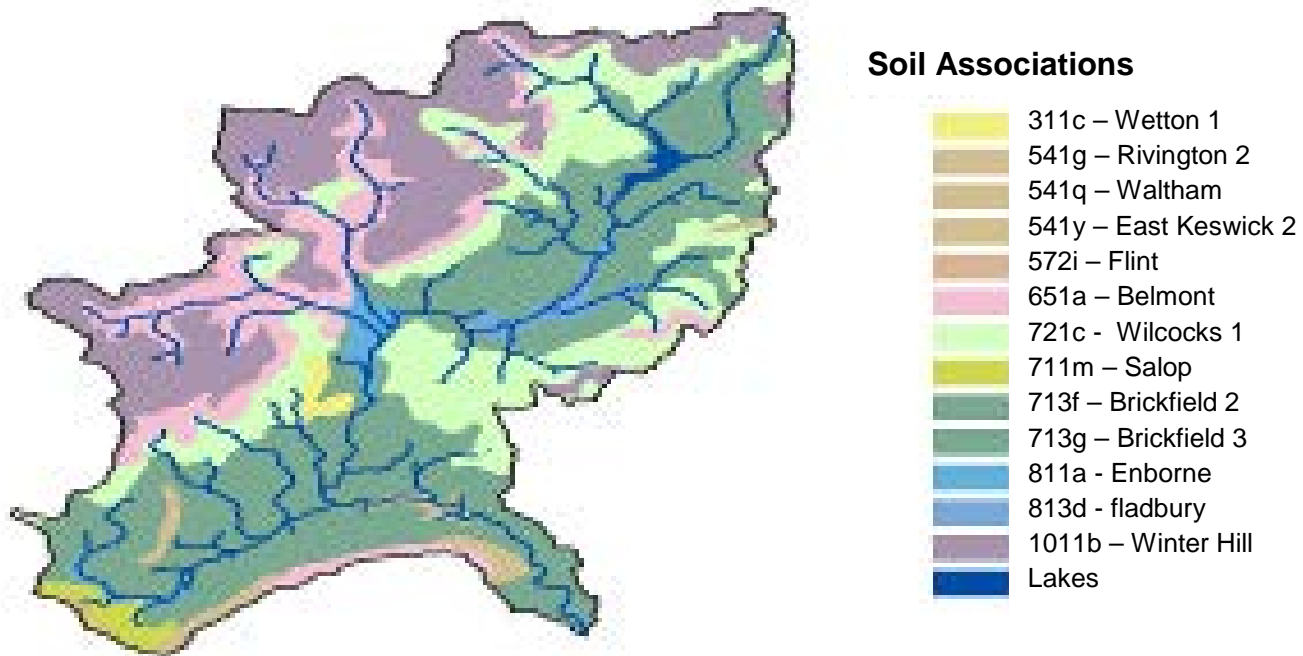


Figure 2.2 Soil associations 1:250,000

Source: Avery (1980)

The Belmont association (651a) typically forms over thin drift and Millstone Grit deposits on steep valley slopes adjacent to the Winter Hill covered plateaus. It comprises a black humified peat surface horizon overlying stony, sandy loam or clay loam. The association supports ericaceous moorland vegetation of ling (*Calluna vulgaris*), bilberry (*Vaccinium myrtillus*), *Nardus* and *Deschampsia* grasses with bracken (*Pteridium aquilinum*) on deeper soils. Due to the low bearing strength of the top soil, there is a great risk of poaching. Infiltration through the series is often impeded by thin sub-rooting zone ironpans.

In the northern valley bottoms, the Belmont soils give way to the Wilcocks 1 association (721c), consisting of strongly gleyed soils with peaty or humose topsoils. These soils support grasslands dominated by *Molinia*, *Nardus*, *Festuca* and *Agrostis* grasses, ling (common heather) and *Juncus* (rush) species. These areas are generally used for rough grazing, the quality of which can be improved through the application of lime. The surface horizons are typically waterlogged in winter and prone to poaching.

To the south and west of the Hodder catchment, the Brickfield 2 and 3 associations (713f, 713g, respectively) dominate. These comprise gleyed soils, with slowly permeable subsurface horizons. Supported vegetation consists of grass, with rush infestation common at higher elevations, which is used for permanent pasture. Due to low permeability, the soils experience surface waterlogging and there is a significant risk of poaching (Ragg et al. 1984). There are some opportunities for winter sown crops at lower elevations. Above Stocks Reservoir, the Brickfield soils have been drained for the Sitka Spruce plantations of Gisburn Forest (Ragg et al. 1984).

The other soil associations present in the Hodder are not extensive; brief descriptions are provided in Table 2.2.

Table 2.2 Soil associations of the Hodder catchment

Association	Brief description	Water regime	Typical land use
311c – Wetton 1	Occurs on steep valley sides in Carboniferous limestone country Shallow soils over rock	Well drained and readily absorbs winter rainfall, except on steep slopes where surface run-off may occur	Associated with steep slopes, so mainly used for rough grazing
541g – Rivington 2	Loamy brown earths and brown podzolic soils on moderate to steep valley sides	Well drained, with excess winter rainfall passing rapidly downwards through permeable subsoil Some run-off on steeper slopes	Sheep and beef cattle
541q – Waltham	Loamy soils over Carboniferous limestone	Permeable and well drained	Livestock rearing
541y – East Keswick 2	Well drained coarse loamy soils	Well drained, with little winter run-off	Poor grazing, scrub or deciduous and coniferous plantations
572l – Flint	Stagnogleyic argillic brown earths	Some degree of waterlogging, which can be alleviated by underdrainage	Mixed farming, but autumn cultivation may cause structural damage
651a – Belmont	Marked organic horizon, sand or clayey loam at depth	Formation of iron pans can impede drainage	Poor grazing or scrub
721c – Wilcocks 1	Strongly gleyed soil with peaty or humose topsoils	Severely waterlogged near the surface	Rough grazing or, if underdrained and limed, improved pasture. Potential for poaching.
711m – Salop	Stagnogley soils with slowly permeable sub soils	Waterlogged for long periods in winter	Grazing, but due to poor drainage poaching is a potential problem
713f – Brickfield 2	Fine loamy soils	Seasonally water logged, but responds to underdrainage	Grassland and coniferous plantations
713g – Brickfield 3	Loamy and clayey surface-water gleyed soils	Seasonally water logged, run-off via lateral flow at shallow depths	Livestock and dairy production
811a – Enborne	Fine loamy and clayey alluvial soils on floodplains	Seasonally waterlogged, but can be improved through underdrainage	Permanent pasture dominates
813d – Fladbury 3	Clayey alluvial soils on floodplains	Soils are affected by groundwater and are waterlogged for long periods in winter	Permanent grassland
1011b – Winter Hill	Raw oligo-fibrous peat soils forming on flat or gently sloping ground	Almost permanently waterlogged, with rapid run-off	Sheep grazing and grouse moor

2.2.2 Superficial deposits (excluding peat)

A glacial till sheet is present in the east and south of the Hodder catchment (Figure 2.3). It consists of an ill-sorted mixture of rock fragments, up to boulder size, set in a matrix of clay and sandy-clay. In the lower Hodder catchment, till thicknesses of 4–14 m are common, but the drift thins to the north, to only patchy coverage on the lower slopes of the Bowland Fells. The upland summits are largely free of till, with the exception of isolated reworked deposits generally less than 1 m thick (Aitkenhead et al. 1992).

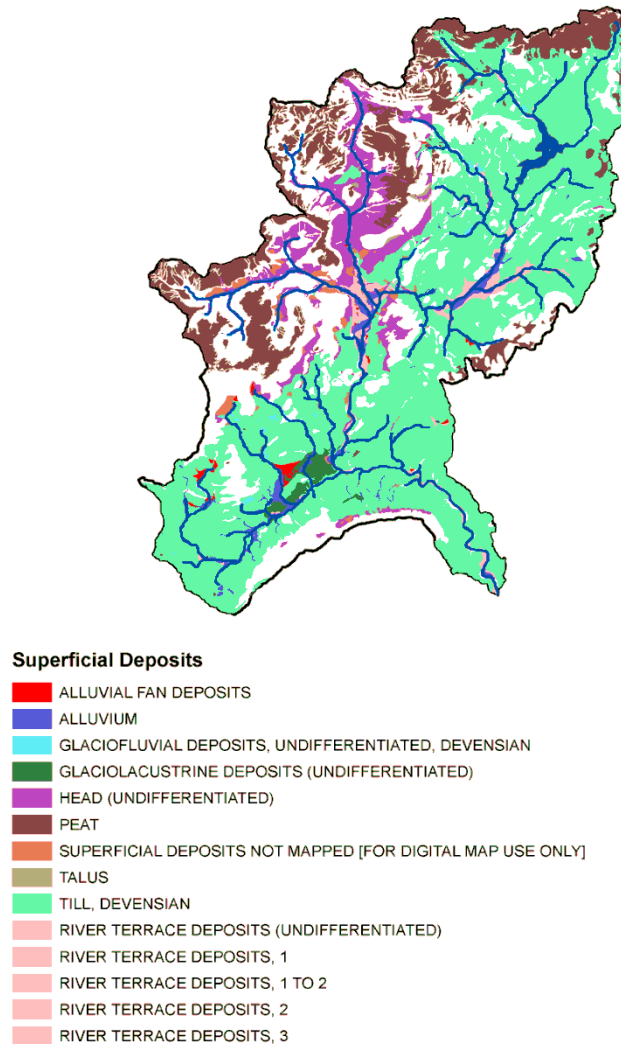


Figure 2.3 Superficial deposits (BGS 1:50,000 map)

In the valley floor areas of the Bowland Fells, head deposits are prevalent. These heterogeneous deposits comprise weathered near-surface bedrock (typically unsorted sandstone fragments) and/or drift material, mobilised through erosive forces and transported down slope by solifluction. Depths exceed 12 m on the western flanks of Hodder Bank Fell and 4 m in the Langden valley. On the lower slopes of the Bowland Fells, the head deposits overlap the till sheet (Aitkenhead et al. 1992).

An area of superficial deposits, presumed to be glaciolacustrine in origin, extends approximately 3 km along the lower Loud river valley to the Hodder confluence. The

deposits are approximately 1 m in depth, consisting of soft sand and stiff, grey to red-brown, stone-free clay.

Alluvium deposits up to 4 m in depth, and river terrace deposits comprising gravels, silty clays and mudstone fragments, are present along riparian corridors of the Hodder downstream of Slaidburn and the Dunsop valley downstream of Dunsop Bridge. Three terrace levels have been measured in the Dunsop at heights of 8, 4–5 and 2–3 m above the current floodplain (Harvey and Renwick 1987).

There are several areas of alluvial fan deposits in the Hodder catchment, the largest of which is centred to the south-east of the village of Chipping. These may have been deposited in 1851 after flash flooding, originating from a deeply incised valley above the village (Weld 1851). Aitkenhead et al. (1992) provide details of a number of small alluvial fans within the Langden Brook catchment.

2.3 Geology and hydrogeology

The main solid geological strata at higher elevations in the Hodder catchment are the Carboniferous Pendle and Brennand Grit formations of the Millstone Grit Group (shaded red in Figure 2.4). These consist of interbedded sequences of sandstones, silty mudstone and siltstone. Numerous outcrops occur in areas where the superficial till deposits are thin. Significant water yields can be drawn from the Pendle Grits using large diameter boreholes to overcome the relatively low bulk permeability caused by interbedded shale sequences of low transmissivity. Along Longridge Fell, in the south of the catchment, springs emerging from the Grits are utilised for domestic water supply (Brandon et al. 1998).

The Chatburn Limestone Group occurs in central areas of the Hodder catchment and in the vicinity of Slaidburn and Newton (shaded dark blue in Figure 2.4). These limestones are of Dinantian (Carboniferous) age and consist of well-bedded, dark grey, fine-grained packstones and calcareous mudstones. Exploitation has yielded only small quantities of groundwater, suggesting low bulk permeability.

The remainder of the catchment is associated with mudstone and limestone formations of moderate permeability. The Bowland Shale, comprising mudstone with variable amounts of sandstone, limestone and limestone debris beds, covers large areas of the lower catchment, and feeds numerous springs in the Loud catchment. Caves occur in the Clitheroe Limestone Formation where it outcrops in the gorge of the River Hodder to the south of Whitewell, suggesting some karstification (Aitkenhead et al. 1992).

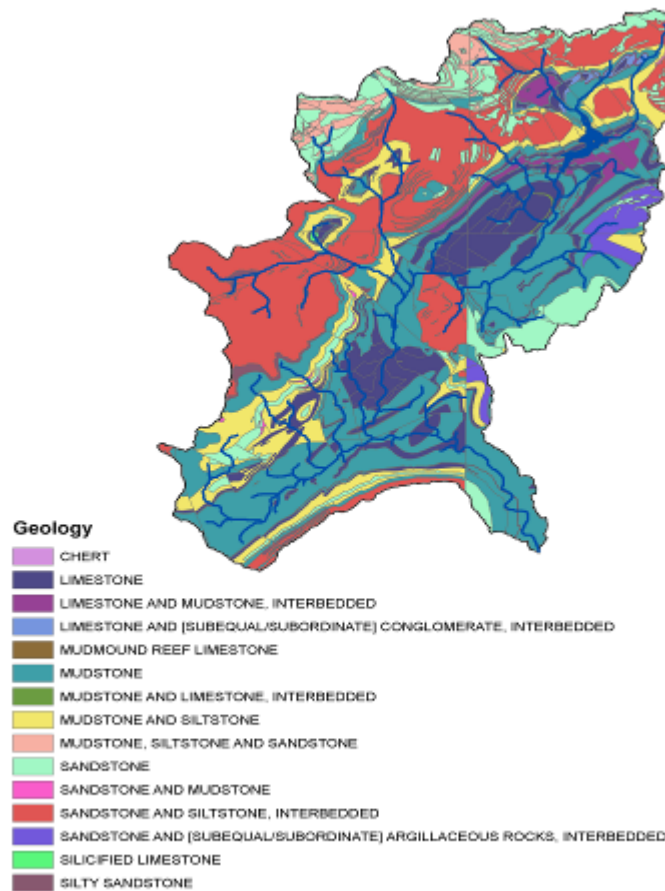


Figure 2.4 Solid geology (BGS 1:50,000 map)

2.4 Water supply infrastructure

Surface waters, and to a far lesser extent groundwaters, in the Hodder catchment have long been exploited for domestic supply by United Utilities and its predecessors North West Water, the Fylde Water Board and the Fylde Water Company.

Two major water intake systems are operated by United Utilities:

- the Bowland system in the Langden Brook catchment
- the Dunsop system in the River Dunsop catchment

Consultations have been held with United Utilities to establish the operation of these systems and digital abstraction data have been provided.

2.4.1 Bowland abstraction system

A schematic of the Bowland System in the Langden Brook catchment is shown in Figure 2.5. The system was constructed in the 1870s and upgraded in the 1920s to the current maximum capacity, 109.1 million litres per day (MLD).

There are two main surface water intake structures, located on Langden Brook and the Hareden Brook tributary; the abstraction licences require minimum compensation flows

of 8.6 MLD and 2.7 MLD, respectively. In addition, there are five minor intakes and two groundwater abstraction points. The abstractions from the system feed a reservoir complex located several kilometres away, near the village of Longridge. The daily operation of the system depends on water colour, reservoir storage capacity and the prevailing weather conditions.

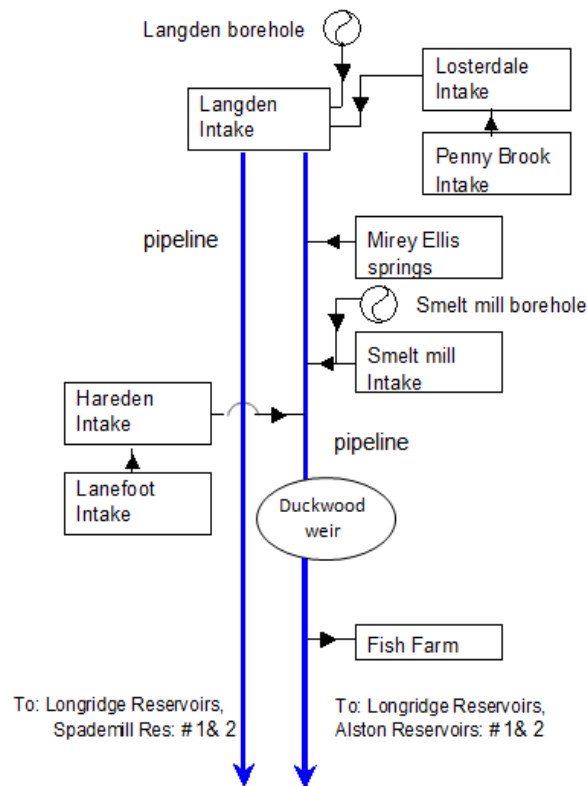


Figure 2.5 Schematic representation of United Utilities' Bowland water intake system

Notes: Based on discussions with United Utilities.

2.4.2 Dunsop abstraction system

The Dunsop system was designed in the 1880s as a temporary measure, with the intention of replacing it by a reservoir in either the Brennand or Whitendale catchments. However, a geological survey found that these were unsuitable for reservoir construction and so the original system remains in operation.

There were originally 22 intakes in the Whitendale and Brennand catchments, but the system was reduced in 2000 to its present form, shown in Figure 2.6. The system comprises two major surface intakes on the main Brennand and Whitendale rivers, and three minor intakes located on tributaries, providing a system total of 35 MLD. The minimum compensation flow for the River Dunsop at Footholme is 6.1 MLD. To meet this requirement during periods of low flow, water from the Brennand intakes are released into the Whitendale River immediately upstream of the Footholme pumping station (Figure 2.6). The Footholme borehole provides additional compensation flows in the summer months.

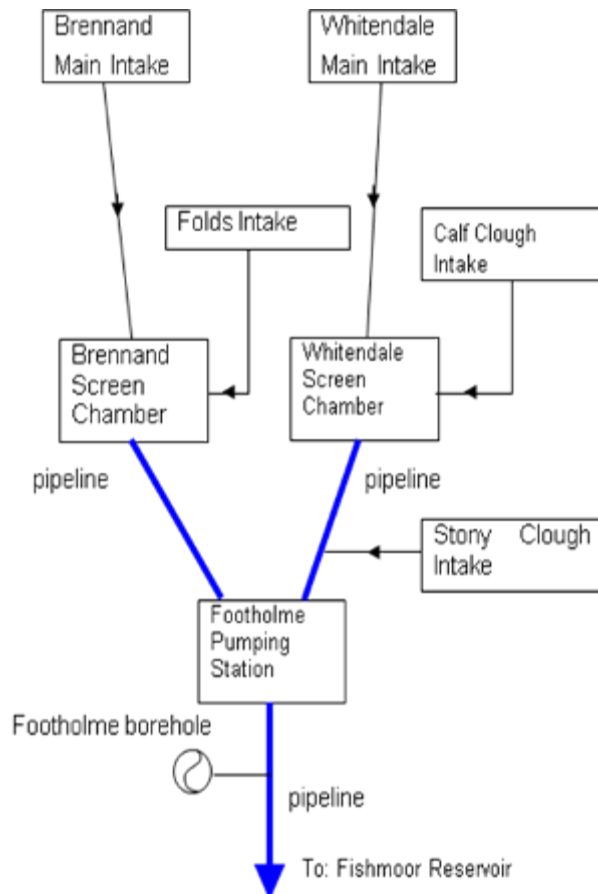


Figure 2.6 Schematic representation of United Utilities' Dunsop water intake system

Notes: Based on discussions with United Utilities.

2.4.3 Stocks Reservoir

Stocks Reservoir has a contributing area of 37 km² and surface area of 1.4 km². The planning and design of the reservoir began in 1910 to meet rapidly rising water demands from the Fylde coast. Construction began in 1922 and continued until the reservoir was officially opened in July 1932.

The percentage annual run-off for the Bottoms Beck tributary (10.6 km²) that flows into the reservoir is 67%, but the percentage run-off at the outfall to the reservoir is only 30%, giving an indication of the magnitude of the abstractions. Note that these percentages were measured over 14 years at Bottoms Beck (1960–1974) and 44 years at Stocks Reservoir (1936–1980). Releases occur in every month of the year, but tend to be largest in the wettest months, October to March. Figure 2.7 shows the releases in 1998 and the maximum releases in 1998–2008 inclusive (that is, time series showing hour by hour through the year the largest release seen in any of the 11 years). In general, major releases are usually of short duration and there can be large gaps with no release.

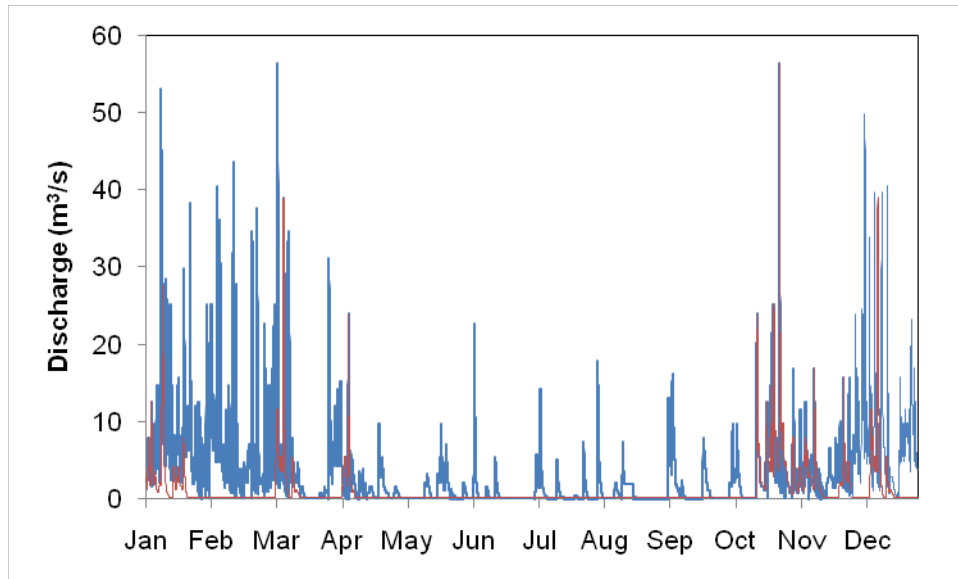


Figure 2.7 Releases from Stocks Reservoir

Notes: Blue = maximum in 1998–2008; red = 1998

2.5 Flood inundation

The Environment Agency online Flood Map for the Hodder catchment is reproduced in Figure 2.8.

Flood risk in the catchment is generally very low as most of the land is rural in nature (Environment Agency 2006), but there are local problems at Slaidburn, located at the confluence of Croasdale Brook and the River Hodder, and Dunsop Bridge, adjacent to the River Dunsop (Environment Agency 2007). These problem areas are indicated on the flood map by red ellipses. On the British Geological Survey (BGS) superficial deposit map (Figure 2.3), these areas have alluvial deposits which indicate a history of flooding.

In 2008, a Flood Alleviation Scheme was completed to protect Slaidburn against future flooding from Croasdale Brook, but there still remains a residual risk from the river Hodder. Some major inundation events have been recorded in the Hodder catchment. For example, during a localised event in 1851, it was reported that houses in Chipping, a village in the Loud catchment, were inundated by six feet of water (Weld 1851).

Although there is discussion in this report about flood hazard and the impact that the SCaMP works might have on the Flood Frequency Curve (FFC) at the flow gauge at Hodder Place, Hodder Place itself is not particularly at risk from flooding. The FFC at Hodder Place does, however, show the potential of the Hodder catchment for releasing high peak flows into the River Ribble, which may contribute to flooding further downstream.

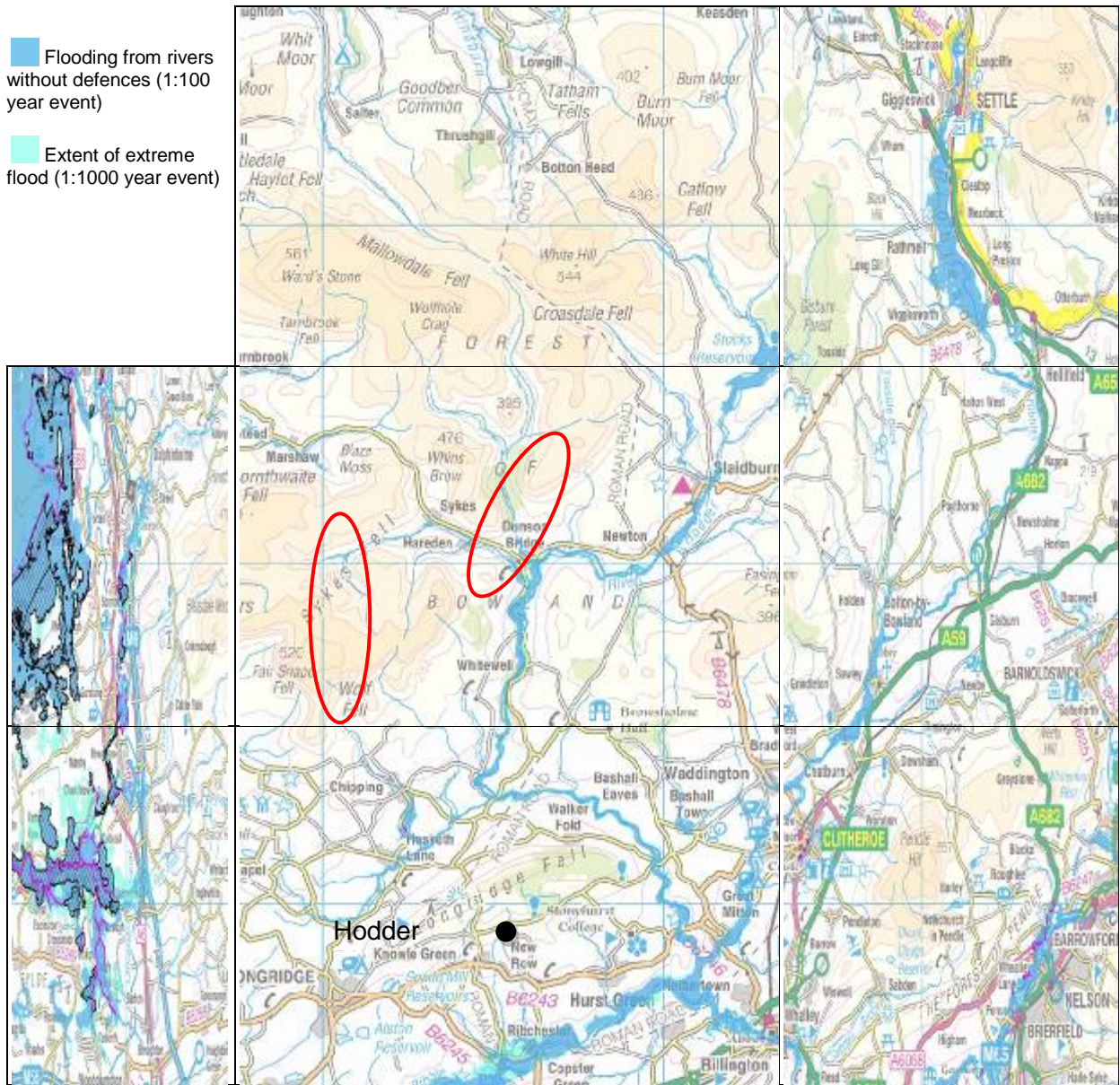


Figure 2.8 Environment Agency Flood Map for the Hodder

Notes: Red ellipses = areas at risk upstream of Hodder Place

3 Land use/management changes in the Hodder catchment

The SCaMP changes in land use/management are just the latest in a long series of changes in the Hodder catchment. For example, as part of agricultural intensification after the Second World War, there have been changes throughout north-east Lancashire including:

- gripping of peat
- stocking density changes
- forestation/logging
- modifications to river channels

Recent and proposed future changes are discussed in Section 4 when the SCaMP works are described.

3.1.1 Gripping

Like much of the Pennines, moorland gripping was undertaken in the middle of the 20th century with the aim of draining and 'improving' upland soils for game rearing and pasture (Holden et al. 2004). The grips typically consist of narrow open surface drains of 1 m in depth, with varying orientation from acute to perpendicular to hillslope contours.

Historical Ordnance Survey maps, which are available from 1843 via the Digimap collection, provide a useful indication of the timing of grip installation. The extent of the mapped surface drainage network increased significantly in the 1950s and 1960s, often dominated by strongly linear features in upland headwaters (see, for example, Figure 3.1). This may be the result of a change in the level of detail of cartographic reporting, but the timing does coincide with a period when government grants were available for upland drainage.

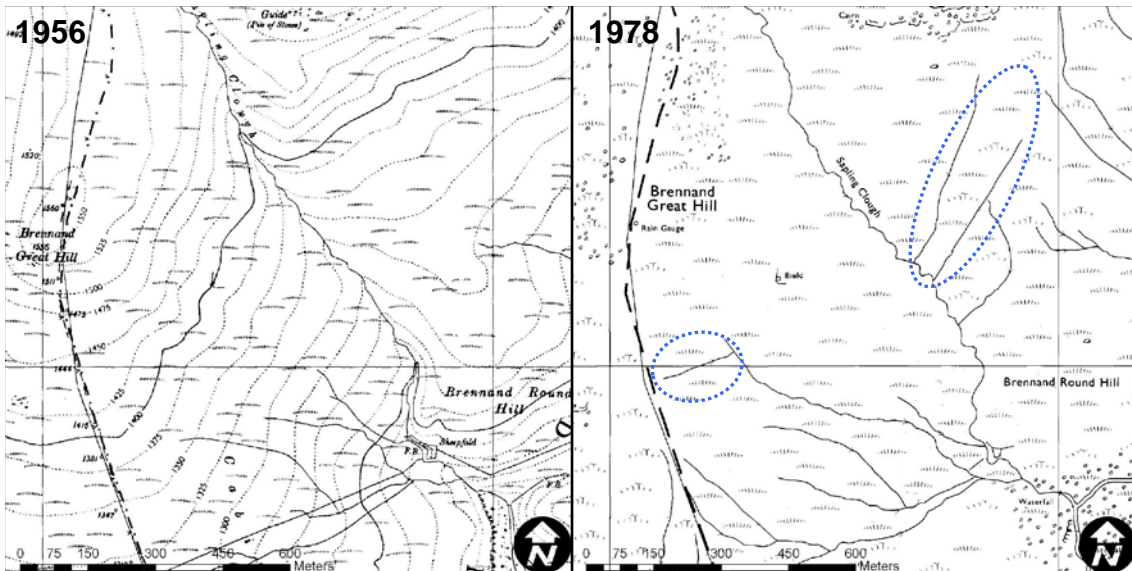


Figure 3.1 Extensions to the mapped drainage network in Sapling Clough (Brennand)

Many of the linear features in the maps are labelled as ‘drain’, providing some reassurance that they are man-made. The drains shown in Figure 3.2 were visited as part of a ‘ground-truth’ exercise; they are large grips.

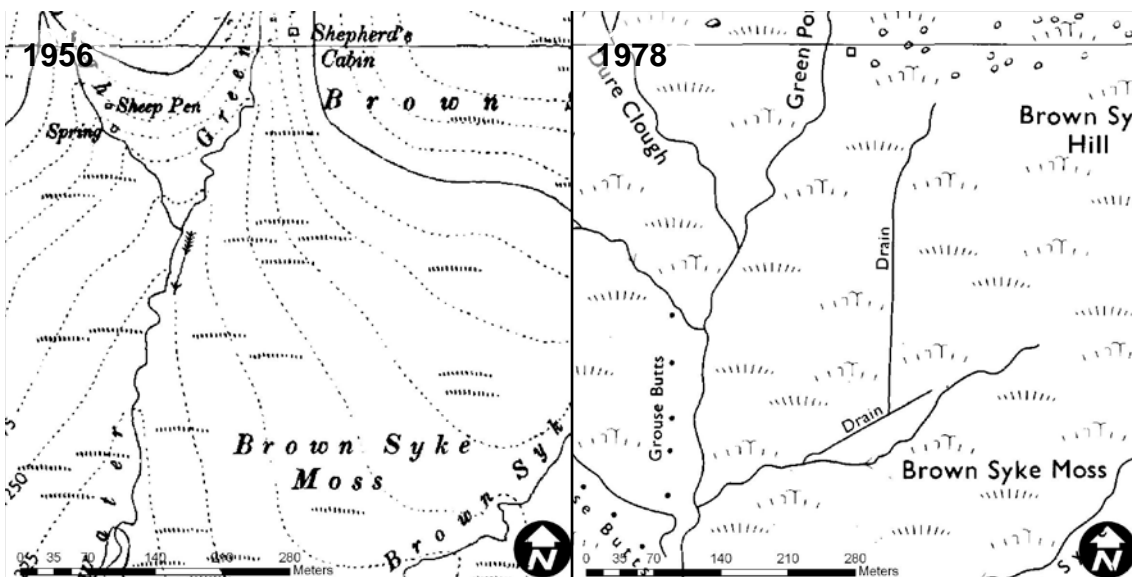


Figure 3.2 Large land drains appearing on Brown Syke Moss (Brennand) between 1956 and 1978

Notes: The drains are visible in aerial photographs from the 1960s.

In field surveying to construct maps, subjective decisions are taken on which features to include. This could potentially result in underestimation of the spatial extent of gripping. Historical aerial photographs do not suffer from this limitation. In Figure 3.3, public archive aerial photographs show that distinctive ‘herring bone’ land drainage patterns appear between the 1940s and 1960s.

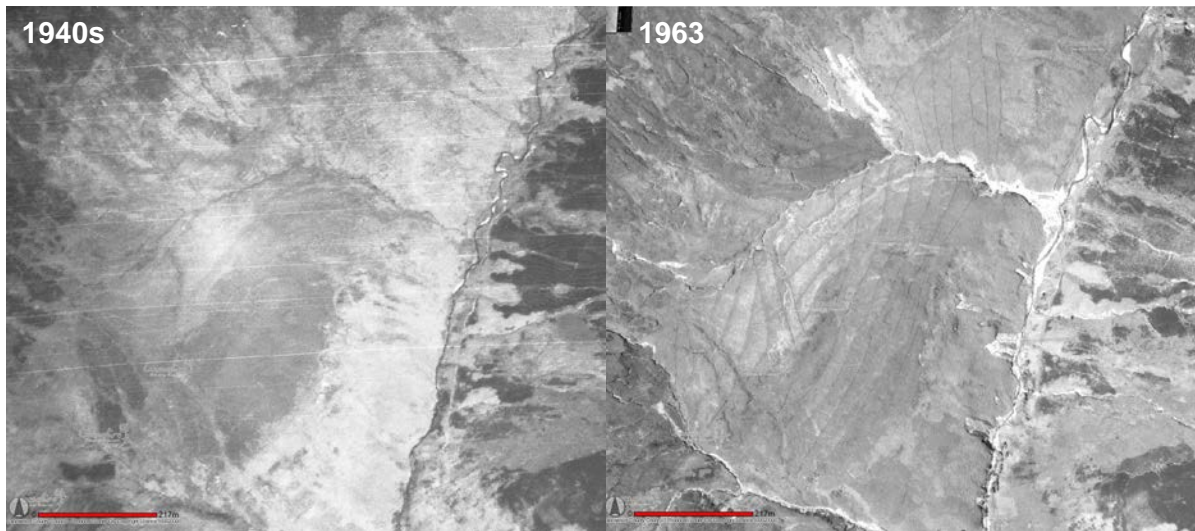


Figure 3.3 Moorland gripping on White Bank in the Whitendale River catchment between 1940 and 1963

Notes: Photographs courtesy of Lancaster County Council

Table 3.1 provides a summary of gripping. Dates have been assigned from the investigations of OS maps and aerial photographs, and the lengths are based on detailed ground surveys performed by Dinsdale Moorland Associates on behalf of United Utilities.

Table 3.1 Moorland gripping in the Bowland Fells

Catchment	Period of gripping	Approximate total gripped length (km)
Brennand	1956–1969	28.3
Whitendale	1956–1963	10
Croasdale	1956–1969	0.5
Upper Hodder (upstream of Stocks Reservoir)	1956–1963	10

3.1.2 Stocking density changes

Changes in agricultural practices and the associated changes in vegetation cover at Bleasdale Parish in the Langden Brook catchment over the period 1895 to 1988 were investigated by Mackay and Tallis (1994, 1996). They used parish agricultural and rainfall records, peat accumulation rates, evidence of atmospheric pollution, and peat core pollen and macrofossil records in their analysis.

Total sheep numbers rose steadily over the period 1895 to 1970 from approximately 5,000 to 8,000, and then increased dramatically to 15,000 in 1988 (Mackay and Tallis 1996).

Mackay and Tallis (1996) suggest that the high grazing densities in the late 1900s (Figure 3.4) restricted re-colonisation of bare areas of peat, which are subject to erosion. These bare areas are thought to have developed due to a series of factors, which combined to cause a catastrophic upland burn in 1921, including:

- a period of below average rainfall in the early 1900s

- an exceptional drought in 1921
- declining management standards due to gamekeeper shortages after the First World War

Current upland agri-environment initiatives in the SCaMP area (see Section 4) aim to reverse the deterioration of the peatland.

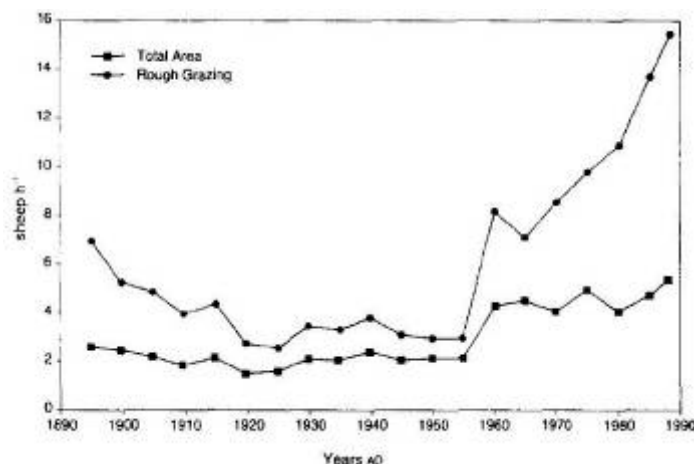


Figure 3.4 Sheep stocking density in the Bleasdale Parish relative to the land area available and that set aside for rough grazing

Notes: Taken from Mackay and Tallis (1996)

3.1.3 Forestry

The Forestry Commission manages three main areas of coniferous forest in the Hodder catchment:

- a strip of forest along the River Dunsop near Footholme, known as the Dunsop Valley
- an area in Bottoms Beck, upstream of Stocks Reservoir, known as Gisburn Forest
- a large predominantly coniferous woodland on the northern slopes of Longridge Fell in the south of the catchment

The Dunsop Valley area has been owned by the Forestry Commission since 1952 and the Gisburn Forest has been leased from United Utilities since 1949. Information on the management of the Longridge Fell area has not yet been received from the Forestry Commission. The forests are reaching maturity and felling plans are in place.

In Dunsop Valley, the dominant species are Sitka spruce, Norwegian spruce and larch. For the purposes of the Forestry Felling Plan, the plantation has been divided into six sub-areas. Every five years, a sub-area is felled and replanted with native species (for example, birch, oak, ash, alder and hazel) – see Figure 3.5 and Table 3.2.

According to forest management guidelines, remnant branches are placed on the extraction routes during forest clearance to minimise erosion and soil compaction.

Felling Plan Dunsop Valley, Forestry Commission

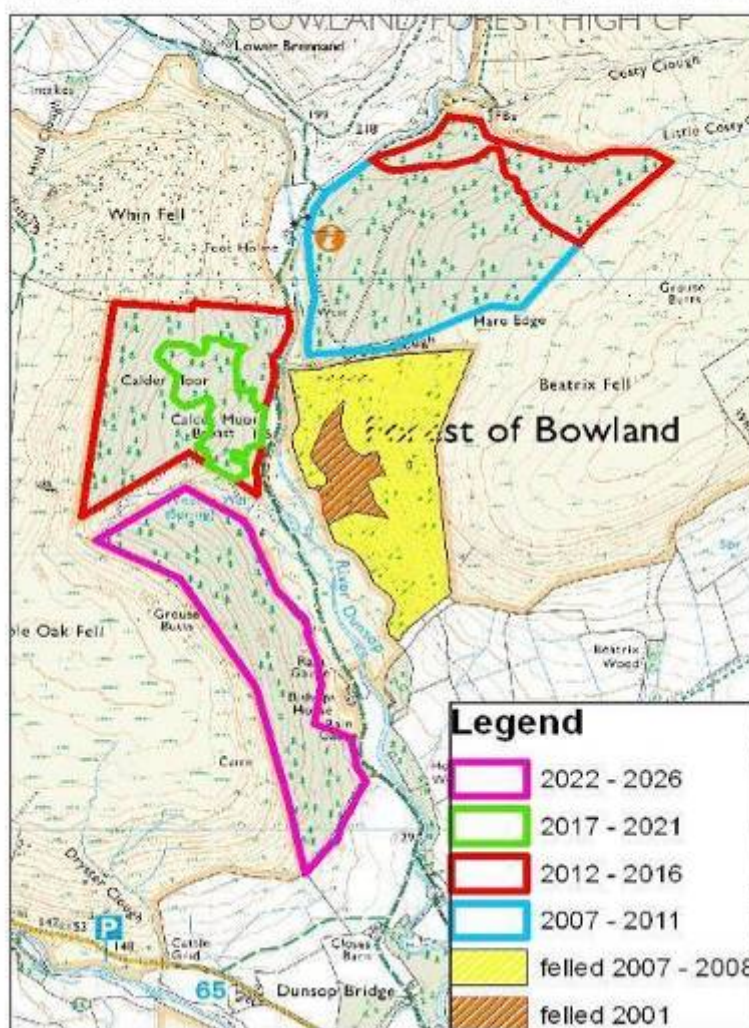


Figure 3.5 Dunsop Valley Felling Plan

Source: Forestry Commission, personal communication

Table 3.2 Area of forest patches involved in Dunsop Valley Felling Plan

Fell timing	Area (ha)
2001	5.9
2007–2008	32.9
2008–2011	45.5
2012–2016	42.2
2017–2021	9.0
2022–2026	35.6

Gisburn Forest is the largest forest in Lancashire, being approximately 12.2 km² in area. Sitka spruce is the predominate species, being suited to the gleyed soils and exposed location (Forestry Commission 2005). Felling in Gisburn follows a five-year plan similar to Dunsop valley. However, the felling in Gisburn is planned to be gradual and for isolated smaller patches (that is, there will be no large, contiguous areas felled).

This area is of less interest in the context of this project, given that it lies upstream of Stocks Reservoir.

Woodland planting under the SCaMP is summarised in Section 4.5.

3.1.4 Channel changes and modifications

There are no extensive areas of channelisation for flood protection purposes anywhere in the Hodder catchment, but there are some localised flood defences near the outlet of the River Loud and at Slaidburn (Environment Agency 2006) and some minor modifications associated with the water intake structures in the headwater areas. The Ribble Catchment Conservation Trust (Fisheries) has recently carried out channel modifications on Langden Brook, working with United Utilities, with the channel being made more braided (personal communication, Jack Spees, Ribble Catchment Conservation Trust).

Long-term changes in channel morphology in the region are described by Harvey and Renwick (1987) and Foster et al. (2009). Through the assessment and dating of terrace sequences in the upper Hodder and Langden Brook, Harvey and Renwick (1987) suggest human-induced land use changes may have affected sediment supply. Two major periods of alluvial fan aggradation were identified:

- the first associated with climatic deterioration between 2500 BP and 1900 BP
- the second at 900 BP which could have been influenced by human activity (for example, woodland clearing and agricultural expansion)

Foster et al. (2009) note similar landscape sensitivities to erosion and increased channel migration in the adjacent Calder catchment following the onset of woodland removal and increasingly intensive land use in the late Holocene. Increased anthropogenic pressure on upland hillslopes since 1500 AD may also have been crucial in priming the Bowland slopes for gullying during major storm events (Chiverrell et al. 2007).

Major episodic changes in sediment supply and channel form due to recent extreme events in the Loud valley were reported by Weld (1851), while Newson and Bathurst (1990) documented the impact of the 1967 major flood on erosion in the Dunsop catchment and the resulting siltation of the water supply infrastructure.

4 United Utilities' SCaMP

The main purpose of the United Utilities' Sustainable Catchment Management Plan (<http://www.unitedutilities.com/scamp>) is to:

- help prevent further deterioration of raw water quality (especially water colour production)
- improve the condition of Sites of Special Scientific Interest (SSSIs)

The scheme is being undertaken at four upland sites, but only one site, Forest of Bowland, is in the Hodder catchment; the other sites are Dark Peak, the Goyt Valley and South Pennines.

Eight types of restoration works are being implemented:

1. Blocking gullies and grips to increase the water levels in blanket peat, to help improve the condition of the peatland
2. Tree planting
3. Reducing or relocating sheep grazing
4. Controlling the extent and frequency of burning
5. Controlling bracken
6. Restoring vegetation on eroding bare peat
7. Additional management (for example, re-seeding) of the plant communities of heath and blanket bog
8. Scrape creation to provide habitat for wading birds.

The data given here on the SCaMP works are based on:

- the farm plans for the works prepared by United Utilities
- Higher Level Scheme agreements
- discussions with the SCaMP site manager, Nigel Pilling (United Utilities)

The instrument network installed as part of this project was designed to monitor the whole Hodder catchment, but with some concentration at smaller scales where SCaMP works are being implemented. It was decided to concentrate the smaller scale monitoring on areas subject to grip blocking, tree planting and stocking density (that is, work types 1, 2 and 3), because these works are implemented over relatively large areas.

The control of bracken and the extent and frequency of burning (work types 4 and 5) could have an effect on the hydrology. However, the affected locations are decided from year to year, making monitoring impractical. The restoration works (work types 6 and 7) are similarly patchy. Only around ten 50 m³ scrapes were created in the Dunsop catchment (work type 8). These have plastic liners to ensure they remain wet nearly all year to provide habitat for wading birds. Only after a prolonged dry period could these provide extra storage of run-off and then only an extremely small amount.

Details for the SCaMP works are summarised in Table 4.1 and maps are given in Section 4.2. The table and these maps do not cover the area upstream of Stocks Reservoir, as this is of less interest because the flood response will be dominated by

the effect of water storage in the reservoir. The works being carried out upstream of the reservoir are summarised in Section 4.1.

Table 4.1 SCaMP works

Catchment	Change	Date	Description
Brennand	Grip blocking	November–December 2008	All grips in the Brennand catchment have been blocked; total length 28.3 km.
	Stocking density changes	June 2008	Fences have been placed along the river banks and on the moors. Low stocking levels are being maintained in the headwaters (habitat regeneration). Stock is excluded on the western slope of the Brennand River and in the riparian zones where trees have been planted.
	Tree planting	June 2008	Mixed broadleaf trees have been planted in riparian zones throughout the catchment and on some hill slopes near Fox Clough and Tarn Clough on the western slopes of the Brennand River.
Croasdale	Grip blocking	February 2009	A relatively large grip system has been blocked in the Swine Clough catchment. The total length affected is ~0.5 km.
	Stocking density changes	Spring/summer 2008	Low stocking levels are being maintained in the headwaters (habitat regeneration).
	Logging	November 2008	Two coniferous forested patches (~0.025 km ² each) have been logged. There is the possibility that a scrape will be created on one of the logged patches; otherwise, the patch will be used for rough grazing or be reseeded. The other patch will be replanted with broadleaf trees.
Hareden, Losterdale and Upper Langden	Stocking density changes	February 2009	Fences were erected to limit stocking to help maintaining upland habitats on the moors of Losterdale, Upper Langden and Hareden.
	Tree planting	March 2009	Mixed broadleaf trees have been planted in the riparian zones of Swine Clough (Losterdale), Hareden and Upper Langden.
	Logging	September 2009	Logging of coniferous trees has taken place in patches in the Hareden catchment. There is the possibility that these patches will be replanted with broadleaf species.
Whitendale	Tree planting	Spring 2008	Trees have been planted in the riparian zones throughout the catchment and on the eastern hill slopes of Middle Knoll.
	Stocking density changes	Spring/summer 2008	Low stocking levels are being maintained in the headwaters (habitat regeneration). Stock is excluded from the eastern hill slopes of Middle Knoll and from the riparian zones where trees have been planted.
	Logging	Under negotiation	There may be logging of old forested patches (pine) near Good Greave, but this is still under negotiation.

4.1 Works upstream of Stocks Reservoir

Upstream of Stocks Reservoir, there are SCaMP works on Lamb Hill Farm, Saddle End Farm, Catlow Farm and Halsteads Farm (Table 4.2). No information is available for Halsteads Farm.

Table 4.2 Works upstream of Stocks Reservoir

Farm	Grip blocking	Tree planting	Stocking density changes	Controlled burning	Bracken management	Vegetation restoration	Scrape creation
Lamb Hill Farm	no	yes	-23% and relocation	yes	yes	yes	no
Saddle End Farm	no	yes	relocation only	yes	yes	yes	no
Catlow Farm	no	yes	-28% and relocation	no	no	yes	no
Halsteads Farm	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Notes: Based on farm management plans prepared for United Utilities.

4.2 Maps of SCaMP works

Maps are given here for the SCaMP works in the Brennand (Figure 4.1), Croasdale (Figure 4.2), Hareden (Figure 4.3), Losterdale (Figure 4.4), Upper Langden (Figure 4.5) and Whitendale catchments (Figure 4.6).

Some information on the nature and timing of the works is given in the following sections.

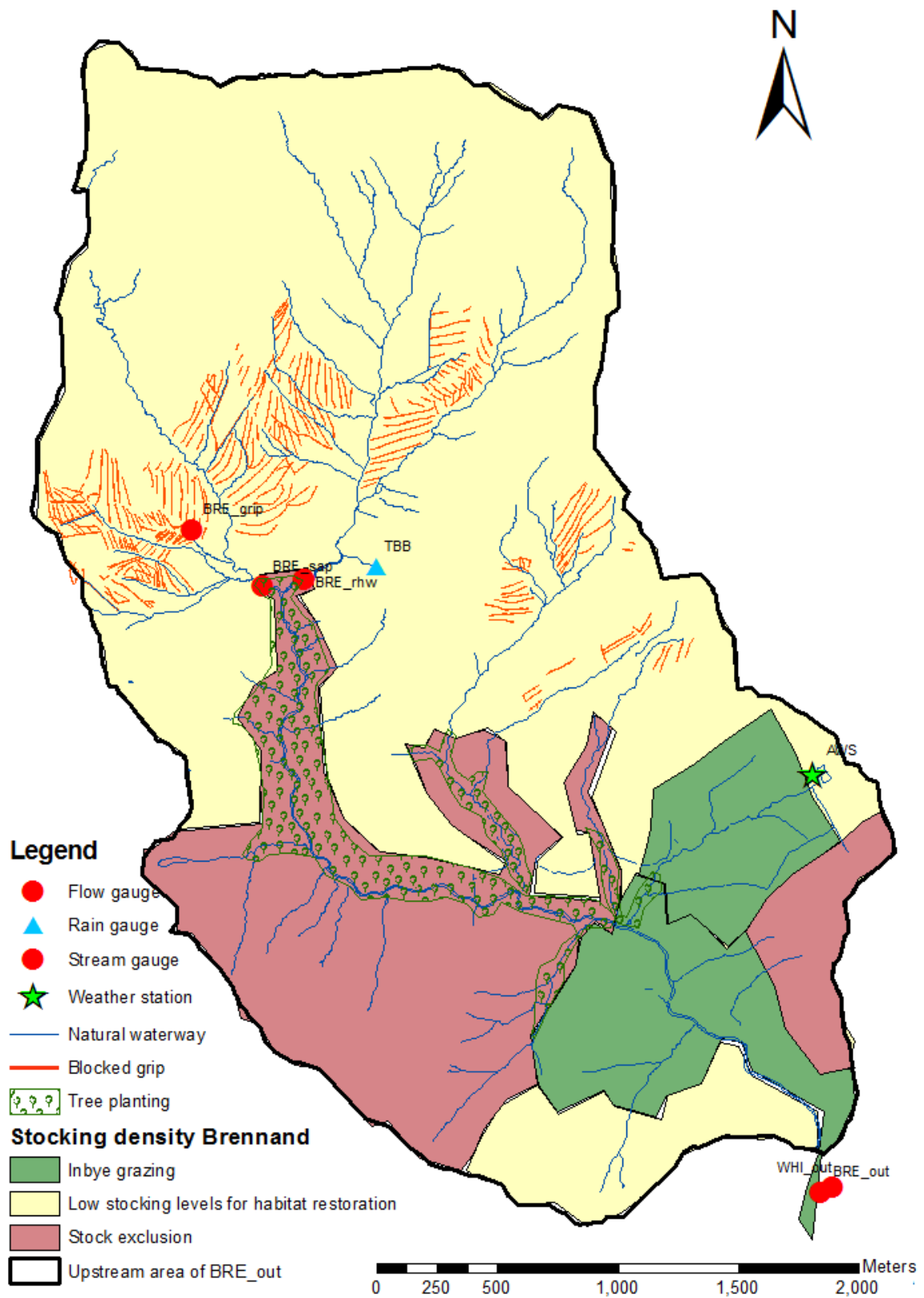


Figure 4.1 SCaMP works in Brennard catchment

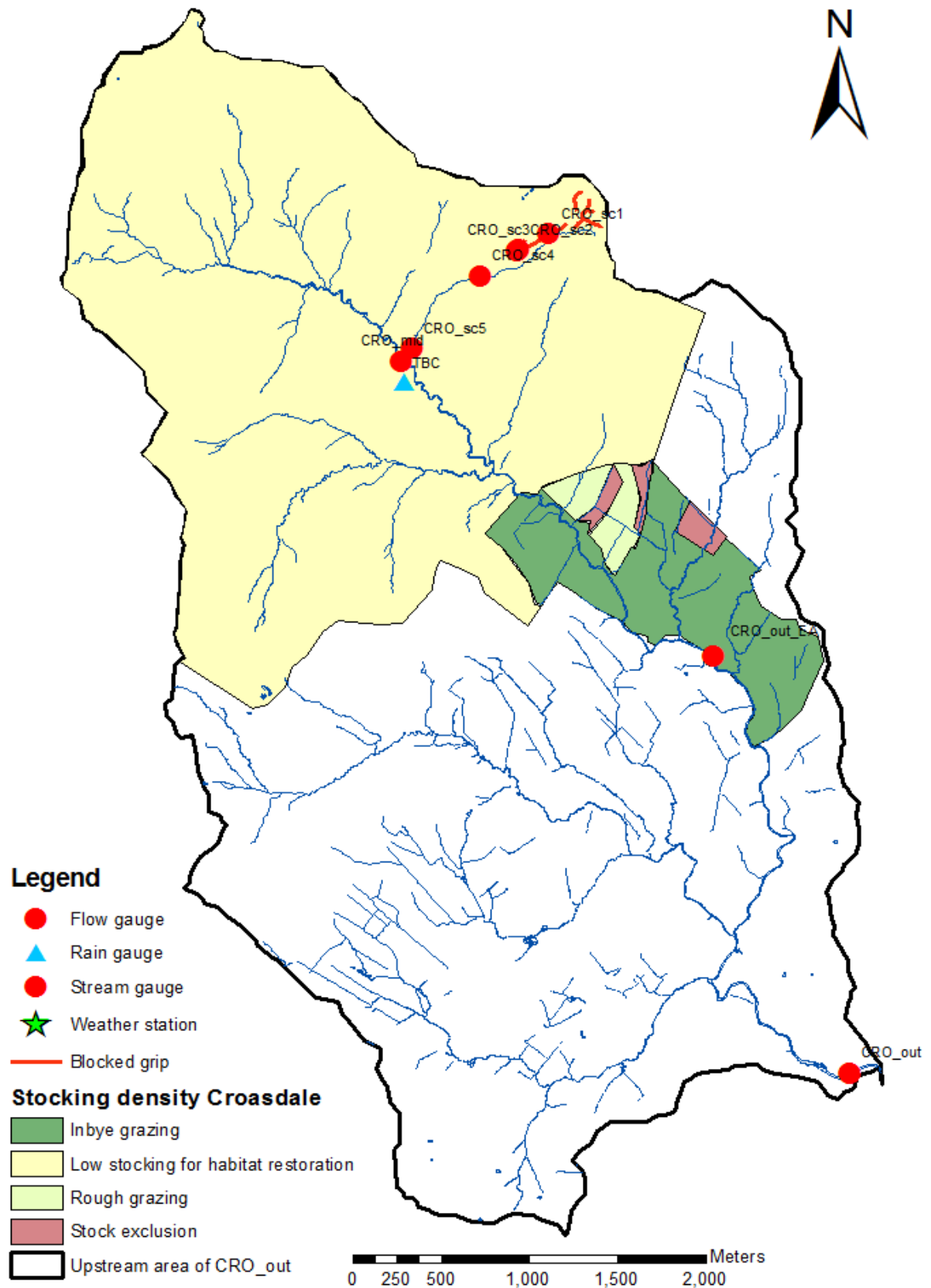


Figure 4.2 SCaMP works in Croasdale catchment

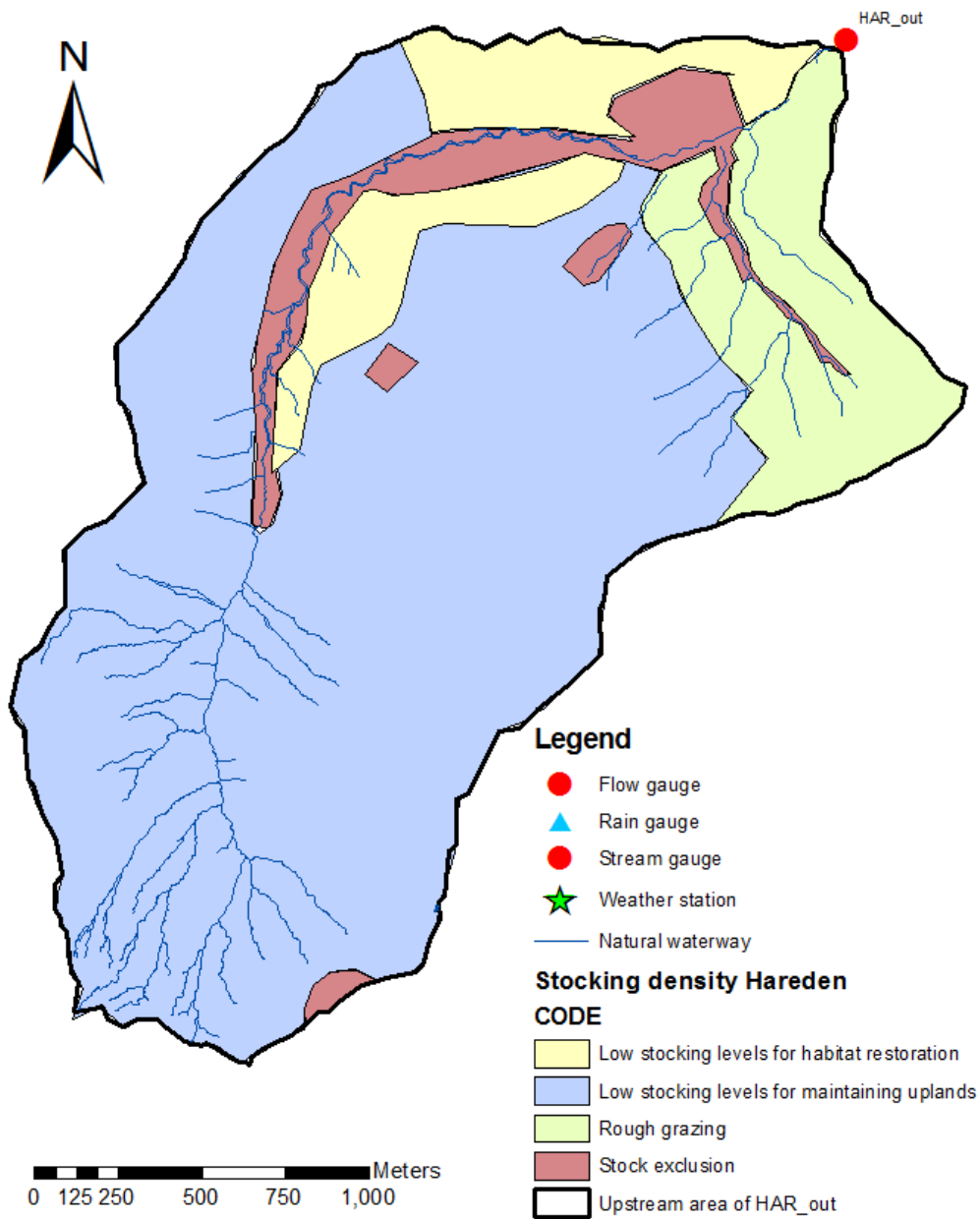


Figure 4.3 SCaMP works in Hareden catchment

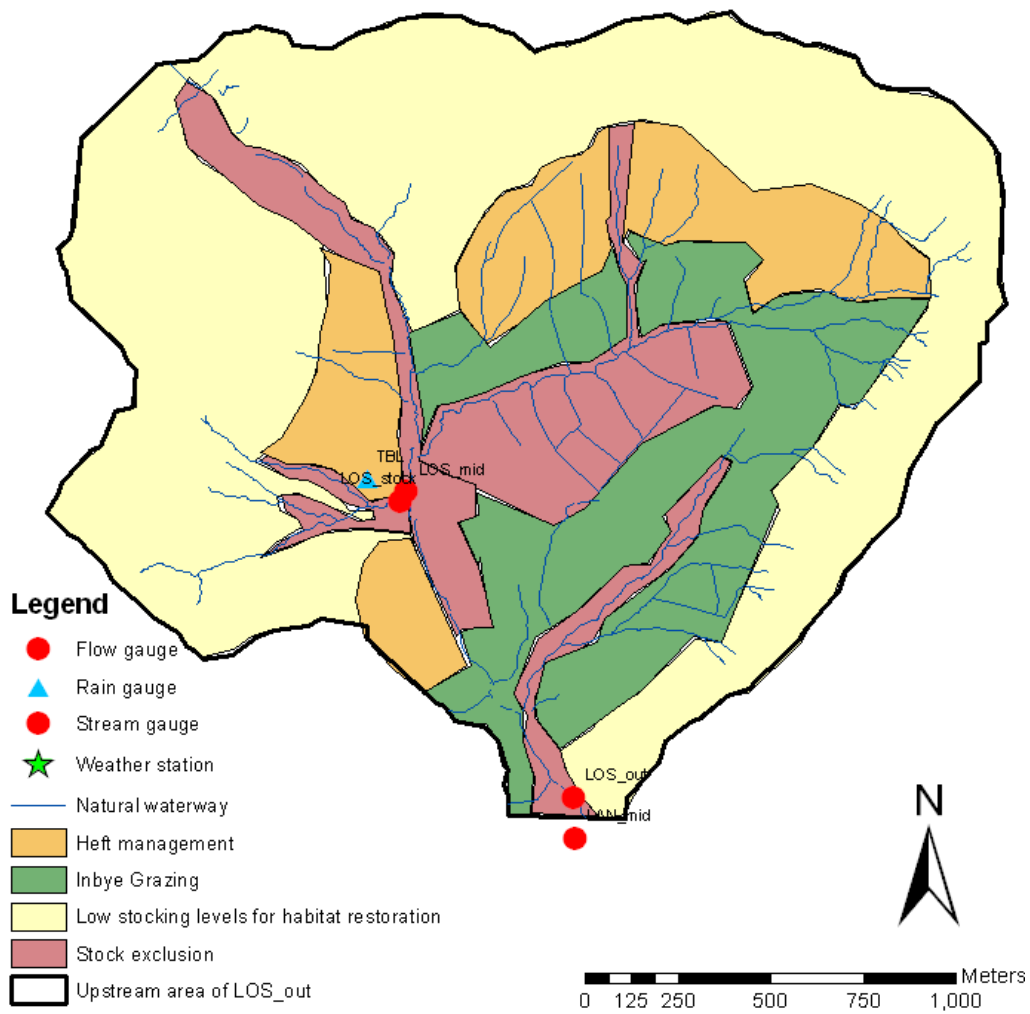


Figure 4.4 SCaMP works in Losterdale catchment

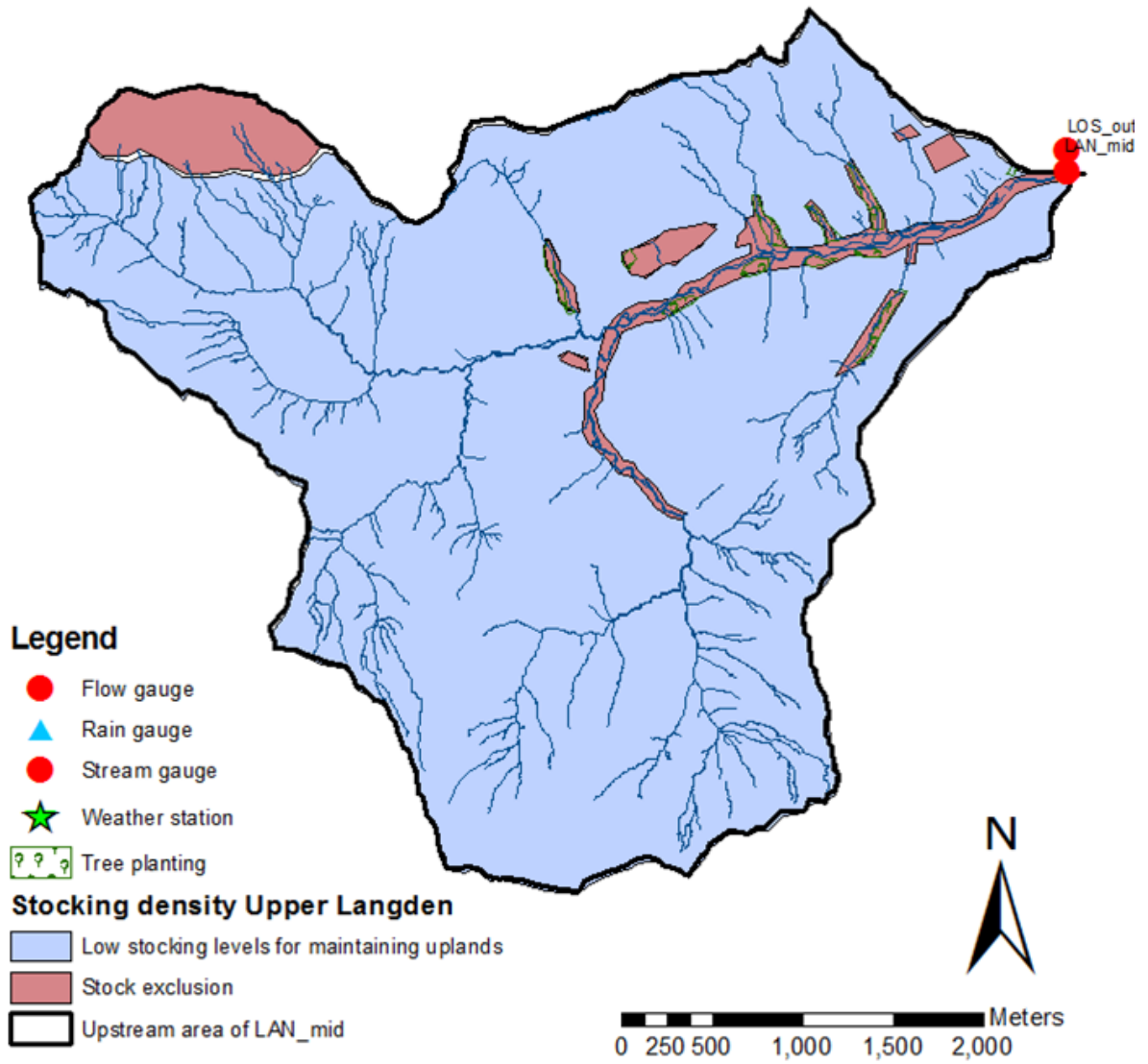


Figure 4.5 SCaMP works in Upper Langden catchment

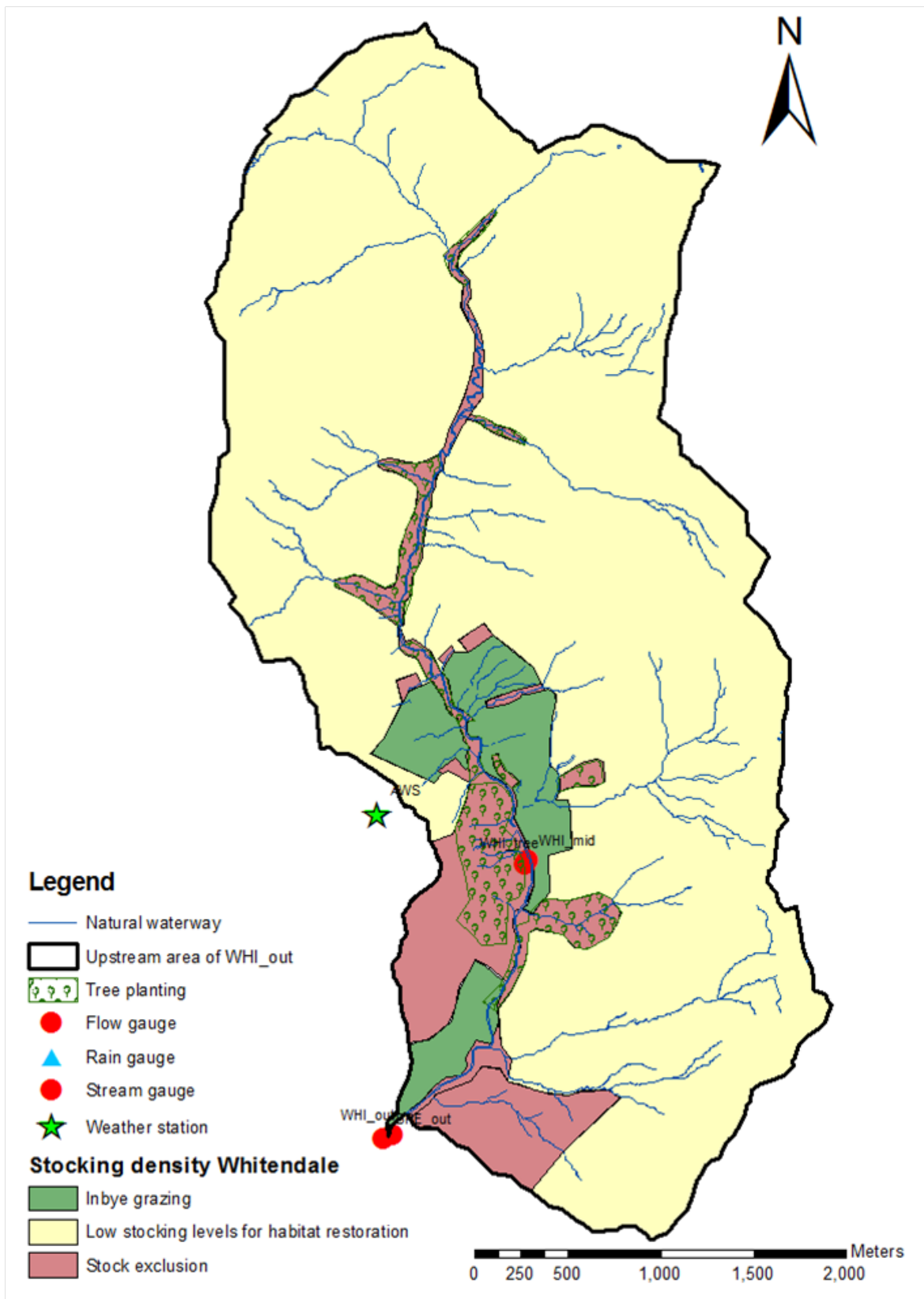


Figure 4.6 SCaMP works in Whitendale catchment

4.3 Grip blocking

The extent of the grip blocking is shown on the maps in Figures 4.1 to 4.6. Grip blocking has recently been completed in the upper Brennand catchment and for a grip system on the Swine Clough tributary in Croasdale. Grips were blocked in Whitendale in 2005 (Armstrong et al. 2006).

From field inspections, three main blocking techniques have been used (Figure 4.7). A combination of Techniques 1 and 3 is the most commonly used. This involves creating a crescent-shaped dam by scraping peat from areas adjacent to the grip, supplemented with peat bales cut from adjacent areas. Usually this is combined with Technique 2, in which the channel banks are collapsed into the grip. The spacing between blocks is approximately 10 m.

(1) Material is scraped from the area perpendicular to the channel and a peat dam is built.

(2) The channel banks are made to collapse and the peat is pushed into the channel.

(3) Peat bales are dug from intact bog in the neighbourhood and used to build a peat dam in the channel.

Figure 4.7 Grip blocking techniques

Grip blocking was implemented in Brennand during November 2008 (Figure 4.1). A total of 28.3 km of grips were blocked: 13.9 km in the Sapling Clough tributary; 11.5 km in Round Hill Water; and 2.9 km in Lee End.

The grip system in Swine Clough, Croasdale (Figure 4.8), consists of a relatively large grip (400 m long, 0.5 m deep and 0.5 m wide), running perpendicular to the contours, and a minor grip (100 m long) joining at 45° angle. The system was blocked in mid-February 2009 with material scraped from adjacent areas to form crescent shaped dams (Figure 4.9). There are 26 blocks on the main grip and seven on the minor grip. During wet periods, water collects behind the blocks and, on reaching capacity, the excess water spills onto the adjacent peat mire; the blockages are not overtopped.

At approximately 20 km per km², the density of grip blocking in the Hodder is similar to the blocking underway at other sites in the UK. However, the total length of grips blocked is relatively modest – some tens of kilometres compared with, for example, plans to block 1,000 km by 2012 in the Peatscape Project in the North Pennines.

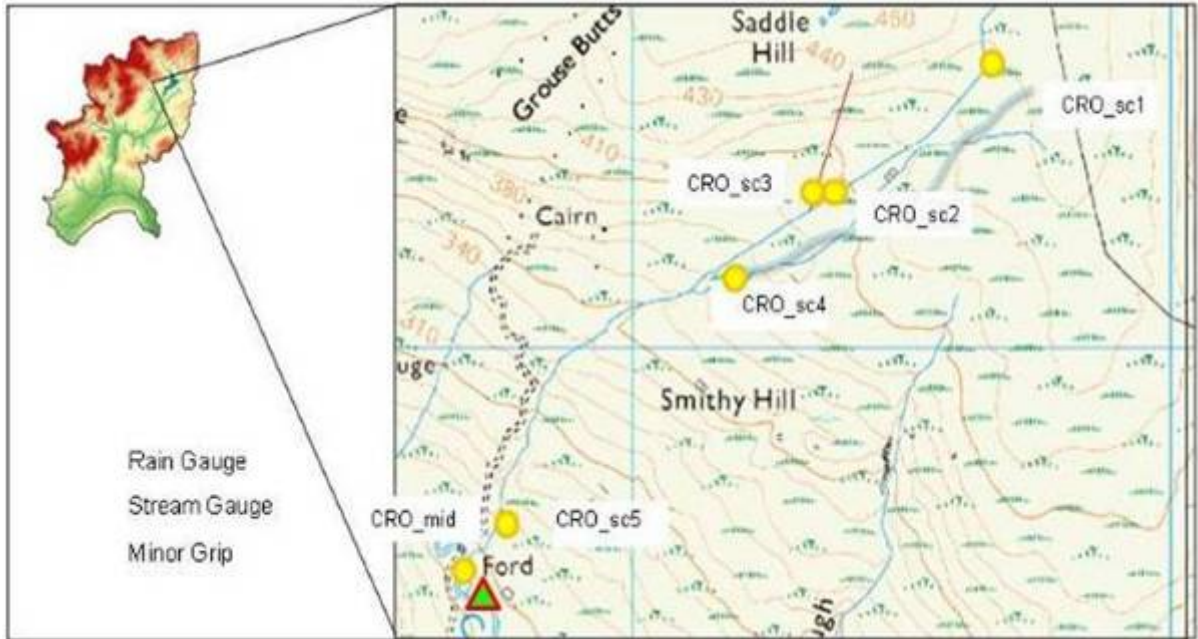


Figure 4.8 Grip system in Swine Clough, Croasdale



Figure 4.9 Croasdale grip before blocking (13 March 2008) and after blocking (5 March 2009)

4.4 Stocking density

The extent of the stocking density changes is shown on the maps in Figures 4.1 to 4.6. The impact of grazing on upland moorland vegetation is illustrated in Figure 4.10, which shows an enclosed ungrazed area surrounded by an open grazed area. The land outside the enclosure is predominantly acid grassland and has an ‘unfavourable recovering’ status. Within the enclosure, the blanket bog vegetation has recovered.



Figure 4.10 Impacts of overgrazing in Hareden catchment

Source: United Utilities’ Farm Plan

To maintain and restore SSSI land, Natural England recommends the stocking densities given in Table 4.3. Estimated stocking densities for individual farms are given in Figure 4.11.

Table 4.3 Natural England recommended sheep stocking density

Land cover (state)	Density (ewes/ha)
Blanket bog (restoration)	0.134
Blanket bog (maintenance)	0.267
Dry heath (restoration)	0.564
Dry heath (maintenance)	1.128

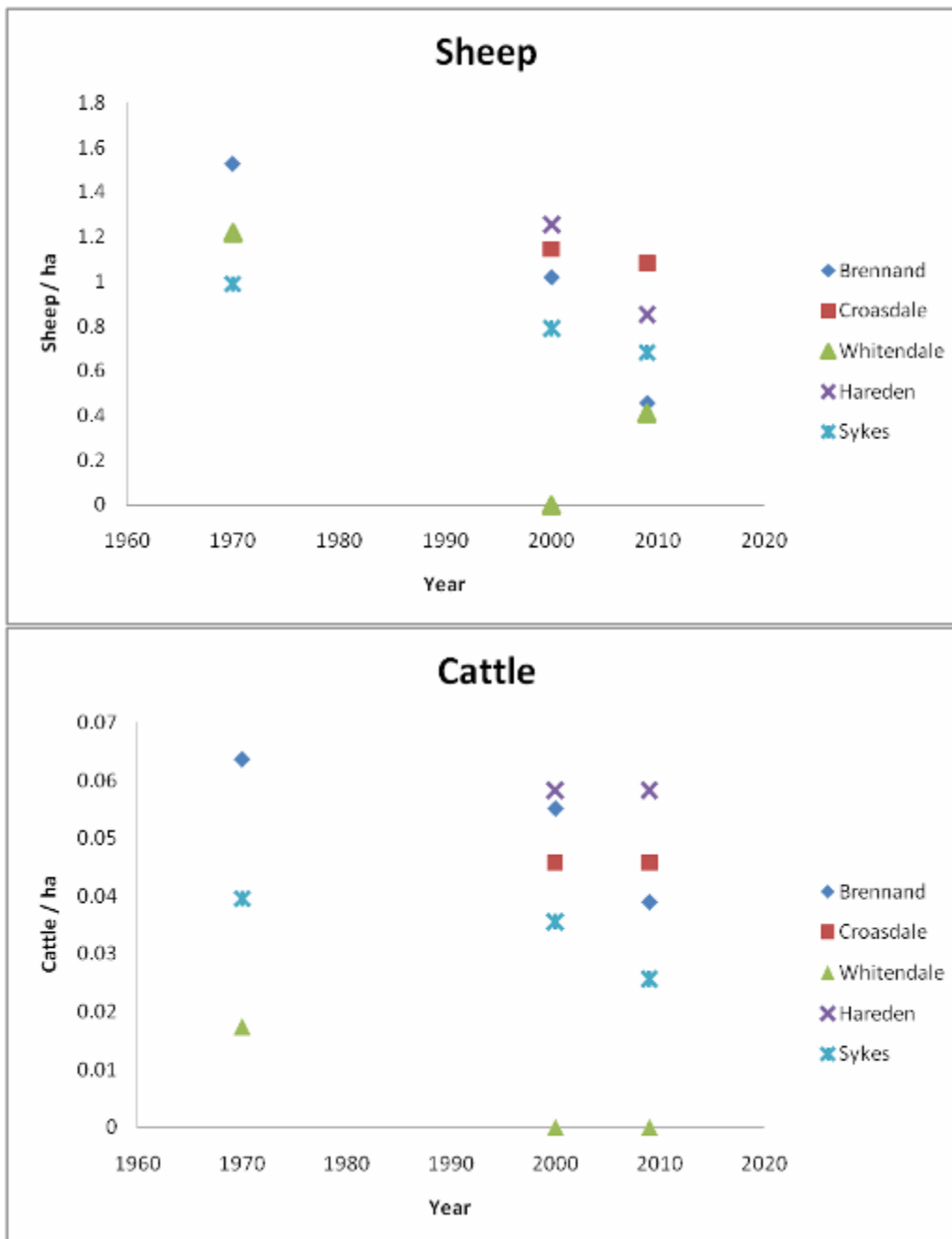


Figure 4.11 Sheep and cattle stocking densities by farm

Notes: Sykes Farm is in the Langden catchment.

Stocking was reduced in Brennand in June 2008 from approximately 1,200 ewes and 65 cattle to 535 ewes and 46 cattle. On Brennand Fell (670 ha), the Natural England recommended density has been applied, while in the areas of rough grazing in the lower catchment, the density is five ewes per hectare. Stock is being excluded from the west banks of the Brennand near to the confluence with the Whitendale.

At Croasdale Farm (982 ha), the stock has been reduced from 900 to 850 sheep. Low levels are being maintained on Croasdale Fell for habitat regeneration. Stock is excluded from three small logged patches.

Sheep stocks are being reduced from 1,400 ewes to 952 ewes on the moorland in Hareden (880 ha), in line with the Natural England recommended density. In addition, livestock have been fenced off from 7.9 km of watercourses.

In Losterdale, there has been a general reduction in stocking by approximately 15%. In the Swine Clough tributary (80 ha), the number of ewes has been reduced from 120 to 80. In addition, there is to be winter exclusion in the uplands. There has been total exclusion in the lowest part of the valley for the past seven years.

In Upper Langden, stocking densities are being kept low for maintenance of upland habitats. There is stock exclusion in the riparian zones and on some parts of the moors.

A Wildlife Enhancement Scheme agreement was put in place in 1999 for the removal of all stock from the moorland in Whitendale. This agreement did not, however, cover the in-byes and rough grazing areas, which have a combined area of approximately 100 ha. After the agreement expired in October 2004, sheep were re-introduced at low stocking densities, with approximately 370 ewes on the moor (990 ha).

4.5 Tree planting

The extent of the tree planting is shown on the maps in Figures 4.1 to 4.6. The tree planting is designed to increase slope stability and to provide bird habitat. Native species are being planted including sessile oak, hazel, alder, birch and pine. Typically, the trees are planted in the riparian corridor and on some hillslopes. The run-off from a hillslope (Figure 4.12; gauge name is WHI_tree) is being monitored in this project to observe the effects of planting. Figure 4.13 gives some idea of the density of planting.

Tree planting in the Brennand occurred along 3 km of the main riparian corridor and several major tributaries (50 ha) in June 2008.

In the Croasdale catchment, two small areas of conifer forest, approximately 0.025 km² each, were logged in early November 2008 (Figure 4.14; areas are labelled Area 1 and Area 2). There is a possibility that a scrape will be created on Area 1 (Figure 4.15) of the logged patches. Otherwise, the patch will be used for rough grazing or reseeded. The other patch (Area 2) will be replanted with broadleaf trees.

During a survey of the Hareden and Losterdale catchments, it was noted that some planting a few years previously had not yet appeared on the OS map. There has been mixed broadleaf planting in riparian zones in Losterdale and Upper Langden; the planting in Upper Langden appears to be at lower density than elsewhere. There has been similar planting in Hareden (not yet mapped).

In the Whitendale catchment, tree planting occurred in spring 2008 over an area of approximately 30 ha in the upper catchment. Additionally 3 ha of coniferous plantations may be removed to restore upland heath.



Figure 4.12 Tree planting on hillslope in Whitendale catchment



Figure 4.13 Tree planting on Middle Knoll, Whitendale

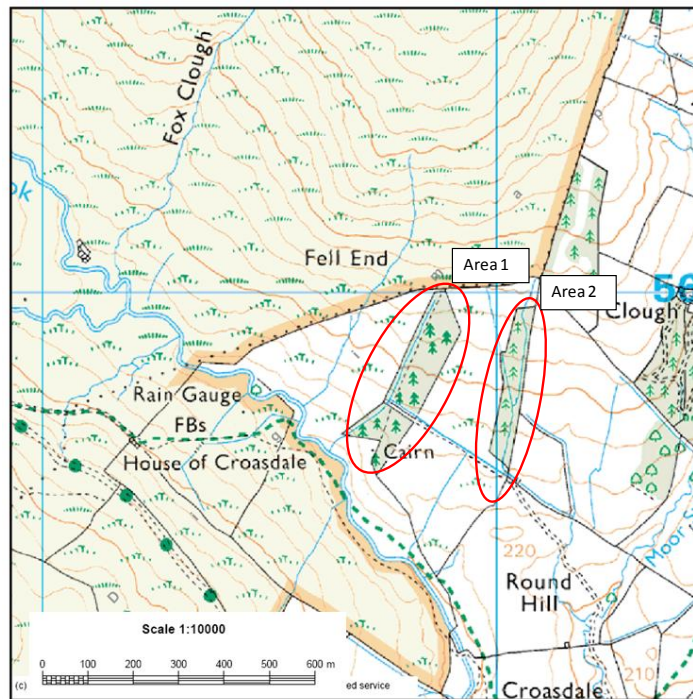


Figure 4.14 Location of two logged patches of forest in the Croasdale catchment



Figure 4.15 Logged Area 1 in the Croasdale catchment

5 Electronic Project Record

Details on how to use the Electronic Project Record (EPR) are given in Appendix B. As a reaction to years of frustration in piecing together fragmented and degraded information as a basis for driving computer models, the purpose of the EPR is to make the Hodder data readily available in a useful and useable form for future research and researchers. This approach is particularly relevant for this project, as the full impact of the SCaMP works might not be seen for many decades.

The basic rule of thumb in deciding what to include in the EPR is: if something is available or used in this project or associated FREE or FRMRC2 work, then it should go in.

Currently the EPR contains data up to the end of January 2010, in effect creating a 'time capsule' of data for future researchers. However, plans have recently been put in place to continue the monitoring to end March 2011 and to update the EPR in April 2011.

A simple quality assurance system is used to audit the procedures for collecting, checking and archiving the monitored data.

The Environment Agency will act as custodians of the EPR, ensuring the information is not lost or dispersed.

5.1 Licensing

There are no licensing restrictions with regard to the data and information collected and generated within this project. All data sets, reports, photographs and so on will be made freely available to the research community via the EPR.

5.2 Contents

The data contents of the EPR record are listed in Table 5.1. The data are organised into five high-level groupings, each of which has sub-groups. The 'Access' column in the table indicates whether the data are restricted by licence agreements. To satisfy licence restrictions for copyright material and to make the EPR open access, some entries will be hyperlinks to other sites:

- Documents > Reports (public reports, miscellaneous reports) – link to the report
- Documents > Papers (peat hydrology, Hodder hydrology) – link to hydrology document

Table 5.1 Current contents of the Electronic Project Record

High-level groups	Sub-groups	Access ¹	Description
Overview	Introduction	O	Introduction to the website and what it's about
	Description of catchment	O	Describing the Hodder Catchment area
	Land use changes	O	Details of changes to land use in the Hodder catchment area
	Key findings	O	Key findings from the research
	How to use this database	O	Instructions, with screenshots on how to use the website
SC060092 products	Data	O	Provides an interactive map of all monitoring sites installed by Newcastle University (NU). Details of individual sites (including photographs, channel surveys and time series data) can be obtained by clicking on a pin or through the table to the right of the map.
	Virtual tour	O	A virtual tour of the catchment in the form of photographs
	Data FAQ	O	Explanation of the data collected and collection instruments used
Documents	Papers	R	Links to important papers (including papers cited in the reports generated under this project)
	Reports	O	Relevant reports in the public domain
Time series data	Environment Agency rain gauges	R	Details of Environment Agency meteorological stations and time series data
	Environment Agency flow gauges	R	Details of Environment Agency flow gauges stations and time series data
	Met Office stations	O	Details of relevant Met Office stations available in the Met Office Integrated Data Archive System (MIDAS) data set held at the British Atmospheric Data Centre (http://badc.nerc.ac.uk/data/ukmo-midas/), access free for research purposes).
	Grip surveys	O	Maps of grip surveys conducted by RSPB for United Utilities and gripping blocking conducted by Dinsdale Moorland Associates
	SCaMP maps	O	Catchment maps showing types and extent of SCaMP works
	River habitat surveys	O	Environment Agency river habitat survey data, providing cross-sectional survey measurements and ecological indicators

Notes ¹ R = restricted to institutions with appropriate licences; O = open access.

6 Instrumentation for monitoring

Five types of hydrometric instruments have been installed in the Hodder catchment for the purposes of this project (Table 6.1). These instruments complement the existing instruments operated by the Environment Agency.

Table 6.1 Hydrometric instruments installed in the Hodder catchment

Type	Number, supplier and purpose
Weir	Three weirs are used to measure the discharge from small areas undergoing SCaMP works.
Stage and flow	23 Divers (Van Essen Instruments) After calibration against stage-discharge measurements, these give discharge.
Barometric pressure (baros)	Four atmospheric BaroDivers (Van Essen Instruments) These give barometric pressure, essential for calibration and use of the stage and flow data (that is, 2, above).
Rainfall	Three ARG100 aerodynamic tipping bucket rain gauges (Environmental Measurements Ltd) These are designed to minimise the effect of wind-induced undercatch by presenting a reduced side area to the wind.
Automatic weather station (AWS)	One AWS (Environmental Measurements Ltd) This measures wind speed/direction, relative humidity, temperature, net radiation and rainfall at 15-minute intervals for use in estimating potential evaporation.

6.1 Flow measurement in the Hodder catchment

The river network and the network of flow gauges in the Hodder catchment are shown in Figures 6.1 and 6.2, respectively.



Figure 6.1 Hodder river network

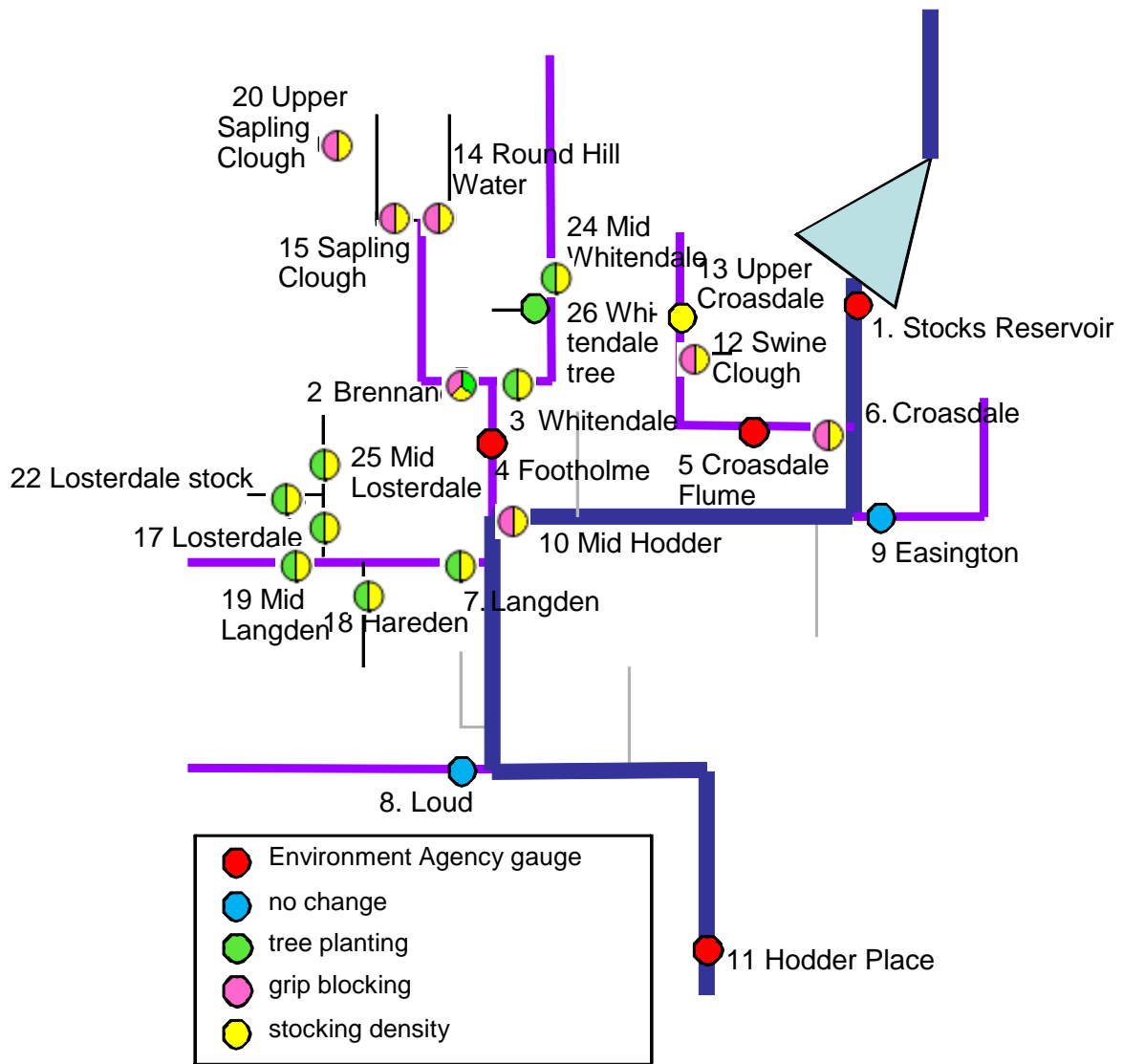


Figure 6.2 Schematic showing locations of flow gauges in the Hodder catchment

Notes: Colour coding shows the type or types of works undertaken upstream.

The overall design is for a multiscale nested network of flow measurement (Table 6.2).

Table 6.2 Definitions of scale

Scale	Definition
Mesoscale	~100 km ²
Mini-scale	~10 km ²
Micro-scale	~1 km ²
Process-scale	~0.01 km ²

The mesoscale gauge sites are at Hodder Place (location 11 in Figure 6.2) and mid-Hodder (location 10). The mini-scale gauge sites are at the outlets from the major tributaries of the Hodder.

The micro-scale gauge sites are all nested in mini-scale sites, mostly downstream of or within areas affected by SCaMP work, and the process-scale gauge sites are all nested

in micro-scale sites. Note that there is nesting up to five deep (gauges at locations 20, 15, 2, 4 and 11).

In the EPR, the gauges have reference codes. For example, the gauge at location 11 in the Hodder catchment is called HOD_out. These codes are given in the tables below.

6.1.1 Mesoscale and mini-scale flow gauges

There are a total of 13 mesoscale and mini-scale gauges in the Hodder catchment (Table 6.3). There are moderately long records for the four gauges operated by the Environment Agency (Table 6.4).

It is not practical to gauge all the numerous inflows to the Hodder, so the mesoscale gauge at mid-Hodder will help in estimating the contributions from the ungauged sub-catchments in the northern part of the catchment (approximately 40 km² in total). There are approximately a further 47 km² of ungauged sub-catchments between mid-Hodder and Hodder Place.

No mini-scale sites were selected upstream of Stocks Reservoir (location 1 in Figure 6.2) because the reservoir itself controls the impact of the SCaMP works being undertaken upstream. The Loud catchment (location 8) and Easington (location 9) lie outside the SCaMP area, but are gauged so that their contributions to the flow peaks at Hodder Place can be analysed. Easington has large areas of peat, so it has the potential to be used in comparison studies against catchments where there is grip blocking.

The gauge at Langden Works (the works are operated by United Utilities) is necessary because they affect the flows from the upper catchment.

Table 6.3 Mesoscale and mini-scale gauges in the Hodder catchment

Site			Comment	Rain gauges	Flow gauges	Area (km ²)
1	STO_out	Stocks Reservoir			1*	37.4
2	BRE_out	Brennand	Dunsop catchment: undergoing grip blocking, stocking density changes, forest planting, tree felling	1	1	11.0
3	WHI_out	Whitendale		1*	1	13.6
4	FTH_flu	Dunsop		1* daily AWS	1*	25.0
5	CRO_flu	Croasdale Flume	Grip blocking and stocking density changes	1	1*	10.0
6	CRO_out	Croasdale			1	20.1
7	LAN_out	Langden Brook	Stocking density changes and tree planting	1 1* daily	1	27.7
8	LOU_out	Loud	Outside SCaMP area – some potential as a reference subcatchment	1* 1* daily	1	47.3
9	EAS_out	Easington Brook	Outside SCaMP area – some potential as a reference subcatchment (peat)		1	13.3
10	HOD_mid	Mid-Hodder			1	110.3
11	HOD_out	Hodder	Hodder catchment outlet		1*	261

Site			Comment	Rain gauges	Flow gauges	Area (km ²)
		Place				
19	LAN_mid	Langden Works	Stocking density change and minor tree planting		1	15.0
24	WHI_mid	Mid-Whitendale	Tree planting and stocking density change		1	10.0

Notes * Operated by the Environment Agency.

Table 6.4 Environment Agency flow gauges

Station (site)	NRFA No.	Grid ref.	Period of digital record	Description	Maximum gauged level (m) / (m ³ /s)
Stocks Res. (1 STO_out)	71002	SD 719 544	1977 to present	Over flow weir	N/A
Footholme (4 FTH_flu)	71015	SD 653 529	1995 to resent	Flume	N/A
Croasdale (5 CRO_flu)	71003	SD 704 549	1982 to present	Compound trapezoidal flume	(No rating curve; stage only)
Hodder Place (11 HOD_out)	71008	SD 710 382	1976 to present	Compound crump profile weir	2.12 / 286.9

6.1.2 Micro-scale flow gauges

Details of the micro-scale gauges in the Hodder catchment are given in Table 6.5 and their locations are shown in Figure 6.3.

Table 6.5 Micro-scale flow gauges in the Hodder catchment

Site			Comment	Rain gauges	Flow gauges	Area (km ²)
12	CRO_sc5	Swine Clough	Major perennial grip blocked		1	1.0
13	CRO_mid	Upper Croasdale	Reference peat subcatchment, minor stocking density changes	1	1	3.6
14	BRE_rhw	Round Hill Water	Extensive grip blocking and stocking density changes	1	1	2.8
15	BRE_sap	Sapling Clough			1	1.7
16	*	Brennand Intake			1	6
17	LOS_out	Losterdale	Stocking density change and tree planting	1	1	4.0
18	HAR_out	Hareden Brook			1	4.9
22	LOS_stock	Upper Losterdale	Stocking density change	1	1	1.0

Site			Comment	Rain gauges	Flow gauges	Area (km ²)
25	LOS_mid	Mid- Losterdale	Stocking density change		1	2.5

Notes * Operated by Penny Anderson Associates.

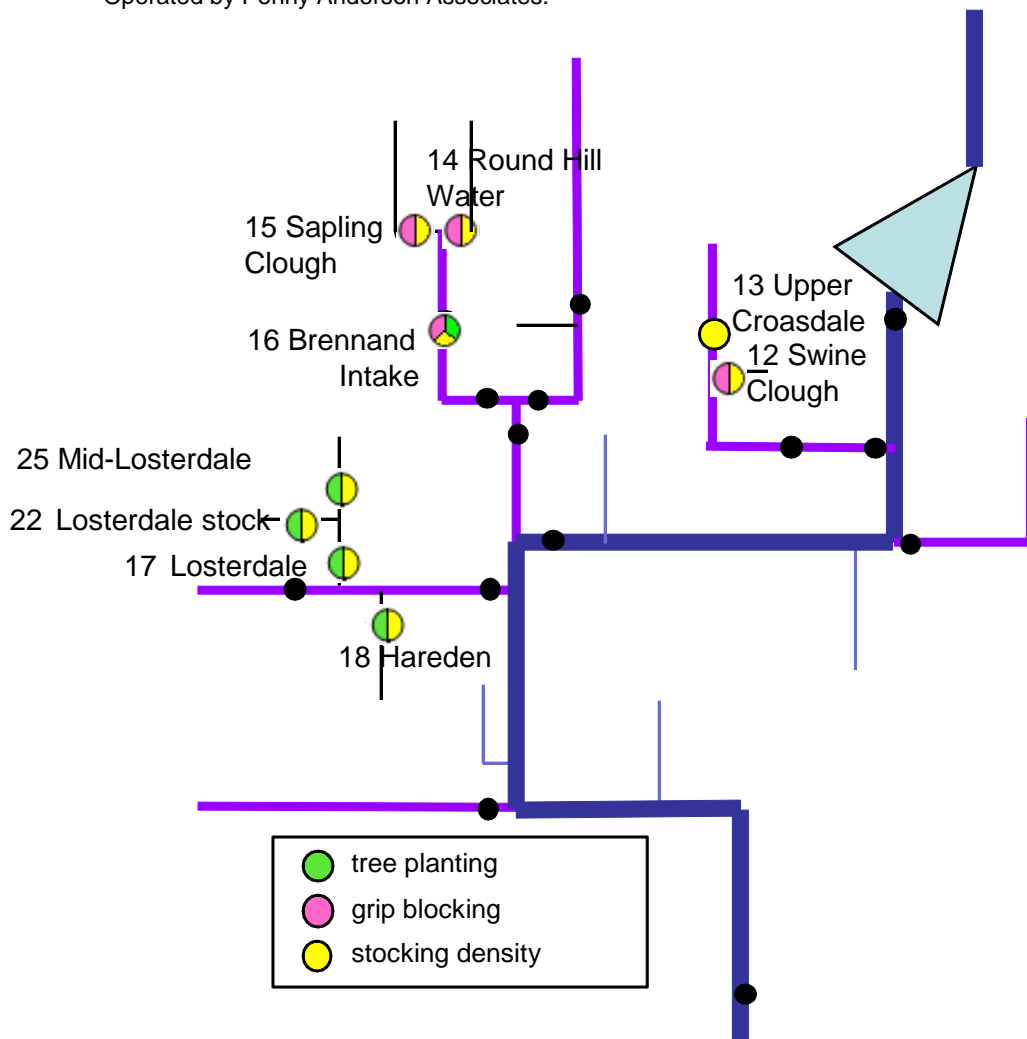


Figure 6.3 Schematic showing locations of the micro-scale gauges in the Hodder catchment

Notes: Colour coding shows the type or types of works undertaken upstream

Within the upper Brennand, Sapling Clough (location 14 in Figure 6.3) and Round Hill Water (location 15) are important sub-catchments, as they have undergone widespread grip blocking. Penny Anderson Associates also has instruments at locations 14 and 15 (not shown or listed here).

6.1.3 Process-scale flow gauges in the Hodder catchment

Details of the process-scale gauges are given in Table 6.6.

Table 6.6 Process-scale gauges in the Hodder catchment

Site		Comment	Rain gauges	Flow gauges	Weirs	Area (Km ²)
12	CRO_sc1	Swine Clough	Major perennial grip blocked	1		0.04
	CRO_sc2			1		0.35
	CRO_sc3			1		0.0005
	CRO_sc4			1		0.35
20	BRE_grip	Sapling Clough, Brennand	Grip blocking	1	1	0.0014
	BRE_grip_weir				1	0.0014
22	LOS_stock_weir	Upper Losterdale	Stocking density change	1	1	0.12
26	WHI_tree	Whitendale riparian corridor	Woodland planting	1	1	0.06
	WHI_tree_weir				1	0.06

6.1.4 Manual flow gauging in the Hodder catchment

The following river gauging equipment is being used to collect sets of stage/discharge data. These data are necessary when converting the Diver readings to discharges.

- **Acoustic Doppler current profiler:** avoids the need to enter the water, so is ideal for larger channels in floods.
- **Impeller flow meters:** suitable for micro-scale monitoring.
- **Electromagnetic velocity meter:** capable of operating in water depths of <5 cm, so is ideal for grips and flows at process-scale sites.

6.2 Rain gauges and AWS

The Environment Agency operates four high-resolution (15 minute) tipping bucket rain gauges (TBRs) in the Hodder catchment (Table 6.7 and Figure 6.4). Note that there are data for a number of daily and monthly rain gauges in the Met Office's MIDAS database.

Table 6.7 Environment Agency rain gauges in the Hodder catchment

Rain gauge	Grid reference	Catchment	Elevation (m)	Period of digital record
Footholme	SD 652 528	Dunsop	167	December 1990 to present
Chipping	SD 614 440	Loud	115	December 1990 to present
Stocks Reservoir	SD 716 547	Upper Hodder	192	January 1991 to present
Croasdale House	SD 704 550	Croasdale	183	January 1990 to September 2000

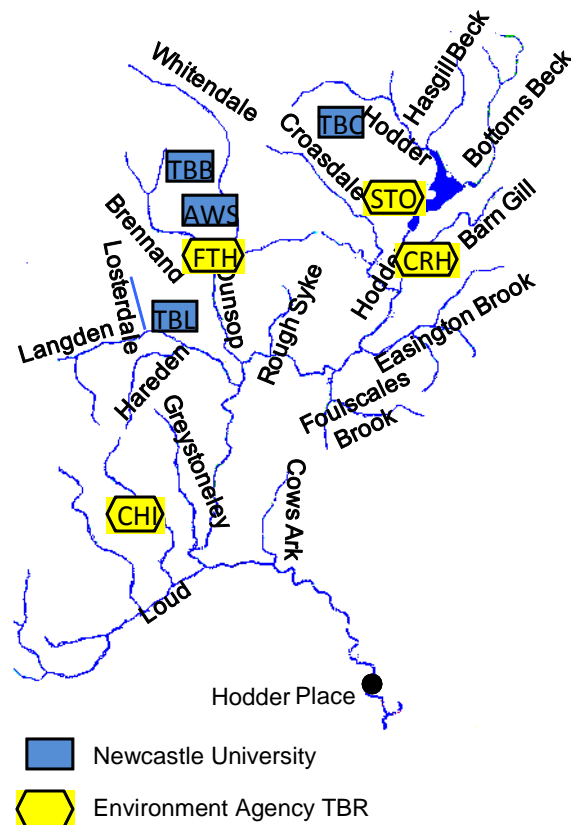


Figure 6.4 Tipping bucket rain gauges and automatic weather stations in the Hodder catchment

Notes: AWS = Brennand AWS; CHI = Chipping; CRH = Croasdale House; FTH = Footholme; STO = Stocks Res.; TBB = Upper Brennand; TBC = Croasdale Brook; TBL = Losterdale

The existing Environment Agency rain gauge network is sparse in the northern regions of the catchment, particularly at higher elevations (Figure 6.5), so TBRs were installed at:

- Croasdale (TBC), near to micro-scale location 12 (Swine Clough)
- Round Hill Water in the Brennand (TBB), close to process-scale location 20
- micro-scale location 17 (Losterdale; TBL)

In addition, an AWS was installed at Middle Knoll at the catchment boundary of the Brennand and Whitendale catchments. This AWS measures rainfall, so it is part of the rain gauge network. It gives the necessary meteorological data (at 15-minute intervals) for calculating the evaporation rate in the upland areas.

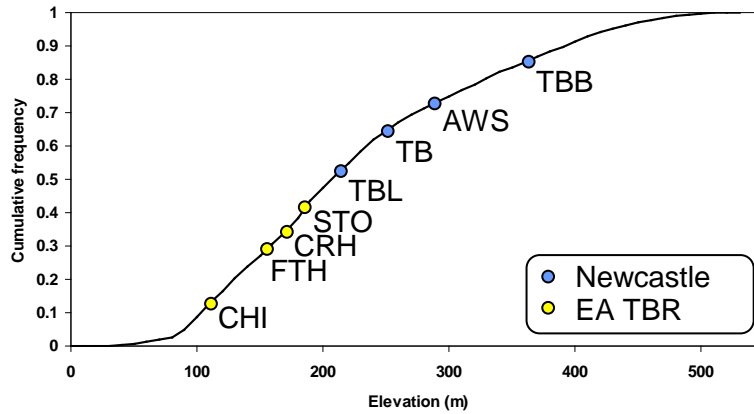


Figure 6.5 Hypsometric curve showing the elevations of the rain gauges

Notes: AWS = Brennand AWS; CHI = Chipping; CRH = Croasdale House; FTH = Footholme; STO = Stocks Res.; TBB = Upper Brennand; TBC = Croasdale Brook; TBL = Losterdale

MORECS (Meteorological Office Rainfall and Evapotranspiration Calculation System) data were obtained from the Met Office to give estimates of evaporation to be used when establishing the baseline (pre-SCaMP) behaviour. The MORECS data include actual and potential evaporation rates for a number of reference crops (Hough and Jones 1997).

7 Scope for analysis

As explained in Section 1, this work is about the effect that changes in rural land use/management in the headwaters of the River Hodder catchment can have on flooding downstream, for example, at Hodder Place (261 km²). The ultimate aim is to estimate the effect that the SCaMP works will have on the Flood Frequency Curve at Hodder Place.

This project is concerned mainly with the instrumentation of the catchment to enable an analysis of the impact of the SCaMP works, but includes some preliminary work on the analysis of the collected data. The main elements of the analysis, including the modelling of impact, is being carried out in the FREE and FRMRC2 projects. To give an overall picture, however, and so that the Hodder data set can be seen in its full context, some results from the FREE project are used in the following sections.

The FFC in the extreme value plot in Figure 7.1 shows the T-year return period flood, Q_T , derived using the method prescribed in Volume 3 of the *Flood Estimation Handbook* (Robson and Reed 1999). The curve shows the product of the index flood, Q_{index} , and the T-year growth factor, x_T , and was derived using the (at-site) annual maximum flood data for 1970 to 2008. Following the recommendations in the *Flood Estimation Handbook*, the index flood was taken to be the median annual flood (225.6 m³/s; the median for the set of 39 annual values) and the growth curve [that is, $x(T)$] was derived using L-moments, assuming a generalised logistic distribution.

Any analysis must rely on estimated FFCs (that is, estimated using a set of observations or simulations), based on the assumption that there is some underlying true population FFC. Estimated FFCs are simply fits to observations or simulations, which can be used as a guide to likely future behaviour (arguably, the concept of a true population FFC does not make physical sense). By definition, the return period for, say, a 500 m³/s flood is the (likely) average interval between occurrences of floods that exceed 500 m³/s. For the Hodder at Hodder Place, this is of the order of 100 years, based on the fitted distribution.

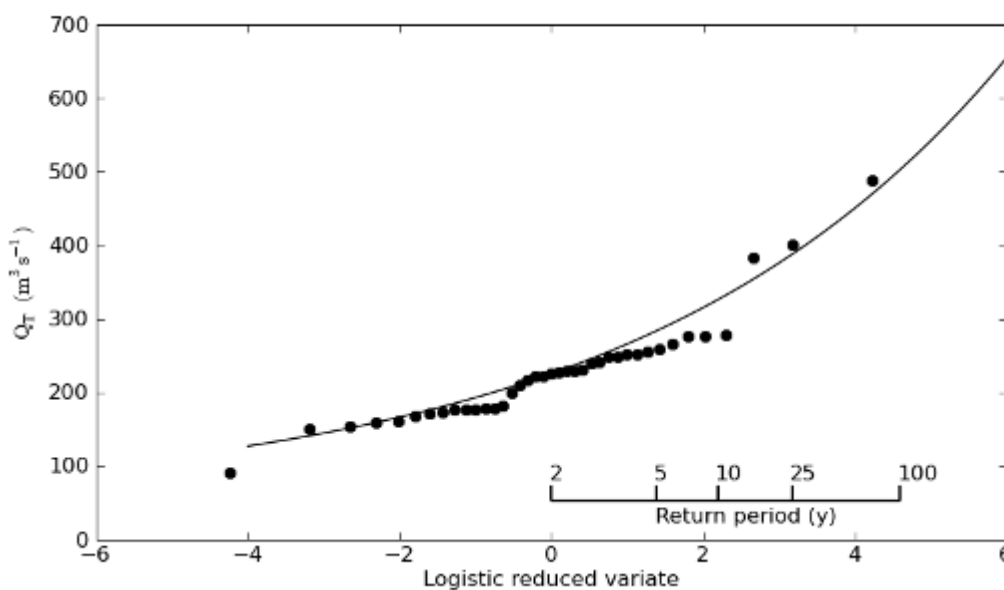


Figure 7.1 Extreme value plot for Hodder at Hodder Place (1970 to 2008), with logistic distribution fitted using L-moments

Perhaps the ideal question is: if SCaMP has an impact over the next 100 years, how strongly, and at what return periods, would this impact show up in the FFC calculated by an engineer looking at this problem in 100 years' time. This impact could be shown in a plot of the change in Q_T against the return period, T (for example, showing the percentage change in Q_T as a function of T).

A far less ambitious question is considered below: what would the impact plot look like if the SCaMP works had caused an impact on the annual maximum flood in 2008?

These questions raise an important general question: are the Hodder data collected in this project useful in estimating the impact that the SCaMP works have on the FFC? The SCaMP works are being carried out in subcatchments of the Hodder, so there is also the underlying question of how impacts at small spatial scales propagate downstream and result in impacts at larger scales.

Figure 7.2 shows the extreme value plot and fitted logistic distribution for the Dunsop (25 km²). Although only 13 annual maximum flood values are available for the Dunsop, they are analysed here to gain insight into how the estimated FFC propagates from the Dunsop at Footholme to the Hodder at Hodder Place.

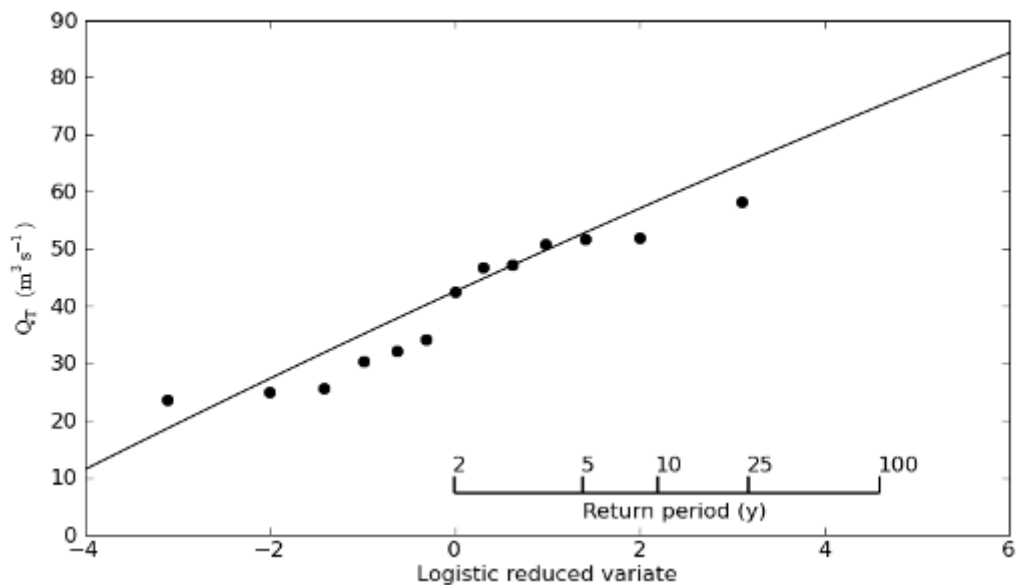


Figure 7.2 Extreme value plot for Dunsop at Footholme (1996 to 2008), with logistic distribution fitted using L-moments

Using the fitted FFC in the extreme value plots, it is possible to read off the return period for observed events. For example, the 21 January 2008 flood has a return period of 1.4 years at Footholme (30.3 m³/s) and 11 years at Hodder Place (279 m³/s).

With the following simple thought experiment, it is possible to:

- explore the link between SCaMP works made in a subcatchment and the impact on the FFC at Hodder Place
- create impact plots

Suppose that the SCaMP works had caused the annual maximum flood at Footholme on 21 January 2008 to be 10% higher than the observed value, and for simplicity, that the increase in flow propagated downstream directly to Hodder Place without decay.

Because the FFCs used in analysis are estimated FFCs (estimated from peak data), any impacts on peaks will cause impacts on the estimated return period floods, Q_T .

Built in to this thought experiment, therefore, is the conclusion that an impact on a flood at Footholme that has a return period of only 1.4 years can cause an impact at much higher return periods at Hodder Place.

The resulting impact plots (Figure 7.3), however, are quite difficult to interpret because they show the combined effect of the sensitivity to the 21 January 2008 flood and large artefacts from the statistical fitting process (the artefacts are large because the data sample is very small). Note that there is no impact at a return period of two years because the 10% rise does not affect the median annual flood (which has a return period of two years).

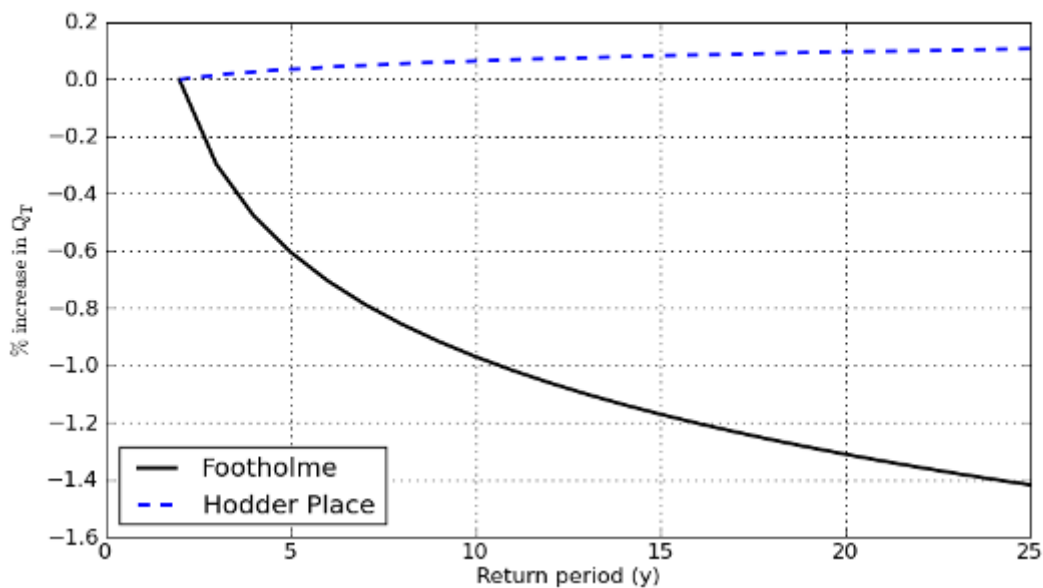


Figure 7.3 Impact on T-year return period flood

Notes: The result is dominated by artefacts from the statistical fitting process, because the data sample is very small.

What all this raises is the question of how many data are needed when estimating impacts on FFCs.

The *Flood Estimation Handbook* recommends that at least $2T$ years of annual maximum flood data should be used when estimating the T -year flood. In theory then, an estimate of the impact on the T -year flood needs at least $4T$ years of data ($2T$ pre-change and $2T$ post-change). This needs to be considered in the context of the timescales of the data available for the Hodder.

Figure 7.4 is the space–time diagram for the flow data for the Hodder. Each horizontal line (gauge line) represents a different flow gauge, showing its timescale. A gauge line running from, say, five minutes to one year has data that represent the response on a scale from five minutes to one year. The broken red line in Figure 7.4 marks the maximum suitable resolution for data used to detect peaks in flow (for example, appropriate values for storm peaks could not be extracted from a set of monthly data, so the red line lies well below a timescale of one month). Also shown in Figure 7.4 are links (broken green lines) between the Footholme and Hodder gauge lines. One of these broken green lines is for the 2008 flood described earlier, and the other is for a contrasting flood where the event return period at Hodder Place is greater than that at Footholme (5 May 1997; 3.7 years at Hodder Place and 2.2 years at Footholme). Most of the gauge lines are very short and those that are long have only short sections (approximately one year) that are post-change.

Return periods are measures of frequency, so as the definition of a flood is constrained or conditioned, the conditional return period increases. For example, the results above show that the return period is 11 years for an event with peak $>279 \text{ m}^3/\text{s}$ at Hodder Place (no constraint being placed on the flow at Footholme). If the definition is now constrained to an event with, say, $>279 \text{ m}^3/\text{s}$ at Hodder Place and $<40 \text{ m}^3/\text{s}$ at Footholme, then the return period at Hodder place conditional on the Footholme constraint must be >11 years.

This raises questions about the rarity of the events where the SCaMP works will have an impact on the FFC, because any sampling procedure for measuring or predicting the FFC must take into account the rarity of the events that contribute to the impact. For this reason, 4T is probably an underestimate for the required sampling time. This problem is exacerbated because impact is calculated as the difference between large numbers (that is, difference between Q_T pre-change and post-change) and small differences between large numbers are inherently difficult to estimate accurately.

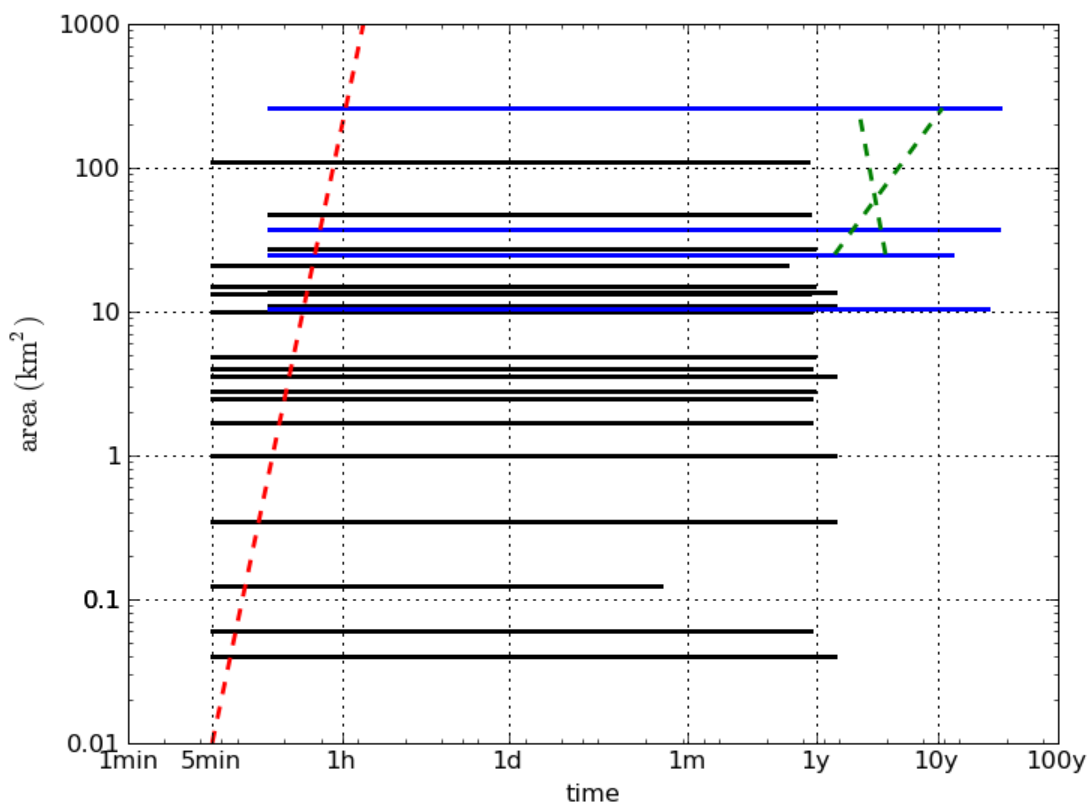


Figure 7.4 Space-time diagram for Hodder flow data

- Notes:
- Black = new flow gauges
 - Blue = existing Environment Agency gauges
 - Red = upper limit for detecting peaks
 - Green = trajectories for two floods linking Footholme and Hodder Place

The SCaMP works themselves will also have scales, and one aspect of this is the timescale for the physical effects of the SCaMP works to be established, mature and decay. Grip blocking, for example, has the potential to have an immediate effect on surface storage and flow (as soon as a block is installed it can dam the flow). However, it may have slower developing secondary effects that take some time to develop such as effects on vegetation and the hydraulic properties of peat that control infiltration and surface flow.

Based on the discussion above, the conclusions are as follows.

- Although the Hodder data can be used to analyse the short-term early effects of the SCaMP works on the hydrographs at various spatial scales, they cannot be used directly to estimate the impact on the FFC at Hodder Place.
- Further work is needed on the space–time analysis of the propagation of peaks to better understand the data needs for estimating the impact on FFCs.

The analysis described in this report therefore concentrates on short-term early effects, tackling the fundamental problem of detecting impacts at a range of spatial scales by looking in detail at the observed hydrographs. This analysis will be continued in the PhD work. To give some context for this analysis, some aspects of storm variability are discussed below, including storm seasonality and the hydrological state of the catchment (Sections 7.1–7.3).

In the FREE and FRMRC2 projects, the approach being taken is to build a distributed model that can use the Hodder data and can be run with very long time series of synthetic rainfall and evaporation data to create synthetic FFCs and estimate impacts. The distributed model will use metamodels developed by Professor Wheeler’s team at Imperial College, and hydraulic network modelling and information tracking models developed at Newcastle University. In effect, this ‘bottom–up’ approach allows scaling up from the available data to the FFC and impact estimates, while filling all the gaps in knowledge with models that are transparent and testable (testable, that is, once sufficient data are available). The analysis here on detecting short-term early impacts will contribute to this bottom–up approach, complementing the work by Imperial College on representing small-scale impacts using metamodels calibrated against small-scale field data collected at several catchments, including the Hodder. The metamodels are currently under development at Imperial College, and so are not used here or discussed further in this report.

Another reason for performing the short-term early analysis is to use the data. Both to test and evaluate it, and to see if there are any problems, especially problems that can be eliminated while the instruments are still in place and the catchment is still being visited regularly.

The fact that the records are short clearly limits the analysis in that the data set contains only a small sample of the possible pre-change and post-change behaviours that have been (or may be) seen in the catchment.

In an early stage of this work, the Dunsop was modelled using the physically based distributed model SHETRAN (Ewen et al. 2000) and a prototype of the FREE/FRMRC2 distributed model. This has been superseded and so is not reported here.

7.1 Seasonality and weather

The radial plots in Figure 7.5 shows the seasonality of the annual maximum and peak over threshold (POT) floods (threshold 145.45 m³/s) for the Hodder for 1969 to 2008. December is historically the wettest month and most of the largest floods are caused by winter frontal storms.

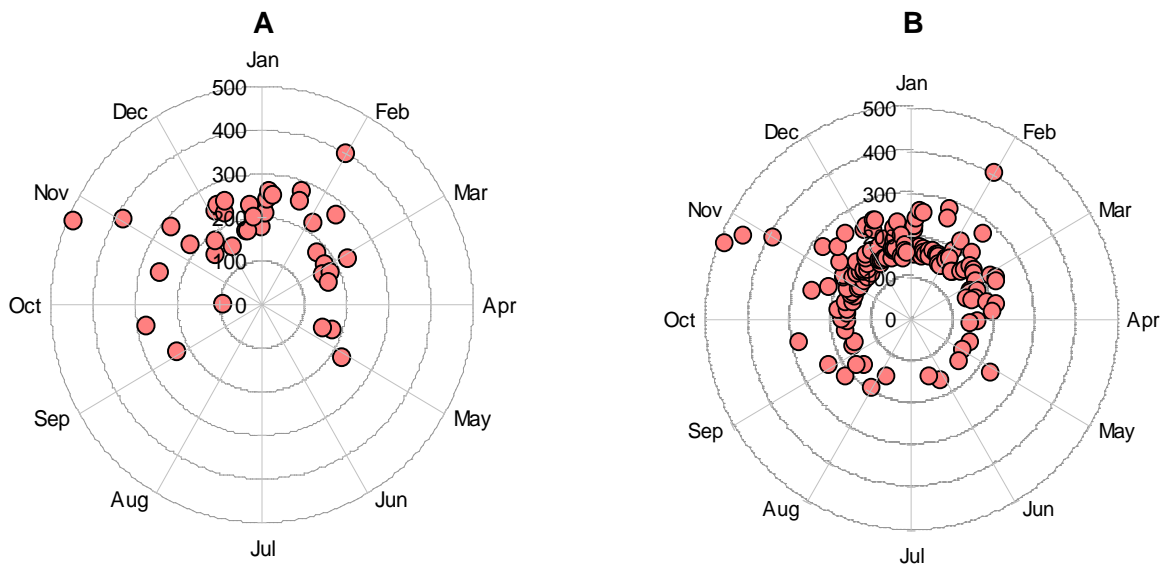


Figure 7.5 Seasonality of flooding for Hodder Place: (A) annual maximum and (B) POT.

Notes: Radial scale in m^3/s

The *Flood Estimation Handbook* gives some results for the Hodder for flood events of varying return periods in the late 1960s and the first half of the 1970s (Table 7.1). The lag time is the elapsed time between the centroid of the storm rainfall hyetograph and the run-off peak, and ranges only from 2.3 to 7.6 hours; the storm responses are therefore quite 'flashy'.

Table 7.1 Flood event analyses for the Hodder

Date	Catchment average rainfall (mm)	Event duration (hours)	Peak flow (m^3/s)	Lag (hours)	Run-off (%)
20 December 1969	32.0	40	97.26	4.3	70.9
17 January 1970	14.7	18	58.12	7.3	45.9
22 April 1970	54.5	31	176.45	5.9	64.9
25 January 1972	28.2	31	88.37	2.3	37.5
28 April 1972	33.4	32	37.83	4.2	14.4
26 January 1973	27.2	12	162.65	4.0	52.3
1 October 1974	20.5	11	71.25	5.9	29.1
30 April 1975	30.1	23	54.92	7.6	25.9
14 November 1975	24.3	34	56.98	5.6	32.3
30 November 1975	64.7	36	125.46	4.3	45.9

Notes Source: Houghton-Carr (1999, p. 228)

Other notable events in the Hodder between 1969 and 2008 show that the three lowest annual maximum floods followed droughts in the catchment:

- 29 September 1996 (90 m³/s): below average rainfall was recorded in north-west England in 17 of the 18 months between April 1995 and September 1996, and hosepipe bans were in place in Lancashire (Walker and Smithers 1998).
- 2 December 1992 (150 m³/s): followed exceptionally low winter UK rainfall in 1991 to 1992 (Marsh et al. 2007).
- 22 April 1977 (154 m³/s): followed the major drought of 1976 (Marsh et al. 2007).

(Stocks Reservoir was probably low at these times: in 1996 there were no releases during the year. There was a release rate of 24 m³/s recorded around the time of the 1992 peak, and for the 1977 peak, there was a minor release rate of 2.5 m³/s.)

Three of the annual maximum floods on the Hodder between 1969 and 2008 exceeded 300 m³/s:

- 23 October 1980 (488 m³/s): coincided with major flooding throughout the north-west of England.
- 31 January 1995 (401 m³/s): associated with widespread flooding in Lancashire in January following an exceptionally wet winter (Walker and Smithers 1998).
- 31 October 2000 (382 m³/s): September – November saw the wettest Autumn on record in England, Wales and Northern Ireland since records began in 1766. Lancashire had

(There was no release from Stocks Reservoir for the 1980 peak; the value for the 1995 peak was 62 m³/s. No data were obtained for the 2000 peak.)

In the 1980 flood, the Hodder flow peaked first at 488 m³/s and then at 450 m³/s (Figure 7.6).

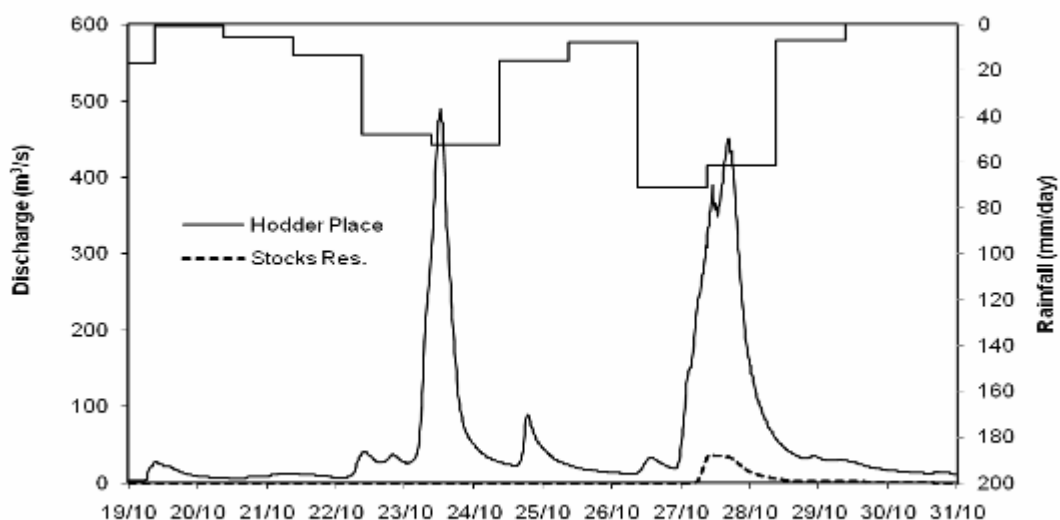


Figure 7.6 Hodder floods, October 1980

In 2000, the autumn total rainfall for the UK was 251 mm greater than the long-term seasonal average (335 mm), making it the wettest since records began in 1766. In October of that year, an average of 188 mm of rain was recorded in England and

Wales, and the monthly return period for October rainfall in the Hodder catchment was around 200 years (Met Office 2001). A deep depression became anchored near south-west Iceland in late October, resulting in the development of a cold front that trailed far down into the north Atlantic. Three very active depressions formed from waves on the cold front, tracking across the UK on successive days – 28, 29 and 30 October (Met Office 2001). The effects of all three active depressions can be seen in the rainfall and flow data in Figure 7.7; the largest flow was on 30 October 2000.

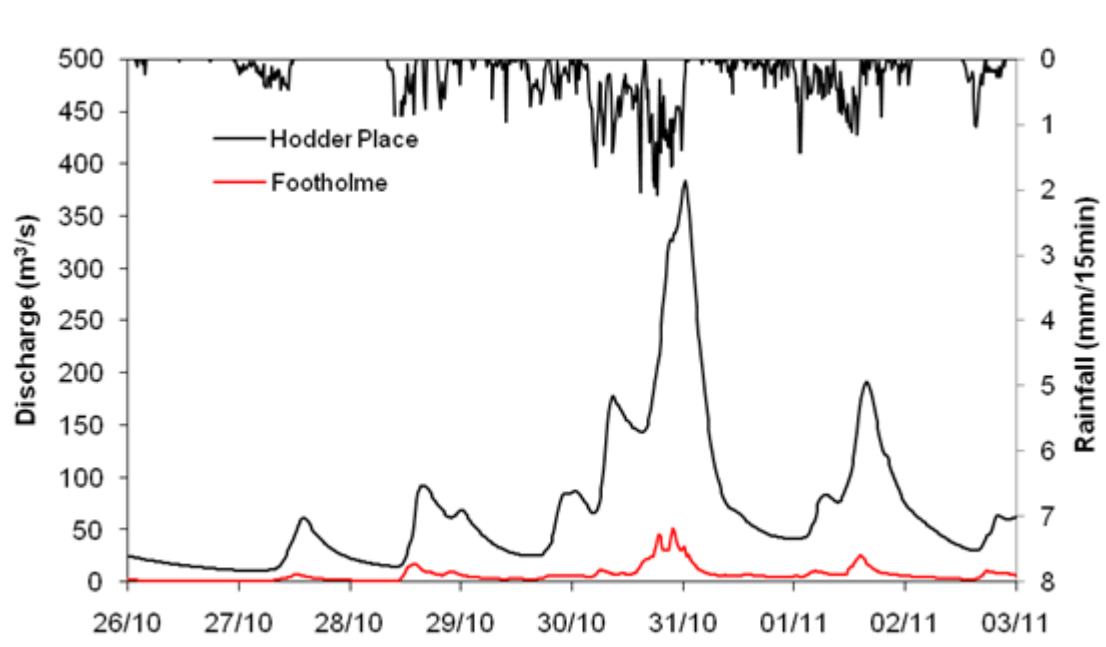


Figure 7.7 Hodder floods, October 2000

7.2 Dispersion

It is instructive to re-plot part of Figure 7.7 as depth-equivalent discharge per unit time (Figure 7.8). From the plot it can be seen that the hydrograph for the Hodder (261 km²) is smoother than the hydrograph for the Dunsop (25 km²), which in turn is smoother than the rainfall hyetograph (spatial scale <1 m²).

Viewed from a general perspective, the degree of ‘smoothness’ in a hydrograph depends on:

- the spatial and temporal variability in run-off generation
- the spatial and temporal aggregation and averaging that affect run-off generation and flow routing

Macroscopically, it is as if the smoothness of the hydrograph is controlled by a dispersion process. Such a process is, for example, implicitly recognised in the concept of geomorphological dispersion (Rodriguez-Iturbe and Valdes 1979).

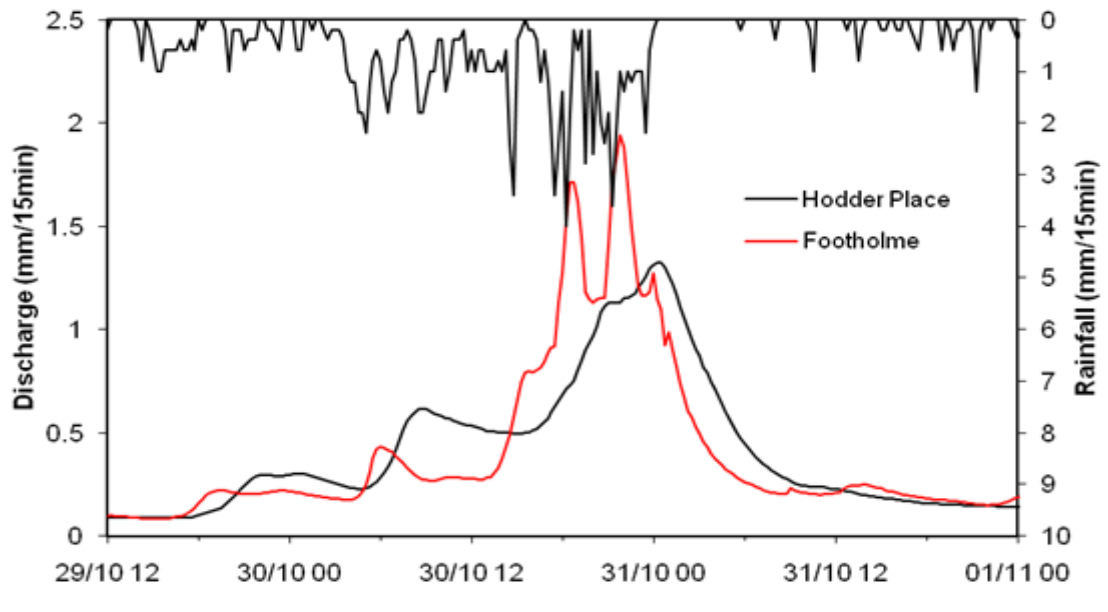


Figure 7.8 Hodder flood, October 2000 (re-plot of Figure)

7.3 Hydrological state

The hydrological state (for example, wetness) of a catchment can be different at different spatial scales, so the actual state at the large scale needs to have no time correlation to the actual state at the small scale.

One way to study the relative hydrological states of the Hodder and Dunsop, eliminating the complication that they have different areas, is to work with ranked flows. A ranking was created for the hourly discharge at Hodder Place for the period 2004 to 2007 inclusive (high rank equates to high flow).

Travel time must somehow be allowed for before creating a corresponding ranking for Footholme. Each value in the Footholme hourly discharge record was therefore first replaced by the maximum discharge seen in the previous five hours. This window of five hours was chosen to be consistent with the expected travel time for a flood wave to propagate from Footholme to Hodder Place (typically at speeds of somewhere between 1 and 3 m/s). There are a total of 35,065 values in the Hodder and Footholme records. The correspondence between rank and flow is shown in Figure 7.9.

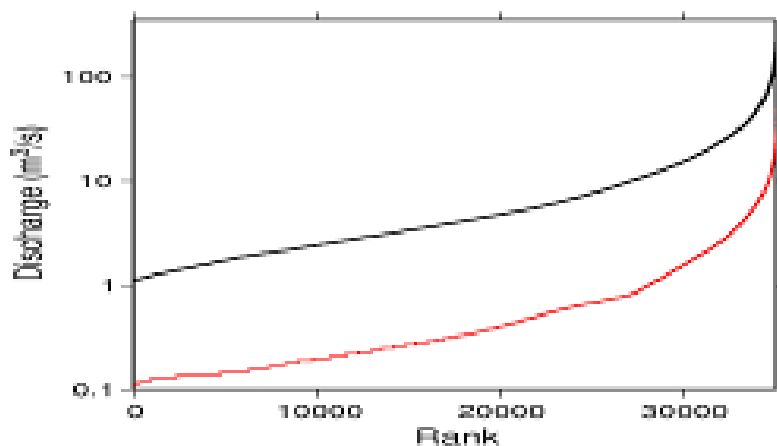


Figure 7.9 Correspondence between rank and flow for Footholme (red) and Hodder (black)

The scatter plot in Figure 7.10 shows the relative ranking for each of the 35,065 hours in the record. This plot has a colour coding indicating the month of the year. Most of the low flows are summer flows (bottom left-hand corner) and most of the high flows are winter flows (top right-hand corner).

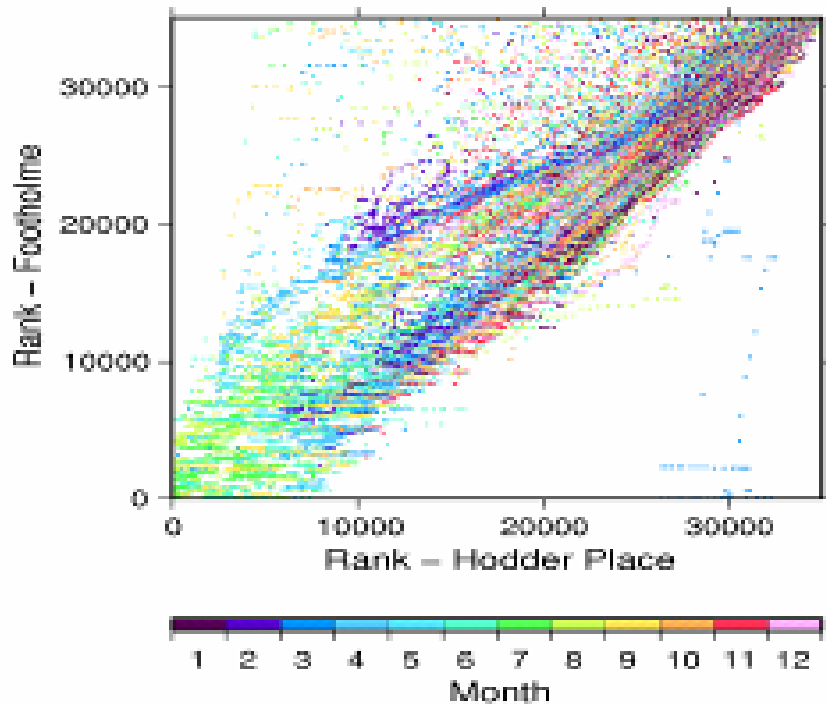


Figure 7.10 Hourly ranks for flows at Hodder Place and Footholme

Notes: High rank equates to high flow

Had the correspondence between the hydrological states been straightforward, the points would have lain on the straight line that has a unit slope and passes through the origin. Some scatter about the line is to be expected given the origin of the data. More points fall well above the unit slope line than fall well below, so there is asymmetry. This is because the Dunsop contributes only a part of the total flow at Hodder Place, and the fraction it contributes depends among other things on the space–time pattern of rainfall and the spatial pattern of antecedent wetness.

The interesting points are those that fall below the line, which correspond to times when the Dunsop is (in loose terms) less ‘active’ than the Hodder (‘drier’ might be a better word to use here, but it has its own problems). The reason why these points are interesting is that changes in land use/management can affect the ‘activity’ of the Dunsop, and the change in activity may be far more substantial at low activity than at high activity. The information in the scatter plot could be used in creating statistical distributions that summarise the likely relative hydrological states of the Dunsop and Hodder during floods.

8 Method of analysis

The detailed review in Project FD2114 (O'Connell et al. 2005) showed that traditional modelling and analysis methods are not adequate to estimate the impact of upstream small-scale changes in land use/management on large-scale flooding downstream. There is a further difficulty here in that the Hodder data set is short and the characteristics of some aspects such as rating curves for river cross-sections are not yet fully established, though work is well underway as described in Sections 9 and 10. It would be simple to use traditional modelling and analysis methods (and no doubt the results would appear to be good and useful), but in light of the conclusions from Project FD2114, an attempt is being made in the FREE and FRMRC2 programmes to develop and test new models and methods.

An important aspect of the method is that it involves iteration between different models and spatial scales:

lumped \Leftrightarrow distributed modelling

small-scale \Leftrightarrow large-scale

The aim is to reconcile the way the Hodder data are represented and used in the different models, and at the different scales, to make it possible to track the downstream propagation of information through the catchment (including information on impacts).

Transparent links must be maintained between the models and scales, so it is important to limit the use of calibration; for example, because the physical accuracy and appropriateness gained in using small-scale information to parameterise a distributed model can be partly or completely lost if the distributed model is then calibrated against, say, a hydrograph observed at a large scale.

As shown later, the lumped model (SDD; run once for each flow gauge) consists of a single bucket and the distributed model (DNRM) is a physically based hydraulic model and runs for the Hodder catchment on a 500 metre grid. The main steps in the iteration process are listed below.

1. Make assumptions about the rating curves. (Rating exercises will continue over the next year, gradually reducing the importance of this step.)
2. Calibrate SDD against the flow recessions observed at the gauges.
3. Run SDD and **detect short-term impacts** of SCaMP by comparing the pre-and post-change SDD simulations.
4. Use SDD results to parameterise the run-off from the 500 metre cells in DNRM.
5. Test (but not calibrate) DNRM against independent data at large scales (for example, the observed discharges at Environment Agency gauges at Footholme and Hodder Place).
6. Use the adjoint version of DNRM to **create maps of sensitivity** to changes in run-off, as a basis for developing maps of vulnerability to change in land use/management.
7. Automatically derive (physically based) rating curves from DNRM.
8. Use DNRM, with synthetic rainfall data, to **assess the potential for long-term impacts** from the SCaMP works.

9. Use the DNRM rating curves from step 7 to revise the assumptions made in step 1.
10. Go back to step 1 with the aim of further testing and reconciling how the Hodder data are represented and used in SDD and DNRM.

This method may appear messy, but detecting and predicting impacts are messy problems. Note that the main outcomes are underlined in steps 3, 6 and 8, and there is independent testing in step 5.

One obvious question is: what are the consequences of having to make assumptions? Consider, for example, the consequences of step 1 on step 3. Step 3 requires a test of consistency of simulation pre- and post-change rather than a test of simulation accuracy pre-and post-change, and any sensible consistency test will be largely insensitive to any sensible assumption made in step 1. The question, then, is what is sensible? The answer to this boils down to little more than that the assumptions should be consistent with the available rating data and that the model should conserve mass.

Two points must be stressed.

This is not conventional modelling and care must be taken in interpreting the results. For example, the presence of assumptions should be borne in mind when studying the lumped model results. For example, the Nash and Sutcliffe efficiency for the pre-change lumped modelling for the BRE_sap gauge is quoted later as 0.966, but both the 'observed' and simulated hydrographs used in calculating the efficiency are subject to the assumptions made in step 1. There is no reason to believe that this efficiency will fall significantly as the iteration progresses and as further rating data are collected in the field.

The whole process of data preparation and analysis has been automated (a considerable task) and no special treatment has been allowed for any gauge or data point. The automated process simply remorselessly crunches the raw data obtained from the field instruments. Human intervention can easily (subconsciously) add or eliminate information. This means that the data are seen here 'warts and all', which is unusual in work of this kind. It also means that:

- the full analysis, including the generation of plots and reporting, can be updated very simply and quickly when new data become available
- the updating can be done safely by someone unfamiliar with the details of the mathematical and statistical methods of analysis

Steps 2 and 8 stand out in the list of steps because step 2 involves calibration against a time series and step 8 involves impact prediction without (necessarily) there being any data on impacts. How these steps are handled in the later iterations will need some careful thought.

Results are given in this report for steps 1–7 of the first iteration.

9 Data preparation prior to analysis

The raw data collected from the field instruments has to be prepared prior to use in analysis. To minimise the effort required and to reduce the opportunity for errors to be introduced, this task was automated using software written in FORTRAN and Python. The full set of data is listed in Table 9.1; the fourth column ('Prepare') shows the time series and equations that have to be prepared for use in analysis.

The main preparation work is for the stage and potential evaporation time series and the rating curve. Two main problems need to be overcome.

- The pressures readings from the gauges (data items 3 and 5 in Table 9.1) are temperature sensitive.
- There are few data for high flows in the set of manually measured stage-discharge data (data item 13).

The raw readings from stage gauges (Divers) are for water pressure and temperature, and these readings must be converted to give 'stage'. Part of the compensation required is for atmospheric pressure and this compensation uses data from a nearby barometric gauge (Baro). 'Stage' is the number indicating the water surface elevation relative to a local datum and the local datum is the top of the lid on the tube that holds the Diver. The local coordinates (x,y) apply when facing downstream. Coordinate x is horizontal and increases from left to right, and y increases vertically upwards. Throughout this report, stage is given as y at the water surface.

For simplicity, detailed results in the following are given for only one gauge, BRE_sap (which has a relatively poor data set). Detailed results for two further gauges, EAS_out and LOU_out, are given in Appendix C.

These three catchments were selected because:

- they cover the range of scale from micro- to mesoscale
- they are not subject to abstractions for water supply
- LOU_out and EAS_out are not undergoing SCaMP works, so in some respects can act as references when trying to detect change

For important findings, results are given for all the relevant gauges.

Table 9.1 Data for detailed analyses of hydrographs

No.	Data	Symbol	Prepare	Nature	Source	Units
1	Catchment area	A	–	–	Digital Elevation Model	m ²
2	Rainfall	r	Rainfall	Time series	rain gauges	mm/hour
3	Pressure at stage gauge	p	Stage (y)	Time series	Stage gauge	cm H ₂ O
4	Temperature at stage gauge	T			Stage gauge	°C
5	Barometric pressure	p _b			Barometric gauge	cm H ₂ O
6	Barometric temperature	T _b			Barometric gauge	°C
7	Stage				Manual measurement	m
8	Air pressure	a	Potential evaporation rate (e)	Time series	Barometric gauge	cm H ₂ O
9	Air temperature	T _a			Automatic weather station (AWS)	°C
10	Relative humidity	h			AWS	–
11	Average wind speed at 2 m	u			AWS	m/s
12	Net radiation	r _n			AWS	W/m ²
13	Stage-discharge data		Rating curve	Limited set	Manual measurement during rating exercises	m and m ³ /s
14	Cross-section at stage gauge			(x,y) pairs for channel banks and bed	Manual measurement	m

9.1 Stage time series

Stage is measured manually whenever a gauge is visited (data item 7), so that the readings from the Diver can be calibrated to give the stage time series, $y(t)$. For gauge BRE_sap, the result is:

$$y = -0.784 + 0.01(p-p_b) - 0.00176T \quad \text{Equation 9-1}$$

Note that only the offset (-0.784) and temperature compensation (-0.00176T) were calibrated. The temperature compensation is required because the instrument readings are sensitive to temperature.

Figure 9.1 shows the effect of temperature compensation: it causes the shift from the blue circles to the red squares. Some further results on temperature compensation are given in Appendix D. The range of stage plotted in the figure is 180 mm and the

average and worst errors (after compensation) are approximately 10 and 35 mm respectively. The average manual measurement error is estimated to be approximately 5 mm because of a combination of factors including:

- access difficulties
- water ripples
- thermal expansion of the tube that is used as the measurement datum
- the usual general small repeatability problems associated with making manual measurements in the field

For flood peak measurement, the average error in the rise in stage is less than 5% (that is, less than 10/180, because manual measurements have not yet been made at peak flows at this site). It is estimated that the corresponding contribution to the error in estimating peak flows will be less than 10%; this is larger than the stage error because flow tends to rise nonlinearly with stage. Note that a large fraction of this error arises from manual measurement error.

The reason for using manual measurements was to firmly anchor the measurement system so that the effect of temperature could be fully investigated. The method used to estimate temperature compensation was designed to be such that the effect which manual measurement errors have on the estimated stage will gradually diminish towards zero as the number of manual measurements increases. The plan is therefore to run the monitoring for as long as possible and to collect many manual measurements. The errors tend to be relatively smaller for larger catchments. For example, in the calibration plots in Appendix C, the temperature compensated data for EAS_out (13.3 km²) and LOU_out (47.3 km²) have much less scatter than is shown in Figure 9.1, which is for BRE_sap (1.7 km²).

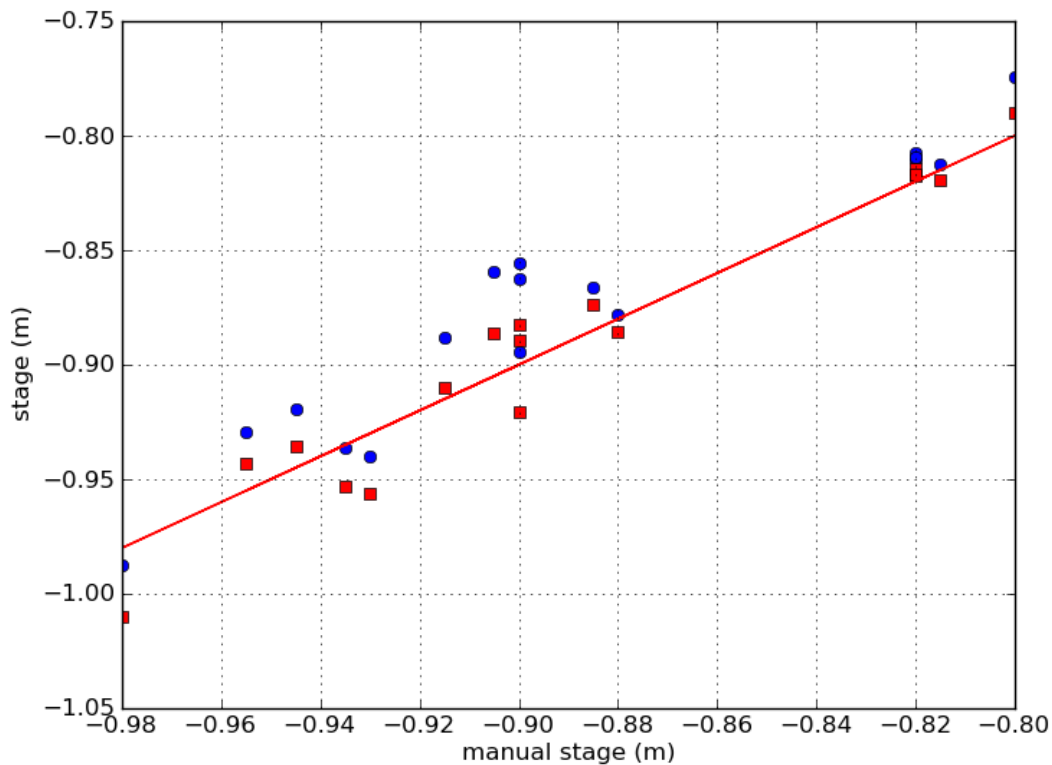


Figure 9.1 Calibration of stage derived from readings against manually measured stage

Notes: Red squares = temperature compensated; blue circles = uncompensated

9.2 Potential evaporation time series

Potential evaporation is calculated using data from the nearest appropriate AWS. The calculations use the UN Food and Agricultural Organization (FAO) Penman–Monteith equation, as defined in equation 53 in Allen et al. (1998). This gives an estimate for:

‘a hypothetical crop with an assumed height of 0.12 m, with a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered’.

Given that permanent pasture and rough grazing are the dominant land use types in the Hodder catchment, this estimate was assumed to apply over the entire catchment. Calder (1993) reported that, compared with grassland, *Calluna vulgaris* (common heather) has smaller transpiration losses but larger interception losses. This, perhaps, should be taken into account if fine detail modelling is at some later date attempted for the moorland.

To be consistent with the FAO report, the calculation steps introduce variables which have kPa as units for pressure. The calculation steps are as follows:

$$\gamma = 0.665 \times 10^{-4} p_b \quad \text{Equation 9-2}$$

where γ (kPaK^{-1}) is the psychrometric constant.

$$T' = T_a + 237.3 \quad \text{Equation 9-3}$$

$$e^0 = 0.6108 \exp\left(\frac{17.27T_a}{T'}\right) \quad \text{Equation 9-4}$$

where e^0 (kPa) is the saturated vapour pressure.

$$\Delta = \frac{4098e^0}{T'^2} \quad \text{Equation 9-5}$$

where Δ (kPaK^{-1}) is the slope of the saturation vapour pressure curve.

$$r_g = \begin{cases} 0.1r_n & \text{day time} \\ 0.5r_n & \text{night time} \end{cases} \quad \text{Equation 9-6}$$

where r_g (W/m^2) is the soil heat flux.

Finally this gives:

$$e = \frac{0.408\Delta[0.0036(r_n - r_g)] + \gamma \frac{37}{T_a + 273} u e^0 (1 - 0.01h)}{\Delta + \gamma(1 + 0.34u)} \quad \text{Equation 9-7}$$

where e (mmh^{-1}) is the potential evaporation rate.

9.3 Rating curve

Ideally there would be sufficient data so that the measured discharge can be calibrated against the measured stage using data collected during rating exercises (data item 13). There are, however, too few data at high flows; the plan was for field exercises during the winter of 2009 to 2010, and perhaps also the following autumn and winter, to concentrate on weaknesses in the data sets.

Using the cross-section data (for example, Figure 9.2), stage–area look-up tables can be generated (for example, Figure 9.3) and the mean velocity can be calculated for each pair of stage–flow data (for example, Figure 9.4). The rating curve for high-flows

can then be based on calibrating and extrapolating the velocity curve, taking into account the stage–area curve.

This approach is intrinsically more robust than calibrating and extrapolating the discharge curve directly. The drainage network in the distributed model DNRM is represented using a physically based hydraulic model which generates rating curves automatically. As part of the iteration and reconciliation process described in Section 8, these generated rating curves are being reconciled with the observed data and the extrapolated rating curve. Some results are shown later in Section 12.2.

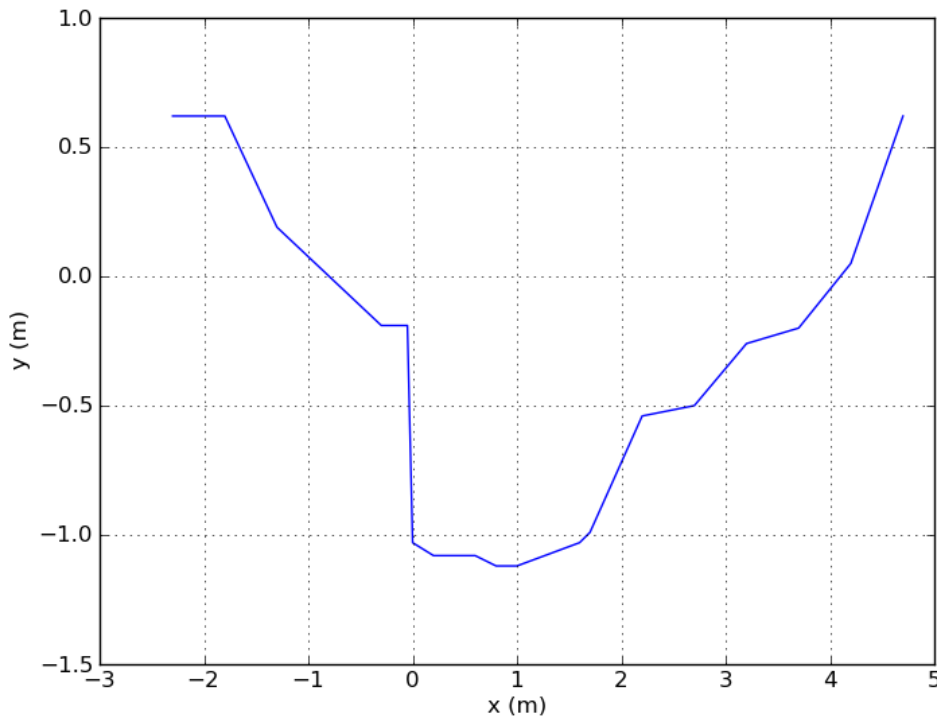


Figure 9.2 Cross-section for BRE_sap

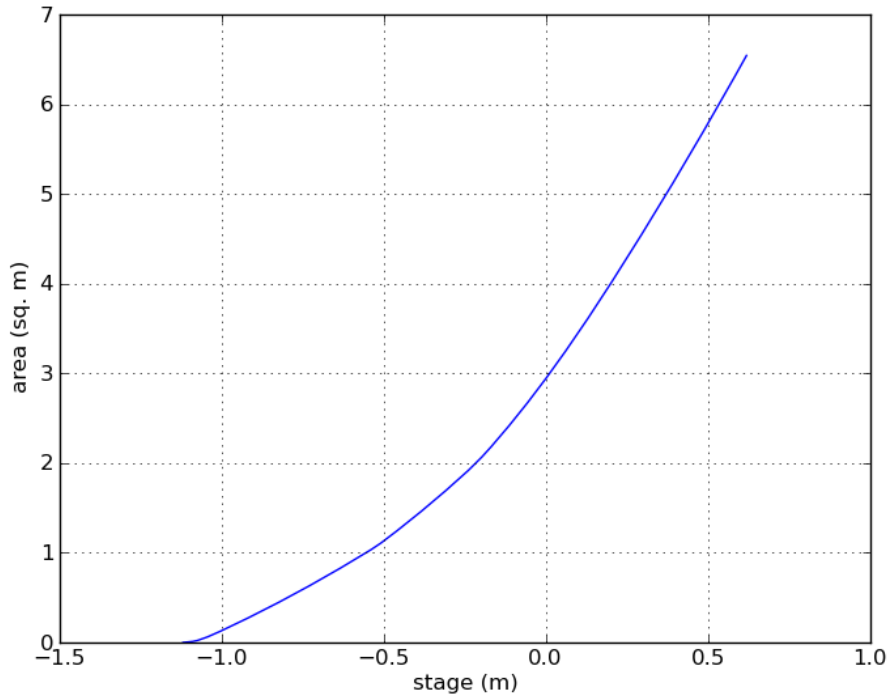


Figure 9.3 Stage-area curve for BRE_sap

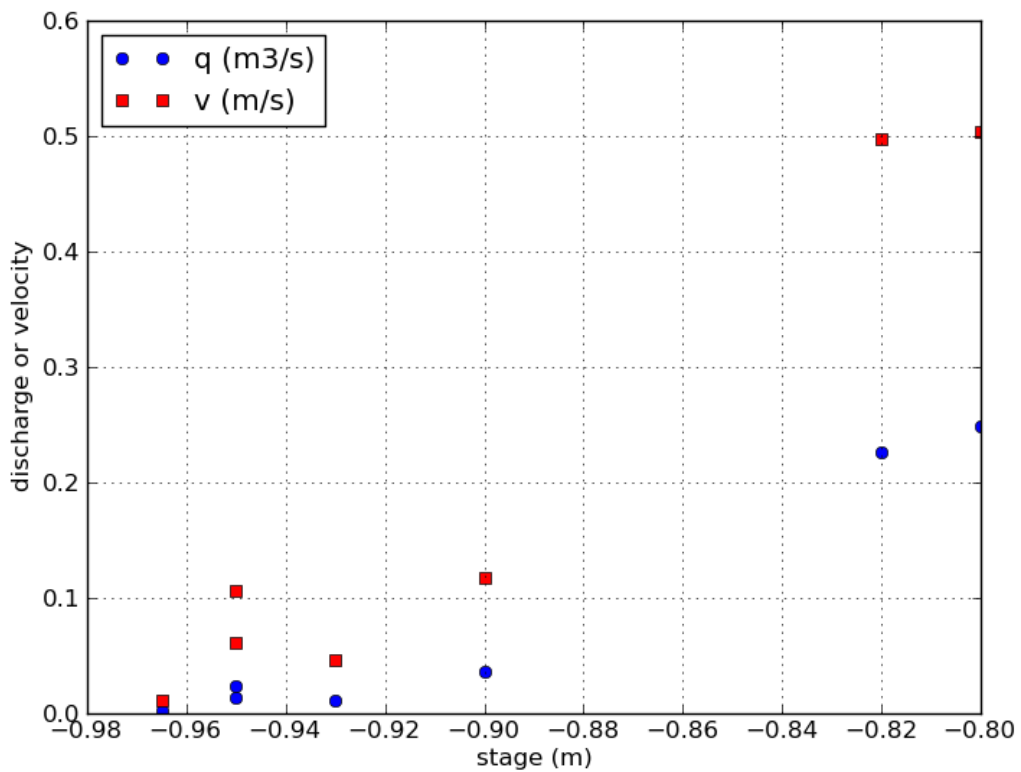


Figure 9.4 Rating data for BRE_sap, as of 31 May 2009

Notes: Blue circles = discharge m³/s
 Red squares = velocity m/s

As discussed earlier, assumptions have to be made about the rating curve. A velocity equation is used which has a sigmoidal function G (custom-designed) that varies smoothly between two limits (in this case the limits are the minimum and maximum velocities, v_{min} and v_{max}):

$$X = MIN \left(1, \frac{y - y_{min}}{y_{max} - y_{min}} \right) \quad \text{Equation 9-8}$$

$$G = \frac{1}{2} \left[1 + \frac{\tanh(2\alpha X^\beta - \alpha)}{\tanh(\alpha)} \right] \quad \text{Equation 9-9}$$

$$v = v_{min} + (v_{max} - v_{min})G \quad \text{Equation 9-10}$$

There is some support in the literature for using such an approach (for example, Beven 1979). If the velocity is assumed zero at the bottom of the channel, then v_{min} and y_{min} are known. This leaves four parameters that can be set or calibrated:

- v_{max} , the maximum velocity
- y_{max} , the stage where the velocity reaches the maximum
- the parameters α and β that control the shape of the transition from low to high velocity

If, for example, v_{max} is set at 1.5 m/s, based on physical arguments, then the remaining three parameters can be calibrated to minimise the error in the prediction of the measured discharges while simultaneously satisfying any other prescribed conditions (for example, conditions based on mass balance are used when accounting for water abstractions). Figure 9.5 shows a typical result (y_{max} , 0.1747, α , 4.959 and β , 0.5376).

Some limitations in this approach will have to be addressed in future iterations (for example, to allow pooling in the cross-sections at low flow).

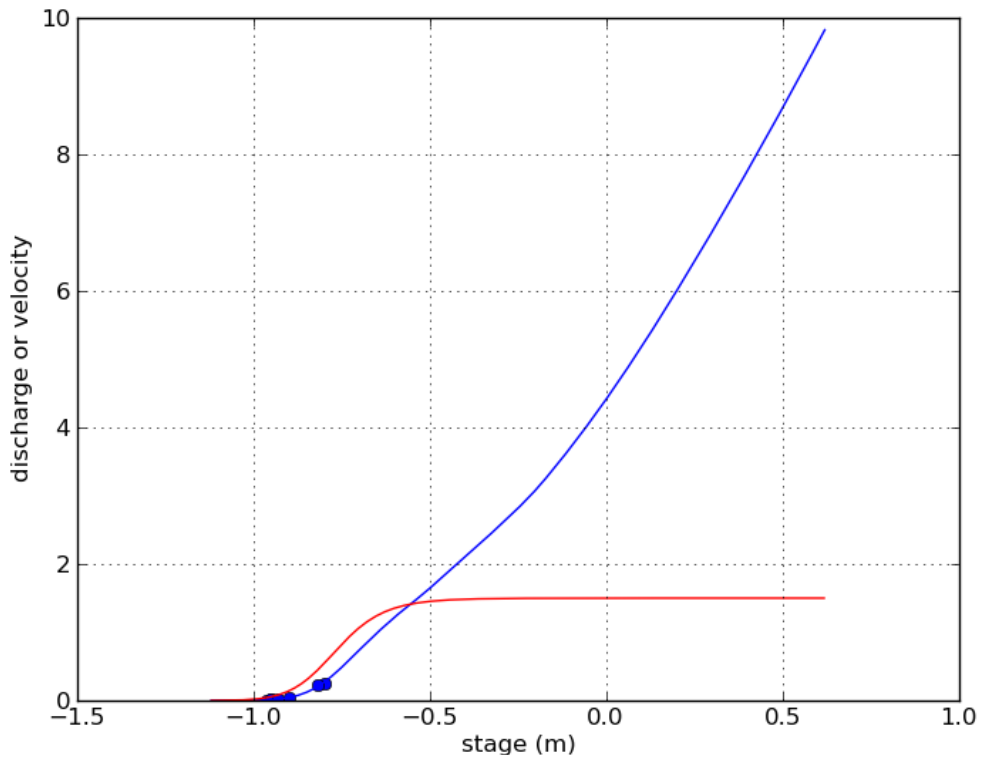


Figure 9.5 BRE_sap rating curve assuming a maximum velocity of 1.5 m/s

Notes: Blue circles = measured stage-discharge (m^3/s)
 Blue line = discharge (m^3/s)
 Red line = velocity (m/s)

10 Analysis of short-term early effects of SCaMP works: lumped modelling

As discussed earlier, the purpose here is to analyse the short-term early effects of the SCaMP works on the hydrographs measured at various spatial scales. This involves trying to detect impacts, gauge by gauge, by comparing pre-change hydrographs with post-change hydrographs using a simple lumped model (SDD).

The progress to date is summarised in Table 10.1. This table is given here to demonstrate the scope of the work; the various data contained in the table are described and discussed in the following sections.

The smallest scale (that is, process scale) gauges were installed to give data for use by Imperial College and the data for these gauges have not been analysed.

To minimise the overall effort required and to reduce opportunities for introducing errors, the analysis was automated using software written in FORTRAN and Python. This incorporates the software for data preparation that implements the equations and methods described in Section 9. The software accepts a set of raw instrument data, carries out the data preparation and analysis, and then plots the results.

Table 10.1 Summary showing scope and results for the lumped modelling

Gauge	Location number	Scale	Area (km ²)	Gauge installed	Main work	Work carried out	% area affected	Annual abstractions	Parameters		Nash and Sutcliffe ¹ pre-change	Storage calibration	Comments
									b	c			
BRE_grip	20.1	Process	0.0014	May 2008	Grip blocking	Nov 2008	100						Process site – no modelling yet
BRE_grip_weir	20.2	Process	0.0014	Nov 2008	Grip blocking	Nov 2008	100						Process site – no modelling yet
BRE_out	2	Mini	11	Dec 2007	Grip blocking	Nov 2008	15	215	6.523	1.943	0.622	yes	
BRE_rhw	14	Micro	2.8	May 2008	Grip blocking	Nov 2008	20		5.807	1.696	0.919	yes	
BRE_sap	15	Micro	1.72	Jun 2008	Grip blocking	Nov 2008	35		6.883	1.468	0.966	no	
CRO_mid	13	Micro	3.5	–	–	–	–		6.563	1.314	0.798	yes	
CRO_out	6	Mini	21.1	Oct 2008	Grip blocking	Feb 2009	2		5.708	1.044	0.834	yes	
CRO_sc1	12.1	Process	0.04	Dec 2007	Grip blocking	Feb 2009	100						Process site – no modelling yet
CRO_sc2	12.2	Process	0.35	Dec 2007	Grip blocking	Feb 2009	100						Process site – no modelling yet
CRO_sc3	12.3	Process	0.0005	Dec 2007	Grip blocking	Feb 2009	100						Process site – no modelling yet
CRO_sc4	12.4	Process	0.35	Dec 2007	–	–	–						Process site – no modelling yet

Gauge	Location number	Scale	Area (km ²)	Gauge installed	Main work	Work carried out	% area affected	Annual abstractions	Parameters		Nash and Sutcliffe ¹ pre-change	Storage calibration	Comments
									b	c			
CRO_sc5	12.5	Micro	1.0	Dec 2007	Grip blocking	Feb 2009	35		1.832	0.660	0.763	no	
EAS_out	9	Mini	13.3	Jun 2008	–	–	–		5.919	1.302	0.676	yes	
HAR_out	18	Micro	4.9	May 2008	Stocking density	Feb 2009	100	143 12/12–6/9	8.171	1.494	0.884	yes	
HOD_mid	10	Meso	110	Jun 2008	Grip blocking	Feb 2009	<1		9.729	1.090	0.769	no	Affected by reservoir
LAN_mid	19	Micro	15	May 2008	Stocking density	Feb 2009	100	90	5.508	0.975	0.742	yes	
LAN_out	7	Mini	27.7	May 2008	Stocking density	Feb 2009	85	125	7.181	1.215	0.708	yes	
LOS_mid	25	Micro	2.5	Jun 2008	Stocking density	Feb 2009	100		15.739	2.740	0.712	yes	
LOS_out	17	Micro	4.0	Jun 2008	Stocking density	Feb 2009	100	203	11.410	1.717	0.862	yes	Modelling used daily abstracts.
LOS_stock	22.1	Micro	1.0	Jun 2008	Stocking density	Feb 2009	100						Originally intended as process site
LOS_stock_weir	22.2	Process	0.12	Apr 2009	Stocking density	Feb 2009	100						Process site - no modelling yet
LOU_out	8	Meso	47.3	May 2008	–	–	–		7.890	1.034	0.739	no	
WHI_mid	24	Mini	10.0	Jun 2008	Tree planting	Spring 2008	5						Abstractions not yet quantified
WHI_out	3	Mini	13.6	Dec 2007	Tree planting	Spring 2008	5	280	5.174	1.073	0.829	yes	

Gauge	Location number	Scale	Area (km ²)	Gauge installed	Main work	Work carried out	% area affected	Annual abstractions	Parameters		Nash and Sutcliffe ¹ pre-change	Storage calibration	Comments
									b	c			
WHI_tree	26.1	Process	0.06	Jun 2008	Tree planting	Spring 2008	100						Process site – no modelling yet
WHI_tree_weir	26.2	Process	0.06	Nov 2008	Tree planting	Spring 2008	100						Process site – no modelling yet

Notes: ¹ The model was not calibrated to maximise the Nash and Sutcliffe efficiencies; the efficiencies are given for information only.

10.1 Detecting early short-term impacts

There are several ways in which a detailed analysis of hydrographs could be attempted to detect early short-term impacts, all of which can be classified as being associated with one of three approaches (Table 10.2).

Table 10.2 Analysis methods for detecting impacts in hydrographs

Method number	Approach	Modelling
1	Data based	–
2	Downwards (top–down)	Lumped
3	Upwards (bottom–up)	Distributed

Method 1 involves deriving statistics and testing for changes in these statistics, as in the method used by Archer and Newson (2002). At the other extreme, Method 3 could involve using detailed physically based distributed models such as SHETRAN (Ewen et al. 2000).

In Method 2, changes are detected in the parameters of a lumped rainfall–run-off model, assuming of course that a suitable model structure can be found. Possibilities for finding a structure include:

- (a) Select a standard model such as the unit hydrograph model from Volume 1 of the *Flood Estimation Handbook* (Reed 1999).
- (b) Select the appropriate mathematical structure automatically from a pre-defined set, for example, the approach used in Project FD2120 (Beven et al. 2008).
- (c) Guess (based on experience) the necessary model structure (and then test it is correct) based on an analysis of the flow dynamics and storage–discharge behaviour, as in the lumped hysteretic approach used by Ewen and Birkinshaw (2007).

Method 2(c) is used here because it is flexible and can be adapted to suit the nature of the available data and the short length of the records. The iteration approach described earlier involves iterating between Methods 2(c) and 3. The distributed modelling for Method 3 is described in Section 11.

10.2 Lumped storage–discharge modelling

If time is denoted by t and the storage $s(t)$ is the average depth of drainable water in the catchment, then the governing equation for mass balance in the catchment is:

$$\frac{ds}{dt} = r - \beta e - q \quad \text{Equation 10-1}$$

where $q(t)$ is the discharge in mm/h and $\beta(t)$ the evaporation multiplier. This ordinary differential equation describes how the storage will vary through time, assuming some initial condition:

$$s(t_0) = s_0 \quad \text{Equation 10-2}$$

The storage curve just moves up and down with s_0 , so the numerical value of s_0 is unimportant in the example described below.

Provided $\beta(t)$ is known, Equations 9-1 and 9-2 can be solved to give the observed storage time series $s(t)$ that corresponds to the observed discharge and potential evaporation rates, $q(t)$ and $e(t)$.¹

Figure 10.1 shows a typical result, including cumulative plots, assuming that the maximum velocity v_{\max} used in Equation 9-10 is 1.5 m/s. Note that the net change in storage over the period is quite small. If the maximum velocity was set smaller, then the discharge would be smaller with the result that the net increase in storage would be larger.

In this example, the grip blocking took place in November 2008 and the first storms in December 2008 show a behaviour not seen at any other time: an increase in storage is followed after some time with enhanced discharge (this will be easier to see later when hydrographs are plotted). Rather than any effect of blocking, however, this different behaviour could well be the result of snowfall being followed by rainfall on snow.

There is clearly significant room for improvement in the rating curve because it results in a storage response that has a minimum storage in March; analysis shows this is related mainly to overestimation of the observed discharge at low flows. However, the whole procedure for analysis is automated and is applied consistently to all the data sets, and the aim is to improve the physical reasonableness of the modelling as a whole in a systematic and transparent manner over several iterations. This problem with storage was therefore not simply ‘calibrated away’ on the first iteration. As argued earlier, the lumped modelling can be used in impact detection even in the presence of such errors.

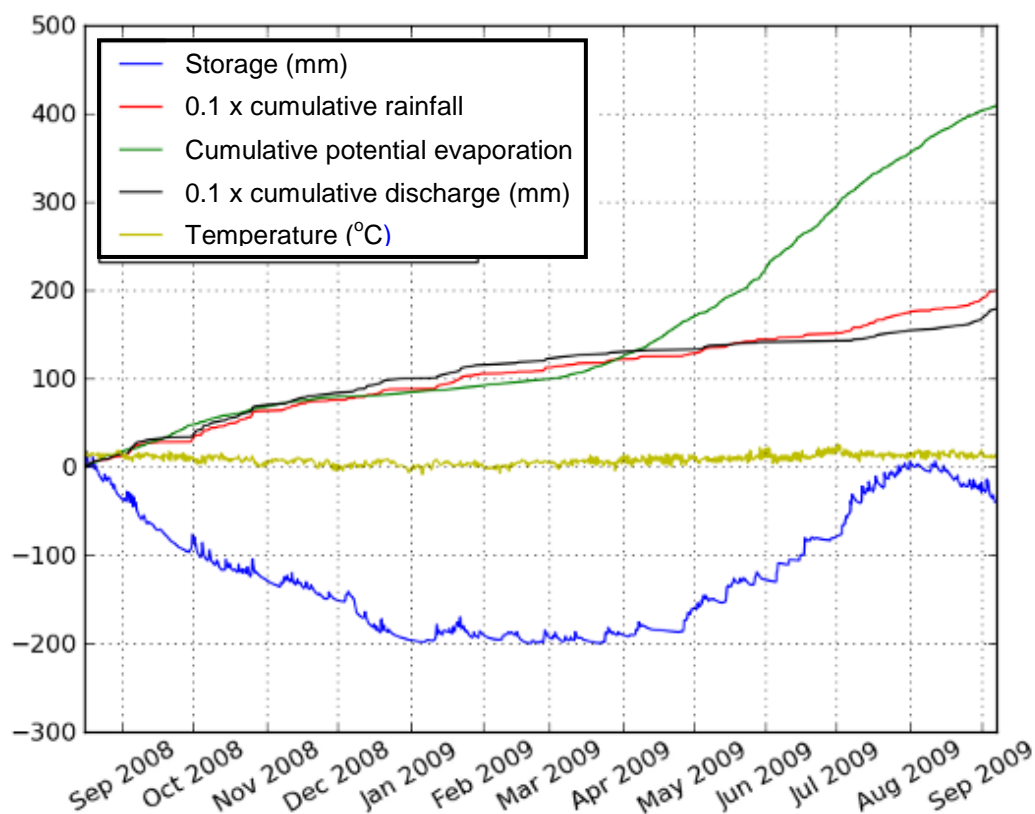


Figure 10.1 Example mass balance results for BRE_sap ($\beta = 1$)

¹ The term ‘observed’ is used here simply to denote values calculated directly from observations.

The hysteretic nature of the storage–discharge relationship can be seen in Figure 10.2. The hysteresis does not appear to be strong (that is, the loops are quite narrow).

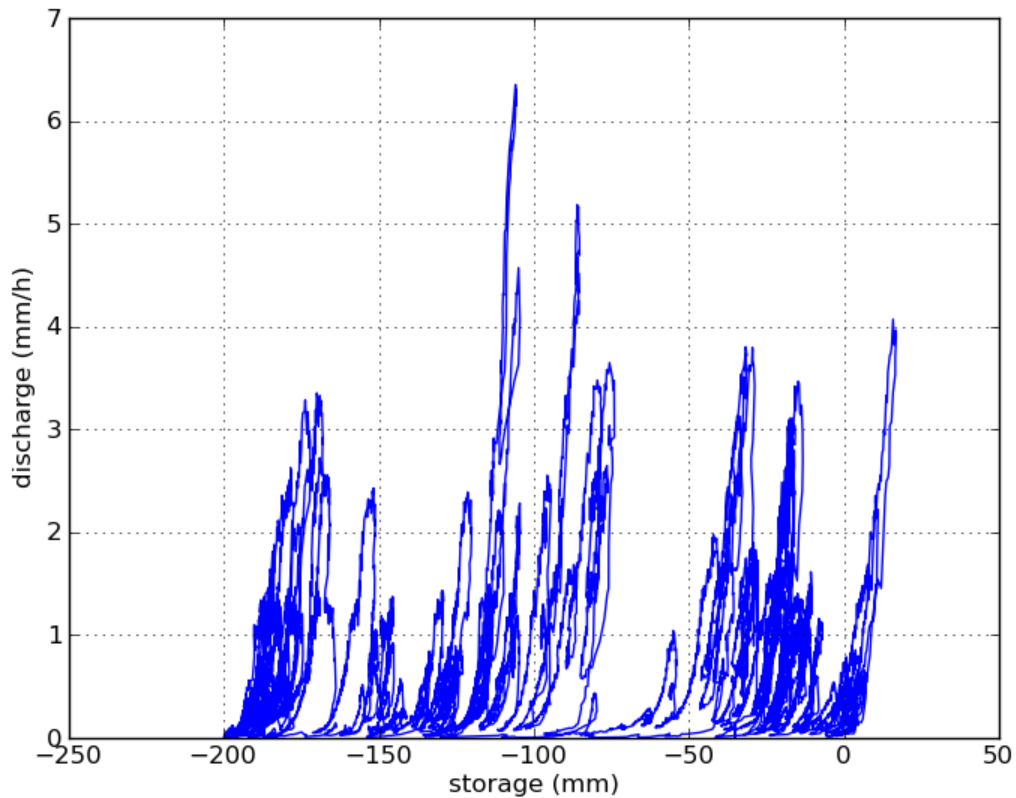


Figure 10.2 Example storage-discharge history for BRE_sap

10.3 Building a lumped model

On analysing storage–discharge plots for the Slapton Wood research catchment in Devon, Ewen and Birkinshaw (2007) found repeating hysteretic loops that have a similar shape for all large storms. This similarity was so marked that it was possible, by inspection, to define the mathematical structure for a lumped model – a new type of model they called the ‘lumped hysteretic model’.

One of the important behaviours represented in this lumped hysteretic model is that the discharge–storage relationship is attracted to a common curve in the discharge–storage plot, called the ‘attractor’ curve. When there is rainfall, the line tracing out the discharge–storage response tends to be pushed away from the attractor curve, but then tends to be drawn back (‘attracted’) to the curve:

$$q = (s/b)^c \quad \text{Equation 10-3}$$

where q is discharge, s is storage, and b and c are constants. For Slapton Wood, b is 98 mm (for q in mm/h) and c is 1.6. Equation 10-3 has been used elsewhere to represent recessions; basically, the attractor curve is simply a form of master recession curve (Lamb and Beven 1997).²

² Some values for c from other sources for other catchments are given in Ewen and Birkinshaw (2007).

One way to find the attractor curve is to extract data pairs for the discharge (q) and its rate of change (dq/dt) from the recessions in the hydrograph and then use them to calibrate the following equation:

$$dq/dt = mq^n \quad \text{Equation 10-4}$$

where m is the multiplier and n the power. Neglecting the effect of evaporation, the constants for the attractor equation are then given by:

$$c = 1/(2-n) \quad \text{Equation 10-5}$$

$$b = -c/m \quad \text{Equation 10-6}$$

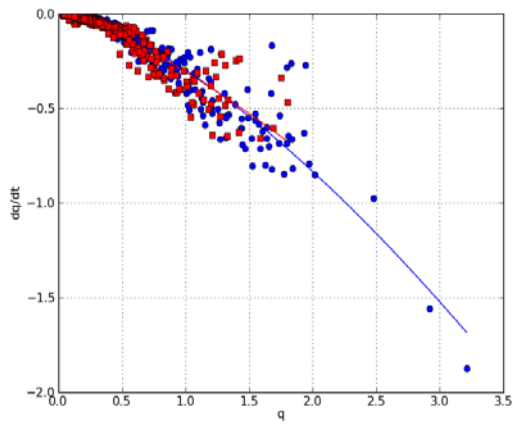
Figure 10.3 shows results for 11 catchments that have undergone SCaMP works using data extracted automatically from the stage hydrographs using a simple algorithm that searches for times where the discharge is falling continuously. Two sets of data are plotted for each catchment. One is for the time period before the SCaMP works and the other is for the period after the works.

Given the similarity between the pre- and post-change results, it appears that the works have had little short-term effect on the flow recessions. However, a full analysis for detection of change must have a scale of reference (for example, based on differences commonly seen between catchments) and an accompanying statistical analysis of significance – neither of these are considered here. Part of the small difference that can be seen before and after the SCaMP works might possibly be explained by seasonal differences in evaporation.

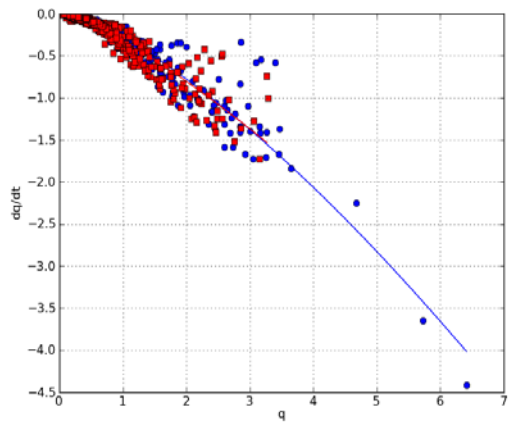
Two of the plots stand out from the rest.

- CRO_sc5 has widely scattered data because its peaks are bell-shaped, so will require (in future iterations) a slightly more sophisticated method to decide exactly when after a peak the recession has begun.
- The post-change period for LOS_out starts in April and runs over the summer, so the difference shown for LOS_out could well be due to winter/summer differences rather than pre-change/post-change differences. This will be tested with data collected for winter 2009 to 2010.

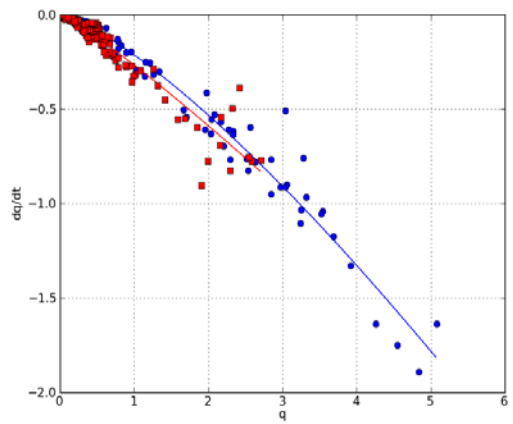
For the pre-change period, b and c for BRE_sap are 6.9 mm and 1.5, respectively (values for the other gauges are given in Table 10.1). Note that these values are sensitive to the objective function and to the value assumed for the maximum velocity.



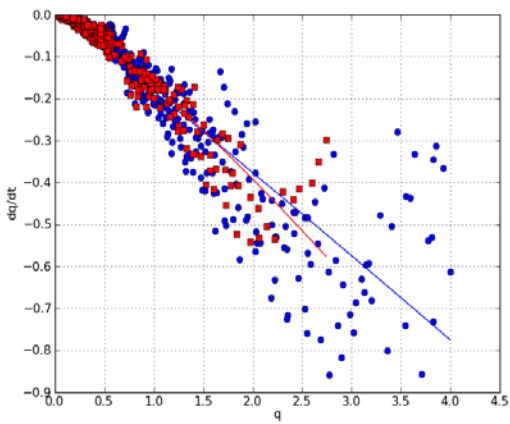
BRE_out



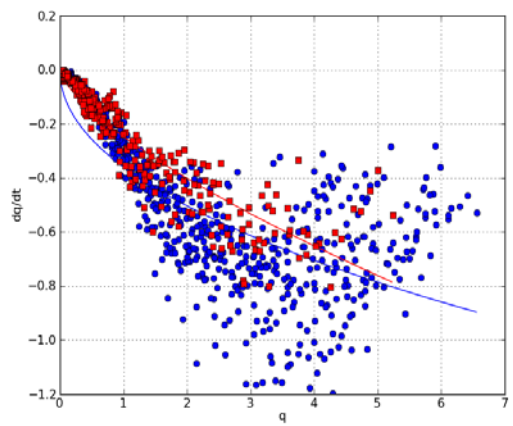
BRE_rhw



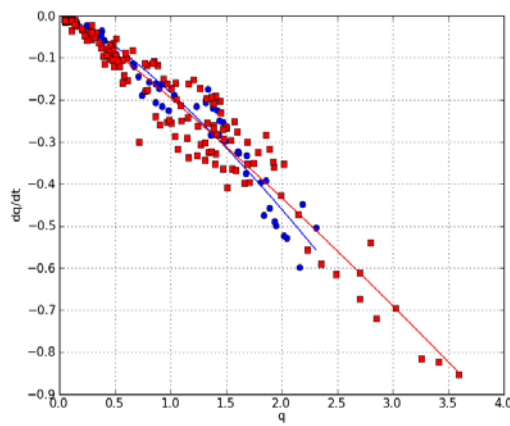
BRE_sap



CRO_out

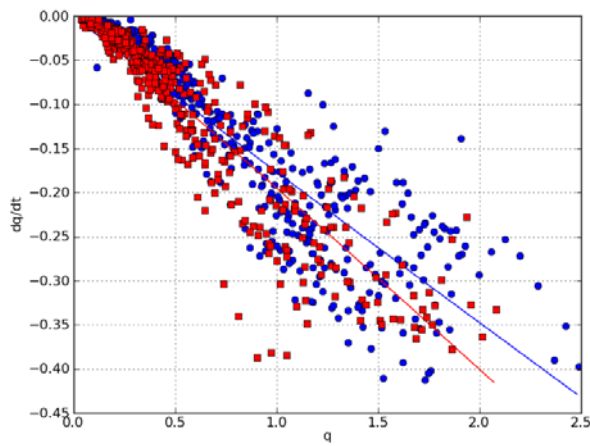


CRO_sc5

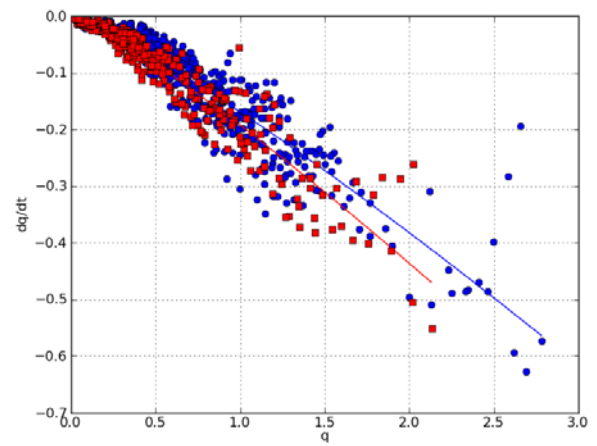


HAR_out

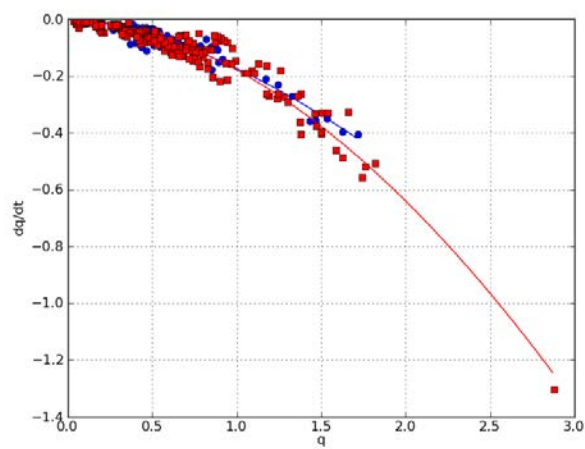
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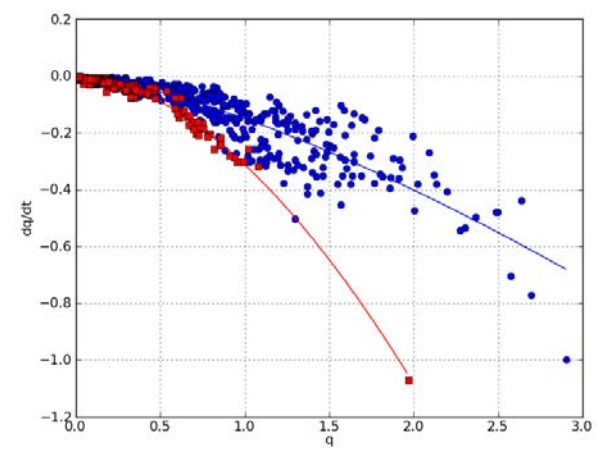
LAN_mid



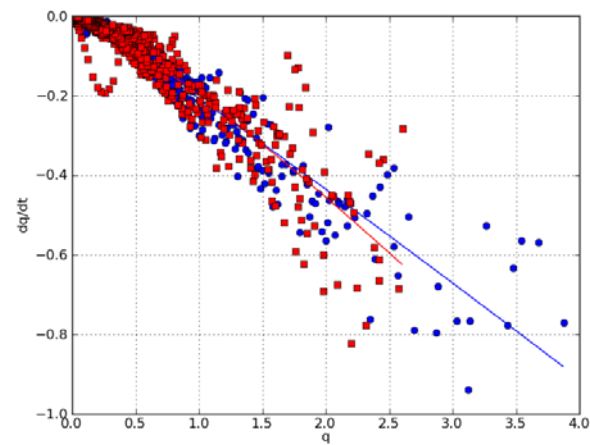
LAN_out



LOS_mid



LOS_out



WHI_out

Figure 10.3 Recession data for catchments subject to SCaMP works

Notes: Pre-change = blue circles
 Post-change = red squares
 The units are mm/h for q and mm for dq/dt

The narrowness of the hysteresis loops, and the general simplicity of the storage–discharge response, suggests that a very simple model structure will be adequate for simulating the discharge hydrograph. The governing equation for the simplest possible model consistent with the attractor equation is:

$$\frac{ds}{dt} = r - \beta e - q(s) \quad \text{Equation 10-7}$$

where $q(s)$ is the attractor equation, and a suitable initial condition is derived by assuming the simulation starts from the attractor curve. For simplicity, β is assumed to rise linearly from 0 at $q = 0$ to 1 at $q = 0.05$, and then levels off at 1. This implicitly uses discharge as a surrogate measure for wetness and probably tends to over-predict evaporation.

10.4 Detecting impacts using lumped storage–discharge modelling

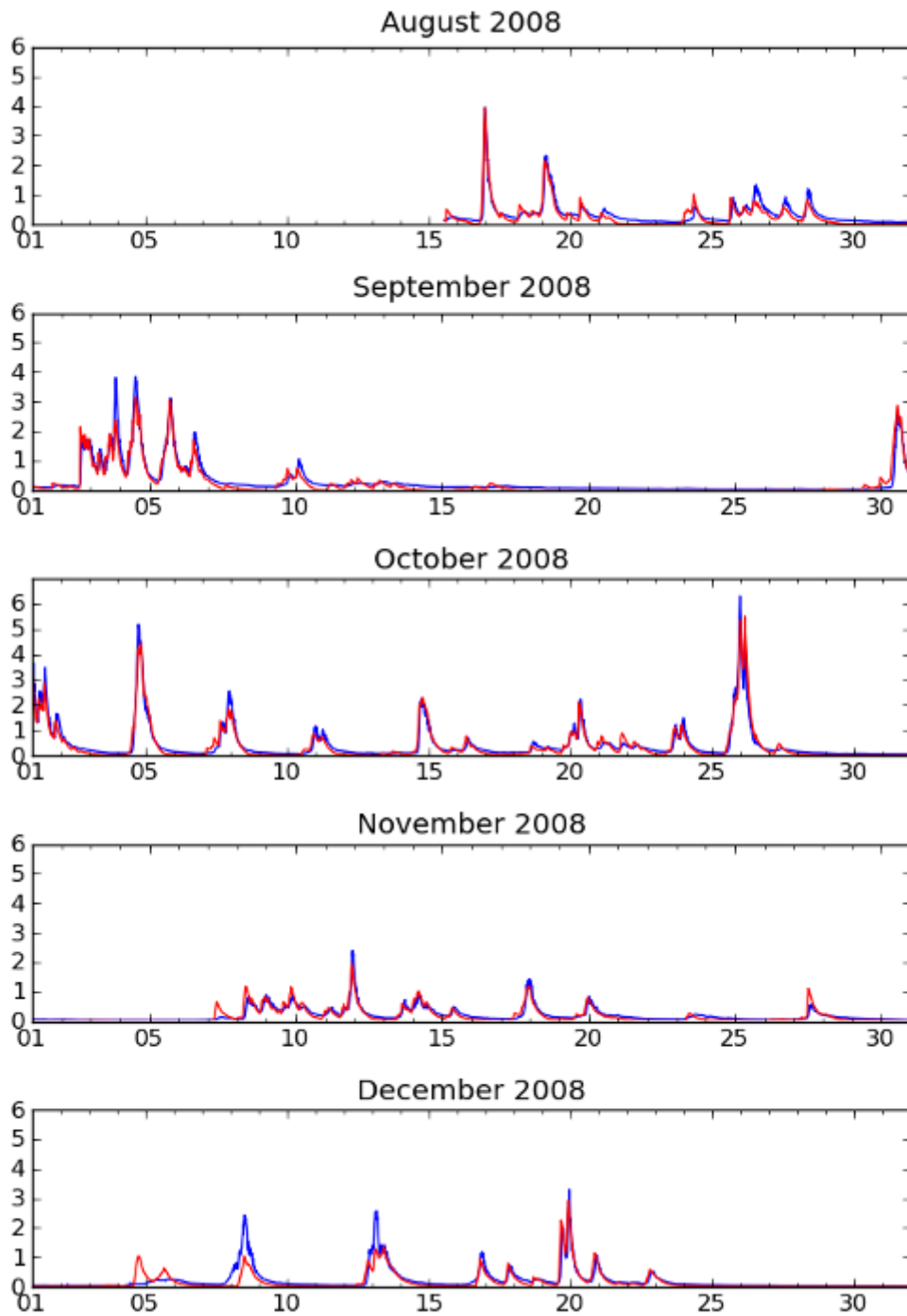
This simple model works well for predicting the hydrograph at BRE_sap (Figure 10.4). If there were significant changes in hydrological behaviour after the grip blocking, they would show up as a change in the quality of the simulations. The only real difference before and after blocking is for the first storms in December 2008, though as noted above, this difference may be the result of snow events being followed by rain-on-snow events. Similar results for other gauges are given in Appendix C.

Note that the main part of the SCaMP work upstream of the BRE_sap gauge was implemented in November 2008, so this analysis will be revisited using the data collected in autumn 2009. The model over-predicts the run-off during summer 2009, but there are no summer 2008 data to test this against. Appendix C shows that over-prediction in summer is a feature of the modelling, even for catchments that have not undergone change.

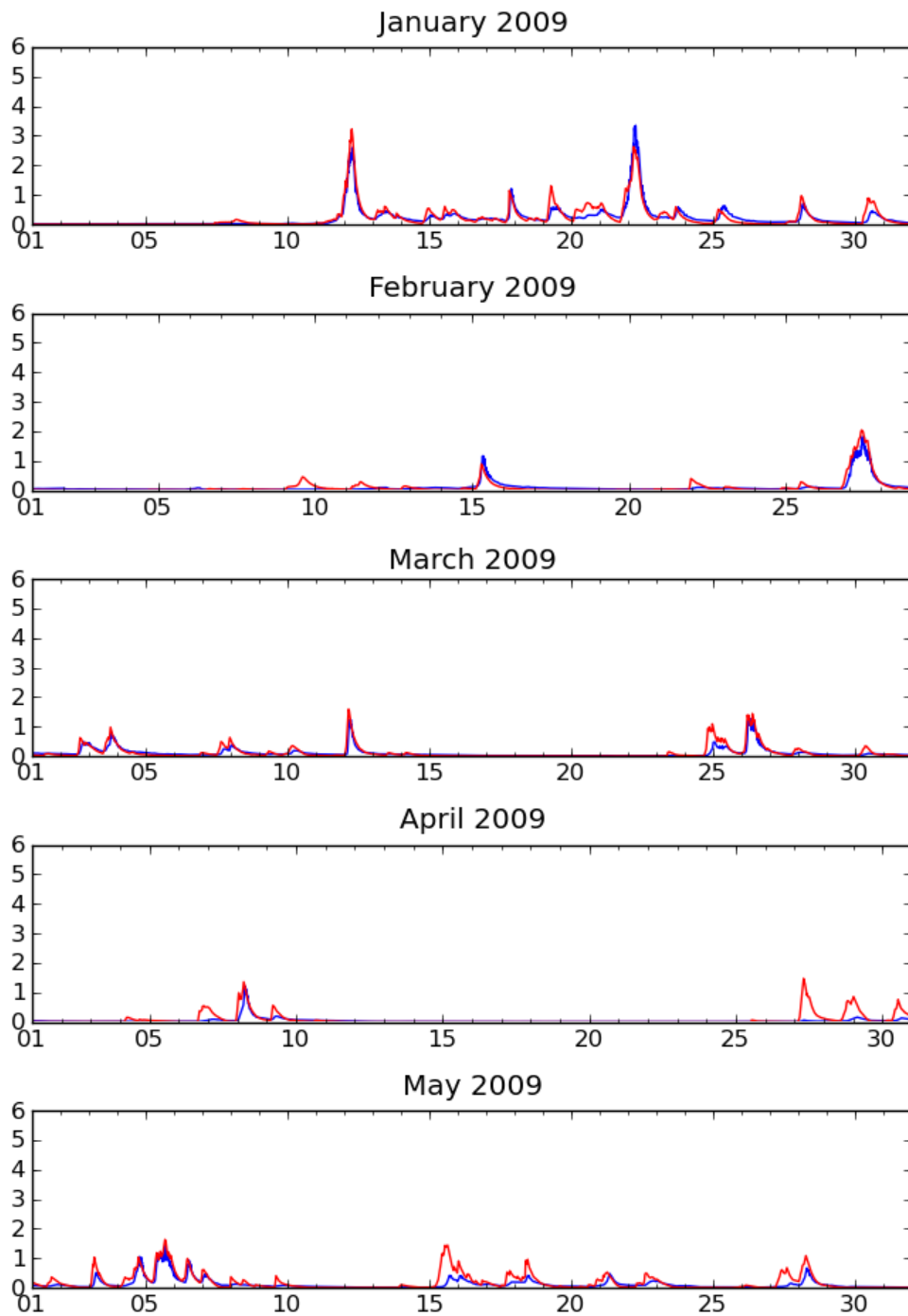
In Table 10-1, some indication of the quality of the simulations pre-change is given by the Nash and Sutcliffe efficiencies of the fit of the simulated to observed discharge. From the efficiencies it can be seen that the quality of the simulation hydrographs plotted here and in Appendix C is typical, rather than exceptional, in comparison with those for the other gauges.

The calibrations used in producing the above results can be summarised as follows: the lumped model was calibrated against manually measured stage, manually measured rating data, and observed recessions in stage. It is important to note that it was not calibrated to optimise the Nash and Sutcliffe efficiencies, and the efficiencies quoted in Table 10-1 are given solely as an indication of the quality of the simulation. Recall the warning in Section 8 that this is not conventional modelling and care must be taken in interpreting the results.

The quality of simulation is low for the prediction of low flows (Figure 10.4), as expected given the problem described earlier when discussing the storage response plotted in Figure 10.1.



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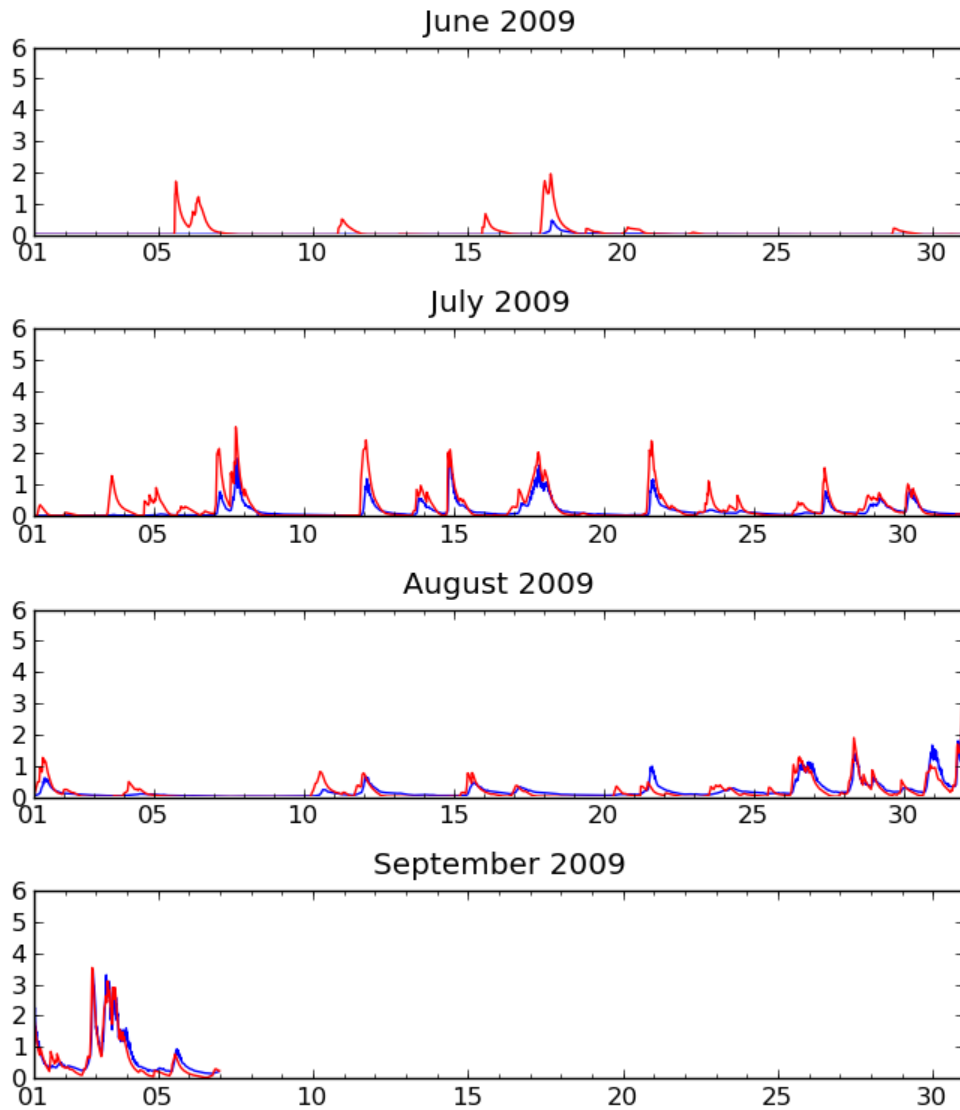


Figure 10.4 Hydrographs for BRE_sap (mm/h): blocking took place on November 2008

Notes: Observed = blue
 Simulated = red

What counts most here, in the context of detecting the short-term impact of the SCaMP works, is the comparison between the observed and simulated peaks and how this comparison changes from the pre-change period to the post-change period. Some comparisons are plotted in Figure 10.5, showing all the data available for six storms. The broken lines in that figure are for Equation 10-8:

$$Q = Q_1 \left(1 - \frac{\ln(A^2)}{20} \right) \quad \text{Equation 10-8}$$

where Q_1 is a parameter for the peak discharge at an area of 1 km² and A is the catchment area in sq. km.

Note that peak discharges are notoriously difficult to predict and this is only the first iteration of the modelling method.

It is in the nature of the problem of detecting impacts that every possible detection method ultimately relies on detecting differences between observed peaks and predicted peaks (for example, what the peak would have been if the change had not taken place). This means that all possible methods are subject, either directly or indirectly, and either in deterministic or stochastic modelling, to the difficult problem of estimating peaks.

Statistical analysis of significance could be performed on data such as that presented in Figure 10.5, but this is better left until a later iteration, especially given that the manipulation of the comparison between observed and simulated peaks should not drive the iteration process, as it must be an independent outcome from the iteration. The one exception to this is the possibility of an iteration approach in which the peaks are predicted perfectly (neglecting the effect of observation error). This approach would, in effect, show how much change in parameters b and c are required to force perfect comparison, so that the degrees of change pre- and post-change can be compared and this comparison used as the basis of a method for detecting impacts. Such arguments and discussions might seem a little abstract, but the problem of detection does not appear to be simple.

Implicitly, the underlying principal for the method described above for detecting the effects of the SCaMP works is as follows.

- If a discharge–storage model calibrated for the pre-change period also accurately simulates the post-change hydrograph, it indicates that change has **not been detected**.

The current conclusion from the analysis is that:

- no impact from SCaMP has been detected for significant floods in the autumn, winter and spring – but the analysis is continuing
- no conclusion can yet be drawn about the summer

The plots of the seasonality of peak flows at Hodder Place showed no annual maximum events in June or July. They do, however, show a few POT events, so summer floods are potentially important. In the SDD modelling, the threshold for evaporation in the model was set low, yet the model produced falsely high peaks in the summer. This suggests that there is a failure in the model to accurately represent the relationship between storage and discharge in the summer, rather than simply a failure by underestimating evaporation. It is a simple matter to improve the model in the next iteration, but there are very few pre-change data on which to base an analysis of the short-term effects of the SCaMP works on summer floods. Many of the gauges were installed in summer 2008 but the data sets are incomplete prior to August 2008; the last instrument to be installed was the AWS in August 2008.

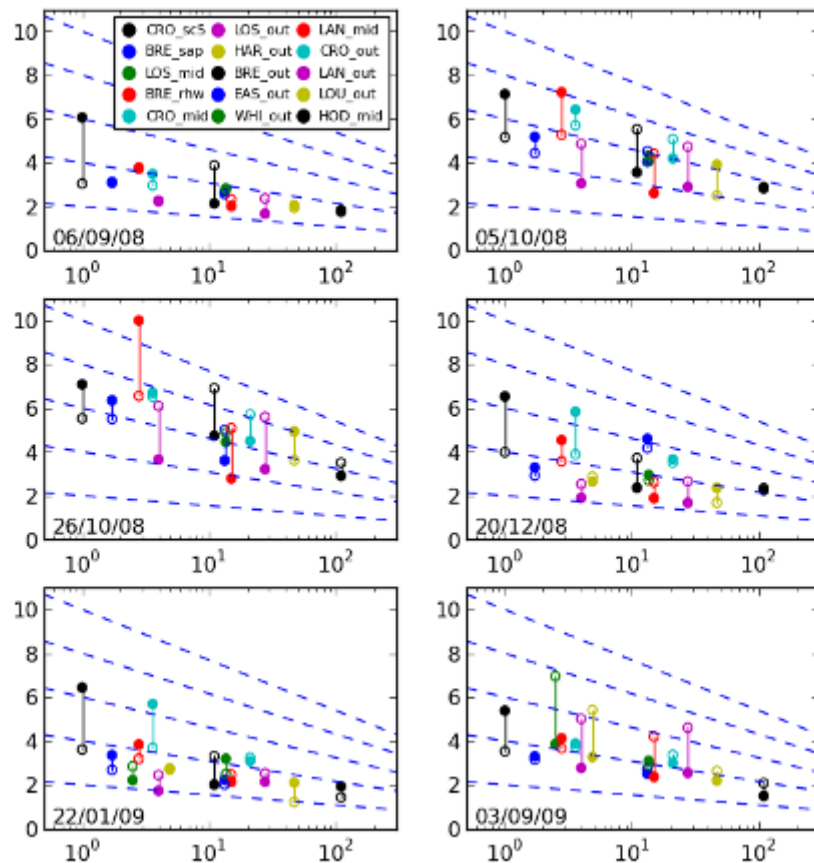


Figure 10.5 Peak discharge (mm/h) plotted against catchment area (km²) for six storms

Notes: Catchments are listed in legend in order of size.
 Observed = closed circle
 Simulated using SDD = open circle
 Broken lines are for Equation 10-8 with $Q_1 = 2, 4, 6, 8$ and 10 .

10.4.1 Scale and impact detection

Any structure found in the results from the field monitoring and catchment modelling that shows there is some systematic variation in properties or hydrological behaviour with catchment size (such as the structure apparent in Figure 10.5) could potentially help greatly in simplifying the analysis of the potential for the downstream propagation of impacts of changes in land use/management.

In the simple detection modelling, the lumped equation for run-off is:

$$q = (s/b)^c \quad \text{Equation 10-9}$$

where q (mm/h) is discharge, s (mm) is catchment average storage, and b and c are parameters.

Figure 10.6 was created using Equation 10-9, with b and c taking the calibrated values from Table 10.1, which are for calibration against the stage recessions observed at the flow gauges. Each plot in Figure 10.6 is for a different value of discharge and shows the relationship between catchment area (x axis) and catchment average storage (y

axis). Note that Equation 10-9 was shown earlier to apply at all discharges, including at storm peaks.

The lines in the plots (fitted by eye) are for:

$$s = q \ln(A^2) \quad \text{Equation 10-10}$$

where A (km^2) is the catchment area.

This equation gives a reasonable fit, especially for the eight catchments with areas greater than 10 km^2 . Equation 10-10 is equivalent to Equation 10-9 with $b = \ln(A^2)$ and $c = 1$, so $b = \ln(A^2)$ is a scale relationship for the lumped modelling.

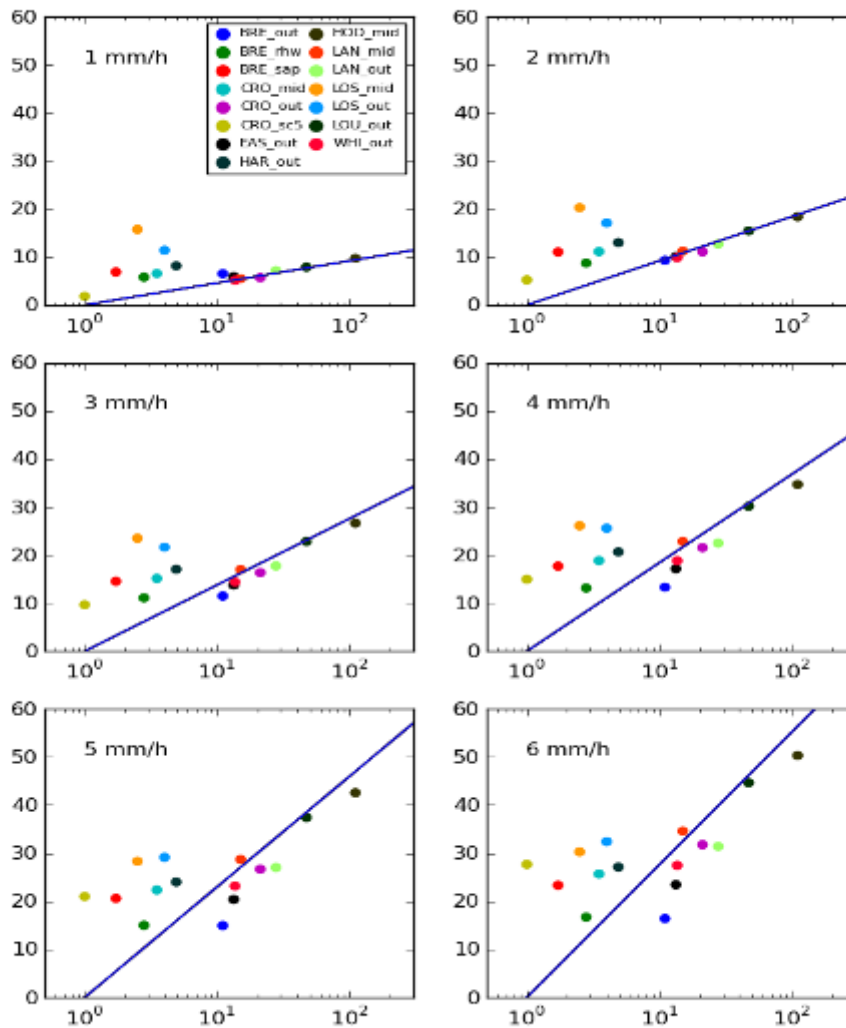


Figure 10.6 Storage (mm) plotted against catchment area (km^2) for six discharge rates

Notes: Lines are for Equation 10-10

10.4.2 Scaling up the effect of grip blocking

Useful data on grip blocking were recorded for United Utilities by Dinsdale Moorland Services Ltd, including the data plotted in Figure 10.7. The blocks were classified depending on grip depth: 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 metres (personal communication, N. Pilling, SCaMP, Bowland Estate).

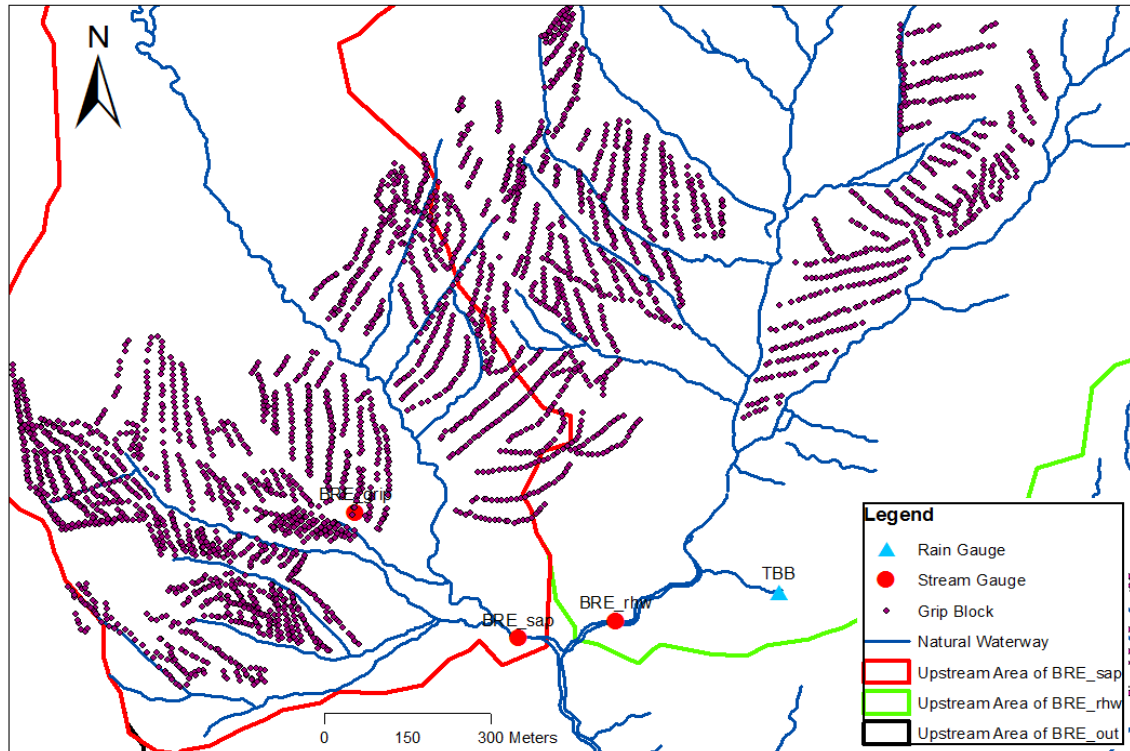


Figure 10.7 Grip blocks in Upper Brennand

In this project, the potential maximum storage upstream of three blocks selected randomly from each of four classes was estimated by detailed measurements of the ponds upstream of the blocks (Table 10.3) and the total potential calculated for blocked grip storage for the Brennand catchment (Table 10.4).

Table 10.3 Measured block storage volumes measured in Brennand catchment

Class (m depth)	Maximum storage (m ³)	Standard deviation (m ³)
1.0	0.23	0.083
1.5	0.81	0.084
2.0	6.79	2.5
2.5	21.57	2.8

Table 10.4 Potential blocked grip storage in Brennand catchment

Grip category	0.5 m	1.0 m	1.5 m	2.0 m	2.5 m	3.0 m	Total
Total length (m)	772.83	17922.64	6671.96	2254.09	576.37	73.95	28271.84
Number of blocks	77	1792	667	225	58	0	
Potential storage of a block (m ³)	0.15	0.23	0.81	6.79	21.57	0	
Total storage (m ³)	11.55	412.16	540.27	1527.75	1251.06	0	3742.79

The total potential storage is equivalent to 0.34 mm when averaged over the catchment area, while the scaled value for b is $\ln(11^2) = 4.8$ mm. The catchment response is very flashy (indicated by b being so low), with rapidly rising and falling discharge.

For a storm peak of 6 mm/h at the outlet from the Brennand catchment, the catchment storage would have had to rise quickly to $4.8 \times 6 = 28.8$ mm, suggesting that a process associated with 0.34 mm of storage is not important. Looking at it another way, if the peak storage were reduced by 0.34 mm because of the need to first satisfy the blocked grip storage, the discharge would have been $6 - 0.34/4.8 = 5.93$ mm/h (instead of 6 mm/h).

This problem is being studied in far more detail in the PhD work, including a review of what is known of the local effects of blocking on storage as free water and in the peat. If it were to be suggested that the grip blocking under the SCaMP programme of works does significantly affect the flood peaks at Hodder Place (or even at the outlet from the Brennand), it would probably have to be argued that either: (a) the above estimates of grip block storage are gross underestimates; and/or (b) the simplicity and robustness of the above arguments about scale are wrong because some different process becomes active or important after blocking, which causes the nature of the storage–discharge relationship to change dramatically.

Note that the arguments about scale, encapsulated in the storage–discharge and scale equations, seem to apply reasonably well at all the monitored mini- and mesoscale catchments whatever their topography, land use, land cover or their history of change in land use and management practices over the past years, decades or centuries. This all suggests there is inherent simplicity, stability and insensitivity to change in land use/management.

11 Analysis of short-term early effects of SCaMP works: distributed modelling

The distributed model is called the Dense Network Routing Model (DNRM). It was developed specifically for use in work of this type to analyse the roles played by various physical processes and spatial regions in flood generation and the impact of changes in climate and land use/management. Here, it is being used with a 500 metre grid, but a 200 metre or finer grid would be better given the small size of some of the gauged catchments. It is intended that a 200 metre or finer grid will be used at some stage in the future.

On the grid, a detailed drainage network is generated using a digital elevation map. This network drains every 500 metre cell (Figure 11.1). A custom-designed hydraulic routing model is run for the network. This is based on a fully implicit finite difference approximation to the non-inertia form of the Saint Venant equations (Akan and Yen 1981). The custom-designed fully implicit solution incorporated in DNRM conserves mass perfectly, as it was originally designed for use with mass tracking methods. It solves the global problem accurately (for example, for mutual backwater effects at the hundreds of confluences within the network).

The main data sets fed into the DNRM include:

- data from rain gauges and automatic weather stations (to feed the run-off production model for the 500 metre cells)
- drainage network derived from a 10 metre digital elevation map
- data from cross-section surveys, including geometry and vegetation
- library of channel roughness coefficients
- run-off model parameters, derived from the lumped modelling
- automatic and manual stage measurements (for use in testing and when reconciling the distributed and lumped modelling)
- discharge rating measurements (for use in testing and when reconciling the distributed and lumped modelling)

Figure 11.2 shows the nearest rain gauge to each cell in the grid. Where data are missing, data from the next nearest gauge are used.

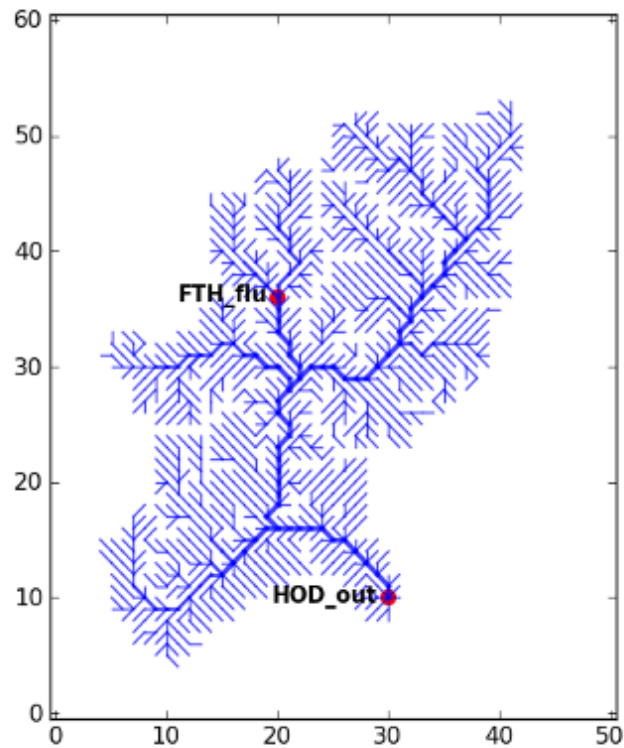


Figure 11.1 Drainage network represented in DNRM, showing locations of the Environment Agency gauges at Footholme flume and Hodder Place

Notes: x and y axes show cell column and row numbers, respectively

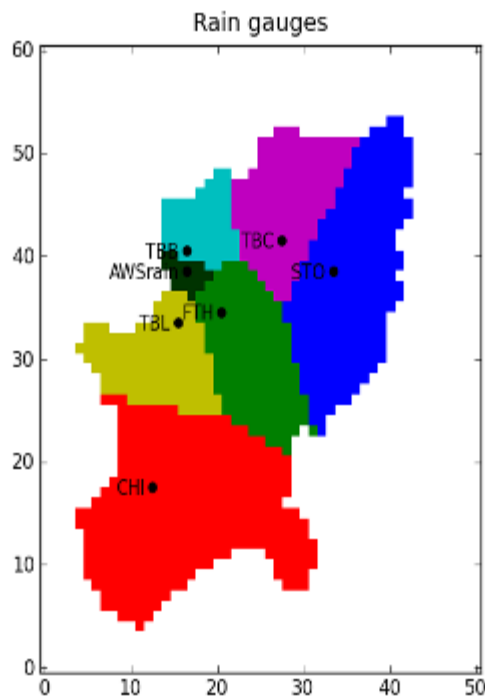


Figure 11.2 Nearest rain gauge to every 500 metre cell (with gauge labels)

11.1 Use of scaling

Cross-sectional data are imported into DNRM from a survey of 35 cross-sections, including the cross-sections at all the flow gauges. Using these data, as realistic as possible a drainage network geometry is created using an interpolation and extrapolation approach. Where data on the cross-section are missing, an automatic procedure is used based on hydraulic geometry equations derived for the Hodder catchment:

$$\text{Bank-full width} = 1.54(\text{upstream area})^{0.562} \quad \text{Equation 11-1}$$

$$\text{Bank-full area} = 0.603(\text{upstream area})^{0.693} \quad \text{Equation 11-2}$$

where the bank-full width and bank-full area are in metres and square metres, respectively, and the upstream area is in square kilometres.

The variation in vegetation cover and states along the cross-sections were recorded in the surveys, allowing a detailed estimate of Manning's n coefficient using a library of values based primarily on lists from Chow (1959). This estimate varies with stage, as different vegetation and surfaces are captured and submerged. The DNRM has the capability to allow Manning's n to vary with time, but this was not used.³

There is a scaling problem in reconciling the lumped and distributed modelling when setting the run-off parameters in the distributed model using the results from the lumped modelling. Each 500 metre cell supplies water to the network link that drains the cell. However, there are two fundamental problems.

First, ground-truth can be tested for the derived network but inevitably the quality of the network decays as the scale reduces, because the network geometry is constrained to follow the cell geometry (Figure 11.1). In effect, at a scale of 500 metres the attempt to represent the network is stopped and behaviour at scales below 500 metres is represented using the run-off modelling.⁴ The question that has to be asked, and which can be answered, partly, by using ground-truth from field surveys, is the following: is the network as represented at scales just above 500 metres appropriate and representative?

The second fundamental problem is dealing with scale in the representation of the run-off from the cells. In Section 11.1 it was shown that the b parameter from the lumped modelling is scale dependent. It should therefore not be used directly in parameterising the run-off for the cells at a scale of 500 metres. However, the process of iteration between the lumped and distributed modelling has to start somewhere. Each grid cell was therefore allocated to the nearest downstream gauge (Figure 11.3) and adopted the calibrated run-off parameters b and c (Table 10.1) for that gauge. The results reported here use this parameterisation.

³ This capability was designed, primarily, for use when floods cause vegetation flattening and there is subsequent recovery of vegetation stands.

⁴ There is, in effect, some trade-off between characterising the variability of the landscape and characterising the geometry of the network.

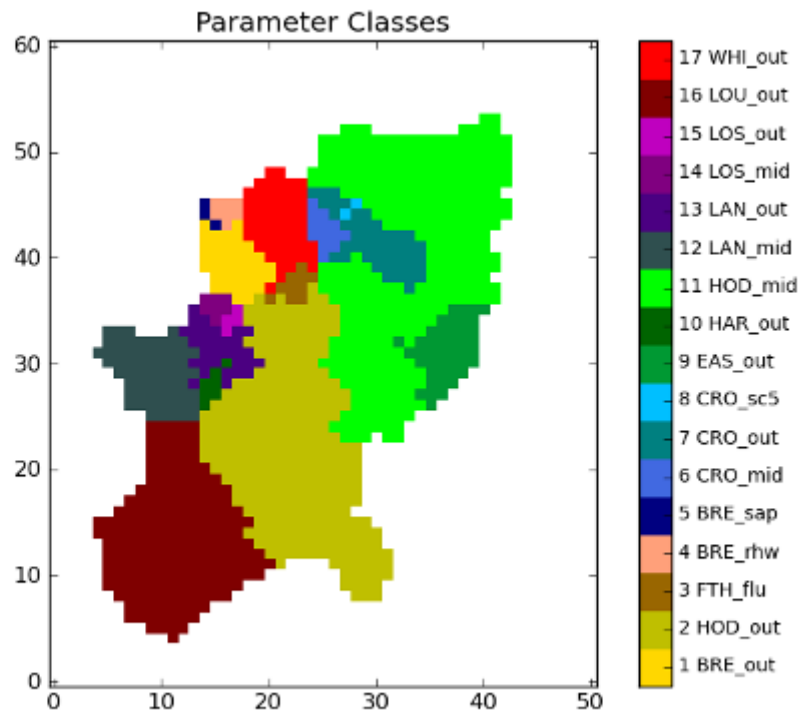


Figure 11.3 Parameter classes used in the DNRM run-off modelling

12 Testing and using DNRM

The main independent test of the distributed modelling is whether it accurately simulates the observed discharge at the Environment Agency gauges at Footholme and Hodder Place (Figure 12.1 and Figure 12.2, respectively). Both are simulated accurately; the error in early December is possibly the result of snow.

It should be borne in mind that the distributed modelling is not calibrated directly, so for example, there is no direct calibration based on the Nash and Sutcliffe efficiency, against the Environment Agency data for the gauges at Hodder Place and Footholme. The quality of the simulations depends on the quality of the small-scale data (including for rainfall and the cross-sections) and, as discussed in Sections 8 and 10.4, it depends on the calibration against:

- manually measured stage data
- manually measured rating data
- observed recessions that in turn depend on the assumptions made about the rating curves

Had the distributed model been calibrated directly on the Hodder Place and Footholme data, this would have broken the link between the small-scale information and the large-scale prediction of flow.

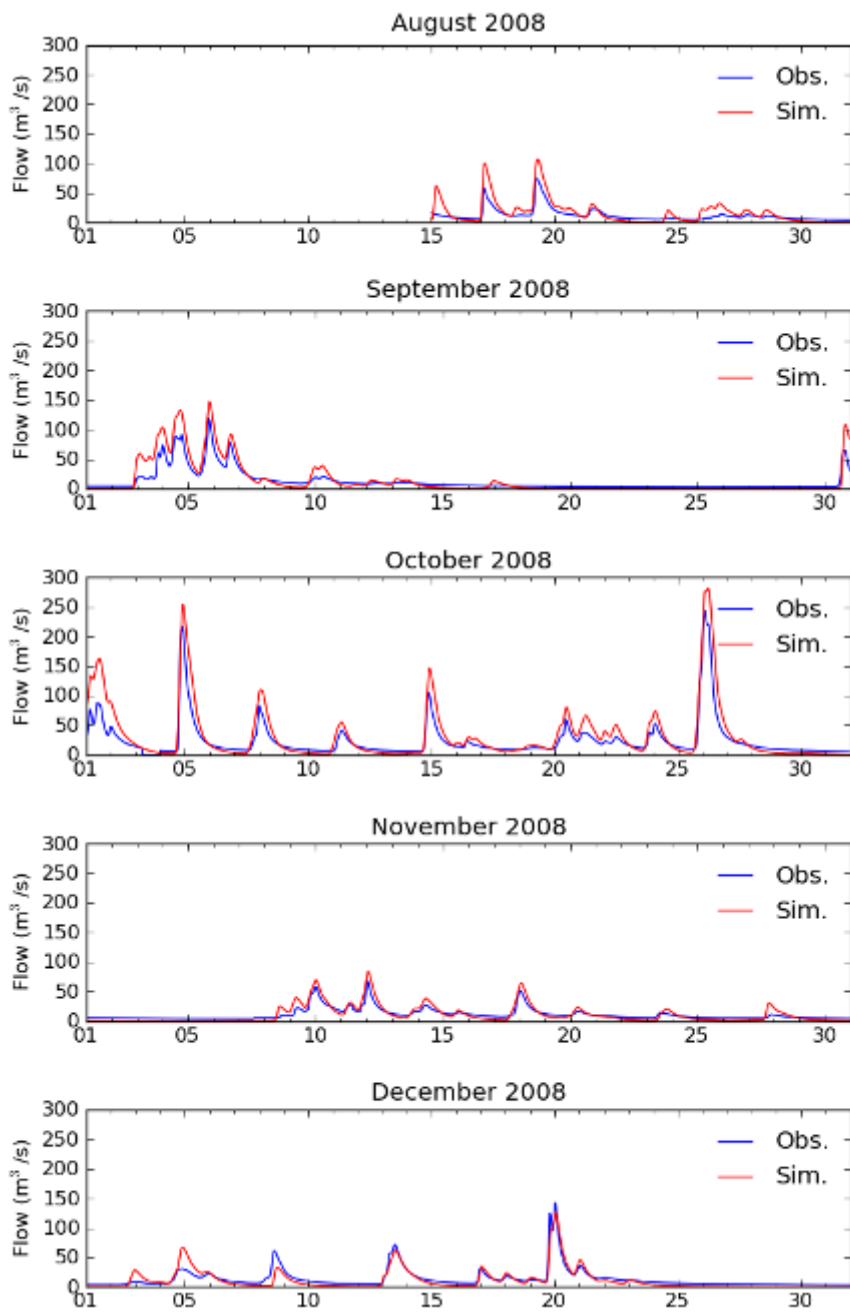


Figure 12.1 DNRM simulation and Environment Agency data for Hodder Place (HOD_out)

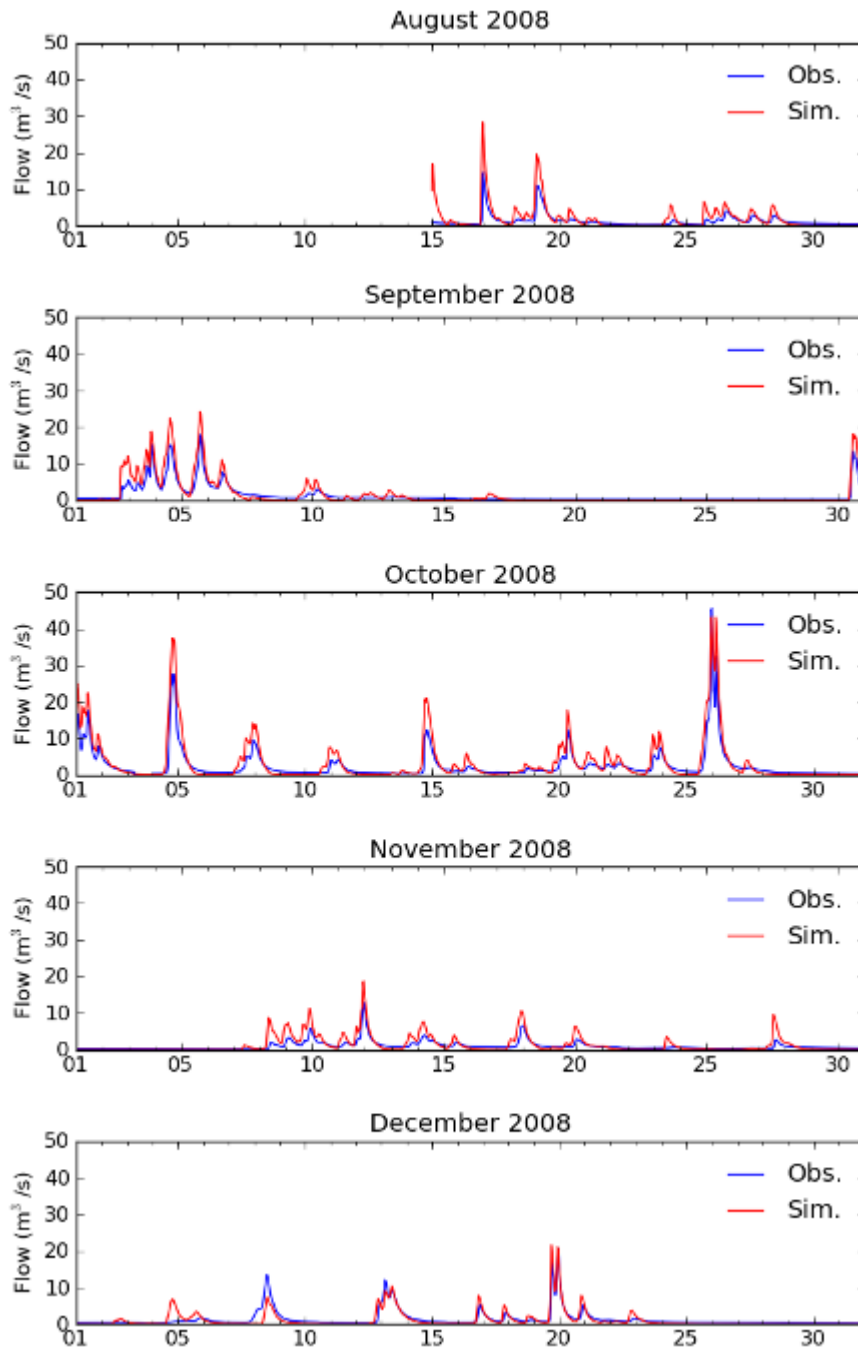


Figure 12.2 DNRM simulation and Environment Agency data for Footholme (FTH_flu)

12.1 DNRM simulations of stage

DNRM predicts stage, which can be compared directly to the observed stage (Figure 12.3). Fully reconciling the stage time series will require:

- adjusting the DNRM elevations (derived originally from the DEM)
- accounting for channel bed irregularities that give dead volumes
- adjusting or extending the roughness library

There is therefore quite a lot to learn from (and about) this process.

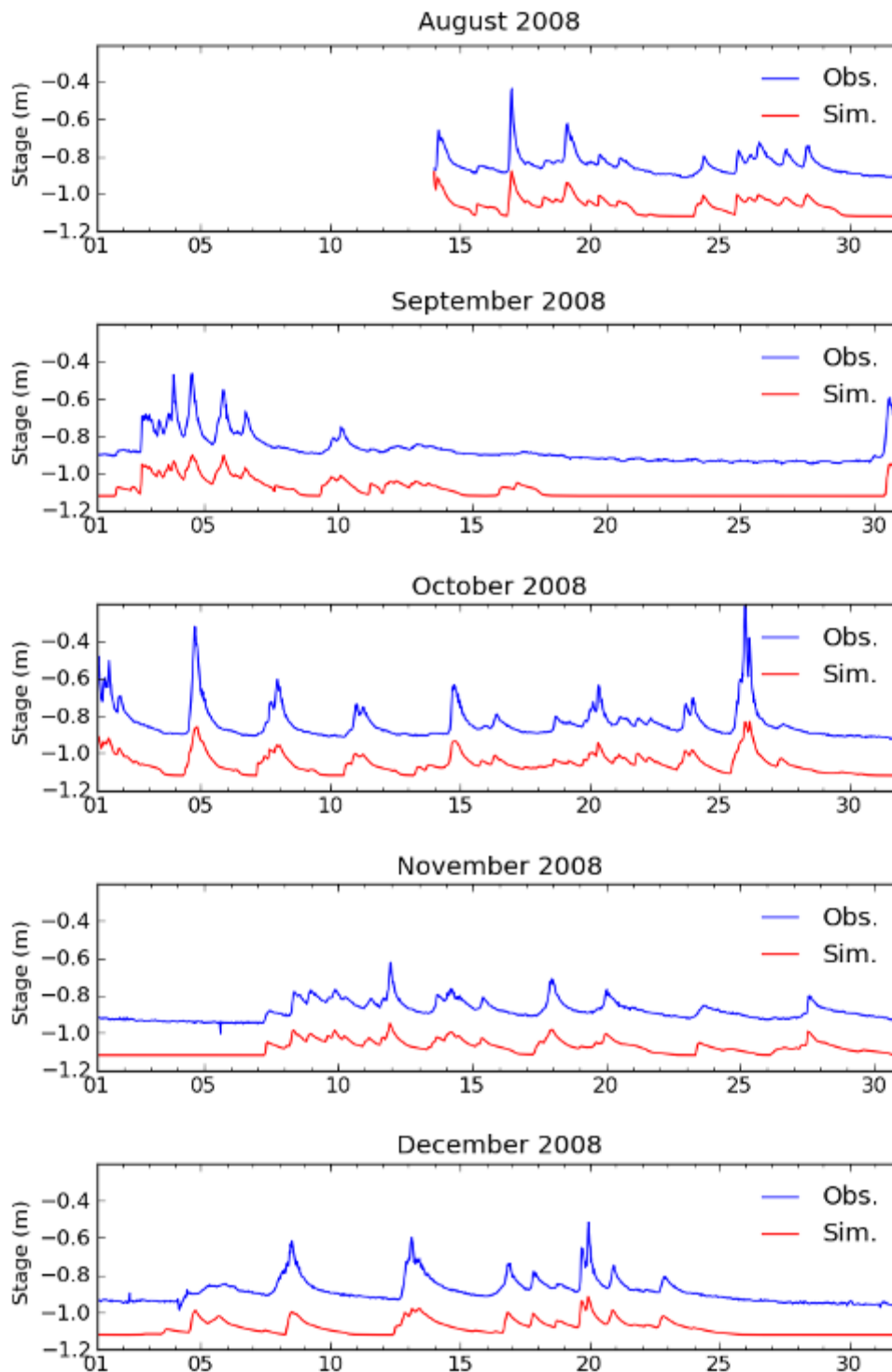


Figure 12.3 Observed and simulated stage for BRE_sap

12.2 DNRM simulation of rating curves

DNRM automatically gives hysteretic stage–discharge rating curves for each grid cell, which can be compared with the observed rating data and used to improve the representation of flow velocity (that is, the sigmoidal function) in the lumped model. Some examples of the rating curves derived using the DNRM are plotted in Figure 12.4.

The basic controls on the stage–discharge relationship are the channel geometry and friction, but the local flow dynamics and backwater effects can result in hysteresis (see plot for EAS_out in Figure 12.4). Part of the reconciliation of the lumped and distributed modelling will involve improving the quality of these plots. The improvement will involve:

- reconciling the elevations in the two models
- improving the representation of the bed slope in the DNRM – currently it is based on the 500 metre grid values, but the local slope has been measured in the field
- accounting for dead volume in the cross-sections using results from flow gauging
- improving the sigmoidal function in the lumped velocity modelling
- refining the method used to calculate the average Manning’s n over the cross-section using the field data on cross-section vegetation cover and condition

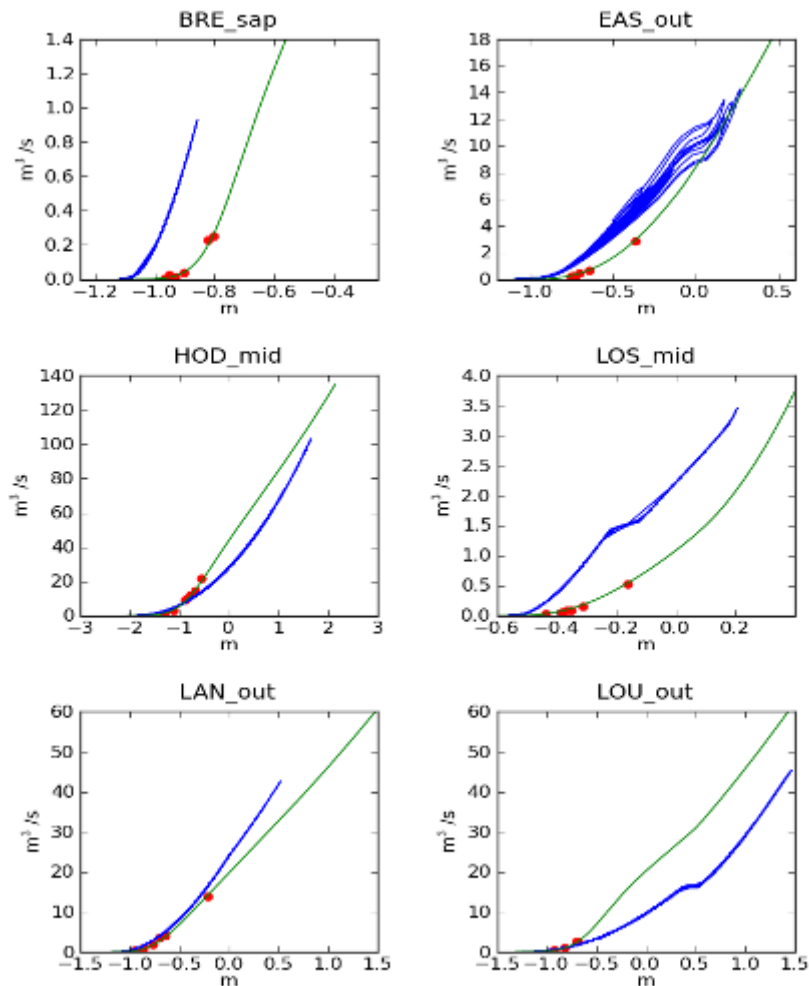


Figure 12.4 Comparison between observed discharge (dots), the sigmoidal rating curve (green) and the DNRM-derived rating curve (blue)

12.3 Sensitivity maps derived from DNRM adjoint modelling

It would be very useful to be able to estimate the downstream flood impact associated with changes in run-off processes upstream (as represented, for example, by changes in the run-off parameters b and c). If such estimation were possible, tools for flood risk management could be developed for use when assessing the flood impact of various schemes for rural land use/management.

Consider, for example, the impact of a change in parameter b . One very simple measure of the potential for downstream impact is the spatially variable sensitivity $\partial Q/\partial \Lambda(x,y)$ where Q is a peak discharge at a flood site and $\Lambda(x,y)$ is a spatially-variable change in parameter b .

Say, for example, that at cell i (centred at coordinates x_i, y_i), parameter b is increased to $b+\varepsilon$, where ε is linked to some small change in the physical properties in the land covered by cell i . The estimated impact downstream (that is, the change in peak discharge) is then $\varepsilon \partial Q/\partial \Lambda(x_i, y_i)$. If two cells, i and j are changed, then the estimated impact is $\varepsilon_i \partial Q/\partial \Lambda(x_i, y_i) + \varepsilon_j \partial Q/\partial \Lambda(x_j, y_j)$. This approach involves a linearisation (superposition) of impact and its accuracy will tend to fall with the magnitude of change and with the number of cells involved.

Two advantages of working with the spatially variable sensitivity are that:

- grid maps of sensitivity can be calculated extremely quickly and accurately using algorithmic differentiation (Griewank 2000)
- these maps give some insight into some of the less tractable problems in estimating impacts

Note that sensitivities of this type can be calculated for any of the thousands of numbers that are entered into the DNRM including rainfall rates, time steps and channel roughnesses.

A reverse algorithmic differentiation (adjoint) version of DNRM was created using Tapenade (Hascoët and Pascual 2004). There are many potential pitfalls when working with algorithmic differentiation, so the DNRM code (FORTRAN95) was written in a style (learned by bitter experience) which minimises the difficulty of obtaining an accurate and reliable adjoint code. This code was then tested for accuracy. Typically it is accurate to 1 part in 10^{10} , far in excess of the accuracy required for work of this type.

Three peaks in flow at Hodder Place were studied:

- 254 m³/s on 4 October 2008
- 288 m³/s on 26 October 2008
- 147 m³/s on 17 July 2009

Figure 12.5 shows the sensitivities of these peaks to parameter b . As expected, the spatial patterns for sensitivity depend on the spatial pattern of parameter values and rainfall (Figure 11.2 and Figure 11.3).

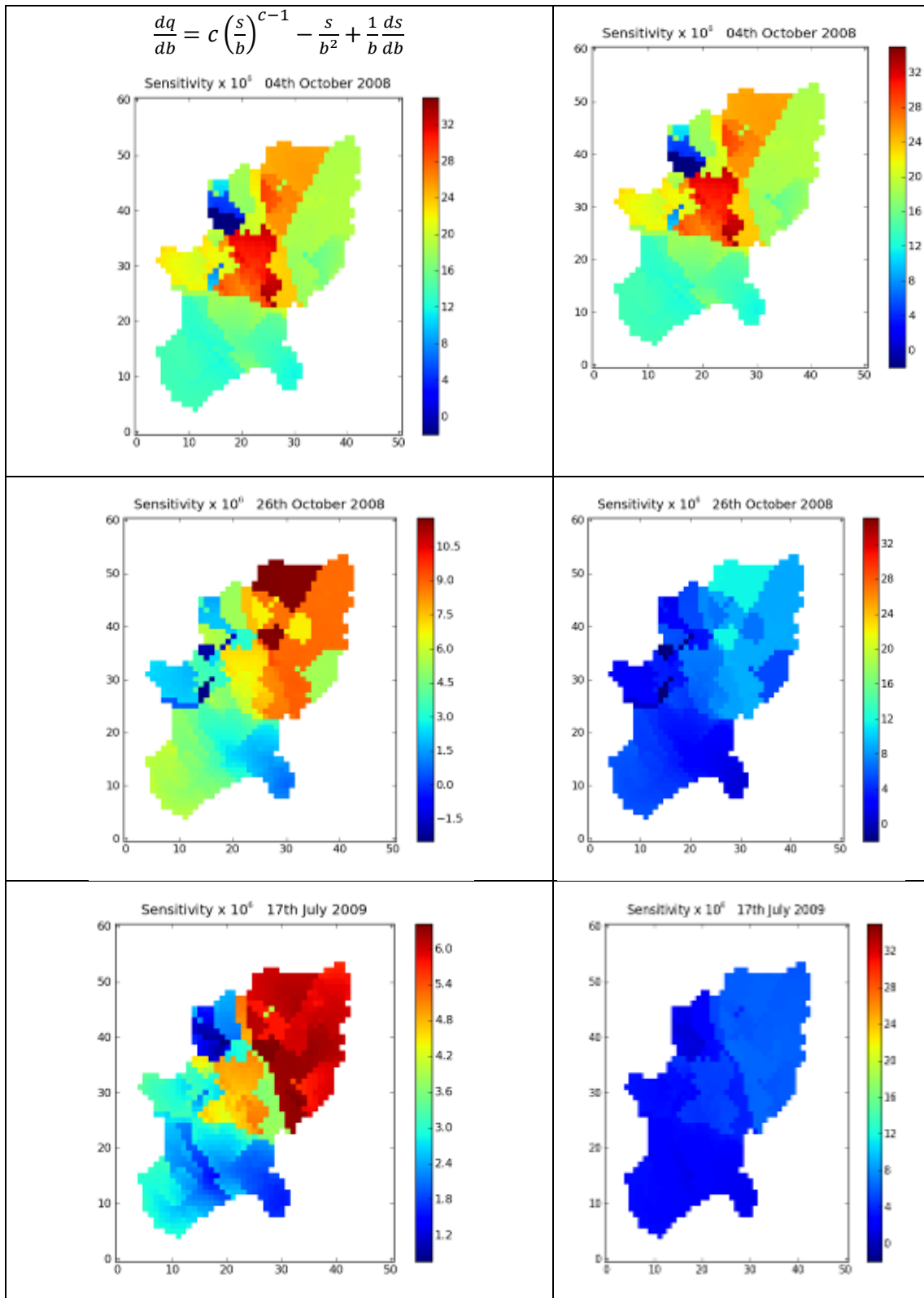


Figure 12.5 Sensitivity of magnitude of three peaks to a change in parameter b

Notes: The same data are plotted twice for each peak; for ease of comparison between the peaks, all three plots on the right have the same scale.

Something of the complexity of the sensitivity is described below. For each cell, the sensitivity to b is given by:

$$\frac{dq}{db} = c \left(\frac{s}{b}\right)^{c-1} - \frac{s}{b^2} + \frac{1}{b} \frac{ds}{db}$$

Equation 12-1

This sensitivity depends on the current storage, s , and so depends on the history of impact that a change in b has on the storage. The peak flow downstream, Q , is some complicated function of $q(x,y,t)$. This function is, effectively, described by DNRM, as a solution of the Saint Venant equations, solved on a network. The conclusion is that the sensitivities shown in the sensitivity maps depend on the space–time behaviours, in run-off and network flow, that result in the peak.

In the FREE and FRMRC2 projects, this approach is being used to produce maps designed to be generally useful in flood risk management.

13 Discussion and conclusions

The need for new data sets, models and methods for estimating the impact that changes in rural land use/management have on downstream flooding was laid out in detail in the FD2114 review (O'Connell et al. 2005). This project (SC060092) exploited an opportunity (Ewen et al. 2006b) which arose to monitor the impact of the extensive upland restoration works being carried out in the Hodder catchment in north-west England under the United Utilities' SCaMP. A detailed EPR has been created so that the Hodder data collected and assembled in this project can be made available to researchers, now and in the future.

The ultimate goal for the work with the Hodder and the SCaMP is to estimate the impact that the SCaMP works have on the flood hazard downstream, as represented by the impact on the FFC at the catchment outlet (Hodder Place, 261 km²). This is well beyond the scope of this project, but it is a goal in the NERC-FREE and EPSRC-FRMRC2 programmes where the EPR is currently being used to help develop and test new models and methods for estimating impacts.

Some early results from that work are included here to show how the data collected in Project SC060092 are being used to create sensitivity maps for the Hodder catchment. Sensitivity maps are being used as a basis for creating maps of vulnerability to changes in land use/management for use in flood risk management. A less ambitious analysis, partly performed in this project, is also described. This involves trying to detect any early short-term impacts that the SCaMP works have on hydrographs measured at a range of spatial scales in the catchment.

One of the problems with measuring, detecting and predicting impacts is that catchment hydrology is inherently complex and variable, and any measurement, detection or prediction must be made in the appropriate context. A substantial part of this report is therefore about context, summarising various results from surveys on the nature of the catchment, its climate and hydrology. Given the lack of knowledge about the mechanics of impacts, the surveys were quite wide-ranging, so that a wide scope can be represented in the EPR; they cover subjects such as geology, soils, water abstractions, forestry, and the history of rainfall and run-off.

Central to understanding the context is an understanding of the space scales and time scales associated with the various information and data available for the catchment, and of the space scales and time scales for impacts. This topic is discussed in the report. Inevitably, there is a mismatch between the scales for a FFC (large space scale and long time scale) and the scales for the Hodder monitoring data. There is little that can be done about time scales for the monitoring data, other than to let time pass and continue with the monitoring, but considerable effort was expended to make sure that space scales are well represented.

The instrument network for flow measurement installed in this project is a multiscale nested network, which allows the propagation of flood peaks to be monitored. In total there are 31 gauges, nested up to five deep (for example, 0.0014, 1.7, 11, 25 and 261 km² in the nested catchments of Sapling Clough, Brennand, Dunsop and Hodder). To complement the flow network, rain gauges and an AWS were installed.

The methods used to prepare the raw monitoring data for use in the analysis of early short-term impacts, and the analyses themselves, are described in detail in this report. These methods have all been automated (using FORTRAN and Python) so they can be applied accurately and consistently to all the data from all the gauges. So far, analyses of early short-term impact have been performed for 15 flow gauges.

This project funded a PhD studentship (Josie Geris) but the resulting PhD thesis is not due for submission until January 2011, well after the formal end of Project SC060092 (February 2010). The field monitoring and analysis work will therefore continue and the results from that work will continue to be used in the FREE and FRMRC2 projects until at least June 2011.

13.1 Outcome, errors and limitations

This is very much a work in progress and a fuller analysis will be possible using the data collected during the autumn and winter of 2009 to 2010.

The analysis of early short-term impacts seems to indicate that the SCaMP works did not have a marked effect on discharge in the river network. A simple rainfall–run-off catchment model was developed and calibrated for the pre-change conditions and then run for the post-change conditions. The parameterisation for the pre-change conditions proved to be perfectly adequate for representing post-change conditions, albeit based on limited data.

The methods used were designed to make an analysis of errors and uncertainty possible. For example, the raw stage data from the flow gauges were calibrated against manual measurements and the outcome from the calibrations can be used to derive error estimates for stage. This will be done in the PhD work. In addition, the entire work was designed in such a way that it can be used in sensitivity analysis using algorithmic differentiation; an example was given of how maps of sensitivity to changes in land use/management can be derived for the catchment. This will be used in the FREE project to estimate the overall sensitivity to errors, so that the error and uncertainty analysis can focus on the particular data and modelling that are really important in producing the overall results.

What is worth remarking on is the simplicity and robustness of the modelling, which suggests insensitivity to errors. It also probably indicates simplicity and robustness in the hydrology, and this suggests insensitivity to change in land use/management. The ability for this simplicity and robustness to emerge in the analysis clearly relies on the design of the field programme; in particular it relies on the high density of the monitoring of rainfall and flow. Note, however, that the simple modelling suggests there is significant sensitivity to weather variability, because there is a direct and fundamental link between rainfall rates and peak discharges.

There are weaknesses in this work, associated with the monitoring period being short and therefore not covering the full range of hydrological variability expected in the Hodder catchment. This may partly explain the apparent simplicity and robustness of the hydrology. Relatively few data were collected in the summer period prior to the implementation of the SCaMP works and the modelling is poor for the summer period. An iterative method of analysis has been developed that uses lumped and distributed modelling to help overcome the difficulties of predicting impacts and the limitations of the data set. Summer flows will be considered in more detail in future iterations, but the lack of summer data – and the shortness of the Hodder data set in general – will continue to be a problem.

The question of whether the SCaMP works will have an effect on flooding in the long term is addressed by the iterative method, but is not discussed in any detail in the report. It was noted that grip blocking may have effects that develop over time, and similar arguments can be made for changes in stocking density (for example, effects on soil compaction and infiltration in particularly wet seasons) and for changes over the lifetime of woodland growth and felling. It is worth noting that the tree planting was carried out without installing extra drainage or the need for frequent access by heavy vehicles.

The modelling seems to show that the storm response of the catchment can be modelled adequately using descriptions of very short-term behaviours, associated with small transient changes in water storage. However, the three lowest annual maximum discharges measured at the catchment outlet at Hodder Place occurred after droughts. This suggests there may be long-term behaviours. Two obvious possibilities for controls on long-term behaviours are:

- water abstraction, including storage and releases from Stocks Reservoir
- natural temporal patterns in climate

Neither of these will necessarily affect the impact of the SCaMP works. Any significant long-term effect on impact would probably require a dramatic change in the water storage and/or flow within the subsurface of the catchment.

13.2 Meeting the project objectives

The first two of the three objectives listed in the inception report for this project were designed to address the problem of understanding and improving the database (called the change-effects database in the inception report) which supports future research and operational needs for the prediction of the impact of changes in rural land use/management on downstream flooding. The three objectives were given as:

1. Analyse the requirements and value of the change-effects database, and create a database that defines and stores the data required for analysing and modelling change effects (this will be a template for use in future field and modelling programmes).
2. Contribute to, and widen, the change-effects database.
3. Run preliminary analyses of the link between land use/management change and flood impact, using the new data collected during the project.

The EPR, which stores and makes available everything learned in this project, is central to meeting these objectives. The EPR stores the Hodder data (Objective 1), is intended as a general contribution to the information available on the impacts on flooding (Objectives 1 and 2), and will be used to supply data for analyses and to record the outcomes from these analyses (Objective 3). It is also, in a general sense, a template for use in future field and modelling programmes (Objective 1). In her PhD thesis, Josie Geris will include specific recommendations for monitoring designs that directly address the problem of estimating impacts (Objective 1). Work in this project (and in the FREE project) on analysing the downstream impact of the SCaMP works is described in this report (Objective 3).

Three specific hypotheses that required testing were developed soon after the project got underway.

- **Hypothesis 1:** the downstream flood impact of the SCaMP changes in the Hodder catchment can be detected and predicted with a level of accuracy that would make such detections and predictions useful in management systems such as MDSF.
- **Hypothesis 2:** the propagation of flood impacts downstream can be predicted using models validated against data from multiscale nested flow monitoring networks, such as the network implemented in the Hodder catchment in this project.

- **Hypothesis 3:** inexpensive large-scale measurements can be made that are surrogates for hydrological state, and these can be used in the estimation of downstream flood impact.

Hypothesis 1 is addressed directly by the work on detecting and predicting impacts, and work on this hypothesis will continue in the PhD study and in the FREE and FRMRC2 programmes. All that can be said at the moment is that there is no evidence yet that the SCaMP works have had, or will cause, a large, easy-to-detect impact at Hodder Place.

Hypothesis 2 is addressed directly by Section 7 of this report on the scope for analysis using the Hodder data. This section showed the fundamental difficulty of predicting the impact on the T-year flood, based on discussions on the way that FFCs propagate through the catchment. The question of whether validated models can be created for the effects that the SCaMP works have on impacts at a range of scales is addressed in the work on detecting early short-term impacts (Section 10). This work has made the maximum possible use of the multiscale nested flow monitoring data collected for the Hodder.

Very little progress has been made with Hypothesis 3, other than that the catchment discharge is used as a surrogate for hydrological state in some of the storage–discharge modelling. This hypothesis will be considered again (in the PhD study) when developing specific recommendations for monitoring designs that directly address the problem of estimating impacts.

13.3 General comments

Five aspects of the way this project was carried out are worth further comment.

First, multiple nested flow gauges were used to capture as much as practical of the response of the drainage network, but no attempt was made to monitor local variables such as phreatic surface levels or moisture contents. This reflects decisions made in prioritising the use of resources, while taking into account that researchers from Imperial College (partners in the FREE and FRMRC2 projects) are monitoring local variables at their experimental site at Pontbren in mid-Wales. The argument for monitoring local variables is that these are the variables most directly and immediately affected by changes in land use/management. Had some impact of the SCaMP works been detected in the drainage network, then local variable data could have proved useful in testing hypotheses about the origin of these impacts. However, as is argued at length in the FD2114 review, there are no existing models or methods that can reliably use local variable data to predict such impacts.⁵

Second, an electronic project record was created that will be a legacy for this project, which should be useful to researchers in the future. This was time-consuming but worthwhile. It is a response to repeated frustration over the years when trying to construct and reconstruct data sets using fragmented information held by numerous people and bodies in numerous locations and in various states of decay. The effort involved in creating the EPR amounted to approximately 15% of the total effort put into data collection and archiving.

Third, scripts and codes were used to automate the analysis in such a way that there is an auditable trail between the raw data collected in the field and the final outcomes such as sensitivity maps. This was done to maintain the link between scales to make possible a full analysis of the propagation of impact of change effects from the small-

⁵ Work towards developing suitable models continued at Imperial College through the FREE and FRMRC2 programmes.

scale to the large-scale. This link is invariably broken in standard analyses, usually when there is calibration of some outcome. This was also time-consuming but worthwhile. One further advantage of this approach is that the full analysis, including the generation of plots and reporting, can be updated very simply and quickly when new data become available, and the updating can be done safely by someone unfamiliar with the details of the mathematical and statistical methods of analysis.

Fourth, an iteration approach has been developed in the FREE and FRMRC2 programmes that tries to reconcile small-scale and large-scale information in a way that allows the downstream propagation of impacts to be predicted, leading to the creation of vulnerability maps useful in flood risk management. This faces the following enormous problems.

- The major review in Project FD2114 concluded that traditional models and methods are not fit for the purpose of predicting impacts, let alone predicting detailed upstream spatial patterns associated with the generation of downstream impact.
- There is a lack and sparsity of data on catchment hydrology in general and impact responses in particular.
- The data set for the Hodder catchment is particularly short.

The work reported here is an encouraging start towards developing methods and models in which scale information can be tested, visualised and interpreted, giving a basis for new impact prediction methods and models that derive from, and are validated within, closely integrated programmes of field work and modelling.

Finally, full analysis of the impact of changes in land use/management would require good quality data sets covering several-year-long periods both pre- and post-change. This would require planning, preparation and long-term commitment to detailed monitoring. This project took an unconventional but appropriately simple and direct approach to monitoring for the detection of impacts. Despite the shortness of the monitoring, some interesting results are emerging about the nature of the storm response and its scaling with drained area. When used with new modelling methods in the FREE and FRMRC2 programmes, these results promise to give some important insights into the potential for downstream impact.

13.4 Future work

If field studies similar to that described here are implemented elsewhere then a strong recommendation is made that:

- the work is started early so that the pre-change hydrology can be investigated (for example, five years prior to the planned changes being implemented)
- an electronic project record is created and released for general use, so that the research community can extract the maximum outcome from the investment
- the monitoring continues for at least five years after the change

Even with a 10-year record, there will be considerable uncertainty in any estimate for the impact on the FFC. However, valuable analysis of the type described in this report should be possible. The question then arises as to whether more studies are actually needed. It was noted earlier that both Defra's 'Making Space for Water' strategy and Sir Michael Pitt's review of the summer 2007 floods recommended using land use to

reduce flooding. If the preliminary results presented in this report are taken at face value, however, they seem to show that for the Hodder it would be difficult to achieve a significant reduction in flood hazard because downstream discharges are only weakly sensitive to upland changes in land use/management, and any management strategy may have to be complex in nature because there is spatial complexity in the sensitivity. The only way to find out if this is correct, and if it applies to other sites, is to conduct more studies.

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List of abbreviations

AWS	automatic weather station
BGS	British Geological Survey
CHASM	Catchment Hydrology and Sustainable Management
DEM	digital elevation model
DNRM	Dense Network Routing Model
EPR	Electronic Project Record
EPSRC	Engineering and Physical Sciences Research Council
FAO	Food and Agricultural Organization
FFC	Flood Frequency Curve
FREE	Flood Risk from Extreme Events
FRMRC2	Flood Risk Management Research Consortium 2
MDSF	Modelling and Decision Support Framework
MIDAS	Met Office Integrated Data Archive System
MLD	million litres per day
mOD	metres above Ordnance Datum
MORECS	Meteorological Office Rainfall and Evapotranspiration Calculation System
NERC	Natural Environment Research Council
PBD	Physically Based Distributed
POT	peak over threshold
SCaMP	Sustainable Catchment Management Plan
SDD	simple storage/discharge [model]
SPR	Source–Pathway–Receptor
SSSI	Site of Special Scientific Interest
SWP	Super Work Package
TBR	tipping bucket rain gauge

Appendix A: Chapter outline for PhD thesis

The following is a chapter outline (under review) for Josie Geris' PhD thesis: 'Multiscale experimentation, monitoring and analysis of the impacts of local scale, upstream, land use management changes on downstream flooding'.

Rather than following a strict formula (for example, introduction, methods, results, discussion and conclusions), the thesis will present the work as a coherent story, building up to the main conclusions.

Chapter 1: Introduction

Chapter 1 will introduce the reader to the subject and set the context of the study (that is, the increasing problems concerning flooding and the knowledge gap regarding the effects of land use/management changes on flooding across scales). Additionally, it will present the main research aims (that is, to gain a better understanding of the effect of local-scale land use/management changes on downstream flooding) and propose some hypotheses to be tested. It will also give an overview of the further thesis structure.

Chapter 2: Literature review

The second chapter will present a literature review. It will include an evaluation of peat hydrology, as peat is the dominant material in the headwaters of the Hodder. Secondly, the main relevant land use/management changes (grip blocking, tree planting and stocking density changes) and their effects on the hydrological behaviour of the catchment will be reviewed. In addition, scaling issues in hydrology with regard to the effects of land use/management changes will be examined. This chapter will also include a review on some of the methods used (for example, modelling tools, change detection).

Chapter 3: Experimental catchment description, land use/management changes, and the monitoring design

Firstly, chapter 3 will give a description of the study catchment (climate, geology, geomorphology, land use, soils, and so on). It will then describe the land use/management changes that the catchment has been subjected to (historical changes as far as known, but mainly the changes implemented in SCaMP and by the Forestry Commission). This chapter will also include the multiscale nested monitoring design that has been implemented so as to study the catchment behaviour before, during and after the implementation of the land use/management changes.

Chapter 4: General catchment behaviour

This chapter will describe how the sub-catchments and the catchment as a whole function, especially when generating flood hydrographs. An understanding of the catchment prior to the implementation of any land use/management changes is needed to understand the potential changes in behaviour as a result of land use/management changes.

Chapter 5: The local scale sites

This chapter will analyse and discuss if and how the specific land use/management changes have affected the run-off generation at the local scale. At four locations in the catchment, small-scale monitoring of the three main land use/management changes is carried out and the data analysis at these sites will be discussed here. Special attention

will be paid to the timing and shape of the hydrograph. Method, results, discussion and conclusion will be included.

Chapter 6: Scaling

A scaling relationship is needed that links the findings from the previous chapter to the data at the catchment outlet. This chapter will deal with the question of how the effects of local-scale land use/management changes propagate downstream. Method, results, discussion and conclusion will be included.

Chapter 7: Modelling

The DNRM distributed modelling of the Hodder catchment being used in the NERC-FREE and EPSRC-FRMRC2 projects will be used to integrate the small-scale results from Chapter 5 and the scaling information from Chapter 6 to make predictions of the impact of the SCaMP works at larger scales. These results will be used in Chapter 8 in the study of the value of the field data in estimating the impacts of changes in rural land use/management on downstream flooding. The model is called DNRM (Dense Network Routing Model). It runs on a fine grid (ideally 200 metres or smaller) and the results from Chapter 5 will be used to alter the modelling of the run-off from the grid squares to see the resulting impact at large scales. Method, results, discussion and conclusion will be included.

Chapter 8: Worth of multiscale field data

The PhD project is very much field-based and a large amount of time has been spent on data acquisition. Chapter 8 will evaluate these data and ask whether the Hodder data are comprehensive or good enough to answer the research questions. This will include an analysis of errors. Recommendations for future studies of impact, outlining the requirements for instrumentation and data, will be included. Method, results, discussion and conclusion will be included.

Chapter 9: Conclusions

Finally, this chapter will summarise the study and present the main conclusions. In addition, suggestions for further research will be made.

Appendix B: Accessing and using the Electronic Project Record

Access

Access to the Electronic Project Record (EPR) is available through the Environment Agency.

Appearance

The EPR has the appearance of a web page with a menu bar across the top of the page (see Figure B.1). This menu bar is divided into five high-level groups, each of which has one or more sub-groups. The second high-level group, 'Products', is the most important. It contains all the maps, photographs and measurements created/collected by Newcastle University.

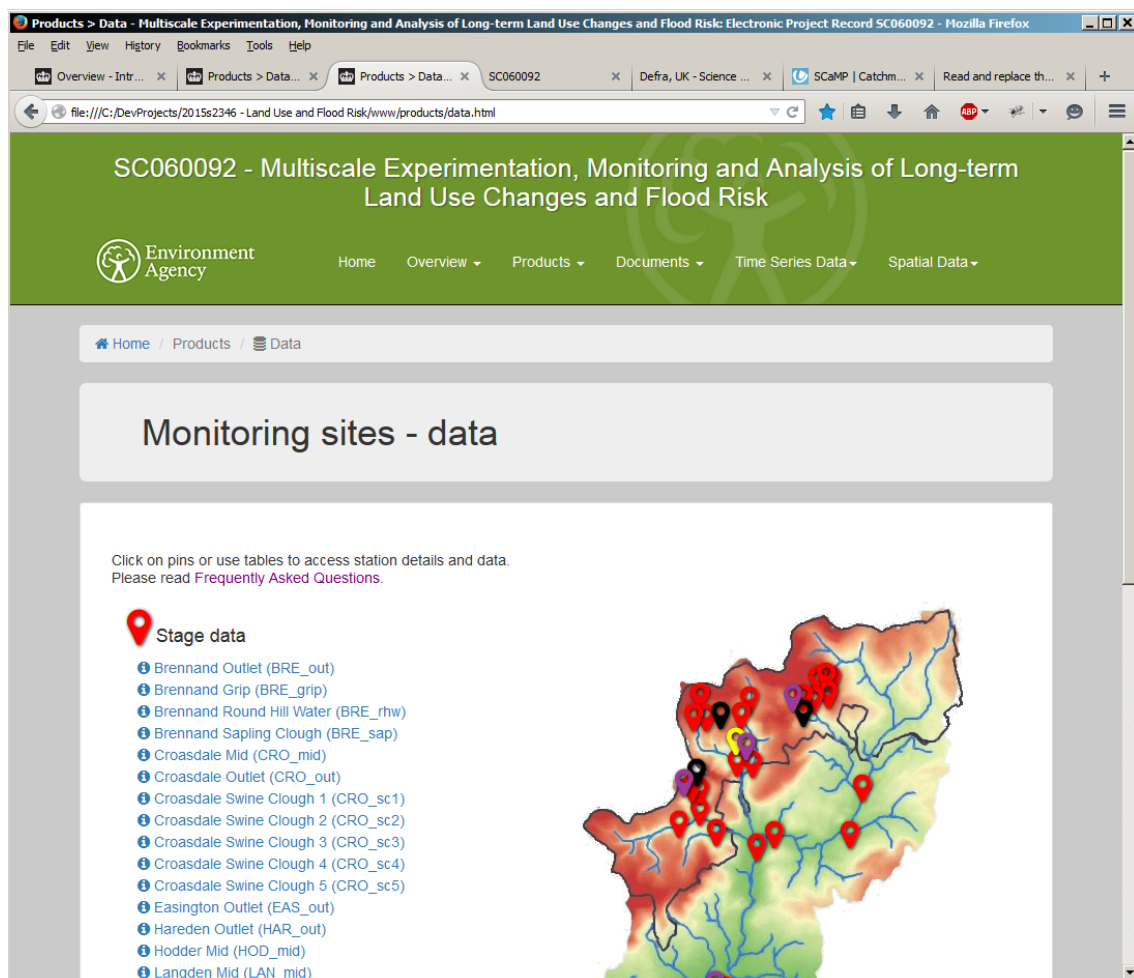


Figure B.1 Electronic project record screenshot

Icons

Icons are used throughout the database, to make data and information elements more visible to the user (Figure B.2).









-  Further information
-  Map point or marker
-  Data in compressed document (zip file)
-  Data in MS Excel file
-  Data in ASCII data
-  Data plots
-  PDF file
-  Indicates an external link, requiring internet access to view

Figure B.2 Icon key

Breadcrumbs

For convenience, a 'breadcrumb' trail is shown. This shows you where you are in the database hierarchy (Figure B.3).

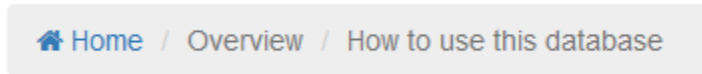


Figure B.3 Breadcrumbs

Navigation menu

On a larger screen such as on a desktop computer, navigation through the EPR is via the menu bar at the top of the page (Figure B.4).

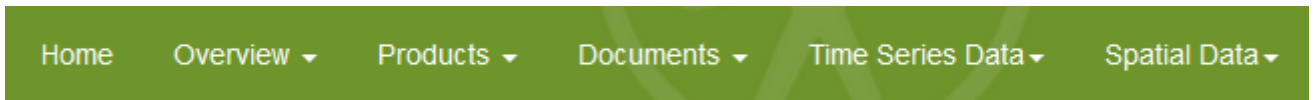


Figure B.4 Navigation men

On a smaller screen such as a mobile device, the standard menu will be hidden, but accessible via a 'menu' button. Once this button is clicked, a menu will appear running from top to bottom. This contains the main groups. Clicking on a group will expand the group, making its items visible (Figure B.5).

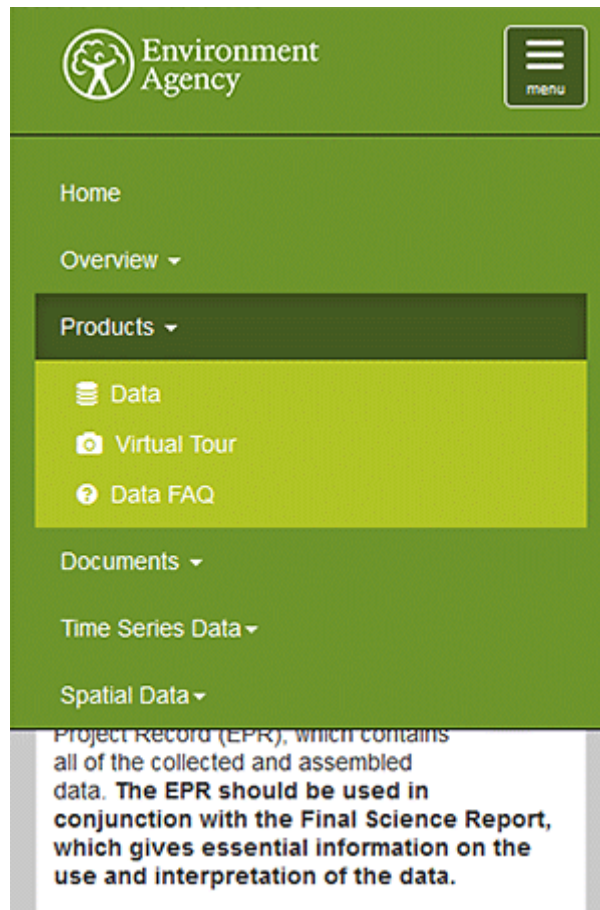


Figure B.5 Navigation menu for mobiles

Sub-menus

Clicking an item on the main menu will open a sub-menu. The main menu bar is divided into sub-menus, each containing related links relevant to that group. Click on any main link to access its sub-menu (Figure B.6).

The group 'Products' is the most important. It has all the maps, photographs and measurements created/collected by Newcastle University.

To access the field monitoring data, click on 'Data' in the 'Products' menu group (Figure B.8). This will take you to the Data page.

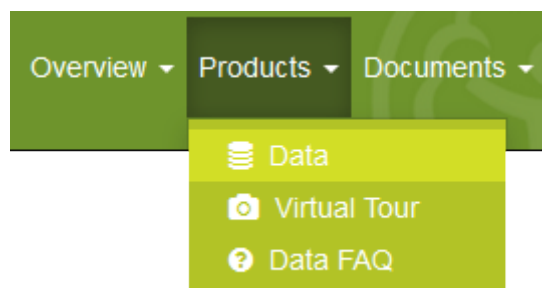


Figure B.6 Sub-menus and data access

Products > Data

The pins shown on the map in the Products > Data page are active. When a pin is clicked, a new page is called up.

Alongside the map is a list of links to the same data pages (Figure B.7).

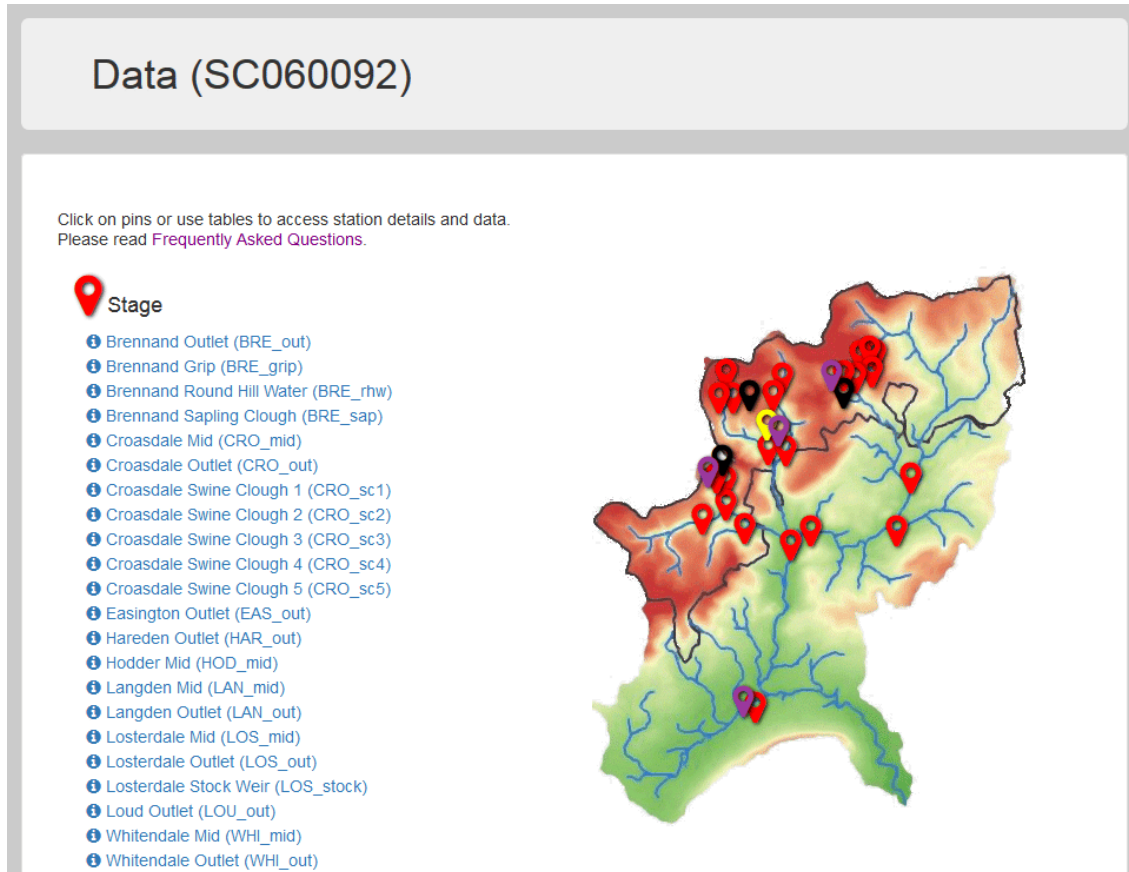


Figure B.7 Data pins

Example data page (Brennand Outlet, BRE_out)

The Products > Data page shows all the instruments.

Clicking on a pin or an 'information' icon brings up an instrument page such as the Products / Data / BRE_out page shown in the example in Figure B.8.

The instrument pages have a range of useful information including locations, photographs, channel cross-sections and time series measurements.

Instrument: Brennand Outlet

Summary Details

ID	BRE_out
Location #	2
Measurement	Stage
Catchment	Brennand
OS Grid ref	SD 65271 53214
Elevation	172.7 m
Area	11.0 km ²
Data availability	07/12/2007 - 31/01/2010 (data unreliable between 06/06/2009 - 25/06/2009 due to disturbance by livestock; gauge relocated: 25/06/09)
Location	Immediately upstream of confluence with Whitendale (WHI_out)
Abstractions	There are a number of upstream United Utilities abstraction points
Related sites	Upstream sites, BRE_sap and BRE_rhw ; downstream site, Footholme (EA gauge) ; other sites in Brennand subcatchment, BRE_grip

Data Download

Cross section survey data, stage/discharge data (including manual measurements of stage) and time series of levels (not corrected for atmospheric pressure) may be downloaded [here](#) (514kb). (For details on using the data click [here](#))

Land Use / Management Changes

All grips in the Brennand catchment have been blocked; total length 28.3 km. Fences have been placed along the river banks and on the moors. Low stocking levels for habitat regeneration are being maintained in the headwaters. Stock is excluded on the western slope of the Brennand River, and in the riparian zones where trees have been planted. Mixed broadleaf trees have been planted in riparian zones throughout the catchment and on some hill slopes near Fox Clough and Tarn Clough on the western slopes of the Brennand River.

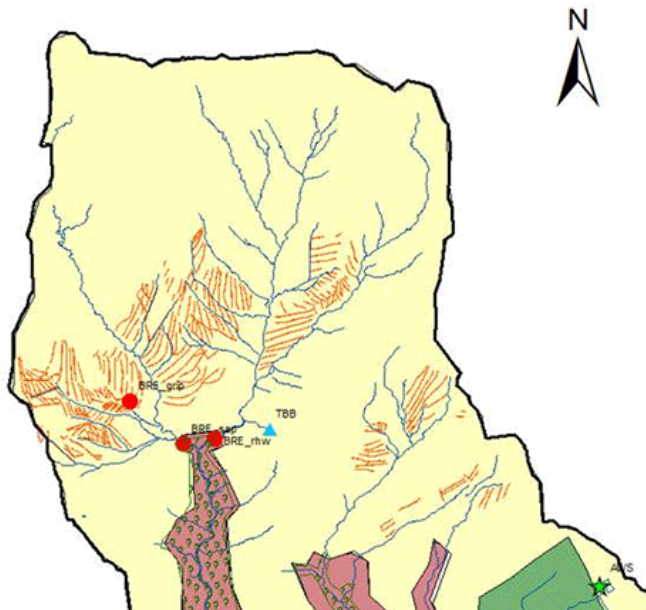


Figure B.8 Summary of data from each site

Appendix C: Example results for EAS_out and LOU_out

Plots for lumped modelling of EAS_out

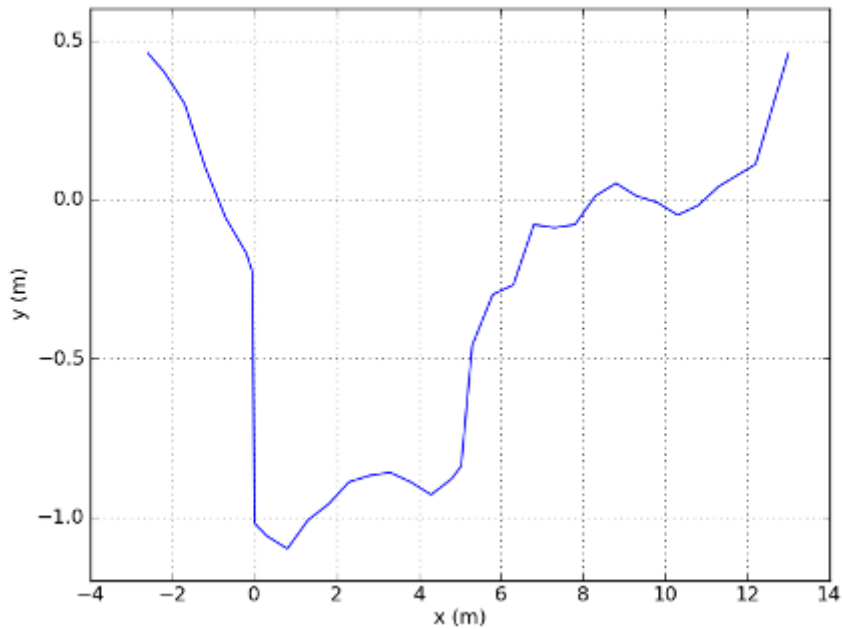


Figure C.1 EAS_out: cross section at gauge

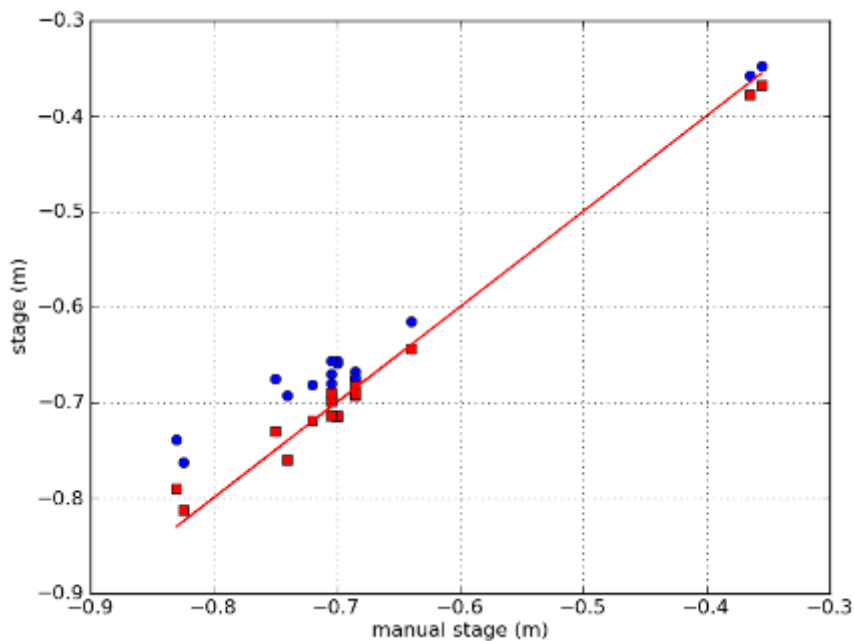


Figure C.2 EAS_out: calibration of automatic stage measurement

Notes: Red is temperature compensated.

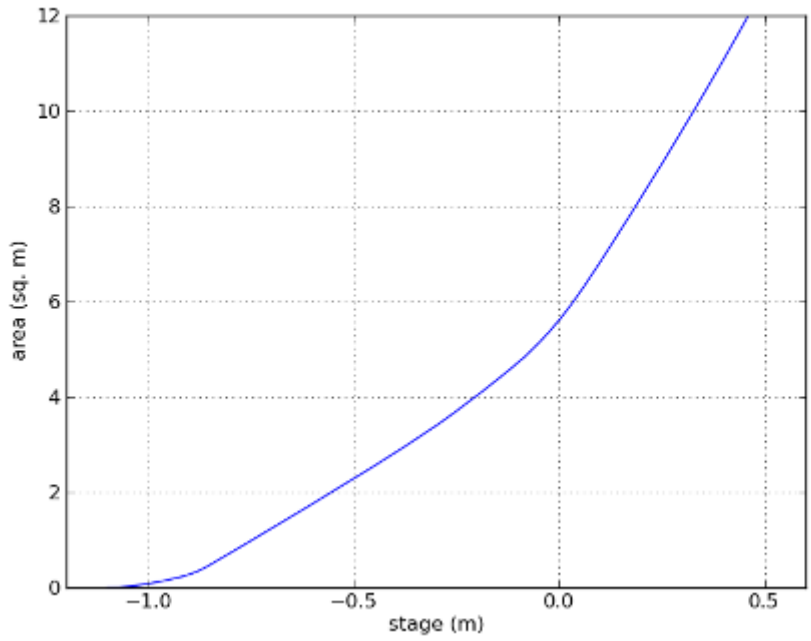


Figure C.3 EAS_out: stage-area relationship for cross-section at gauge

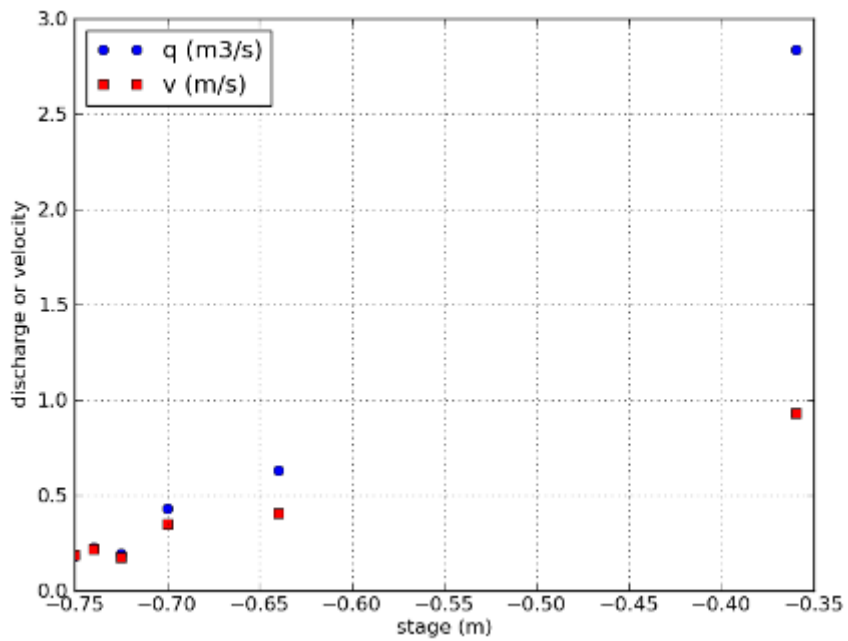


Figure C.4 EAS_out: rating data

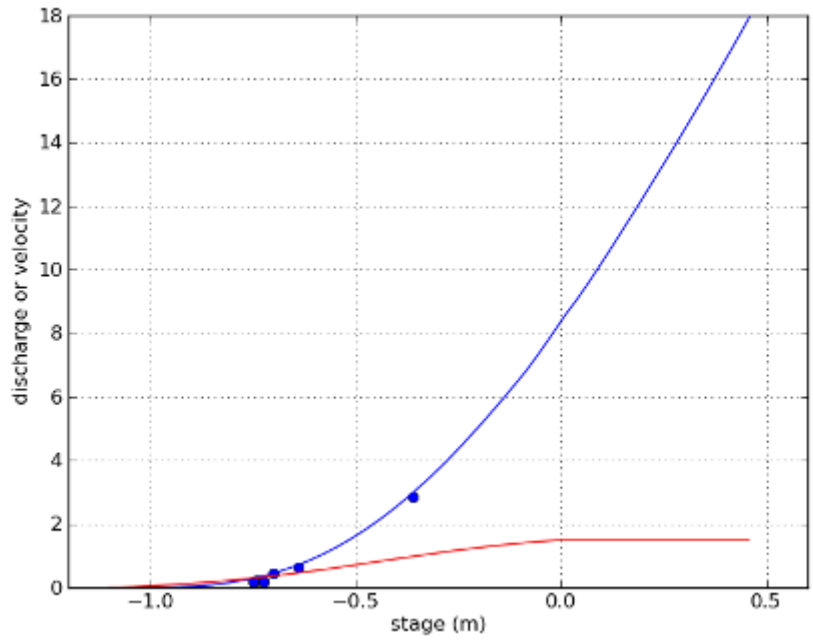


Figure C.5 EAS_out: observed discharge and velocity and fitted curves

Notes: Blue =discharge
Red =velocity

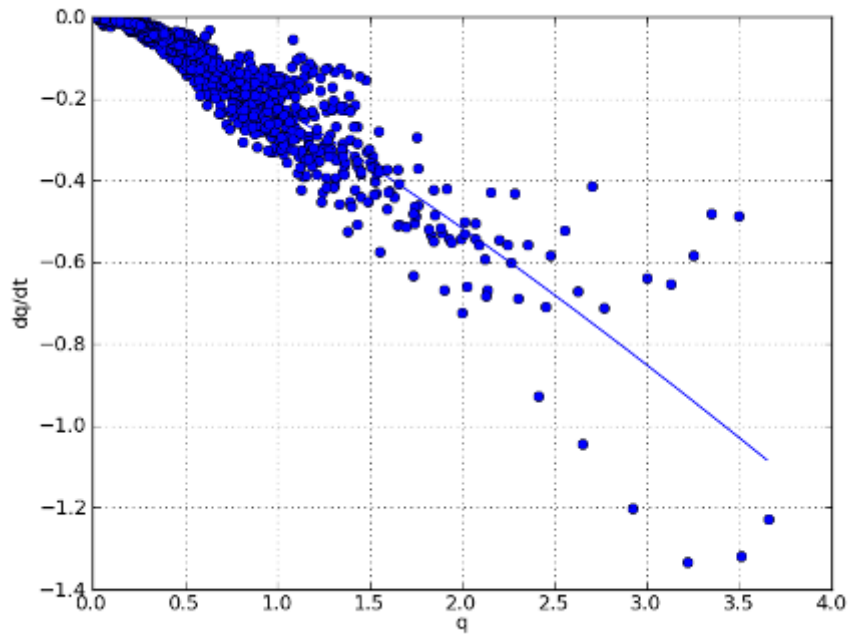


Figure C.6 EAS_out: recession data

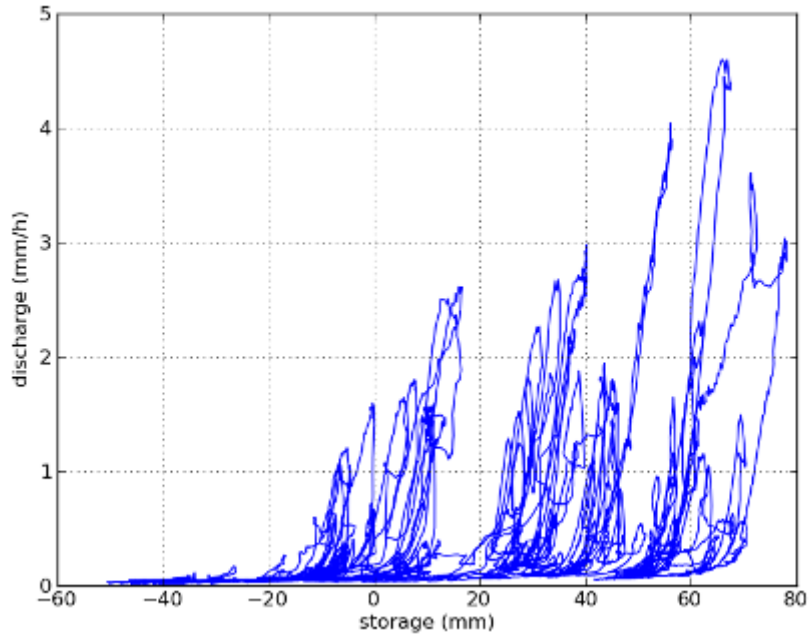


Figure C.7 EAS_out: observed storage and discharge

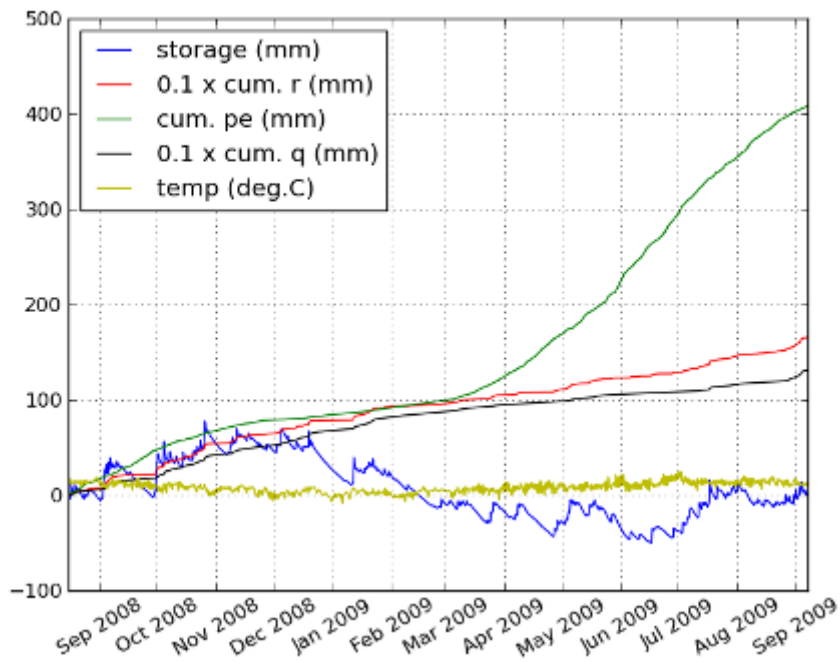
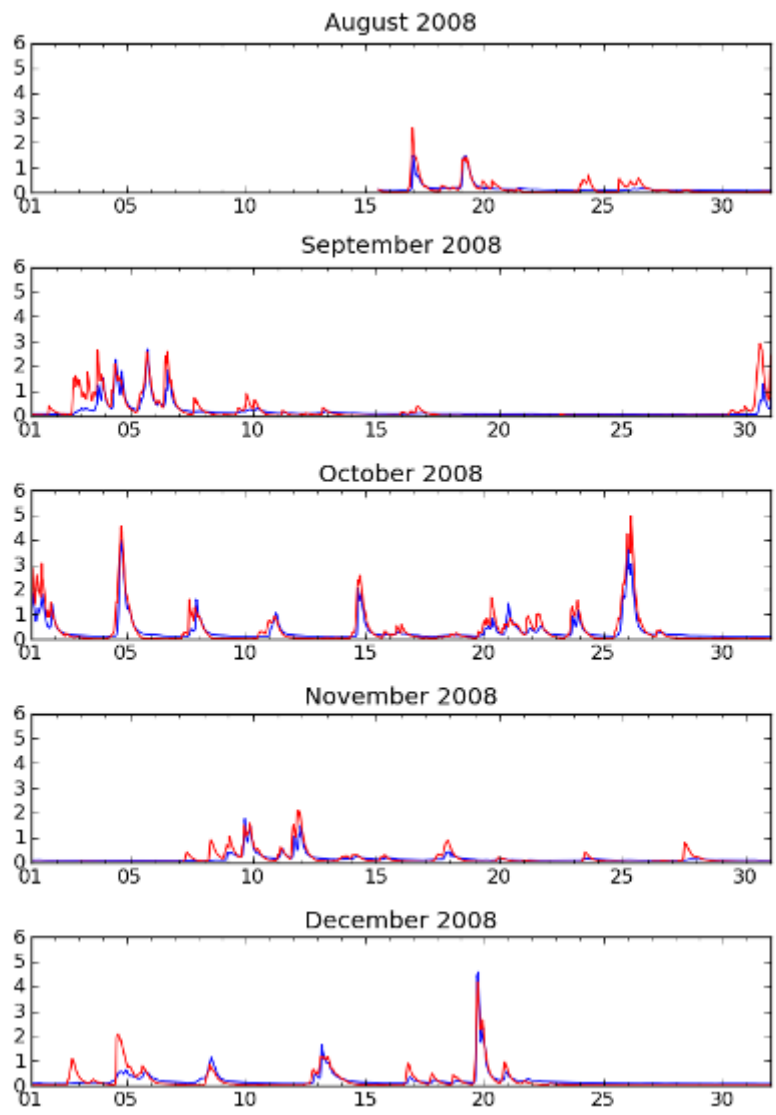
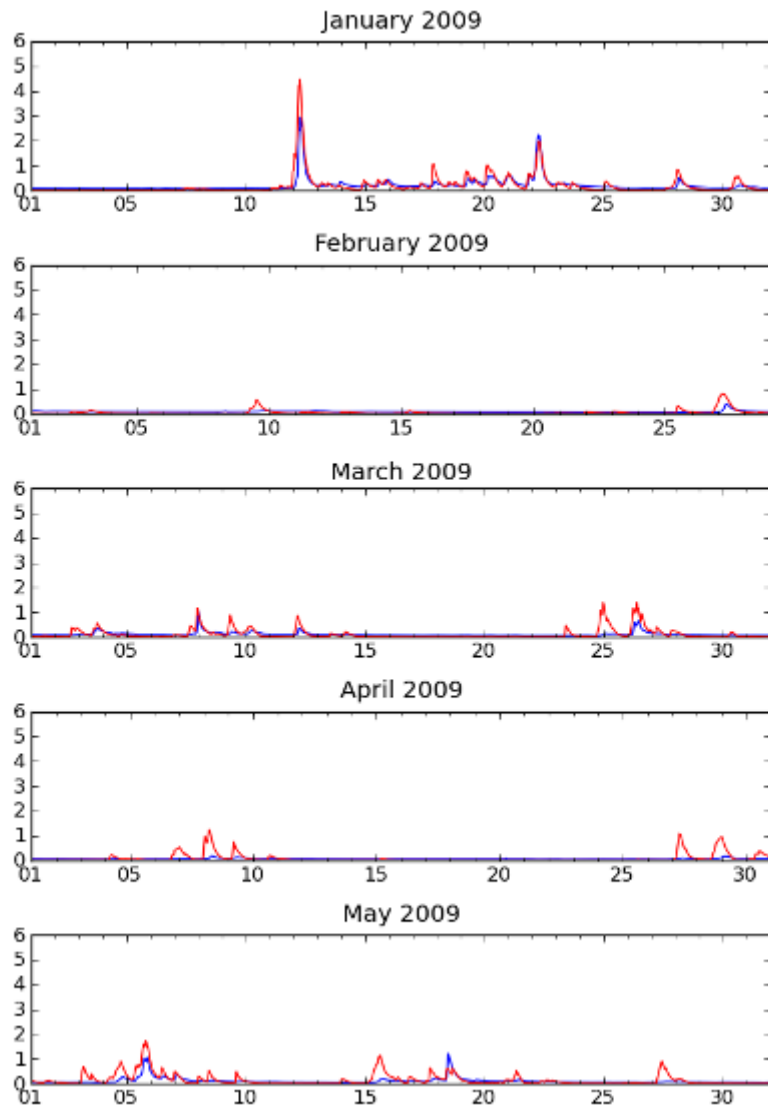


Figure C.8 EAS_out: observed cumulative mass balance and temperature



(continued on next page)



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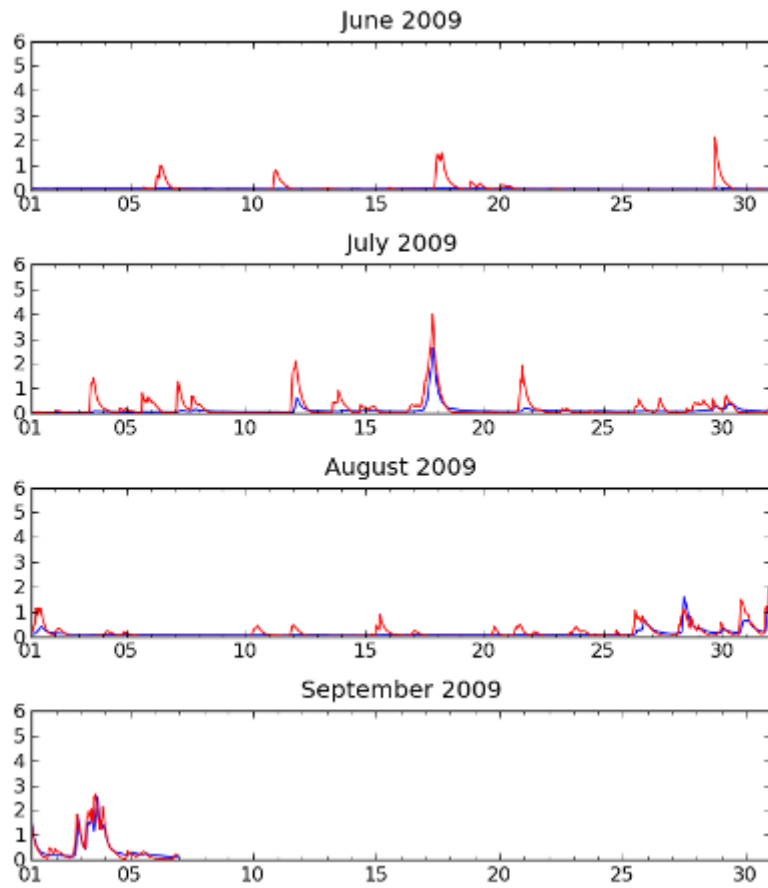


Figure C.9 EAS_out: simulated (blue) and observed (red) hydrographs

Plots for lumped modelling of LOU_out

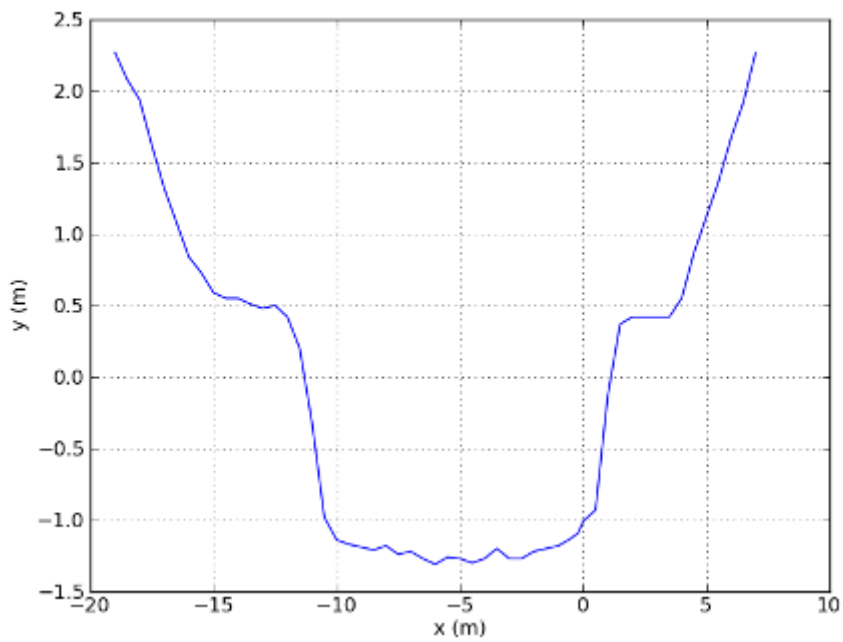


Figure C.10 LOU_out: cross section at gauge

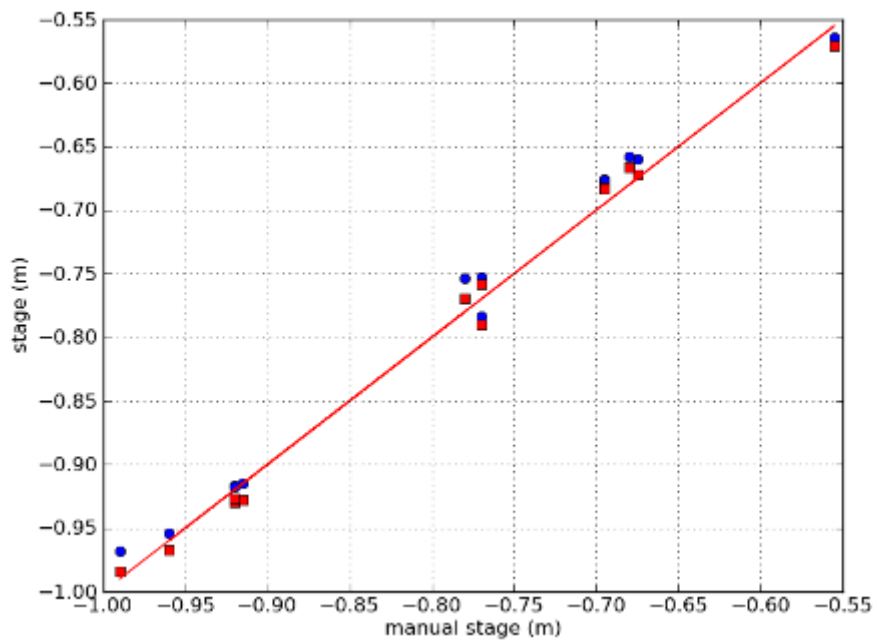


Figure C.11 LOU_out: calibration of automatic stage measurement

Notes: Red is temperature compensated.

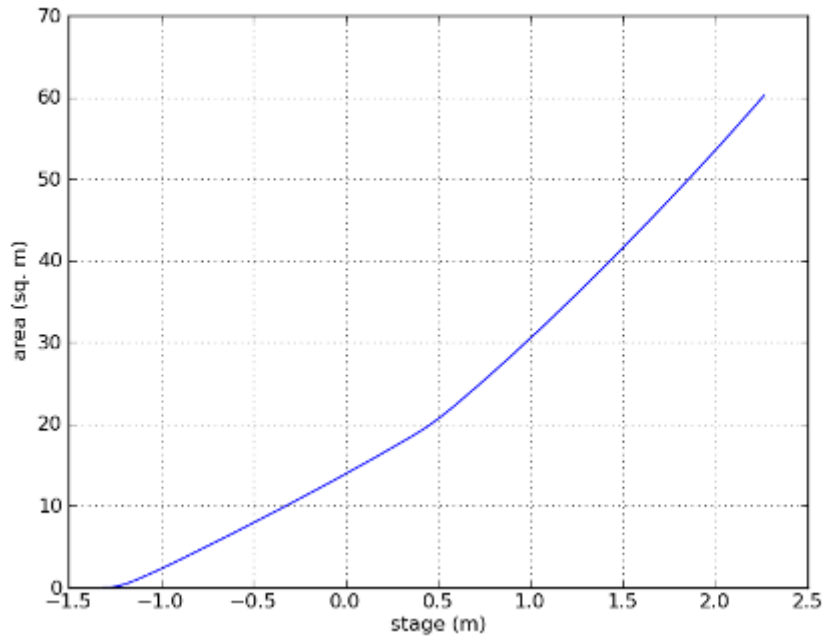


Figure C.12 LOU_out: stage-area relationship for cross-section at gauge

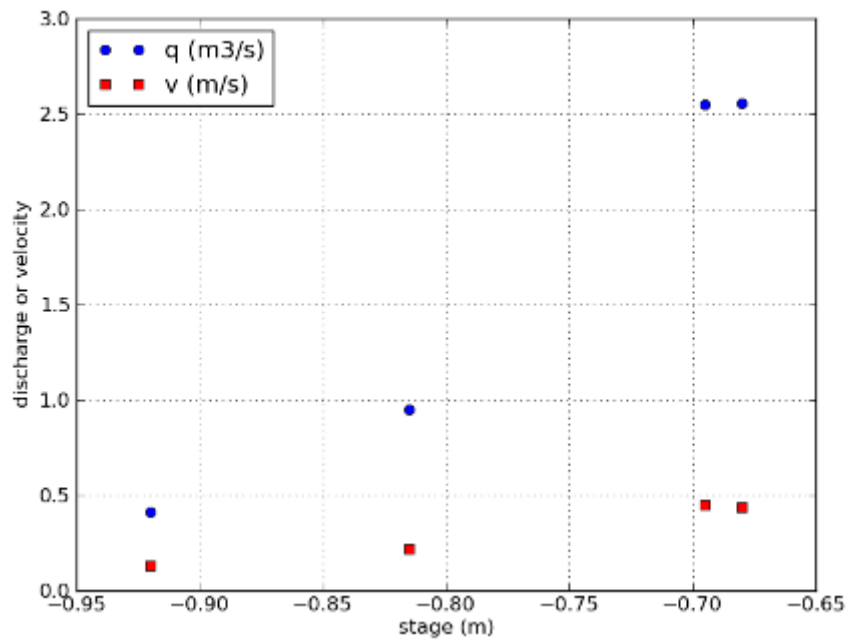


Figure C.13 LOU_out: rating data

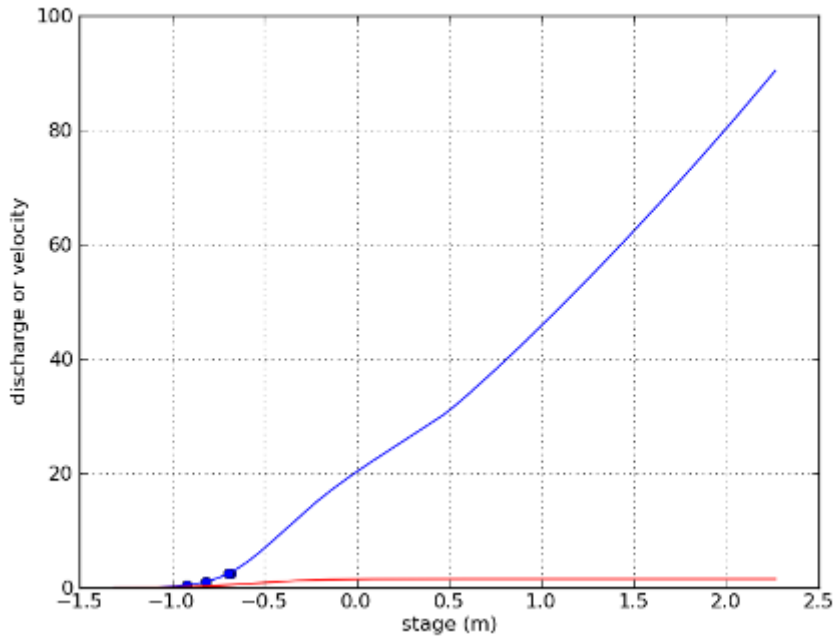


Figure C.14 LOU_out: observed discharge and velocity and fitted curves

Notes: Blue = discharge
Red = velocity

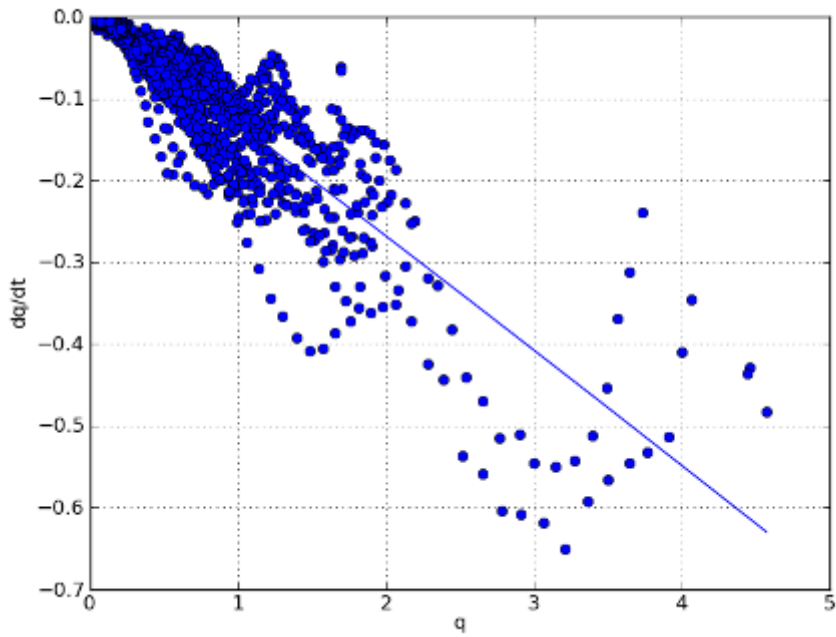


Figure C.15 LOU_out: calibration of recessions

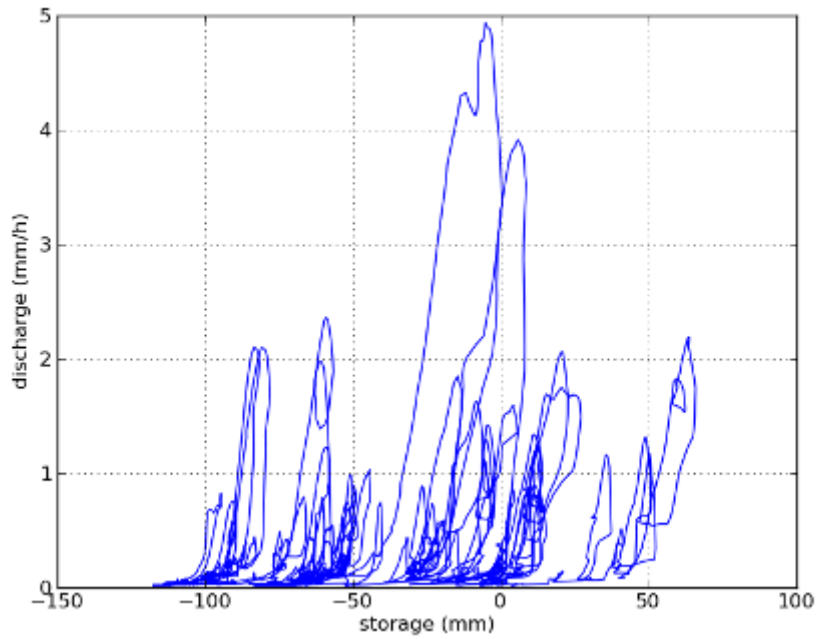


Figure C.16 LOU_out: observed storage and discharge

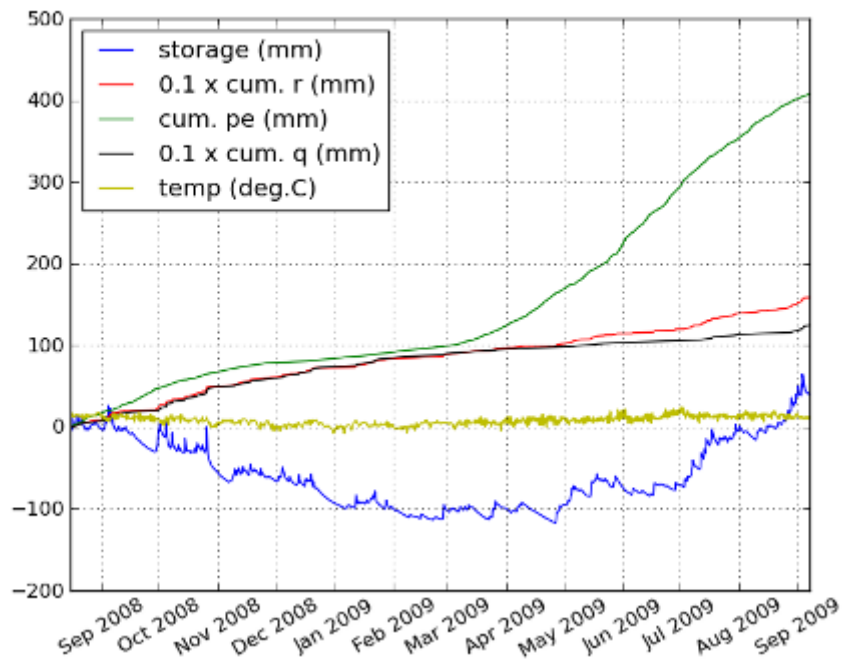
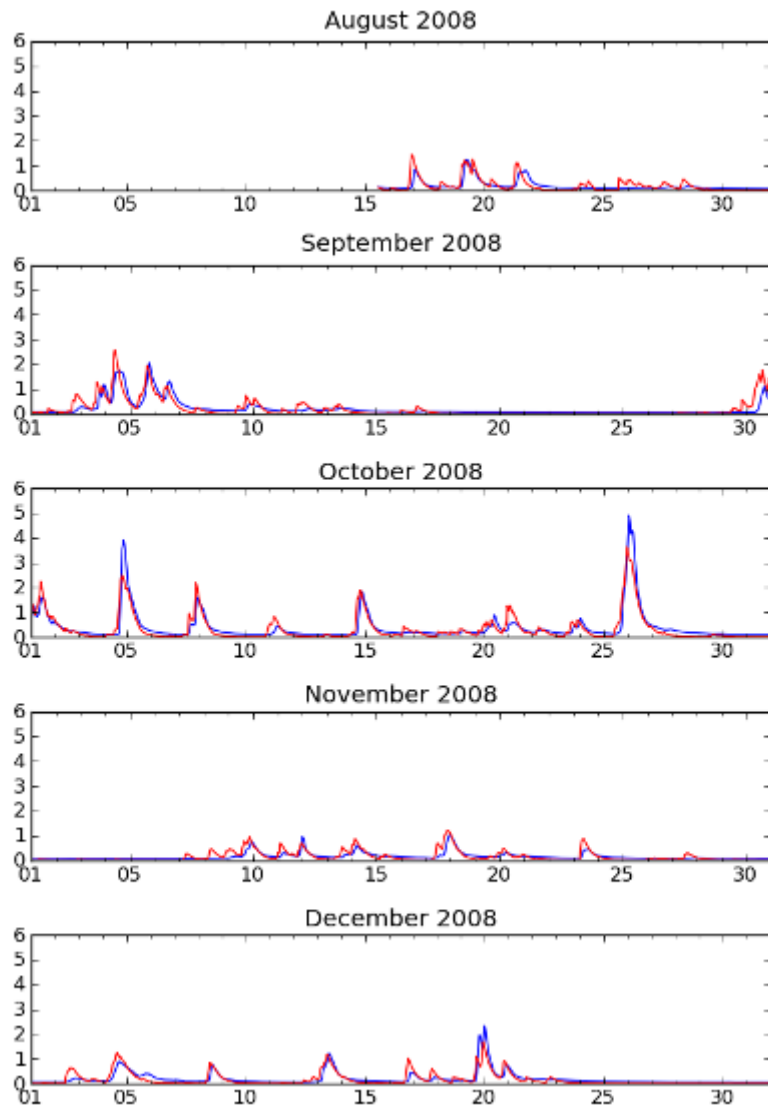
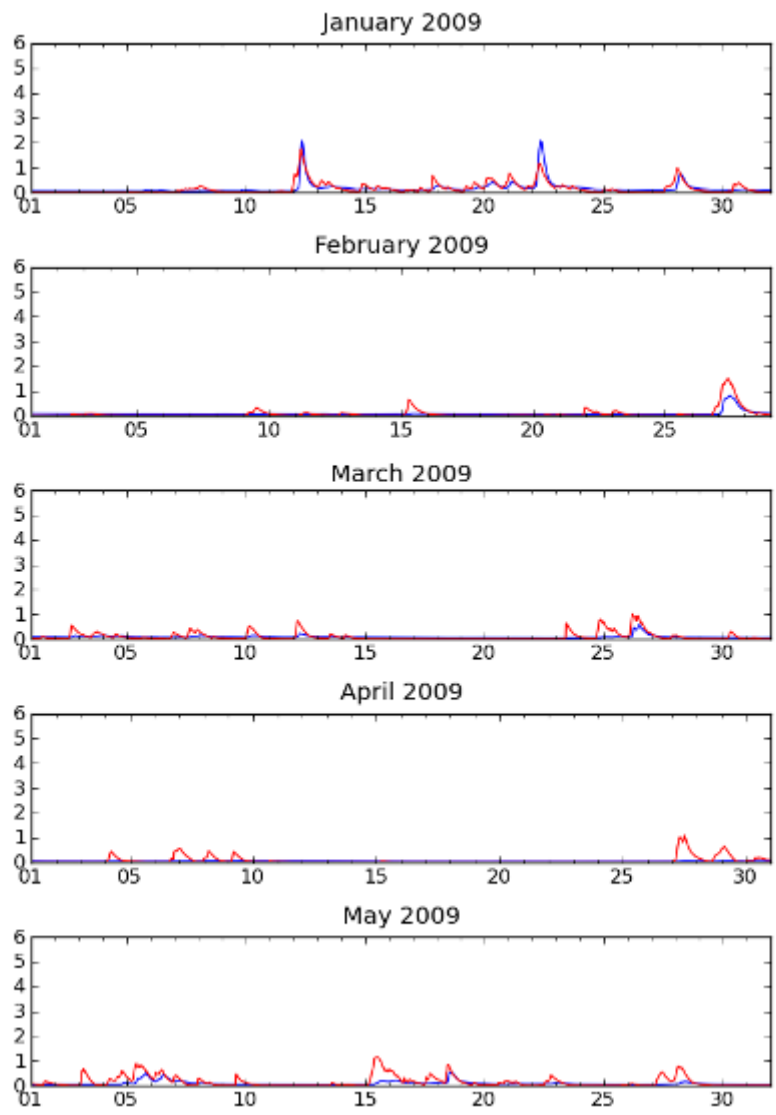


Figure C.17 LOU_out: observed cumulative mass balance and temperature



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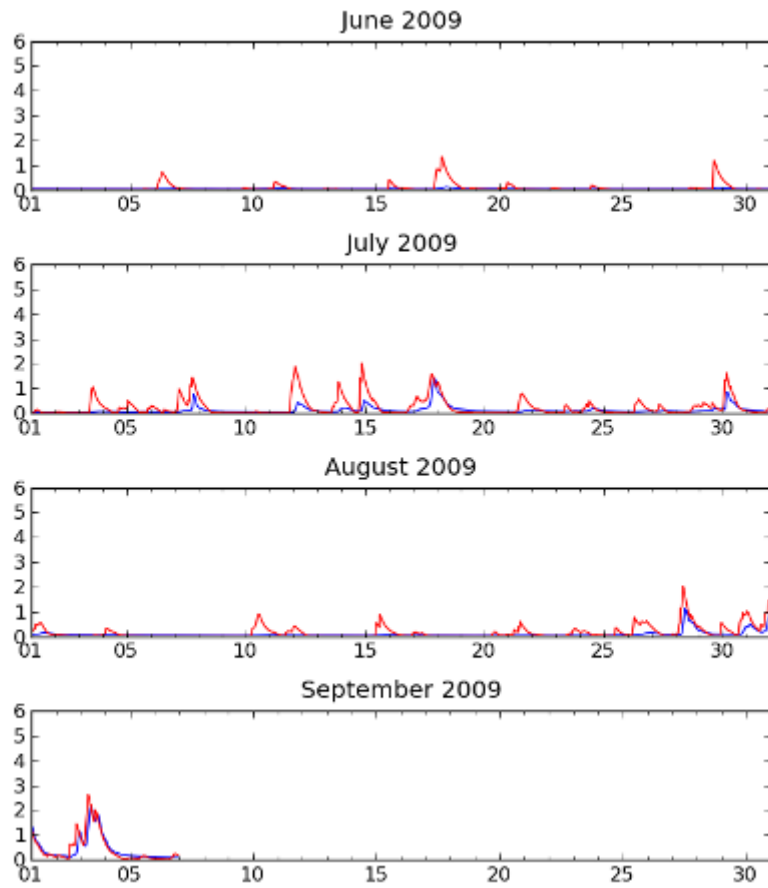


Figure C.18 LOU_out: simulated (blue) and observed (red) hydrographs

Appendix D: Monitoring low flows

Reviewers of the draft of this report requested some information on whether the Hodder data set contains useful information on low flows in warm weather. The research team would not recommend using the Hodder data set to analyse low flows in warm weather because there are problems with the flow gauges that make them unsuitable for this purpose.

Stage is measured using the difference between two pressure measurements:

- the pressure at a fixed point in the stream
- and the barometric pressure at the water surface

The gauges have an inherent sensitivity to temperature, so large errors can result when measuring low stages in warm weather. This is because the difference being measured can be very small and there can be large temperature differences and fluctuations with time. Some results are given below that illustrate this problem.

After searching through the data sets looking for anomalous results at low flows, the data from the CRO_mid gauge was selected for study. This was selected for the following reasons.

- There are low flows and particularly large anomalies in June 2009 when the gauge temperature rose quickly during early morning periods when the gauge was in full sunshine (see location of gauge in Figure D.1). The anomalies are particularly marked for 5 am to 9 am on 1 and 2 June, and much less marked on 3 and 4 June, when the solar irradiance is lower.
- The set of manual measurements for stage used when calibrating this gauge is relatively poor compared with the other gauges.
- There are independent measurements of stage available downstream at the Environment Agency flume at Croasdale (gauge 711008 coordinates 370640 454680). The Environment Agency gauge (10.4 km²) is approximately 3 km downstream of CRO_mid (3.6 km²), so exact comparisons are not possible.

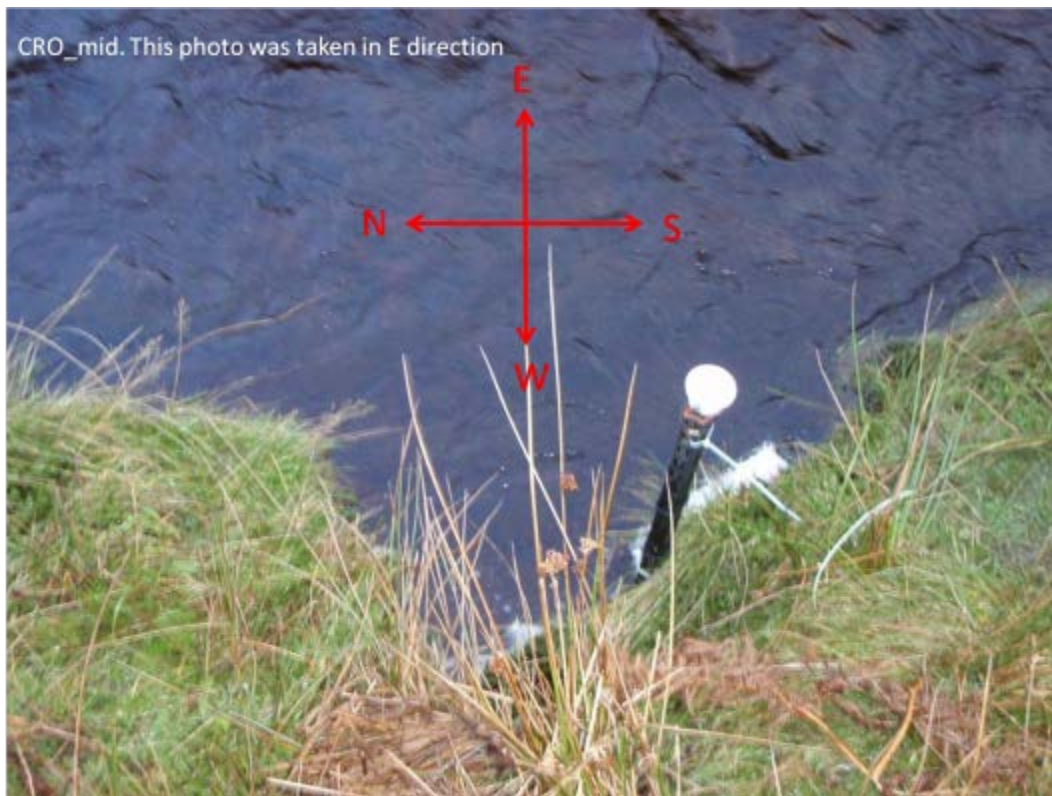


Figure D.1 CRO_mid gauge

A temperature compensation approach (Section 9.1) is used when calculating stage from the instrument readings. To show the effect of this compensation, stage is shown in Figure D.2 calculated with and without compensation. A diurnal signal is present in all the plots, including for the Environment Agency gauge. The maximum stage is reached at around 5 am. Presumably, if the diurnal signal in the Environment Agency data is a physical signal, it is likely to be controlled by evaporation, but a full analysis would require a study of mass and energy budgets. The magnitude of the diurnal variations in stage depend on the cross-section geometry and flow conditions, so it is not possible to compare directly the magnitude of diurnal variation between the two gauges (the CRO_mid variation does look high). The timings are reasonably similar between the two gauges.

The purpose of the temperature compensation is to generally reduce temperature-related errors, helping to reconcile the calculated stages against the manual measurements made throughout the year (with a tape measure). As noted above, the manual data are relatively poor for this gauge. To improve the estimation of stage at low flows in warm weather would require the collection of a set of manual measurements at low stage in warm weather and a willingness to search for mathematical relationships between the manual and calculated values that help improve the accuracy achieved by the calculation method. It would be better, the research team believes, to search instead for a more robust method for monitoring low flows in warm weather.

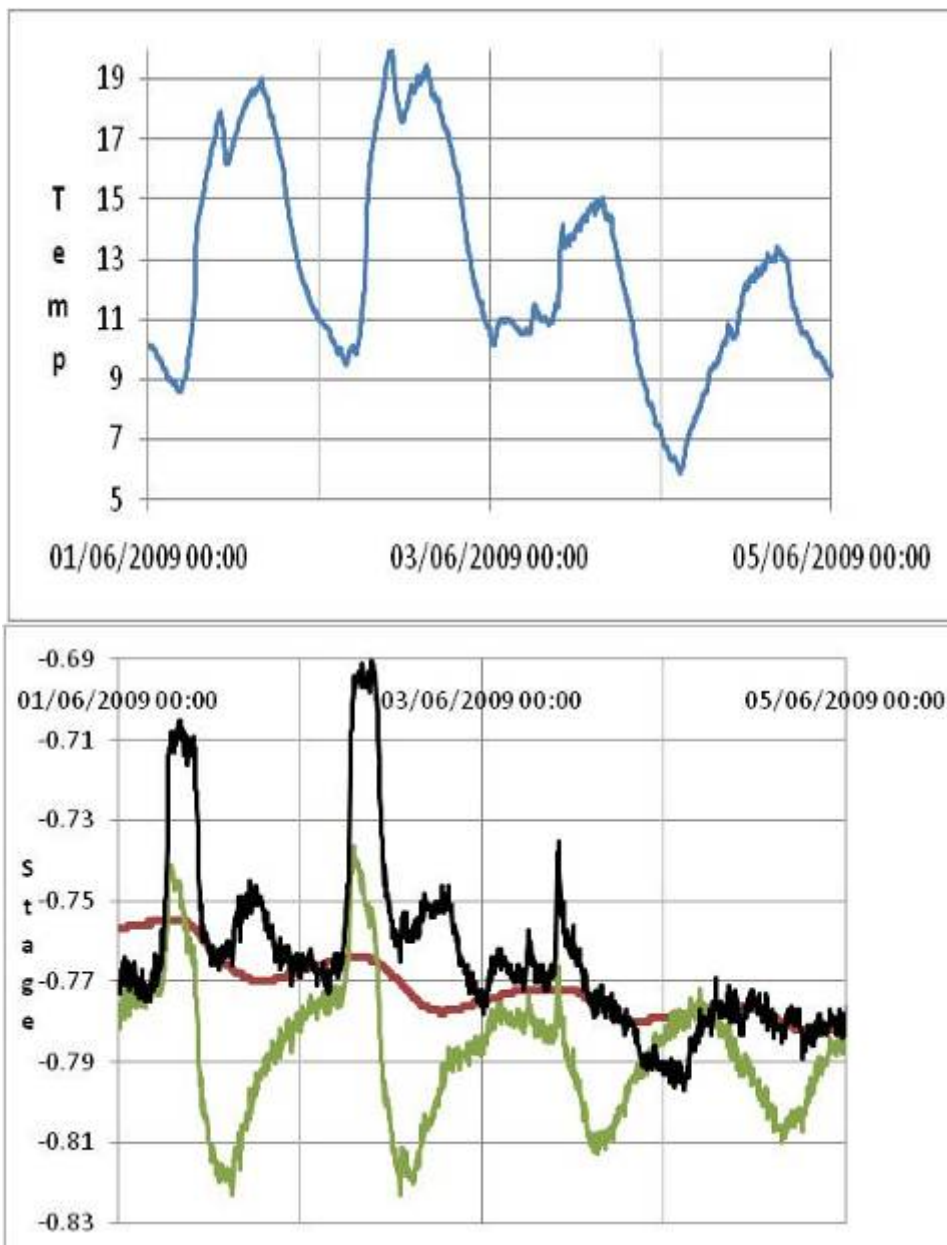


Figure D.2 Temperature of gauge (top plot) and stage

Notes: Black = uncompensated
 Green = compensated
 Red = Environment Agency gauge

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