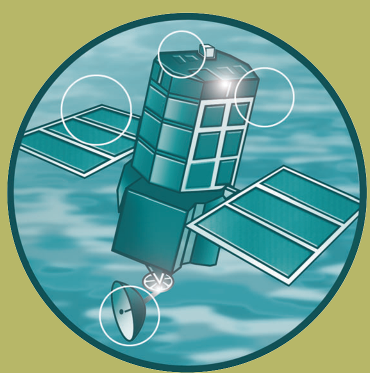
Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme

Extreme Events Recognition Phase 2

Spatio-temporal rainfall datasets and their use in evaluating the extreme event performance of hydrological models

The Extremes Dataset

R&D Project Report FD2208/PR



Environment Agency

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Department for Environment Food and Rural Affairs

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Spatio-temporal rainfall datasets and their use in evaluating the extreme event performance of hydrological models

The Extremes Dataset

R&D Project Report FD2208/PR

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Statement of Use

This report documents the Extremes Dataset produced under Work Package 4 of Project FD2208 "Extreme Event Recognition Phase 2" concerned with spatio-temporal rainfall datasets and their use in evaluating the extreme event performance of hydrological models. The Work Package aims to provide an extremes dataset and methodology of use to the Environment Agency in flood management.

Dissemination status

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This document is also available on the Defra website
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Executive Summary

This report documents the Extremes Dataset, and associated Storm Transposition software, produced on DVD as a major output of the study "Spatio-temporal rainfall datasets and their use in evaluating the extreme event performance of hydrological models". The dataset contains a selection of extreme storms of different type (convective, orographic and frontal) and recent enough to have supporting weather radar data. It also contains artificially-enhanced forms of these storms produced using a Rainfall Transformation Tool developed as part of the study. This tool can be used to change the position, movement, orientation, size and shape of a chosen storm.

Some of the historical storms were chosen in the study as hydrological model case studies. For these, additional hydrometric data and model information are included in the Extremes Dataset for illustration purposes and to support further model investigations. These case studies were used in the study to evaluate model performance during extreme storms. Experiments using the amplified historical storms were used with hydrological models to gain further insight into the genesis of flood response during even more extreme storms and to 'destruction test' models. For a given catchment, duration and return period, spatio-temporal rainfall series have been generated that attain FEH-derived rainfall amounts. The modified extreme storms used in the flood response experiments are catalogued here and form an important part of the Extremes Dataset.

For the historical extreme storm events (and additional periods used for model calibration) the dataset includes point raingauge data and radar rainfall data. Also provided are gridded rainfalls, based on raingauge data only and in combination with radar rainfall data, estimated using integrated multiquadric surface techniques.

The document describes how Hyrad can be used to visualise the spatio-temporal rainfall data as animated images. Also, it explains how Hyrad can be used with the new Storm Transposition software to relocate a chosen storm over a different catchment and upscale the rainfall values to attain a desired catchment total. This total may be chosen to correspond to a required return period obtained using an FEH-based method. The mechanics of this process is illustrated through worked examples and exercises.

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1 Introduction

This report documents the Extremes Dataset, and associated Storm Transposition software, produced on DVD as a major output of the study "Spatio-temporal rainfall datasets and their use in evaluating the extreme event performance of hydrological models". If forms a supplement to the main report of the study (Moore *et al.*, 2006) which herein is referred to as the Main Report. The report aims to illustrate how the Extremes Dataset can be used to investigate the mechanisms controlling extreme flood genesis and to assess and 'destruction test' models.

1.1 Study overview

The study, documented in the Main Report, aimed to develop a spatio-temporal rainfall dataset of extreme storms for use in evaluating the extreme event performance of hydrological models. The Extremes Dataset contains a selection of extreme storms, recent enough to have weather radar coverage, along with artificially-enhanced forms of them. Some of the historical storms – embracing convective, orographic and frontal types – were chosen for hydrological model case studies. One lumped and one distributed model, representative of other models of these types, were used in the study to evaluate model performance. The lumped model, the PDM (Probability Distributed Model), is used operationally for flood forecasting by the Environment Agency whilst the distributed Grid-to-Grid model was specifically developed for use with radar data.

The study recognised the importance of areal rainfall estimation on rainfall-runoff model performance. New methods for deriving linear weights for combining raingauge values for catchment and gridded areas were developed based on an integrated multiquadric surface technique. These methods were extended to obtain rainfall estimators that combine raingauge and radar measurements.

A Rainfall Transformation Tool was developed that can change the position, movement, orientation, size and shape of a chosen storm. It was used in flood response experiments involving the hydrological models – allowing a storm to be transposed over a catchment and modified in speed and direction, as well as shape and magnitude – to understand the genesis of flood response as a function of storm characteristics, catchment form and soil wetness. Associating a frequency of occurrence to the amplified storms was achieved by using the Flood Estimation Handbook (FEH) methodology. For a given catchment, duration and return period, spatio-temporal datasets were generated that attained the FEH derived rainfall amounts.

1.2 Extremes Dataset overview

For the historical extreme rainfall events (and additional periods used for model calibration) the dataset includes point raingauge data and radar rainfall data.

Also provided are gridded rainfalls estimated using integrated multiquadric surface techniques, based on raingauge data only and in combination with radar rainfall data. These spatial estimators of rainfall are referred to as *raingauge-only surface* and *gauge-adjusted radar* respectively. For the hydrological case studies, hydrometric river data are also included along with the calibrated PDM model input files. Inclusion of the model calibration event data allows other models to be calibrated and assessed in an identical way. The modified extreme storms generated during the flood response experiments (see Section 8 of the Main Report) are catalogued and form an important part of the Extremes Dataset.

The general directory structure of the Extremes Dataset is given in Figure 1.1. To access and use the dataset fully the user **must copy** the *Extremes Dataset* directory from the DVD to a local disk, e.g. the C drive.

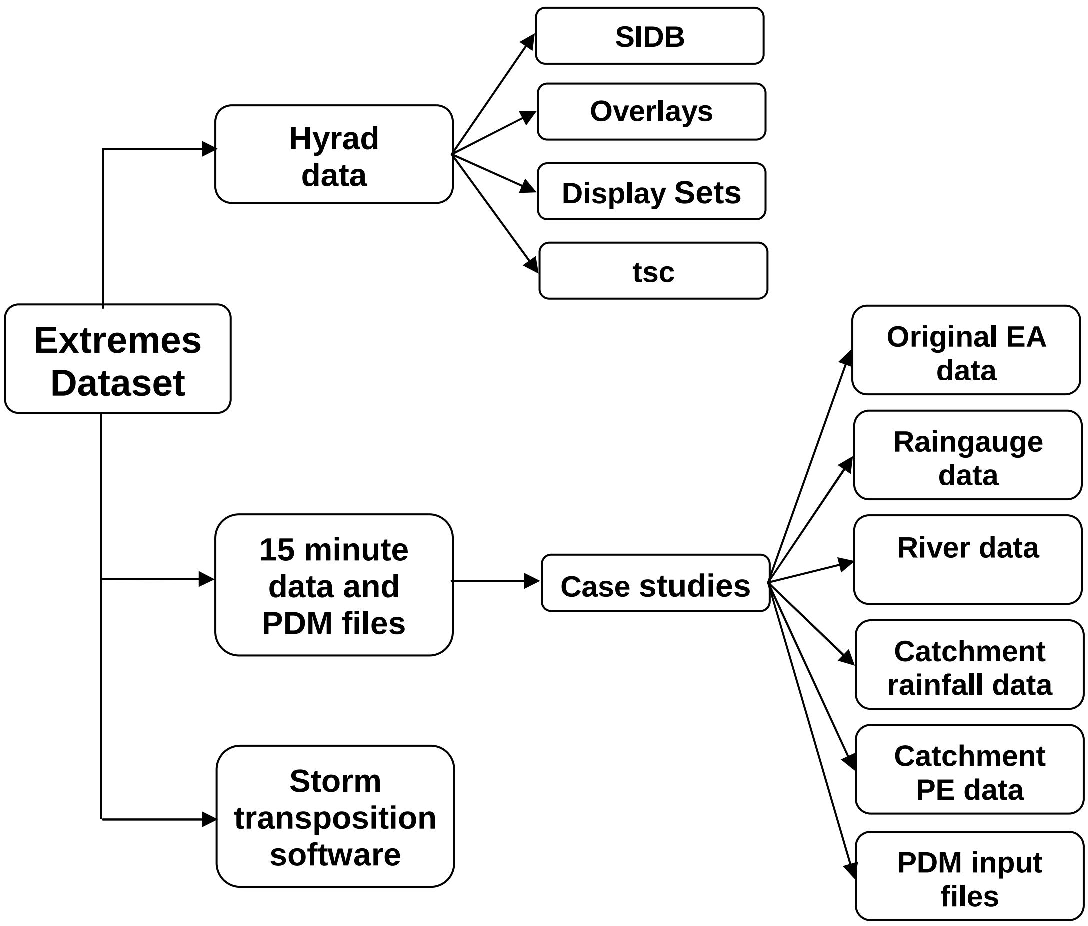


Figure 1.1 Directory structure of Extremes Dataset

1.3 Documentation overview

This documentation accompanies the Main Report and is intended to be as concise and self-contained as possible. As such, a limited amount of material is common to both reports. However, the reader is pointed to relevant sections of the Main Report for more details where necessary. A brief outline of the documentation structure is set down below.

Section 2 gives a brief summary of the historical extreme storms contained in the dataset. The methodology for artificially-enhancing the historical storms to be more extreme is summarised in Section 3. This section also provides guidelines on how to transform the different types of extreme storm and explains the information given in the catalogue of modified storms (Appendix A). The reader must refer to Section 8.5 of the Main Report concerning the flood response experiments as this provides the context as to how and why the amplified storms were created.

The structure of the Extremes Dataset, outlined in Figure 1.1, provides the structural basis for the remainder of the documentation. The *15 minute data and PDM files* directory is detailed in Section 4 whilst Section 5 sets down the structure of the *Hyrad data* directory including how to display the spatial rainfall data through the Hyrad Display Client. Finally, Section 6 explains how the *Storm Transposition software* can be used with Hyrad to relocate a chosen storm over a different catchment and upscale the rainfall values to attain a desired catchment total. The total may be chosen to correspond to a required return period using an FEH-based method. The mechanics of this process is illustrated through worked examples and exercises.

2 Historical Extreme Storms

Section 2 of the Main Report explains the process used to select the historical extreme storms contained within the dataset and how the catchments for hydrological modelling were identified. The historical extreme storms selected had to be recent enough to have radar coverage and included storms of frontal, orographic and convective type. The catchments selected for modelling had to have an observational record of the historical flood and, preferably, a reliable rating curve for high flows. Table 2.1 lists the type, date, location and rainfall magnitude for each event and also which catchments were selected for hydrological modelling. Section 5 of the Main Report discusses the extreme storms and catchments studied in more detail.

Table 2.1 Summary of case study events of orographic, convective and frontal type

Event Date	Event location(s)	Rainfall magnitude	Hydrological modelling
Orographic rainfall			
30 Jan – 3 Feb 2004	River Kent at Kendal, Northwest Region	229.2mm in 96 hours, Brotherswater (NW).	1. Kent at Sedgwick 2. Kent at Vic. Bridge 3. Sprint at Sprint Mill 4. Mint at Mint Bridge 5. Kent at Bowston
Frontal rainfall			
8-9 Apr 1998	Stour at Shipston, Midlands Region. River Cherwell and Sor, Thames Region	76.6mm in 14 hours, Pershore. 66mm in 15 hours, Shipston.	1. Stour at Shipston 2. Cherwell at Banbury 3. Sor at Bodicote
Convective rainfall			
14 Jun 2002	River Darwen, Blackburn, Northwest Region.	31.4mm in 1 hour, Darwen Sunnyhurst.	1. Darwen at Blue Bridge 2. Darwen at Ewood
10 Aug 2003	Carlton-in-Cleveland, North Yorkshire, Northeast Region.	49mm in 15 minutes, Carlton-in-Cleveland.	N/A
19 May 1989	Halifax Storm, Northwest Region	193mm in 2 hours, Walshaw Dean.	N/A
16 Aug 2004	Boscastle, Southwest Region.	200.4mm daily total, Otterham. 153.6mm in 6 hours, Lesnewth (TBR)	N/A

3 Modified Extreme Storms

Section 8 of the Main Report presents a set of flood response experiments for the case study catchments using the historical extreme storms in amplified and/or transposed form. The aim is to investigate the mechanisms controlling extreme flood genesis and to assess and 'destruction test' models.

The flood response experiments presented in the Main Report use historical storms and amplified forms of them following Approach 1 of Section 4.6 of the Main Report. Essentially, for a given catchment, the historical storms are amplified to attain FEH catchment average amounts for given durations and return periods (e.g. 100, 200, 500 or 1000 years). The Rainfall Transformation Tool, outlined in Section 4.3 of the Main Report, requires certain characteristics of the historical storm to be estimated (e.g. speed and direction of travel) before the storm modification and transposition options can be applied. A methodology for identifying these from historical radar data, and the resulting estimated characteristics for each storm, are given in Section 3.1. Guidelines for applying the storm modification and transposition options are given for each storm type in Section 3.2. Section 3.3 gives summary information on each amplified storm catalogued in detail in Appendix A.

Sections 3.1 to 3.3 and Appendix A have been taken from Sections 8.2 to 8.4 and Appendix H of the Main Report respectively. The reader is reminded that the details of the flood response experiments given in Section 8.5 of the Main Report provide additional context for the amplified storms.

3.1 Historical storm characteristics

A general methodology for estimating the historical storm characteristics needed to modify the storms has been derived. The methodology takes into account the storm type (orographic, frontal or convective) and is summarised in Table 3.1. It is intended to be a quick procedure that can be applied through visual inspection of the storm radar data, rather than a more complicated computational approach. The main purpose is to obtain reasonable estimates that can be utilised by the Rainfall Transformation Tool (see Section 4.3 of the Main Report). Hyrad was used to visualise the radar data.

The historical storm characteristics derived using this methodology are summarised in Table 3.2. It was not possible to identify the orientation of major bands of rainfall from the radar data for the frontal and orographic events. Since the Boscastle event comprised of several convective storms, initiated by a common orographic trigger, there is little benefit in assigning a storm velocity as modifying it would only emphasise one of the storms. Also the location of the greatest rainfall accumulation was used, rather than the highest instantaneous rain-rate, to spatially locate the event (this differs depending on the radar used) and the temporal location is simply the temporal mid point of the event.

Table 3.1 Summary of the methodology used in identifying historical storm characteristics

Storm characteristic	Orographic	Frontal	Convective
Spatial Position	Centre storm over orography	Select a suitable location, e.g. location of highest accumulation	Centre storm on highest intensity observed
Temporal origin	Use mid time point of event	Use mid time point of event	When the highest intensity was observed
Movement	Orographically enhanced storms are generally long duration events involving several bands of rain. Therefore estimate the speed and direction of the storm from time frames near the temporal origin.	Frontal storms are generally long duration events involving several bands of rain. Therefore estimate the speed and direction of the storm from time frames near the temporal origin.	Convective storms are generally short duration events. Therefore estimate speed and direction of the storm from a time frame near the start of the convective cell with highest intensity and one near the end.
Orientation of major bands of rainfall, distinct from direction of travel	Estimate the orientation, if possible, from time frames near the temporal origin.	Estimate the orientation, if possible, from time frames near the temporal origin.	Generally not appropriate.

The start time and duration of the storms are also given in Table 3.2. Note that the duration of each convective storm covers the duration of the storm as observed by radar (i.e. until the storm finishes or until the storm leaves the range of the radar) and is not solely focussed on the period of the greatest point raingauge recording. This allows the full duration of the storm to be included when modifying it (i.e. not just the period associated with the heaviest point rainfall totals) and is particularly relevant when ‘slowing down’ storms such as the fast-moving Carlton-in-Cleveland storm.

For the long duration 4-day orographic event affecting the River Kent, the characteristics quoted correspond to the period of the storm that generated the peak flood, i.e. the last 24 hours.

Table 3.2 Historical storm characteristics. (O) denotes orographic, (C) denotes convective and (F) denotes frontal.

Event	Start time	Duration	Temporal Centre	Spatial Centre	Storm Velocity East km hr^{-1}	Storm Velocity North km hr^{-1}	Storm Speed km hr^{-1}
River Kent (O) 2km QC	19:30 02/02/04	24 hours	07:30 03/02/04	335000 511000	96	64	115
Darwen (C) 1km raw	15:30 14/06/02	2 hours	16:20 14/06/02	371500 423500	54	42	68
Darwen (C) 2km QC	15:15 14/06/02	2 hours 45 min	16:20 14/06/02	371000 424000	54	42	68
Carlton-in-Cleveland (C) 2km QC	06:45 10/08/03	3 hours	09:20 10/08/03	433000 489000	40	40	56
Halifax (C) 2km raw	13:45 19/05/89	5 hours 15 min	17:00 19/05/89	409000 425000	8	-6	10
Boscastle (C) 2km QC (Cobbacombe)	11:30 16/08/04	5 hours 30 min	14:15 16/08/04	215000 089000	n/a	n/a	n/a
Boscastle (C) 2km QC (Predannack)	11:30 16/08/04	5 hours 30 min	14:15 16/08/04	217000 091000	n/a	n/a	n/a
Upper Thames and Stour (F) 2/5km raw	03:00 09/04/98	16 hours	11:00 09/04/98	432500 247500	-44	12	46

3.2 Guidelines for applying storm modification and transposition options

Section 4.3 of the Main Report details the storm modification and transposition options available as part of the developed software. Guidelines for the application of the different options are given in Table 3.3 for each type of extreme storm. For each hydrological case study, the historical extreme storms have been relocated to the case study catchments without further modification and the return period of the rainfall assessed. Secondly, the historical storms have been modified to attain given FEH-estimated return periods for a particular catchment. The return periods of interest are 100, 200, 500 and 1000 years.

Guidelines for appropriate seasons in which to apply the modified storms have been derived using the analysis of 20th Century historical extreme storms in the Phase I Study Report (Collier *et al.*, 2002) and are summarised in Table 3.3. This analysis indicates that the extreme frontal events only occurred between June and January with peak occurrence between July and September. However, the extreme frontal Easter 1998 event affecting the Upper Thames and Stour occurred during April and so April and May should also be considered.

Table 3.3 Guidelines for applying storm modification and transposition options by storm type

Storm Modification	Orographic	Frontal	Convective
Relative Temporal Position	These storms should only be applied between November and mid-February.	These storms should only be applied between April and January, i.e. not in February or March.	These storms should only be applied between May and October with particular focus on June, July and August.
	It is recommended that modified storms are applied at the same time of day as the historical storms. This is particularly relevant to convective events where insolation is an important forcing factor.		
Relative Spatial Position	These storms should only be 'relocated' to other catchments known to be affected by orographic enhancement. The target storm centre should correspond to the centre of the orography affecting the target catchment.	Storms can be freely moved to *lowland* parts of the country. Should not be moved to regions seriously affected by orographic enhancement.	Storms can be freely moved around the country.
Relative Orientation	Orientation of the storms can be altered but within meteorological limits i.e. orographic events on the west coast of the UK are generally caused only by a westerly or south-westerly flow.	Retain historical orientation.	Free to choose orientation of isolated convective events (not necessarily true for embedded convection; however only isolated events are considered here).
Speed and Direction of travel	Not suitable as storm must retain spatial location of orographic enhancement.	Retain historical speed and direction of travel.	Free to change speed and direction.
Upscaling of amounts	Free to upscale amounts within reason. The FEH provides point and area estimates of event rarity.		
Spatial squeezing (preserving rainfall amounts)	Not suitable, rain generally widespread already.	Could be appropriate to alter in direction of bands.	Free to change. In particular to investigate what effect squeezing may have in creating a more localised and intense storm.

Table 3.3 continued

Storm Modification	Orographic	Frontal	Convective
Spatial expansion (not preserving rainfall amounts)	Not suitable, rain generally widespread already.	Could be appropriate to alter in direction of bands.	Free to change. In particular to investigate what effect expansion may have in creating a larger convective cell of the same intensity.
Time squeezing (preserving rainfall amounts)	Free to use for all rain types. In particular to investigate what effect increasing rainfall rates, but not total rainfall amounts, and decreasing event duration will have.		
Time expansion (not preserving rainfall amounts)	Free to use for all rain types. In particular to investigate what effect increasing event duration and total rainfall amounts, but not rainfall rates, will have.		

3.3 Summary information on modified storms

For each hydrological case study, modified extreme storms have been generated using the Rainfall Transformation Tool. Details of each modified storm are listed in Appendix A. The details listed are set down below.

- **Year.** This is a fictitious year used to identify the storm within the dataset
- **Period.** This is the total period used for hydrological modelling. Over the period the modified spatial rainfall for each storm consists of three parts:
    1. **Warm-up.** Uses historical radar data to allow model warm-up. This usually ends with a period of low rainfall.
    2. **Modified storm.** Modified storm spatial data is used
    3. **Cool down.** Zero rainfall
- **Historical storm modified.** Identifies which historical storm was modified.
- **Storm modification settings.** Lists the settings used for storm modification. Only settings that are altered are listed.
- **Comments.** This gives the catchment average rainfall amount, duration and estimated return period (using FEH) and any other points of interest.

Details of which spatial rainfall data are used as the basis for the storm modifications are listed later in Table 5.1.

4 Time-series data and PDM rainfall-runoff model input files

4.1 Directory structure and contents

Time-series data provided by the EA in support of the case study storms are contained within the *15 minute data and PDM files* directory. This directory also includes the PDM model input files and 15 minute time-series data used in the hydrological modelling case studies and flood response experiments (see Table 2.1 for catchments studied). Rainfall data used for modelling are either calculated from raingauges or catchment average totals derived from spatial rainfall data (e.g. radar data or modified storm data). The spatial rainfall data are contained in the *Hyrad data* directory: see Section 5.

A sub-directory exists for each case study (see Figure 1.1) and their structure is detailed below.

1. **Original EA data.** This contains hydrometric data provided by the Environment Agency in support of the case studies and any extra information received e.g. catchment descriptions, rating curve analysis.

For case studies with hydrological models, the hydrometric data provided by the Environment Agency have been converted into a common format accessible by the modelling software. For these case studies the following sub-directories are also present:

2. **Raingauge data.** This contains 15 minute raingauge totals.

3. **River data.** This contains 15 minute instantaneous river flow and/or level data.

4. **Catchment rainfall data.** This contains 15 minute catchment average rainfall data for each catchment studied. For the historical storms (and model calibration events) catchment averages have been formed using the following rainfall estimators:
    - raingauge-only rainfall surface – a spatial surface fitted to point raingauge values
    - radar rainfall data – the finest resolution radar data that covered the catchment
    - gauge-adjusted radar rainfall data – the radar data are adjusted by comparing the raingauge values with the radar values of the grid squares coincident with the raingauge network and forming a spatial surface of adjustment factors which are then applied to the radar data.

    Section 5.2 details the rainfall estimators available for each historical storm and which have been used to form catchment average totals. Catchment rainfalls are also provided for the modified storms and are labelled by the fictitious year assigned to the modified storm: see Appendix A for details.

5. **Catchment PE data.** This contains 15 minute catchment average potential evaporation data derived from monthly MORECS data available on a 40km grid.

6. **PDM files – catchment.** Each study catchment has a directory that contains PDM model input files, identified by the filename ending **.inp**, which use the calibrated model parameters listed in Appendix F of the Main Report. The folder also contains the corresponding File-1 Data Interface files, identified by the filename ending **.f1i**, which are required to link the PDM model software to the hydrometric data. An input file exists for both model calibration and evaluation (i.e. the historical storm) events using different types of rainfall estimator: see Section 4.2. Input files also exist for the modified storms and are discussed in more detail in Section 4.3. Users who have access to the PDM for PCs software can employ the model input files in the usual way.

4.2 PDM input files for historical extreme storms and calibration events

Within each *PDM files – catchment* directory, PDM input files (***.inp**) and corresponding File-1 Data Interface files (***.f1i**) exist for both model calibration and evaluation (i.e. the historical extreme storm) events using different types of rainfall estimator. Section 5.2 details the estimators used for each historical extreme storm. The input file names are of the form

catchment_event_rainfall.inp

where

catchment	is the catchment name, e.g. Sedgwick	
event	is the type of event studied:	
	calib	calibration events
	eval	evaluation events, i.e over the extreme historical storm
rainfall	identifies the type of rainfall used:	
	rgweights	weighted raingauge data
	rgsurf	raingauge-only rainfall surface
	2kmQC	2km Nimrod data
	2kmQC_recal	gauge-adjusted 2km Nimrod data
	2km_raw	2km raw radar
	2km_raw_recal	gauge-adjusted 2km raw radar
	1km_raw	1km raw radar
	1km_raw_recal	gauge-adjusted 1km raw radar
	2_5km_raw	composite 2 and 5km raw radar
	2_5km_raw_recal	gauge-adjusted composite 2 and 5km raw radar

4.3 PDM input files for modified extreme storms

Within each *PDM files – catchment* directory, PDM input files (***.inp**) and corresponding File-1 Data Interface files (***.f1i**) are provided that access the catchment average rainfalls created from the modified extreme storms.

The filename structure for these files is

c*atchment_mod_#1-#2.inp*

where

catchment	is the catchment name, e.g. Sedgwick
mod_#1-#2	identifies that the input file is set to use modified extreme storm data from years #1 to #2, e.g mod_3000-3008 means modified storm data from years 3000 to 3008 can be used. The title line of each input file also contains this information.

Changing the modified storm that is being used is simply achieved using the following steps.

1. Open the appropriate File-1 Data Interface file, e.g sedgwick_mod_3000-3008.f1i, using a text editor (e.g. WordPad)

2. Edit the year of the filename used in the rainfall datablock to select the appropriate storm, e.g. 3006, see Figure 4.1.

3. Save the File-1 Data Interface file and exit the text editor.

4. Re-run the PDM selecting the appropriate input file, e.g. sedgwick_mod_3000-3008.inp

```
NAME not known
! above should be a descriptive site name, if known
!
! Data should cover at least the following period
! First time-point 09:00 29 JAN 2004
! Last  time-point 09:00  8 FEB 2004
! Minumum number of data-points in file      961
FIRST 09:00 29 JAN 2004
LAST  09:00  8 FEB 2004
SFILE ../River data/sedgwick_flow.dat
CLOSE
DATA     <<KENT_730511>>
END      <<KENT_730511>>
!
!
! ----------------------------------------------------------------
! NEXT data-series required is for site-id=<MOD>
! data-type = rainfall
! time-step =     15 minutes! this is event-data
!
! Requirements for event rainfall are
! totals date-labelled by end of interval
!
NAME not known
! above should be a descriptive site name, if known
!
! Data should cover at least the following period
! First time-point 09:00 29 JAN 2004
! Last  time-point 09:00  8 FEB 2004
! Minumum number of data-points in file      961
FIRST 09:00 29 JAN 2004
LAST  09:00  8 FEB 2004
SFILE ../Catchment rainfall/Modified storms/sedg_3006_mod.dat
CLOSE
DATA     <<MOD>>
END      <<MOD>>
!
```

Figure 4.1 An example of a File-1 Data Interface file configured to use modified storm data from the year 3006. The necessary change is highlighted by bold text.

5 Hyrad space-time image data

The spatio-temporal rainfall data for the historical storms (e.g. radar data, raingauge-adjusted radar data or raingauge-only rainfall surface) and the modified storms used in the flood response experiments are contained in the *Hyrad data* directory. The sub-directory structure, previously outlined in Figure 1.1, is detailed below.

1. **SIDB** (Spatial Image DataBase)**.** This contains the spatial rainfall data for historical and modified extreme storms in Hyrad. Note that all modified storms are stored as **average** intensites for the preceding time interval for consistency between raingauge- and radar-based rainfall estimators.

2. **Overlays.** This contains two overlay files that can be used by Hyrad:

catchment_boundaries.dat	Catchment boundaries for all case studies used
Raingauges_TBR.dat	Raingauge names and locations

3. **Display sets.** This contains sample display sets: see Section 5.4 for more details.

4. **tsc.** This contains a single file, *TSCIndex_EXTREMES.vbf*, needed by Hyrad to create catchment average rainfalls and time-series charts for the case study catchments.

Once the Hyrad Display Client has been configured to use the Extremes Dataset (see Section 5.1) the historical and modified storm data can be displayed: see sections 5.2 and 5.3 respectively. Hyrad can then be used to extract catchment average rainfall data as 15 minute time-series for use with the PDM rainfall-runoff model: see Section 5.5.

It is assumed that the user has a basic knowledge of using the Hyrad Display Client. However, the user should refer to the Hyrad User Guide (CEH, 2006) for more details of the procedures outlined below.

5.1 Configuring Hyrad to use the Extremes Dataset

The Hyrad Display Client must be configured to use the SIDB contained within the dataset. This is done following the steps below.

1. Run the Hyrad Display Client.

2. Open the Hyrad connection wizard by selecting the *Connection…* option under the *Setup* menu. It is advisable to note the current connection settings before altering them so that they can be reset.

3. Select *Using a local file system* and click *Next*>

4. Select *Browse…* and locate the SIDB directory in the Extremes Dataset, e.g. *C:\Extremes Dataset\Hyrad data\sidb*

5. Click *Next>* and then *Finish*

6. If your Hyrad Display Client has been configured to use a Default Display Set on start up, it is advisable to disable this by selecting *Default Display Set* from the *Setup* menu and then clicking *None.*

7. Close the Hyrad Display Client.

8. Rerun the Hyrad Display Client. The display client is now connected to the Extreme Event Recognition dataset.

When connecting to the Extremes Dataset for the first time and before rerunning the Hyrad Display Client it is recommended (if possible) to follow the steps below.

1. Copy the file

   C:\Extremes Dataset\Hyrad data\tsc\TSCIndex_EXTREMES.vbf

   into the folder

   C:\Program Files\hyrad\Hyrad Display Client\tsc\.

   This allows the Display Client to create catchment average rainfalls for the case study catchments listed in Table 2.1.

2. Copy the folder

   C:\Extemes Dataset\Hyrad data\Overlays\Extremes

   into the folder

   C:\Program Files\hyrad\Hyrad Display Client\overlays

   This allows the Display Client to use the catchment and raingauge overlays employed by the example display sets (see Section 5.4).

   To add these to the list of overlays available to the user, first open the overlay dialog box by selecting the *Overlays…* option under the *Setup* menu. Then click *Add* and locate the 2 overlay files: *catchment_boundaries.dat* and *Raingauges_TBR.dat*. Save the revised list and click *OK.*

5.2 Displaying historical storm data through Hyrad

The different types of historical spatial rainfall data available for each case study are given in Table 5.1. These can be displayed using the Display Wizard by selecting the *Create display…* option from the *Display* menu. The user is then guided through a set of dialogs, the first of which brings up a list of data source types. The source types which relate to historical rainfall data have a *Historical:* prefix. These are listed in Table 5.2 along with an explanation of the data types included in each.

Once a source type and data type have been selected a source must be selected. For the raingauge-only rainfall surface and raingauge-adjusted radar source types the list of sources comprise of the hydrological case studies. For the single site radar and Nimrod product source types the list of sources are

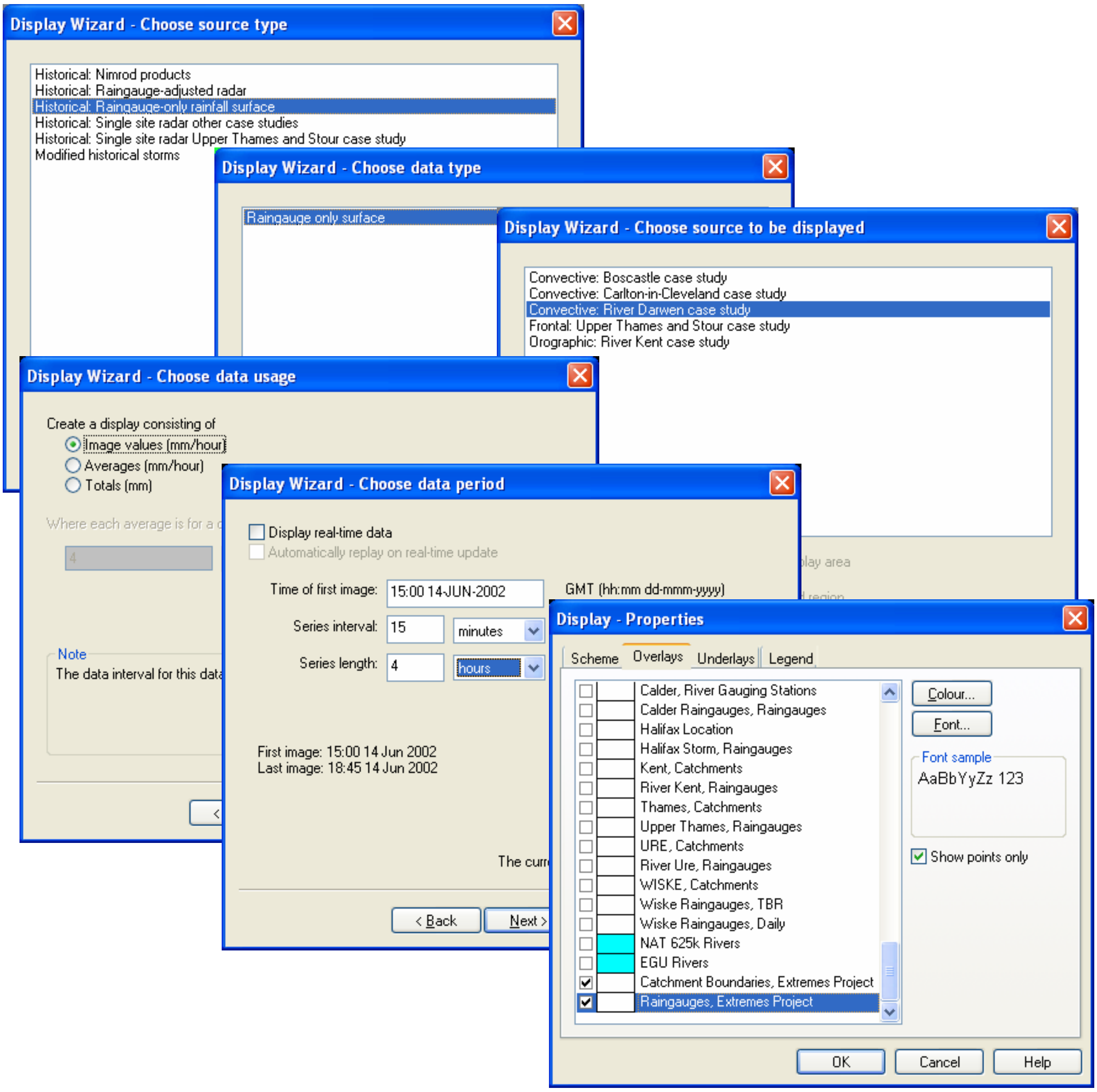


Figure 5.1 Example of completed Display Wizard dialog boxes for displaying the raingauge-only rainfall surface over the River Darwen case study

Table 5.1 Summary of spatial rainfall data available for historical extreme storms including information on which storms have been used for hydrological modelling and which rainfall estimator is used as the basis for the modified storms

Event *Radar(s) used*	Historical spatial data available	Used for hydrological modelling?	Used for modified storms?
Orographic rainfall			
11:00 30 Jan – 19:30 3 Feb 2004 River Kent *Hameldon Hill*	1. 2km raw radar 2. 2km Nimrod QC radar 3. Raingauge-only rainfall surface 4. Raingauge-adjusted 2km raw radar 5. Raingauge-adjusted 2km Nimrod QC radar	Yes Yes Yes Yes Yes	 Yes
Frontal rainfall			
03:00 – 19:00 9 Apr 1998 Upper Thames and Stour *Chennies*	1. 2km raw radar 2. 5km raw radar 3. Composite 2 and 5km raw radar 4. 2km Nimrod QC radar 5. 5km Nimrod QC radar 6. Composite 2 and 5km Nimrod QC radar 7. Raingauge-only rainfall surface 8. Raingauge-adjusted 2km raw radar 9. Raingauge-adjusted 5km raw radar 10 Composite gauge-adj. 2 and 5km raw radar	No No Yes No No No Yes No No Yes	 Yes
Convective rainfall			
15:00 – 18:30 14 Jun 2002 River Darwen *Hameldon Hill*	1. 1km raw radar 2. Raingauge-only rainfall surface 3. Raingauge-adjusted 1km raw radar	Yes Yes Yes	Yes
06:45 – 09:45 10 Aug 2003 Carlton-in-Cleveland *Hameldon Hill*	1. 2km raw radar 2. 2km Nimrod QC radar 3. 5km raw radar 4. 5km Nimrod QC radar 5. Raingauge-only rainfall surface	N/A N/A N/A N/A N/A	 Yes
13:45 – 19:00 19 May 1989 Halifax *Hameldon Hill*	1. 2km raw radar	N/A	Yes
11:30 – 17:00 16 Aug 2004 Boscastle *Cobbacombe and Predannack*	1. 2km raw radar 2. 2km Nimrod QC radar 3. 5km raw radar 4. 5km Nimrod QC radar 5. 1/2/5km composite Nimrod QC radar 6. Raingauge-only rainfall surface	N/A N/A N/A N/A N/A N/A	 Yes (Cob)

Table 5.2 Summary of data source types and data types for the historical extreme storm spatial data

Data source type	Data types	Comments
Historical: Nimrod products	1/2/5km composite Nimrod QC data	Only used for Boscastle case study
Historical: Single site radar Upper Thames and Stour case study	2km raw radar 5km raw radar Composite 2 and 5km raw radar 2km Nimrod QC radar 5km Nimrod QC radar Composite 2 and 5km Nimrod QC radar	A separate source type is needed for the Upper Thames and Stour to accommodate the single site composite data
Historical: Single site radar other case studies	1km raw radar 2km raw radar 5km raw radar 1km Nimrod QC radar 2km Nimrod QC radar 5km Nimrod QC radar	Used for all case studies other than the Upper Thames and Stour case study. Must select appropriate radar given in Table 5.1.
Historical: Raingauge-adjusted radar	Raingauge-adjusted 1km raw radar Raingauge-adjusted 2km raw radar Raingauge-adjusted 5km raw radar Composite gauge-adj. 2 and 5km raw radar Raingauge-adjusted 2km Nimrod QC radar	Extent of data only covers the raingauge network and is therefore less than the single site radar data.
Historical: Raingauge-only rainfall surface	Raingauge-only rainfall surface	Extent of data only covers the raingauge network and is therefore less than the single site radar data.

relevant subsets of those usually listed for the Environment Agency. The *Choose display type* and *Choose display period* dialogs are completed as required by the user; note that the *Display real-time data* check box needs to be unchecked. An example of completed dialog boxes for displaying the raingauge-only rainfall surface over the Darwen case study is given in Figure 5.1. The catchment boundaries and raingauge overlays for the case study catchments can be selected under the *Advanced options* window.

Hyrad display sets for each historical storm are provided and can be loaded, see Section 5.4 for details.

5.3 Displaying modified storm data through Hyrad

Details of each modified storm included in the dataset are listed in Appendix A. These can be displayed using the Display Wizard by selecting the *Create display…* option from the *Display* menu. From the list of source types, select *Modified historical storms* followed by the data type *Modified storms* to bring up a dialog window containing a list of sources: see Figure 5.2. Recall that all modified storms are stored as **averages** of rainfall over the previous time-step rather than instantaneous values.

For a given modified storm select the appropriate source e.g. *River Darwen case study* and click *Next>*. This brings up a *Choose data usage* dialog window. Select the desired data to be displayed e.g. *Image values (mm/hr)* and click *Next>*.

The *Choose data period* window is next. Firstly uncheck the *Display real-time data* check box. Secondly select an appropriate time period that covers the modified extreme storm of interest using the information contained in Appendix A. Figure 5.2 shows an example for displaying storm 3018 of the River Darwen

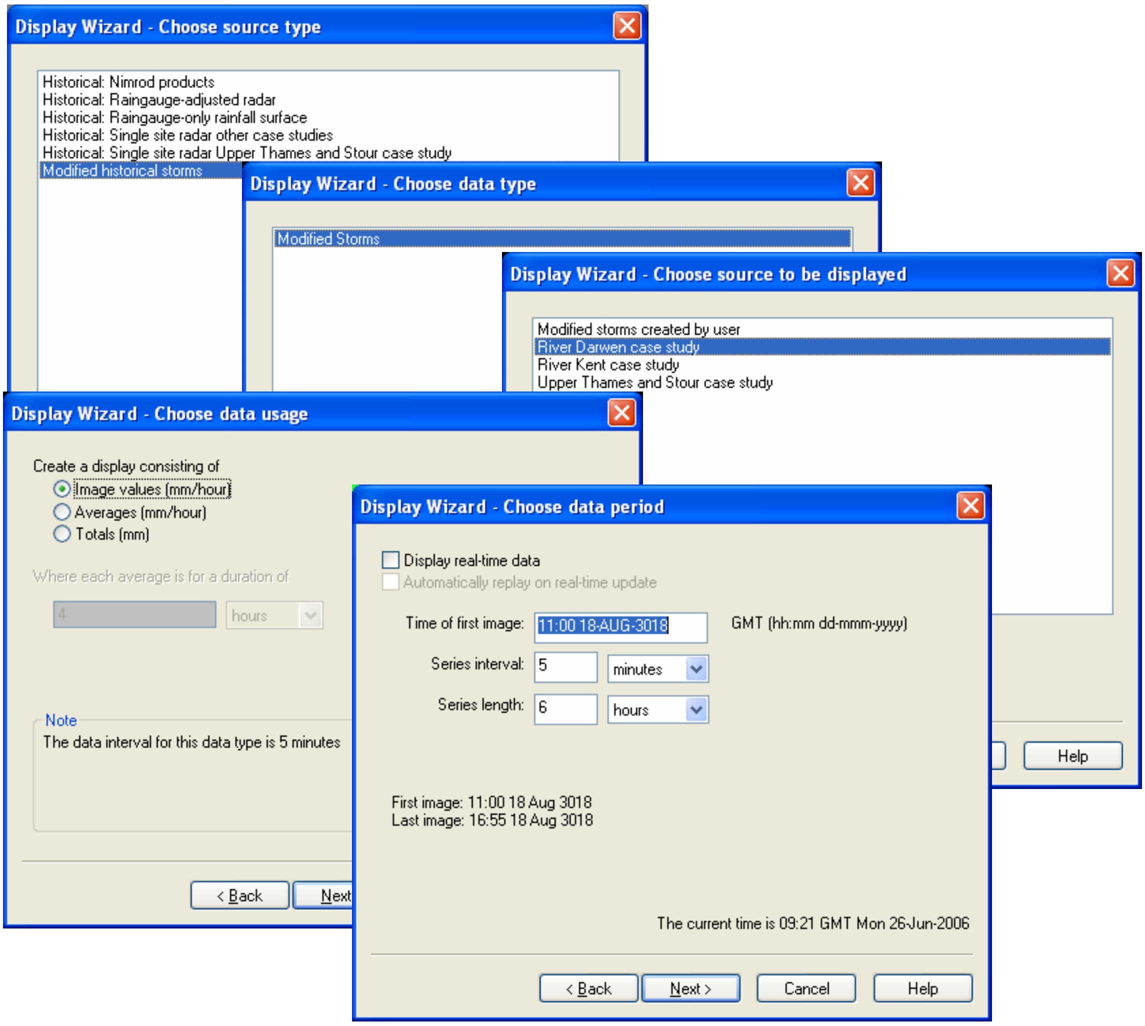


Figure 5.2 Example of completed Display Wizard dialog boxes for displaying storm 3018 of the River Darwen case study

case study. Note the year 3018 is used in the *Time of first image* field and that hours have been used in the *Series length*. The catchment boundaries and raingauge overlays for the case study catchments can be selected under the *Advanced options* window.

Hyrad display sets for certain modified storms have been provided and can be loaded: see Section 5.4 for details.

5.4 Hyrad display sets

Saved Hyrad display sets have been provided for all the historical extreme storms and a selection of the modified extreme storms and are grouped by case study. These can be loaded by selecting *Load Display Set…* from the *File* menu and navigating to the appropriate display set within the dataset. A brief summary of the provided display sets is given in Table 5.3 for the historical storms and Table 5.4 for the modified storms.

Table 5.3 Summary of Hyrad display sets provided for historical storms

~\River Kent case study\kent_historical1.hds
River Kent orographic storm using 2km Nimrod QC data from Hameldon Hill. 21 hour time-series using 15 minute averages and a 4 day accumulation showing orographic enhancement.
~\River Kent case study\kent_historical2.hds
River Kent orographic storm using 2km Nimrod QC data from Hameldon Hill (15 minute averages), gauge-adjusted 2km Nimrod QC (15 minute averages) and the raingauge-only rainfall surface. 21 hour time-series at 15 minute intervals.
~\Upper Thames and Stour case study\thames_historical1.hds
Upper Thames and Stour frontal storm using composite 2 and 5km raw radar data from Chenies (15 minute averages). 16 hour time-series at 15 minute intervals and storm accumulation.
~\Upper Thames and Stour case study\thames_historical2.hds
Upper Thames and Stour frontal storm using composite 2 and 5km raw radar data from Chenies (15 minute averages), gauge-adjusted radar (15 minute averages) and the raingauge-only rainfall surface. 16 hour time-series at 15 minute intervals.
~\River Darwen case study\darwen_historical1.hds
River Darwen convective storm using 1km and 2km raw radar data from Hameldon Hill. 3 hour time-series at 5 minute intervals.
~\River Darwen case study\darwen_historical2.hds
River Darwen convective storm using 1km raw radar data from Hameldon Hill (15 minute averages), gauge-adjusted 1km raw radar (15 minute averages) and the raingauge-only rainfall surface. 3 hour time-series at 15 minute intervals.
~\Carlton-in-Cleveland case study\carlton_historical1.hds
Carlton-in-Cleveland convective storm using Nimrod 2km QC radar data from Hameldon Hill. 2 hour time-series at 5 minute intervals and storm accumulation over sequence.
~\Carlton-in-Cleveland case study\carlton_historical2.hds
Carlton-in-Cleveland convective storm using Nimrod 2km QC radar data from Hameldon Hill (15 min. averages) and the raingauge-only rainfall surface. 2 hour time-series at 15 min. intervals.
~\Halifax case study\halifax_historical.hds
Halifax convective storm using 2km raw radar data from Hameldon Hill. 5¼ hour time-series at 5 minute intervals and storm accumulation over sequence.

Table 5.3 continued

~ \Boscastle case study\boscastle_historical1.hds	
Boscastle convective storm using Nimrod 1/2/5km composite radar data. 5½ hour time-series at 5 min intervals and storm accumulation over sequence.	
~\Boscastle case study\boscastle_historical2.hds	
Boscastle convective storm using Nimrod 1/2/5km composite radar data (15 minute averages) and the raingauge-only rainfall surface. 5½ hour time-series at 15 minute intervals.	

Table 5.4 Summary of Hyrad display sets provided for modified storms

~\River Kent case study\kent_3000_3001_3002_3004.hds	
Simple upscaling of the River Kent storm to attain different 4 day return periods.	
~\River Kent case study\kent_3009_3018_3021.hds	
Relocated and reoriented the Carlton-in-Cleveland convective storm. 3009 – transposition only (SW to NE storm track), 3018 – South to North storm track, 3021 – North to South storm track.	
~\River Kent case study\kent_3010_3014_3016.hds	
Relocated Carlton-in-Cleveland convective storm. Stretched time to attain 100 year return period rainfalls for different durations: 3010 – 30 mins, 3014 – 1 hour, 3016 – 2 hours.	
~\River Kent case study\kent_3024_3025.hds	
Relocated Halifax convective storm. 3024 – simple transposition, 3025 – upscaled to 3 hour, 100 year return period storm.	
~\River Darwen case study\darwen_3000_3005_3010.hds	
Reoriented River Darwen convective storm. 3000 – original orientation, 3005 – West to East storm track, 3010 – East to West storm track.	
~\River Darwen case study\darwen_3019_3022_3025.hds	
Relocated and modified Boscastle convective storm. 3019 - catchment headwater, 3022 – mid to lower catchment, 3025 – stretched spatially to cover majority of catchment.	
~\River Darwen case study\darwen_3027_3030.hds	
Relocated and reoriented Carlton-in-Cleveland convective storm. 3027 – NW to SE storm track, 3030 – SE to NW storm track.	
~\River Darwen case study\darwen_3037_3041_3043_3045.hds	
Relocated, stretched in time and upscaled Upper Thames frontal storm to attain 100 year return periods for different durations. 3037 – 15hrs, 3041 – 24hrs, 3043 – 36hrs, 3045 – 48hrs.	
~\Upper Thames and Stour case study\thames_3001_3005_3007_3009.hds	
Stretched in time and upscaled Upper Thames frontal storm to attain 100 year return periods for different durations. 3001 – 15hrs, 3005 – 24hrs, 3007 – 36hrs, 3009 – 48hrs.	
~\Upper Thames and Stour case study\thames_3011_3014_3017_3020.hds	
Relocated and upscaled different convective storms to attain 100 year return periods. 3011 – Boscastle, 3014 – Carlton-in-Cleveland, 3017 – Halifax, 3020 – Darwen.	
~\Upper Thames and Stour case study\stour_3030_3034_3036_3038.hds	
Stretched in time and upscaled Upper Thames frontal storm to attain 100 year return periods for different durations. 3030 – 15hrs, 3034 – 24hrs, 3036 – 36hrs, 3038 – 48hrs.	
~\Upper Thames and Stour case study\stour_3040_3043_3046.hds	
Relocated and transformed Boscastle convective storm. 3040 – West of catchment, 3043 – reflected in N-S axis and placed at East of catchment, 3046 – Reoriented to give W to E track.	

5.5 Extracting catchment average rainfall data for use with the PDM rainfall-runoff model

Functionality has been added to the Hyrad Display Client to allow 15 minute catchment average rainfall data to be extracted in a format that can be immediately accessed by the PDM. The procedure is outlined below and example screen shots are given in Figure 5.3.

1. Create a Hyrad display of the desired storm.

2. Right click on the display and choose the *Select Catchment…* option from the *Data-Analysis* menu.

3. Select the desired catchment, e.g. Darwen at Blue Bridge.

4. Right click on the display and choose the *Data Export…* option from the *Data-Analysis* menu: this activates the Data Export wizard.

5. From the *Choose usage of data* dialog box select *Totals (mm)* and a duration of 15 minutes. Click *Next*> to move to the *Choose data period* dialog box.

6. Select an appropriate time period for the data export, e.g. 4 days from 09:00 13 June 2002, and set the *Series interval* field to 15 minutes.

7. From the *CSV export format* dialog select *PDM format*.

8. Give the export file a suitable name, e.g. blue_br_eval_rgsurf.csv

9. The exported rainfall data are accessed by the PDM through using the SFILE command within the appropriate ***.f1i** file. An example of an amended ***.f1i** file is given in Figure 5.4.

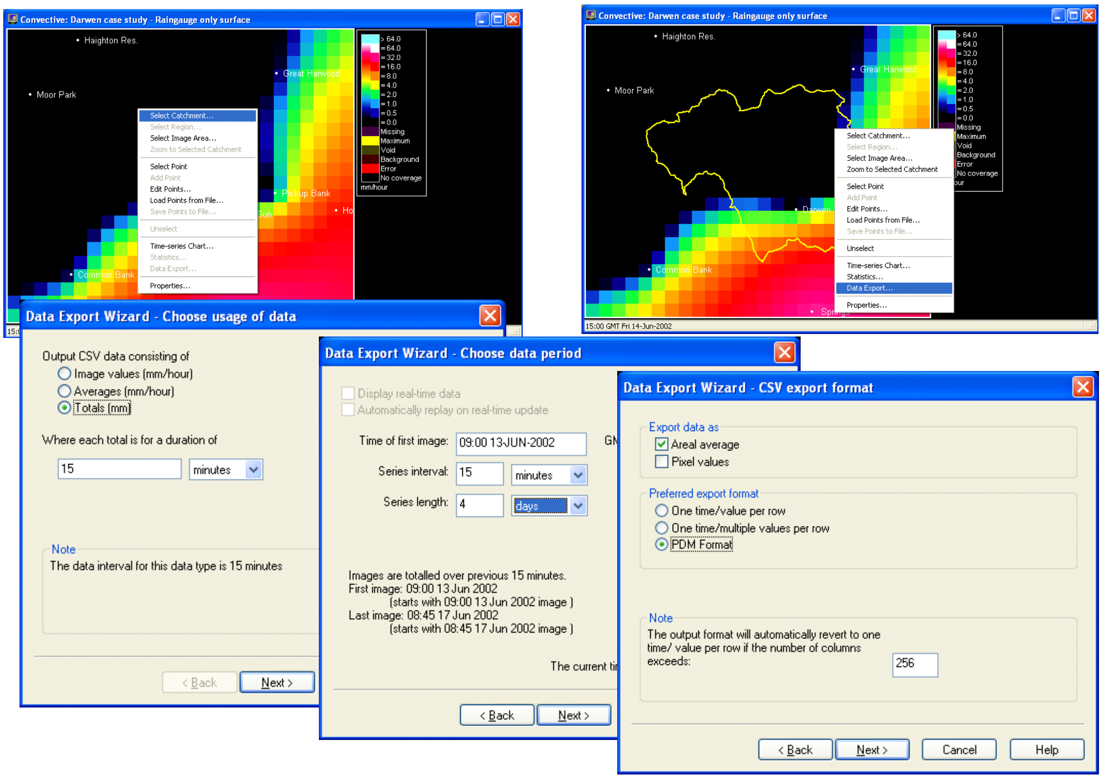


Figure 5.3 Example Hyrad screen shots for exporting 15 minute catchment average rainfall data in PDM format

```
!
! ---------------------------------------------------------------
! NEXT data-series required is for site-id=<RGSURF>
! data-type = rainfall
! time-step =     15 minutes! this is event-data
!
! Requirements for event rainfall are
! totals date-labelled by end of interval
!
NAME not known
! above should be a descriptive site name, if known
!
! Data should cover at least the following period
! First time-point 09:00 13 JUN 2002
! Last  time-point 09:00 16 JUN 2002
! Minumum number of data-points in file      289
FIRST 09:00 13 JUN 2002
LAST  09:00 16 JUN 2002
SFILE blue_br_eval_rgsurf.csv
CLOSE
DATA      <<RGSURF>>
END       <<RGSURF>>
!
```

Figure 5.4 An example of a File-1 Data Interface file configured to use 15 minute catchment average rainfall data exported from Hyrad. The necessary change is highlighted by bold text.

6 Storm transposition software

The *Storm transposition software* directory contains the executable *transposition.exe* which allows the user to transpose historical or modified storms to particular catchments of interest. The user is also able to upscale the storms to achieve desired catchment average storm totals, e.g. design rainfall amounts from the Flood Estimation Handbook CD-ROM (FEH CD-ROM). This transposition can be spatial and/or temporal and the user is referred to the guidance on storm transposition contained in Section 3.2. The transposed data are added to the SIDB database by the software allowing the data to be displayed through Hyrad. This is achieved by following the steps set down in Section 5.3 and selecting the source *Modified storms created by user.* All storms transposed are in the form of **average** rainfall intensities over the preceding time interval (rather than instantaneous values).

The executable *transposition.exe* must be run in the *Storm transposition software* directory by double clicking it. A prompt window appears that guides the user through the storm transposition options. A flowchart outlining the sequence of options is given in Figure 6.1.

Care must be taken to keep track of the transposed storms created by the user. To help with this a summary of the storm transposition is created each time the software is run and written to the file *user_created_storm_details.dat* (beware that previous summaries are overwritten). Example summaries are given in Figure 6.2. Furthermore the software checks if the user has already transposed data to the proposed time period selected and, if so, asks if it should be overwritten.

A worked example is given in Section 6.1 and includes exporting 15 minute catchment average rainfall data from Hyrad and using these in a PDM simulation. Two exercises are also given in sections 6.2 and 6.3.

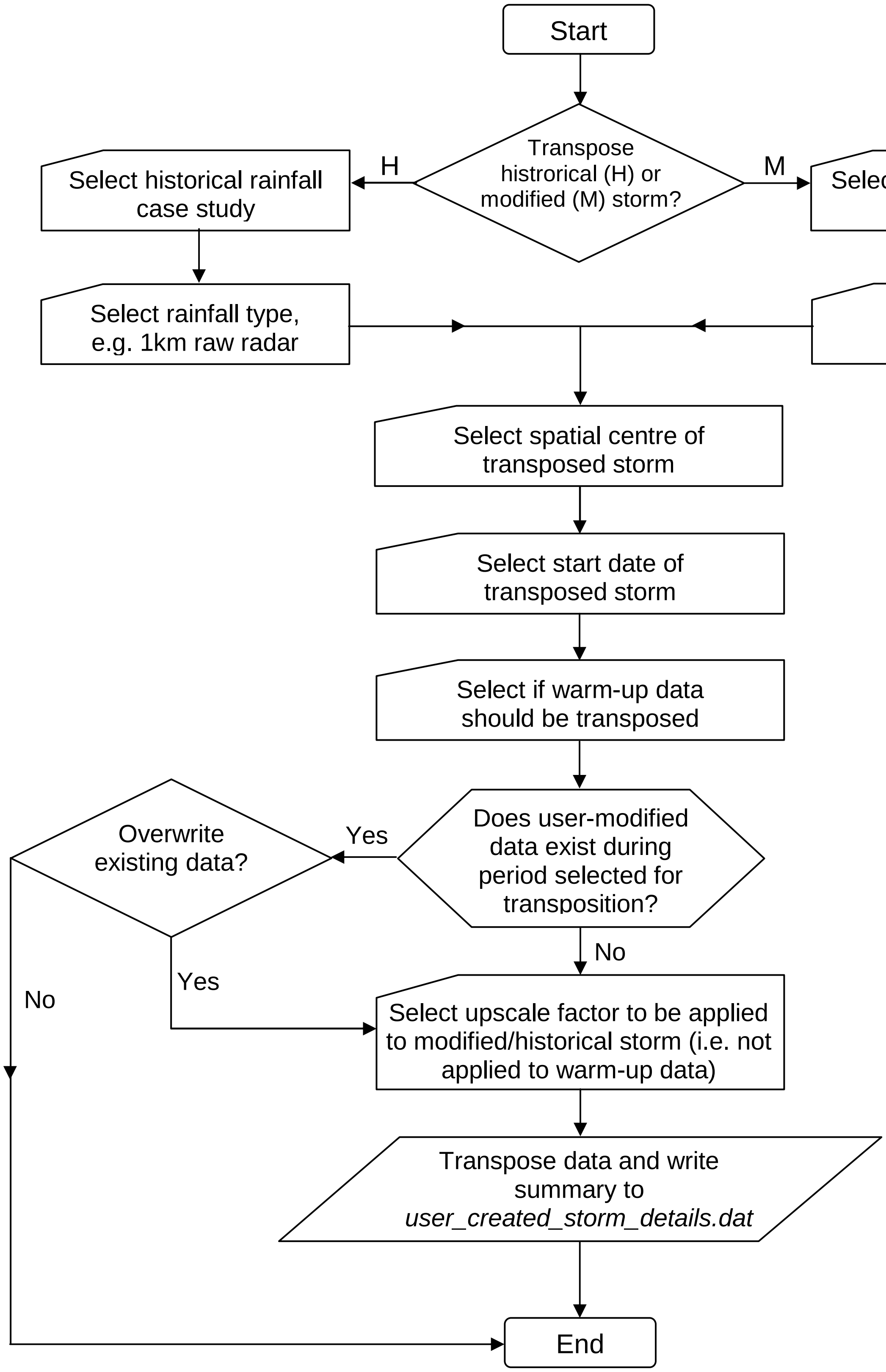


Figure 6.1 Program flowchart for *transposition.exe*

(a) Transposing a historical storm

```
Historical case study storm selected:
River Kent orographic rainfall case study

Historical rainfall data used:
2km Nimrod QC radar, Hameldon Hill

Historical storm has spatial centre of (335000,511000)
Transposed storm has spatial centre of (335000,511000)

Start date of historical storm: 2004/01/30 11:00
End date of historical storm:   2004/02/03 19:30
Start date of transposed storm: 2006/01/30 11:00
End date of transposed storm:   2006/02/03 19:30

Storm upscale parameter:  1.2300

Warm-up rainfall data from
2004/01/22 09:00 to
2004/01/30 11:00 have been transposed
```

(b) Transposing a modified storm

```
Modified case study storm selected:
Storm 3015 for the River Darwen case study

Modified rainfall data used:
River Darwen convective storm, 1km raw radar (Hameldon Hill)

Modified storm has spatial centre of   (371500,423500)
Transposed storm has spatial centre of (380000,424000)

Start date of modified storm:   3015/08/02 15:30
End date of modified storm:     3015/08/02 18:30
Start date of transposed storm: 2006/08/02 15:30
End date of transposed storm:   2006/08/02 18:30

Storm upscale parameter:  1.5000

No warm-up rainfall data have been transposed.
```

Figure 6.2 Example summaries written to *user_created_storm_details.dat*

6.1 Worked example

Before transposing a storm the following key points need to be considered:

- select a storm for transposition
- select a target location/catchment for transposed storm
- select a start date for the transposed storm

In this example the historical Boscastle storm is selected and will be transposed to the River Kent catchments. A grid reference of (351000,500000) has been identified as the centre for the transposed storm (note that the centre can be iterated upon if the storm is not exactly in the desired location). A start date of 11:30 16/08/2010 has been selected following the guidance provided in Section 3.2. Note that a fictitious future date has been used in this example.

Make the initial storm transposition

To make the desired transposition, run the executable *transposition.exe* in the *Storm transposition software* directory. Answer the prompts as below.

1. Select an historical storm for transposition (enter H)
2. Select the Boscastle case study (enter 6)
3. Select 1/2/5km Nimrod QC radar data (enter 9)
4. Enter the spatial centre of the transposed storm (enter 351000 500000)
5. Enter the start date for the transposed storm (enter 2010 8 16 11 30)
6. Do not transpose warm-up data (enter 0)
7. Do not upscale the rainfall (enter 1)
8. Press return to exit
9. Open the file *user_created_storm_details.dat* to view a summary of the storm transposition performed and check this against the above steps.

The spatial rainfall data have now been transposed and are contained within the SIDB database ready to be viewed through Hyrad.

View initial storm transposition through Hyrad

10. Following the instructions in Section 5.3, view the modified storm by displaying a 67 frame sequence (5½ hours) starting at 11:30 16/8/2010. Remember to select the source *Modified storms created by user.*

11. Use the *Video* toolbar to scroll through the storm images.

12. Use the overlay *Catchment boundaries, Extremes project* to display the River Kent catchments.

To calculate the catchment average rainfall of the storm for the River Kent at Sedgwick catchment carry out steps 13 to 16 below.

13. Right click on the display and choose the *Select Catchment…* option from the *Data-Analysis* menu.

14. Select the River Kent at Sedgwick catchment.

15. Right click on the display and choose the *Time-series Chart…* option from the *Data-Analysis* menu.

16. Select a time period of 6 hours and click *OK.*

This produces a time-series chart of the catchment average rainfall similar to that in Figure 6.3. Note that the catchment average rainfall total over the storm is 36.1mm.

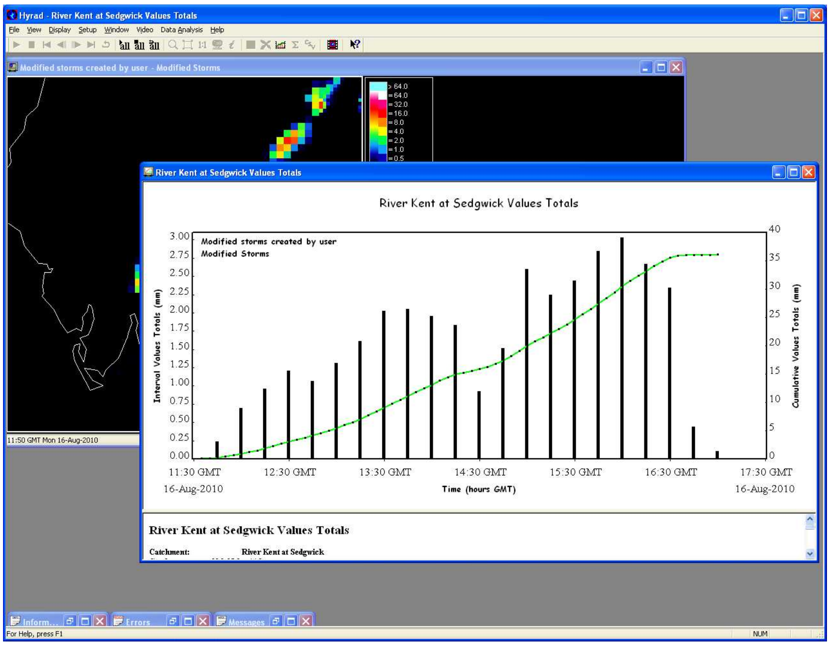


Figure 6.3 Worked example: a time-series chart created by Hyrad

Using the FEH CD-ROM to derive a 100 year return period storm

17. Using the FEH CD-ROM with the Sedgwick gauging station location (SD 5090 8745) gives a design catchment average rainfall of 70.0mm for a 100 year return period, 5.5 hour duration storm (see Figure 6.4).

18. To transpose and upscale the Boscastle storm to give a 100 year storm for the River Kent to Sedgwick catchment, repeat steps 1 to 8 but using a storm upscale factor of 1.939 (=70.0/36.1). Note that when asked if you want to overwrite existing data enter 1 for yes.

Extracting 15 minute catchment average rainfall data for input into the PDM

19. Firstly the Hyrad display needs to be updated to show the upscaled transposed storm. This can be achieved by saving the display set made during step 10 and then reopening it. A suitable filename for saving the display set would be:

    ~\Extremes Dataset\Storm transposition software\Examples and Exercises\Worked Example\Example1.hds

20. Following instructions 2 to 7 in Section 5.5 export 15 minute catchment average rainfall for the River Kent at Sedgwick catchment. Make sure the time period covers the entire storm, e.g. 6 hours from 11:30 16/8/2010. Use the filename *Sedgwick_mod1.csv* and export it to the directory:

    ~\Extremes Dataset\Storm transposition software\Examples and Exercises\Worked Example

    The exported file should look like Figure 6.5 when opened in a text editor (e.g. WordPad).

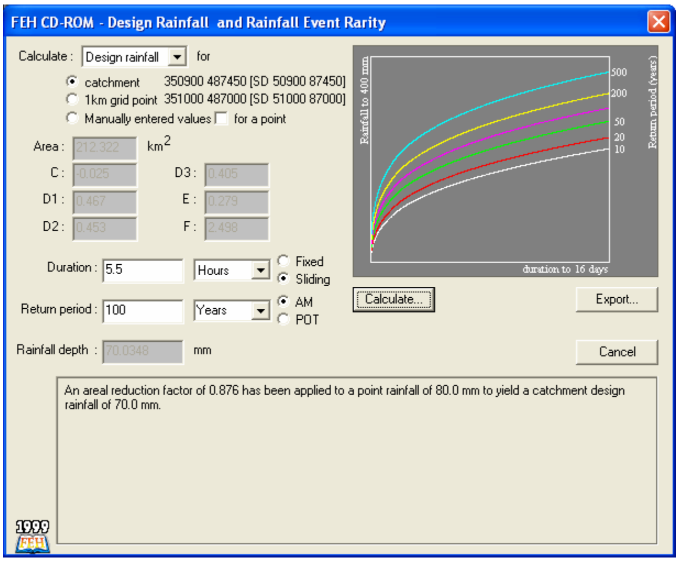


Figure 6.4 Worked example: calculating design rainfall amounts using the FEH-CDROM

```
"VERSION        ","Hyrad Display Client Version: 2.6.1"
"Exported at    ","14:28:11,GMT,28-JUN-2006"
"FORMAT         ","PDM format"
"Data Source    ","Modified storms created by user"
"Data Type      ","Modified Storms"
"Output type    ","Values (totalled over 15 minutes)"
"Units          ","mm"
"Catchment      ","River Kent at Sedgwick"
"Area           ","212.30km^2"
"Areal coverage%","100.0"
"Sequence Period","11:30 GMT 16 Aug 2010-17:00 GMT 16 Aug 2010"
"Output Interval","15 minutes"
"Number Images  ","23"
"Year","Month","Day","Hour","Minute","Second","Reading"
2010,08,16,11,45,00,    0.456
2010,08,16,12,00,00,    1.343
2010,08,16,12,15,00,    1.859
2010,08,16,12,30,00,    2.343
2010,08,16,12,45,00,    2.068
2010,08,16,13,00,00,    2.546
2010,08,16,13,15,00,    3.124
2010,08,16,13,30,00,    3.919
2010,08,16,13,45,00,    3.974
2010,08,16,14,00,00,    3.793
2010,08,16,14,15,00,    3.555
2010,08,16,14,30,00,    1.791
2010,08,16,14,45,00,    2.941
2010,08,16,15,00,00,    5.043
2010,08,16,15,15,00,    4.354
2010,08,16,15,30,00,    4.734
2010,08,16,15,45,00,    5.512
2010,08,16,16,00,00,    5.880
2010,08,16,16,15,00,    5.179
2010,08,16,16,30,00,    4.535
2010,08,16,16,45,00,    0.848
2010,08,16,17,00,00,    0.202
```

Figure 6.5 Worked example: exported 15 minute catchment average rainfall

Using the exported rainfall data in the PDM

Within the directory

~\Extremes Dataset\Storm transposition software\Examples and Exercises\Worked Example

there is a PDM input file called *sedgwick_example.inp* that contains the calibrated PDM parameters for the River Kent to Sedgwick catchment. It is set up to run between the event dates of 09:00 15/8/2010 and 09:00 20/8/2010 which covers the transposed storm created earlier.

A ‘dummy’ File-1 Data Interface file, *sedgwick_example.f1x*, needs to be created using the steps that follow.

21. Left click on the *PDM* from the menu-tree *Start-Programs-CEH Model Calibration.*

22. Choose the directory containing the *sedgwick_example.inp* file. Click on the input file and press *run*.

23. Initially two windows will appear. The lower window will show an error message indicating that the software has created a 'dummy' File-1 Data Interface file, *sedgwick_example.f1x,* in the *Worked Example* directory*.*

24. Press *enter* to exit the software*.*

The 'dummy' File-1 Data Interface file, *sedgwick_example.f1x*, needs to be amended to reflect the data location and format.

25. Open the 'dummy' File-1 Data Interface file, *sedgwick_example.f1x*, in a text editor, e.g. WordPad.

26. Rainfall data: amend the data block for the rainfall by adding the lines

    ```
    SFILE sedgwick_mod1.csv
    CLOSE
    ```

    before the `DATA` command (see Figure 6.6).

27. River flow data: since there is no observed flow a fictitious value needs to be supplied to PDM and is used to initialise the various water stores. This is achieved by ensuring the `FIRST` and `LAST` commands within the river flow data block have the same date and by entering a single value between the `DATA` and `END` statements.

Figure 6.6 shows an example of an amended File-1 Data Interface file. Historical flow records suggest the river flow value of 10 m^3s^{-1} is representative of low flow conditions. Different initial river flow conditions can be investigated by changing this value in the File-1 Data Interface file.

28. Close the 'dummy' File-1 Data Interface file, *sedgwick_example.f1x*.

29. Rename the file *sedgwick_example.f1x* as *sedgwick_example.f1i*.

30. Rerun the PDM software.

The PDM for Sedgwick should now run using the transposed storm data and produce a hydrograph like Figure 6.7.

The above steps relating to the PDM are deliberately brief and assume some knowledge of the software. For more details on running the PDM and connecting it to rainfall data via the File-1 Interface the user is referred to the Practical User Guides to the PDM and File-1 User Interface (CEH, 2005).

```
!
! -------------------------------------------------------------
! NEXT data-series required is for site-id=<KENT_730511>
! data-type = river flows
! time-step =     15 minutes! this is event-data
!
! Requirements for event river flows are
! instantaneous values at date-time given
!
NAME not known
! above should be a descriptive site name, if known
!
! Data should cover at least the following period
! First time-point 09:00 15 AUG 2010
! Last  time-point 09:00 20 AUG 2010
! Minumum number of data-points in file      481
FIRST 09:00 15 AUG 2010
LAST  09:00 15 AUG 2010
DATA     <<KENT_730511>>
10.0
END      <<KENT_730511>>
!
! ------------------------------------------------------------
! NEXT data-series required is for site-id=<MODIFIED>
! data-type = rainfall
! time-step =     15 minutes! this is event-data
!
! Requirements for event rainfall are
! totals date-labelled by end of interval
!
NAME not known
! above should be a descriptive site name, if known
!
! Data should cover at least the following period
! First time-point 09:00 15 AUG 2010
! Last  time-point 09:00 20 AUG 2010
! Minumum number of data-points in file      481
FIRST 09:00 15 AUG 2010
LAST  09:00 20 AUG 2010
SFILE sedgwick_mod1.csv
CLOSE
DATA     <<MODIFIED>>
END      <<MODIFIED>>
```

Figure 6.6 An example of a File-1 Data Interface file amended to use exported rainfall data. The changes are highlighted by bold text.

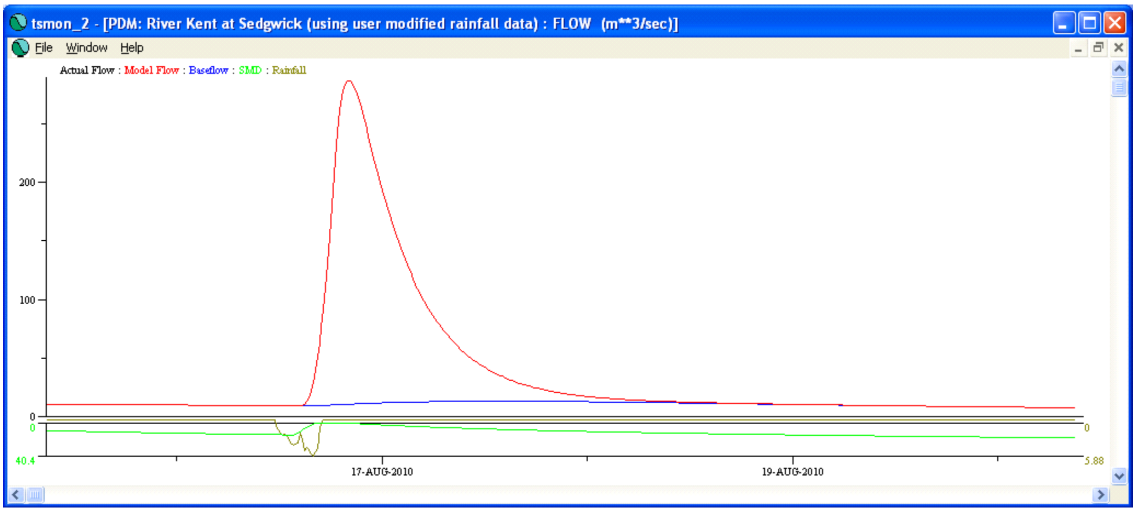


Figure 6.7 Worked example: PDM hydrograph using transposed storm data

6.2 Exercise 1

In this exercise the historical Upper Thames frontal storm will be transposed to the River Darwen at Blue Bridge catchment and a 100 year 15 hour duration storm created. 15 minute catchment average rainfall data will be exported for use with the PDM.

Task 1 – Initial storm transposition

- Run the storm transposition software, *transposition.exe*, and select the historical Upper Thames and Stour case study. Then select the raingauge-adjusted composite 2/5km raw radar.
- Transpose the storm to (370000,430000) with a start date of 03:00 9/4/2011. Do not transpose the warm-up data and do not upscale the data.

Task 2 – View the Initial storm transposition through Hyrad

- Using Hyrad, create a display of the transposed storm for a period of 16 hours starting at 03:00 9/4/2011. Use the overlay *Catchment boundaries, Extremes project* to display the River Darwen catchments. Scroll through the storm images using the *Video* toolbar.
- Select the *Darwen at Blue Bridge* catchment and create a time-series chart for the duration of the transposed storm. The catchment average storm total rainfall should be 56.58mm (see Figure 6.8).

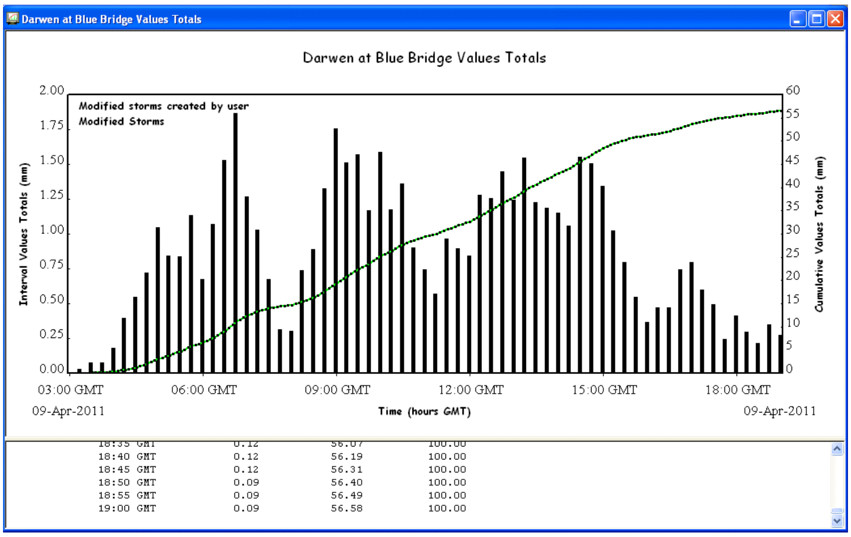


Figure 6.8 Exercise 1: a time-series chart produced by Hyrad

Task 3 – Using the FEH CD-ROM , derive a 100 year return period storm

- Using the FEH CD-ROM with the Blue Bridge gauging station location (SD 565 278) calculate the design rainfall for a 100 year return period, 16 hour duration storm. (This should give an answer of 93.4mm). Calculate the upscale factor needed to create a 100 year storm for the River Darwen to Blue Bridge catchment.

- Create the 100 year storm by re-running the storm transposition software, *transposition.exe*, using the upscale factor calculated above.

Task 4 – Extracting 15 minute average rainfall in PDM format

- Update the Hyrad display to show the upscaled storm (i.e. save the display set and reopen it).

- Extract 15 minute catchment average rainfall totals for the River Darwen at Blue Bridge catchment. Make sure the series interval is 15 minutes and that the time period covers the entire storm, e.g. 17 hours from 03:00 9/4/2011. Use the filename *blue_br_mod1.csv* and export the PDM format file to the directory:

  ~\Extremes Dataset\Storm transposition software\Examples and Exercises\Exercise 1

  The exported data should look like Figure 6.9 when viewed through a text editor.

```
"VERSION        ","Hyrad Display Client Version: 2.6.1"
"Exported at    ","15:55:48,GMT,29-JUN-2006"
"FORMAT         ","PDM format"
"Data Source    ","Modified storms created by user"
"Data Type      ","Modified Storms"
"Output type    ","Values (totalled over 15 minutes)"
"Units          ","mm"
"Catchment      ","Darwen at Blue Bridge"
"Area           ","135.68km^2"
"Areal coverage%","100.0"
"Sequence Period","03:00 GMT 09 Apr 2011-19:45 GMT 09 Apr 2011"
"Output Interval","15 minutes"
"Number Images  ","68"
"Year","Month","Day","Hour","Minute","Second","Reading"
2011,04,09,03,15,00,    0.045
2011,04,09,03,30,00,    0.127
2011,04,09,03,45,00,    0.122
2011,04,09,04,00,00,    0.299
2011,04,09,04,15,00,    0.653
2011,04,09,04,30,00,    0.904
2011,04,09,04,45,00,    1.188
2011,04,09,05,00,00,    1.725
2011,04,09,05,15,00,    1.393
2011,04,09,05,30,00,    1.385
```

Figure 6.9 Exercise 1: exported 15 minute catchment average rainfall totals

Task 5 - Using the exported rainfall data in the PDM

Within the directory

~\Extremes Dataset\Storm transposition software\Examples and Exercises\Exercise 1

there is a PDM input file called *blue_br_exercise1.inp* that contains the calibrated PDM parameters for the River Darwen to Blue Bridge catchment.

- Alter the input file *blue_br_exercise1.inp* to run between the event dates of 09:00 8/4/2011 and 09:00 12/4/2011 by replacing the line

  ```
  '09:00 13 JUN 2002' '09:00 16 JUN 2002'   96   '09:00 16 JUN 2002'
  ```
  with
  ```
  '09:00  8 APR 2011' '09:00 12 APR 2011' /
  ```

- Create the 'dummy' File-1 Data Interface file, *blue_br_exercise1.f1x*, by running the PDM.

- Amend the 'dummy' File-1 Data Interface file, *blue_br_exercise1.f1x*, to link to the rainfall data file, *blue_br_mod1.csv* by adding the lines

  ```
  SFILE blue_br_mod1.csv
  CLOSE
  ```

  before the `DATA` command in the rainfall data block.

- Amend the 'dummy' File-1 Data Interface file, *blue_br_exercise1.f1x*, to have a single river level value of 0.8 m by ensuring the `FIRST` and `LAST` commands within the river level data block have the same date and by entering the single value of `0.8` between the `DATA` and `END` statements. The river level of 0.8 m is converted by the PDM using a rating equation to give a river flow of 13.3 m^3s^{-1}. This flow value is then used for model initialisation.

  The amended 'dummy' File-1 Data Interface file, *blue_br_exercise1.f1x*, should look like Figure 6.10.

- Rename the file *blue_br_exercise1.f1x* as *blue_br_exercise1.f1i* and rerun the PDM software. This should produce a hydrograph like Figure 6.11.

Task 6 – Further investigation

- Use different river levels for model initialisation and investigate their effect on the modelled flood peak from the transposed storm.

- Shorten or lengthen the model warm-up period.

- Create storms with other return periods of interest, e.g. 200, 500 or 1000 year storms.

```
!
! ------------------------------------------------------------
! NEXT data-series required is for site-id=<DAR_71014>
! data-type = river levels
! time-step =     15 minutes! this is event-data
!
! Requirements for event river levels are
! instantaneous values at date-time given
!
NAME not known
! above should be a descriptive site name, if known
!
! Data should cover at least the following period
! First time-point 09:00  8 APR 2011
! Last  time-point 09:00 12 APR 2011
! Minumum number of data-points in file      385
FIRST 09:00  8 APR 2011
LAST  09:00  8 APR 2011
DATA      <<DAR_71014>>
0.8
END       <<DAR_71014>>
!
! ----------------------------------------------------------
! NEXT data-series required is for site-id=<MODIFIED>
! data-type = rainfall
! time-step =     15 minutes! this is event-data
!
! Requirements for event rainfall are
! totals date-labelled by end of interval
!
NAME not known
! above should be a descriptive site name, if known
!
! Data should cover at least the following period
! First time-point 09:00  8 APR 2011
! Last  time-point 09:00 12 APR 2011
! Minumum number of data-points in file      385
FIRST 09:00  8 APR 2011
LAST  09:00 12 APR 2011
SFILE blue_br_mod1.csv
CLOSE
DATA      <<MODIFIED>>
END       <<MODIFIED>>
```

Figure 6.10 Exercise 1: File-1 Data Interface file amended to use exported rainfall data. The changes are highlighted by bold text.

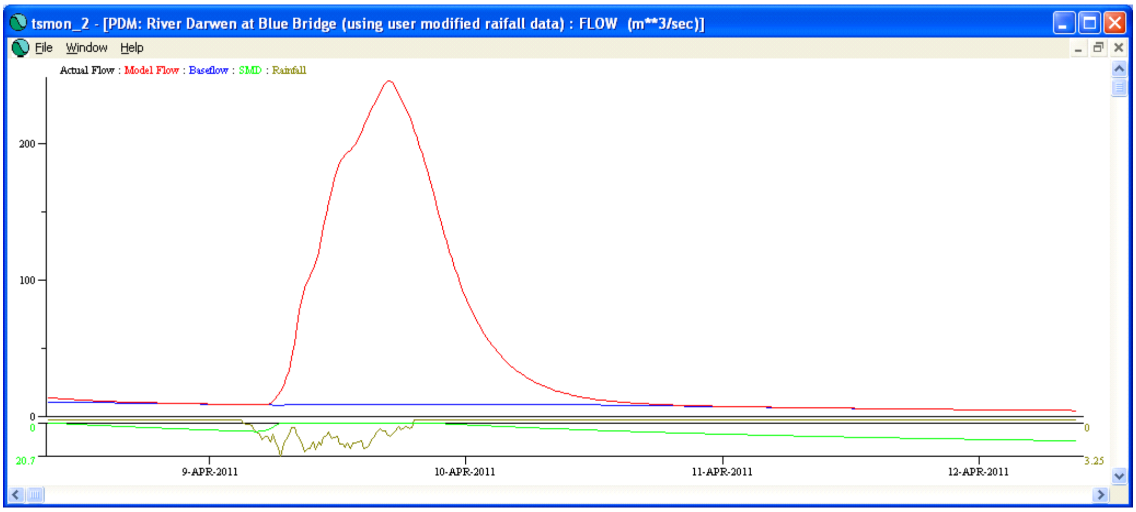


Figure 6.11 Exercise 1: PDM hydrograph using transposed storm data

6.3 Exercise 2

In this exercise modified forms of the Carlton-in-Cleveland storm are transposed to the Cherwell at Banbury catchment. Storms of 30 min, 1¼ hour and 2½ hour duration will be created with return periods of 100 years. 15 minute catchment average rainfall data will be exported for use with the PDM.

Task 1 – Initial storm transposition

- Run the storm transposition software, *transposition.exe*. Select modified storm 3010 from the River Kent case study.
- Transpose the storm over the Banbury catchment to (446000,239000) with a start date of 08:30 16/8/2012. Do not transpose the warm-up data and do not upscale the data.

Task 2 – View the Initial storm transposition through Hyrad

- Using Hyrad, create a display of the transposed storm for a period of 11/2 hours starting at 08:30 16/8/2012. Use the overlay *Catchment boundaries, Extremes project* to display the Upper Thames and Stour catchments. Scroll through the storm images using the *Video* toolbar.
- Select the *Cherwell at Banbury* catchment and create a time-series chart for the duration of the transposed storm. The catchment average storm total rainfall should be 24.54mm (see Figure 6.12).

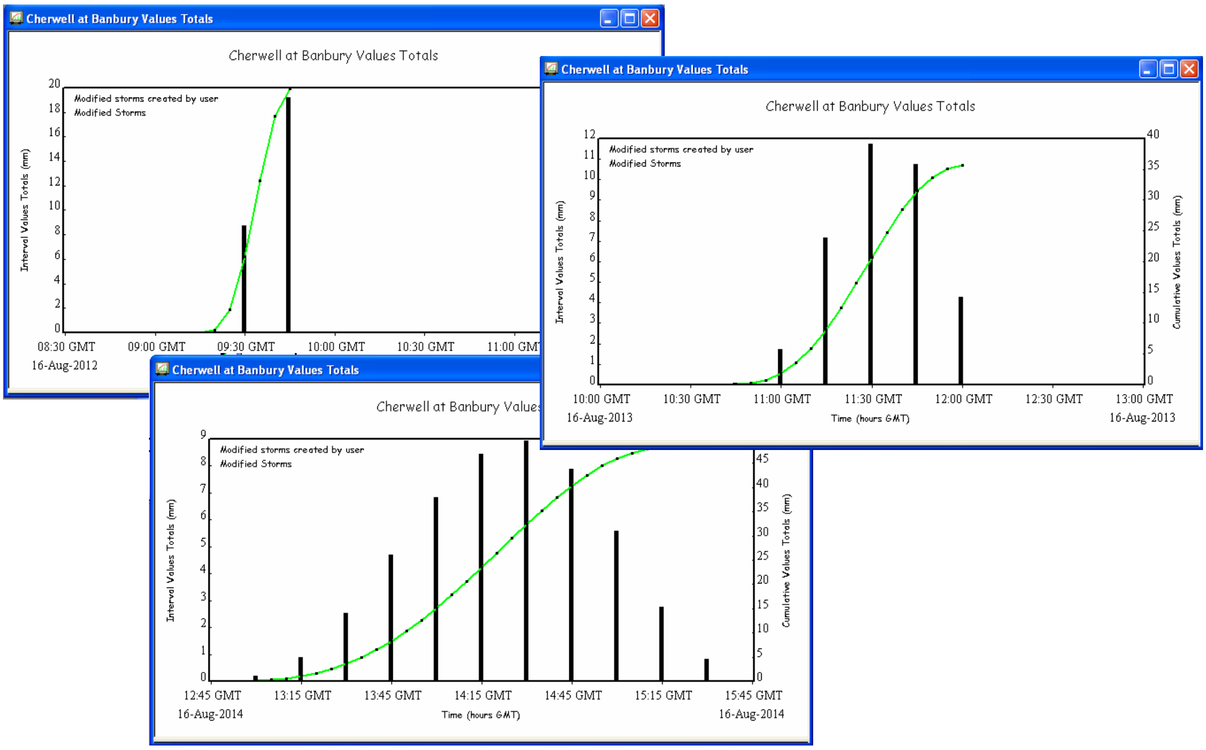


Figure 6.12 Exercise 2: time-series charts produced by Hyrad

Task 3 – Using the FEH CD-ROM , derive a 100 year return period storm

- Using the FEH CD-ROM with the Banbury gauging station location (SP 457 414) calculate the design rainfall for a 100 year return period, 30 minute duration storm. (This should give an answer of 27.9mm). Calculate the upscale factor needed to create a 100 year storm for the River Cherwell to Banbury catchment.

- Create the 100 year storm by re-running the storm transposition software, *transposition.exe*, using the upscale factor calculated above.

Task 4 – Extracting 15 minute average rainfall in PDM format

- Update the Hyrad display to show the upscaled storm (i.e. save the display set and reopen it).

- Extract 15 minute catchment average rainfall totals for the Cherwell at Banbury catchment. Make sure the time period covers the entire storm, the series interval is 15 minutes and the PDM export format is used. Use the filename *banbury_mod1.csv* and export it to the directory:

  ~\Extremes Dataset\Storm transposition software\Examples and Exercises\Exercise 2

Task 5 - Using the exported rainfall data in the PDM

Within the directory

~\Extremes Dataset\Storm transposition software\Examples and Exercises\Exercise 2

there is a PDM input file called *banbury_exercise2.inp* that contains the calibrated PDM parameters for the River Cherwell at Banbury catchment. Note that although MORECS potential evaporation data were used during model calibration, a sine curve profile (generated internally by the PDM) has been used here as no MORECS data exist for the time period of the transposed storm.

- Alter the input file *banbury_exercise2.inp* to run between the event dates of 09:00 15/8/2012 and 09:00 22/8/2012.

- Create the ‘dummy’ File-1 Data Interface file, *banbury_exercise2.f1x*, by running the PDM.

- Amend the ‘dummy’ File-1 Data Interface file, *banbury_exercise2.f1x*, to link to the rainfall data file, *banbury_mod1.csv* by adding the lines

  ```
  SFILE banbury_mod1.csv
  CLOSE
  ```

  before the `DATA` command in the rainfall data block.

- Amend the 'dummy' File-1 Data Interface file, *banbury_exercise2.f1x*, to have a single river flow value of 10.0 m^3s^{-1} by ensuring the `FIRST` and `LAST` commands within the river level data block have the same date and by entering the single value of `10.0` between the `DATA` and `END` statements.

- Rename the file *banbury_exercise2.f1x* as *Banbury_exercise2.f1i* and rerun the PDM software. This should produce a hydrograph like Figure 6.13 (a).

Task 6 – Creating more 100 year return period storms with differing durations

- Repeat tasks 1-5 but with the following changes indicated below.
  - Transpose storm 3014 from the River Kent case study.
  - Use a start date of 08:30 16/8/2013 for the transposed storm.
  - The time-series chart for the catchment at Banbury should look like Figure 6.12. The storm has a catchment total of 35.66 mm over the 1 ¼ hours to 12:00 16/8/2013.
  - The FEH CD-ROM should give a design rainfall of 39.5 for a1¼ hour duration, 100 year return period storm.
  - Export the 15 minute catchment average totals to *banbury_mod2.csv*.
  - Run the PDM between 09:00 15/8/2013 and 09:00 22/8/2013. The resulting hydrograph should look like Figure 6.13 (b).

- Repeat tasks 1-5 but with the changes below.
  - Transpose storm 3016 from the River Kent case study.
  - Use a start date of 08:30 16/8/2014 for the transposed storm.
  - The time-series chart for the catchment at Banbury should look like Figure 6.12. The storm has a catchment total of 49.36 mm over the 2½ hours to 15:30 16/8/2014.
  - The FEH CD-ROM should give a design rainfall of 49.7 for a 2½ hour duration, 100 year return period storm.
  - Export the 15 minute catchment average totals to *banbury_mod2.csv*.
  - Run the PDM between 09:00 15/8/2014 and 09:00 22/8/2014. The resulting hydrograph should look like Figure 6.13 (c).

Task 7 – Further investigation

This exercise investigates, for a fixed return period of 100 years, the effect of increasing storm duration (and hence increasing storm total) on the modelled PDM flow response. Further investigation could involve the tasks below.

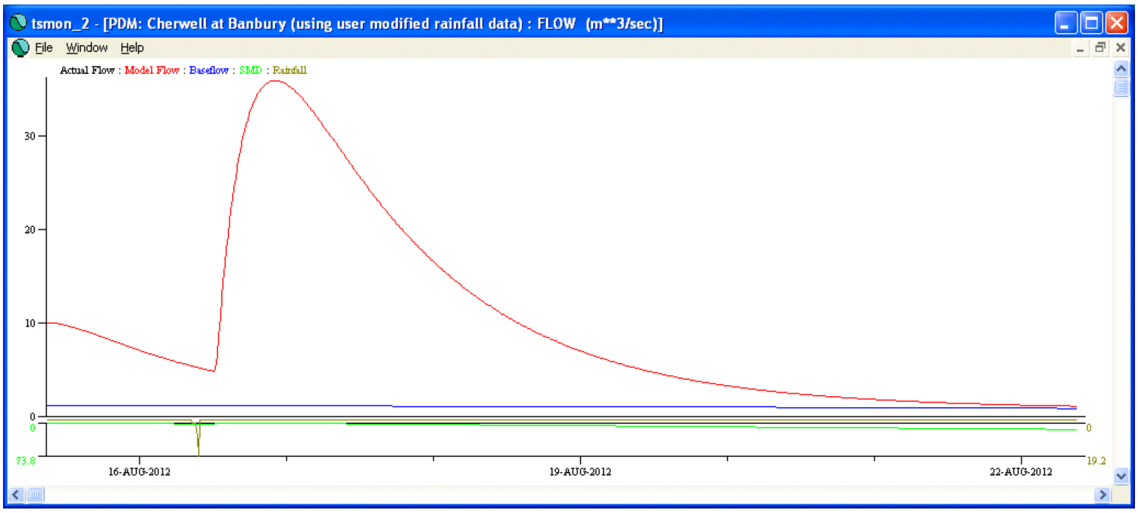
- Using different river flow values for model initialisation.

- Shortening or lengthening the model warm-up period.

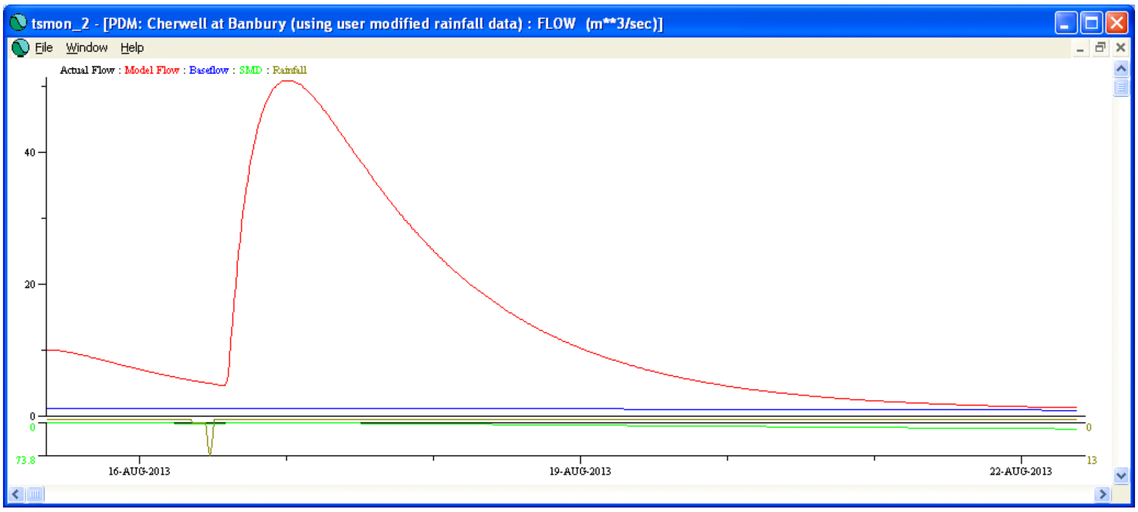
- Creating storms with other return periods of interest, e.g. 200, 500 or 1000 year storms.

- Using the rainfall as input into other calibrated river flow models.

(a) 30 min, 100 year return period storm



(b) 1¼ hour, 100 year return period storm



(c) 2½ hour, 100 year return period storm

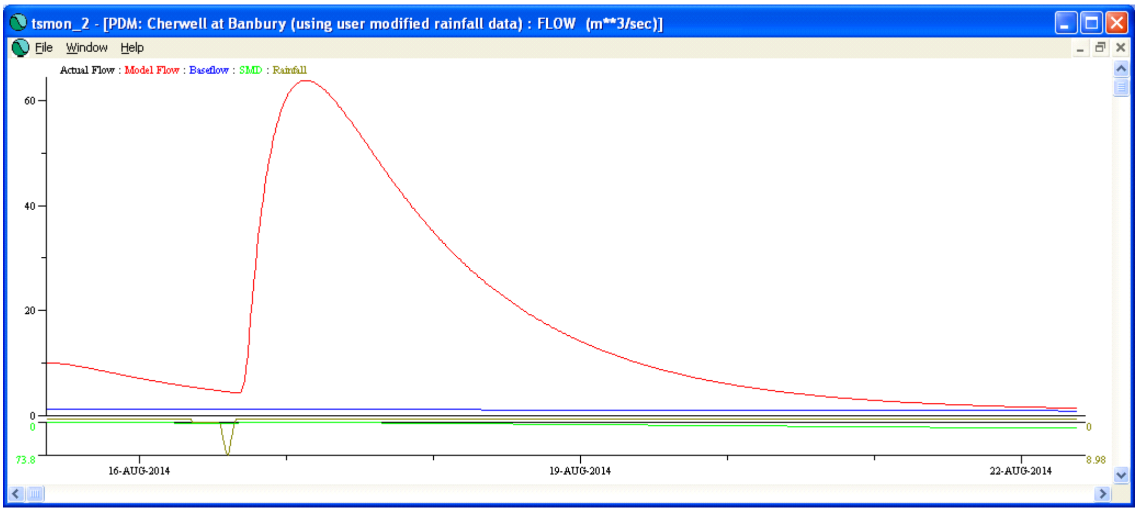


Figure 6.13 Exercise 2: example PDM hydrographs using transposed storm data

References

CEH Wallingford, 2005. *PDM Rainfall-Runoff Model*. Version 2.2, Centre for Ecology & Hydrology, Wallingford. (Includes Guide, Practical User Guides, User Manual and Training Exercises).

CEH Wallingford, 2006. *Hyrad User Guide.* Version 1.3, Centre for Ecology & Hydrology, Wallingford, 89pp.

Collier, C.G., Fox, N.I. and Hand, W.H., 2002. *Extreme Rainfall and Flood Event Recognition.* Contract Report FD2201 to Defra/Environment Agency, 57pp.

Moore, R.J., Bell, V.A., Cole, S.J. and Jones, D.A., 2006. Spatio-temporal rainfall datasets and their use in evaluating the extreme event performance of hydrological models. R&D Technical Report FD2208, Report to Defra and the Environment Agency, CEH Wallingford, 259pp.

Appendix A Catalogue of Modified Storms

This appendix lists details of the amplified storms that have been created. The details given for each storm are set down below.

- **Year.** This is a fictitious year used to identify the storm within the dataset.
- **Period.** This is the total period used for hydrological modelling. Over the period the modified spatial rainfall for each storm consists of three parts:
    1. **Warm-up.** Uses historical radar data to allow model warm-up. This usually ends with a period of low rainfall.
    2. **Amplified storm.** Amplified storm data are used
    3. **Cool-down.** Zero rainfall
- **Historical storm modified.** Identifies which historical storm was modified.
- **Storm modification and transposition settings.** Only settings that are altered are listed.
- **Comments.** This gives the catchment average rainfall amount, duration and estimated return period (using FEH) and any other points of interest.

The modified storms created for each hydrological case study are listed below.

A.1 River Kent case study

The details of the amplified storms are listed in Table A.1. Note that the rainfall amount, duration and FEH-estimated return period quoted relate to the River Kent at Victoria Bridge catchment.

Table A.1 Details of the amplified storms created for the River Kent case study. Note that the rainfall amount, duration and FEH-estimated return period quoted relate to the River Kent at Victoria Bridge catchment.

Year	Period	Historical storm modified	Storm modification and transposition settings	Comments
3000	22/01 – 08/02	Kent (Orographic)	None, used original 2 km QC gauge-adjusted radar.	**195.9 mm in 4 days** to 11:00 02/02. Estimated return period of **69** years
3001	22/01 – 08/02	Kent (Orographic)	*f*=1.165	**208.5 mm in 4 days** to 11:15 02/02. Estimated return period of **100** years
3002	22/01 – 08/02	Kent (Orographic)	*f*=1.50	**234 mm in 4 days** to 11:15 02/02. Estimated return period of **200** years

3003	22/01 – 08/02	Kent (Orographic)	f=2.022	**273.8 mm in 4 days** to 11:15 02/02. Estimated return period of **500** years
3004	22/01 – 08/02	Kent (Orographic)	f=2.467	**307.7 mm in 4 days** to 11:15 02/02. Estimated return period of **1000** years
3005	22/01 – 08/02	Kent (Orographic)	f =1.36 s_{time} =2.5	**223.8 mm in 5 days** to 10:45 03/02. Estimated return period of **100** years
3006	22/01 – 08/02	Kent (Orographic)	f =1.71 s_{time} =2.5	**250.4 mm in 5 days** to 10:45 03/02. Estimated return period of **200** years
3007	22/01 – 08/02	Kent (Orographic)	f =1.244 s_{time} =2.5	**291.1 mm in 5 days** to 10:45 03/02. Estimated return period of **500** years
3008	22/01 – 08/02	Kent (Orographic)	f =2.702 s_{time} =2.5	**326.0 mm in 5 days** to 10:45 03/02. Estimated return period of **1000** years
3009	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,489000) $\left(u_0^T, v_0^T\right)$=(3333,3333)	Historical storm orientation, velocity and direction have been preserved. **14.4 mm in 30mins** to 09:45 16/08. Estimated return period of **19** years
3010	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,489000) $\left(u_0^T, v_0^T\right)$=(3333,3333) f=1.642	Historical storm orientation, velocity and direction have been preserved. **23.7 mm in 30mins** to 09:45 16/08. Estimated return period of **100** years
3011	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,489000) $\left(u_0^T, v_0^T\right)$=(3333,3333) f=2.015	Historical storm orientation, velocity and direction have been preserved. **29.1 mm in 30mins** to 09:45 16/08. Estimated return period of **200** years

3012	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,489000) $\left(u_0^T, v_0^T\right)$=(3333,3333) f=2.642	Historical storm orientation, velocity and direction have been preserved. **38.1 mm in 30mins** to 09:45 16/08. Estimated return period of **500** years
3013	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,489000) $\left(u_0^T, v_0^T\right)$=(3333,3333) f=3.242	Historical storm orientation, velocity and direction have been preserved. **46.8 mm in 30mins** to 09:45 16/08. Estimated return period of **1000** years
3014	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,489000) $\left(u_0^T, v_0^T\right)$=(1190,1190) f=0.855 e_{time}=2.8	Historical storm orientation and direction have been preserved. Storm velocity and time altered to make 1 hr storm. Amounts downscaled. **33.8 mm in 1 hour** to 12:00 16/08. Estimated return period of **100** years
3015	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,489000) $\left(u_0^T, v_0^T\right)$=(1190,1190) f=1.338 e_{time}=2.8	As per 3014 except amounts upscaled. **52.8 mm in 1 hour** to 12:00 16/08. Estimated return period of **500** years
3016	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,489000) $\left(u_0^T, v_0^T\right)$=(606,606) f=0.606 e_{time}=5.5	Historical storm orientation and direction have been preserved. Storm velocity and time altered to make 2 hr storm. Amounts downscaled. **46.6 mm in 2 hours** to 12:00 16/08. Estimated return period of **100** years
3017	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,489000) $\left(u_0^T, v_0^T\right)$=(606,606) f=0.924 e_{time}=5.5	As per 3016 except amounts upscaled. **71.1 mm in 2 hours** to 12:00 16/08. Estimated return period of **500** years

3018	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(351000,501000) $\left(u_0^T, v_0^T\right)$=(0,2000) $\theta_{turn} = 45°$	Storm velocity and orientation changed to give a south to north storm track. **19.8 mm in 1 hour** to 9:45 16/08. Estimated return period of **15** years
3019	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(351000,501000) $\left(u_0^T, v_0^T\right)$=(0,2000) $\theta_{turn} = 45°$ f=1.703	As per 3018 except amounts upscaled. **33.8 mm in 1 hour** to 9:45 16/08. Estimated return period of **100** years
3020	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(351000,501000) $\left(u_0^T, v_0^T\right)$=(0,2000) $\theta_{turn} = 45°$ f=2.661	As per 3018 except amounts upscaled. **52.8 mm in 1 hour** to 9:45 16/08. Estimated return period of **500** years
3021	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,505000) $\left(u_0^T, v_0^T\right)$=(0,-2000) $\theta_{turn} = 225°$	Storm velocity and orientation changed to give a north to south storm track. **20.1 mm in 1 hour** to 9:45 16/08. Estimated return period of **15** years
3022	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,505000) $\left(u_0^T, v_0^T\right)$=(0,-2000) $\theta_{turn} = 225°$ f=1.678	As per 3021 except amounts upscaled. **33.8 mm in 1 hour** to 9:45 16/08. Estimated return period of **100** years
3023	04/08 – 18/08	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(347000,505000) $\left(u_0^T, v_0^T\right)$=(0,-2000) $\theta_{turn} = 225°$ f=2.621	As per 3021 except amounts upscaled. **52.8 mm in 1 hour** to 9:45 16/08. Estimated return period of **500** years
3024	17/05 – 29/05	Halifax Storm (Convective)	$\left(x_0^T, y_0^T\right)$=(351000,500000) $\left(u_0^T, v_0^T\right)$=(667,-500)	Historical storm orientation, velocity and direction have been preserved. **37.8 mm in 4 hours** to 16:30 16/08. Estimated return period of **13** years

3025	17/05 – 29/05	Halifax Storm (Convective)	$\left(x_0^T, y_0^T\right)$=(351000,500000) $\left(u_0^T, v_0^T\right)$=(667,-500) f=1.669	As per 3024 except amounts upscaled. **63.1 mm in 4 hours** to 16:30 16/08. Estimated return period of **100** years
3026	17/05 – 29/05	Halifax Storm (Convective)	$\left(x_0^T, y_0^T\right)$=(351000,500000) $\left(u_0^T, v_0^T\right)$=(667,-500) f=2.476	As per 3024 except amounts upscaled. **93.6 mm in 4 hours** to 16:30 16/08. Estimated return period of **500** years
3027	17/05 – 29/05	Boscastle Storm (Convective)	$\left(x_0^T, y_0^T\right)$=(351000,500000)	Historical storm orientation, velocity and direction have been preserved. **37.8 mm in 4 hours** to 16:30 16/08. Estimated return period of **13** years
3028	17/05 – 29/05	Boscastle Storm (Convective)	$\left(x_0^T, y_0^T\right)$=(351000,500000) f=1.669	As per 3027 except amounts upscaled. **63.1 mm in 4 hours** to 16:30 16/08. Estimated return period of **100** years
3029	17/05 – 29/05	Boscastle Storm (Convective)	$\left(x_0^T, y_0^T\right)$=(351000,500000) f=2.746	As per 3027 except amounts upscaled. **93.6 mm in 4 hours** to 16:30 16/08. Estimated return period of **500** years

A.2 River Darwen case study

The details of the amplified storms are listed in Table A.2. Note that the rainfall amount, duration and FEH-estimated return period quoted relate to the River Darwen at Blue Bridge catchment.

Table A.2 Details of the amplified storms created for the River Darwen case study. Note that the rainfall amount, duration and FEH-estimated return period quoted relate to the River Darwen at Blue Bridge catchment.

Year	Period	Historical storm modified	Storm modification and transposition settings	Comments
3000	06/06 – 16/06	River Darwen (Convective)	None, used original 1km raw radar.	**11.9 mm in 1 hour** to 16:30 14/06. Estimated return period of **2.5** years
3001	06/06 – 16/06	River Darwen (Convective)	f=3.21	**38.2 mm in 1 hour** to 16:30 14/06. Estimated return period of **100** years
3002	06/06 – 16/06	River Darwen (Convective)	f=3.95	**47.0 mm in 1 hour** to 16:30 14/06. Estimated return period of **200** years
3003	06/06 – 16/06	River Darwen (Convective)	f=5.19	**61.8 mm in 1 hour** to 16:30 14/06. Estimated return period of **500** years
3004	06/06 – 16/06	River Darwen (Convective)	f=6.39	**76.0 mm in 1 hour** to 16:30 14/06. Estimated return period of **1000** years
3005	06/06 – 16/06	River Darwen (Convective)	(x_0^T, y_0^T)=(366500,428500) (u_0^T, v_0^T)=(5667,0) $\theta_{turn}=308°$	Storm velocity and orientation changed to give a west to east storm track. **22.1 mm in 2 hours** to 17:30 14/06. Estimated return period of **6.3** years
3006	06/06 – 16/06	River Darwen (Convective)	(x_0^T, y_0^T)=(366500,428500) (u_0^T, v_0^T)=(5667,0) $\theta_{turn}=308°$ f =2.22	As per 3005 except amounts upscaled. **49.1 mm in 2 hours** to 17:30 14/06. Estimated return period of **100** years

3007	06/06 – 16/06	River Darwen (Convective)	(x_0^T, y_0^T)=(366500,428500) (u_0^T, v_0^T)=(5667,0) θ_{turn}=308° f =2.70	As per 3005 except amounts upscaled. **59.8 mm in 2 hours** to 17:30 14/06. Estimated return period of **200** years
3008	06/06 – 16/06	River Darwen (Convective)	(x_0^T, y_0^T)=(366500,428500) (u_0^T, v_0^T)=(5667,0) θ_{turn}=308° f =3.48	As per 3005 except amounts upscaled. **77.1 mm in 2 hours** to 17:30 14/06. Estimated return period of **500** years
3009	06/06 – 16/06	River Darwen (Convective)	(x_0^T, y_0^T)=(366500,428500) (u_0^T, v_0^T)=(5667,0) θ_{turn}=308° f =4.24	As per 3005 except amounts upscaled. **93.8 mm in 2 hours** to 17:30 14/06. Estimated return period of **1000** years
3010	06/06 – 16/06	River Darwen (Convective)	(x_0^T, y_0^T)=(366500,428500) (u_0^T, v_0^T)=(5667,0) θ_{turn}=128°	Storm velocity and orientation changed to give an east to west storm track. **22.5 mm in 2 hours** to 17:30 14/06. Estimated return period of **6.7** years
3011	06/06 – 16/06	River Darwen (Convective)	(x_0^T, y_0^T)=(366500,428500) (u_0^T, v_0^T)=(5667,0) θ_{turn}=128° f=2.18	As per 3010 except amounts upscaled. **49.0 mm in 2 hours** to 17:30 14/06. Estimated return period of **100** years
3012	06/06 – 16/06	River Darwen (Convective)	(x_0^T, y_0^T)=(366500,428500) (u_0^T, v_0^T)=(5667,0) θ_{turn}=128° f=2.66	As per 3010 except amounts upscaled. **59.7 mm in 2 hours** to 17:30 14/06. Estimated return period of **200** years
3013	06/06 – 16/06	River Darwen (Convective)	(x_0^T, y_0^T)=(366500,428500) (u_0^T, v_0^T)=(5667,0) θ_{turn}=128° f=3.43	As per 3010 except amounts upscaled. **77.0 mm in 2 hours** to 17:30 14/06. Estimated return period of **500** years
3014	06/06 – 16/06	River Darwen (Convective)	(x_0^T, y_0^T)=(366500,428500) (u_0^T, v_0^T)=(5667,0) θ_{turn}=128° f=4.17	As per 3010 except amounts upscaled. **93.7 mm in 2 hours** to 17:30 14/06. Estimated return period of **1000** years

3015	23/07 – 12/08	River Darwen (Convective)	*f*=3.21	As per 3001 except relocated in time to occur immediately after a hydrograph peak. **38.2 mm in 1 hour** to 16:30 02/08. Estimated return period of **100** years
3016	23/07 – 12/08	River Darwen (Convective)	*f*=3.21	As per 3015 except relocated in time to occur 1 day after a hydrograph peak. **38.2 mm in 1 hour** to 16:30 03/08. Estimated return period of **100** years
3017	23/07 – 12/08	River Darwen (Convective)	*f*=3.21	As per 3015 except relocated in time to occur 2 days after a hydrograph peak. **38.2 mm in 1 hour** to 16:30 04/08. Estimated return period of **100** years
3018	12/08 – 24/08	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(370000,423000)	Relocated to headwaters of Darwen catchment. **43.3 mm in 4 hours** to 16:30 18/08. Estimated return period of **26** years
3019	12/08 – 24/08	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(370000,423000) *f*=1.427	As 3018 but upscaled amounts. **61.8 mm in 4 hours** to 16:30 18/08. Estimated return period of **100** years
3020	12/08 – 24/08	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(370000,423000) *f*=2.182	As 3018 but upscaled amounts. **94.4 mm in 4 hours** to 16:30 18/08. Estimated return period of **500** years
3021	12/08 – 24/08	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(364000,426000)	Relocated to outlet of Darwen catchment. **46.9 mm in 4 hours** to 16:30 18/08. Estimated return period of **42** years

3022	12/08 – 24/08	Boscastle (Convective)	$\left(x_0^{\mathrm{T}}, y_0^{\mathrm{T}}\right)$=(364000,426000) f=1.318	As 3021 but upscaled amounts. **61.8 mm in 4 hours** to 16:30 18/08. Estimated return period of **100** years
3023	12/08 – 24/08	Boscastle (Convective)	$\left(x_0^{\mathrm{T}}, y_0^{\mathrm{T}}\right)$=(364000,426000) f=2.013	As 3021 but upscaled amounts. **94.4 mm in 4 hours** to 16:30 18/08. Estimated return period of **500** years
3024	12/08 – 24/08	Boscastle (Convective)	$\left(x_0^{\mathrm{T}}, y_0^{\mathrm{T}}\right)$=(367000,424000) S_n=2.0 S_a=2.0	Relocated to Darwen catchment and stretched spatially to cover entire catchment. **21.3 mm in 4 hours** to 16:30 18/08. Estimated return period of **2.3** years
3025	12/08 – 24/08	Boscastle (Convective)	$\left(x_0^{\mathrm{T}}, y_0^{\mathrm{T}}\right)$=(367000,424000) S_n=2.0 S_a=2.0 f=2.907	As per 3024 except amounts upscaled. **61.8 mm in 4 hours** to 16:30 18/08. Estimated return period of **100** years
3026	12/08 – 24/08	Boscastle (Convective)	$\left(x_0^{\mathrm{T}}, y_0^{\mathrm{T}}\right)$=(367000,424000) S_n=2.0 S_a=2.0 f=4.44	As per 3024 except amounts upscaled. **94.4 mm in 4 hours** to 16:30 18/08. Estimated return period of **500** years
3027	12/08 – 24/08	Carlton-in-Cleveland (Convective)	$\left(x_0^{\mathrm{T}}, y_0^{\mathrm{T}}\right)$=(363000,424000) $\left(u_0^{\mathrm{T}}, v_0^{\mathrm{T}}\right)$=(3333,-3333) $\theta_{\mathrm{turn}}=270°$	Relocated storm to Darwen catchment, velocity modified to give NW to SE storm track. **14.2 mm in 30 mins** to 09:45 18/08. Estimated return period of **11** years
3028	12/08 – 24/08	Carlton-in-Cleveland (Convective)	$\left(x_0^{\mathrm{T}}, y_0^{\mathrm{T}}\right)$=(363000,424000) $\left(u_0^{\mathrm{T}}, v_0^{\mathrm{T}}\right)$=(3333,-3333) $\theta_{\mathrm{turn}}=270°$ f=2.03	As per 3027 except amounts upscaled. **28.9 mm in 30 mins** to 09:45 18/08. Estimated return period of **100** years
3029	12/08 – 24/08	Carlton-in-Cleveland (Convective)	$\left(x_0^{\mathrm{T}}, y_0^{\mathrm{T}}\right)$=(363000,424000) $\left(u_0^{\mathrm{T}}, v_0^{\mathrm{T}}\right)$=(3333,-3333) $\theta_{\mathrm{turn}}=270°$ f=3.379	As per 3027 except amounts upscaled. **48.1 mm in 30 mins** to 09:45 18/08. Estimated return period of **500** years

3030	12/08 – 24/08	Carlton-in-Cleveland (Convective)	(x_0^T, y_0^T)=(370000,430000) (u_0^T, v_0^T)=(-3333,3333) $\theta_{turn} = 90°$	Relocated storm to Darwen catchment, velocity modified to give SE to NW storm track. **16.1 mm in 30 mins** to 09:45 18/08. Estimated return period of **16** years
3031	12/08 – 24/08	Carlton-in-Cleveland (Convective)	(x_0^T, y_0^T)=(370000,430000) (u_0^T, v_0^T)=(-3333,3333) $\theta_{turn} = 90°$ f=1.794	As per 3027 except amounts upscaled. **28.9 mm in 30 mins** to 09:45 18/08. Estimated return period of **100** years
3032	12/08 – 24/08	Carlton-in-Cleveland (Convective)	(x_0^T, y_0^T)=(370000,430000) (u_0^T, v_0^T)=(-3333,3333) $\theta_{turn} = 90°$ f=2.985	As per 3027 except amounts upscaled. **48.1 mm in 30 mins** to 09:45 18/08. Estimated return period of **500** years
3033	02/05 – 12/05	Halifax Strom (Convective)	(x_0^T, y_0^T)=(370000,430000)	Relocated to Darwen catchment. **23.1 mm in 3 hours** to 17:15 08/05. Estimated return period of **4.2** years
3034	02/05 – 12/05	Halifax Strom (Convective)	(x_0^T, y_0^T)=(370000,430000) f=2.431	As per 3033 except upscaled amounts. **56.2 mm in 3 hours** to 17:15 08/05. Estimated return period of **100** years
3035	02/05 – 12/05	Halifax Strom (Convective)	(x_0^T, y_0^T)=(370000,430000) f=3.764	As per 3033 except upscaled amounts. **87.0 mm in 3 hours** to 17:15 08/05. Estimated return period of **500** years
3036	02/04 – 15/04	Upper Thames and Stour (Frontal)	(x_0^T, y_0^T)=(370000,430000)	Relocated to Darwen catchment. **59.0 mm in 15 hours** to 19:00 09/04. Estimated return period of **15** years
3037	02/04 – 15/04	Upper Thames and Stour (Frontal)	(x_0^T, y_0^T)=(370000,430000) f=1.569	As per 3036 except upscaled amounts. **92.6 mm in 15 hours** to 19:00 09/04. Estimated return period of **100** years

3038	02/04 – 15/04	Upper Thames and Stour (Frontal)	$\left(x_0^T, y_0^T\right)$=(370000,430000) f=1.842	As per 3036 except upscaled amounts. **108.7 mm in 15 hours** to 19:00 09/04. Estimated return period of **200** years
3039	02/04 – 15/04	Upper Thames and Stour (Frontal)	$\left(x_0^T, y_0^T\right)$=(370000,430000) f=2.276	As per 3036 except upscaled amounts. **134.3 mm in 15 hours** to 19:00 09/04. Estimated return period of **500** years
3040	02/04 – 15/04	Upper Thames and Stour (Frontal)	$\left(x_0^T, y_0^T\right)$=(370000,430000) f=2.669	As per 3036 except upscaled amounts. **157.5 mm in 15 hours** to 19:00 09/04. Estimated return period of **1000** years
3041	02/04 – 15/04	Upper Thames and Stour (Frontal)	$\left(x_0^T, y_0^T\right)$=(370000,430000) e_{time}=1.6 f=1.118	Relocated to Darwen catchment, stretched time and upscaled amounts. **105.5 mm in 24 hours** to 04:30 10/04. Estimated return period of **100** years
3042	02/04 – 15/04	Upper Thames and Stour (Frontal)	$\left(x_0^T, y_0^T\right)$=(370000,430000) e_{time}=1.6 f=1.591	Relocated to Darwen catchment, stretched time and upscaled amounts. **150.1 mm in 24 hours** to 04:30 10/04. Estimated return period of **500** years
3043	02/04 – 15/04	Upper Thames and Stour (Frontal)	$\left(x_0^T, y_0^T\right)$=(370000,430000) e_{time}=2.4 f=0.832	Relocated to Darwen catchment, stretched time and scaled amounts. **117.8 mm in 36 hours** to 17:15 10/04. Estimated return period of **100** years
3044	02/04 – 15/04	Upper Thames and Stour (Frontal)	$\left(x_0^T, y_0^T\right)$=(370000,430000) e_{time}=2.4 f=1.164	Relocated to Darwen catchment, stretched time and upscaled amounts. **164.8 mm in 36 hours** to 17:15 10/04. Estimated return period of **500** years

3045	02/04 – 15/04	Upper Thames and Stour (Frontal)	(x_0^T, y_0^T)=(370000,430000) e_{time} =3.2 *f*=0.674	Relocated to Darwen catchment, stretched time and scaled amounts. **127.2 mm in 48 hours** to 06:15 11/04. Estimated return period of **100** years
3046	02/04 – 15/04	Upper Thames and Stour (Frontal)	(x_0^T, y_0^T)=(370000,430000) e_{time} =3.2 *f*=0.932	Relocated to Darwen catchment, stretched time and scaled amounts. **176.0 mm in 48 hours** to 06:15 11/04. Estimated return period of **500** years

A.3 Upper Thames and Stour case study

The details of the amplified storms for the Upper Thames case study are listed in Table A.3. Note that the rainfall amount, duration and FEH-estimated return period quoted relate to the Sor at Bodicote catchment.

The details of the amplified storms for the Stour at Shipston case study are listed in Table A.4. Note that the rainfall amount, duration and FEH-estimated return period quoted relate to the Stour at Shipston catchment.

Table A.3 Details of the amplified storms created for the Upper Thames case study. Note that the rainfall amount, duration and FEH-estimated return period quoted relate to the Sor at Bodicote catchment.

Year	Period	Historical storm modified	Storm modification and transposition settings	Comments
3000	01/01-20/04	Upper Thames and Stour (Frontal)	None, used composite 2 and 5km raingauge-adjusted raw radar	**47.1 mm in 15 hours** to 18:45 09/04. Estimated return period of **10.5** years
3001	01/01-20/04	Upper Thames and Stour (Frontal)	*f*=1.706	**80.4 mm in 15 hours** to 18:45 09/04. Estimated return period of **100** years
3002	01/01-20/04	Upper Thames and Stour (Frontal)	*f*=2.003	**94.4 mm in 15 hours** to 18:45 09/04. Estimated return period of **200** years

3003	01/01-20/04	Upper Thames and Stour (Frontal)	*f*=2.478	**116.8 mm in 15 hours** to 18:45 09/04. Estimated return period of **500** years
3004	01/01-20/04	Upper Thames and Stour (Frontal)	*f*=2.911	**137.2 mm in 15 hours** to 18:45 09/04. Estimated return period of **1000** years
3005	01/01-20/04	Upper Thames and Stour (Frontal)	s_{time} =1.6 *f*=1.914	Stretched time and upscaled amounts. **90.2 mm in 24 hours** to 04:15 10/04. Estimated return period of **100** years
3006	01/01-20/04	Upper Thames and Stour (Frontal)	s_{time} =1.6 *f*=2.730	Stretched time and upscaled amounts. **128.7 mm in 24 hours** to 04:15 10/04. Estimated return period of **100** years
3007	01/01-20/04	Upper Thames and Stour (Frontal)	s_{time} =2.4 *f*=2.109	Stretched time and upscaled amounts. **99.4 mm in 36 hours** to 16:45 10/04. Estimated return period of **100** years
3008	01/01-20/04	Upper Thames and Stour (Frontal)	s_{time} =2.4 *f*=2.964	Stretched time and upscaled amounts. **139.7 mm in 36 hours** to 16:45 10/04. Estimated return period of **500** years
3009	01/01-20/04	Upper Thames and Stour (Frontal)	s_{time} =3.6 *f*=2.257	Stretched time and upscaled amounts. **106.4 mm in 48 hours** to 05:30 11/04. Estimated return period of **100** years
3010	01/01-20/04	Upper Thames and Stour (Frontal)	s_{time} =3.6 *f*=3.138	Stretched time and upscaled amounts. **147.9 mm in 48 hours** to 05:30 11/04. Estimated return period of **500** years
3011	01/04 – 25/06	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(441000,241000)	Relocated storm. **59.2 mm in 4 hours** to 16:30 15/06. Estimated return period of **113** years

3012	01/04 – 25/06	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(441000,241000) f=0.968	As per 3011 except scaled amounts. **57.3 mm in 4 hours** to 16:30 15/06. Estimated return period of **100** years
3013	01/04 – 25/06	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(441000,241000) f=1.481	As per 3011 except scaled amounts. **87.7 mm in 4 hours** to 16:30 15/06. Estimated return period of **500** years
3014	01/04 – 25/06	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(445000,237000)	Relocated storm. **15.0 mm in 30 mins** to 09:45 15/06. Estimated return period of **11** years
3015	01/04 – 25/06	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(445000,237000) f=2.040	As per 3014 except scaled amounts. **30.6 mm in 30 mins** to 09:45 15/06. Estimated return period of **100** years
3016	01/04 – 25/06	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(445000,237000) f=3.380	As per 3014 except scaled amounts. **50.7 mm in 30 mins** to 09:45 15/06. Estimated return period of **500** years
3017	01/04 – 25/06	Halifax storm (Convective)	$\left(x_0^T, y_0^T\right)$=(453000,233000)	Relocated storm. **36.0 mm in 2.5 hours** to 16:00 15/06. Estimated return period of **30** years
3018	01/04 – 25/06	Halifax storm (Convective)	$\left(x_0^T, y_0^T\right)$=(453000,233000) f=1.402	As per 3017 except scaled amounts. **50.4 mm in 2.5 hours** to 16:00 15/06. Estimated return period of **100** years
3019	01/04 – 25/06	Halifax storm (Convective)	$\left(x_0^T, y_0^T\right)$=(453000,233000) f=2.186	As per 3017 except scaled amounts. **78.6 mm in 2.5 hours** to 16:00 15/06. Estimated return period of **500** years
3020	01/04 – 25/06	Darwen (Convective)	$\left(x_0^T, y_0^T\right)$=(441500,241500)	Relocated storm. **14.4 mm in 1 hour** to 16:30 15/06. Estimated return period of **4.2** years

3021	01/04 – 25/06	Darwen (Convective)	(x_0^T, y_0^T)=(441500,241500) f=2.666	Relocated storm. **38.5 mm in 1 hour** to 16:30 15/06. Estimated return period of **100** years
3022	01/04 – 25/06	Darwen (Convective)	(x_0^T, y_0^T)=(441500,241500) f=4.301	Relocated storm. **62.1 mm in 1 hour** to 16:30 15/06. Estimated return period of **500** years
3023	1/7/22 – 1/9/23	River Darwen (Convective)	(x_0^T, y_0^T)=(441500,241500) f=2.666	As per 3021 except relocated in time to occur immediately after a hydrograph peak. **38.5 mm in 1 hour** to 16:30 15/02. Estimated return period of **100** years
3024 *	1/7/23 – 1/9/24	River Darwen (Convective)	(x_0^T, y_0^T)=(441500,241500) f=2.666	As per 3021 except relocated in time to occur 1 month after a hydrograph peak. **38.5 mm in 1 hour** to 16:30 15/03. Estimated return period of **100** years
3025*	1/7/24 – 1/9/25	River Darwen (Convective)	(x_0^T, y_0^T)=(441500,241500) f=2.666	As per 3021 except relocated in time to occur 2 months after a hydrograph peak. **38.5 mm in 1 hour** to 16:30 15/04. Estimated return period of **100** years
3026*	1/7/25 – 1/9/26	River Darwen (Convective)	(x_0^T, y_0^T)=(441500,241500) f=2.666	As per 3021 except relocated in time to occur 2 months after a hydrograph peak. **38.5 mm in 1 hour** to 16:30 15/05. Estimated return period of **100** years
3027*	1/7/26 – 1/9/27	River Darwen (Convective)	(x_0^T, y_0^T)=(441500,241500) f=2.666	As per 3021 except relocated in time to occur 2 months after a hydrograph peak. **38.5 mm in 1 hour** to 16:30 15/06. Estimated return period of **100** years

3028*	1/7/27 – 1/9/28	River Darwen (Convective)	$\left(x_0^T, y_0^T\right)$=(441500,241500) f=2.666	As per 3021 except relocated in time to occur 2 months after a hydrograph peak. **38.5 mm in 1 hour** to 16:30 15/07. Estimated return period of **100** years

* Note that for amplified storms 3024 to 3028 the same PE values taken from February (i.e. storm 3023) are used so that the different model responses are purely due to the initial condition at the start of the storm.

Table A.4 Details of the amplified storms created for the Stour at Shipston case study. Note that the rainfall amount, duration and FEH-estimated return period quoted relate to the Stour at Shipston catchment.

Year	Period	Historical storm modified	Storm modification and transposition settings	Comments
3029	06/02-20/04	Upper Thames and Stour (Frontal)	None, used composite 2 and 5km raingauge-adjusted raw radar	**46.4 mm in 15 hours** to 18:15 09/04. Estimated return period of **8.6** years
3030	06/02-20/04	Upper Thames and Stour (Frontal)	f=1.774	**82.3 mm in 15 hours** to 18:15 09/04. Estimated return period of **100** years
3031	06/02-20/04	Upper Thames and Stour (Frontal)	f=2.078	**96.4 mm in 15 hours** to 18:15 09/04. Estimated return period of **200** years
3032	06/02-20/04	Upper Thames and Stour (Frontal)	f=2.563	**118.9 mm in 15 hours** to 18:15 09/04. Estimated return period of **500** years
3033	06/02-20/04	Upper Thames and Stour (Frontal)	f=3.002	**139.3 mm in 15 hours** to 18:15 09/04. Estimated return period of **1000** years
3034	06/02-20/04	Upper Thames and Stour (Frontal)	s_{time} =1.6 f=1.774	**92.8 mm in 24 hours** to 03:35 10/04. Estimated return period of **100** years
3035	06/02-20/04	Upper Thames and Stour (Frontal)	s_{time} =1.6 f=2.839	**131.7 mm in 24 hours** to 03:35 10/04. Estimated return period of **500** years

3036	06/02-20/04	Upper Thames and Stour (Frontal)	s_{time} =2.4 f=2.216	**102.8 mm in 36 hours** to 15:45 10/04. Estimated return period of **100** years
3037	06/02-20/04	Upper Thames and Stour (Frontal)	s_{time} =2.4 f=3.093	**143.5 mm in 36 hours** to 15:45 10/04. Estimated return period of **500** years
3038	06/02-20/04	Upper Thames and Stour (Frontal)	s_{time} =3.2 f=2.382	**110.5 mm in 48 hours** to 04:00 11/04. Estimated return period of **100** years
3039	06/02-20/04	Upper Thames and Stour (Frontal)	s_{time} =3.2 f=3.283	**152.3 mm in 48 hours** to 04:00 11/04. Estimated return period of **500** years
3040	14/03-01/05	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(417000,237000)	Relocated storm to west of catchment. **29.9 mm in 4 hours** to 16:15 22/04. Estimated return period of **9** years
3041	14/03-01/05	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(417000,237000) f=1.902	As per 3040 but amounts upscaled. **58.9 mm in 4 hours** to 16:15 22/04. Estimated return period of **100** years
3042	14/03-01/05	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(417000,237000) f=2.901	As per 3040 but amounts upscaled. **89.9 mm in 4 hours** to 16:15 22/04. Estimated return period of **500** years
3043	14/03-01/05	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(433000,237000) θ_{band}=0° e_n =-1.0	Relocated storm to east of catchment and reflected about the N-S axis. **26.5 mm in 4 hours** to 16:15 22/04. Estimated return period of **6** years
3044	14/03-01/05	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(433000,237000) θ_{band}=0° e_n =-1.0 f=2.151	As per 3043 but amounts upscaled. **58.9 mm in 4 hours** to 16:15 22/04. Estimated return period of **100** years
3045	14/03-01/05	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(433000,237000) θ_{band}=0° e_n =-1.0 f=3.281	As per 3043 but amounts upscaled. **89.9 mm in 4 hours** to 16:15 22/04. Estimated return period of **500** years

3046	14/03-01/05	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(433000,237000) $\theta_{turn} = 0°$	Rotated storm to cover majority of catchment. **55.8 mm in 4 hours** to 16:30 22/04. Estimated return period of **93** years
3047	14/03-01/05	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(433000,237000) $\theta_{turn} = 0°$ f=1.020	As per 3046 but amounts upscaled. **58.9 mm in 4 hours** to 16:30 22/04. Estimated return period of **100** years
3048	14/03-01/05	Boscastle (Convective)	$\left(x_0^T, y_0^T\right)$=(433000,237000) $\theta_{turn} = 0°$ f=1.556	As per 3046 but amounts upscaled. **89.9 mm in 4 hours** to 16:30 22/04. Estimated return period of **500** years
3049	14/03-01/05	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(420000,229000)	Relocated storm to Stour catchment. **13.2 mm in 30mins** to 09:45 22/04. Estimated return period of **10** years
3050	14/03-01/05	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(420000,229000) f=2.119	As per 3049 but amounts upscaled. **28.0 mm in 30mins** to 09:45 22/04. Estimated return period of **100** years
3051	14/03-01/05	Carlton-in-Cleveland (Convective)	$\left(x_0^T, y_0^T\right)$=(420000,229000) f=3.518	As per 3049 but amounts upscaled. **46.5 mm in 30mins** to 09:45 22/04. Estimated return period of **500** years
3052	14/03-01/05	Halifax Storm (Convective)	$\left(x_0^T, y_0^T\right)$=(432000,231000)	Relocated storm to Stour catchment. **23.7 mm in 3hours 30mins** to 17:30 22/04. Estimated return period of **5** years
3053	14/03-01/05	Halifax Storm (Convective)	$\left(x_0^T, y_0^T\right)$=(432000,231000) f=2.310	As per 3052 but amounts upscaled. **54.7 mm in 3hours 30mins** to 17:30 22/04. Estimated return period of **100** years
3054	14/03-01/05	Halifax Storm (Convective)	$\left(x_0^T, y_0^T\right)$=(432000,231000) f=3.544	As per 3052 but amounts upscaled. **83.9 mm in 3hours 30mins** to 17:30 22/04. Estimated return period of **500** years

3055	14/03-01/05	Darwen storm (Convective)	$\left(x_0^T, y_0^T\right)$=(421000,231000)	Relocated storm to Stour catchment. **12.1 mm in 1hour 30mins** to 17:00 22/04. Estimated return period of **2** years
3056	14/03-01/05	Darwen storm (Convective)	$\left(x_0^T, y_0^T\right)$=(421000,231000) *f*=3.444	As per 3055 but amounts upscaled. **41.9 mm in 1hour 30mins** to 17:00 22/04. Estimated return period of **100** years
3057	14/03-01/05	Darwen storm (Convective)	$\left(x_0^T, y_0^T\right)$=(421000,231000) *f*=5.467	As per 3055 but amounts upscaled. **66.5 mm in 1hour 30mins** to 17:00 22/04. Estimated return period of **500** years

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