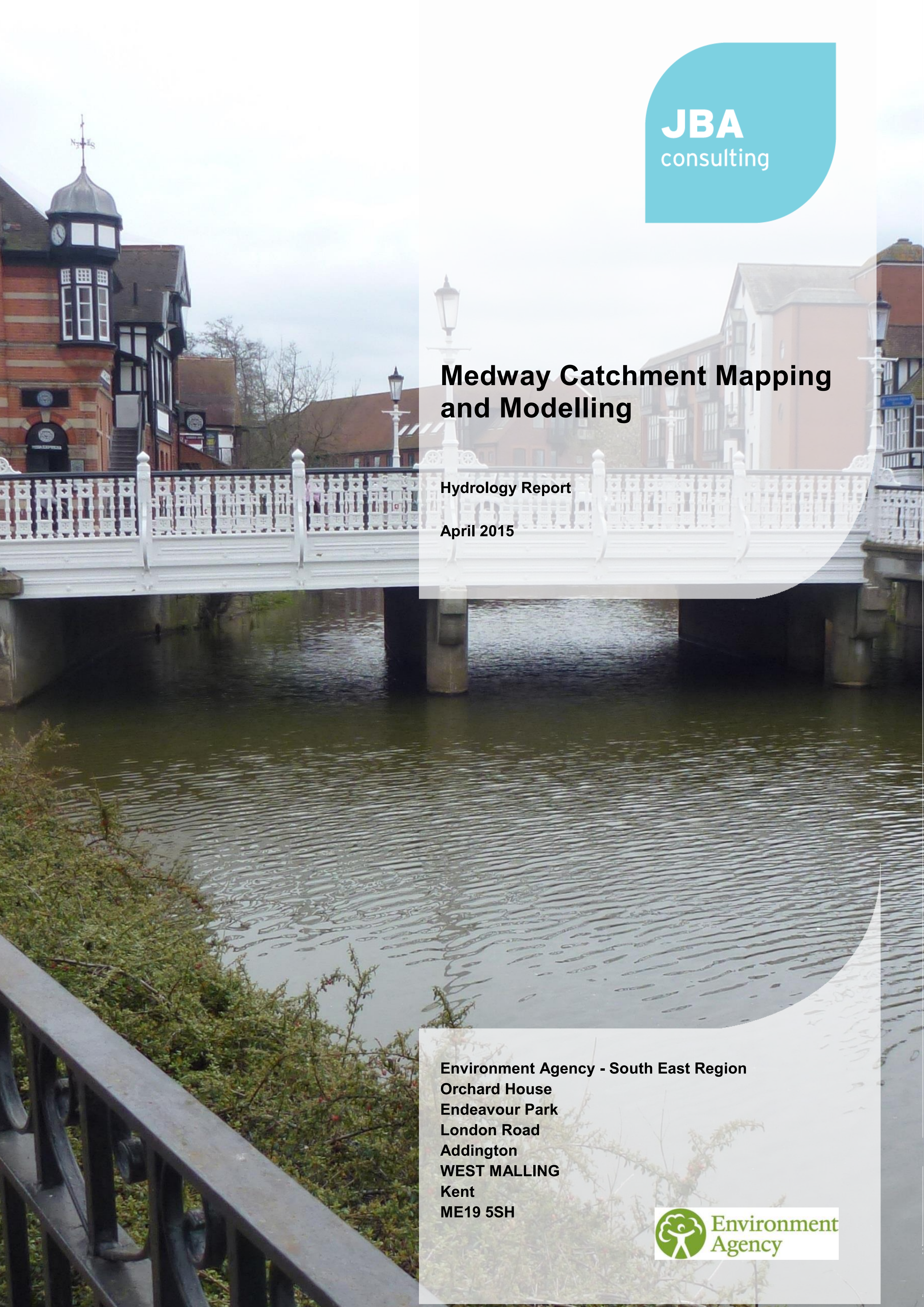

Medway Catchment Mapping and Modelling

Hydrology Report

April 2015

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Revision History

Revision Ref / Date Issued	Amendments	Issued to
v1 / December 2014	-	Emma Dauben (Environment Agency)
v2 / April 2015	Incorporating comments made by the EA, compiled in JBA Note to file ' 2013s7661 - Medway - combined hydrology comments (v1 Feb 2015).pdf'. Change of approach to rainfall modelling and new results.	Emma Dauben (Environment Agency)

Contract

This report describes work commissioned by Emma Dauben, on behalf of Environment Agency South East Region, for the Medway Catchment Mapping and Modelling commission under the Environment Agency's Water and Environment (WEM) Framework. Environment Agency's representative for the contract was Emma Dauben. Paul Wass and David Cameron of JBA Consulting carried out this work.

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Purpose

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Executive Summary

Background

Recent severe flooding and planned protection works on the Medway have prompted a new flood mapping study to better understand risk. A comprehensive hydraulic model, with some 2D domains, is being assembled to carry out this task. It will also be used to help design any new flood protection works. The model covers most of the Eden, Medway and Beult and needs inflows that simulate floods of the required rarity. This report describes the work done to develop those inflows. Our approach is innovative and moves forward from more traditional methods of design flow estimation. This executive summary communicates the work done in clear technical language, with more detail provided in the report and its appendices.

Selection of a method

Several features make the Medway a challenging catchment for design flow estimation. Its large physical extent (1,260km^2 at East Farleigh) mean that the critical storm duration varies considerably from upstream to downstream. Headwater catchments that respond quickly to rainfall are sensitive to short duration, high intensity rainfall. Downstream locations are sensitive to long duration, catchment wide, events which mean all the tributaries are responding together. Rainfall intensities in these events tend to be lower.

Large catchment extent also means the severity of a flood is likely to be different between tributaries, so a large flood might occur on one catchment but not a neighbour, as happened in 1968 when flows were extreme on the Eden but barely registered on the Beult. The three main sub catchments of the Medway are: the Medway itself, gauged at Colliers Land Bridge; the Eden, gauged at Vexour; the Teise, gauged at Stonebridge; and the Beult, gauged at Stilebridge (refer to Figure 1-3 for a map of the catchment)

Runoff rates in the catchment are highly variable between seasons as low rainfall and high potential evaporation combine to create a large seasonal soil moisture deficit. Floodplains also act to attenuate flows, but their effectiveness in doing this reduces in extreme events as they fill.

Added to this is the Leigh Flood Storage Area (FSA), which impounds water upstream of Tonbridge (just downstream of the Eden-Medway confluence) to protect the town. The FSA limits flows to 75m^3/s, but can be operated differently depending on the magnitude and duration of the flood about to occur.

Continuous simulation

All of these issues led to the conclusion that continuous simulation (CS) is needed to give robust flow boundaries to the detailed mapping model. CS is a method for calculating design flows for complex hydrological problems like the Medway. It involves applying a very long synthetic rainfall series to a model of the catchment, thereby simulating flows over a very long period. If the synthetic rainfall series has the same 'statistical properties' as observed rain, and the catchment model is accurate, the results at any location can be analysed to get a peak flow for an AEP. For example, the 1% AEP flow at a particular model node would be the 50th ranked annual maximum flow (AMAX) in a 5,000-year series. The event that gave rise to that AEP flow is likely to differ, depending on where you are in the catchment, for the reasons outlined above. Pre requisites for continuous simulation are therefore:

- A model that generates a long series of rainfall that is representative of that expected for the catchment. For the Medway, this needs to be spatially varying because of its size; and
- A catchment model capable of reliably converting this rainfall into river flows and routing them through the river network.

Rainfall modelling

A spatially varying synthetic daily rainfall series was derived for points around the Medway catchment using a model called GLIMCLIM. Daily values were disaggregated to an hourly time step using outputs from another rainfall model (a Bartlett Lewis Rectangular Pulse Generator). Catchment rainfalls for each basin of the rainfall runoff/river model were calculated by weighting an average from these point data.

The synthetic rainfall model was calibrated on observed data. Outputs from GLIMCLIM were post processed so that daily rainfall depths have the same growth rates as those predicted by the FEH depth, duration and frequency (DDF) model. For example, the FEH might predict that the 1% AEP rainfall depth is 2.5 times the median (RMED). We forced daily rainfall totals to match this growth rate prior to disaggregation as the growth rate above the 1% AEP event was too shallow.

Observed rainfall data was found to contain many errors before 2006 and significant efforts were made to correct these. In some cases, such as October 2000, this was still not enough to render the data suitable for use in model calibration. A list of the edits made to rainfall series is available as an electronic deliverable.

Catchment model

Existing flood forecasting models were adapted to become the 'catchment model' - in fact three ISIS river models are coupled to 17 PDM rainfall runoff models, with results cascading between. This is described as the catchment model. The main developments were to:

- Extend the models up the Eden, Medway and Beult to the boundaries of the new mapping model;
- Recalibrate the rainfall runoff inputs to the models;
- Validate the models against observed data; and
- Change the operation of the radial gates at the Leigh FSA storage area. This aspect is expanded on below.

Performance of the catchment model is reasonable, especially considering it simulates flow entirely from rainfall and pre-determined potential evaporation (varying annually according to a seasonal curve). There is some over prediction at Colliers Land Bridge, Vexour and Stonebridge, but it predicts December 2013 flows well at most locations.

Leigh FSA

Leigh FSA is the key piece of flood defence infrastructure in the middle catchment. The existing forecasting model includes the FSA but simulates a fixed pass forward flow of 75m^3/s. If the maximum level of 28.05mAOD is exceeded, the gates start releasing the inflow (i.e. there is no attenuation). We changed the gate rules so that different pass forward flows could be specified by users part way through a model run. A computer programme was written to simulate how operators choose the pass forward flow on the basis of flow forecasts and implement that in the continuous simulation. It was checked against the choices made by real operators when confronted with our continuously simulated flows for three events. After some iteration, the programme reliably replicated the choices of operators. The main assumptions made by this procedure are that:

- A decision to change operation of the FSA is made 24 hours before releases have to exceed the normal target outflow. No subsequent revision of this decision is made for the remainder of the model run. In reality, the target outflow would be adjusted as new information came to light.
- Uncertainty in forecast flows was not considered; the flows referenced by the programme are the actual simulated flows fed to the model.
- An optimum pass forward flow is selected (to the nearest 10m^3/s) that gives the lowest outflow without exceeding 28.05mAOD. If no scenario is less than that level, the one that gives the lowest level is chosen.

Our complete catchment model was run using the adjusted synthetic rainfall series as its sole input. Although the rainfall runoff components were run continuously, only the largest AMAX flood events were simulated in the three ISIS river models. Results from the catchment model were extracted at key locations throughout the catchment. Ranking the AMAX flows allows us to identify the simulated event, for a given location, that give the n% AEP flow/level. Running that event through the detailed mapping model gives us the result we seek, i.e. flood extent and depth.

Results

Flood frequency curves from the CS were compared to the FEH single site frequency curve (obtained from the December 2013 Medway flood event severity report) at gauged locations. Simulated peak flows (and volumes) were consistently higher than the single site curve at all locations. We corrected this by globally reducing rainfall inputs by 5%. This improved performance at all gauged locations.

Even with the adjustment, there are discrepancies at some locations:

- On the Eden at Vexour, the 1968 flood is particularly extreme, making the single site growth curve steeper than at any other gauge in the catchment. The CS flow frequency curve is less steep and predicts the 1968 event to be close to a 400-year flow. This more consistent with the estimate of return period for the rainfall in that event than its plotting position.
- At Stilebridge, on the Beult, the CS flows are higher than the single site growth curve. Despite thorough investigation, no explanation for the discrepancy was forthcoming. The discrepancy has been accepted.

CS flow frequency curves match well at all of the other gauging stations in the upper catchment. Operation of the Leigh FSA is correctly predicted to happen one year in six and 'alternative operation' is also predicted at a reasonable frequency of just over one year in twenty five. Design flows in the lower catchment, at East Farleigh, match the plotted AMAX reasonably well but the catchment model does not simulate the impact (on flows) of the floodplain filling in extreme events (like December 2013). In that event, flows rose more steeply later in the event as all storage was exhausted (see Figure 3-9). When this event is simulated in the detailed mapping model, the hydrograph shape is improved, but not significantly so, and the peak flow is similar. This led to the conclusion that it would not be possible to make the forecasting model replicate this behaviour. The implication of this is that an adjustment should be made to the flows being passed downstream to the Lower Medway to account for this.

Finally, users of the dataset should note: the continuous simulation and catchment model are a means of selecting the correct flow boundary conditions to apply to the detailed mapping model. They are NOT used to determine the flow and level at all locations in the catchment. The results outputted from the mapping model are definitive.

A full set of recommendations from this work can be found in Section 6.2.

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Abbreviations

1D .... One Dimensional (modelling)
2D .... Two Dimensional (modelling)
Abbreviations .... Abb
ADCP .... Accoustic Doppler Current Profiler
AMAX .... Annual Maximum
CS .... Cross Section
DDF .... Depth Duration Frequency
FEH .... Flood Estimation Handbook
FORTRAN .... Programming language (FORmula TRANslation)
FSA .... Flood Storage Area
FSR .... Flood Studies Report
GPD .... Generalised Pareto Distribution
ID .... Identifier
IED .... ISIS Event Data file
ISIS .... Hydrology and hydraulic modelling software
mAOD .... metres Above Ordnance Datum
NFFS .... National Flood Forecasting System (Environment Agency)

NGR	National Grid Reference
OS	Ordnance Survey
PDM	Probability Distributed Model
PE	Potential Evaporation
QMED	Median Annual Flood (with return period 2 years)
R&D	Research and Development
ReFH	Revitalised Flood Hydrograph method
SAAR	Standard Average Annual Rainfall (mm)
STW	Sewage Treatment Works
TBR	Tipping Bucket Raingauge
VPMC	Variable Parameter Muskingum Cunge (flow routing unit in ISIS)

1 Introduction

1.1 Context

23-24th December 2013 saw the highest flows on the Upper Medway since records began in 1960, and the highest flows in the Lower Medway since Leigh FSA was built in 1981. Flows on the Eden, Beult and Teise were also very high, with their peaks ranking 2nd or 3rd in the gauged records. This was a severe event and its rarity is discussed in a parallel report (JBA, 2014 Flood Event Severity Report).

Figure 1-1: Flooding in Tonbridge, 3 January 2014

Against this backdrop, the Environment Agency commissioned a flood mapping study to redefine flood zones throughout the catchment and update modelling tools so they might be used to reduce risk in the following locations: the River Eden around Edenbridge, the River Medway at East Peckham and the River Beult between Smarden and Stilebridge. Understanding the Leigh Flood Storage Area (FSA) and its impact on flood frequency in Tonbridge and downstream is of particular interest to the Environment Agency.

This report describes how flow boundaries to the flood mapping model have been obtained. It begins with an overview of the methods available to do this and why continuous simulation was chosen. We then go on to describe how a synthetic rainfall series was obtained for the catchment (Section 2), how we built a catchment-wide flow routing model (based largely on the existing forecasting model, Section 3) and how these two were combined to give a long simulated flow series at critical locations in the catchment (Section 4). An explanation of how the results are used to derive design flows for the mapping model is outlined (Section 5) and results are discussed. Several conclusions and recommendations arise from this work and those are discussed at the end of the report (Section 6).

1.2 Purpose

As well as updating hydraulic models using the latest 2D techniques, this study revises the design flows applied to the models at their boundaries. The brief required that we simulated flows from the 20% AEP flood (5-year) to the 0.1% AEP (1,000-year return period). This hydrology report explains how this has been achieved using 'continuous simulation' - a method that will be explained fully later. Robust inflow series are needed for the flood risk mapping part of the study, and to support the design of flood alleviation schemes that may involve storage.

The chosen approach needs to deliver:

- Design flows at hydraulic model boundaries which give the required annual exceedence probability at locations within the model. For example, if a hydraulic model extends from the headwaters to the tidal limit, then the 'design flow' for an intermediate location must arise from sensible inflows upstream; it cannot be specified directly.

- A consistent dataset, applicable across the catchment, that is believable, robust, and can be used for all purposes. Uses include: flood risk mapping; evaluation of new flood defence schemes that may include storage; and small, local, studies like flood risk assessments.
- Design flows that account for the influence of flood storage and widely differing critical storm durations across the catchments.

Our approach also had to take account of the long run times of large 1D-2D hydraulic models.

1.3 Catchment overview

Covering 1,380km^2 (at Maidstone), the Medway catchment drains a significant proportion of Kent (see Figure 1-3). It has four main tributaries:

- The Eden, gauged at Vexour Bridge (catchment area of 224km^2)
- The Upper Medway, gauged at Colliers Land Bridge (252km^2)
- The Teise, gauged at Stonebridge (134km^2); and
- The Beult, gauged at Stilebridge (278km^2).

There is also a long gauged record at East Farleigh (1,260km^2), near the catchment outlet.

Defining characteristics of the catchment's hydrology are its:

- Mostly gentle topography and deep soils;
- Dry climate;
- Evident floodplains; and
- The Leigh FSA.

Although mostly low-lying, some parts of the catchment do have steep gradients, particularly the headwaters of the Upper Medway and Teise. Both of these drain north from the Ashdown Forest where elevations exceed 200m. This generates a quicker response to rainfall than seen anywhere else in the Medway. Average rainfall LAG at Forest Row is 6.6hrs, even with Weir wood reservoir just upstream.

The Medway tributaries converge in a gently sloping valley where floodplain attenuation can be significant, particularly at lower flows. Figure 1-2 shows how the hydrograph shape in the Teise, gauged at Stonebridge, is impacted by floodplain storage. Lesser events (7 to 9 in the figure) are flat topped, as flows over a threshold are spilled and stored upstream. In larger floods, this storage is exhausted towards the end of an event (6) and the river begins to rise again. In the largest events, the storage manifests itself as a 'notch' on the rising limb of the hydrograph. A similar process can also be seen at Vexour and Stonebridge.

The Eden is the most westerly catchment, lower lying, and with shallower gradients, than its neighbour (the Upper Medway). These rivers join upstream of Tonbridge, where the Leigh FSA has been regulating flow since 1981. It aims to limit pass forward flows to 75m^3/s, but higher flows are passed when there is insufficient storage - as was the case in December 2013.

There is extensive floodplain downstream of the FSA. The Teise and Beult join at the end of that reach, just downstream of East Peckam. Although the largest tributary by area, the Beult can have smaller peak flows than its neighbour (the Teise) because its catchment is significantly flatter and runoff is attenuated. Catchment lag at Stilebridge is 20hrs compared to 7.1hrs at Stonebridge.

Two catchments have significant water supply reservoirs in their headwaters: the Upper Eden at Weir Wood and the Teise at Bewl Reservoir. Previous modelling has lumped these features into a single rainfall runoff model for the catchment. Results from the lumped models are generally better for the reservoired catchments (Medway at Forest Row and Teise at Stonebridge) than the unreservoired catchments (refer to model evaluation sheets in Appendix A), so it is assumed that this approach is reasonable. We consider it reasonable to assume that the reservoirs can be modelled this way. In large events (where soil moisture deficits are satisfied) the reservoirs are likely to be full, or filled during the event.

Figure 1-2: Influence of floodplain storage on hydrograph shape on the Teise at Stonebridge

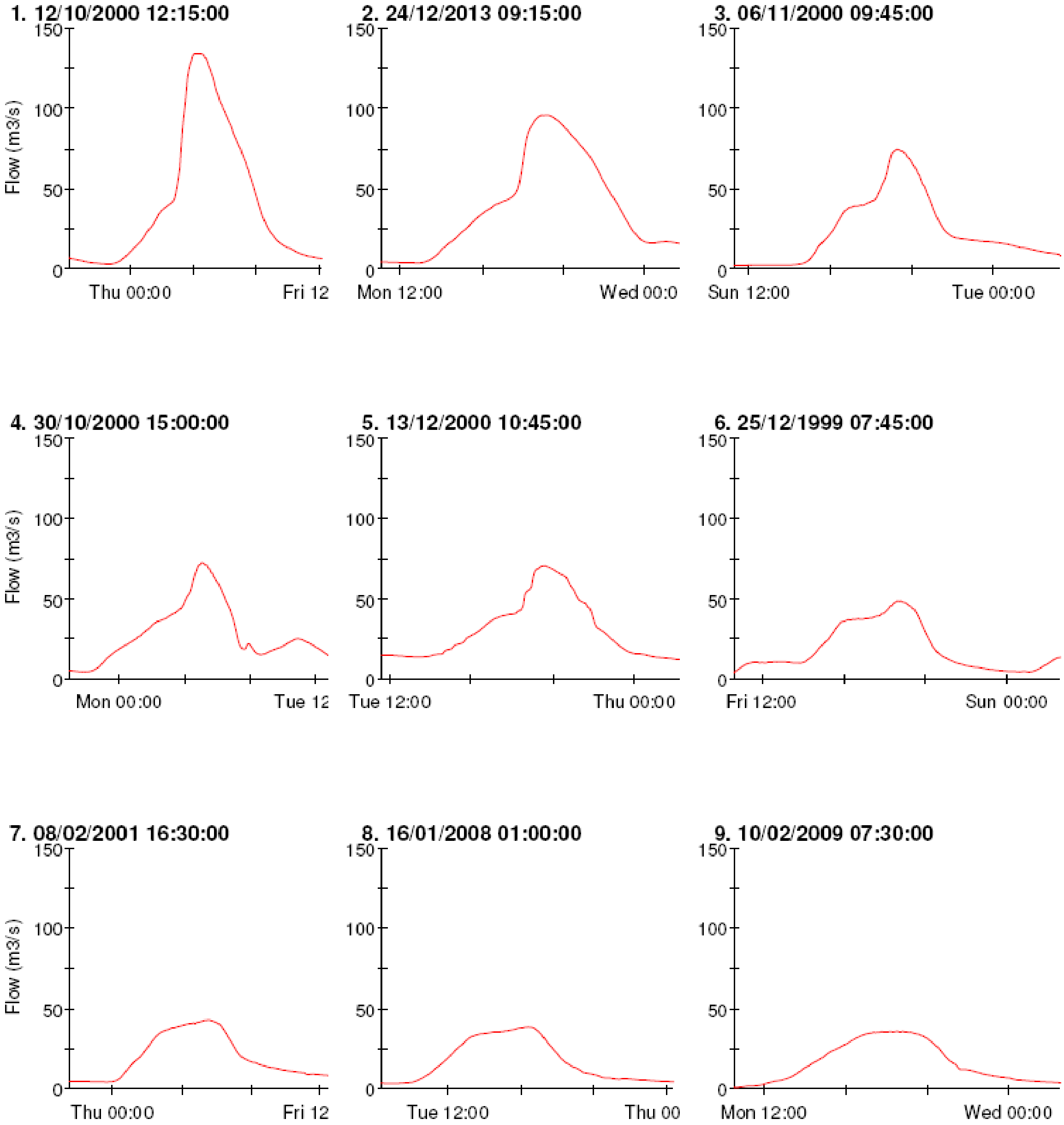
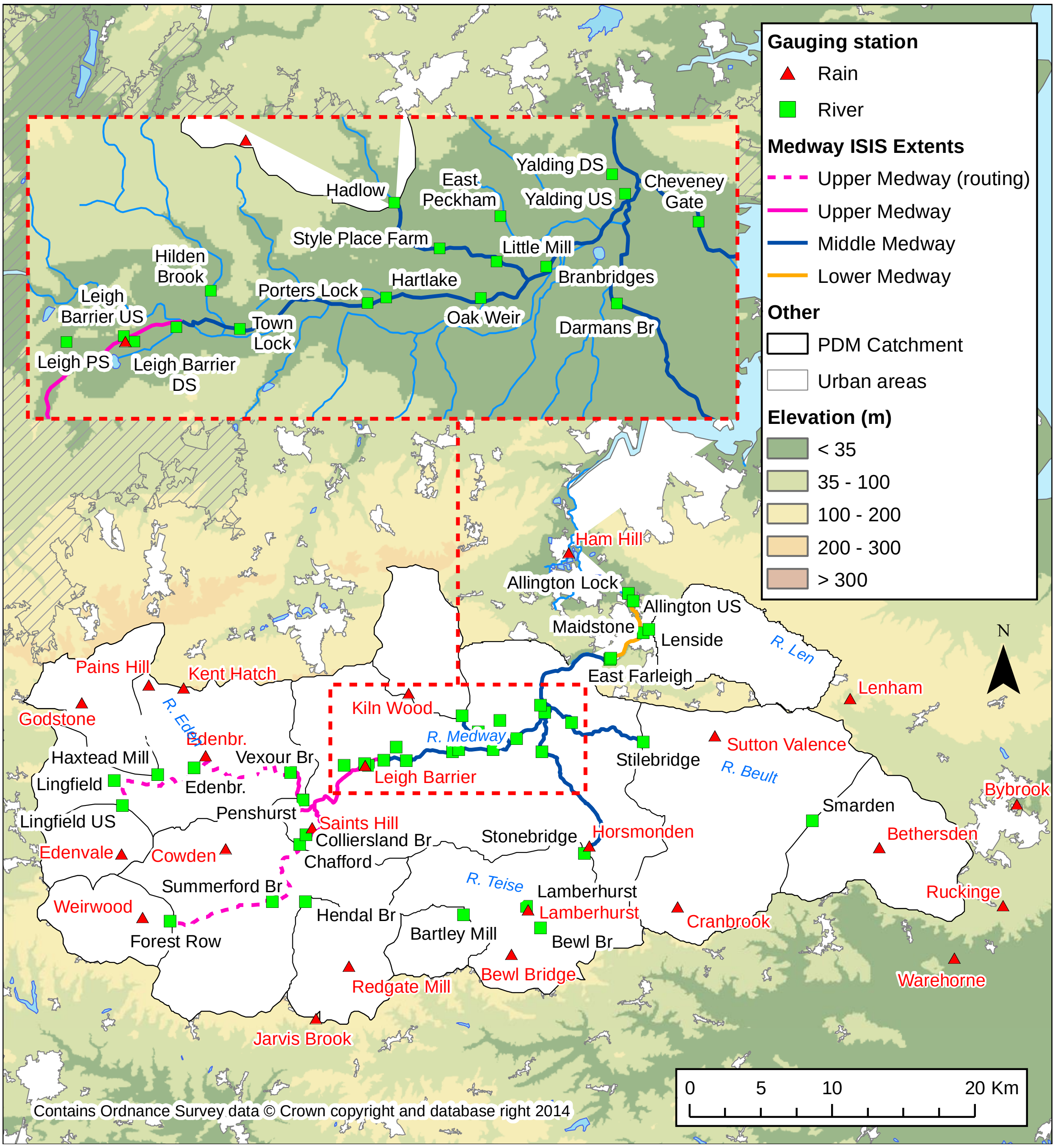


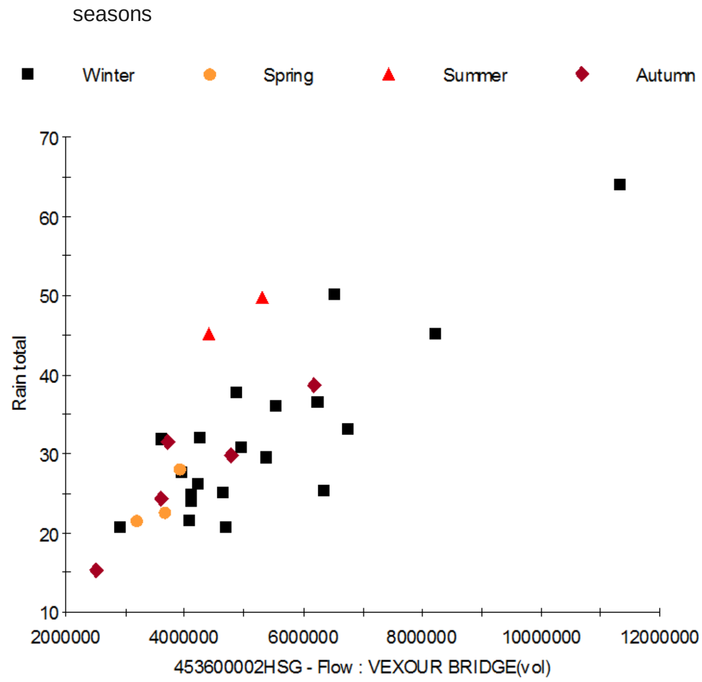
Figure 1-3: The Medway catchment and its hydrometric network



The Medway leaves its flat middle reach through a narrow valley, where it is gauged at East Farleigh. It then flows on to Maidstone and the tidal limit. The River Len, with a permeable chalk catchment, is the last tributary to join in the town. At East Farleigh, the hydrograph is highly attenuated and the catchment lag has extended to an average of 23 hours, but this can be longer.

Rainfall across all of the Medway is less than the UK average. SAAR is 739mm, although it exceeds 800mm in the headwaters. Underlying geology is not particularly permeable, but deep soils accumulate a large moisture deficit in summer. This means that summer runoff rates are much lower than winter ones. All the rivers are therefore sensitive to antecedent soil conditions and, as a consequence, long periods of wet weather. Figure 1-4 shows how summer events (red triangles) with a high rainfall depth generate low volumes of runoff on the Eden compared to those in winter (black squares).

Figure 1-4: Correlation of catchment average rainfall (mm) and total runoff (m^3) from the Eden for events from different



1.4 Flood history

Our severity report described the December 2013 flood event in detail. That flood produced the highest recorded flow at Colliers Land Bridge, in the headwaters of the Eden, and at East Farleigh near the catchment outlet. Elsewhere, it was either ranked second or third in the gauged series. Its main features were the particularly wet catchment on which rain fell, and that the rainfall was widespread - causing a large response in all tributaries. The antecedent conditions and the catchment-wide rainfall were the most unusual aspects of that flood.

Another flood occurred in October 2000 during an exceptionally wet autumn. Again, antecedent conditions were significant and the catchment response was widespread - although less severe than in December 2013. Rain that fell heaviest over the Eastern Medway produced the highest recorded flows on the Teise and Buelt.

September 1968 was the most severe flood recorded on the Eden, and reputedly the most severe since 1853 (Tonbridge Weather web site1). It was caused by two days of persistent rainfall over the far western part of the catchment. 168.4mm were recorded over two water days at Godstone (0.43% AEP or 230-year RP) and 162.6mm at Limpsfield (Godstone also recorded 123.7mm in one day - 0.72% AEP or 138-year RP). The Eden flood that ensued had a peak discharge of 201m^3/s at Vexour: 8.7 times QMED (23m^3/s). The rainfall was very uneven however, with rain gauges in the Beult and Teise catchments recording less than 20mm for the same period. Despite severe rainfall only affecting half the catchment, the peak flow at East Farleigh was still 350m^3/s (very similar to that gauged in December 2013).

A significant Autumn flood affected the Medway catchment on 3 November 1960. Over 170mm of rain was recorded at Weir Wood Reservoir between the 28th October and the 3 November, creating very wet antecedent conditions and giving rise to the rank 2 peak flow (after December 2013).

These historical events demonstrate the importance of antecedent conditions on the flood generation process. They remind us that rainfall distribution is an important control on flooding on the Medway. Flooding can also occur as a result of quite different rainfall events - even locally concentrated ones.

[1] http://www.tonbridge-weather.org.uk/wx-notes.htm

1.5 Key challenges

Four key challenges to delivering hydrological estimates for the hydraulic models present themselves. A successful methodology needs to surmount these challenges, discussed below.

1.5.1 Leigh FSA

Formal flood storage, like the Leigh FSA, causes particular problems for flood estimation. The ability of an in-line storage area to limit pass forward flow depends on both the magnitude of the event and its volume. A short duration storm with a high flow may pass safely downstream, whereas a long duration event with a lower peak flow may not. Storage is also sensitive to multi peaked flood events, where one rainstorm arrives quickly after another (which may have exhausted storage). A further complication is how operation of the FSA changes when an event is likely to fill the storage area and force high pass forward flows. Operators use forecasts to optimise the operation of the gates to minimise the flow passed forward in these circumstances. Calculating a robust design flow downstream of the FSA needs to recognise these features and deal with them in a sound probabilistic framework.

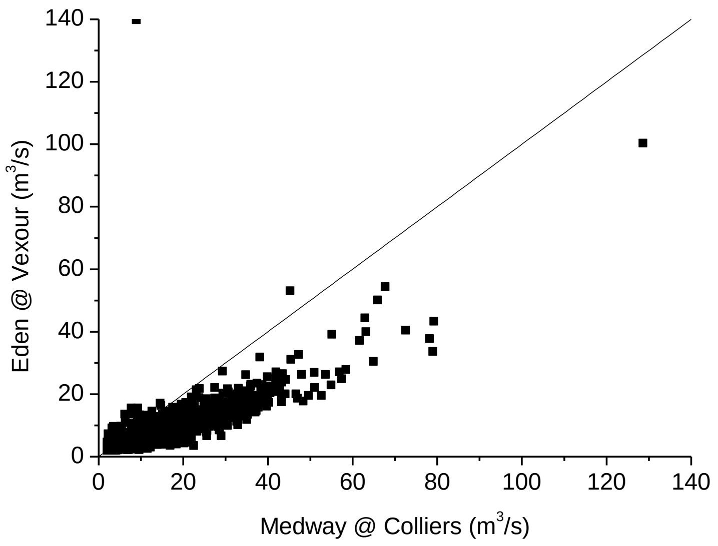
1.5.2 Tributary phasing

Relative contributions from the four Medway tributaries differ between flood events. Their individual response times also mean that they might combine with a particular phasing at key risk areas. For the Lower Medway, the large combined contribution of all tributaries is likely to cause the largest flood (as happened in December 2013). On individual tributaries, flooding may be a product of a locally intense storm - like September 1968. Catering for this behaviour within a single hydrological framework is a challenge for the project.

1.5.3 Natural floodplain

As well as the formal storage at Leigh, there is an extensive natural floodplain in the Medway catchment and its tributaries. Its effect is to attenuate flows - even those below the median annual maximum (QMED). Figure 1-2 showed how the shape of the hydrograph at Stonebridge is affected by floodplain storage. Comparing peak flows in the Eden (at Vexour) and Medway (at Colliers Land Bridge) (see Figure 1-5) shows how, in lower order events, peak flows are attenuated differently to higher order events. In this case, the Eden continues to attenuate for longer than the Medway. Above a certain point, peak flows increase in unison - presumably once the floodplain is fully active and showing less storage.

Figure 1-5: Impact of flood plain attenuation on growth rates at Colliers and Vexour (excluding September 1968)



Understanding this is important when using FEH statistical methods, which use QMED as the index flood. In pooled analysis, a growth rate is applied to QMED to generate a flow of a given probability. If QMED is supressed because of floodplain storage, this will lead to a significant underestimation of the design flow.

1.5.4 Locally extreme events

Finally, we need to consider locally extreme events. September 1968 has a flood growth rate of 8.7 on the River Eden. A value this high is much larger than most estimates of the 0.1% AEP event - and yet it was observed in the Eden. Similarly large growth rates have been noted in other catchments with long gauged records (The Rye in North Yorkshire in June 2005, the Dearne in South Yorkshire in June 2007). This highlights a potential weakness in pooled analysis - based on many individual short records - and emphasises the importance of incorporating local data into flood estimates.

1.6 Approach

1.6.1 Options available

Potential flood estimation methods are constrained by the issues outlined above. Peak flow methods (such as FEH statistical) are discounted because of the FSA's effect and the need for flows at the models' boundaries. A need for inflows at multiple tributaries restricts us to methods that provide inflow hydrographs. The various options for doing this are discussed below. Ultimately, we have used continuous simulation as the only really robust way of dealing with the various challenges posed by this modelling problem.

1.6.2 Continuous simulation

Continuous simulation modelling (CSM) is a framework for solving multi variate problems. In this context, the method involves simulating a very long rainfall series and applying it to a complete model of the Medway catchment - including rainfall runoff, flow routing and operation of the Leigh FSA. The result is 5,000 years' worth of simulated annual maxima, for any model node, which may then be treated as if it were an observed series. Simulated annual maxima of the parameter of interest (flow or level) are ranked for the location of interest and an AEP assigned using the Gringorton formula. If the stochastic rainfall series is representative of what might be expected in reality, and the catchment model is accurate, results using this method should be robust.

1.6.3 Why continuous simulation is necessary

Simulating flow and FSA operation continuously allows us to obtain design flow estimates anywhere in this catchment. The continuous series contains events of different shapes and durations having the correct probability associated with each. To understand why continuous simulation is necessary, it is easier to discount the other potential methods.

Statistical techniques for deriving design flows from observed data are eliminated first. Pooled analysis of annual maximum (AMAX) flows is not possible because:

- Floodplains continually influence the flow in the Upper and Middle Medway. As well as changing flows through the system, they affect QMED and make the application of the index flood - growth rate package difficult.
- Outflows from the Leigh FSA depend on event volume as well as peak flow; and
- Inflows to models are needed at their upstream extent;

Although single site statistical analysis can be applied, gauged records are only available at particular points and, in any case, do not take account of flood event volume. Single site flood estimation is more problematic downstream of the FSA which was only built in 1981 and whose operational procedures have changed over time. Its influence on peak flows also wanes with distance downstream.

Accounting for the behaviour of the Leigh FSA, floodplain storage, the change in critical storm duration and the phasing of tributaries is a pre-requisite of any design flow estimation technique. Only simulation within a river model can simulate their unique influence and test the impact of the FSA's operational procedures. If this is accepted, the question of design flow estimation shifts to the model's boundary conditions: i.e. what flows should be input to the model to determine a design flow for nodes within it. The remainder of this chapter is concerned with obtaining these boundary conditions.

There are three possible choices for doing this, considered in turn below:

1.6.3.1 Scaling an observed event to statistical flow estimates at upstream boundaries

This approach could ensure that the model inflows have a peak flow that matches the n% AEP event at one or more boundaries. The main drawbacks are that the flow in different parts of the system depends on the volume of the overall simulation as well as the peak flow. Choosing a single event shape is a big assumption that could lead to design flows being too high or low. An additional problem is that applying the same probability flow at each boundary is likely to give a conservative result when they are combined in the model. A 1% AEP flow at East Farleigh is unlikely to be accompanied by 1% AEP flows on all of the tributaries because each has its own critical storm duration and event rainfall distribution.

1.6.3.2 Applying the ReFH rainfall runoff model

Rainfall runoff approaches like ReFH package together a depth, duration and frequency of rainfall with a rainfall runoff model to give a flow of a given probability. This should give volumes and peak inflows for a given probability. However, the assumption of a design hyetograph (single peaked) is not reasonable and the method does not account for multi peaked events. It is such an event that caused the flooding seen on the Medway in December 2013. Added to this, the joint probability of high rainfall on top of a wet catchment is a particularly important for the Medway. Further reasons to discount ReFH for the Medway are that its catchment area exceeds the recommeded limit for the method at the downstream end. It would also involve applying long-duration design storms (necessary given the FSA) on small sub-catchments, and ReFH can give unreliable results in such situations, calculating an unrealistically large volume of baseflow.

1.6.3.3 Continuous simulation

Continuous simulation makes fewer assumptions than the alternatives and is therefore a more viable choice. It provides multi peaked rainfall events within a rational framework for assigning a probability to those. When applied to a rainfall runoff model continuously, this approach should give a peak flow series that reflects the FEH single site statistical approach at gauged locations while preserving realistic hydrograph shapes and volumes. As an added safeguard, the continuous simulation peak results can be manipulated to give the required peak flood frequency curve at key locations without losing the benefit of the variability in hydrograph shape, timing and volume. Such locations include long gauged flow records where we have some confidence in the rating curve and recorded level series.

1.6.4 Overview of method

While continuous simulation is conceptually straightforward, it is technically challenging to apply. It may be broken down into three broad processes:

1. Developing a stochastic rainfall series. This is a long synthetic rainfall series that mimics real rainfall, producing realistic wet and dry periods and multi peaked events. It should reproduce rainfall depths with the same duration and frequency that one might find in an observed series. It is produced using sophisticated statistical modelling software. It is the main input to the model and the process of deriving the rainfall series is described in Section 2. This project is unusual in having applied a spatially varying statistical rainfall generator;
2. Building a catchment-wide model. This is a model that simulates what happens to the rainfall after it reaches the soil and flows through the river system. In our case it is based on the existing flood forecasting model, constructed from Probability Distributed Moisture (PDM) rainfall runoff models and ISIS river models. This system must also simulate the default and alternative operation of the Leigh FSA; and
3. Applying (1) to (2) and extracting results in the form of peak flows at critical risk areas.

In the Medway's case, there is a further complication. The catchment river model (2) is different to that being used to map flood extents. A means of identifying design events in the simple model and applying them in the fully hydraulic model is therefore needed.

2 Rainfall modelling

2.1 Overview

Rainfall is the main input to the continuous simulation. For the process to work, a long rainfall series is needed that has the same depth, duration and frequency statistics as might be observed (if there were a long enough record). Those statistics need to be closest to the observed at the critical storm duration of the catchment.

Other realistic properties such as dry periods between storms are also required. For catchments with strong seasonal changes in soil moisture deficit, it is also important that annual average rainfall is reasonable - to give sensible soil moisture accounting between events. The large size of the Medway catchment means that rainfall totals can differ significantly for its tributaries. Spatially varying rainfall was therefore a necessary part of the continuous simulation. This section of the report describes the method used to derive a 5,000-year rainfall series at an hourly timestep for use in continuous simulation.

Our method can be simplified and summarised as follows:

1. Collate daily rainfall at gauges representative of the catchment. We used accumulated data from tipping bucket rain gauges that feed the PDM models in the current forecasting system.
2. Fit a daily rainfall generator model to these data (we used GLIMCILIM, see Section 2.4). It should generate a long daily rainfall series with spatially coherent wet and dry days for the catchment. For wet days, the rainfall totals should also reflect the spatial coherence inherent in real data.
3. Adjust the GLIMCLIM rainfall outputs so that they also reproduce the rainfall growth rates (rainfall depth for a return period divided by RMED) seen in the FEH DDF model for 24 hour durations at the expected frequency.
4. Develop an hourly rainfall generator model, calibrated to a long hourly rainfall series (we used Weir Wood Reservoir).
5. Adjust its parameters so that generated rainfall depths and frequencies for durations less than 24 hours match those of the FEH depth, duration and frequency (DDF) model.
6. Disaggregate the spatially varying daily rainfall for all gauge locations to hourly values. This is done by creating a large 'library' of rainfall profiles from the hourly rainfall series for one location (Weir Wood). For each wet day, the hourly profile with a total that most closely matches the rainfall on that day is selected to disaggregate all data (but the spatial variability of the total rainfall is retained).
7. Calculate catchment average rainfalls using the individual gauges and weights.
8. Check the resulting rainfall series against the frequency of rainfall depths seen in observed series'.
9. Check the AMAX flows that result from applying the rainfall series to calibrated PDM models.
10. In our case, it was necessary to reprocess the rainfall slightly to get a better fit to observed rainfall depths and observed flow AMAX by applying a global 5% reduction.

Each of these steps is described in more detail below.

2.2 Introduction to stochastic rainfall models

A stochastic rainfall model generates artificial rainfall data with statistical characteristics that are intended to be similar to real rainfall. There are two broad classes of stochastic rainfall model:

- "Point" rainfall model, which produces a single sequence of rainfall at a representative point in a catchment, often at an hourly timestep. In catchments where there is little spatial-temporal variability or in catchments where rainfall variability is damped by a slow catchment response (e.g.in some chalk catchments), the "point" rainfall series can be applied catchment wide as an input for reasonable rainfall-runoff simulation for flood events.
- "Spatial" rainfall model, which produces sequences of rainfall at many different locations within a catchment (e.g. raingauge locations). This type of model is appropriate for catchments where spatial variability of rainfall is significant, such as the Medway, where

flood generating rainstorm events can occur over certain parts of the catchment but not over others.

There are numerous examples of stochastic rainfall models in the hydrological literature, including: for example: Cowpertwait (1998)[2], Cameron *et al*. (2000)[3], Chandler and Wheater (2002)[4] and Burton *et al.* (2008)[5].

A growing number of studies have used such models in conjunction with a continuous simulation rainfall-runoff model to produce flood estimates. Examples in the published literature include Faulkner and Wass, 2005[6]; Blanc *et al.*, 2012[7], Grimaldi *et al.*, 2012[8] and Smith *et al.* 2014[9]. Several Environment Agency flood mapping studies have applied continuous simulation, including some on highly permeable catchments, low-lying catchments with tide locking, and rivers with controlled flood storage areas. However, the vast majority of UK and Irish flood studies continue to be based either on statistical analysis of flow or on rainfall-runoff models that simulate single design rainfall events.

In addition, the recent continuous simulation studies have generally used point rainfall models. As identified above, this approach may not be suitable for the Medway. A spatially varying rainfall model was therefore deemed to be more appropriate. Following the recommendations of FD2105/TR[10] for developing spatially varying rainfall inputs for continuous rainfall runoff simulation, we have used the Generalised Linear Modelling (GLM) package GLIMCLIM to estimate spatial rainfall at a daily timestep across the Medway catchment. GLM is an extension of linear regression and uses various predictors (which can include, for example, seasonal variation, and raingauge location) to estimate the occurrence of rainfall on particular days ("wet" days) and the amount of rainfall on those days. GLIMCLIM achieves this by utilising an Occurrence model and an Amounts model together for simulation. Five thousand years of daily rainfall data were generated for each tipping bucket location used in the existing PDM models.

Per FD2105/TR, daily data were disaggregated to an hourly level to simulate the behaviour of the catchments at a realistic timestep. This was achieved by using the same hourly rainfall profile at all points where daily rainfall was simulated. In this study, this was achieved by using scaled rainstorm profiles derived from output from a Bartlett-Lewis Rectangular Pulse Model which had been fitted to a point location within the catchment. This process allowed 1 to 5,000 years of hourly rainfall data to be produced at each raingauge.

2.3 Choice of rain gauge data

There are numerous raingauges (both storage and tipping bucket, TBR) within the Medway catchment which could be used for model fitting. Sufficient rainfall data were required for the following purposes:

11. GLIMCLIM Occurrence model. Adequate representation for the occurrence of wet days.
12. GLIMCLIM Amounts model. Adequate representation of the rainfall amounts on those wet days.
13. Bartlett-Lewis model. Representative rainfall statistics (e.g. 1 h mean, variance, percentage dry, etc).

[2] Cowpertwait, P.S.P. (1998). A Poisson-cluster model of rainfall: high-order moments and extreme values. Proc. R. Soc. Lond. A (1998) **454**, 885-898.

[3] Cameron, D., Beven, K. and Tawn, J. (2000) An evaluation of three stochastic rainfall models. *J. Hydrol.* **228**, 130-149.

[4] Chandler, R.E. and Wheater, H, S. (2002) Analysis of rainfall variability using generalized linear models: A case study from the west of Ireland, *Water Resources Research* **38** (10), 10.1-10.11.

[5] Burton, A., Kilsby, C.G., Fowler, H.J., Cowpertwait, P.S.P., O'Connell, P. E. (2008). RainSim: A spatial‐temporal stochastic rainfall modelling system. Env. Modelling & Software **23** (12), 1356-1369.

[6] Faulkner, D. and Wass, P. (2005) Flood estimation by continuous simulation in the Don catchment, South Yorkshire, UK. WEJ (Journal of CIWEM), **19** (2), 78-84.

[7] Blanc, J., Hall, J.W., Roche, N., Dawson, R.J., Cesses, Y., Burton, A. and Kilsby, C.G. (2012). Enhanced efficiency of pluvial flood risk estimation in urban areas using spatial–temporal rainfall simulations. J. Flood Risk Man. **5**, 143-152.

[8] Grimaldi, S., Petroselli, A. and Serinaldi, F. (2012). A continuous simulation model for design-hydrograph estimation in small and ungauged watersheds. Hyd. Sci. J., **57** (6), 1035-1051

[9] Smith, A., Freer, J., Bates, P. and Sampson, C. (2014). Comparing ensemble projections of flooding against flood estimation by continuous simulation. J. Hydrol. **511**, 205–219

[10] DEFRA/EA (2006) Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme: Improved methods for national spatial-temporal rainfall and evaporation modelling for BSM R&D Technical Report F2105/TR

14. Bartlett-Lewis model. Representative extreme rainfall statistics. The FEH DDF curves were used for this purpose.
15. PDM model. As far as was practicable, directly relate the stochastic rainfall series to rainfall input locations used by the PDMs. (Where appropriate, the synthetic rainfall data were further scaled via an iterative process using the PDM to improve fits to the flood growth curves).

Given the above considerations, the approach taken here was to fit GLIMCLIM to TBR data (aggregated to daily amounts) for the TBRs which are already used within the PDMs configured in NFFS. The Bartlett-Lewis model was fitted to data from a single TBR, with further calibration using FEH statistics. This approach allowed the stochastic rainfall series to be used directly with the PDMs.

Table 2-1 lists the raingauges selected for analysis. Record length and data quality was found to be variable. Although GLIMCLIM does not strictly require a common period of record for fitting, it was assumed that a common period of record with a suitably representative sample of appropriate rainfall statistics would ease model fitting. Following a period of testing the 10 year period 2004 to 2013 was used[11]. It is recognised that this is a fairly short record, however, it was judged sufficient for identifying rainstorm occurrences and incorporated the notable December 2013 rainfall amounts. It also avoided the period of poorest data quality. The Bartlett-Lewis model (which was used to assist in the disaggregation of daily data to an hourly timestep) was also fitted to FEH statistics which represent a longer term record (section 2.6.5).

Table 2-1: Tipping bucket raingauges used in analysis

Name	Gauge ID	Start	End	Record Length (Years)	NGR	Elevation (mAOD)
Bethersden STW	463214509	18 Oct 1990	6 Jun 2014	24	TQ92396 40265	33.34
Bewl Bridge Res	463234504	8 Jan 1991	31 Jul 2013	23	TQ66612 32853	74.80
Cranbrook STW	463215906	10 Mar 1992	6 Feb 2014	22	TQ78256 36138	66.40
Eden Vale STW	463655903	3 Apr 1993	7 Feb 2014	21	TQ39216 39924	89.65
Edenbridge STW	463610906	10 Mar 1992	6 Feb 2014	22	TQ45247 46879	40.15
Godstone STW	463641904	10 Sep 1999	5 Jun 2014	15	TQ36437 50447	84.40
Jarvis Brook	463521918	9 Sep 1999	5 Jun 2014	15	TQ52941 28392	139.28
Kent Hatch Res	463622502	14 Apr 1992	6 Jun 2014	22	TQ43615 51546	202.70
Kiln Wood	463312902	19 Jan 2006	6 Feb 2014	8	TQ59430 51189	86.80
Lamberhurst STW	463230905	10 Mar 1992	6 Feb 2014	22	TQ67818 35976	43.05
Pains Hill Res	463630901	3 Apr 1993	6 Feb 2014	21	TQ41150 51325	89.90
Redgate Mill	463521512	27 Jul 1990	6 Jun 2014	24	TQ55334 32107	70.33
Saints Hill PS	463400901	6 Apr 1993	6 Jun 2014	21	TQ52312 41471	42.00
Sutton Valance STW	463210512	10 Mar 1992	6 Feb 2014	22	TQ80954 48140	33.90
Weir Wood Res	292554	10 Jan 1991	6 Jun 2014	23	TQ40698 35388	63.41

2.4 GLIMCLIM

GLIMCLIM[12] is a generalised linear modelling package which allows the development of relationships between different co-variates (such as seasonal effects and raingauge location) in order to explain variances in rainfall and ultimately allow simulation. Originally developed in FORTRAN, the current version of the package is implemented in the R programming language (RGLIMCLIM[13]).

With respect to rainfall, RGLIMCLIM utilises two modelling packages which are developed separately and then run together for simulation:

- An Occurrence model. This package simulates whether or not a given day is "wet". In RGLIMCLIM, this is achieved using a logistic regression model where the response variable (calculated from a vector of covariates such as seasonality, raingauge location,

[11] For Kiln Wood, the model was fitted from 2006 to 2013.

[12] Chandler, R.E. and Wheater, H, S. (2002) Analysis of rainfall variability using generalized linear models: A case study from the west of Ireland, *Water Resources Research* **38** (10), 10.1-10.11.

[13] http://www.ucl.ac.uk/~ucakarc/work/glimclim.html

and the occurrence of rainfall in preceding days) takes values of 0 (i.e .no rainfall) or 1 (i.e. rainfall).

- An Amounts model. This package simulates the amount of rainfall which occurs on a "wet" day. A gamma distribution is sampled to simulate rainfall amounts.

RGLIMCLIM is flexible and it is a user decision as to which covariates are used to build each model type. The goal in this study was to generate rainfall series which produced realistic flows when coupled with the PDM. To this end, the following candidate model types were considered:

- Model 1:
    i. Occurrence model: "Soft" threshold for rainfall occurrence[14]: 0.45 mm. The purpose of the threshold is to help define a "wet" day and remove very small rainfall amounts. During model fitting, values below this threshold are set to zero and all other values are reduced by this threshold (to ease model fitting). After fitting, the threshold is added back on to the non-zero values.
    ii. Amounts model: above threshold, with a constant correlation for spatial dependence between sites. This approach is similar to a previous GLIMCLIM fit to rainfall data in the Blackwater catchment in FD2105/TR .
- Model 2:
    iii. Occurrence model: "Soft" threshold for rainfall occurrence: 1.00 mm.
    iv. Amounts model, above threshold, but with a powered exponential correlation for spatial dependence between sites. Figure 2-4 provides an example of the fit to the observed data with respect to quantiles and inter-site correlation.

Per the techniques recommended in the RGLIMCLIM manual[15], maximum likelihood estimates of model parameters were obtained via iterative least squares. The model parameters are summarised in Table 2-2 and Table 2-3 for the occurrence and amounts models, respectively.

As described in FD2015/TR, a common approach for comparing observed and modelled values for the Occurrence model is to use Pearson residuals. The Pearson residual for the *i*th case is defined as:

$r_i^{(P)} = [Y_i - \mu_i] / \sigma_i$

Where Y_i, μ_i and σ_i are respectively the observed value, the mean of the distribution predicted by the GLM and the standard deviation of this distribution. In an ideal model, all Pearson residuals should come from distributions with zero mean and the same variance. On a monthly and annual basis, Figure 2-1 and Figure 2-2 provide sample plots of Pearson residuals for the alternative Occurrence model fits. The zero mean is shown together with the expected standard deviation value of 1. The dashed lines show the range within which most of them would be expected to lie under the model. It can be seen that both models are acceptable and that there is very little difference in performance between the two Occurrence models.

Fits to the Amounts models are evaluated using quantile-quantile plots and inter-site correlations (Figure 2-3 and Figure 2-4). The quantile-quantile plot shows standardised residuals from the gamma distribution, defined as:

$\Gamma_{st} = Y_{st} / \mu_{st}$

Where Γ_{st} is the *st*th residual, Y_{st} is an observation and μ_{st} is the modelled mean of the distribution. On the plot, the observations are shown as points and the fitted distribution as a dashed line.

Per FD2015/TR, the inter-site correlations for the intensity model were calculated by first deriving Anscombe residuals for each site (the relationship between a given wet day amount and the average rainfall amount from a gamma distribution, see below), calculating the correlation between all pairs of sites, and then plotting against inter-site distance.

An Anscombe residual is defined as:

$r_i^{(A)} = [Y_i / \mu_i]^{1/3}$

[14] DEFRA/EA (2006) Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme: Improved methods for national spatial-temporal rainfall and evaporation modelling for BSM R&D Technical Report F2105/TR

[15] Chandler, R. (2014) RGCLIMCLIM, A Multisite, Multivariate Daily Weather Generator Based on Generalized Linear Models. User Guide.

Where Y_i is the observed value on the ith wet day and μ_i is the modelled mean of the gamma distribution.

From Figure 2-3 and Figure 2-4, it can be seen that the choice of threshold and correlation structure does have an influence on the quality of the Amounts model. Figure 2-3 and Figure 2-4 provide examples of the amounts models' fit to the observed data with respect to quantiles and inter-site correlation. It can be seen that Model 2B appears to give a slightly better fit to rainfall amounts overall. (Fits to extreme rainfall amounts are described in section 2.6.8).

The daily data from both sets of models were disaggregated to an hourly level (section 2.6.7) and trialled with the PDM for comparison with statistical flood frequency results and runoff amount checks. The output from Model 2 was selected following this test.

For Model 2, a comparison of observed (2004 to 2013; this period was selected because this is the period the model was fitted to) and simulated average annual rainfalls for each raingauge is provided in Table 2-4. When the average over all of the raingauges is considered, the model is within 1% of the observed. At an individual raingauge level the simulated values are generally within a few percent of the observed. An exception is Pains Hill, where the model underestimates by almost 11%. Overall, however, the model is judged to be fit for purpose.

Figure 2-1: Example of fit for occurrence model 1A (0.45 mm threshold)

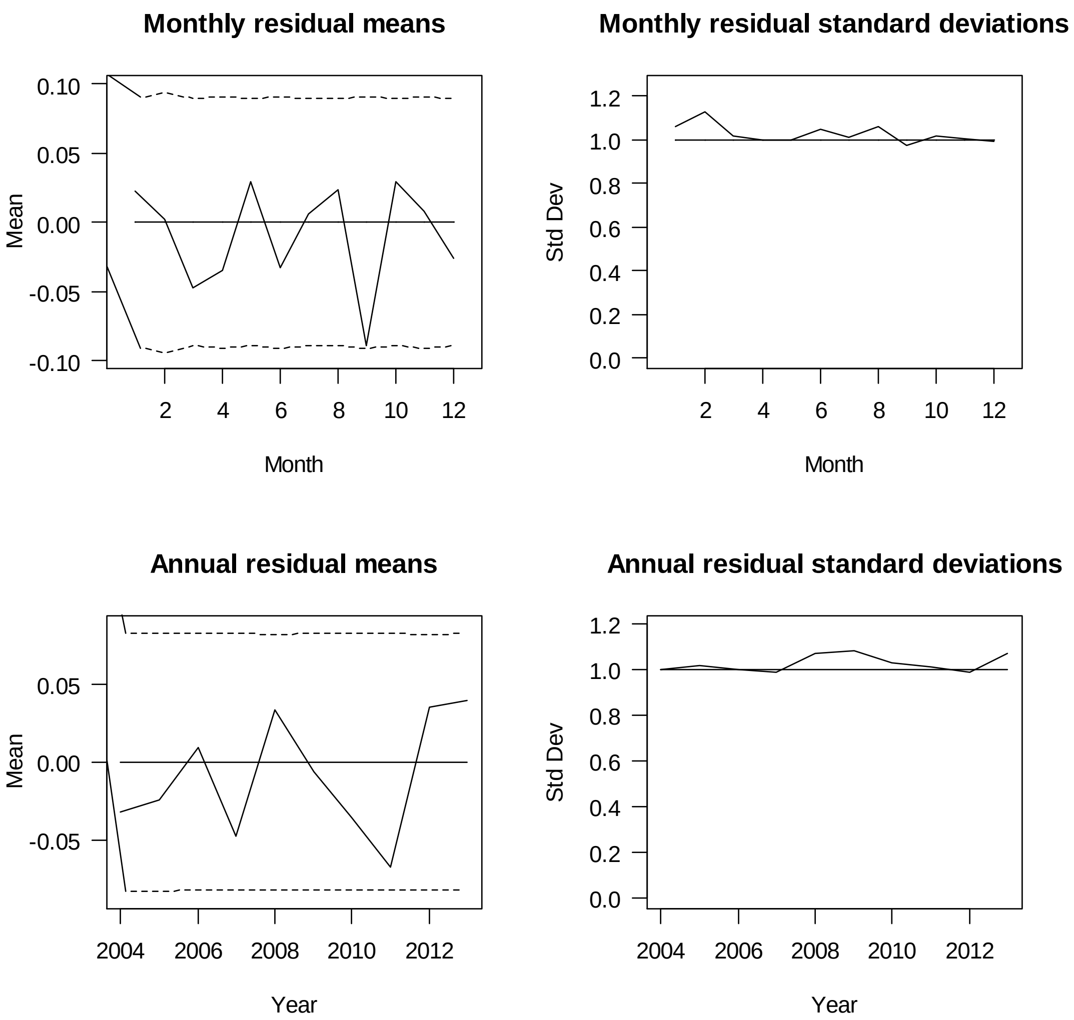


Figure 2-2: Example of fit for occurrence model 2A (1.00 mm threshold)

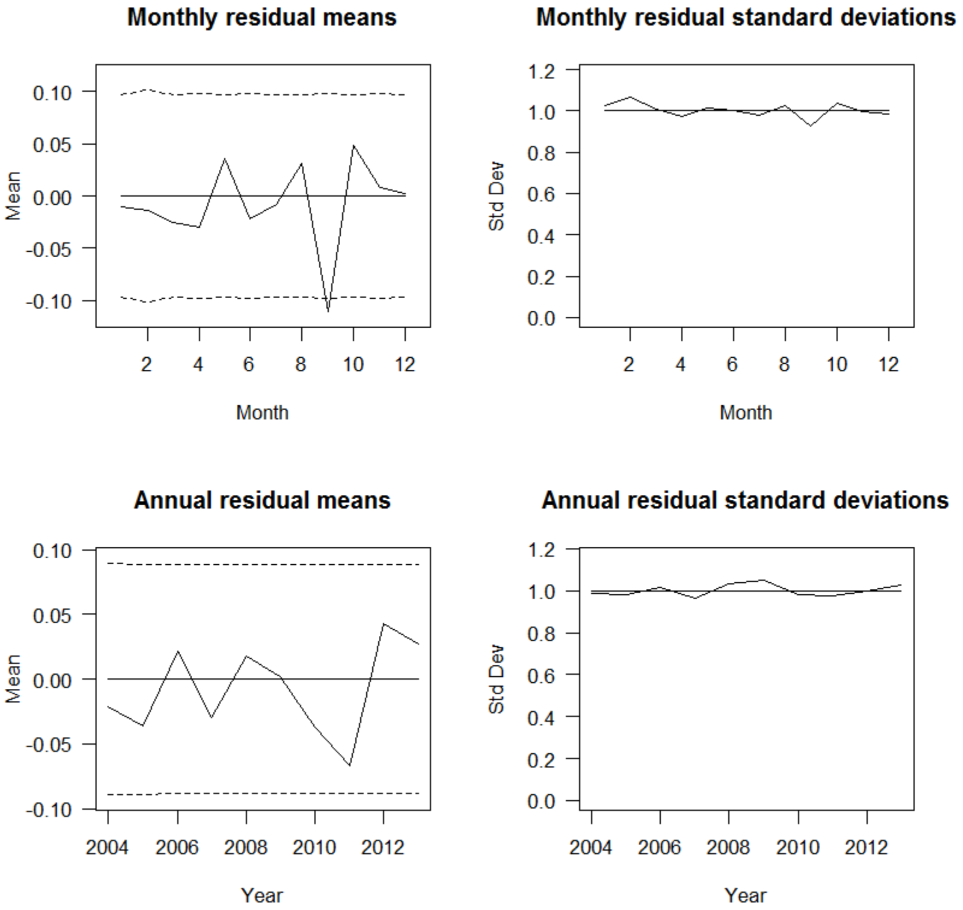


Figure 2-3: Example of fit for amounts model 1B (0.45 mm threshold; constant correlation)

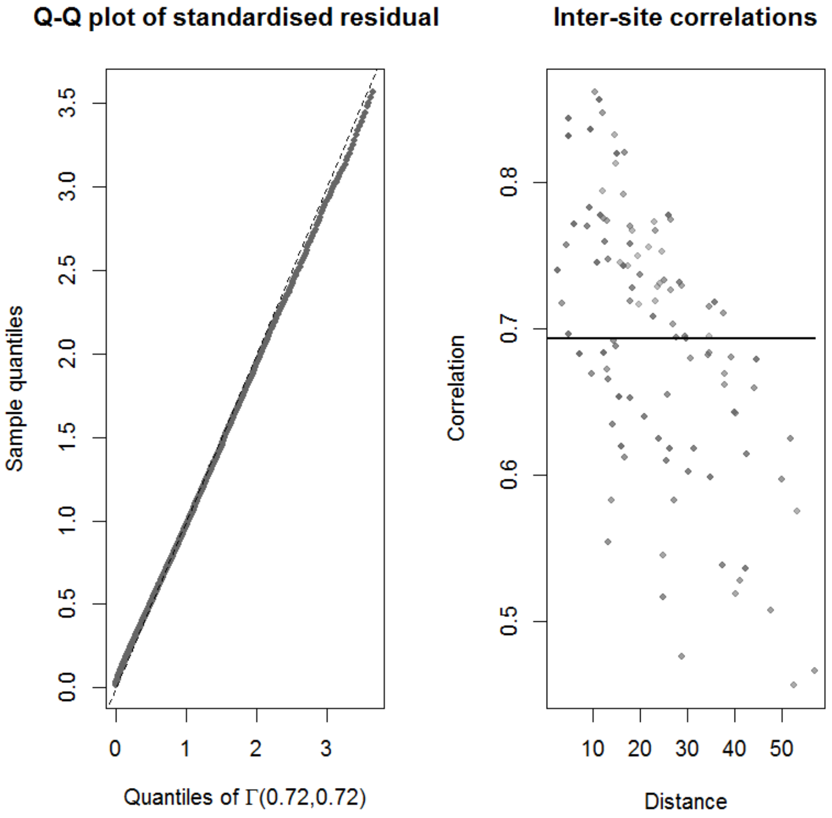


Figure 2-4: Example of fit for amounts model 2B (1.00 mm threshold; powered exponential correlation)

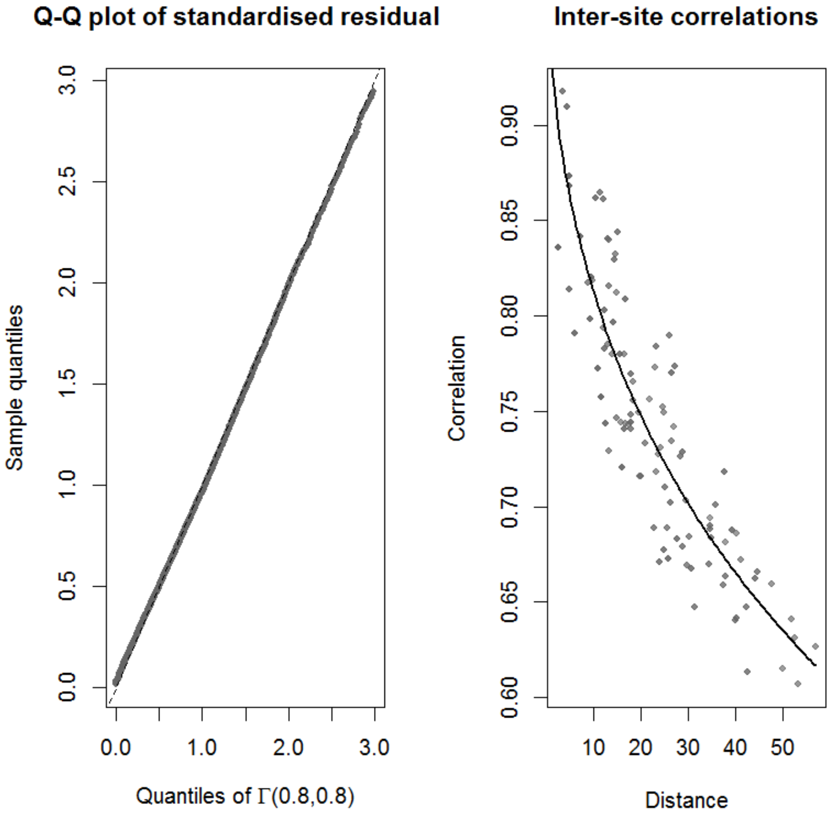


Table 2-2: RGLIMCLIM Occurrence Model Parameters

Main Effect	Coefficient - Model 1A	Coefficient - Model 2A
Constant	-1.3277	-1.3457
Legendre polynomial 1 for Eastings (OS grid, km)	0.0428	-0.0003
Legendre polynomial 2 for Eastings (OS grid, km)	0.1029	-0.0134
Legendre polynomial 1 for Northings (OS grid, km)	0.1155	0.0676
Legendre polynomial 2 for Northings (OS grid, km)	0.0618	0.1818
Legendre polynomial 1 for Elevation (m)	-0.3607	0.0584
Legendre polynomial 2 for Elevation (m)	-0.2295	-0.0667
Daily seasonal effect, cosine component	0.2419	0.1555
Daily seasonal effect, sine component	-0.0863	-0.1078
Mean of I(Rainfall[t-1]>0)	0.1327	0.1165
Mean of I(Rainfall[t-2]>0)	0.5889	0.4850
Mean of I(Rainfall[t-3]>0)	0.3906	0.4767
Mean of I(Rainfall[t-4]>0)	0.3328	0.2276
Two way interactions		
Legendre polynomial 2 for Eastings with Legendre	-0.2290	0.1198

Main Effect	Coefficient - Model 1A	Coefficient - Model 2A
polynomial 1 for Northings		
Legendre polynomial 2 for Eastings with Legendre polynomial 2 for Northings	-0.4247	0.1417
Legendre polynomial 2 for Elevation with Mean of I(Rainfall[t-1]>0)	0.0018	-0.0033
Daily seasonal effect, cosine component with Mean of I(Rainfall[t-1]>0)	-0.0074	0.0031
Daily seasonal effect, sine component with Mean of I(Rainfall[t-1]>0)	0.0560	0.0439
Legendre polynomial 2 for Elevation with Mean of I(Rainfall[t-2]>0)	-0.0019	-0.0162
Daily seasonal effect, cosine component with Mean of I(Rainfall[t-2]>0)	-0.1029	-0.0369
Daily seasonal effect, sine component with Mean of I(Rainfall[t-2]>0)	-0.0983	-0.0258
Parameters in non-linear transformations		
Legendre polynomial for Eastings (OS grid, km)		
Lower limit	530	530
Upper limit	600	600
Legendre polynomial for Northings (OS grid, km)		
Lower limit	125	125
Upper limit	160	160
Legendre polynomial for Elevation (m)		
Lower limit	30	30
Upper limit	205	205
Global quantities		
"Soft" threshold for positive value (mm)	0.45	1.00
Spatial dependence structure		
Conditional independence	4.55	5.32

Table 2-3: RGLIMCLIM Amounts Model Parameters

Main Effect	Coefficient - Model 2B	Coefficient - Model 2B
Constant	1.278	1.4562
Legendre polynomial 1 for Eastings (OS grid, km)	-0.0237	-0.074
Legendre polynomial 2 for	-0.2057	-0.1538

Main Effect	Coefficient - Model 2B	Coefficient - Model 2B
Eastings (OS grid, km)		
Legendre polynomial 1 for Northings (OS grid, km)	0.1909	0.0304
Legendre polynomial 2 for Northings (OS grid, km)	0.0004	0.0052
Legendre polynomial 1 for Elevation (m)	-0.4693	-0.1496
Legendre polynomial 2 for Elevation (m)	-0.1478	-0.0383
Daily seasonal effect, cosine component	-0.1146	-0.0335
Daily seasonal effect, sine component	-0.136	-0.1307
Mean of Ln(1+Rainfall[t-1])	0.1764	0.128
Mean of Ln(1+Rainfall[t-2])	0.0347	-0.0048
Mean of Ln(1+Rainfall[t-3])	0.1045	0.0821
Mean of Ln(1+Rainfall[t-4])	0.023	-0.0089
Two way interactions		
Daily seasonal effect, cosine component with Mean of Ln(1+Rainfall[t-1])	0.0825	0.0343
Daily seasonal effect, cosine component with Mean of Ln(1+Rainfall[t-2])	0.0569	0.0449
Parameters in non-linear transformations		
Legendre polynomial for Eastings (OS grid, km)		
Lower limit	530	530
Upper limit	600	600
Legendre polynomial for Northings (OS grid, km)		
Lower limit	125	125
Upper limit	160	160
Legendre polynomial for Elevation (m)		
Lower limit	30	30
Upper limit	205	205
Global quantities		
"Soft" threshold for positive value (mm)	0.45	1.00
Amounts		
Dispersion parameter	1.5898	1.2433
Spatial dependence structure		
Constant correlation / Parameter 1	0.7176	0.0679
Parameter 2	n/a	0.4858

Table 2-4: Comparison of Observed and Simulated (Model 2) Average Annual Rainfalls

Raingauge	2004 - 2013 Observed Average Annual Rainfall (mm)	Simulated Average Annual Rainfall (mm)	% Difference
Eden Vale STW RTS	842	843	0.03
Saints Mill	646	695	7.69
Godstone STW RTS	739	788	6.72
Pains Hill Res RTS	837	748	-10.57
Kiln Wood	644	657	2.08
Redgate Mill tbr	913	972	6.36
Jarvis Brook	765	820	7.09
Lamberhurst WWTW	759	688	-9.41
Bethersden STW tbr	684	666	-2.56
Cranbrook	740	732	-1.18
Sutton Valence	614	601	-2.06
Bewl Bridge Res tbr	760	750	-1.36
Weir Wood Res RF	830	805	-3.05
Edenbridge STW RTS	680	679	-0.09
Kent Hatch Res RTS	759	718	-5.36
Average	**747**	**744**	**-0.45**

2.5 Post processing adjustment of GLIMCLIM extreme daily rainfall amounts

2.5.1 Introduction

While GLIMCLIM provided generally good representations of wet day occurrences, rainfall amounts and average annual rainfall totals, a comparison with extreme rainfall amounts estimated using the FEH indicated that the GLIMCLIM values were generally lower than the corresponding FEH values (Figure 2-5 shows an example for Weir Wood). As closer consistency with the FEH was desirable for the purposes of flood estimation in the rainfall-runoff modelling, the GLIMCLIM outputs were adjusted. This was undertaken as a post-processing exercise (as testing suggested that changing GLIMCLIM model parameters to improve extreme rainfall simulation adversely affected other aspects of the simulation, such as annual rainfall amounts). In order to minimise possible effects on average annual rainfall totals, only GLIMCLIM rainfall amounts above the GLIMCLIM value for RMED were adjusted[16]. The following procedure was used for the post processing exercise for each raingauge location:

16. The FEH growth factors were extracted for representative points along the growth curve (corresponding to return period increments of: 2 to 10 years, 10 to 25 years, 25 to 50 years, 50 to 100 years, 100 to 500 years and 500 to 1000 years, respectively).
17. For that gauge, the existing GLIMCLIM rainfall amounts associated with those return periods (2, 10, 25, 50, 100, 500 and 1000 years, corresponding to AEP values of 50%, 10%, 4%, 1%, 0.2% and 0.1%) were identified and used as thresholds.
18. The entire GLIMCLIM 5000 year daily rainfall sequence for that raingauge was then analysed. Where a daily rainfall amount exceeded a threshold, then that amount was scaled upwards using a value calculated using the corresponding FEH growth curve factor (where linear interpolation was used between FEH growth curve increments to obtain an appropriate value).

[16] An alternative approach using the exact FEH growth curve was also tested. However, this resulted in large increases to average annual rainfall amounts and was therefore rejected.

19. This process was repeated for all of the raingauges and the reprocessed daily data then disaggregated to an hourly timestep (section 2.6).

An example of the adjusted daily data for the Weir Wood raingauge location is shown in Figure 2-5. It can be seen that, the adjusted GLIMCLIM values are much closer to the FEH values, both in terms of growth curve steepness and rainfall magnitude, than the unadjusted GLIMCLIM values.

Figure 2-5: Comparison of FEH daily rainfall amounts with initial and adjusted GLIMCLIM rainfalls for Weir Wood rainaguge.

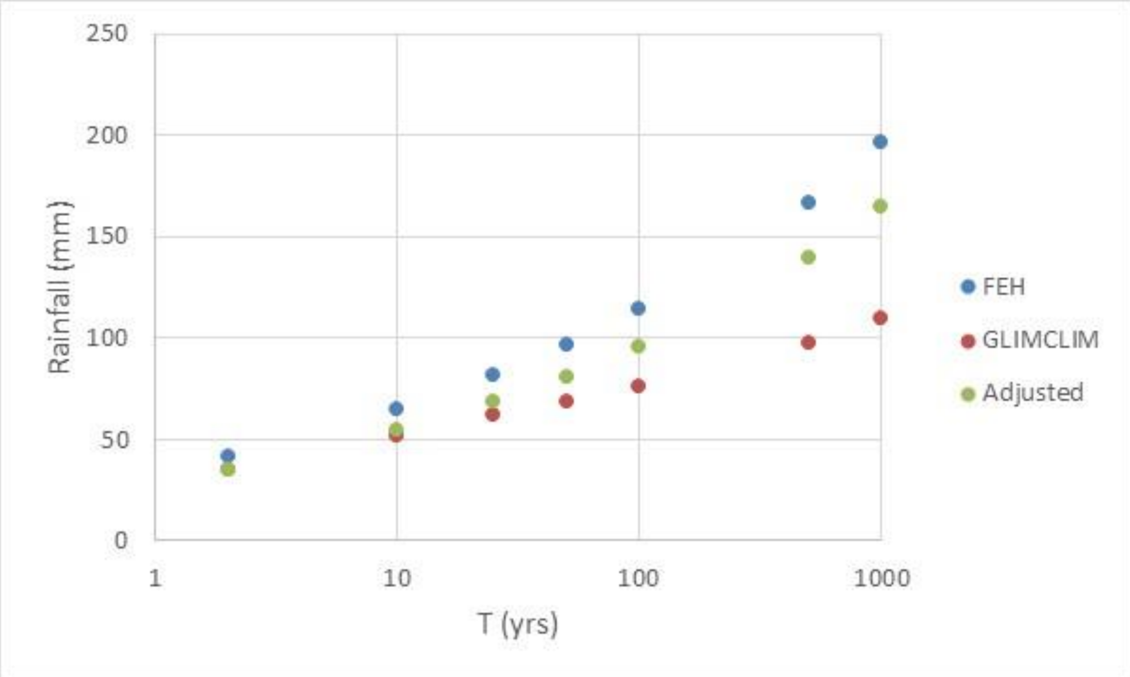


Table 2-5: FEH growth factors used for GLIMCLIM adjustment

Raingauge location	FEH growth curve value for return period increment (years)					
	2 to 10	10 to 25	25 to 50	50 to 100	100 to 500	500 to 1000
Eden Vale STW RTS	1.56	1.25	1.18	1.18	1.46	1.18
Saints Mill	1.56	1.25	1.18	1.18	1.46	1.18
Godstone STW RTS	1.54	1.24	1.17	1.17	1.45	1.17
Pains Hill Res RTS	1.56	1.25	1.18	1.18	1.46	1.18
Kiln Wood	1.57	1.26	1.18	1.18	1.47	1.18
Redgate Mill tbr	1.55	1.25	1.18	1.18	1.46	1.18
Jarvis Brook	1.55	1.25	1.18	1.18	1.46	1.18
Lamberhurst WWTW	1.56	1.25	1.18	1.18	1.46	1.18
Bethersden STW tbr	1.57	1.25	1.18	1.18	1.47	1.18
Cranbrook	1.56	1.25	1.18	1.18	1.47	1.18
Sutton Valence	1.55	1.25	1.18	1.18	1.46	1.18

Raingauge location	FEH growth curve value for return period increment (years)					
Bewl Bridge Res tbr	1.55	1.25	1.18	1.18	1.46	1.18
Weir Wood Res RF	1.56	1.25	1.18	1.18	1.46	1.18
Edenbridge STW RTS	1.56	1.25	1.18	1.18	1.47	1.18
Kent Hatch Res RTS	1.57	1.26	1.18	1.18	1.47	1.18

2.6 Disaggregation of simulated daily rainfall amounts

2.6.1 Introduction

Hourly rainfall amounts were required to drive the rainfall runoff models. Temporal disaggregation of the daily rainfall amounts simulated using RGLIMCLIM was therefore needed. The recommended approach[17] is to use the HYETOS package which utilises a Bartlett-Lewis model parameterisation to disaggregate the daily rainfall. Unfortunately, tests using the current HYETOS package (implemented in R[18]) indicated that disaggregation using this approach would be impractical due to the time constraints of the software when handling large datasets. This may be because studies to date[19] using HYETOS have generally focussed upon 30 year runs for climate change studies and not the 5000 year, multiple site approach considered here. An alternative method, which also used the Bartlett-Lewis model was therefore adopted for this study.

This approach entailed:

- Fitting the Bartlett Lewis model to point rainfall data.
- Generating 5000 years of hourly rainfall data at that location.
- Analysing the 5000 years of hourly data to create a database of daily storm profiles.
- Disaggregating the post processed RGLIMCLIM outputs (section 2.5) using the daily storm profiles (adjusted to the post processed RGLIMCLIM daily rainfall amounts, section 2.6.7).

The method adopted here is actually very similar to HYETOS. This is because HYETOS also uses a Bartlett-Lewis approach to disaggregate the daily data to an hourly level. HYETOS therefore requires Bartlett-Lewis parameters such as those obtained from fitting to hourly rainfall data from a point source. The main difference between HYETOS and the adopted approach is that, for a given wet day, the Bartlett Lewis process is run within HYETOS, and the resulting hourly rainfall values adjusted to the daily total from GLIMCLIM. In the approach adopted here, the storm profiles are pre-processed by generation from the Bartlett Lewis model first and then applied to the daily rainfall totals. In both approaches, the same rainstorm profile is applied at all gauges. Perhaps the most important assumption in the adopted approach is that the profile database developed here contains as many representative storm profiles as would have been generated using the Bartlett Lewis process within HYETOS.

2.6.2 Bartlett Lewis Model Description

The Bartlett-Lewis Rectangular Pulse Model is an example of a “pulse-based” rainfall model. It generates storms composed of a cluster of rain cells. Each cell has a random duration and a random constant intensity. Several cells can be active at once. The total storm intensity at a certain time is found by adding the intensities of all active cells.

Various versions of the Bartlett-Lewis model have been developed, partly to improve its representation of extreme rainfalls. Four successive versions are described by Onof and Wheater

[17] DEFRA/EA (2006) Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme: Improved methods for national spatial-temporal rainfall and evaporation modelling for BSM R&D Technical Report F2105/TR

[18] http://www.itia.ntua.gr/en/softinfo/3/

[19] Segond, M.L., Onof, C and Wheater, H.S (2006) Spatial–temporal disaggregation of daily rainfall from a generalized linear model, Journal of Hydrology 331, 674–689.

(1993[20], 1994[21]), Cameron et al (2001)[22] and Faulkner and Wass (2005). The versions have 6, 7, 8 and 9 parameters respectively. These correspond to different approaches to raincell intensity simulation. Onof and Wheater (1993) initially used an exponential distribution, which was later replaced with a gamma distribution for improved intensity simulation (Onof and Wheater, 1994). In order to improve the simulation of short duration extreme rainfalls, Cameron et al (2001) added a Generalised Pareto Distribution (GPD) to the exponential model of Onof and Wheater (1993). Faulkner and Wass (2005) used a similar approach but with the gamma distribution (Onof and Wheater, 1994) representing low intensity raincells and the GPD representing high intensity raincells.

In this study, for consistency with the alternatives available in HYETOS, the gamma distribution version (Onof and Wheater, 1994) of the model was used. This model selects a cell intensity from a gamma distribution with shape parameter ρ and scale parameter $1/\delta$. This version of the rainfall model has seven parameters. The model is programmed in FORTRAN.

2.6.3 Model calibration

In calibrating the model the objective is to reproduce the features of rainfall in the study catchment that are important for producing high flows. The main aims in calibration were to reproduce extreme rainfall depths for a wide range of durations and provide an overall hourly rainfall dataset which could be used to guide the disaggregation of the daily GLIMCLIM outputs to an hourly level.

Separate parameter sets were derived for summer and winter seasons (defined as April to September and October to March).

Average rainfall depths and statistics such as lengths of dry spells can be obtained from relatively short periods of observed rainfall data. However, extreme rainfall depths for very small AEPs cannot be reliably estimated from single rainfall records. Instead, they are obtained using the statistics given in the Flood Estimation Handbook[23] (FEH), which are derived by fitting growth curves to local and regional rainfall data. The strategy for calibrating the model involved an initial calibration to observed rainfall data (section 2.6.4), then adjustment of the parameters to reproduce some of the FEH rainfall statistics for the study catchment (section 2.6.5).

2.6.4 Calibration to local rainfall data

For initial calibration of the stochastic rainfall model it is necessary to have hourly rainfall data with no gaps in the record for as long a period as possible. The Weir Wood Reservoir TBR was selected for use in initial model calibration.

The stochastic model was fitted by choosing a set of characteristic variables describing the rainfall data and solving equations that define these variables in terms of the model parameters. The equations, which have been determined analytically from the structure of the model, are given in the papers listed above.

The variables, chosen to emphasise the properties of rainfall totals and dry spells over a wide range of durations, are given in Table 2-6, along with their values calculated at the chosen raingauge.

[20] Onof, C.J. and Wheater, H.S. (1993) Modelling of British rainfall using a random parameter Bartlett-Lewis Rectangular Pulse Model. *J. Hydrol.* **149**, 67-95.

[21] Onof, C.J. and Wheater, H.S. (1994) Improvements to the modelling of British rainfall using a modified random parameter Bartlett-Lewis Rectangular Pulse Model. *J. Hydrol.* **157**, 177-195.

[22] Cameron, D., Beven, K. and Tawn, J. (2001) Modelling extreme rainfalls using a modified random pulse Bartlett-Lewis stochastic rainfall model (with uncertainty). *Adv. Water Resour*. **24**, 203-211.

[23] Faulkner, D.S. (1999) Rainfall Frequency Estimation. Volume 2, Flood Estimation Handbook. Institute of Hydrology, Wallingford.

Table 2-6: Variables characterising rainfall at Weir Wood Reservoir

Description	Winter value	Summer value	Weight used in fitting model
Mean of 1-hour rainfall depths (mm)	0.1056	0.0701	5
Variance of 1-hour rainfall depths (mm^2)	0.2170	0.2177	5
Lag-1 covariance of 1-hour rainfall depths (mm^2)	0.1362	0.0902	5
Proportion of 1-hour spells that are dry	0.8929	0.9123	4
Variance of 24-hour rainfall depths (mm^2)	28.2930	17.0196	2
Proportion of 24-hour spells that are dry	0.4701	0.5890	2
Variance of 72-hour rainfall depths (mm^2)	126.4570	69.1497	1
Proportion of 72-hour spells that are dry	0.2426	0.3507	1

It can be seen from the above results that, as expected, the summer season has less rainfall and more dry spells for both 1-day and 3-day rain.

To find the model parameters, the equations have to be solved simultaneously. They are highly non-linear, and a unique solution may not exist. They were solved using an approach suggested by Wheater et al. (2000)[24] of minimising the sum of weighted squared differences between observed variables and model variables (given by the equations mentioned above).

Each term in the summation was normalised, converting the differences into proportional differences, to avoid bias due to the different orders of magnitude of the various statistics. The minimisation was carried out by the Simplex method. This gave two initial sets of parameters (two seasons at one location) for the modified Bartlett-Lewis model.

2.6.5 Calibration to FEH rainfall statistics

The Flood Estimation Handbook (FEH) provides extreme rainfall statistics in the form of a model relating rainfall depths, durations and frequencies (a DDF model). There are few examples in the literature of stochastic rainfall models that have been fitted to DDF models rather than solely to observed rainfall records. Onof et al. (1996)[25] fitted a Bartlett-Lewis model to Flood Studies Report rainfall statistics, although this was used to produce discrete events rather than a continuous sequence of rainfall.

The DDF model described in the FEH can be represented as a set of log-Gumbel distributions for different rainfall durations because the log of the rainfall depth is proportional to the Gumbel reduced variate. The DDF model has three segments, divided at 6 and 48 hours. The formula for the equivalent log Gumbel distribution for a given duration depends on which segment the duration occupies. The log-Gumbel distribution is equivalent to an Extreme Value Type 2 (EV2) distribution constrained so that $u = -a/k$ where u, a and k are the location, scale and shape parameters respectively of the EV2 distribution. The relationship between the two distributions is described in the Flood Studies Report (FSR)[26], Volume 1, Section 1.2.5. If U and A are the Gumbel location and scale parameters in the log-Gumbel distribution then:

$U = -\ln(-k/a)$ and $A = -k$.

The moments of the EV2 distribution are also given in the FSR. These enable the calculation of the mean, variance and skewness of the FEH rainfall statistics for any location. This is a useful way of summarising the FEH statistics.

The mean, variance and skewness of the FEH rainfall statistics for the gauge locations is given in Table 2-8. Summary statistics are provided for a range of rainfall durations from 6 hours (relevant in catchments that show some flashy response due to areas of low permeability) up to 6 days (relevant for periods of prolonged rainfall).

[24] Wheater, H.S., Isham, V., Cox, D.R., Chandler, R.E., Kakou, A., Northrop, P.J., Oh, L., Onof, C. and Rodrigeuz-Iturbe, I. (2000) Spatial-temporal rainfall fields: modelling and statistical aspects. *Hydrol. and Earth System Sci.* **4**, 581-601.

[25] Onof, C., Faulkner, D. and Wheater, H.S. (1996) Design rainfall modelling in the Thames catchment. *Hydrol. Sci. J.* **41**, 715-733.

[26] Natural Environment Research Council (1975) Flood Studies Report. NERC, London.

Table 2-7: Moments of FEH rainfall statistics for Weir Wood Reservoir TBR

Rainfall duration (hours)	Mean annual maximum (mm)	Variance of annual maxima (mm^2)	Skewness of annual maxima
6	30.5	213	7.43
24	47.4	346	4.85
72	68.2	514	3.79
144	81.7	592	3.33

The FEH rainfall statistics do not allow for any seasonal variation. However, more recent work[27] can be used to show that, given an annual average rainfall similar to that over the study area:

- For a rainfall duration of 6 hours, the summer maximum rainfall is 98% of the annual maximum.
- For a rainfall duration of 24 hours, the summer maximum rainfall is 96% of the annual maximum.
- For longer durations, seasonal correction factors were not investigated, but it can be expected that the winter maximum rainfall will start to approach the annual maximum as the duration increases to several days, given that frontal rainfall tends to be responsible for most extreme totals over prolonged periods.

The next step in calibration of the stochastic rainfall model was therefore to adjust the summer season parameters so that the modelled extreme rainfalls gave a reasonable match to the above sets of FEH statistics, for durations of 6 and 24 hours, and the winter season parameters to give a match for durations of 72 and 144 hours.

Unfortunately, there are no analytical expressions for the moments of extreme rainfall simulated by the Bartlett-Lewis model. It is therefore not possible to fit the model directly to FEH statistics as can be done for the statistics of observed rainfall. Instead, a trial-and-error approach was adopted. This employs a mixture of judgement and knowledge of the model's structure.

Parameters that control the temporal characteristics of the rainfall, i.e. the rate of storm arrival, the duration of storms and the duration of cells, were left unchanged during this stage. Two parameters that were varied during the trial-and-error procedure: the scale (δ) and shape (ρ) parameters of the gamma distribution of initial cell depth. Multiple runs of 1000 year duration with hourly timestep were conducted for both the winter and summer seasons. The parameters that were judged to give the best results, in terms of matching both extreme rainfalls and annual average totals, are given in Table 2-8.

Table 2-8: Parameter values for the Weir Wood Reservoir rainfall model

Parameter	Symbol	Winter value	Summer value
Rate of storm arrival (hr^{-1})	λ	0.0041	0.0049
Rate of cell arrival divided by cell duration	κ	0.0471	0.0167
Mean storm duration divided by cell duration	ϕ	0.0032	0.0027
Shape parameter of gamma distribution for cell duration	α	3.3451	2.8292
Inverse of scale parameter of above gamma distribution	υ	2.0234	1.0127
Shape parameter of the gamma distribution of initial cell depth	ρ	3.8	5.9
Inverse of scale parameter of above gamma distribution	δ	0.98	0.98

[27] Kjeldsen, T.R., Prudhomme, C., Svensson, C., Stewart, E.J. (2006). A shortcut to seasonal design rainfall estimates in the UK. *Water and Environment J.* **20** (4), 282-286.

In general, the preferred seasonal parameter sets given above managed to match the moments of FEH extreme rainfalls to within about 7% to 13% for the mean, 2% to 25% for the variance and over 40% for the skewness, depending upon the duration and season considered.

A five thousand year hourly rainfall series was then generated for the winter season and summer season.

2.6.6 Profile database

The five thousand year summer series and winter series were analysed and, for each of the days in each series, a daily profile (with hourly timestep) extracted. These daily profiles included periods of zero rainfall. The profiles were used to assist in the temporal disaggregation of the RGLIMCLIM daily rainfall data.

2.6.7 Disaggregation

The winter and summer profile datasets described above were used to disaggregate the post processed daily rainfall output from RGLIMCLIM to an hourly timestep. For a given day, this was achieved as follows:

- The RGLIMCLIM rainfall amount for the Weir Wood Reservoir gauge was identified and the season (winter or summer) noted.
- The seasonal profile database was searched until the profile with the nearest daily rainfall total (to that generated in RGLIMCLIM) was found. This process therefore assumed that a profile associated with a daily rainfall total similar to that of the RGLIMCLIM value provided an adequate representation of sub-daily rainfall.
- That profile was adopted for disaggregation at all gauges.
- Disaggregation at a given gauge included adjustment of the disaggregated rainfall amounts such that, when the hourly totals were summed, the daily total was the same as the RGLIMCLIM rainfall amount at that gauge. This was done in order to preserve the RGLIMCLIM rainfall totals.
- Per established guidance[28], on days where no rainfall was simulated at Weir Wood by RGLIMCLIM, but rainfall was simulated elsewhere, the previous day's profile was used.

This procedure allowed the generation of 5000 years hourly rainfall data at all 15 TBRs for input to the PDMs.

2.6.8 Extreme Value Simulation Following Disaggregation

Figure 2-6 to Figure 2-9 provide examples of AMAX rainfall amounts of 6 h, 24 h, 72 h and 144 h duration for the Jarvis Brook TBR obtained from the disaggregated rainfall amounts for the post-processed GLIMCLIM model 2. The corresponding values from the FEH CD-ROM for the point location are also shown. From these plots, it can be seen that reasonable simulation of the FEH rainfall statistics is obtained.

[28] DEFRA/EA (2006) Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme: Improved methods for national spatial-temporal rainfall and evaporation modelling for BSM R&D Technical Report F2105/TR

Figure 2-6: Example of 6 h AMAX for the Jarvis Brook TBR showing disaggregated output from post-processed GLIMCLIM Model 2 and FEH values.

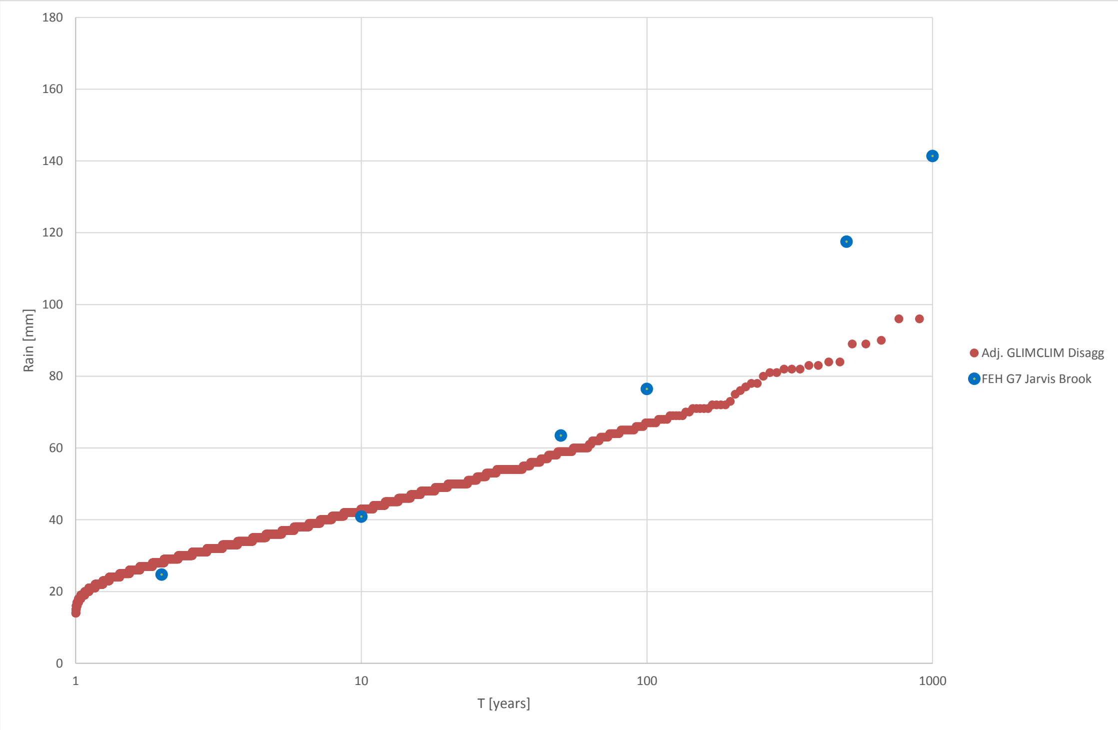


Figure 2-7: Example of 24 h AMAX for the Jarvis Brook TBR showing disaggregated output from post-processed GLIMCLIM Model 2 and FEH values.

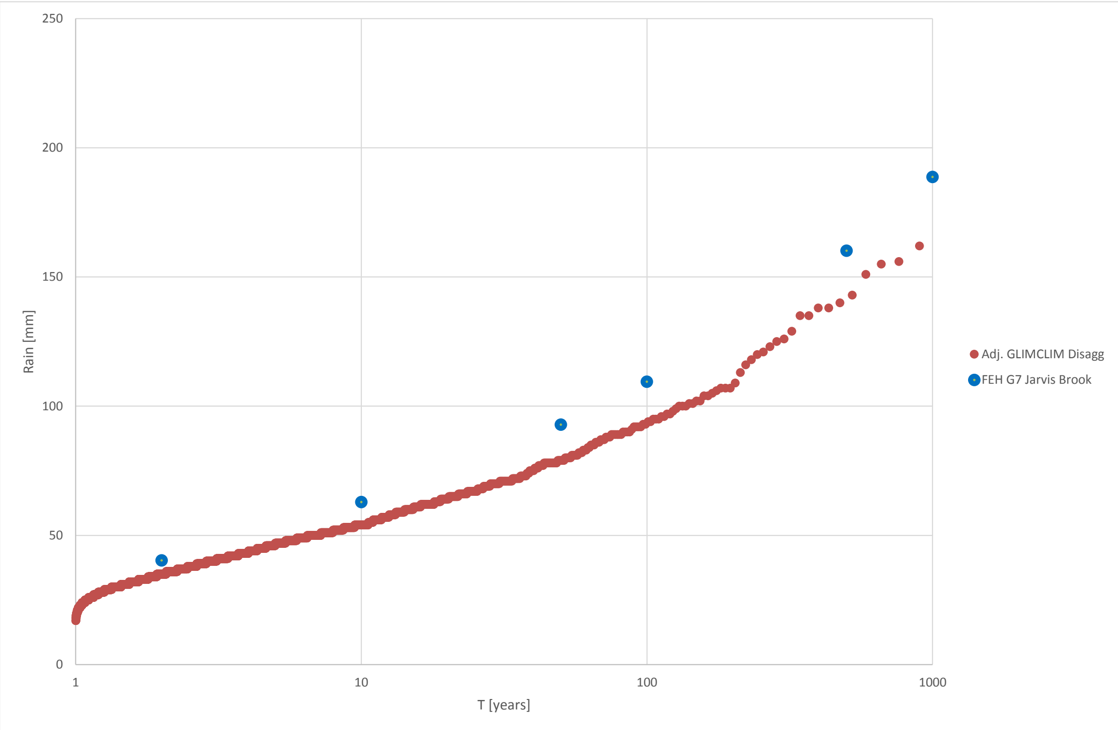


Figure 2-8: Example of 72 h AMAX for the Jarvis Brook TBR showing disaggregated output from post-processed

GLIMCLIM Model 2 and FEH values.

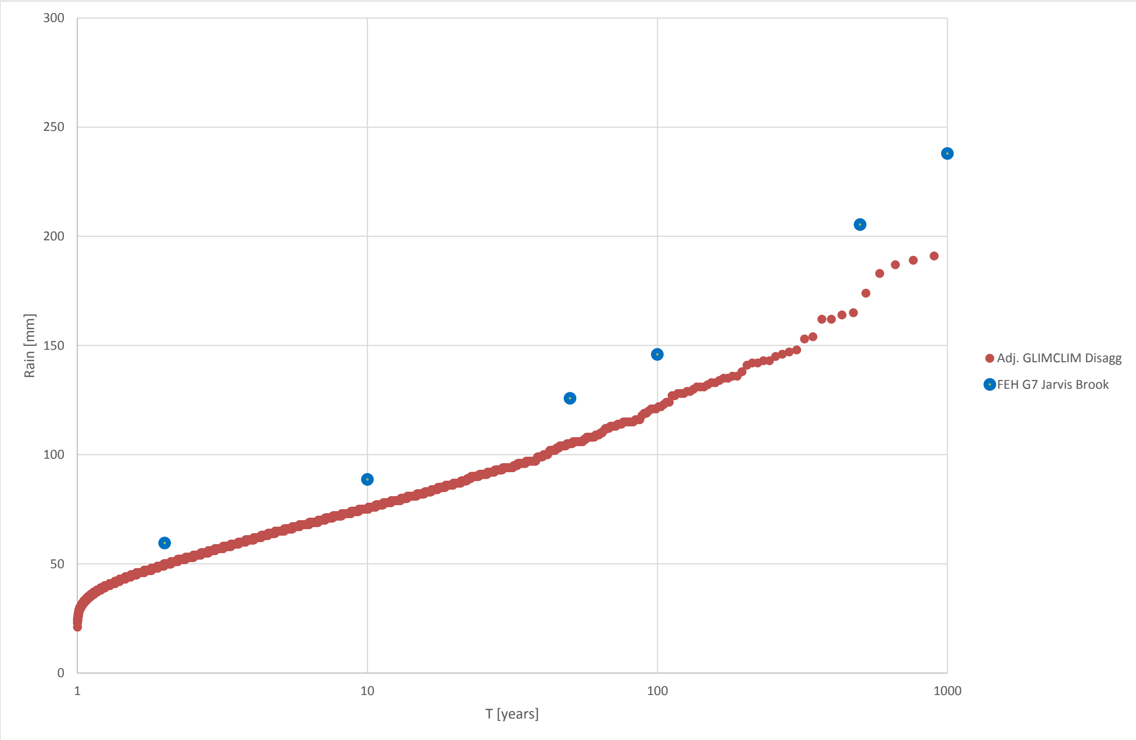
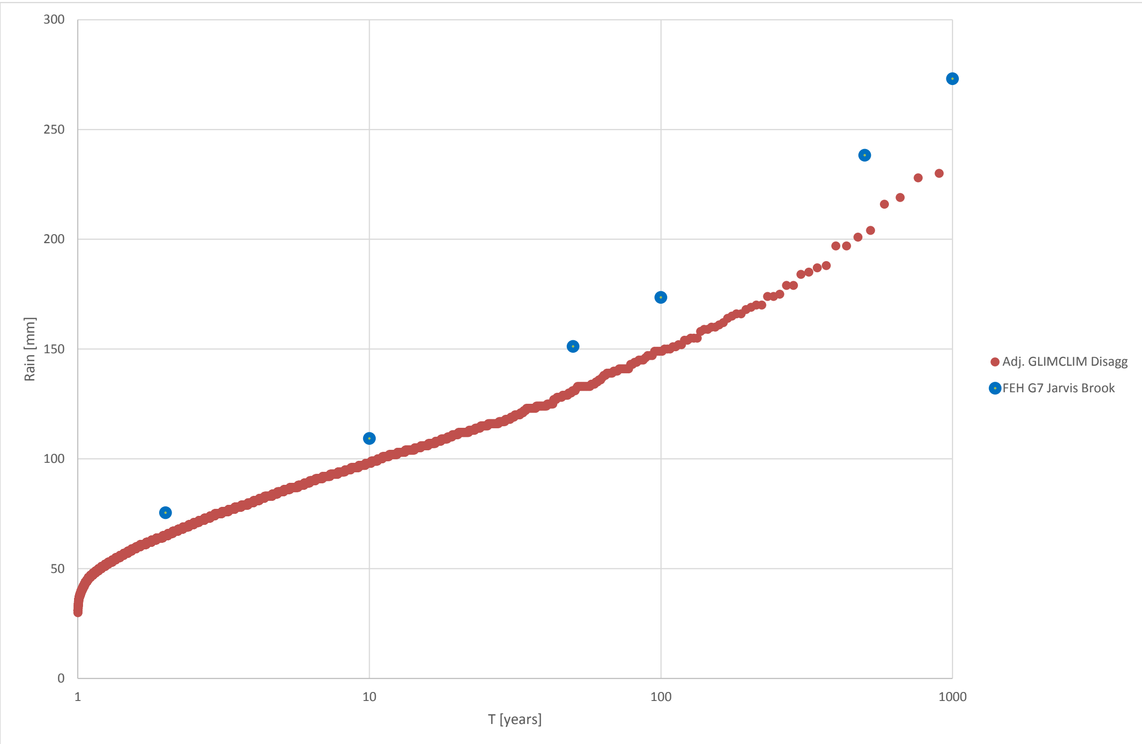


Figure 2-9: Example of 144 h AMAX for the Jarvis Brook TBR showing disaggregated output post-processed GLIMCLIM Model 2 and FEH values.



2.7 Catchment averaging

Out of this process, we derived five thousand years of hourly rainfall time series for the rain gauges listed in Table 2-9. A weighted average was then calculated for each sub catchment of the Medway (each represented by a PDM rainfall runoff model). The weights applied are given in Table 2-9, where each row is a rain gauge and each column a catchment for which an average is needed. Where these do not equal one, the total weighted rainfall was divided by the total weight to eliminate bias. The catchment-averaged series' could then be applied to the rainfall runoff models.

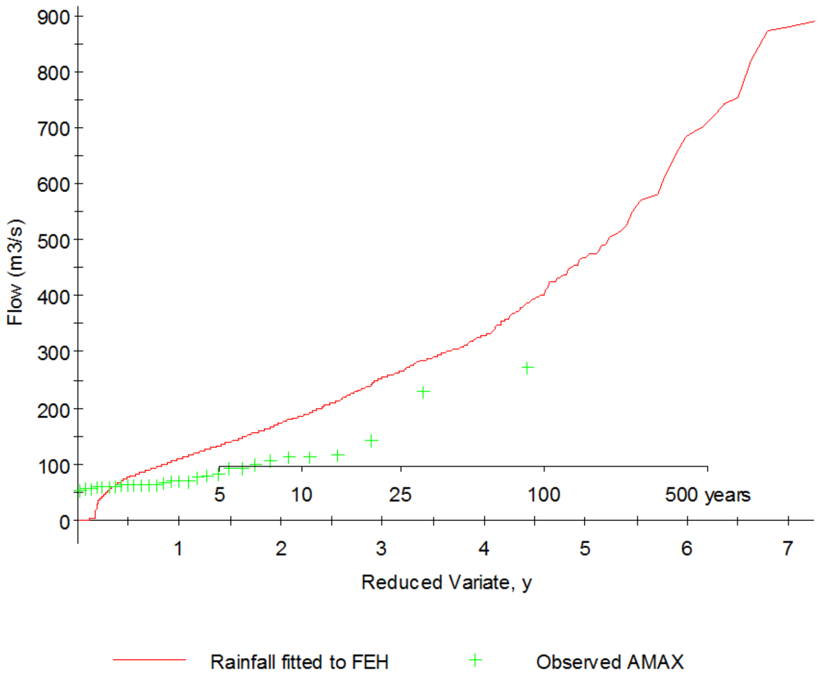
Table 2-9: Weighting scheme used to give catchment average totals for rainfall runoff models

		Hadlow	AS01	HI01	MI01	be_sub_3	be_sub_2	smarden	Stonebridge	Lingfield_01	EdenLat01	Kent_Brook01	HaxsteadMill_01	LingfieldWWT_01	ForestRow	MEDWAYL1	MEDWAYL2	Hendal
G1	**EDEN VALE STW RTS**										0.175		0.065	0.07	0.5		0.2	
G2	**Saints Hill**			0.2	0.2	0.2					0.175			0.13				0.1
G3	**GODSTONE STW RTS**												0.607					
G4	**PAINS HILL RES RTS**										0.162	0.1	0.234					
G5	**Kiln Wood**	1	0.6	0.2	0.2	0.2												
G6	**REDGATE MILL tbr**								0.2							0.2	0.2	0.1
G7	**Jarvis Brook**															0.7		0.8
G8	**Lamberhurst WWTW**		0.4	0.2	0.2	0.2			0.4									
G9	**BETHERSDEN STW tbr**						0.25	0.6										
G10	**Cranbrook**						0.375	0.4										
G11	**Sutton Valence**			0.2	0.2	0.2	0.5											
G12	**BEWL BRIDGE RES tbr**								0.4									
G13	**Weir Wood Res RF**									0.1					0.5	0.1	0.2	
G14	**EDENBRIDGE STW RTS**									0.9		0.1						
G15	**KENT HATCH RES tbr**										0.162	0.2	0.093					
	Total weight	1	1	0.8	0.8	0.8	1.125	1	1	1	0.674	0.4	0.999	0.2	1	1	0.6	1

2.8 Final results

Rainfall totals from the synthetic data tend to be lower than those from the FEH for the same frequency and duration. Our daily GLIMCLIM rainfall was adjusted to fit the FEH growth rates (i.e. the ratio between the RMED depth and that at the target return period), but not the absolute rainfall total. Forcing a fit to FEH rainfall totals gave flows (when the rainfall was applied to the catchment model) that were much higher than observed AMAX at all locations. This is illustrated in Figure 2-10 (below) for the combined flow from Colliers and Vexour, where using the 'FEH fitted' rainfall series gives AMAX flows that exceed all the observations at all return periods. Final frequency curves using the preferred rainfall series are given in Section 4.4.

Figure 2-10: Flood frequency curve from CS for sum of Colliers and Vexour with rainfall fitted to FEH compared to observed AMAX

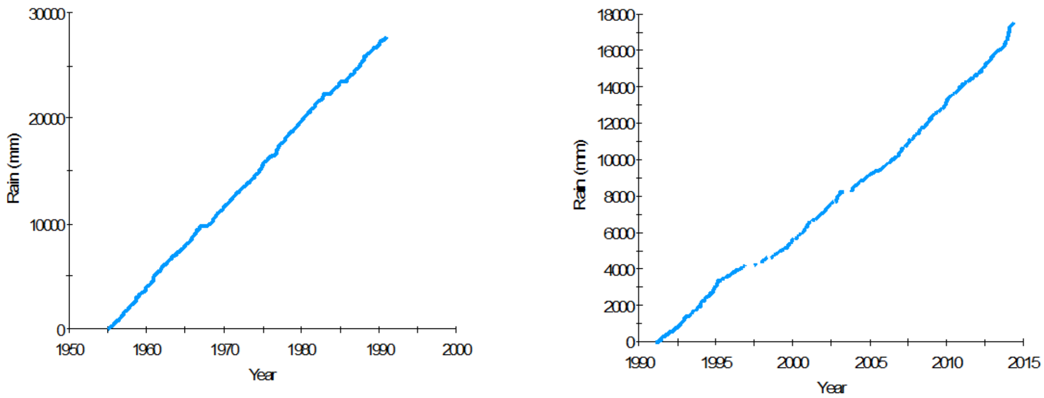


2.8.1 Comparison with FEH and observed rainfall

To give an illustration of how the synthetic rainfall series performs, its depth, duration and frequency is compared with FEH statistics and observed records below. The comparison is made at Weirwood reservoir, which offers the most complete observed series and was the basis for calibrating the Bartlett Lewis rainfall model.

Although many tipping bucket rainfall series have proved problematic, that for Weirwood is better than most. It begins in 1991 and the accumulation plot in Figure 2-11 shows the rainfall to be reasonable progression, with some gaps in the mid 1990s and early 2000s. Weirwood also has a daily record that goes back to 1955. Together with the TBR, that provides almost 60 years of continuous daily data for a single point. Aggregate totals have been extracted from the TBR and daily rainfall record for plotting in the figures below.

Figure 2-11: Rainfall accumulation plots for Weir wood for daily gauge (left, 1955-1991) and TBR (right, 1991-2014)



Each of the following rainfall frequency curve plots (Figure 2-12, below) show:

- Observed rainfall depths from Weirwood TBR for the named duration (from 1991-2014)
- Rainfall depths from the 5,000-year synthetic series at Weirwood for the same duration; and
- Rainfall depths predicted by the FEH DDF rainfall model.

In the 24hr accumulation plot, a combined daily and TBR rainfall record is plotted which covers the period 1955-2014.

CS rainfall depths are mostly less than predicted by FEH - roughly 10% less, although the discrepancy is:

- Smaller at 8 and 12 hour durations where AEP is less than 1% (100-year RP);
- Smaller at the longest duration at all AEPs; and
- Bigger at 8 and 12 hour durations where AEP is greater than 1% (100-year RP);

However, the agreement is generally close.

Observed rainfall are from a relatively short series (22 years for the TBR and 59 years for the combined daily record), but provide valuable information about the trend of the frequency curve and its correctness at lower AEPs. At all accumulations, the observed data suggest smaller rainfall depths than either the FEH or the CS modelling. This perhaps explains why a further reduction in rainfall of 5% was needed to get a good match between the simulated flood frequency curve observed AMAX.

The 1968 flood on the Eden is the most extreme in the hydrometric record. Daily rainfall totals are available from various gauges in the catchment, three of which are listed in Table 2-10: September 1968 daily rainfall totals, their FEH return period and their rank in the synthetic series. We looked at the 24 and 48 hour rainfall totals for the event, calculated their return period using the FEH DDF model and found their rank (and therefore return period) in the 5,000-year synthetic series.

As might be expected from the differences in rainfall depth seen the the previous figures, the FEH attributes the events a less extreme return period than does the CS series. The rarest aspect of the rainfall was its two day depth at Godstone STW (168.4mm). This has an AEP of 0.42% (return period of 237-years) in the FEH and is ranked 5 in the 5,000-year CS series.

Figure 2-12: FEH and CS Rainfall frequency curves at Weirwood Reservoir

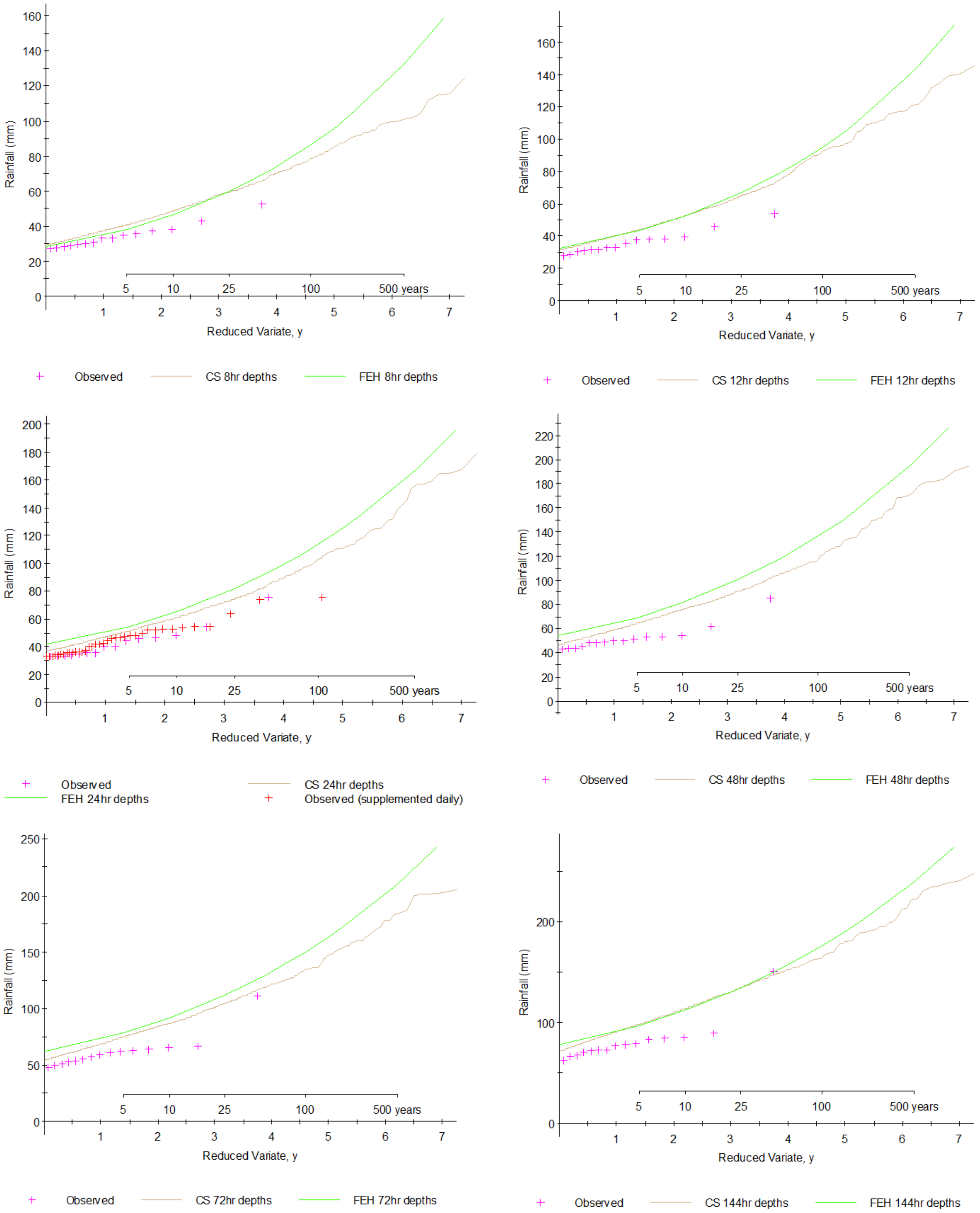


Table 2-10: September 1968 daily rainfall totals, their FEH return period and their rank in the synthetic series

	Rainfall (mm) or Rank		
Date	Godstone STW check	Godstone PS	Limpsfield STW
	Daily Rain	Daily Rain	Daily Rain
17 September 1968	44.7	44.5	101.6
18 September 1968	123.7	105.2	61
48hr accumulation	168.4 (0.42% AEP or 237-years)	149.7 (0.73% AEP or 137-years)	162.6 (0.5% AEP or 202-years)
Rank in 5,000yr CS	5 (0.1% AEP or 1,000-years)	20 (0.4% AEP or 250-years)	13 (7.69% AEP or 384-years)
24hr accumulation	123.7 (1.19% AEP or 84-years)	105.2 (2.5% AEP or 40-years)	101.6 (2.86% AEP or 35-years)
Rank in 5,000yr CS	14 (0.28% AEP or 357-years)	30 (0.6% AEP or 166-years)	36 (0.72% AEP or 139-years)

At this point we considered the synthetic rainfall to be sufficiently robust to apply to the catchment model in continuous simulation.

3 Catchment modelling

3.1 General

Step 2 in the overall CS process is to build a hydrological model of the study catchment. This should simulate the rainfall runoff process and any hydraulically significant features in the river. The Leigh FSA is the most important of these to be incorporated into the catchment model. The model must describe the system accurately and be proven using observed data.

Our starting point for the catchment model was the Medway forecasting network in NFFS. It consists of 17 PDM rainfall runoff models coupled to three ISIS river models. In a large flood event (like December 2013), alternative operation of the Leigh FSA is simulated outside of NFFS using a spreadsheet tool and the results fed back to NFFS. The main problems with using the forecasting tool as a system model for continuous simulation are its:

- Boundaries. The forecasting model extends from Vexour on the Eden, Colliers Land Bridge on the Medway and Stilebridge on the Beult. Our network needed to extend much further up these rivers to map flood risk and enable flood defence options to be assessed.
- Accuracy. Previous testing of the forecasting model (JBA, 2011) showed that large errors are possible at some locations.
- Observed inflows. New rating curves for the four key gauges have been introduced, changing observed flows and therefore model calibration.
- Stability. The Middle Medway 1D ISIS model proved unstable in continuous simulation and required significant work to prevent failures and non convergence.
- Operation of the Leigh FSA gates, which are optimised during an event when outflows are likely to exceed 75m^3/s. Monitoring and Forecasting Duty Officers (MFDOs) change the forecast outflow based on what the Leigh Operators say they are releasing. Only default operation of the gates is represented in the forecasting version of the ISIS model.

The adaption of this model for continuous simulation is discussed in the following sections of the report.

3.2 Catchment model overview

Several requirements were considered when adapting the catchment model. It needed to be able to:

- Simulate runoff and catchment wetness continuously in order to reproduce the observed wetting and drying of soil between events;
- Route flows accurately through the river network, from the head waters to East Farleigh;
- Model water being stored and released from the Leigh FSA. In particular it needed to mimic the FSA's 'alternative' operation during a large flood event.
- Be flexible enough to test flood storage solutions on the Eden and Beult; and
- Be capable of running in continuous simulation over a long (5,000-year) period.

The fact that a forecasting model was already available meant that continuous simulation was feasible from a budget point of view - otherwise continuous simulation may have been prohibitively expensive.

Each of the three catchment model components are described individually in Appendix A in model summary reports. Those self-contained reports describe the model, its origins, boundaries, and PDM parameters and rain gauge weights used, calibration data and performance. The remainder of this section is an overview of the models and does not give full details.

3.2.1 Choice of model software

The existing forecasting model uses PDM to simulate runoff and ISIS for river modelling. Those software were carried forward for this project. Any river reaches not already in the forecasting model were simulated using ISIS routing or existing 1D models.

3.2.2 Data availability

Observed hydrometric data are needed to calibrate and verify the catchment model. Figure 1-3 shows the location of rainfall and river gauges in the catchment and Table 3-1 and Table 3-2 show the period of record available. Prior to April 2006, rainfall data in the catchment can be patchy and its quality variable. This is discussed in more detail below.

Table 3-1: River gauges in the Medway catchment

Station reference	Station name	Type	Start date	End date
453103001	Allington Ultrasonic	Flow	18-Apr-02	05-Feb-14
453103001	Allington Ultrasonic	Stage	04-Sep-03	04-Feb-14
453233001	Bartley Mill	Stage	01-Jul-81	04-Feb-14
453234001	Bewl Bridge	Stage	30-Mar-83	04-Feb-14
453300006	Branbridges	Stage	21-Jun-04	04-Feb-14
453500001L	Chafford	Stage	23-Mar-68	04-Feb-14
453400001H	Colliers Land Bridge	Flow/Stage	23-Mar-68	28-Jul-14
453203002	Cheveney Gate	Stage	01-Nov-03	04-Feb-14
453220001	Darmans Bridge	Stage	07-May-05	15-Aug-13
453300007	East Peckham Gs	Stage	10-Feb-06	05-Feb-14
453101001H	East Farleigh	Flow	10-Jan-74	04-Feb-14
453101001H	East Farleigh	Stage	10-Jan-74	05-Feb-14
453101003	East Farleigh Gate	Stage	01-Sep-99	04-Feb-14
453610001	Edenbridge	Stage	11-Mar-92	04-Feb-14
453500005	Forest Row Telemetry Rl	Stage	31-Aug-01	03-Feb-14
453300001	Hartlake Rl	Stage	27-Sep-94	04-Feb-14
453610002	Haxtead Mill	Stage	01-Jan-04	03-Feb-14
453310001	Hadlow	Flow/Stage	02-Jan-71	05-Feb-14
453520001	Hendal Bridge	Flow/Stage	03-Jul-73	03-Feb-14
453400018	Leigh FSA	Flow	24-Nov-04	05-Feb-14
453120001	Lenside	Flow/Stage	08-Jul-83	05-Feb-14
453650001	Lingfield Gs	Flow	01-Apr-97	04-Feb-14
453650002	Lingfield Wwtw Fw	Stage	03-May-00	03-Feb-14
453300005	Little Mill Rl	Stage	04-Jan-08	04-Feb-14
453400018	Leigh FSA	Stage	03-Mar-05	22-Mar-08
453400019	Leigh FSA D/S	Stage	05-Nov-04	04-Feb-14
453400004	Lucifer Bridge	Flow	10-Nov-05	31-Jul-14
453103002	Maidstone	Stage	04-Sep-03	04-Feb-14
453600001L	Penshurst	Flow	02-Apr-68	05-Feb-14
453210001	Stilebridge	Flow/Stage	21-Mar-68	28-Jul-14
453500004	Summerford Bridge Rl	Flow/Stage	11-Mar-92	03-Feb-14
453217001	Smarden	Flow/Stage	11-Mar-92	03-Feb-14
033048	Stonebridge	Flow/Stage	29-Oct-79	01-Mar-02
453400003	Town Lock	Stage	18-Aug-94	04-Feb-14
453600002H	Vexour Bridge	Flow/Stage	29-Mar-68	28-Jul-14
453202003	Yalding D/S	Stage	10-Mar-92	04-Feb-14
E1910	Yalding Us	Stage	29-Jun-99	29-Feb-12

Table 3-2: Rain gauges in the Medway catchment

Station reference	Station name	Start date	End date
463214509	Bethersden Stw Tbr	18-Oct-90	06-Jun-14
463234504	Bewl Bridge Res Tbr	08-Jan-91	31-Jul-13
664306908	Bybrook	10-Mar-92	06-Jun-14
463501506	Cowden Logger	08-Jan-91	10-Jun-14
463215906	Cranbrook	10-Mar-92	06-Feb-14
463655903	Eden Vale Stw Rts	03-Apr-93	07-Feb-14
463610906	Edenbridge Stw Rts	10-Mar-92	06-Feb-14
463641904	Godstone Stw Rts	10-Mar-92	06-Jun-14
462121501	Ham Hill Stw Tbr	15-Aug-90	17-Nov-11
463220502	Horsmonden Stw Tbr	08-Jan-91	06-Feb-14
463521918	Jarvis Brook	03-Apr-93	06-Jun-14
463622502	Kent Hatch Res Tbr	14-Apr-92	06-Nov-14
463312902	Kiln Wood	19-Jan-06	06-Feb-14
294452	Leigh Tbr	24-Aug-92	06-Feb-14
463230905	Lamberhurst Wwtw	10-Mar-92	06-Feb-14
463630901	Pains Hill Res Rts	03-Apr-93	06-Feb-14
463521512	Redgate Mill Tbr	27-Jul-90	06-Jun-14
664232501	Ruckinge Tbr	20-Aug-02	18-Nov-11
463400901	Saints Hill	06-Apr-93	06-Jun-14
463210512	Sutton Valence	10-Mar-92	06-Feb-14
565113902	Warehorne Stw Rts	10-Mar-92	18-Nov-11
292554	Weir Wood Res Rf	10-Jan-91	06-Jun-14

The rating curves used to calculate flow are either developed by this project or provided by the Environment Agency. All relevant ratings are tabulated in Appendix A or B. Ratings were developed by us at:

- Eden Brook at Lingfield, based on ultrasonic flow data obtained at the site;
- Medway at Forest Row, based on existing results from the ISIS mapping model;
- Eden at Vexour, based on 2D modelling of the gauged site;
- Medway at Colliers Land Bridge, also based on 2D modelling;
- Teise at Stonebridge, again based on 2D modelling
- Beult at Stilebridge, also based on 2D modelling.

Existing models are the other main source of data. Hydraulic models developed for previous mapping projects were supplied along with the forecasting models and the NFFS configuration for these. An existing Beult mapping model was used to simulate the reach between Smarden and Stilebridge.

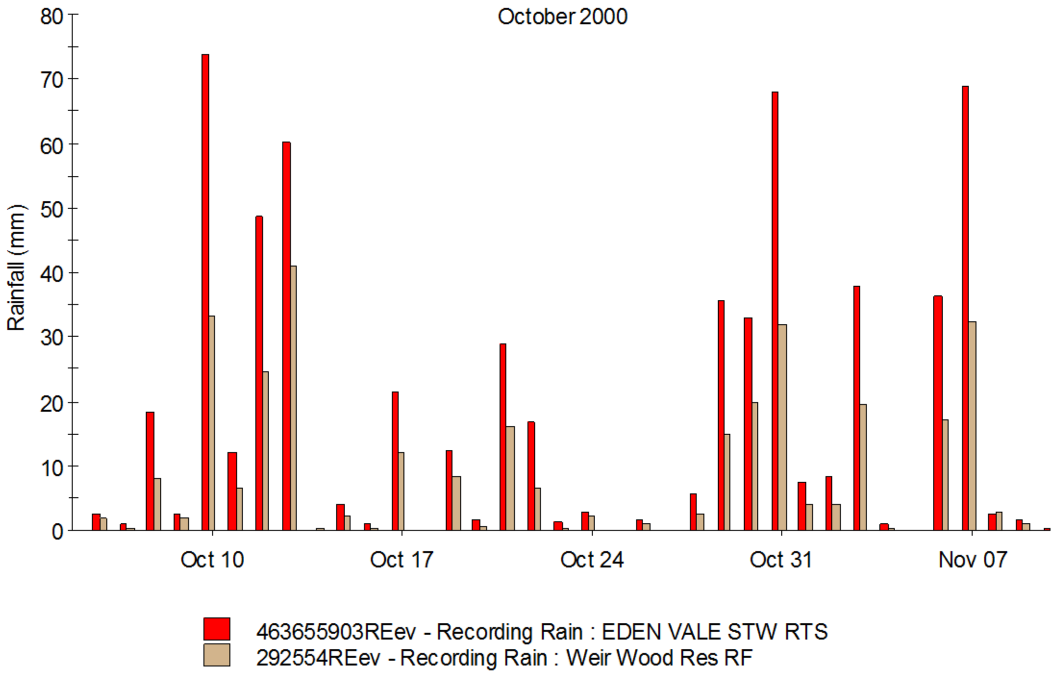
3.2.3 Data quality

We experienced particular problems with rainfall data quality during this project. In general, rainfall data after 2006 seemed reliable and gave reasonable results when used with rainfall runoff models. Data before that date is often suspect, with common problems including:

- Missing data entered as zero (affecting catchment average rainfall);
- Erroneous or suspect values; and

- Periods of strong bias in one or more rainfall records. An example of this is given below, for a period in October 2000 where the Eden Vale rain gauge consistently records around double the values at Weir Wood.

Figure 3-1: Comparison of daily rainfall totals between Eden Vale and Weir Wood TBRs



We put significant effort into cleaning the rainfall data to make it usable in model calibration and verification. Our procedures included:

- Comparing rainfall data at neighbouring gauges over 24 hour accumulations. Where a string of outliers could be identified, these were flagged to be excluded from the rainfall runoff modelling.
- Checking particularly poor rainfall runoff model performance by investigating data quality and the sensibility of the observed catchment average.

We have a database of all the dates where exclusions have been applied. This can be supplied as an electronic deliverable at the end of the project.

3.2.4 Schematisation

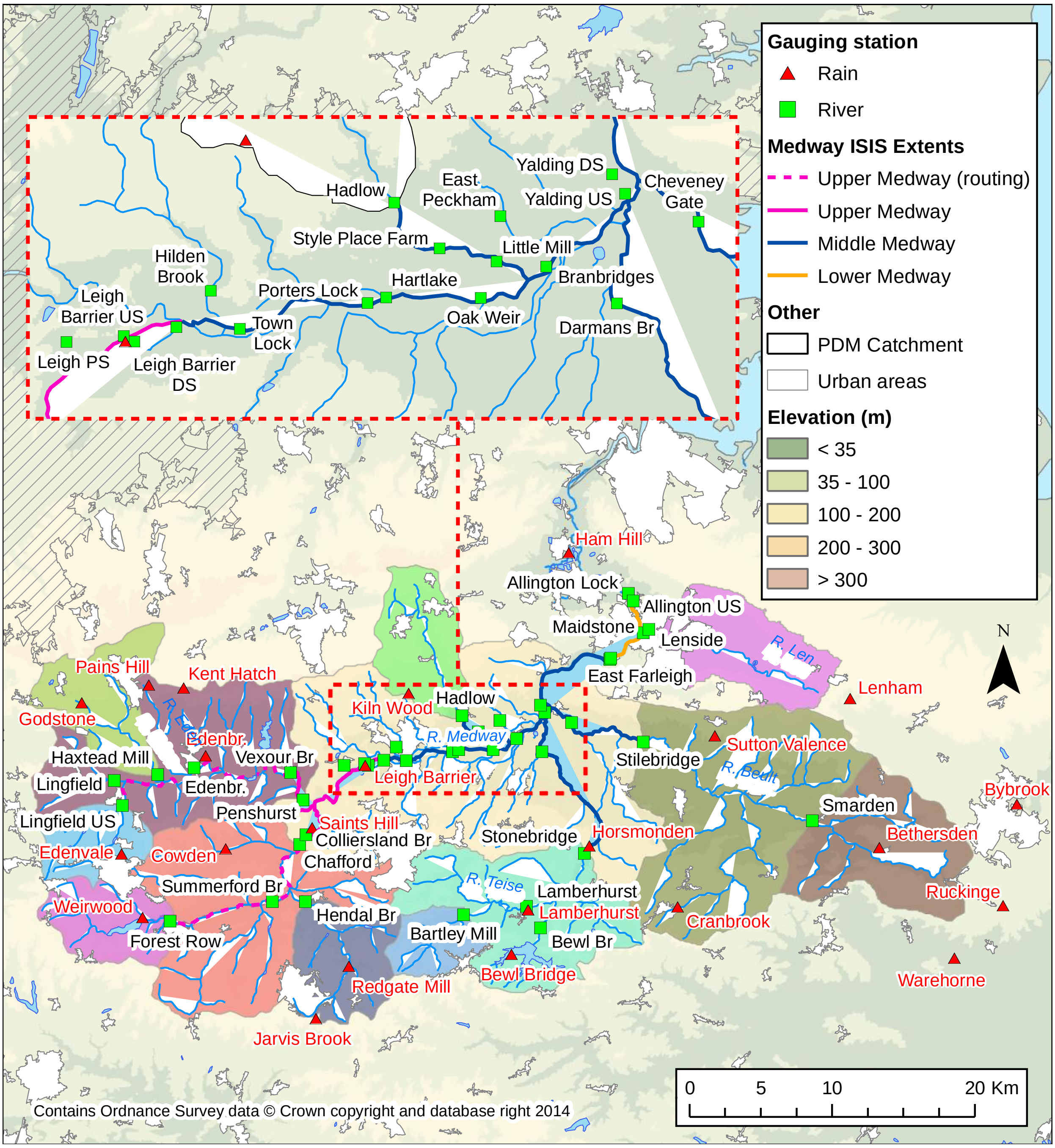
The Medway is a large catchment and can be divided into logical hydrological units. These are respected by the forecasting model which has PDM rainfall runoff models at Vexour, Colliers, Stonebridge and Stilebridge as its primary boundaries. We kept the forecasting model's structure everywhere except the Eden, Medway and Beult, where the model needed to extend upstream into the headwaters. Additions included:

- New flow routing reaches taking the 'Upper Medway' forecasting model up the Eden to Lingfield and up the Medway to Forest Row (see Figure 3-2).
- Six rainfall runoff models to provide inflows to these new reaches.
- Implementing an existing ISIS 1D model, extending the Beult upstream of Stilebridge to Smarden; and
- One new rainfall runoff model to provide lateral inflows to this reach (as well as retaining the Smarden PDM).

Model boundaries are carefully distributed and labelled so that they can be applied to the flood mapping model as well as the hydrological model.

Figure 3-2 shows how the full catchment model is schematised. PDM rainfall runoff models are represented by individual polygons and discrete ISIS models are shown with different line colours and styles. All gauging stations and rain gauges are also shown for information.

Figure 3-2: Medway catchment model schematic



3.3 Model extension

3.3.1 General

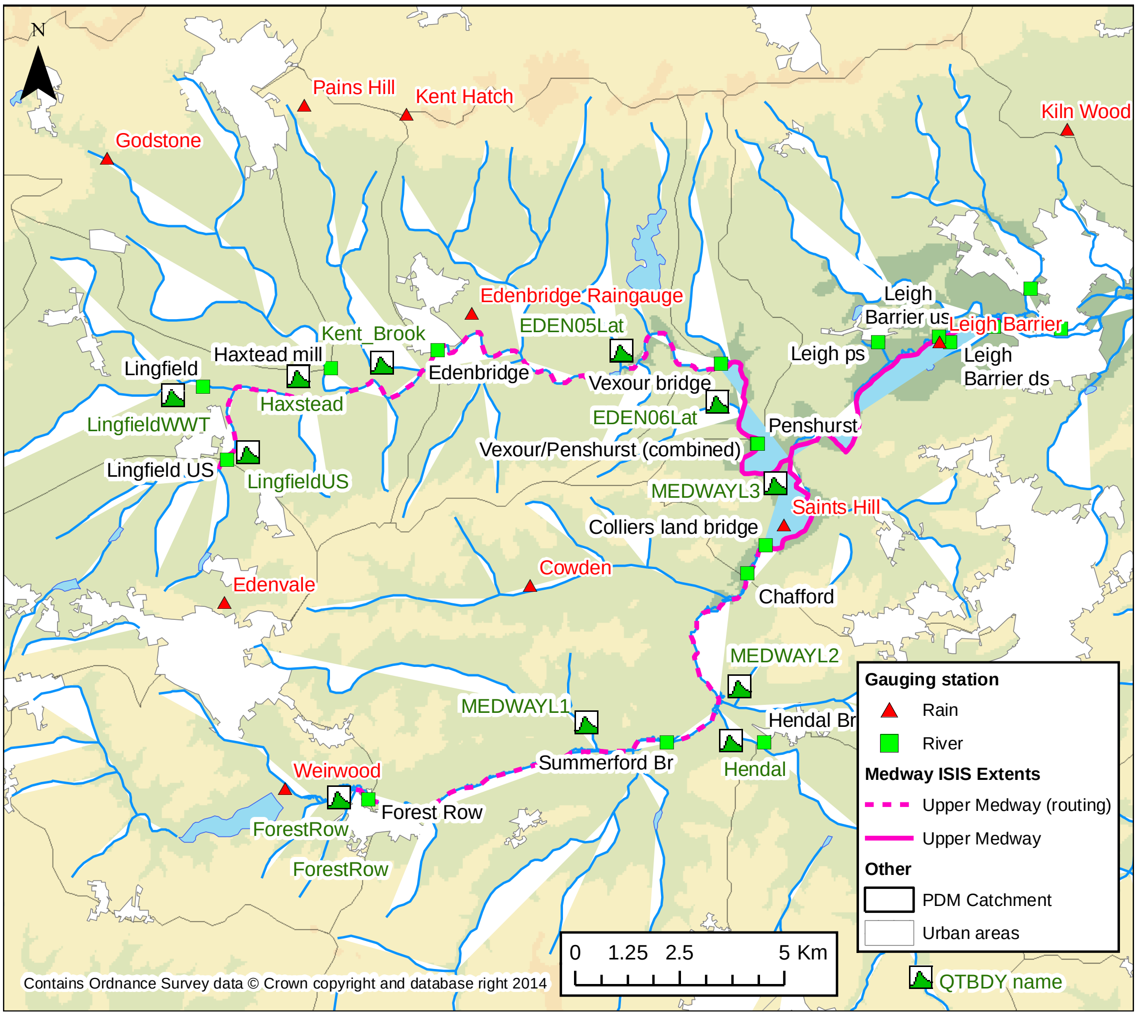
Extending the forecasting model upstream of its current boundaries was achieved by a mixture of:

- Adding flow routing reaches (on the Eden and Medway); and
- Re-using existing 1D models (on the Beult).

As important as the river models themselves was calibrating rainfall runoff inputs to the extended models. The current forecasting system lumps the catchments to the current model boundaries into three PDMs. This aspect of modelling is discussed in Section 3.4.

3.3.2 Eden and Medway

Figure 3-3: Eden and Medway catchment model (model inflows are indicated by the green hydrograph symbols)

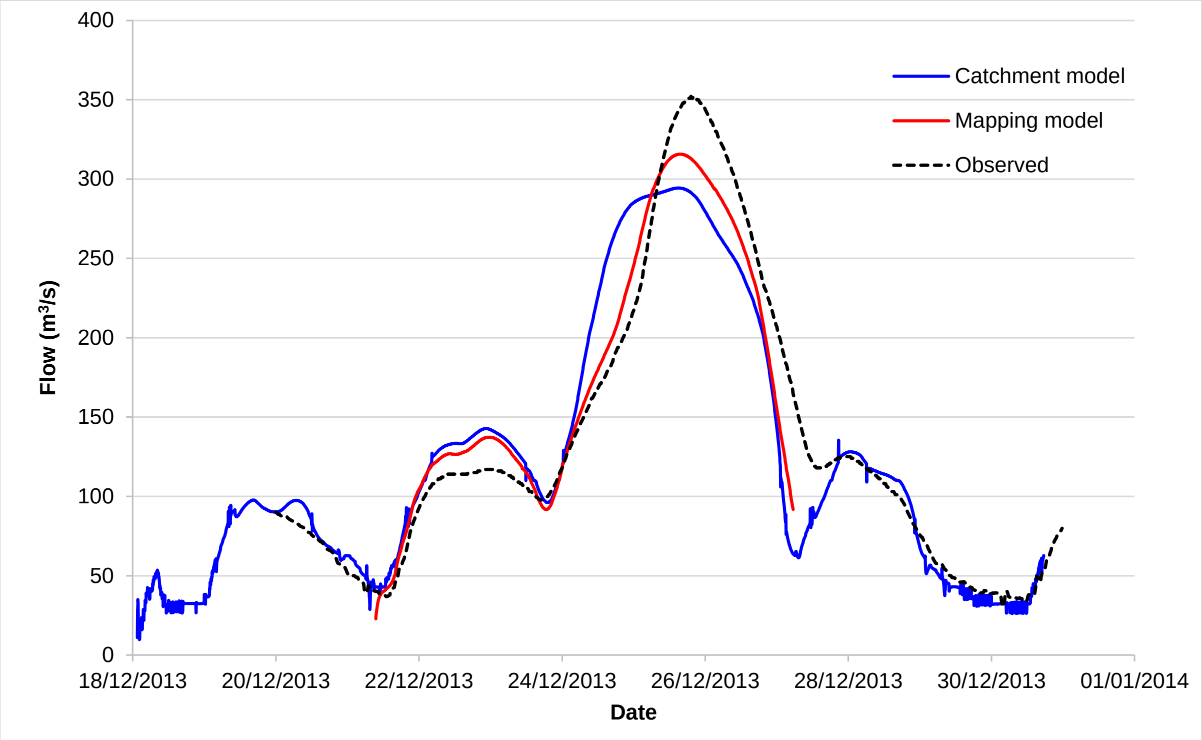


A new model was created to route flows from the upper catchments of the Eden and Medway to Vexour and Colliers Land Bridge. The extended model takes its boundaries at existing river gauges wherever possible (see Figure 2-7) to allow some calibration of the rainfall runoff inputs. It uses Variable Parameter Muskingum Cunge (VPMC) units (which specify a wavespeed) throughout and has prediction points at Edenbridge gauge and Vexour for calibration. Downstream of the Eden-Medway confluence, it joins the 1D forecasting model representing the Leigh FSA.

The river model is very simple. It uses a fixed wavespeed in the VPMC units of between 0.35m/s (upper Medway only) and 0.5m/s. This was initially estimated from observing the time of travel between Edenbridge and Vexour on the Eden and Summerford and Colliers Land Bridge on the Medway. This wavespeed worked well during calibration and varying it did not improve results, so it has been retained. Note that this may differ from wavespeeds estimated from time of travel between peaks because of the influence of lateral inflows. The reservoir at Weirwood is upstream of the model's boundaries and is 'incorporated' into the PDM for that catchment (not explicitly within the river model). This is reasonable for large winter events when the reservoir has a higher likelihood of being full.

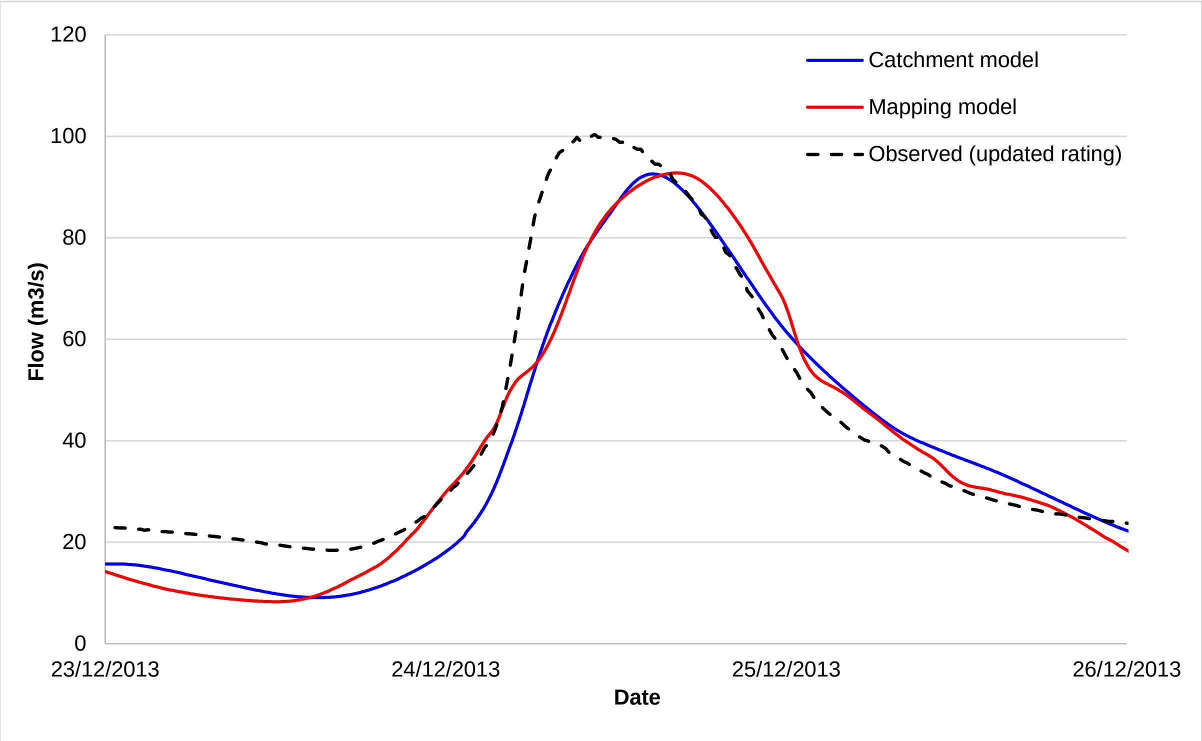
The model has been checked against the detailed mapping model for a number of observed events (using the same boundary conditions) and makes flow predictions consistent with it. Figure 3-4 shows a comparison for the Medway at East Farleigh. Peak flows are very similar for the two simulations but the mapping model better replicates the shape of the hydrograph.

Figure 3-4: Comparison of flows simulated using the mapping and routing model at East Farleigh



One adjustment was necessary to get agreement between the mapping model and the flow routing model. The more detailed model extends further up the Medway than the routing model - beyond Lingfield WWT and Haxted Mill gauges. To account for this, the PDMs for those catchments were made more flashy so that the attenuation and lag happening in those channels is accounted for. With this adjustment, the match to the routed (and observed) flows was very close at Vexour, as shown in Figure 3-5.

Figure 3-5: Comparison of flows routed using the catchment model and the detailed mapping model at Vexour

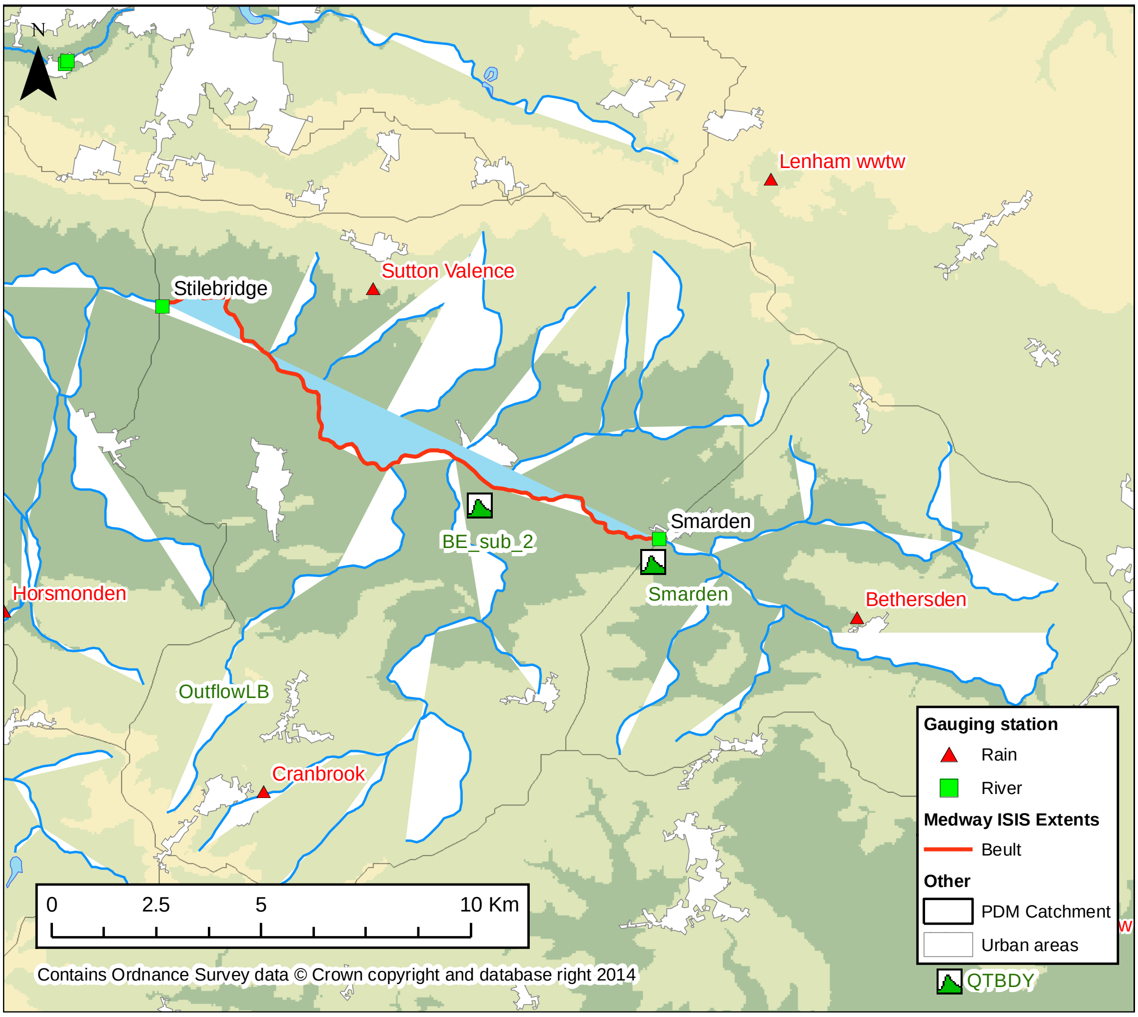


Flows simulated by the catchment model are presented in Appendix A. They are compared with observed data wherever available in model evaluation sheets. These results are discussed in more detail in Section 3.4 because rainfall runoff inputs are a greater source of uncertainty than the river model.

3.3.3 Beult

Attenuation is more significant on the River Beult than the Upper Eden and Upper Medway. Its catchment is low lying with a gentle gradient. The existing 1D mapping model was therefore adapted to route flows from Smarden to Stilebridge, taking lateral inflows from an intervening PDM model. Section 3.4 describes the calibration of the model's rainfall runoff inputs and results at Stilebridge. The model's extent is shown in Figure 3-6 below. Adaption involved only truncating the model at Smarden and Stilebridge gauges.

Figure 3-6: Beult catchment model (model inflows are indicated by the green hydrograph symbols)



3.4 Rainfall runoff inputs

All parts of the catchment are represented by a PDM rainfall runoff model (i.e. not scaled from a gauged boundary). PDM is a conceptual rainfall runoff model that describes a catchment as a series of three main stores (Figure 3-7). A soil store, surface runoff store and baseflow store are parameterised by calibration against observed data. Rainfall is intercepted by the soil store and a proportion, determined by soil wetness, runs off as fast flow. The remainder infiltrates the soil to increase its moisture. Water drains from the soil to a baseflow store at a rate proportional to its water content. The surface runoff and baseflow stores attenuate and smooth their inputs and are combined to give a total catchment flow. The PDM has 12 main parameters, outlined in Figure 3-7. A full description of the PDM is given by Moore (2007)[29].

[29] Moore, R.J. (2007). The PDM rainfall-runoff model. Hydrol. Earth Syst. Sci 11(1), 483-499.

Some catchments, like Lingfield ultrasonic, are gauged directly. Others are only gauged some way downstream, when several catchments (and PDM models) have combined. As outlined below, the approach to developing these models is different.

Figure 3-7: The PDM model structure and main parameters

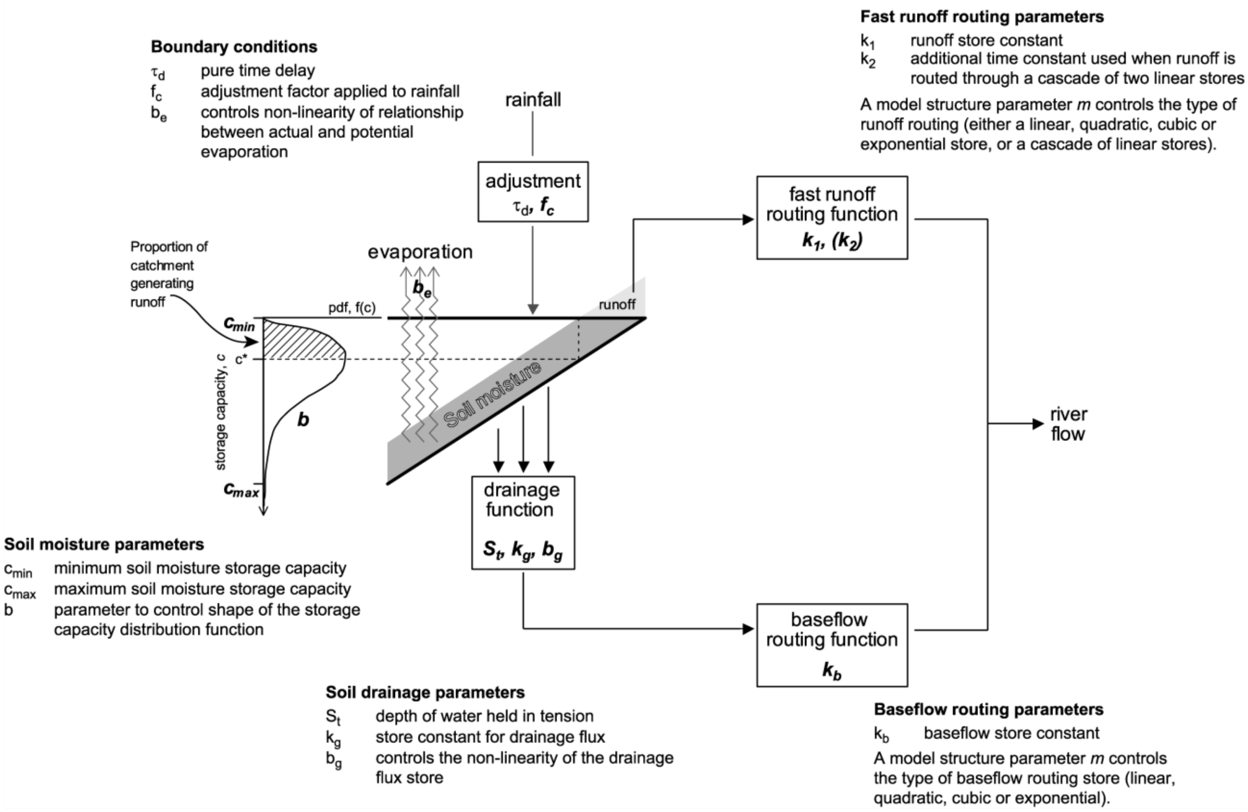


Table 3-3: PDM parameter values for catchment model

	Area	Fc	Cmin	Cmax	b	Be	Kg	Bg	St	K1	K2	Kb	Tdly
	Km^2		mm	mm			hmm^2	m^3/s	mm	hrs	hrs	hmm2	hrs
ForestRow[1,2]	50	1	40	140	1.2	4	3000	1.8	50	3	7	0.5	2
MEDWAYLat01[2]	75	1	30	250	0.4	4	120000	1.8	40	5	n/a	0.5	0
MEDWAYLat02[2]	75	1	30	250	0.4	4	120000	1.8	40	5	n/a	0.5	0
EdenLat01[2]	73	1	30	250	0.4	4	120000	1.8	40	4.3	n/a	0.5	0
Hendal[1]	52	1	30	300	1	4	30000	1.7	20	2.5	n/a	100.1	0
Kent_Brook[2]	13	1	30	250	0.4	4	120000	1.8	40	6	n/a	0.5	0
HaxsteadMill[2]	52	1	30	250	0.4	4	120000	1.8	40	6	n/a	0.5	0
LingfieldWWT[2]	32	1	30	250	0.4	4	120000	1.8	40	9.6	n/a	0.5	0
Lingfield[1,2]	29.5	1	30	300	1	4	30000	1.7	20	5	n/a	0.5	0
Hadlow[1]	51	0.9	0	150	0.25	0.9	50000	2	72	4	6	120	0.13
A_sub_1 v1	37.8	1	20	200	1.1	2	75000	1.8	10	5	n/a	4.6	3.5
H_sub_1	53	0.9	0	150	0.25	0.9	50000	2	72	4	6	120	0.13
M_Sub_1	27	0.9	0	150	0.25	0.9	50000	2	72	4	6	120	0.13
BE_sub_3	157	1.1	0	120	0.25	1.1	100000	1.8	0	9	12	20	3
Stonebridge[1,2]	134	1	30	230	0.5	4	30000	1.7	60	4	n/a	5.8	2
BE_sub_2_JBA01[2]	182	1	20	150	0.4	5	60000	1.6	0	6	n/a	5.8	0
Smarden_JBA01[1,2]	97	1	30	150	0.6	5	60000	1.6	50	8	n/a	5.8	3
Lenside	70	1	30	500	0.6	3	10000	1.6	50	4	20	1260	3

Notes: refer to Figure 3-7 for an explanation of the parameters and to Figure 3-2 to see the location of the catchments. Rain gauge weights are given in the model summary sheets in Appendix A. [1] means that the PDM is calibrated directly, [2] that it was newly calibrated for this project

For gauged catchments, PDM is calibrated against observed data by trial and error adjustment of its parameters. It requires observed rainfall and some measure of potential evaporation as an input. Simulated flows are then compared against observations to make informed adjustments to the parameters. PDM was calibrated against whatever data were available by running the PDM with rainfall and PE continuously and making comparisons with observed data when it was available. Table 3-3 (above) indicates which PDMs are directly gauged (have a superscript of 1) and which are not. It also shows which PDM parameters were calibrated by us (have a superscript of 2) and which were taken from the forecasting model without any adjustment - mainly the ungauged inputs to the Middle Medway (which performed adequately already).

Parameters for the ungauged catchments of the Eden, Medway and Beult were transferred from gauged neighbours, where direct calibration had been undertaken. This included PDMs developed for the lumped catchments of the Eden at Vexour, Medway at Colliers Land Bridge, Teise at Stonebridge and Beult at Stilebridge. However, the PDM developed for Eden Brook using Lingfield flow data proved most useful for parameterising ungauged lateral inflows to the upper catchment. The Smarden PDM fulfilled this role for the Beult ungauged reach. Physically based parameters such as catchment area, inputted rain gauges and their weights were set using observed data. The parameters controlling the timing and shape of the hydrograph were also adjusted. This was achieved by taking the ratio of the time to peak (from FEH catchment descriptors) for the gauged and ungauged catchment and adjusting the surface routing time constant accordingly. Values for all other remaining parameters were retained.

One PDM was calibrated directly outside of the catchment model. The River Len, gauged at Lenside, is a small tributary of the Eden and joins in Maidstone. It has a highly permeable catchment and the flow regime is dominated by chalk baseflow. The Len is part of the Lower Medway mapping model and an inflow was needed that would correspond to the flows cascading from the Medway upstream. It's input is almost insignificant for the Medway (maximum recorded flow of 4.1m^3/s in December 2013 when there was 350m^3/s gauged at East Farleigh, but the Len itself is included in the model and an inflow was required. The PDM calibrated is quite different to the others simulated, being so chalk dominated. Its performance is very good however and it was also successful in continuous simulation - not requiring any additional scaling.

PDM parameters (for all catchments) and calibration performance (for gauged catchments) are documented in model summary sheets in Appendix A and tabulated in Table 3-3 (above). The values are all in line with those expected for dry catchments that accumulate a large seasonal soil moisture deficit. The model was verified as a whole for the longest period possible, as shown in the Model Summary Reports.

3.4.1 Stabilisation

Only the Middle Medway model caused problems with model failures during calibration and continuous simulation. The Model Summary Report describes what changes were required to make the model stable and run for all events in the continuous simulation.

3.5 Leigh Flood Storage Area

3.5.1 General

Since 1982, floods from the Upper Medway have been attenuated by the Leigh Flood Storage Area (FSA). This facility consists of an impounding embankment with an outflow through three radial gates. It is operated to limit pass forward flows to 75m^3/s but has a maximum impounding level of 28.05mAOD. If that level is likely to be exceeded then alternative operation of the FSA is considered by the Environment Agency. The aim of changing the operation of the gates is to pass the minimum flow downstream without exceeding the level limit of 28.05mAOD. This means regulating at a higher flow than 75m^3/s.

Calculations are done to determine this flow on the basis of forecast inflows using a mass balance spreadsheet. Operators use the spreadsheet to come up with an optimum pass forward flow, given the forecast flows and current reservoir state. The operation of the FSA is reviewed regularly in the light of new information.

Our challenge was to simulate the process of determining what the pass forward flow should be for each of the continuously simulated flood events. The main difficulty was to change the operation of the FSA part way through a model run and select the optimum outcome - something that requires iteration.

This part of the report explains how this was done and explains the assumptions made.

3.5.2 Approach

Three main steps were needed to simulate the process undertaken by FSA operators:

- The ISIS model containing the Leigh FSA had to be altered to enable it to change the target regulation flow part way through a model run.
- A series of alternative pass forward simulations had to be run using the model.
- An optimum run had to be chosen out of these simulations and taken forward as the series that would have been chosen by FSA operators.

Together with the Environment Agency, we checked that the procedure worked as expected. This was done by FSA operators simulating flood events from the continuous simulation and then comparing their optimum flow to ours. Each of the steps is explained in the sections below.

3.5.3 ISIS model

Leigh FSA is represented as a 1D model in the Upper Medway catchment model. The FSA and its radial gates were taken forward from the Upper Medway forecasting model. In the current forecasting model, the gates are operated according to logical rules. These set the gate opening according to banded levels in the reservoir. The effect is to enforce a pass forward flow of roughly 75m^3/s on the structure. If the reservoir level reaches 28.05mAOD the gates change operation to release the inflow (as far as they are able) to prevent 28.05mAOD being exceeded.

We altered the model slightly to simplify its operation and allow the target regulation flow to change. This was done by:

- Lumping the north and south gates (which are identical) by doubling the length of the north gate and removing the south.
- Introducing an abstraction unit which acts as a 'variable' to determine the required pass forward flow at any time.
- Changing the logical rules associated with the lumped gate. These now move the gate iteratively to maintain a pass forward flow (indicated by the abstraction unit). To prevent excessive gate movement, a dead zone was introduced so that the gate remained still unless the flow deviated from the target by more than 2m^3/s. The gates still open to discharge the inflow if the maximum level of 28.05mAOD is reached.
- Adding a rule to the central gate to open it fully if the reservoir level reached 28.05mAOD (contrary to expected operation, the gate remained closed even when 28.05mAOD was reached).

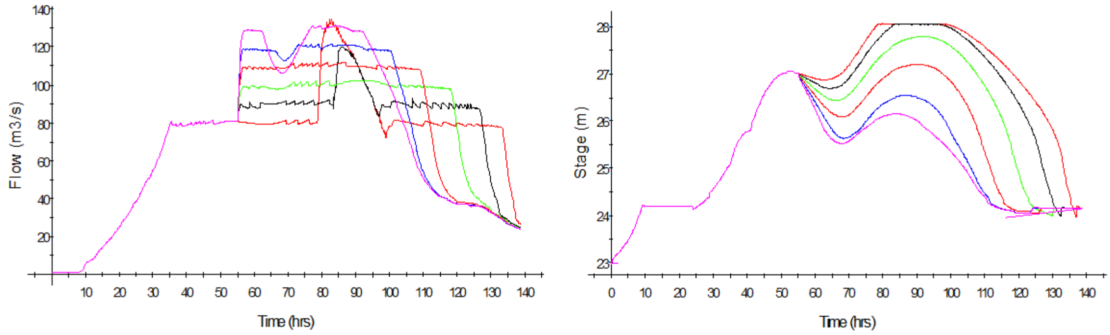
3.5.4 Running multiple scenarios

With the new ISIS model, it was possible to try different outflow scenarios, beginning part way through the model run by setting the abstraction rate to the desired flow from a specified time. In our continuous simulation runs, we considered that the operator might learn of the need to exceed the target outflow of 75m^3/s 24 hours before it actually happened. We developed a small computer programme to mimic this by doing the following:

- Running the ISIS model for all events using the 75m^3/s target outflow;
- Analysing the results to identify which simulations exceeded the target and noting the time at which this happened;
- Creating new simulations for each of the events experiencing an exceedence. These applied a higher target outflow, in steps of 10m^3/s, implemented from a point 24 hours before the exceedence occurred in the baseline run i.e. one simulation at an outflow of 85m^3/s, one at 95m^3/s, one at 105m^3/s and so on..

These simulations were executed to give a suite of scenarios, providing outflow rates and impoundment levels for each (as shown in Figure 3-8). In that example, the gates regulate at 75m^3/s until 55 hours, 24 hours before the (red) 75m^3/s scenario makes forced releases. At that point, the target regulation changes in 10m³/s increments and the impact on levels can be seen in the adjacent plot.

Figure 3-8: Example of output from multiple ISIS scenarios showing outflow (left) and impoundment level (right)



3.5.5 Selecting the optimum

Once the scenarios are executed for all affected events in the continuous simulation, the optimum is chosen by a second computer programme. This chooses the scenario with the lowest outflow that does not exceed 28.05mAOD. In the example above, that is the 100m³/s regulation rate (coloured green). If none of the simulations stay below 28.05mAOD, the code choses the one that gives the lowest reservoir level.

3.5.6 Checks

A set of inflow data from the 1,000-year CS was submitted to the Environment Agency for checking using the Leigh FSA operational spreadsheet. After three iterations, the model results agreed well enough with the operators' choices for the method to be signed off.

3.6 Model proving

To show that the catchment model makes reasonable simulations, it was run for the 47 largest historical events since 1998. Uncertainties about early rainfall records led us to curtail the number of events eventually presented to those after:

- 30 October 2000 for the Upper Medway; and
- 6 November 2006 for the Middle Medway and Beult.

The model was run using observed rainfall only, with simulations from PDMs and ISIS models being cascaded between reaches. Comparisons with observed data were made at all locations where this was available (and exports had previously been configured in NFFS).

The model summary sheets in Appendix A include all of these results (as individual model evaluation sheets for each location) and summarise performance for each location. Our main findings are summarised in the sections below.

3.6.1 Upper Medway

Flow simulations for the Medway are good in the headwaters: particularly so at Forest Row and Lingfield Ultrasonic. There is more uncertainty in the results further downstream and the impact of the floodplain is not always perfectly represented in smaller events, but the model predicts December 2013 flows well at Colliers and Vexour (and the combination of these). Water levels and outflows generally match well at the FSA, although the dataset is incomplete there.

The main sources of error in the catchment model are as follows:

- Runoff rates vary significantly for the Medway because of the large summer soil moisture deficit. Modelling the transition from dry catchment to wet catchment (and vice versa) is always a challenge for hydrological models. Runoff rates can therefore contain significant errors, particularly around these seasonal changes.
- Floodplain attenuation is another potential source of error for the Eden and Medway. There appears to be significant overbank storage in the river system, even at moderate

flows. This attenuates the flow hydrograph. In larger events, the attenuation is less evident as the floodplain 'fills' and stops storing as much water.

- Observed data is also a significant source of error. Rainfall prior to 2006 is often suspicious and some of the Autumn 2000 events could not be reliably simulated because of this. The large floodplain and poor containment of flows is also a significant challenge for flow measurement. Even the primary flow gauges at Vexour and Colliers Land Bridge are highly insensitive at high flows, introducing significant uncertainty. Other rating curves, such as Edenbridge and Summerford Bridge just seem incorrect (but it was outside the scope of this project to correct them) and have not been used directly in model calibration.

3.6.2 Beult

Simulated flow on the Beult is good with limited variability and hydrographs shape well represented. Modelled discharge is higher than observed at Smarden, but that rating curve is unsupported by gaugings. Simulations are not biased at Stilebridge (where the rating is supported by gaugings) suggesting that the rating at Smarden may be in error.

The main sources of error in the catchment model are:

- Runoff from the Beult is highly seasonal and modelling this is a challenge (although the PDM appears to be quite successful once observed rainfall is good).
- Observed rainfall prior to April 2006 is known to be suspect in places (although a significant effort went into cleaning these data up). This limits the accuracy of the PDM in the early record. The observed level series at Smarden has some erroneous data and the rating curve may well over estimate flow.

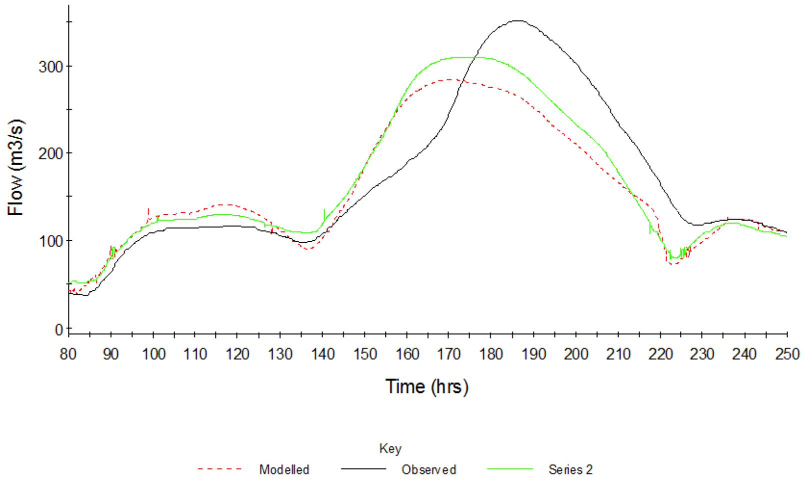
3.6.3 Middle Medway

Model results for the Middle Medway can only be reliably assessed at East Farleigh - the only gauge with reliable flows. Considering flows are all simulated using rainfall as the sole observed input, the model predicts flows at that location very well: with limited uncertainty in the peak and often a good hydrograph shape. However, the model tends to under predict the largest event(s) by over attenuating the peak. Comparisons of modelled and observed water level elsewhere in the system are less good, normally because local hydraulic conditions are not well simulated. The main sources of error in the catchment model are considered below.

The purpose of the Middle Medway model is to route flows through the system from Leigh FSA, the Teise and Beult. How the model is being used here, to identify which continuous simulation event is the design for a given AEP, is critical in the assessment of error. There are three main sources of error seen at individual locations, but not all are relevant to the overall task:

- Runoff. Although the Upper Medway and Beult models account for a large proportion of the area to East Farleigh, there are still significant lateral inflows. Correctly simulating runoff rates (as indicated by the performance of the PDM models at Stonebridge, Stilebridge and Hadlow) is still an important factor in model accuracy, although attenuation means that peak flows tend to be less of an issue.
- Floodplain attenuation. There is substantial attenuation in the middle reaches of the Medway and its tributaries. The model does not always simulate this correctly (see results for December 2013 at East Farleigh below). The observed data shows initial storage attenuation lessening as the flow rises to an extreme (like December 2013) and the flood plain fills. As the model simulates the floodplain as extended 1D sections, this process is not well reproduced by the model. The impact is to over-attenuate in the largest events. As a result, flows outputted from the model are probably less than they would be in reality (given the same inputs). Design flows from the model should not be cascaded to the Lower Medway without accounting for this bias.
- Local hydraulics. Simulated water levels are quite different to observed at several of the river locations. This may not be important for the routing of flows through the Medway (the local effects tend to be related to structure operation or local channel hydraulics) but they should be of concern for the forecasting model.

Figure 3-9: Simulated flows using cascaded and observed inputs (red dashed line and green line respectively) shown against the observed at East Farleigh



3.7 Application for forecasting

These models have the potential to be adapted for use in an updated forecasting system for the Medway. In particular, they could be used to:

- Extend the forecasting network upstream of Stilebridge on the Beult and Vexour on the Eden. If formal flood storage is implemented for these rivers then the models presented here will provide a means of incorporating that into forecasts for the Medway.
- Simulate alternative FSA operation scenarios within NFFS rather than using the 'spreadsheet tool' as currently. NFFS forecasters would be able to run 'what if' scenarios using the forecast model to determine the optimum release strategy. It is possible that some elements of our code could be incorporated to make this 'semi automatic'. This could be configured into the existing forecasting system with relatively little effort.
- Individual PDMs have been developed for the Medway at Forest Row and Eden Brook at Lingfield which would enable forecasts at those locations.
- New PDM parameter sets have been calibrated for the lumped catchments to Vexour, Colliers Land Bridge, Stilebridge and Stonebridge. These are the current boundaries to the forecasting models and could represent an improvement over what's already being used.
- Stabilise the Middle Medway model. We experienced many failures of the Middle Medway model that required adjustments to coefficients and geometry. The version we were working with was stabilised to ensure we got results where we needed them, but these may affect some locations where forecasts are needed. The existing forecasting model has therefore not been updated (only the version used for this project, supplied) and should be stabilised to prevent potential future failures. Its representation of critical local structures could also be improved to make level forecasts more accurate.

4 Continuous simulation

4.1 General

Design flows for specific locations are obtained by running the catchment model 'continuously' with the stochastic rainfall series and analysing the resulting flows. In fact, only the rainfall runoff models are run continuously, with the river model being run for the largest events extracted from those results. This provides the upper portion of a ranked stochastic AMAX series of flow for any node in the model. Applying the Gringorten formula to the ranked series gives a flow for any given AEP (as long as enough AMAX are simulated).

If the stochastic rainfall series is representative of the true rainfall's properties, and the catchment model is accurate, the design flows will be reliable. Although neither of these assumptions can ever hold perfectly, we think that they are close enough to make the design flows fit for purpose.

Our detailed hydraulic model (described in our Hydraulic Modelling Report) is fully hydraulic and partly 2D. It takes many hours to run, making it impractical to use in the CS itself. Instead, design events for particular locations are identified with the catchment model. Outflows from those runs are then applied to the detailed model's boundaries (identical to the routing model's) and the results attributed with the AEP from the CS.

This part of the report explains how the various simulations have been carried out, what assumptions are made and the processes used. It shows how the results relate to flood frequencies from other methods. Finally, it presents results at key locations and explains how those will be taken forward in to the full design simulations using the hydraulic model.

4.2 Approach

Our catchment model, described in Section 3, consists of 17 PDM rainfall runoff models and 3 ISIS river models. The PDMs are run continuously, at an hourly timestep, with the 5,000 year stochastic rainfall series developed in Section 2. We do this using our in-house modelling and hydrological analysis programme, HYDB. Annual maximum flows are extracted for each PDM to allow plotting as flood frequency curves, like those in Figure 4-2.

It is impractical (and unnecessary) to run the ISIS part of the catchment model continuously for the 5,000 years. If we know which events are the annual maxima at various key locations in the catchment, we can simulate the largest of those and be confident that those events will also be the largest at all points within the river network being analysed. A list of AMAX floods was extracted from the continuously simulated PDM flows for the following locations using results from lumped PDMs (all recalibrated for this project). The spread of locations, covering all the major tributaries, ensured that all potential large events are identified from the spatially varying rainfall series:

- The Eden at Vexour;
- The Medway at Colliers Land Bridge;
- The Teise at Stonebridge;
- The Beult at Stilebridge.

We set the threshold for recruiting AMAX to simulate in the river model as the 20% AEP flow at each location (itself derived from the continuous simulation). This list of AMAX was checked for duplicates, so that events were not being simulated multiple times because of their occurrence at more than one location. A set of ISIS boundary time series files (IEDs) were then created which began 50 hours before the AMAX peak (at whichever location) and finished 70 hours later. The asymmetric timing was designed to allow flows to travel through the system to East Farleigh. An additional 20 hour 'ramp up' was added at the start to smooth the transition from initial flows to the first flow in the event from the CS.

ISIS models are executed for all events (3,174 in total) and results extracted at key locations for analysis. Those model nodes are listed in Table 4-1. They mostly represent gauged locations within the model network, or key places of interest.

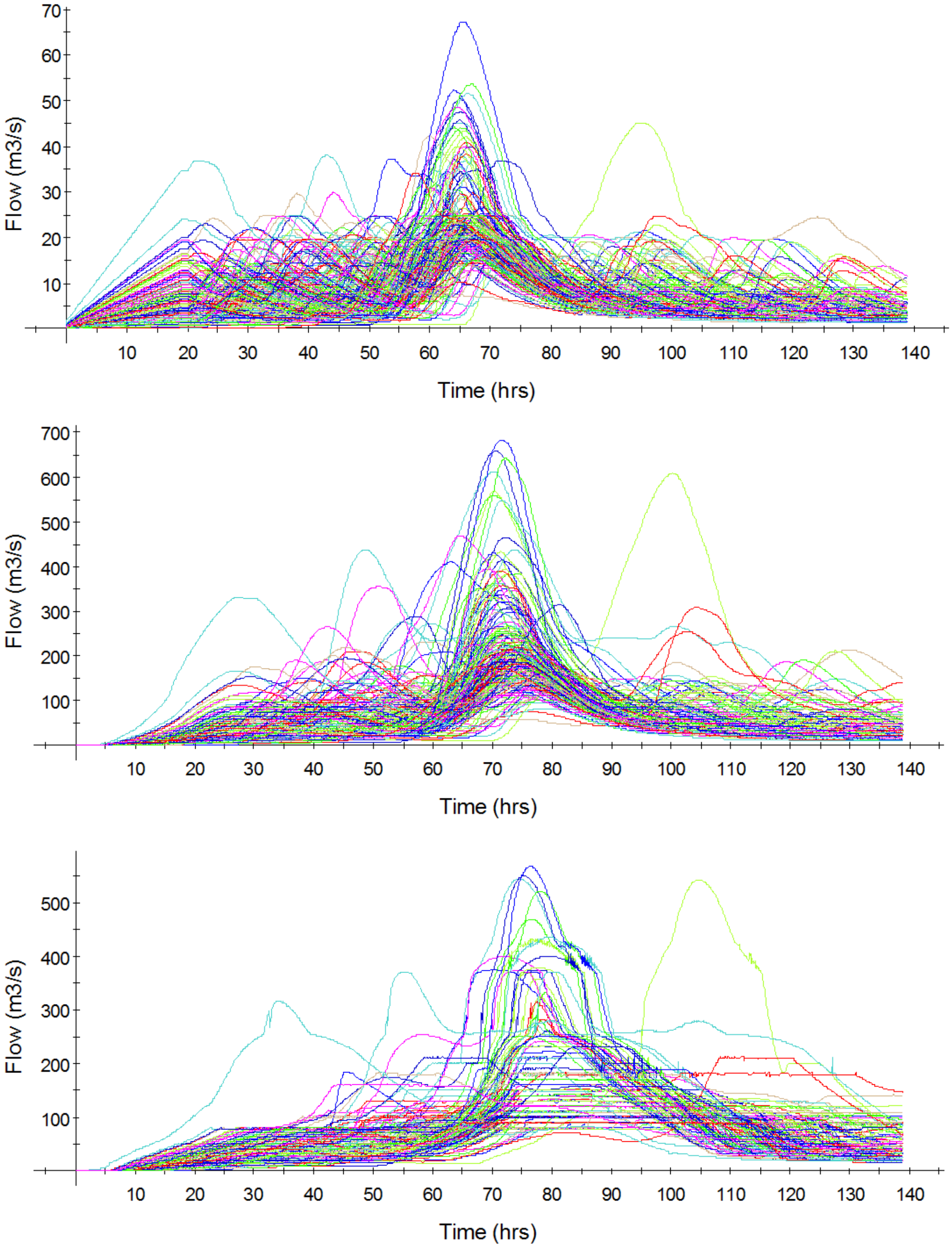
Table 4-1: Model nodes where results are extracted from the CS

Model	Node	Description
Upper Medway	Colliers	Colliers Land Bridge gauge
	CS10	Downstream of Leigh FSA gates
	CSM24	Downstream of Medway-Vexour confluence
	CSM34WD	Weir upstream of Ashour Wood, River Medway
	CSM46BJU	River Medway at Ensfield Bridge
	CSM61	Upstream of the Leigh FSA gates
	CSM61CU	Central Gate
	CSM61NU	North Gate
	EDEN02	Eden Brook immediately downstream of Lingfield US confluence
	EDEN03u	Eden Brook immediately upstream of River Eden confluence
	EDEN03	River Eden immediately downstream of Eden Brook confluence
	EDEN04u	River Eden immediately upstream of Kent Brook confluence
	EDEN04	River Eden immediately downstream of Kent Brook confluence
	EDEN05Lat	River Eden inflows between Edenbridge and Vexour GS
	EDEN06Lat	River Eden inflows between Edenbridge and Vexour GS
	EDEN06	Hever Castle
	EDEN07u	River Eden immediately upstream of River Medway confluence
	EdenBridge	Edenbridge gauging station
	ForestRow	Forest Row gauging station
	Haxstead	Haxstead inflow boundary
	Hendal	Hendal inflow boundary
	KentBrook	Kent Brook inflow boundary
	LingfieldUS	Lingfield Ultrasonic gauging station
	LingfieldWWT	Eden Brook immediately upstream of Lingfield US confluence
	MEDWAY01	Lateral inflows
	MEDWAY02	Approximate location of Forest Row risk area
	MEDWAY03	Downstream of Forest Row
	MEDWAY04	Downstream of Forest Row, upstream of Summerford Bridge
	MEDWAY05	Downstream of Forest Row, upstream of Summerford Bridge
	MEDWAY06	Downstream of Forest Row, upstream of Summerford Bridge
	MEDWAY07	Downstream of Forest Row, upstream of Summerford Bridge
	MEDWAY09	River Medway at downstream of Mottsmill Stream
	MEDWAY10	River Medway at downstream of River Grom
	MEDWAY11	River Medway upstream of Colliers Land Bridge
	MEDWAY12	River Medway downstream of Colliers Land Bridge
	MEDWAY13	Immediately downstream of the Eden and Medway confluence
	MEDWAYL1	River Medway - lateral inflow for left bank tributaries between Forest Row and Colliers Land Bridge
	MEDWAYL2	River Medway - lateral inflow for right bank tributaries between Forest Row and Colliers Land Bridge (excluding Mottsmill Stream)
	MEDWAYL3	River Medway - lateral inflow for inflows downstream of River Medway-River Eden confluence
	Opening	
	Summerfd	Summerford Bridge gauging station
	Vexour	Vexour Bridge gauging station
Beult	Smarden	Smarden gauging station
	Stilebridge	Stilebridge gauging station
	B104-BJU	mid-Beult – upstream of Headcorn
	B90-BJU	mid-Beult – downstream of Headcorn

Model	Node	Description
	B79-ORJU	Further downstream
	B75-BJU	Hawkenbury Bridge
	B64-JU	Hertsfield Bridge
	BE_sub_2	Lateral inflow representing inflows along the River Beult upstream of Stile Bridge
Middle Medway	AS01	Alder Stream inflow
	B13-D1-LJU	Medway upstream of Yalding
	B21-LJU	Cheveney Gate
	B29-JU	River Beult, upstream of Lesser Teise confluence
	B29-JD	River Beult, downstream of Lesser Teise confluence
	BE_sub_3	Lateral inflow representing catchment between: East Farleigh, Stonebridge, Stilebridge and East Farleigh
	BO9-WJD	Little Mill gauging station
	CS114	Branbridges gauging station
	CS121	Hale Street, East Peckham
	CS126	Downstream of East Peckham
	CS147	Anchor Sluice
	CS148	Downstream of Anchor Sluice
	CS156JD	Downstream of confluence of Teise, Beult, Medway
	CS161JD	Downstream of Yalding Marina
	CS166	Bow Bridge, River Medway
	CS172	Upstream of Yalding
	CS189	East Farleigh gauging station
	CS10	Upstream of Lucifer Bridge
	CS19	Railway Line upstream of Tonbridge
	CS28	River Medway upstream of Buley's Weir, Tonbridge
	CS31U	River Medway at Big Bridge, Tonbridge
	CS36	Town Lock gauging station
	CS43JD	Downstream of Tonbridge
	CS57	Downstream of Eldridge's Lock
	CS78BJD	Hartlake Bridge
	CS96	Oak Weir
	Hadlow	Hadlow gauging station
	HI01	Catchment between Leigh FSA and Tonbridge: Hilden Brook, Hawden Stream and Bid Stream
	LT21-BD	Lesser Teise – Spitz Bridge
	LT44-WU	Lesser Teise - upstream
	MI01	Tonbridge Mill Stream inflow
	OutflowLB	Outflow from Leigh FSA
	Stilebridge	Stilebridge gauging station
	Stonebridge	Stonebridge gauging station
	T20-BJD	Duddies radial gate
	T30-BJD	Darmans Bridge gauging station

Figure 4-1 shows what the continuously simulated flows look like as time series at Forest Row (a headwater catchment), upstream of the Leigh FSA and downstream. Events plotted are those which trigger 'alternative operation' of the FSA

Figure 4-1: Events from the continuous simulation at Forest Row, upstream and downstream of the Leigh FSA



AMAX flows are extracted from the individual event simulations in the same way as for continuous PDM results. Applying the Gringorten formula attributes probabilities to them and allows design events to be identified for specific AEPs.

Once the continuously simulated design flows are understood for a location, the inflows to the model that gave rise to a design event may be applied to the full hydraulic model. Water levels and extents for that run, for that locality (where the design event was identified), can then be attributed that AEP. The basic steps in doing this are:

- Choose a node in the catchment model that is representative of the target location;
- Look up the design flow for that location from the CS results (provided with this project in a spreadsheet);

- Use the spreadsheet's functionality to say which of the continuously simulated events gave rise to that flow;
- Retrieve the IED file for that scenario and run the mapping model using it;
- Take the results from the mapping model in the vicinity of the node to be the flood depth and extent for the AEP being analysed.

Section 5 is a more complete user guide to the CS results and explains how a design flow is identified for a location and the correct ISIS boundaries used.

4.3 Simulating Leigh Flood Storage Area

4.3.1 General

Section 3.5 explained how the Leigh FSA has been simulated in the Upper Medway model. Appropriate results, that mimic the way the FSA is operated, have been derived using the methods described earlier. Results are within the boundary files for the Middle Medway model at the Medway inflow. We have explained how the optimum release from the FSA was calculated but have not provided the software used to do this (it could be provided if required, but would require a good level of understanding from the modeller). It might be necessary to repeat the process of optimising reservoir outflows if:

- The FSA's operational rules changed;
- More flood storage is introduced upstream (for example as part of new FCRM schemes); or
- Design inflows are revised significantly (for example if new information becomes available, such as revised rating curves at Colliers or Vexour).

4.3.2 'No defences' simulation

A simulation without flood defences is needed for the detailed hydraulic model. Leigh FSA is the only infrastructure affecting the catchment model's flow simulations. We modelled the removal of the FSA by bypassing it in the model cascade. Instead of taking flows out of the model downstream of the impoundment, they were taken upstream of the impoundment, just before the river reaches the main reservoir (ISIS node CSM24). This bypasses the attenuating effect of the FSA on the models downstream without requiring work on the model to remove the FSA and stabilise that part of the model. The remainder of the model network is identical to the 'with defences' scenario.

4.4 Results

Comparing how the continuous simulation performs against FEH statistics at key locations is an important check on results. Previous experience suggests that it is sometimes necessary to adjust the CS to give a match to a flood frequency curve where we are particularly concerned to achieve parity. Such locations might be trusted gauging stations, or locations where there is good information on historic flooding.

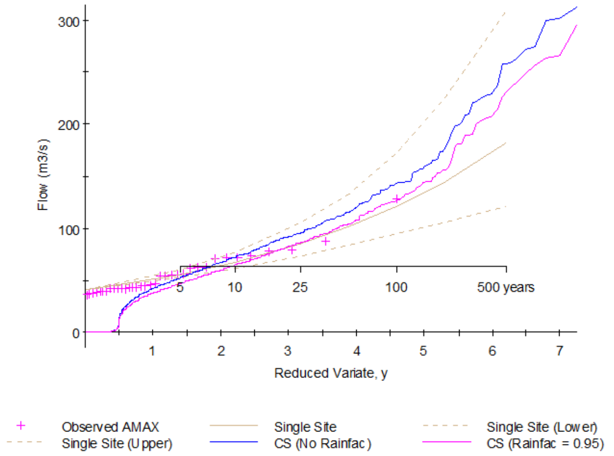
In this case, adjusting the CS meant applying a reductive scaling factor of 0.95 (rainfac) to the synthetic rainfall such that the river model better matches the flood frequency curve at the node of interest.

Flood frequency analysis was carried out at key locations for the December 2013 event severity report. This included the River Eden at Vexour, the Medway at Colliers Land Bridge, Teise at Stonebridge, Beult at Stilebridge and Medway at East Farleigh. These gauges all have long continuous records of 50 years or more, updated with the latest rating curves developed for this project. Flood frequency curves were fitted to the 'single site' AMAX to give design flows. Pooled analysis was tried but gave a flood frequency curve that predicted unreasonably low design flows (i.e. high order events that have been exceeded many times).

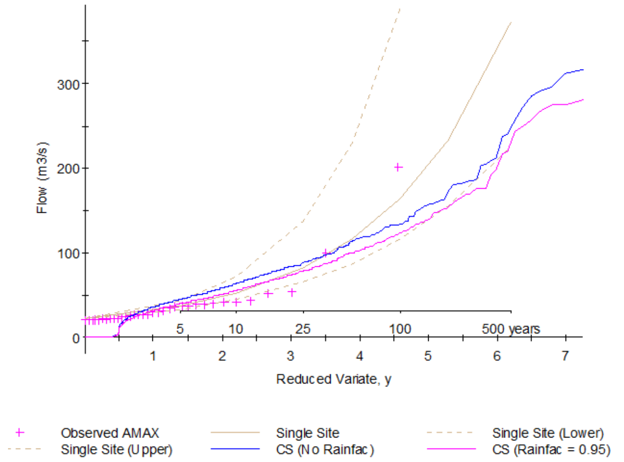
Our CS results, with (magenta line) and without (blue line) the 0.95 rainfac value, were compared to the single site flood frequency (gold line, with 95% prediction intervals) curve and the plotted AMAX (magenta crosses) at those locations, as shown in Figure 4-2. East Farleigh was considered but results there depend on the FSA, which has been in place since 1982 (part way through the record). These comparisons were all done using the full 5,000-year simulation.

Figure 4-2: Comparison of CS flood frequency curves, FEH single site curves (with confidence limits) and plotted AMAX

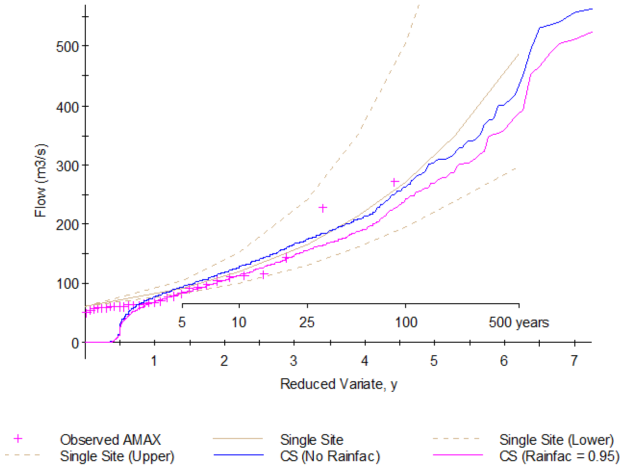
Medway @ Colliers Land Bridge



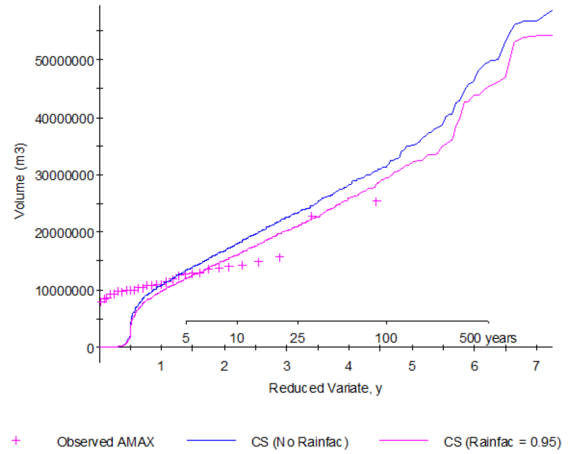
Eden @ Vexour



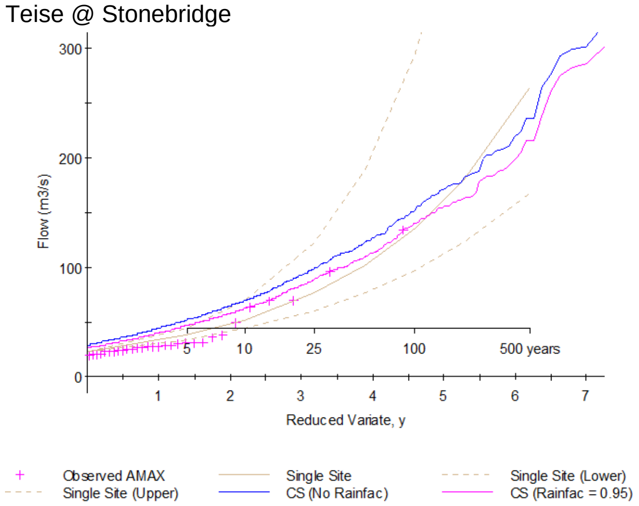
Combined Eden and Medway



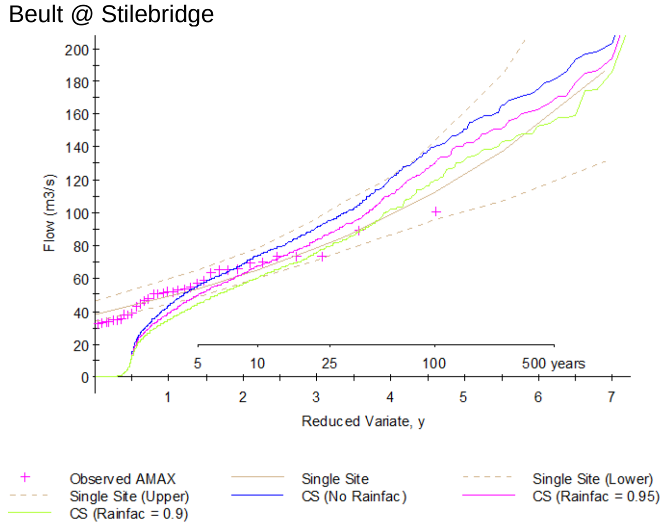
Combined Eden and Medway Volume



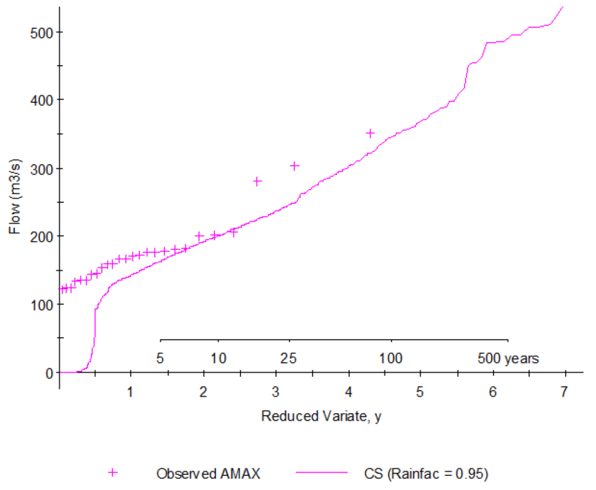
Teise @ Stonebridge



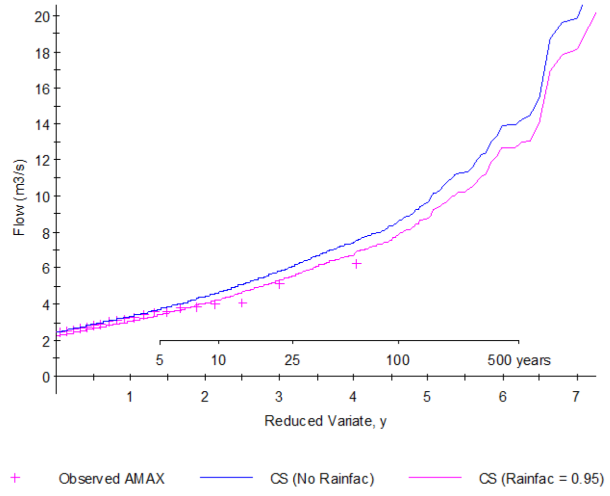
Beult @ Stilebridge



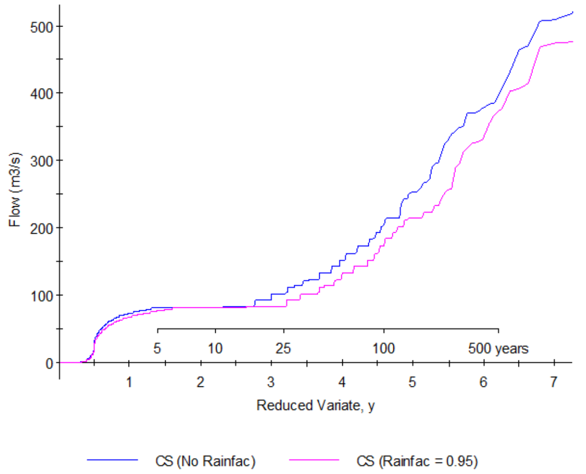
Medway@East Farleigh



Len @ Lenside



Outflow from Leigh FSA



Scaling down the synthetic rainfall gives the best results overall (magenta line in the plots). This modest adjustment was required to get the closest alignment with the plotted AMAX and the single site frequency curve fitted to those data.

Three anomalies with the plotted AMAX remain. Those are:

- Vexour, where the single site growth curve is much steeper than elsewhere because of the 1968 flood. This event's plotting position from a 60 year series is around the 1% AEP (100-year RP). However, the return period for the rainfall that caused the event probably exceeds that AEP by a significant amount (refer to Section 1.4). With this in mind, it is acceptable for the CS frequency curve to lie significantly lower than the single site or upper plotted AMAX.
- Stilebridge, where the CS frequency curve is steeper than the observed. There is no adequate explanation for the discrepancy between the CS results and the observed AMAX. This is particularly so when the results are so close everywhere else and the Beult routing model worked very well. Alternative scaling was trialled (rainfal of 0.9), but this merely shifted the frequency curve down (gradient is unaffected). The difference was accepted as an outcome of using the CS method in a consistent way everywhere.
- East Farleigh, where two AMAX have higher flows than predicted by the CS. This is likely because the Leigh FSA, commissioned in 1981, has supressed flows since 1981, but not before. Furthermore, our modelling has all assumed the FSA is in place and regulating to 75m3/s. These rules were introduced since the large autumn 2000 events, when the regulating flow was lower and consequently, releases could be larger when the reservoir's capacity was reached.

Operation of Leigh FSA is the other comment-worthy result from this work. Two important statistics to report on are:

- The frequency with which the FSA is operated; and
- The frequency with which alternative operation is triggered (see 'Outflow from Leigh FSA' in Figure 4-2).

Analysing the summed flow series of Colliers and Vexour shows that 11 of 47 available AMAX exceed 80m^3/s - around the flow where FSA operation would be necessary. This corresponds very well with the figure of 87m^3/s for the 25% AEP flow at the Medway-Eden confluence.

In the CS, outflows from the FSA remain close to 80m^3/s until the 4% AEP flow. Above that, they increase sharply, indicating alternative operation of the FSA has been necessary. In our simulation of observed events from 1998, alternative operation was only needed in water year 2013 (one AMAX in 15 years). If the FSA were in place in 1968 (just under 50 years), that would certainly have triggered alternative operation (therefore twice in 50 years). These findings tie in well with the CS results (predicting alternative operation four times in 100-years, or the 4% AEP flow).

Runoff volumes into the Leigh FSA are the most critical to simulate accurately as the protection it provides is volume dependent. We therefore checked the frequency curve for simulated volumes flowing into the reservoir against the observed AMAX. These are plotted in Figure 4-2 (above) for a duration of 72 hours. The fit is good, if a little conservative (i.e. modelled volumes are larger).

5 User guide to CS

A user guide, and associated spreadsheet documents, relating to the continuous simulation hydrological information is supplied within the digital deliverables package. The user guide is named *2013s7661 – Continuous simulation user guide (v2 Nov 2015).pdf*. This document should be read when using the hydrological information from this study.

6 Conclusions and recommendations

6.1 Conclusions

Obtaining design flows for the Medway is a challenge because of its large size, seasonal variations in runoff and the Leigh FSA. Continuous simulation has been used to deal with these complexities in a robust probabilistic framework. It involves applying a long synthetic rainfall series to a model of the catchment and simulating flows over a very long period - in this case 5,000 years at an hourly time step. If the synthetic rainfall series has the same 'statistical properties' as observed rain, and the catchment model is accurate, the results at any location can be analysed to get a peak flow for a AEP, much the same as a long observed series can.

The spatially varying synthetic rainfall series was derived using methods set out in Section 2. It was originally calibrated on observed data, then adjusted to fit FEH growth rates (not depths). FEH depth duration and frequency (DDF) statistics give higher rainfall totals than the observed or the CS. Applying FEH rainfall depths gives simulated flow AMAX greatly in observed. The CS was therefore retained, with a global scale factor of 0.95 to give the best match to observed data.

An existing PDM/ISIS forecasting model was used as the basis for the catchment model. It has been extended beyond Colliers Land Bridge up the Medway, beyond Vexour on the Eden and to Smarden on the Beult (beyond Stilebridge). Most of the PDMs are new or have been recalibrated. The combined catchment model generally performs well in terms of peak flows and hydrograph shape, particularly in larger events. However, it predicts higher than observed peak flows at Colliers and Vexour except in the biggest events. This was also a feature of the original forecasting model and difficult to calibrate out of the catchment model without jeopardising performance in the largest events.

Leigh Flood Storage Area (FSA) impounds flows above 75m^3/s to protect Tonbridge and locations downstream. If there is not enough volume to achieve this, higher pass forward flows are considered. We successfully modelled this process with a combination of the ISIS model and some computer code. The catchment model now mimics the way decisions are made about 'alternative operation' of the FSA - something that could potentially be used in the forecasting model (see recommendations below).

The CS flow frequency curves match well at most of the gauging stations. Operation of the Leigh FSA is correctly predicted to happen one year in four and 'alternative operation' is also predicted at a reasonable frequency of just over one year in thirty. Design flows in the lower catchment, at East Farleigh, match the plotted AMAX reasonably well but the catchment model does not simulate the impact (on flows) of the floodplain filling in extreme events (like December 2013). In that event, flows rose more steeply later in the event as all storage was exhausted (see Figure 3-9). The implication of this is that an adjustment should be made to the flows being passed downstream to the Lower Medway to account for this. Alternatively, if the mapping model is more accurate, flows could be cascaded from it into the lower reach of the Medway.

Discrepancies between the CS frequency curve and the observed AMAX at:

- Vexour, where the extreme 1968 event skews the maximum observed; and
- Stilebridge, where the CS frequency curve is steeper than the observed (but still gives flows within acceptable limits of agreement).

The continuous simulation and catchment model are a means of selecting the correct flow boundary conditions to apply to the detailed mapping model. They are NOT used to determine the flow and level at all locations in the catchment. The results outputted from the mapping model are the definitive results. This is the case because it has a more detailed representation of the floodplain and local channel hydraulics than the catchment model (which is fit for the purpose of routing flows and identifying the correct design event to run for a particular location). A spreadsheet is supplied containing the peak flow results for all of the continuously simulated events. It includes a means of identifying the model boundary file that gives rise to the n% event for one of the locations listed in Table 4-1.

6.2 Recommendations

The continuously simulated flows should be used in conjunction with the design model as described in this report. If an exact flow is needed for a particular location and AEP, this should come from the mapping model (which uses the boundaries developed here). If the catchment model is re-run, then the spreadsheet can be used to identify which event should be applied - depending on the location of interest.

It may be necessary to re-run the catchment model if there are changes which affect flows at the model's boundaries or how flows translate the river system. For example, re-running is recommended if:

- Operation of the Leigh FSA is changed;
- Significant new flood storage is introduced on the Eden or Beult as part of scheme development there;
- Rating curves (and therefore FEH single site flood frequency curves) are adjusted at any of the key sites.

We found significant differences between the DDF of rainfall from the 1999 FEH rainfall statistics and those calculated from observed data. FEH design rainfall depths were higher at all of the durations and frequencies looked at (although record lengths limited this comparison to around the 5% AEP). New rainfall statistics are currently being developed[30]. When these are available, we recommend you review how these perform in the Medway catchment and check whether the depths reduce to the values expected (based on observations). Initial indications from this analysis (based on maps in the report) suggest Kent rainfall depths may reduce by between 10 and 18%.

Application of the methods to derive spatially varying synthetic rainfall worked well in this project. Some re-coding of the R scripts provided with R&D report FD2105/TR31 was needed to enable the simulation of very long rainfall periods however. We would recommend the method for future, similar projects, with the proviso that the scripts are re-coded for speed.

Forecasting models have been extended up the Medway, Eden and Beult. These new models could be used in NFFS. If new formal washland storage is introduced to the Eden or Beult, and this has a significant impact on flows at Vexour or Stilebridge, then the models should be integrated into NFFS (with that storage included).

Distributed models like these give the opportunity for downstream forecasts to benefit from error correction at gauges upstream. If this were considered, the ratings at Summerford Bridge and Edenbridge should be redeveloped to make them reasonable and compatible with flows in the model.

As well as extended forecasting models, we recalibrated the lumped PDMs at Vexour, Colliers, Stonebridge and Stilebridge. Although only Stonebridge went forward for use in the catchment model, they are a useful resource for the current forecasting system which still lumps the catchments upstream of those points. We recommend that where these recalibrated PDMs improve the performance of the forecasting system, they are implemented in NFFS alongside the new rating curves.

We developed a means of changing the target outflow from the Leigh FSA in the ISIS model. This would allow forecasters to run 'what if' scenarios with different pass forward flows in NFFS. We recommend that this functionality is incorporated into the NFFS configuration. It should be easier than using the spreadsheet separately. We also recommend investigating whether the 'optimisation routine' could be incorporated into NFFS - or at least part of it - to reduce the manual burden on forecasters. Note that there are complex command and control issues to work through before this is implemented.

Rating curves at Colliers Land Bridge and Vexour are very insensitive (i.e. water levels change little with a big increase in flow or, more importantly, the calculated flow changes enormously with a change in water level once the river is out of bank). Despite best efforts using detailed hydraulic models, uncertainty remains. If possible, we recommend check gaugings are carried out at out of bank flows at both sites. Recent developments in remotely controlled ADCP current meters may allow this. Ratings on the Eden at Edenbridge and Medway at Summerford are poor and considered innacurate. Work is required to bring these into line with the new ratings downstream on both rivers.

Another way to check the flow in the model would be to improve the calculation of outflow from the FSA. If that were reliable, volume checks between the two upstream gauges and the FSA outflow

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[30] DEFRA/EA (2011). Reservoir Safety – Long Return Period Rainfall. R&D Technical Report WS 94/2/39/TR Volume 1

[31] DEFRA/EA (2006) Joint Defra/EA Flood and Coastal Erosion Risk Management R&D Programme: Improved methods for national spatial-temporal rainfall and evaporation modelling for BSM R&D Technical Report F2105/TR

could be used to confirm the ratings are reasonable. We understand a new flow gauge is proposed at Lucifer Bridge, just downstream of the FSA. This would serve the same purpose and is strongly recommended.

Large numbers of errors in the rainfall data prior to 2006 were noted (and some after). A spreadsheet is available with periods identified as suspect by this project. We recommend that the Environment Agency tries to correct or flag these data by reference to adjacent/check gauges.

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Appendices

A Rainfall depth duration and frequency comparisons

A.1 Explanation

The sections that follow tabulate the depth, duration and frequency of rainfall from the:

- FEH CD-ROM version 3;
- Observed catchment average. This was done for the period of record available after 'cleaning' had taken place. We checked whether excluding data prior to 2006 made any difference to the overall results/conclusions and it did not; and
- Continuous simulation (with adjustments made)

Comparisons are made between different sets of data. Differences are colour mapped so that red is negative and blue is positive:

- Observed rainfall depths and the FEH statistics. Predominantly red - shows that observed depth is generally lower than the FEH.
- Adjusted CS rainfall depths and the FEH statistics - also predominantly lower than FEH (but matched more closely before the adjustments)
- Adjusted CS rainfall depths and the observed, smaller differences and a mixture of under and over prediction.
- Adjusted CS rainfall depths and the unadjusted. Shows the reduction in rainfall depths due to the adjustment process.

A.2 Eden to Vexour

Calculated rainfall depths from FEH catchment descriptors								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1	13.2	18.9	23.9	32.3	40.3	45.9	50.3	57.2
8	26.6	35.8	43.6	56.0	67.4	75.0	81.0	90.1
12	30.5	40.6	49.1	62.4	74.5	82.6	88.8	98.5
24	39.9	52.1	62.1	77.6	91.6	100.8	107.9	118.7
36	46.7	60.3	71.3	88.2	103.3	113.2	120.8	132.4
48	52.3	66.8	78.6	96.6	112.5	123.0	130.9	143.0
72	58.6	74.0	86.4	105.1	121.6	132.3	140.4	152.7
144	71.2	88.1	101.5	121.5	138.7	149.8	158.2	170.9
192	77.1	94.8	108.6	129.0	146.5	157.8	166.3	179.0

Rainfall from observed data (catchment average)								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	9.7	13.5	20.3	34.1				
8hrs	26.5	32.4	41	45.2				
12hrs	29.1	35	41	47.6				
24hrs	35.1	39	46.2	48.9				
36hrs	37.7	44.3	52.3	55				
48hrs	43.4	52.8	56.1	61.8				
72hrs	52.5	57.3	70.1	77				
144hrs	63.4	76	88.5	91.4				
192hrs	74.6	92.4	99.8	101.6				

Difference between observed and FEH rainfall statistics								
	2	5	10	25	50	75	100	150
Diff 1hrs	-26%	-28%	-15%	6%				
Diff 8hrs	0%	-10%	-6%	-19%				
Diff 12hrs	-5%	-14%	-16%	-24%				
Diff 24hrs	-12%	-25%	-26%	-37%				
Diff 36hrs	-19%	-26%	-27%	-38%				
Diff 48hrs	-17%	-21%	-29%	-36%				
Diff 72hrs	-10%	-23%	-19%	-27%				
Diff 144hrs	-11%	-14%	-13%	-25%				

Data from continuous simulation (adjusted)								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	9.8	12.5	14.5	18.5	21.6	24.9	25.7	26.5
8hrs	23.4	30.1	33.5	38.4	40.8	43.7	45.1	46.5
12hrs	25.3	32.8	37.9	43.6	47.7	50	52	53.2
24hrs	30.7	38.9	44.8	52.7	58.8	62.2	63.2	63.7
36hrs	35.8	44.9	51.7	60.4	67.5	72.1	73.3	74.7
48hrs	39.5	50.8	56.5	65.6	72.3	76.5	79.7	82.5
72hrs	46.9	59.3	66.4	76.3	83.6	91.1	94.5	96.4
144hrs	64.2	80.9	90.1	102.8	113.3	118.2	121.8	126
192hrs	73.8	91.5	101.3	116.6	123.7	129.9	136.7	141.4

Difference between CS and FEH rainfall statistics								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	-26%	-34%	-39%	-43%	-46%	-46%	-49%	-54%
8hrs	-12%	-16%	-23%	-31%	-39%	-42%	-44%	-48%
12hrs	-17%	-19%	-23%	-30%	-36%	-39%	-41%	-46%
24hrs	-23%	-25%	-28%	-32%	-36%	-38%	-41%	-46%
36hrs	-23%	-25%	-28%	-32%	-35%	-36%	-39%	-44%
48hrs	-24%	-24%	-28%	-32%	-36%	-38%	-39%	-42%
72hrs	-20%	-20%	-23%	-27%	-31%	-31%	-33%	-37%
144hrs	-10%	-8%	-11%	-15%	-18%	-21%	-23%	-26%
192hrs	-4%	-3%	-7%	-10%	-16%	-18%	-18%	-21%

Difference between CS and observed								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	1%	-7%	-29%	-46%				
8hrs	-12%	-7%	-18%	-15%				
12hrs	-13%	-6%	-8%	-8%				
24hrs	-13%	0%	-3%	8%				
36hrs	-5%	1%	-1%	10%				
48hrs	-9%	-4%	1%	6%				
72hrs	-11%	3%	-5%	-1%				
144hrs	1%	6%	2%	12%				
192hrs	-1%	-1%	2%	15%				

Difference between adjusted CS and unadjusted CS								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%
8hrs	-11%	-11%	-12%	-14%	-19%	-18%	-17%	-18%
12hrs	-10%	-11%	-11%	-12%	-14%	-15%	-14%	-13%
24hrs	-8%	-10%	-9%	-12%	-11%	-9%	-9%	-12%
36hrs	-7%	-9%	-9%	-11%	-12%	-9%	-10%	-11%
48hrs	-7%	-7%	-10%	-11%	-10%	-10%	-8%	-11%
72hrs	-6%	-8%	-10%	-10%	-10%	-8%	-7%	-10%
144hrs	-6%	-6%	-8%	-7%	-9%	-10%	-8%	-7%
192hrs	-5%	-6%	-8%	-7%	-9%	-10%	-8%	-7%

A.3 Medway to Colliers

Calculated rainfall depths from FEH catchment descriptors								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1	13.6	19.4	24.6	33.1	41.2	46.9	51.4	58.4
8	27.4	36.9	44.9	57.6	69.2	77.1	83.1	92.5
12	31.5	41.9	50.6	64.2	76.6	84.9	91.3	101.2
24	40.2	52.4	62.5	78.0	91.9	101.2	108.3	119.1
36	46.3	59.7	70.7	87.4	102.3	112.1	119.6	131.0
48	51.3	65.6	77.1	94.7	110.4	120.6	128.4	140.2
72	59.0	74.6	87.1	105.9	122.5	133.3	141.5	153.9
144	75.0	92.9	107.1	128.1	146.4	158.2	167.1	180.5
192	82.8	101.8	116.7	138.7	157.6	169.8	179.0	192.8

Rainfall from observed data (catchment average)								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	8.8	13.5	28	31.1				
8hrs	26.6	32.9	38.3	41.5				
12hrs	27.2	34.8	39.5	43.5				
24hrs	32.1	44.4	46.1	46.7				
36hrs	40.2	47.6	49.1	49.8				
48hrs	48.6	51.1	53.9	58.3				
72hrs	52.4	58.9	62	75				
144hrs	70.6	77.3	83.7	96.3				
192hrs	81.5	90.2	96.2	109.8				

Difference between observed and FEH rainfall statistics								
	2	5	10	25	50	75	100	150
Diff 1hrs	-35%	-30%	14%	-6%				
Diff 8hrs	-3%	-11%	-15%	-28%				
Diff 12hrs	-14%	-17%	-22%	-32%				
Diff 24hrs	-20%	-15%	-26%	-40%				
Diff 36hrs	-13%	-20%	-31%	-43%				
Diff 48hrs	-5%	-22%	-30%	-38%				
Diff 72hrs	-11%	-21%	-29%	-29%				
Diff 144hrs	-6%	-17%	-22%	-25%				

Data from continuous simulation (adjusted)								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	10.4	13.4	15.9	18.7	22.4	26.3	27.4	29.1
8hrs	24.6	30.7	34.6	40	42.2	44.3	45.5	47
12hrs	26.6	33.7	38.8	44.2	48.5	52.7	54.2	58.2
24hrs	32.2	40.7	45.7	52.9	59.6	62.1	63.5	65.3
36hrs	37.1	46.9	52.9	64	71.5	75.7	76.8	77.8
48hrs	41.3	52.1	59.6	69	76.3	80.3	81.6	82.5
72hrs	48.9	61.4	69	82.1	90.2	94.3	98.1	101.4
144hrs	67.7	84.7	94.2	107	119.2	126.5	129.4	132.3
192hrs	76.9	94.6	107.4	122.4	133.4	138.1	140.7	148.3

Difference between CS and FEH rainfall statistics								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	-24%	-31%	-35%	-43%	-46%	-44%	-47%	-50%
8hrs	-10%	-17%	-23%	-31%	-39%	-43%	-45%	-49%
12hrs	-15%	-19%	-23%	-31%	-37%	-38%	-41%	-42%
24hrs	-20%	-22%	-27%	-32%	-35%	-39%	-41%	-45%
36hrs	-20%	-21%	-25%	-27%	-30%	-32%	-36%	-41%
48hrs	-19%	-21%	-23%	-27%	-31%	-33%	-36%	-41%
72hrs	-17%	-18%	-21%	-22%	-26%	-29%	-31%	-34%
144hrs	-10%	-9%	-12%	-16%	-19%	-20%	-23%	-27%
192hrs	-7%	-7%	-8%	-12%	-15%	-19%	-21%	-23%

Difference between CS and observed								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	18%	-1%	-43%	-40%				
8hrs	-8%	-7%	-10%	-4%				
12hrs	-2%	-3%	-2%	2%				
24hrs	0%	-8%	-1%	13%				
36hrs	-8%	-1%	8%	29%				
48hrs	-15%	2%	11%	18%				
72hrs	-7%	4%	11%	9%				
144hrs	-4%	10%	13%	11%				
192hrs	-6%	5%	12%	11%				

Difference between adjusted CS and unadjusted CS								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	-21%	-20%	-20%	-20%	-20%	-20%	-20%	-20%
8hrs	-11%	-12%	-14%	-15%	-18%	-18%	-17%	-17%
12hrs	-11%	-12%	-9%	-13%	-15%	-12%	-15%	-11%
24hrs	-9%	-10%	-9%	-12%	-11%	-13%	-15%	-15%
36hrs	-8%	-9%	-10%	-9%	-12%	-11%	-11%	-12%
48hrs	-8%	-10%	-10%	-9%	-9%	-11%	-12%	-14%
72hrs	-8%	-9%	-8%	-8%	-9%	-10%	-9%	-9%
144hrs	-6%	-7%	-8%	-10%	-9%	-7%	-8%	-10%
192hrs	-6%	-8%	-7%	-7%	-7%	-9%	-10%	-8%

A.4 Teise to Stonebridge

Calculated rainfall depths from FEH catchment descriptors								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1	13.5	19.2	24.2	32.3	40.1	45.5	49.7	56.3
8	27.4	36.9	44.8	57.4	68.9	76.7	82.7	91.9
12	31.5	41.9	50.6	64.2	76.6	84.9	91.3	101.1
24	39.9	52.1	62.2	77.8	91.9	101.2	108.4	119.3
36	45.8	59.3	70.3	87.2	102.2	112.2	119.8	131.4
48	50.6	64.9	76.6	94.4	110.3	120.7	128.6	140.7
72	58.0	73.7	86.4	105.6	122.5	133.5	142.0	154.7
144	73.3	91.6	106.1	127.7	146.6	158.8	168.0	182.0
192	80.8	100.2	115.5	138.2	157.9	170.6	180.2	194.7

Rainfall from observed data (catchment average)								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	9.3	12.1	12.7	16.4				
8hrs	22	31.5	32.4	39.2				
12hrs	28.4	35	36.1	42.5				
24hrs	35.6	40	40.2	49.2				
36hrs	43	49.2	50	61.8				
48hrs	47.8	54.8	55	65.4				
72hrs	54.4	64.9	66	78.9				
144hrs	71.8	81.6	82.6	102.2				
192hrs	86.6	96.4	98.6	120.3				

Difference between observed and FEH rainfall statistics								
	2	5	10	25	50	75	100	150
Diff 1hrs	-31%	-37%	-47%	-49%				
Diff 8hrs	-20%	-15%	-28%	-32%				
Diff 12hrs	-10%	-16%	-29%	-34%				
Diff 24hrs	-11%	-23%	-35%	-37%				
Diff 36hrs	-6%	-17%	-29%	-29%				
Diff 48hrs	-6%	-16%	-28%	-31%				
Diff 72hrs	-6%	-12%	-24%	-25%				
Diff 144hrs	-2%	-11%	-22%	-20%				

Data from continuous simulation (adjusted)								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	11.1	14.1	16.2	19.2	23.3	25	26	28.1
8hrs	23.7	30.2	33.7	38.6	41.1	43	43.6	45
12hrs	25.9	32.6	37.5	42.5	46.6	49.4	50.2	52.1
24hrs	31.2	38.8	44.1	50.9	55	58.6	59.8	64.6
36hrs	36	45.1	51.1	57.2	62.3	69.4	71	73.7
48hrs	39.8	50.1	56.9	65.1	70.9	74.8	75.3	77.9
72hrs	47.1	59.4	66	77.8	83.8	88.5	91.7	94
144hrs	64.1	80.9	91.2	102.3	115.1	121.9	127	131.7
192hrs	73.5	92.1	101.4	116.4	126.4	137.3	142.7	146.4

Difference between CS and FEH rainfall statistics								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	-18%	-26%	-33%	-41%	-42%	-45%	-48%	-50%
8hrs	-14%	-18%	-25%	-33%	-40%	-44%	-47%	-51%
12hrs	-18%	-22%	-26%	-34%	-39%	-42%	-45%	-48%
24hrs	-22%	-26%	-29%	-35%	-40%	-42%	-45%	-46%
36hrs	-21%	-24%	-27%	-34%	-39%	-38%	-41%	-44%
48hrs	-21%	-23%	-26%	-31%	-36%	-38%	-41%	-45%
72hrs	-19%	-19%	-24%	-26%	-32%	-34%	-35%	-39%
144hrs	-13%	-12%	-14%	-20%	-21%	-23%	-24%	-28%
192hrs	-9%	-8%	-12%	-16%	-20%	-20%	-21%	-25%

Difference between CS and observed								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	19%	17%	28%	17%				
8hrs	8%	-4%	4%	-2%				
12hrs	-9%	-7%	4%	0%				
24hrs	-12%	-3%	10%	3%				
36hrs	-16%	-8%	2%	-7%				
48hrs	-17%	-9%	3%	0%				
72hrs	-13%	-8%	0%	-1%				
144hrs	-11%	-1%	10%	0%				
192hrs	-15%	-4%	3%	-3%				

Difference between adjusted CS and unadjusted CS								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%
8hrs	-13%	-13%	-15%	-14%	-19%	-18%	-18%	-17%
12hrs	-11%	-12%	-12%	-12%	-13%	-17%	-16%	-16%
24hrs	-10%	-11%	-11%	-13%	-12%	-12%	-13%	-12%
36hrs	-9%	-10%	-10%	-11%	-13%	-10%	-12%	-11%
48hrs	-9%	-10%	-9%	-11%	-10%	-11%	-13%	-11%
72hrs	-9%	-9%	-10%	-8%	-10%	-12%	-10%	-9%
144hrs	-7%	-8%	-7%	-10%	-8%	-7%	-7%	-9%
192hrs	-7%	-7%	-8%	-9%	-8%	-6%	-7%	-8%

A.5 Beult to Stilebridge

Calculated rainfall depths from FEH catchment descriptors								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1	13.4	19.1	24.0	32.2	40.1	45.5	49.7	56.4
8	26.6	35.8	43.5	55.8	67.1	74.7	80.6	89.7
12	30.3	40.4	48.9	62.1	74.2	82.3	88.6	98.2
24	38.6	50.6	60.4	75.7	89.4	98.5	105.5	116.2
36	44.5	57.6	68.4	84.9	99.7	109.4	116.9	128.3
48	49.2	63.2	74.7	92.2	107.7	117.9	125.7	137.6
72	55.3	70.4	82.6	101.0	117.3	127.9	136.1	148.4
144	67.7	84.6	98.1	118.2	135.7	147.1	155.7	168.7
192	73.6	91.3	105.3	126.1	144.2	155.9	164.7	178.0

Rainfall from observed data (catchment average)								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	7.7	8.8	12.5	10.2				
8hrs	20.5	24.8	29.4	28.2				
12hrs	23.8	27.8	35.6	31.8				
24hrs	30.3	32.7	38	37.7				
36hrs	34.6	40.8	43.3	42.6				
48hrs	38.4	45.7	51.8	49.5				
72hrs	45.6	54.6	59.6	59.2				
144hrs	60.9	78.7	86	81.8				
192hrs	68.1	85.2	108	101.4				

Difference between observed and FEH rainfall statistics								
	2	5	10	25	50	75	100	150
Diff 1hrs	-43%	-54%	-48%	-68%				
Diff 8hrs	-23%	-31%	-32%	-49%				
Diff 12hrs	-22%	-31%	-27%	-49%				
Diff 24hrs	-22%	-35%	-37%	-50%				
Diff 36hrs	-22%	-29%	-37%	-50%				
Diff 48hrs	-22%	-28%	-31%	-46%				
Diff 72hrs	-18%	-22%	-28%	-41%				
Diff 144hrs	-10%	-7%	-12%	-31%				

Data from continuous simulation (adjusted)								
File	**2**	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	10.2	12.9	14.9	17.4	19.9	21.4	23	23.9
8hrs	21.2	26.7	30.4	34.2	36.8	39.6	40.8	41.2
12hrs	22.9	29.1	32.8	38.3	43.3	45.3	46.1	48.5
24hrs	27.6	34.8	38.9	45.7	49.2	51.5	54.5	55.4
36hrs	31.9	40.6	45.9	52.3	57.5	61.1	63.6	65.1
48hrs	35.7	44.8	52	59	63.8	67	69.6	73.3
72hrs	42	53.8	60.7	69.8	77.8	80.7	82.8	83.5
144hrs	57.8	73	83.1	94.7	101.9	106.9	108.4	110.5
192hrs	66	82.6	92.7	104.8	115.8	124.3	127.5	131.5

Difference between CS and FEH rainfall statistics								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	-24%	-32%	-38%	-46%	-50%	-53%	-54%	-58%
8hrs	-20%	-25%	-30%	-39%	-45%	-47%	-49%	-54%
12hrs	-25%	-28%	-33%	-38%	-42%	-45%	-48%	-51%
24hrs	-29%	-31%	-36%	-40%	-45%	-48%	-48%	-52%
36hrs	-28%	-30%	-33%	-38%	-42%	-44%	-46%	-49%
48hrs	-27%	-29%	-30%	-36%	-41%	-43%	-45%	-47%
72hrs	-24%	-24%	-26%	-31%	-34%	-37%	-39%	-44%
144hrs	-15%	-14%	-15%	-20%	-25%	-27%	-30%	-35%
192hrs	-10%	-10%	-12%	-17%	-20%	-20%	-23%	-26%

Difference between CS and observed								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	32%	47%	19%	71%				
8hrs	3%	8%	3%	21%				
12hrs	-4%	5%	-8%	20%				
24hrs	-9%	6%	2%	21%				
36hrs	-8%	0%	6%	23%				
48hrs	-7%	-2%	0%	19%				
72hrs	-8%	-1%	2%	18%				
144hrs	-5%	-7%	-3%	16%				
192hrs	-3%	-3%	-14%	3%				

Difference between adjusted CS and unadjusted CS								
	2	**5**	**10**	**25**	**50**	**75**	**100**	**150**
1hrs	-20%	-20%	-20%	-20%	-20%	-20%	-20%	-20%
8hrs	-10%	-12%	-11%	-14%	-15%	-16%	-16%	-18%
12hrs	-11%	-10%	-11%	-10%	-14%	-14%	-14%	-11%
24hrs	-9%	-10%	-10%	-8%	-13%	-14%	-11%	-16%
36hrs	-8%	-9%	-9%	-11%	-9%	-8%	-11%	-13%
48hrs	-8%	-9%	-9%	-8%	-8%	-11%	-12%	-9%
72hrs	-7%	-7%	-7%	-8%	-7%	-11%	-11%	-12%
144hrs	-6%	-6%	-6%	-5%	-8%	-8%	-8%	-8%
192hrs	-5%	-5%	-5%	-7%	-7%	-6%	-6%	-9%

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B Model Summary Reports

B.1 General

Model summary reports are presented for the:

- Upper Medway;
- Beult; and
- Middle Medway.

Model evaluation sheets for the lumped PDMs are included for the:

- Eden at Vexour;
- Medway at Colliers Land Bridge;
- Teise at Stonebridge;
- Beult at Stilebridge; and
- Led at Lenside.

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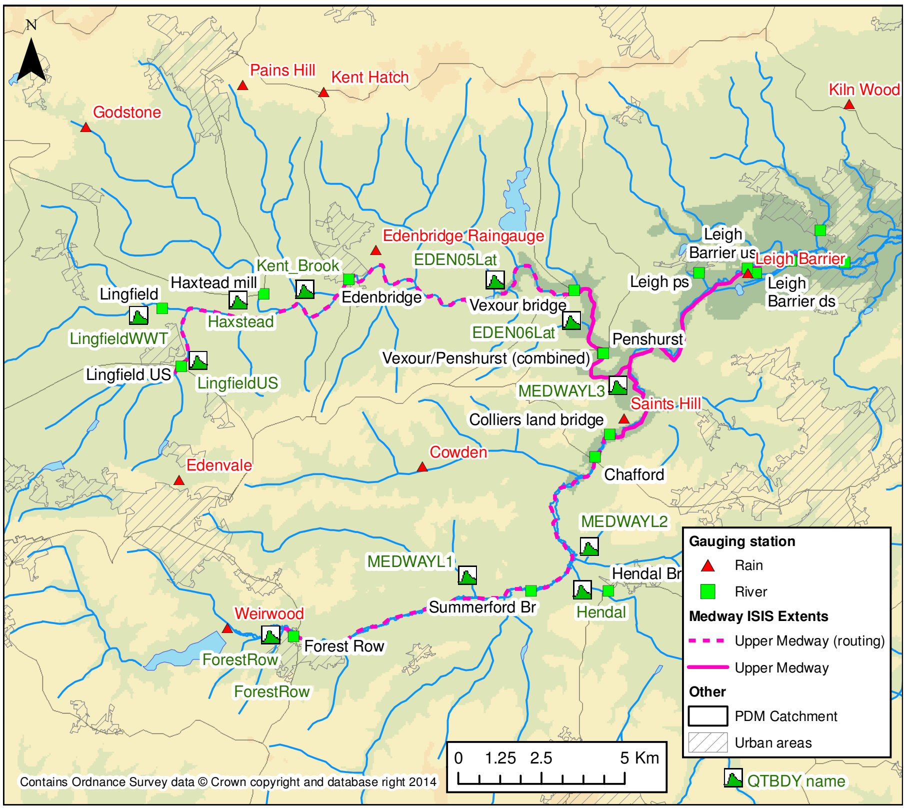
Catchment map



1 River model documentation

1.1 Background

1.1.1 Context

This catchment model (combination of ISIS 1d/routing and PDM rainfall runoff models) is needed to identify design events from a continuously simulated (CS) flow series. It is the first model in a network reaching from the headwaters of the Eden and Medway to East Farleigh. It extends to a point immediately downstream of the Leigh Flood Storage Area (FSA).

Rainfall is continuously simulated at an hourly interval over a 5,000 year period. PDM models representing each sub catchment (see Table "PDM Parameters" above in report template) are executed using the rainfall. Outputs from these PDMs are then fed into the ISIS model via QTBDYs (see Table "Boundaries for ISIS model LeighBarrier01.DAT").

A set of the largest events from lumped PDM simulations at Colliers Land Bridge, Vexour, Stonebridge and Stilebridge are then simulated using the ISIS model. Results at any particular node are then be ranked and the event that gives a design flow identified (using the Gringorton formula). The ISIS IED file giving rise to that event may then be simulated in the fully hydraulic ISIS-TUFLOW model to give flood extents for that return period.

1.1.2 Key hydraulic features

Both the Eden and Medway have extensive floodplains. These tend to attenuate lesser floods. Large floods, like December 2013, are much less attenuated as storage tends to be exhausted by the time the peak arrives. The floodplains are important hydraulic features of the river system.

Leigh Barrier is the other main hydraulic feature. Commissioned in 1982 to protect Tonbridge, it is an on-line flood storage area that seeks to limit pass forward flow to 75m3/s. Flows are restricted by three radial gates (shown below - photo courtessy of bbc.co.uk). Water is stored upstream on the floodplain.

1.1.3 Hydrological features

Located in South East England, the Medway is a low lying river system with moderately low annual average rainfall. High summer evaporation rates combine with deep soils and low rainfall to accumulate a large soil moisture deficit. Floods tend to be seasonal therefore - occuring most often in the winter months.

Headwater catchments are steepest, particularly in the Upper Medway. There is a significant reservoir at Weir Wood (also in the Upper Medway).

The catchment has two main tributaries: the Eden and the Medway. These converge just upstream of the FSA. The Medway usually peaks first and is less attenuated than the Medway.

The catchment can generate extreme flows. In 1968, flow rates exceeded 9 x QMED at Vexour on the Eden.

1.1.4 Available data

Hydrometric data is fairly plentiful (see map). Flows are gauged at two small sub-catchments: Lingfield ultrasonic and Hendal. Outflows from the entire Eden and Medway are gauged at Vexour and Colliers Land Bridge. Rating curves at all these locations (bar Hendal) have been developed for this project and are considered reliable.

Water levels are also recorded at Lingfield WWTW and Haxstead in the Eden catchment and Forest Row and Summerford Bridge on the Medway. Water levels are monitored in the Leigh FSA and downstream.

The rain gauge network is also reasonable (see Map). Data before 2006 is often suspect however and has been subject to significant editing for this project.

1D models of the Eden, Medway and Leigh FSA were available.

Most river gauges are listed in the Table "Model calibration points" and rain gauges in "Rain gauge weights**".**

1.2 River model development

1.2.1 Model Type

The starting point for this model was the existing forecasting model of the Medway. It begins at Vexour on the Eden and Colliers Land Bridge on the Medway. It is a 1D ISIS model that contains the Leigh FSA and the gates, controlled by logical rules. It was essential that this part of the model was hydraulic to represent the storage area.

Extending the model upstream was necessary to reach all locations covered by the mapping model. Its eventual extent is shown in the Map at the begining of this document.

As this model was only being used to route flows, and identify a design event to apply to the mapping model, it was sufficient to model these reaches using flow routing methods. Later comparisons showed that the 1D mapping model performed comparably to the routing model.

The final model file is called LeighBarrier01.DAT

1.2.2 Model Development

The Leigh FSA is modelled in 1D. Geometry is based on the forecasting model, supplied as part of the NFFS configuration (supplied DATE). The remainder of the river network is modelled using Variable Parameter Muskingum Cunge (VMPC) units.

1.2.2.1 Leigh Barrier

The following changes were made to the 1D part of the model:

The North and South gates were lumped into one (CSM61NU). Its logical rules were altered to maintain a target pass-forward flow (i.e. the logical rules 'MOVE' the gate). Previously, the gate was set to a position according to the water level in the reservoir (which also gave the required pass forward flow). The rules are shown below:

```
01. u/s level < 24.00
IF (HEAD(CSM61NU).LT.24)
THEN POSITION = 0
END
02. 24.00 <= u/s level < 24.14
IF (HEAD(CSM61NU).GE.24.AND.HEAD(CSM61NU).LT.24.14)
THEN MOVE = -0.01
END
03. 24.14 <= u/s level < 24.2
IF (HEAD(CSM61NU).GE.24.14.AND.HEAD(CSM61NU).LT.24.2)
THEN MOVE = 0
END
04. 24.20 <= u/s level < 24.35 and opening < 1
IF (HEAD(CSM61NU).GE.24.2.AND.HEAD(CSM61NU).LT.24.35.AND.USTATE(CSM61NU).LT.1)
THEN MOVE = +0.01
END
05. 24.20 <= u/s level < 24.35 and opening >= 1
IF (HEAD(CSM61NU).GE.24.2.AND.HEAD(CSM61NU).LT.24.35.AND.USTATE(CSM61NU).GE.1)
THEN MOVE = -0.01
END
06. 24.35 <= u/s level < 28.05 and Outflow >= Regulated Flow
IF (HEAD(CSM61NU).GE.24.35.AND.HEAD(CSM61NU).LT.28.05.AND.FLOW(CS1).GT.FLOW(Opening)*100+2)
THEN MOVE = -0.15
END
07. 24.35 <= u/s level < 28.05 and Outflow <= Regulated Flow
IF (HEAD(CSM61NU).GE.24.35.AND.HEAD(CSM61NU).LT.28.05.AND.FLOW(CS1).LT.FLOW(Opening)*100-2)
THEN MOVE = +0.05
END
08. 24.35 <= u/s level < 28.05 and Outflow = Regulated Flow
IF   (HEAD(CSM61NU).GE.24.35.AND.HEAD(CSM61NU).LT.28.05.AND.FLOW(CS1).GE.FLOW(Opening)*100-
2.AND.FLOW(CS1).LE.FLOW(Opening)*100+2)
THEN MOVE = 0
END
10. 28.05 <= u/s level, h0 < 4
IF (HEAD(CSM61NU).GE.28.05.AND.USTATE(CSM61NU).LT.4)
THEN MOVE = +0.01
END
11. 28.05 <= u/s level, h0 >= 4
IF (HEAD(CSM61NU).GE.28.05.AND.USTATE(CSM61NU).GE.4)
THEN POSITION = 4
END
```

An abstraction unit, called 'opening', was added to the model. This is used as a variable. The larger gate's logical rules refer to this abstraction unit to know the pass forward flow. This arrangement allows us to 'inject' a new regulation rate part way through a model run i.e. the flow rate in 'opening' can be set for times and the model will respond by regulating to that flow.

An additional logical rule was added to open the central gate when the level in the reservoir exceeds the legal limit of 28.05mAOD. The central gate rules are as follows (with the last rule being the newest).

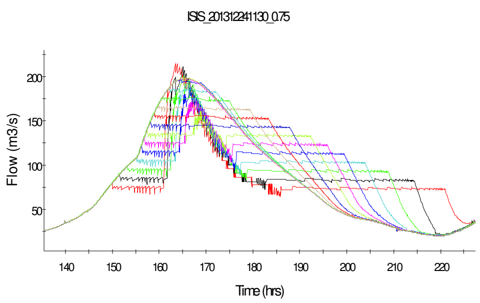
```
01 h1 < 24.35 - gate open
IF (HEAD(CSM61CU).LT.24.35)
THEN POSITION = 2.0
END
02 24.35 <= h1 < 28.050 - gate closed
IF (HEAD(CSM61CU).GE.24.35.AND.HEAD(CSM61CU).LT.28.05)
THEN POSITION = 0.0
END
03 h1 >= 28.050 - gate open
IF (HEAD(CSM61CU).GE.28.05)
THEN POSITION = 3.0
END
```

In simple terms, the lumped gate attempts to limit flows to the rate specified in 'Opening' multiplied by 100 (to keep that number small). There is a 'dead zone' of +/-2m3/s either side of this traget where the gate does not move. This was introduced to reduce hunting. If levels reach or exceed 28.05m then the gate will open to its maximum setting of 4m.

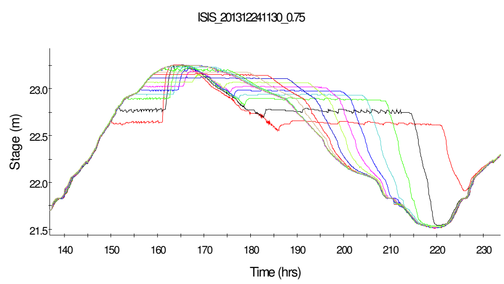
The Central Gate sits open at low flows, but closes as soon as an event begins. It only re-opens if the main gates cannot keep the level below 28.05mAOD. If that level is reached, it opens to its full extent of 3m.

As a result of these rules, the reservoir can limit pass forward flow to a variable amount (as shown for the December 2013 event below). When storage is exhausted, the rules pass forward enough flow to maintain 28.05m in the reservoir (i.e. the inflow is passed forward unattenuated).

Flows out of Leigh FSA for a range of flow regulation rates for December 2013



Levels in Leigh FSA for a range of regulation rates for December 2013



1.2.2.2 Eden and Medway river network

The Eden and Medway reaches are built from VPMC units of > 1,000m in length. The units have a fixed wavespeed of 0.5 or 0.6m/s. Wavespeeds were obtained by:

- Initially analysing the time taken for peaks to translate from Eden Bridge to Vexour on the Medway; and
- Checking sensitivity and, if necessary, calibrating on the basis of observations.

Floodplains are not represented explicitly in the model, only by implementing a slow wavespeed.

1.3 Model boundaries

1.3.1 Flow boundaries

All of the catchment draining to the river model is simulated using PDM. This approach was chosen (rather than scaling some inputs from observed data) because the ultimate aim of the model was to continuously simulate flows uing a stochastic rainfall series. This requires a conceptual rainfall runoff model, capable of continuous soil moisture accounting, like PDM.

Table "PDM Parameters" (above) lists the PDM parameters used for each catchment and Table "Boundaries for ISIS model LeighBarrier01.DAT" shows how they are fed to the ISIS model.

The method for obtaining PDM parameters was to:

- Calibrate PDMs for the lumped gauged catchments available, including Lingfield Ultrasonic (using a rating developed from ultrasonic data), Forest Row (using a rating from a hydraulic model), Hendal (using the existing NFFS rating), Colliers Land Bridge (using our new rating) and Vexour (also using our new rating).
- Set rain gauge weights according to their location relative to the catchment (and some adjustment through calibration)
- Transfer PDM parameters from the gauged catchments to the ungauged ones
- Where gauged levels existed (e.g. Haxstead Mill, Lingfield WWTW), the surface routing contstant was adjusted to match the hydrograph shape.
- Validate the performance of the entire catchment model at Vexour, Colliers Land Bridge and Leigh FSA (actually the sum of Vexour and Colliers).

Most of the ungauged lateral inflows have parameters transferred from Lingfield Ultrasonic, although with a reduced soil store (Cmax of 250mm, adjusted during calibration at Vexour and Colliers). This gauged catchment had catchment characteristics most similar to the other ungauged inputs.

The PDMs were validated at Vexour and Colliers Land Bridge where flows are available - see Section 1.4 for results.

1.3.2 Downstream boundary

The model's downstream boundary is a rating curve just downstream of the Leigh FSA gates. The only change from the forecasting model is that it has been extrapolated to allow runs to a much higher flow than previously. The model is not sensitive to the boundary once the gates are operational as they create a large head difference and do not drown.

1.4 Simulation performance

1.4.1 Calibration points

The table "Model calibration points" lists all the nodes in the model having useful observed data for comparison against stimulations. For the routing reaches (upstream of Vexour and Colliers) this needed to be flow. Water levels could also be compared for the hydraulic reaches (where water level is simulated). Altogether there are ten nodes in the model where comparisons could be made between simulated and observed flows (9) and/or levels (2).

Although 47 events were simultated between November 1998 and April 2014, the first four were discarded because the rainfall could not be corrected. Rainfall is only considered properly reliable after April 2006.

Model results are presented as 'model evaluation sheets' and an explanation of their layout and contents is available at the begining of this Appendix.

1.4.2 Accuracy

The main points from each model evaluation sheet are outlined below:

Eden Brook @ Lingfield Ultrasonic

Observed flows are calculated using a rating derived from ultrasonic flows by us for this project.

This is a model boundary, so flows are from a PDM model. Although observed data can be patchy, the model fit (when data are present) is excellent. This site was a key donor of PDM parameters to ungauged inputs to the model.

Eden @ Eden Bridge

This node is part-way down the River Eden, upstream of Vexour. Observed flows are calculated using a rating from NFFS. It is highly suspect and flow volumes calculated using it do not tally with expectations from Vexour. Despite this, three of the four largest event peaks are predicted within 8%.

Eden @ Vexour

Observed flows are calculated using the new rating, derived for this project. This is the last point with observed data on the Medway and has the most complete/reliable series. Model predictions match the observed reasonably well for the 10 largest events simulated, with a tendency for over prediction in lesser events. Hydrograph shape and timing is generally good.

Medway @ Forest Row

Observed flows are calculated at Forest Row using a rating curve from the 1D mapping model. This is a model boundary, so flows are from a PDM model. Data are only available from 2002, but the model fit is very good, especially considering that there is a sizable reservoir (Weir Wood) in the catchment.

Mottsmill Stream @ Hendal

Observed flows are calculated using the rating in NFFS. The site appears to be subject to out of bank flow not captured in the rating equation (observed flows in large events all tend towards a peak of around 30m3/s). This is a model boundary, so flows are from a PDM model. Performance is mixed, with a lot of variability. The PDM also predicts higher flows than those indicated by the rating - thought to be a result of bypassing or out of bank flows.

Medway @ Summerford Bridge

Summerford Bridge gauges the Medway before the Mottsmill Stream, River Grom and Kent Water join. There is a wide floodplain at this point. Observed flows are calculated using the rating in NFFS and appear to be suspect, with lower levels calculated as having a higher flow than they should and the highest levels a lower flow. It is difficult to make meaningful comparisons with the observed series at this point, but the mapping model (which predicts level as well as flow) has given reasonable results for observed events for this location.

Medway @ Colliers Land Bridge

Observed flows are calculated using the new rating, derived for this project. The rating is highly insensitive and subject to significant uncertainty due to extensive out of bank flow. This is the last point with observed data on the Medway and has the most complete series. Model performance here is good in the largest events, like December 2013, where the floodplain is conveying large quantities of water. In events smaller than this, the model predicts higher flows than the rating. This could be a problem with the rating's sensitivity, lack of attenuation by the model, or too much flow generated by PDMs (or a combination of the three).

Ultimately, the flow series' feeding the model were scaled to ensure that the desired flood frequency was acheived at Colliers Land Bridge. This makes the model's tenedency to predict higher-than-rated flows less of an issue, although the model's usefulness as a forecasting tool would be affected by this.

Medway @ Leigh FSA inflow

An observed inflow series for the Leigh FSA was calculated by summing flows (calculated using the new ratings) from Vexour and Colliers Land Bridge. This is compared to the flow in the model at the node MEDWAY13, just downstream of the confluence and having some travel time from the gauges. This location difference explains why the model series is a little later than the observed. Performance of the model is good here, but there is still evidence of over prediction. The same potential reasons for the this behaviour exist at this node as at Colliers Land Bridge (as the same observed data are used).

Medway @ Leigh FSA level

The observed level series in the Leigh FSA is intermittent and our series ends in 2012 - with only 11 of the events simulated having data (December 2013 is not one of these). The data need to be understood in the context of the inflows to the barrier (Medway @ Leigh FSA inflow) and the outflows from the barrier (Medway @ Leigh FSA outflow below). The model works well in terms of FSA level for February 2009 and is known to have worked reasonably well in December 2013 (information from the operational spreadsheet). The model under predicts levels in a few smaller events, indicating that inflows are smaller than observed, or that there was more outflow than the model predicts (see sheet below for outflow calculations).

Medway @ Leigh FSA outflow

Flows are monitored at the Leigh FSA gates, based on their position and the water level in the impoundment. Observations therefore depend on how the gates have been operated. Observed flow data out of the barrier are only availble for 15 of the 47 events. Model performance is reaonable in terms of volume (see below), although there is a tendency to under predict for some events. December 2013 observations are incomplete, so the volume comparison is not valid (but the hydrograph shapes look reasonable).

The main points of these data are that:

- Flows and volumes for December 2013 appear slightly higher than implied by the data; and
- Flows and volumes for other events are broadly reasonable, but with a slight under predictive bias.

Given that the model over predicts flow at Colliers and Vexour, this throws up some possible data issues between the two. The model appears to work sensibly however.

1.4.3 Predominant sources of error

There are three main sources of error in simulations for the Upper Medway:

Runoff rates vary significantly for the Medway because of the large summer soil moisture deficit. Modelling the transition from dry catchment to wet catchment (and vice versa) is always a challenge for hydrological models. Runoff rates can therefore contain significant errors, particularly around these seasonal changes.

Floodplain attenuation is another potential source of error for the Eden and Medway. There appears to be significant overbank storage in the river system, even at moderate flows. This attenuates the flow hydrograph. In larger events, the attenuation is less evident as the floodplain 'fills' and stops storing quite as much water.

Obsevered data is also a significant source of error. Rainfall prior to 2006 is often suspicious and some of the Autumn 2000 events could not be reliably simulated because of this. The large floodplain and poor containment of flows is also a significant challenge for flow measurement. Even the primary flow gauges at Vexour and Colliers Land Bridge are highly insensitive at high flows, introducing significant uncertainty. Other rating curves, such as Eden Bridge and Summerford Bridge just seem incorrect (but it was outside the scope of this project to correct them).

1.4.4 Potential for model improvement

The model appears to predict larger flows with a good level of accuracy. Lesser events are over predicted compared to observations at Vexour and Colliers, but not at Leigh Barrier. It may be that the insensitive rating curves at Vexour and Colliers are less accurate than the flows at Leigh Barrier. In this case the model's representation of the hydrological response of the catchment is satisfactory.

The model's representation of the floodplain is imperfect. There is sometimes too little attenuation of peak flows at lower discharge rates. However, for events that are likely to cause concern, this is not a serious issue.

If the model were to be used as a forecasting tool (to allow better prediction further upstream in the catchment) then the following improvements might be considered:

- Improvement of the rating curves at Eden Bridge and Summerford Bridge, followed by a check on hydrological performance there.
- Possibly introduce error correction at those locations (and headwater catchments that are gauged) by splitting the model.
- Test whether replacing some of the routing reaches with the existing 1D model improves attenuation and hydrograph shape at Vexour and Colliers.

Boundaries for ISIS model LeighBarrier01.DAT

Type	Node	Source	Name	Scale or offset	Lag	PDM Area (km2)
QTBDY	ForestRow	PDM	ForestRow			50
QTBDY	MEDWAYL1	PDM	MEDWAYLat01			75
QTBDY	MEDWAYL2	PDM	MEDWAYLat02			75
QTBDY	MEDWAYL3	PDM	EdenLat01	*0.5	0	36.5
QTBDY	Hendal	PDM	Hendal			52
QTBDY	EDEN06Lat	PDM	EdenLat01	*0.5	0	36.5
QTBDY	EDEN05Lat	PDM	EdenLat01	*0.5	0	36.5
QTBDY	KentBrook	PDM	Kent_Brook	*1.24	0	16.1
QTBDY	Haxstead	PDM	HaxsteadMill	*1.24	0	64.5
QTBDY	LingfieldWWT	PDM	LingfieldWWT	*1.24	0	39.7
QTBDY	LingfieldUS	PDM	Lingfield	*1	0	29.5
					Total	**511.3**

Model calibration points

Type	Node	Source	Name
Flow	LingfieldUS	Observed	453650001SG (Flow) - LINGFIELD GS
Flow	EdenBridge	Observed	453610001SG (Flow) - Edenbridge
Flow	MEDWAY13	Observed	CollieresVexour (Flow) - Not Known
Flow	Vexour	Observed	453600002HSG (Flow) - VEXOUR BRIDGE
Flow	ForestRow	Observed	453500005SG (Flow) - FOREST ROW TELEMETRY RL
Flow	Hendal	Observed	453520001SG (Flow) - Hendal Bridge
Flow	Summerfd	Observed	453500004SG (Flow) - SUMMERFORD BRIDGE RL
Flow	Colliers	Observed	453400001HSG (Flow) - COLLIERS LAND BRIDGE
Level	CSM61	Observed	E15611SG (Stage) - Leigh Gate US
Level	CS10	Observed	453400019SG (Stage) - Leigh Barrier D/S
Flow		Observed	453400018FQ (Flow) - LEIGH BARRIER

Notes:

Model run with 47 events from the period 01 Nov 1998 to 01 Feb 2014; see individual model evaluation sheets for results

An asterisk (*) indicates scaling in the 'scale' column, otherwise the value is an offset (e.g. datum) - added or subtracted from the raw time series

The area calculated for boundaries is the product of PDM Area and scaling factor

Where two PDMs are indicated for a boundary, their flows are summed to give a combined input

ISIS model documentation for LeighBarrier01.DAT

Rain gauge weights

Name	**Area (km2)**	**COWDEN LOGGER**	**EDEN VALE STW RTS**	**EDENBRIDGE STW RTS**	**GODSTONE STW RTS**	**Jarvis Brook**	**KENT HATCH RES tbr**	**PAINS HILL RES RTS**	**REDGATE MILL tbr**	**Saints Mill**	**Weir Wood Res RF**
ForestRow	50		0.1								0.9
MEDWAYLat01	75	0.33	0.33								0.33
MEDWAYLat02	75					0.33			0.33		0.33
EdenLat01	73	0.325		0.175			0.162	0.162		0.175	
Hendal	52					0.861			0.082	0.057	
Kent_Brook	13			0.259			0.481	0.259			
HaxsteadMill	52		0.065		0.607		0.093	0.234			
LingfieldWWT	32		0.35		0.65						
Lingfield	29.52		0.9								0.1

PDM parameters

Area	**Fc**	**Cmin**	**Cmax**	**b**	**Be**	**Kg**	**Bg**	**St**	**K1**	**K2**	**Kb**	**QConst**	**Tdly**
Km^2		**mm**	**mm**					**mm**	**hrs**	**hrs**	**hmm^2**	**m^3/s**	**hrs**
ForestRow			**Surf.**	Linear cascade			**Base**	Cubic store		**Drainage**		Gravity	
50	1.1	40	140	1.2	4	3000	1.8	50	3	7	0.5	0	2
MEDWAYLat01			**Surf.**	Identical linear cascad			**Base**	Cubic store		**Drainage**		Gravity	
75	1	30	250	0.4	4	120000	1.8	40	3.5	n/a	0.5	0	0
MEDWAYLat02			**Surf.**	Identical linear cascad			**Base**	Cubic store		**Drainage**		Gravity	
75	1	30	250	0.4	4	120000	1.8	40	3	n/a	0.5	0	0
EdenLat01			**Surf.**	Identical linear cascad			**Base**	Cubic store		**Drainage**		Gravity	
73	1	30	250	0.4	4	120000	1.8	40	4.286	n/a	0.5	0	0
Hendal			**Surf.**	Linear Cascade			**Base**	Cubic store		**Drainage**		Gravity	
52	1	0	150	0.2	1	20000	2.3	89.32	4.067	5.988	100.1	0	0.02
Kent_Brook			**Surf.**	Identical linear cascad			**Base**	Cubic store		**Drainage**		Gravity	
13	1	30	250	0.4	4	120000	1.8	40	6	n/a	0.5	0	0
HaxsteadMill			**Surf.**	Identical linear cascad			**Base**	Cubic store		**Drainage**		Gravity	
52	1	30	250	0.4	4	120000	1.8	40	6	n/a	0.5	0	0
LingfieldWWT			**Surf.**	Identical linear cascad			**Base**	Cubic store		**Drainage**		Gravity	
32	1	30	250	0.4	4	120000	1.8	40	9.6	n/a	0.5	0	0
Lingfield			**Surf.**	Identical linear cascad			**Base**	Cubic store		**Drainage**		Gravity	
29.52	1	30	300	1	4	30000	1.7	20	5	n/a	0.5	0	0

Notes:

Please refer to PDM documentation for a definition of parameters

Rating details

Gauge Ref		453650001SG	**Name**	LINGFIELD GS				
No.	**Limb**	**Description**	**K**	**a**	**p**	**Max.**	**Start**	**End**
575	a	Fitted to US	6.500	-48.820	1.500	49.21	01 Apr 1997	01 Jan 2050

575	b			4.000	-48.720	1.300	50.04	01 Apr 1997	01 Jan 2050
575	c			5.000	-48.950	1.600	55.00	01 Apr 1997	01 Jan 2050
Gauge Ref		453610001SG	**Name**	Edenbridge					
99	a	XML		6.766	-37.323	1.432	37.75	01 Jan 1970	01 Jan 2100
99	b	XML		6.766	-37.323	1.432	38.03	01 Jan 1970	01 Jan 2100
99	c	XML		7.426	-37.422	1.185	38.46	01 Jan 1970	01 Jan 2100
99	d	XML		5.585	-37.229	1.582	39.15	01 Jan 1970	01 Jan 2100
99	e	XML		24.852	-38.808	0.428	39.43	01 Jan 1970	01 Jan 2100
99	f	XML		5.670	-37.769	2.520	40.38	01 Jan 1970	01 Jan 2100
Gauge Ref		ColliersVexour	**Name**	Colliers plus Vexour (no rating identifier)					
Gauge Ref		453600002HSG	**Name**	VEXOUR BRIDGE (tabular rating)					
Gauge Ref		453500005SG	**Name**	FOREST ROW TELEMETRY RL (tabular rating)					
Gauge Ref		453520001SG	**Name**	Hendal Bridge					
99	a	XML		22.001	0.020	2.750	0.00	01 Jan 1970	01 Jan 2100
99	b	XML		22.001	0.020	2.750	0.11	01 Jan 1970	01 Jan 2100
99	c	XML		15.609	0.014	2.523	0.31	01 Jan 1970	01 Jan 2100
99	d	XML		10.759	-0.100	1.588	1.00	01 Jan 1970	01 Jan 2100
99	e	XML		10.593	-0.096	1.364	1.48	01 Jan 1970	01 Jan 2100
99	f	XML		0.713	1.500	2.882	2.04	01 Jan 1970	01 Jan 2100
99	g	XML		0.055	3.190	3.755	3.00	01 Jan 1970	01 Jan 2100
Gauge Ref		453500004SG	**Name**	SUMMERFORD BRIDGE RL					
99	a	XML		2.768	-38.700	2.442	39.43	01 Jan 1970	01 Jan 2100
99	b	XML		4.490	-39.000	1.628	41.07	01 Jan 1970	01 Jan 2100
99	c	XML		0.044	-36.744	3.977	41.78	01 Jan 1970	01 Jan 2100
99	d	XML		0.005	-37.384	5.803	42.07	01 Jan 1970	01 Jan 2100
99	e	XML		34.236	-41.000	1.961	42.56	01 Jan 1970	01 Jan 2100
Gauge Ref		453400001HSG	**Name**	COLLIERS LAND BRIDGE (tabular rating)					
Gauge Ref		453400018FQ	**Name**	LEIGH BARRIER (no rating identifier)					

Notes:

Rating equation has the form Q=K*(Stage+a)^p

Stations where flows are stored, and not calculated from a rating, may be listed without a rating

General notes:

Ratings database used: N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\00 Ratings Database\2013s7661 - Medway Rating DB Modelled Ratings Active.accdb

Form settings: N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\Leigh_SIM - Cascade.BTD

Eden Bridge

Data summary

40 peaks analysed at EdenBridge between 20.1m3/s and 77.6m3/s, for period 30 Oct 2000 to 01 Feb 2014 from :

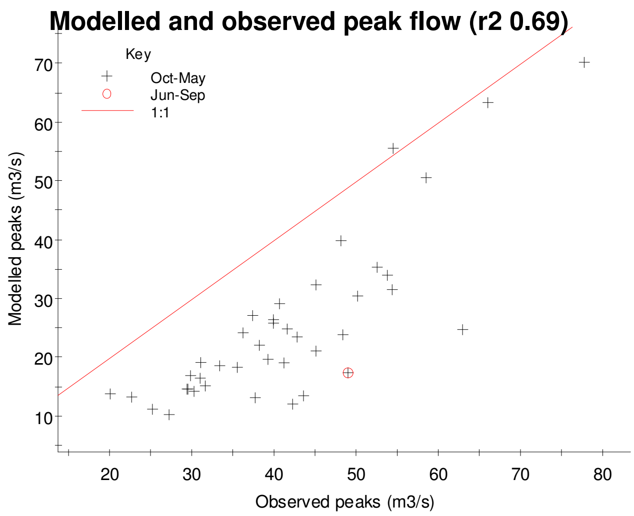
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\09 Cascade

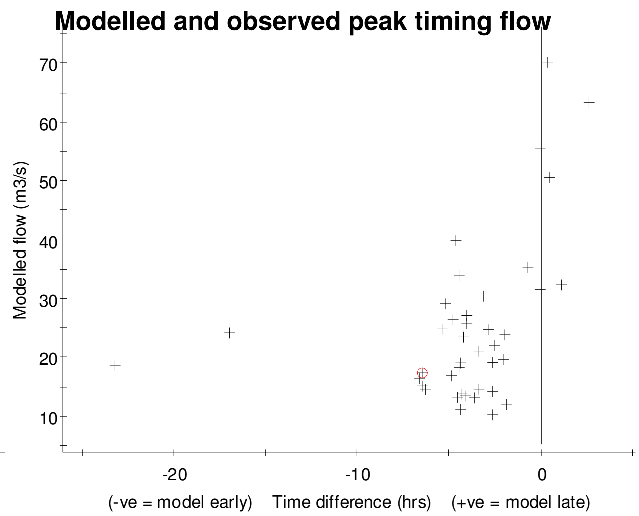
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	77.58	70.17	-7.4	-10%	0.3	0.628	0.902	9.66
2	17 Jan 2014 17:30	65.91	63.34	-2.6	-4%	2.6	0.897	0.914	4.56
3	30 Oct 2000 18:30	62.81	24.86	-38.0	-60%	-2.9	0.233	0.702	13.04
4	31 Dec 2002 04:30	58.40	50.64	-7.8	-13%	0.4	0.567	0.860	8.82
5	01 Feb 2014 12:30	54.40	55.61	1.2	2%	-0.1	0.326	0.375	11.28
6	16 Jan 2008 01:30	54.29	31.63	-22.7	-42%	-0.1	0.541	0.901	8.60
7	06 Nov 2000 19:30	53.68	34.08	-19.6	-37%	-4.5	0.500	0.837	10.43
8	10 Feb 2009 10:30	52.47	35.46	-17.0	-32%	-0.8	0.738	0.912	5.87
9	13 Dec 2000 10:30	50.10	30.58	-19.5	-39%	-3.2	0.515	0.856	8.82
10	12 Jul 2012 22:30	48.93	17.57	-31.4	-64%	-6.5	0.041	0.659	10.63

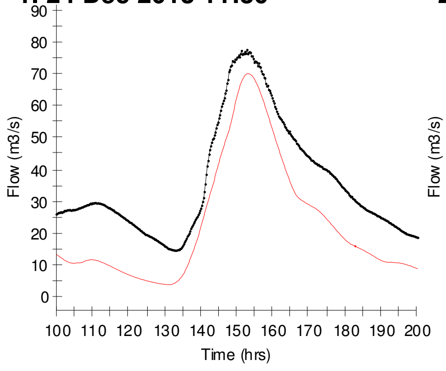
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.76	3.94	3.75	1.84	2.84	0.88	0.20	2.19

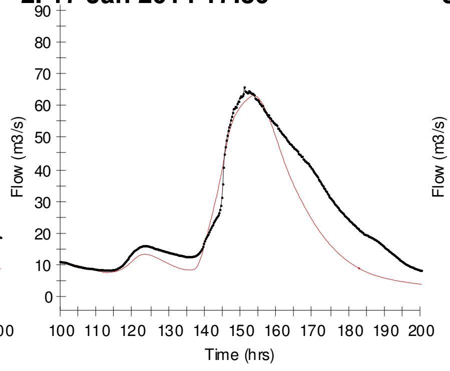




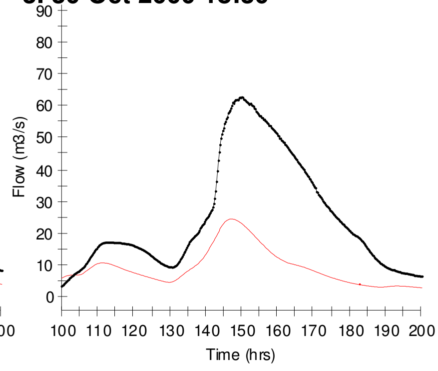
1. 24 Dec 2013 11:30



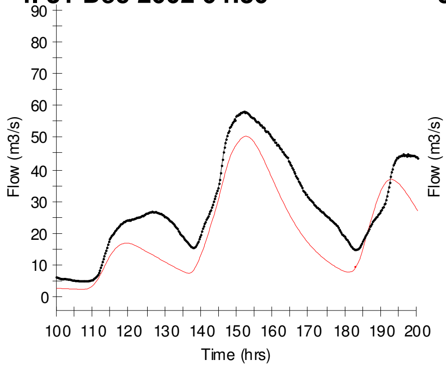
2. 17 Jan 2014 17:30



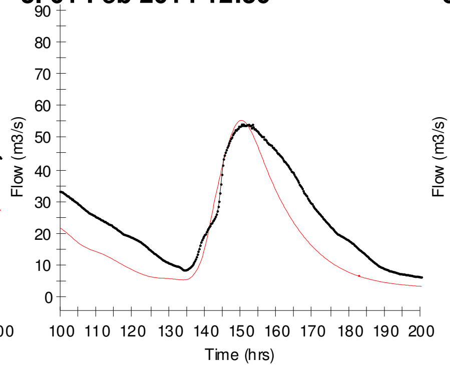
3. 30 Oct 2000 18:30



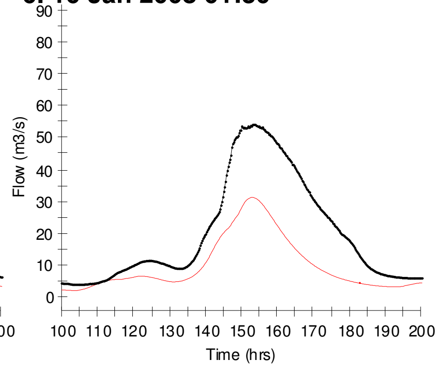
4. 31 Dec 2002 04:30



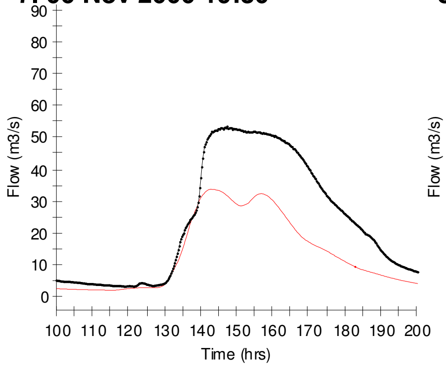
5. 01 Feb 2014 12:30



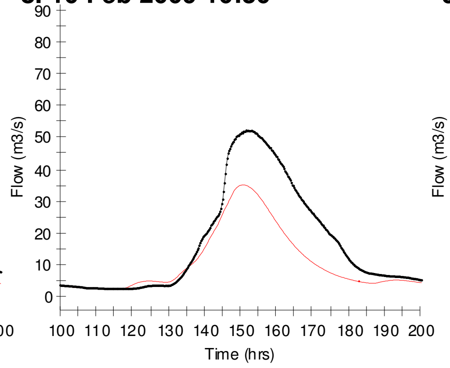
6. 16 Jan 2008 01:30



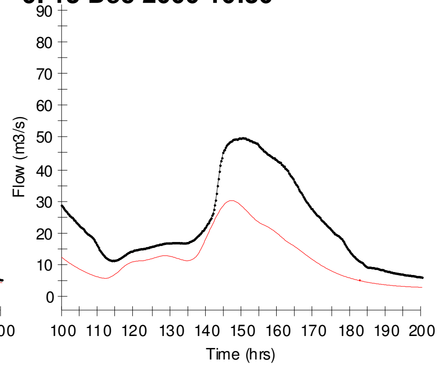
7. 06 Nov 2000 19:30



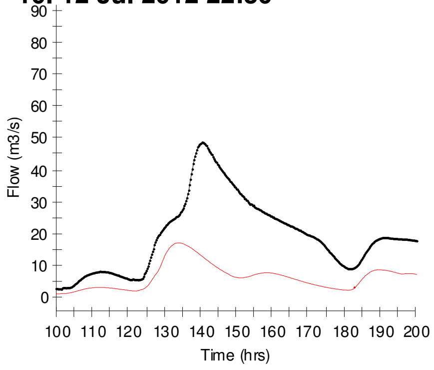
8. 10 Feb 2009 10:30



9. 13 Dec 2000 10:30



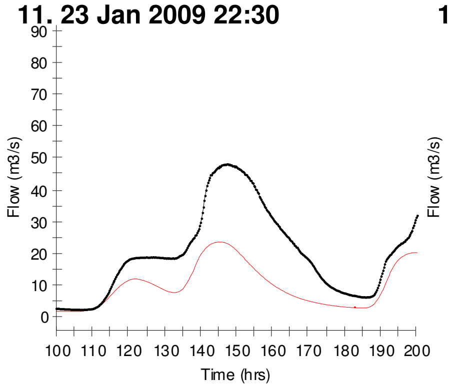
10. 12 Jul 2012 22:30



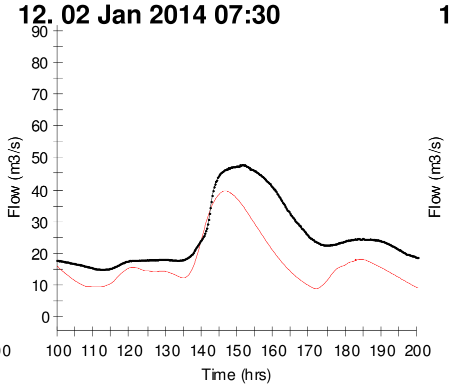
Key
Modelled
Observed

JBA consulting

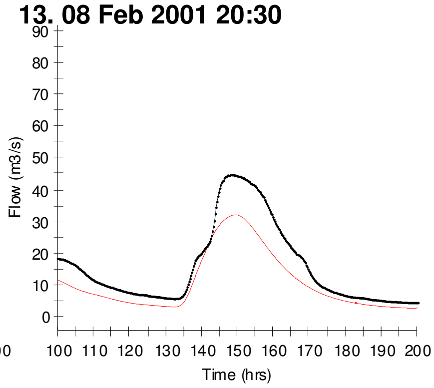
11. 23 Jan 2009 22:30



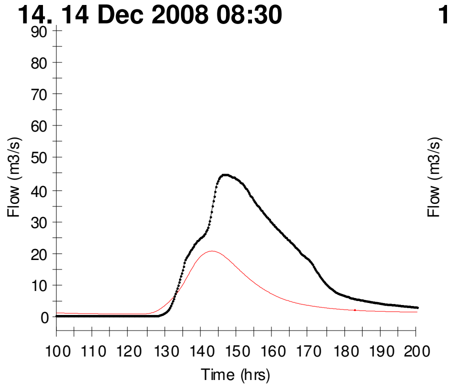
12. 02 Jan 2014 07:30



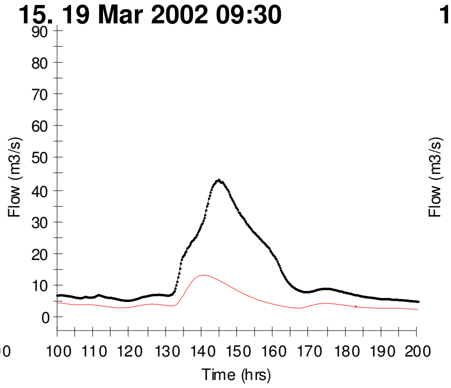
13. 08 Feb 2001 20:30



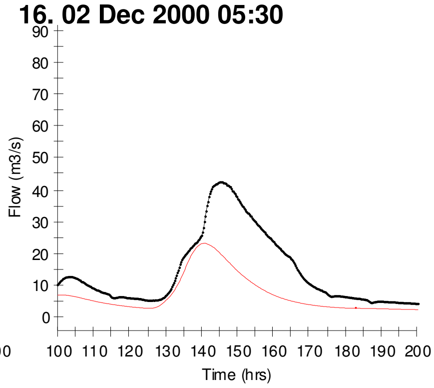
14. 14 Dec 2008 08:30



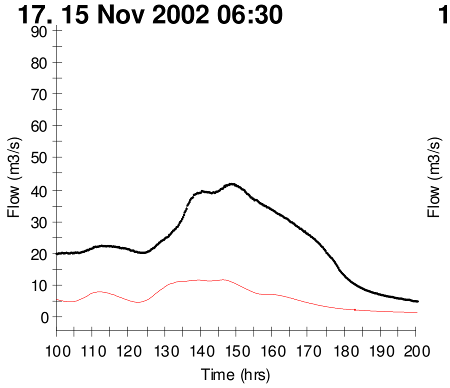
15. 19 Mar 2002 09:30



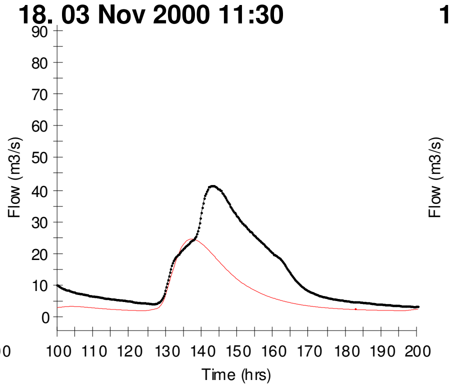
16. 02 Dec 2000 05:30



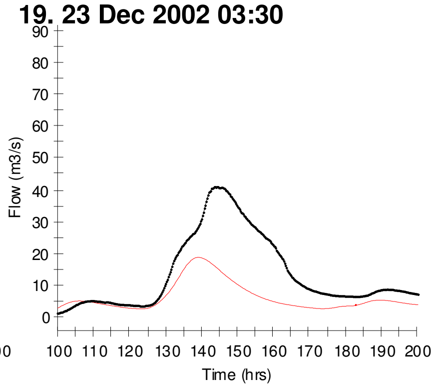
17. 15 Nov 2002 06:30



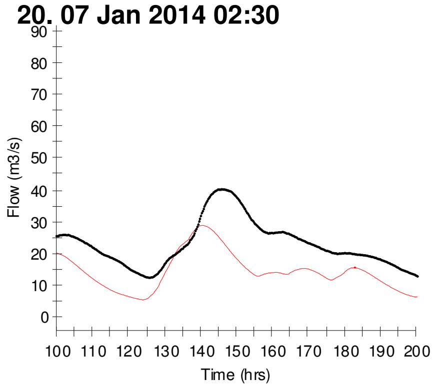
18. 03 Nov 2000 11:30



19. 23 Dec 2002 03:30



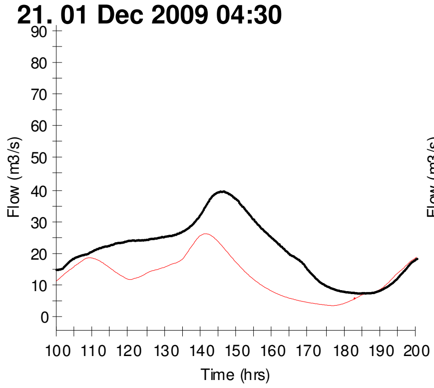
20. 07 Jan 2014 02:30



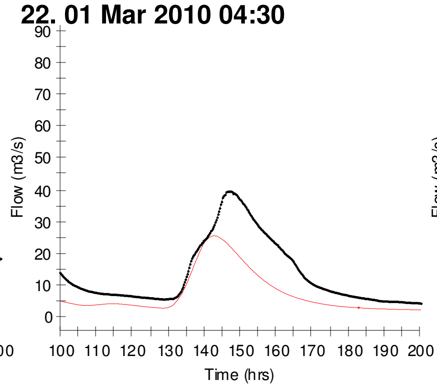
Key
Modelled
Observed

Eden Bridge

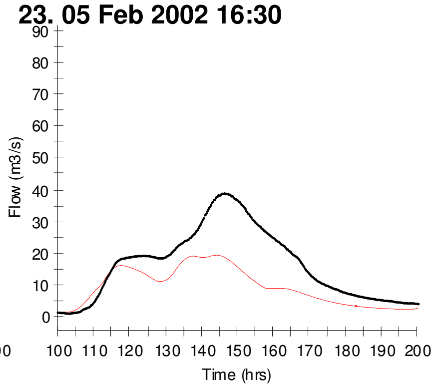
21. 01 Dec 2009 04:30



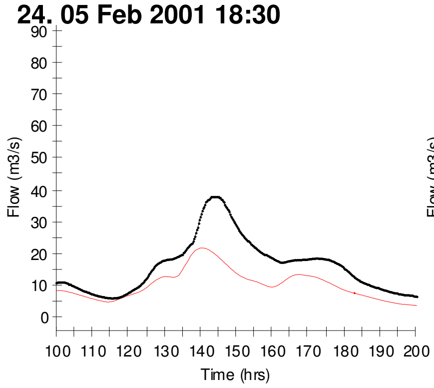
22. 01 Mar 2010 04:30



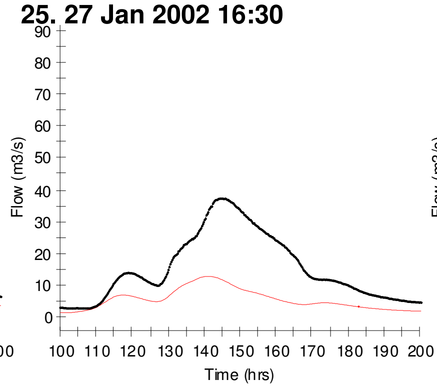
23. 05 Feb 2002 16:30



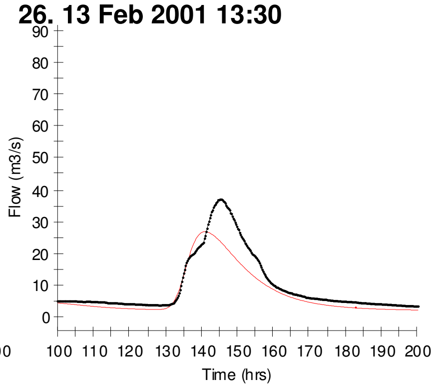
24. 05 Feb 2001 18:30



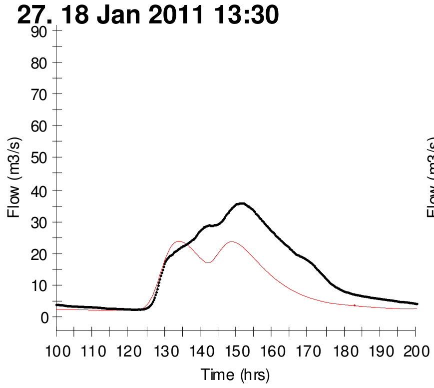
25. 27 Jan 2002 16:30



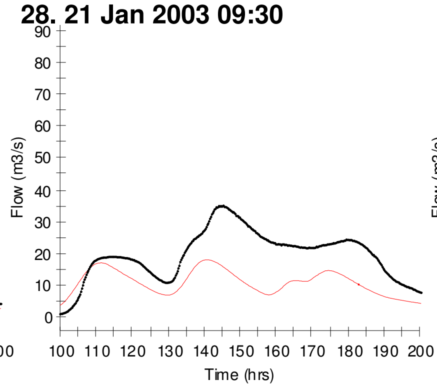
26. 13 Feb 2001 13:30



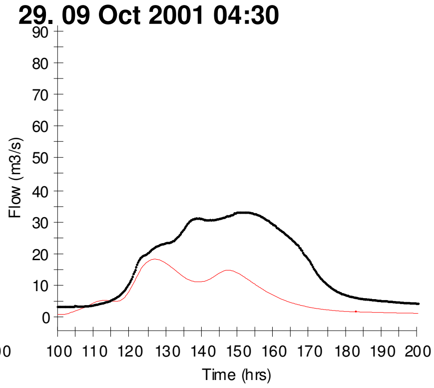
27. 18 Jan 2011 13:30



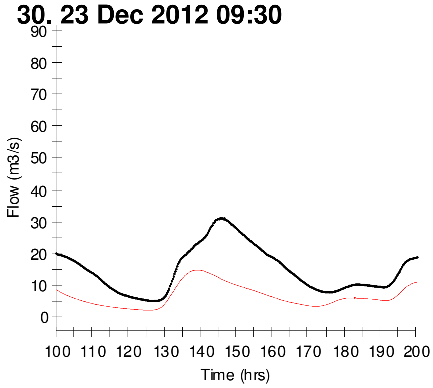
28. 21 Jan 2003 09:30



29. 09 Oct 2001 04:30



30. 23 Dec 2012 09:30



Key
Modelled
Observed

Data summary

40 peaks analysed at Vexour between 17.8m3/s and 100.4m3/s, for period 30 Oct 2000 to 01 Feb 2014 from :

N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\09 Cascade

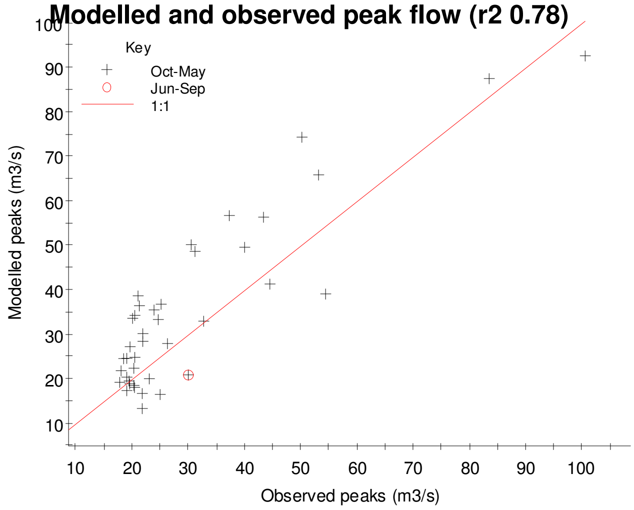
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	100.37	92.58	-7.8	-8%	4.1	0.896	0.922	6.16
2	17 Jan 2014 17:30	83.33	87.46	4.1	5%	0.3	0.913	0.957	4.53
3	30 Oct 2000 18:30	54.35	39.24	-15.1	-28%	-0.4	0.822	0.831	4.54
4	31 Dec 2002 04:30	53.06	65.92	12.9	24%	2.6	0.551	0.877	6.49
5	01 Feb 2014 12:30	50.12	74.39	24.3	48%	-0.1	0.411	0.903	7.49
6	16 Jan 2008 01:30	44.43	41.45	-3.0	-7%	4.7	0.936	0.942	2.38
7	06 Nov 2000 19:30	43.31	56.40	13.1	30%	-6.5	0.615	0.786	6.43
8	10 Feb 2009 10:30	39.95	49.71	9.8	24%	1.8	0.869	0.940	3.02
9	02 Jan 2014 07:30	37.21	56.80	19.6	53%	-2.3	0.091	0.752	6.37
10	23 Jan 2009 22:30	32.70	33.09	0.4	1%	0.3	0.829	0.864	3.05

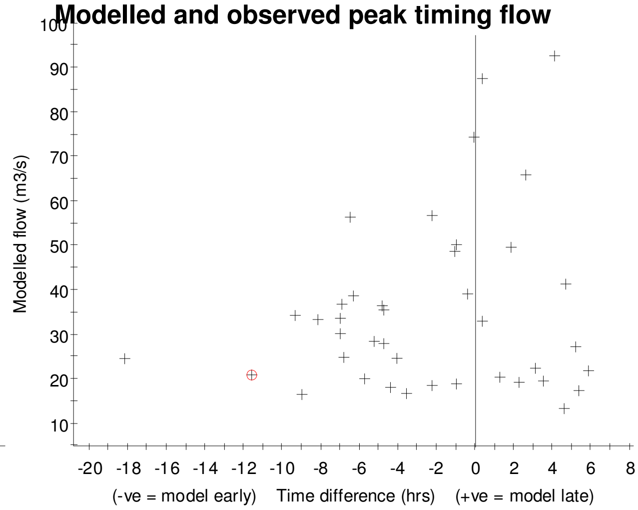
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.17	2.08	1.18	1.66	1.80	0.52	4.00	1.98

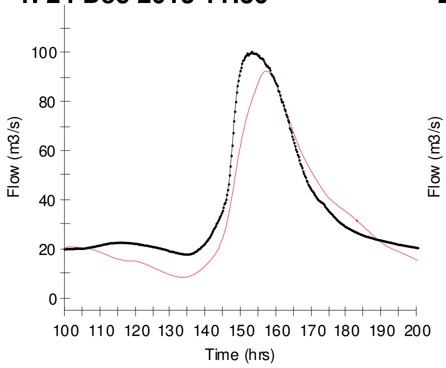
Modelled and observed peak flow (r2 0.78)



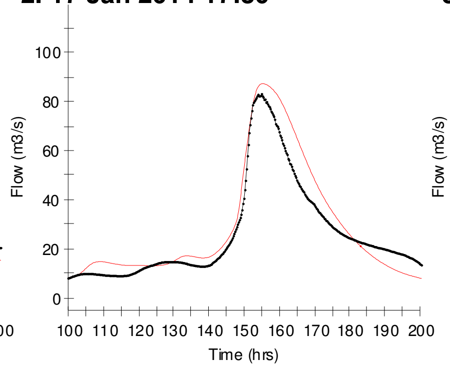
Modelled and observed peak timing flow



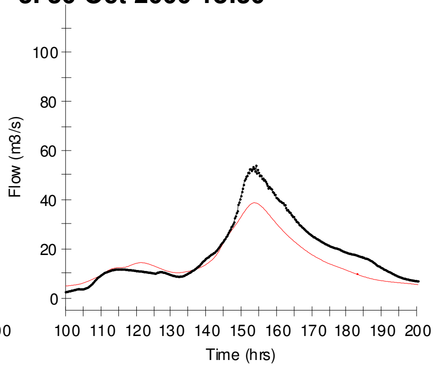
1. 24 Dec 2013 11:30



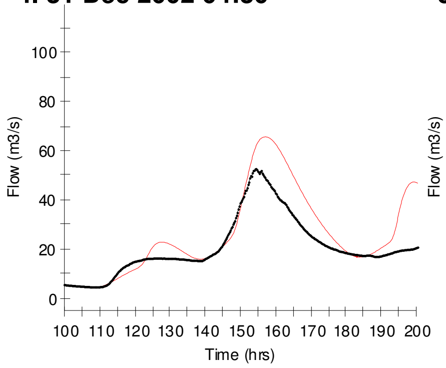
2. 17 Jan 2014 17:30



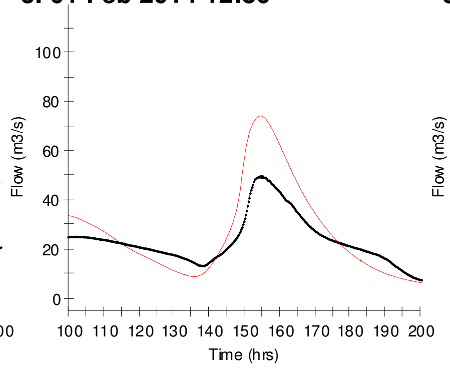
3. 30 Oct 2000 18:30



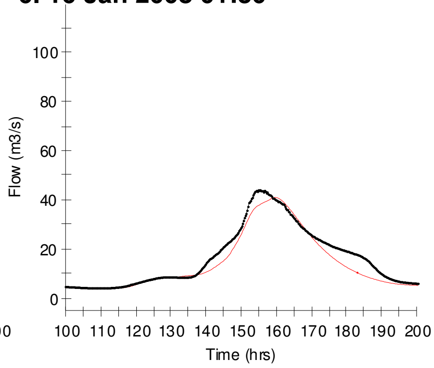
4. 31 Dec 2002 04:30



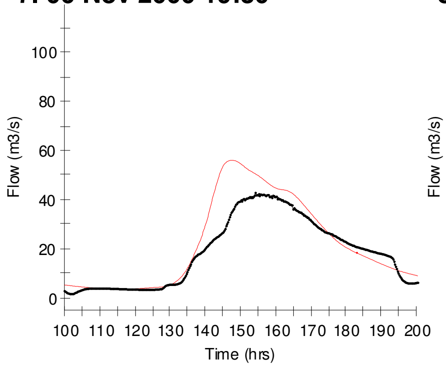
5. 01 Feb 2014 12:30



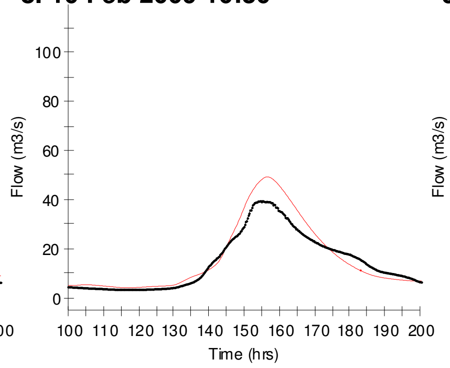
6. 16 Jan 2008 01:30



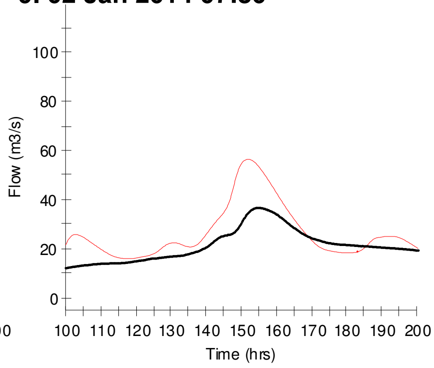
7. 06 Nov 2000 19:30



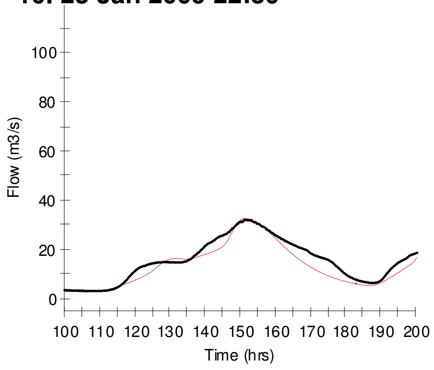
8. 10 Feb 2009 10:30



9. 02 Jan 2014 07:30

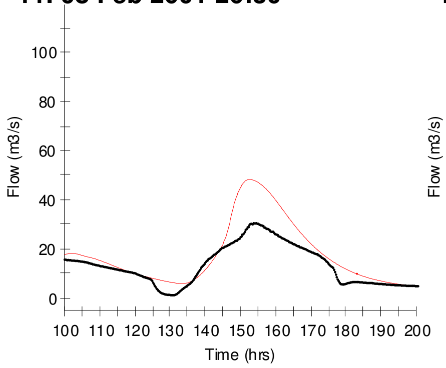


10. 23 Jan 2009 22:30

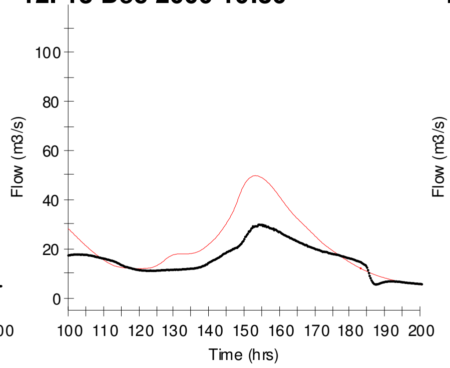


Key
Modelled
Observed

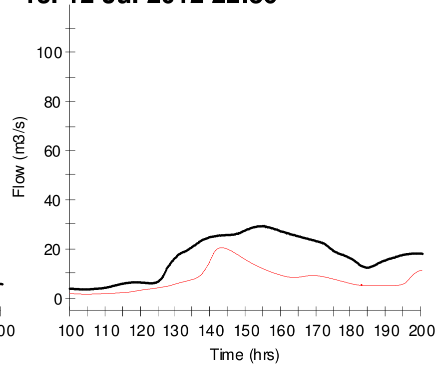
11. 08 Feb 2001 20:30



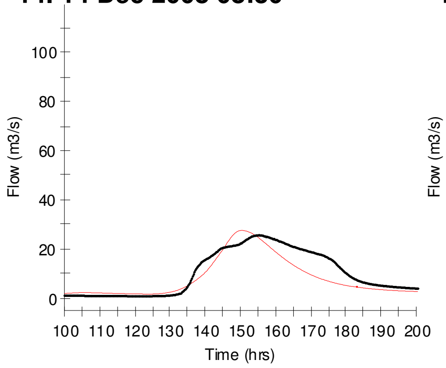
12. 13 Dec 2000 10:30



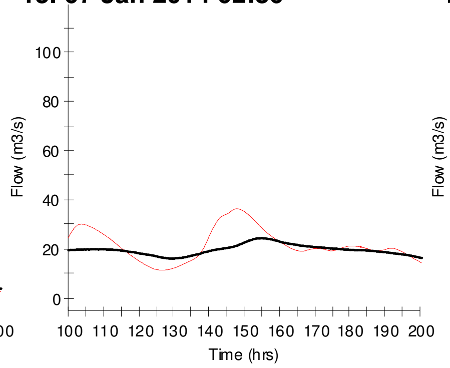
13. 12 Jul 2012 22:30



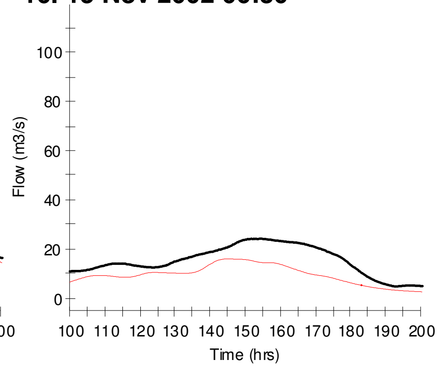
14. 14 Dec 2008 08:30



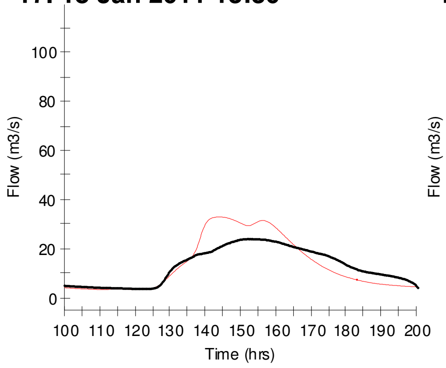
15. 07 Jan 2014 02:30



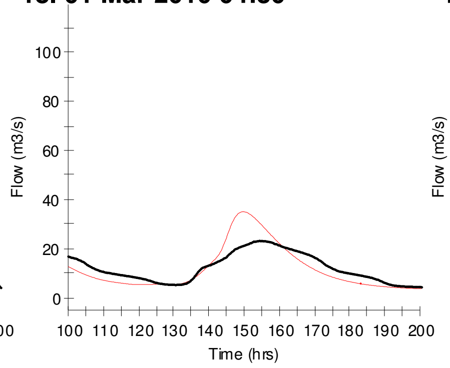
16. 15 Nov 2002 06:30



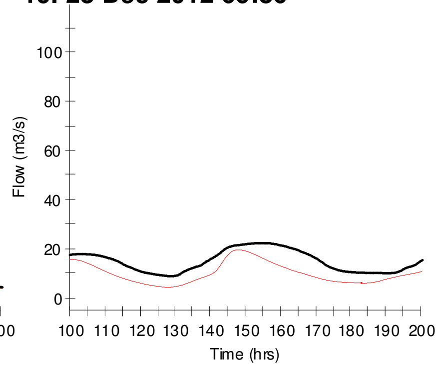
17. 18 Jan 2011 13:30



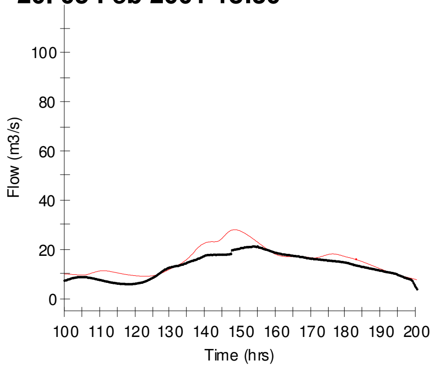
18. 01 Mar 2010 04:30



19. 23 Dec 2012 09:30



20. 05 Feb 2001 18:30

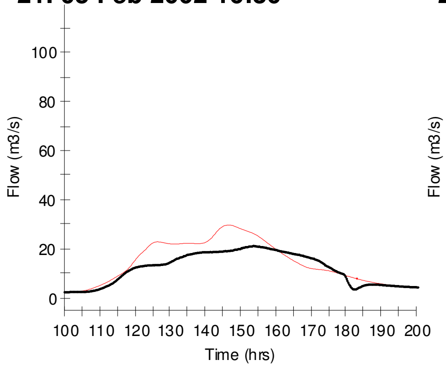


Key

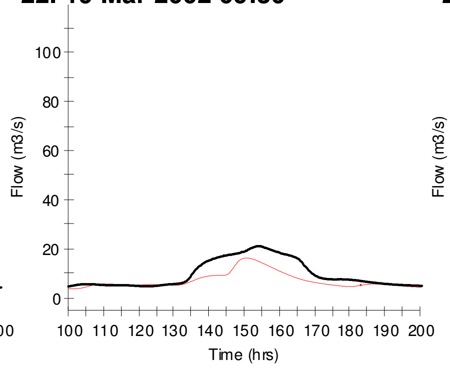
Modelled

Observed

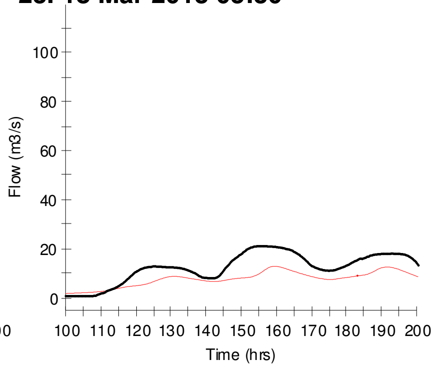
21. 05 Feb 2002 16:30



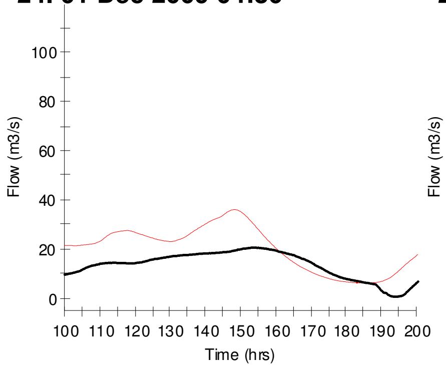
22. 19 Mar 2002 09:30



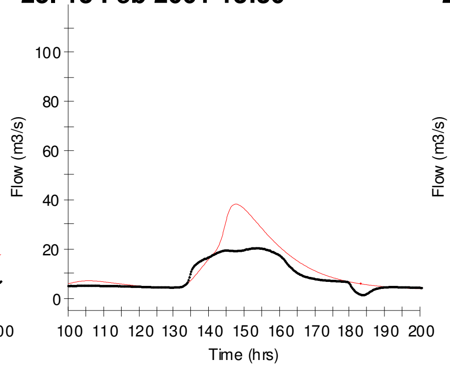
23. 18 Mar 2013 05:30



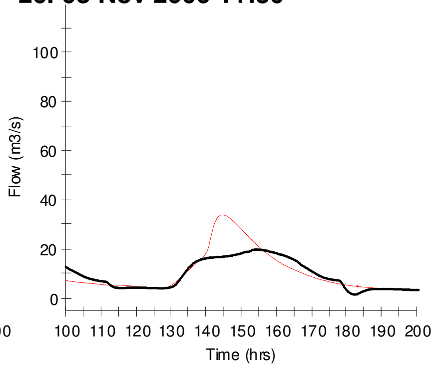
24. 01 Dec 2009 04:30



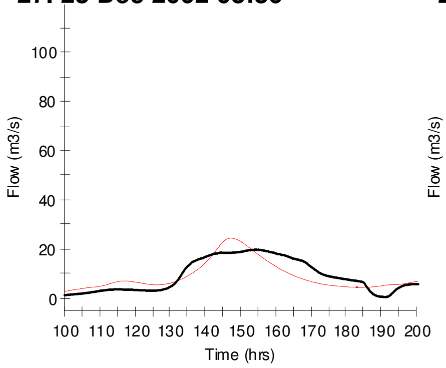
25. 13 Feb 2001 13:30



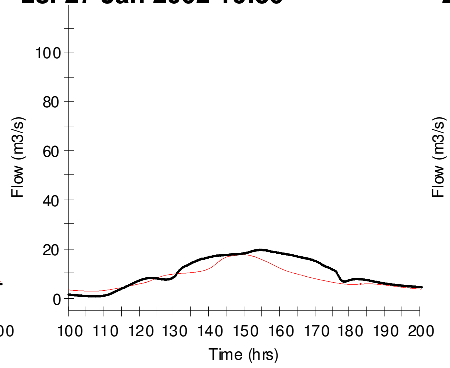
26. 03 Nov 2000 11:30



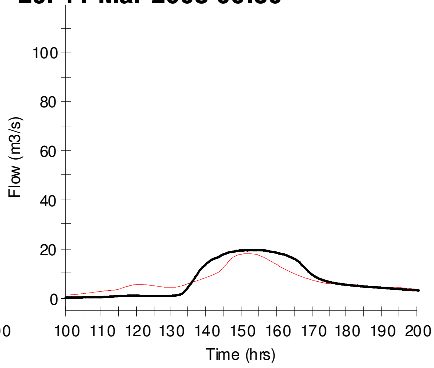
27. 23 Dec 2002 03:30



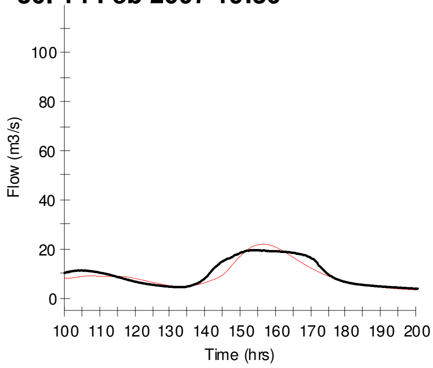
28. 27 Jan 2002 16:30



29. 11 Mar 2008 06:30



30. 14 Feb 2007 19:30



Key
Modelled
Observed

Lingfield Ultrasonic

Data summary

40 peaks analysed at LingfieldUS between 0.0m3/s and 14.6m3/s, for period 30 Oct 2000 to 01 Feb 2014 from :

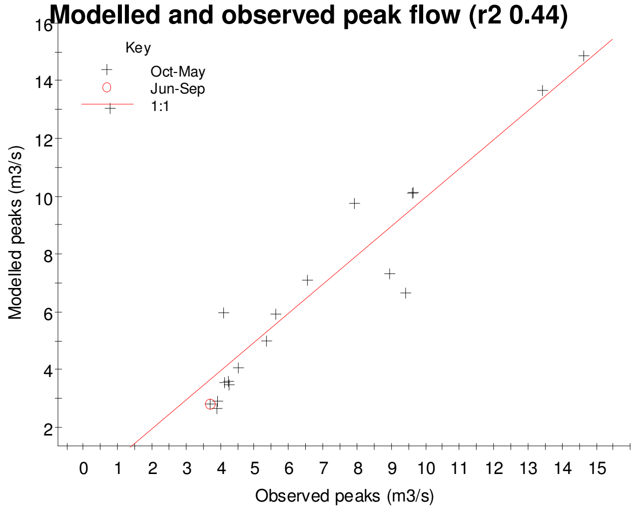
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\09 Cascade

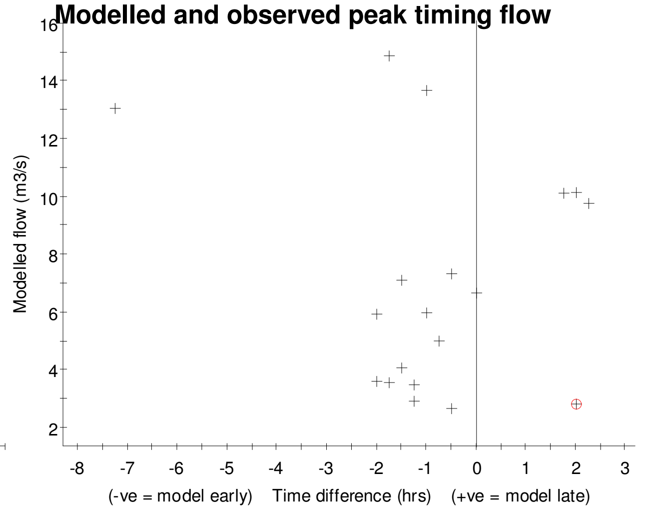
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	14.60	14.86	0.3	2%	-1.8	0.882	0.891	1.05
2	17 Jan 2014 17:30	13.40	13.67	0.3	2%	-1.0	0.330	0.359	3.04
3	16 Jan 2008 01:30	9.63	10.15	0.5	5%	2.0	0.835	0.851	0.90
4	10 Feb 2009 10:30	9.60	10.13	0.5	6%	1.8	0.854	0.898	0.72
5	23 Jan 2009 22:30	9.40	6.68	-2.7	-29%	0.0	0.850	0.852	0.74
6	14 Dec 2008 08:30	8.93	7.35	-1.6	-18%	-0.5	0.865	0.902	0.56
7	02 Jan 2014 07:30	7.91	9.77	1.9	24%	2.3	-0.19	0.747	1.40
8	07 Jan 2014 02:30	6.53	7.12	0.6	9%	-1.5	0.196	0.789	1.23
9	18 Jan 2011 13:30	5.61	5.95	0.3	6%	-2.0	0.709	0.866	0.50
10	01 Mar 2010 04:30	5.34	5.02	-0.3	-6%	-0.8	0.880	0.883	0.33

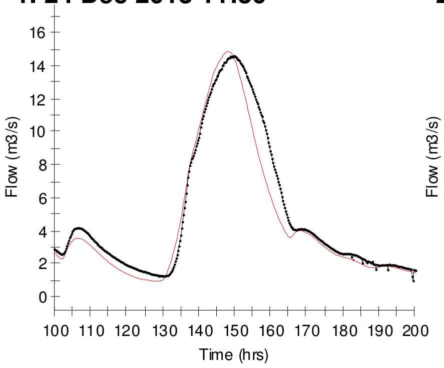
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	3.59	2.43	2.43	0.00	3.02	4.00	4.00	2.76

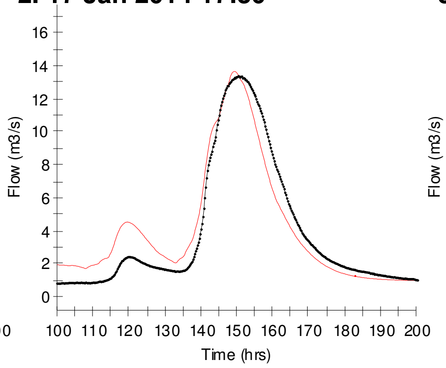




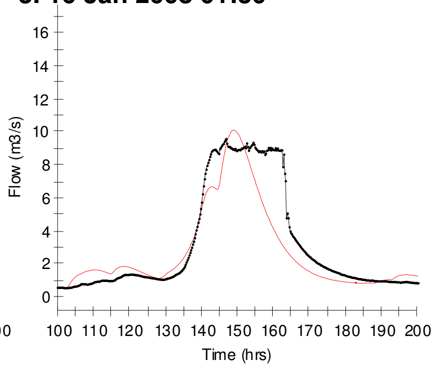
1. 24 Dec 2013 11:30



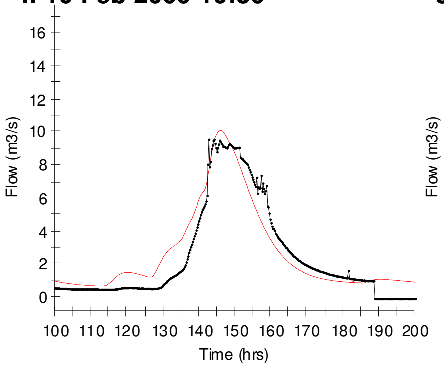
2. 17 Jan 2014 17:30



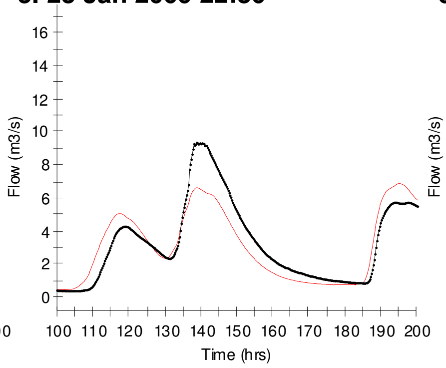
3. 16 Jan 2008 01:30



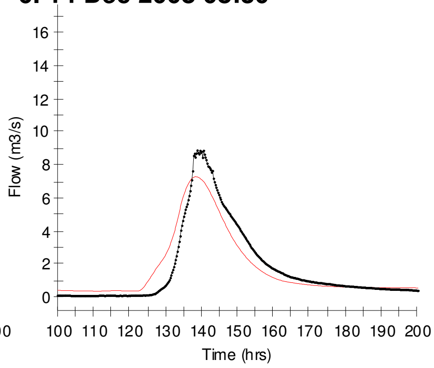
4. 10 Feb 2009 10:30



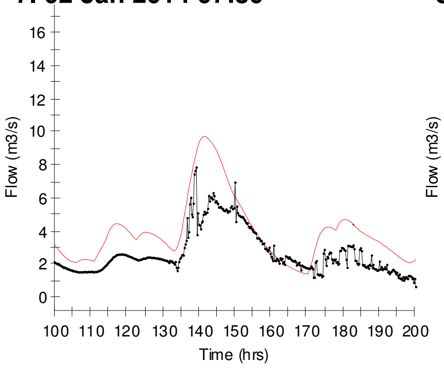
5. 23 Jan 2009 22:30



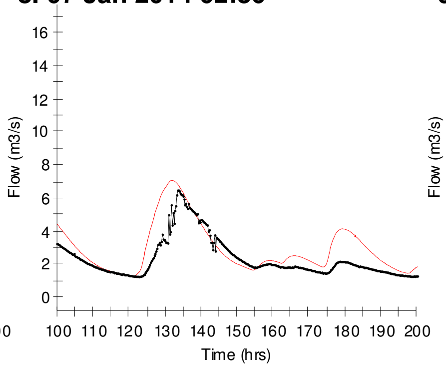
6. 14 Dec 2008 08:30



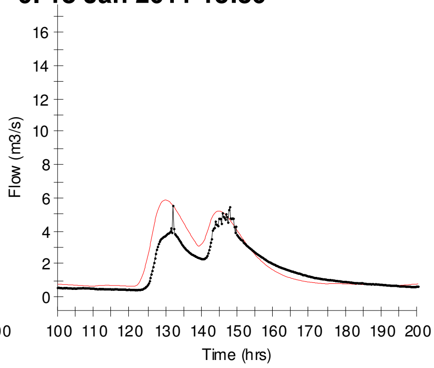
7. 02 Jan 2014 07:30



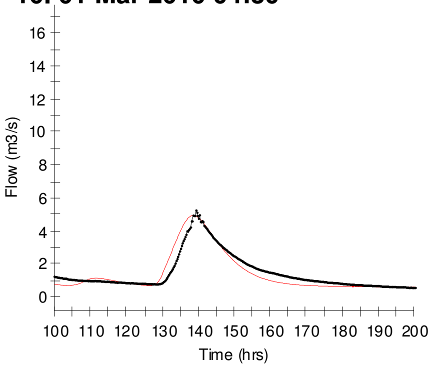
8. 07 Jan 2014 02:30



9. 18 Jan 2011 13:30

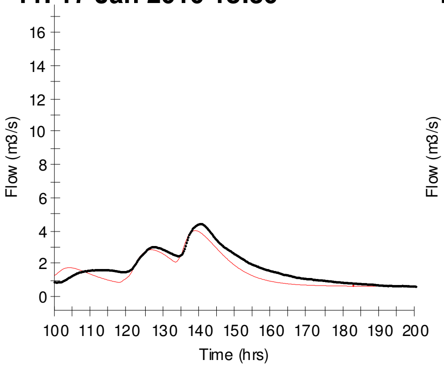


10. 01 Mar 2010 04:30

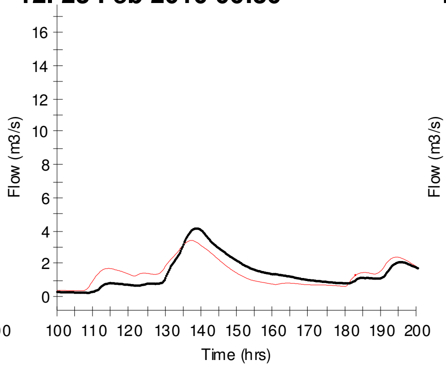


Key
Modelled
Observed

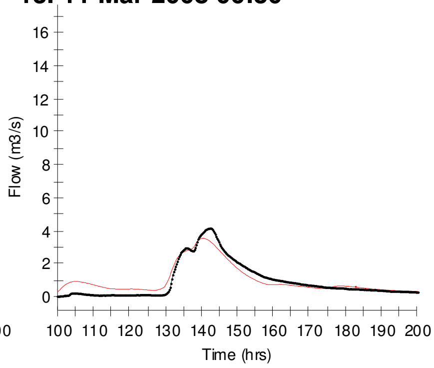
11. 17 Jan 2010 18:30



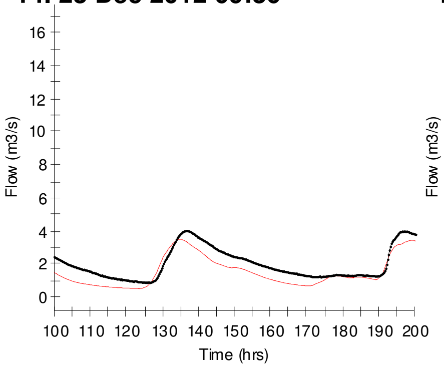
12. 23 Feb 2010 06:30



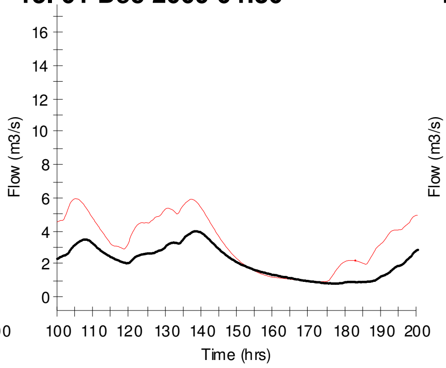
13. 11 Mar 2008 06:30



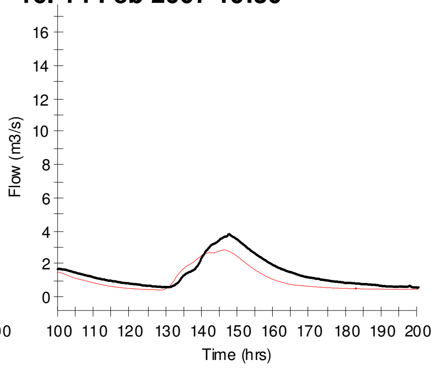
14. 23 Dec 2012 09:30



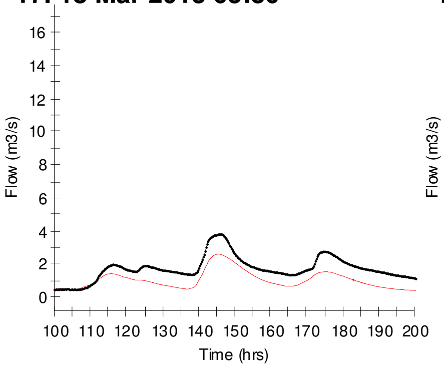
15. 01 Dec 2009 04:30



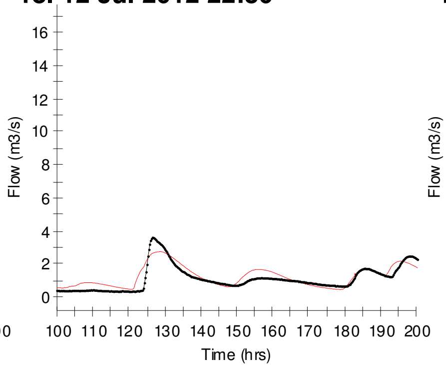
16. 14 Feb 2007 19:30



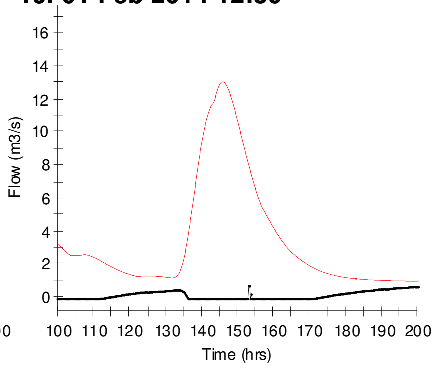
17. 18 Mar 2013 05:30



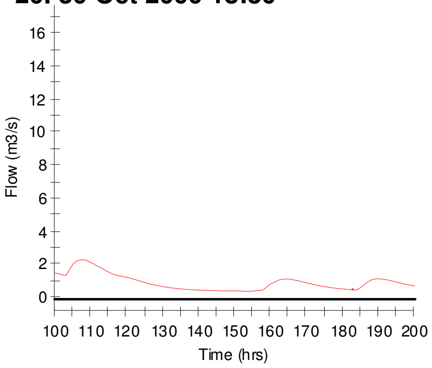
18. 12 Jul 2012 22:30



19. 01 Feb 2014 12:30



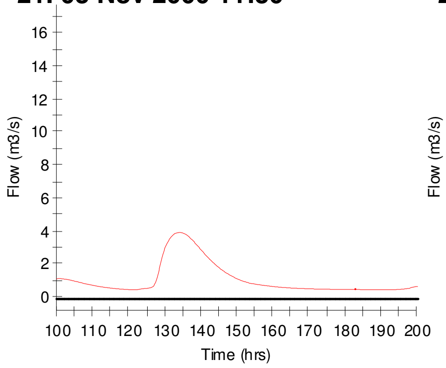
20. 30 Oct 2000 18:30



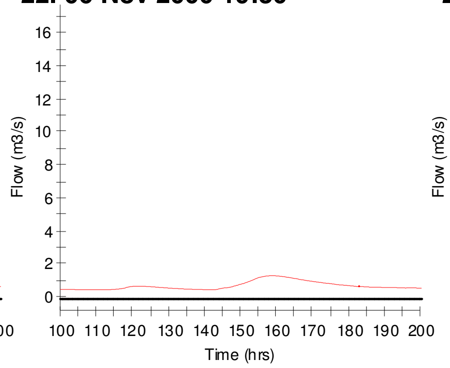
Key

Modelled
Observed

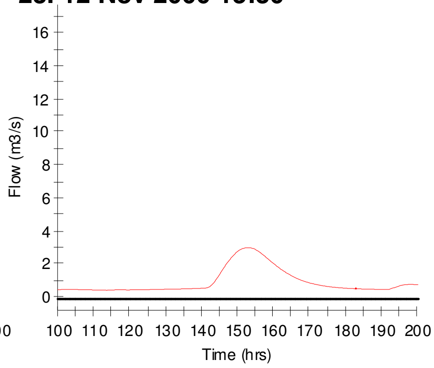
21. 03 Nov 2000 11:30



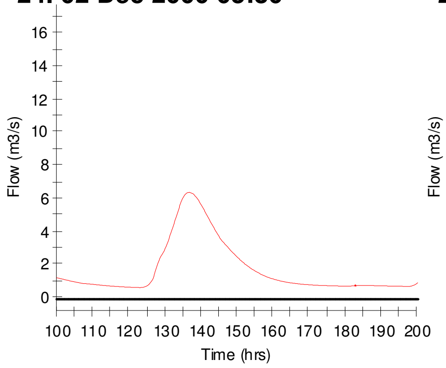
22. 06 Nov 2000 19:30



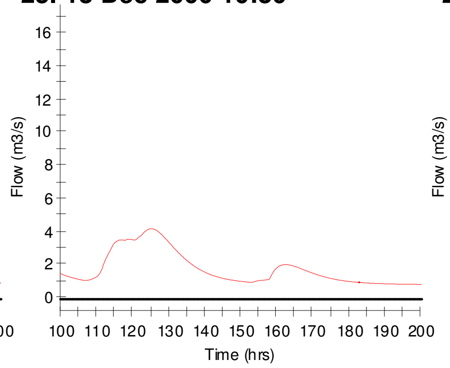
23. 12 Nov 2000 15:30



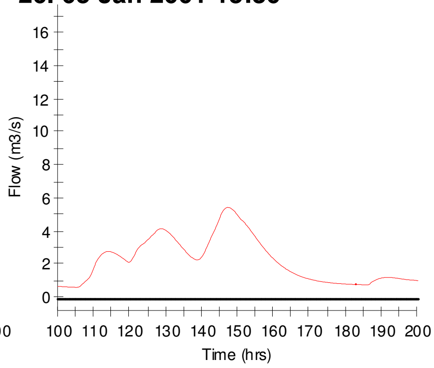
24. 02 Dec 2000 05:30



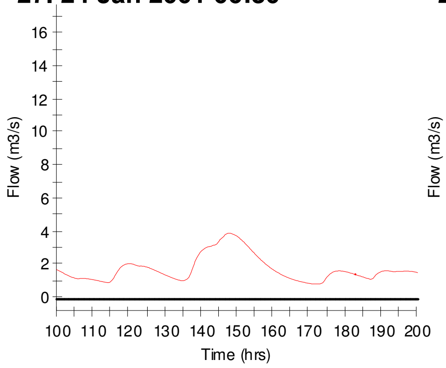
25. 13 Dec 2000 10:30



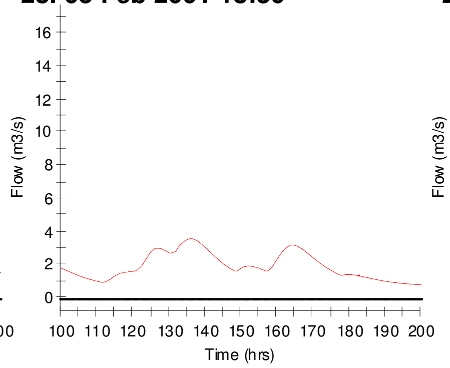
26. 05 Jan 2001 15:30



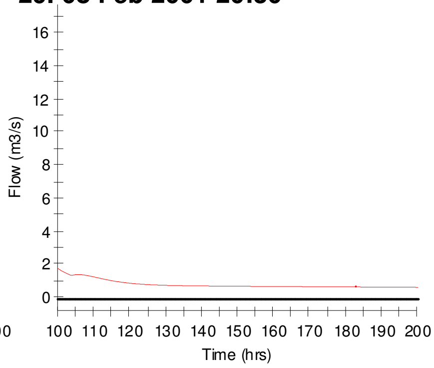
27. 24 Jan 2001 06:30



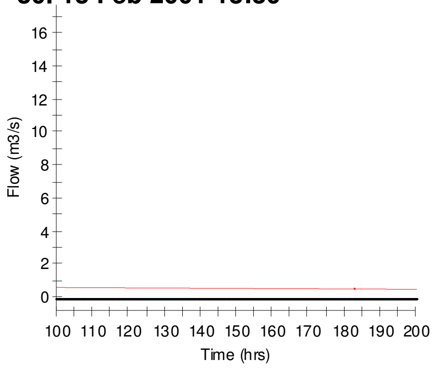
28. 05 Feb 2001 18:30



29. 08 Feb 2001 20:30



30. 13 Feb 2001 13:30



Key
Modelled
Observed

Colliers Land Bridge

Data summary

40 peaks analysed at Colliers between 8.8m3/s and 128.6m3/s, for period 30 Oct 2000 to 01 Feb 2014 from :

N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\09 Cascade

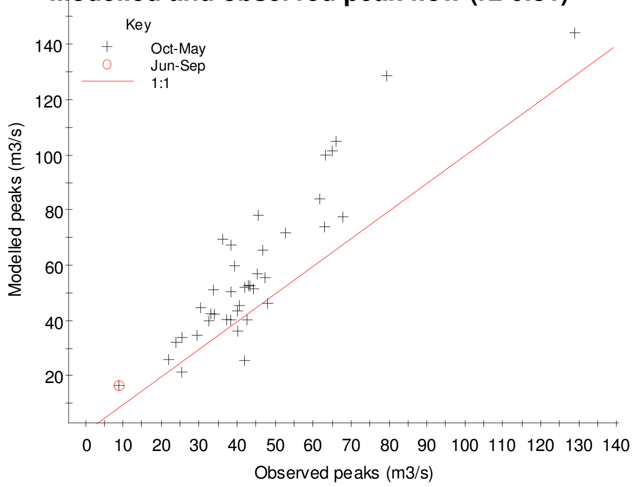
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	128.64	144.23	15.6	12%	4.0	0.922	0.958	7.22
2	06 Nov 2000 19:30	79.21	128.74	49.5	63%	1.1	0.520	0.810	10.52
3	30 Oct 2000 18:30	67.71	77.77	10.1	15%	3.3	0.853	0.868	5.81
4	01 Feb 2014 12:30	65.91	105.12	39.2	59%	-0.3	0.253	0.924	13.30
5	13 Dec 2000 10:30	64.92	101.66	36.7	57%	0.7	0.515	0.873	10.02
6	10 Feb 2009 10:30	63.14	100.12	37.0	59%	2.7	0.516	0.949	8.88
7	16 Jan 2008 01:30	62.91	74.26	11.4	18%	5.3	0.897	0.951	4.45
8	02 Jan 2014 07:30	61.65	84.33	22.7	37%	-1.4	0.399	0.846	9.60
9	05 Jan 2001 15:30	52.64	72.08	19.4	37%	-0.4	0.855	0.948	4.42
10	14 Dec 2008 08:30	47.94	46.58	-1.4	-3%	-3.1	0.965	0.973	1.87

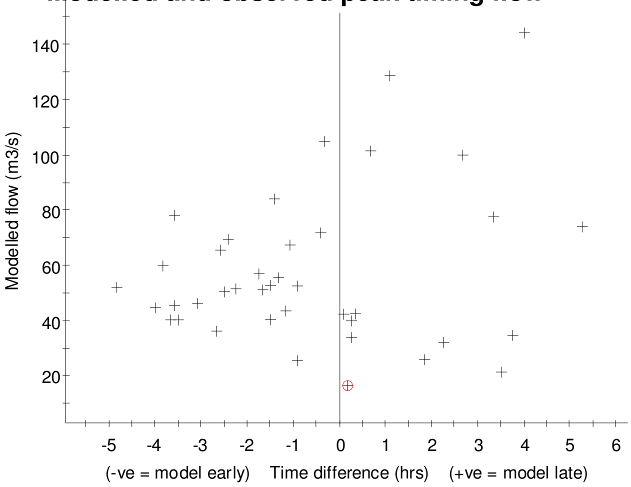
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	1.94	2.94	2.08	1.49	1.07	0.14	4.00	1.96

Modelled and observed peak flow (r2 0.81)

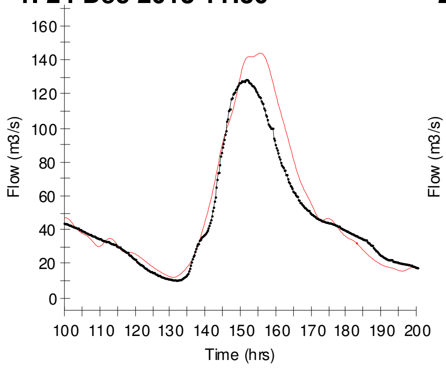


Modelled and observed peak timing flow

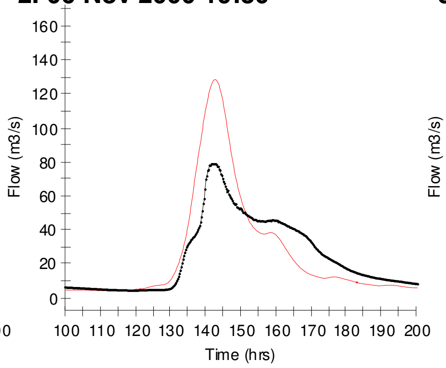


Colliers Land Bridge

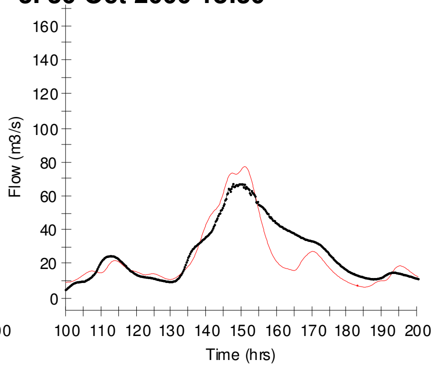
1. 24 Dec 2013 11:30



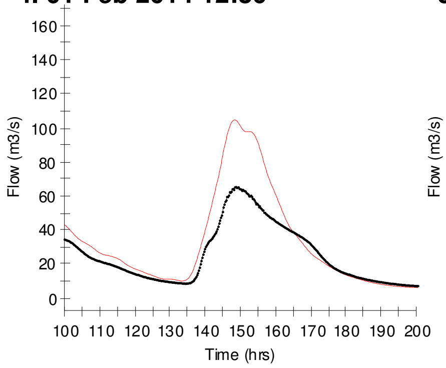
2. 06 Nov 2000 19:30



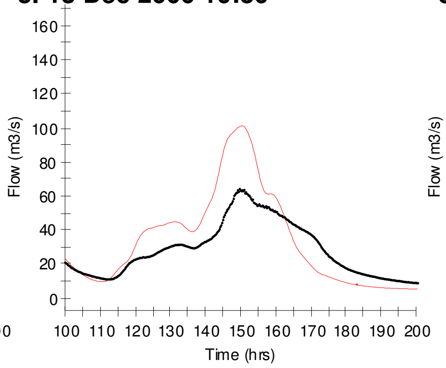
3. 30 Oct 2000 18:30



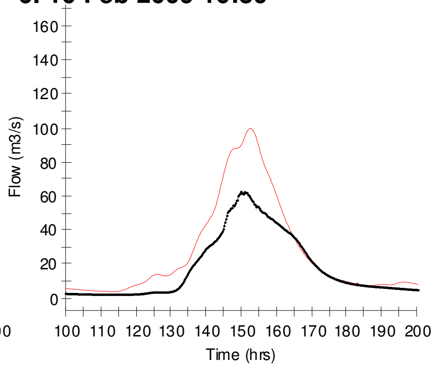
4. 01 Feb 2014 12:30



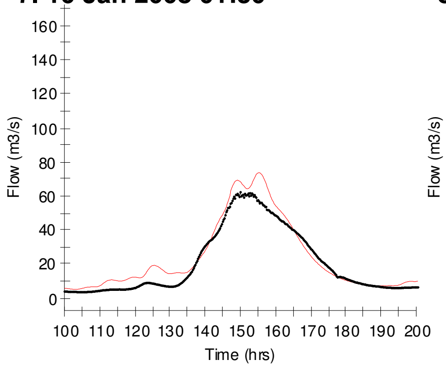
5. 13 Dec 2000 10:30



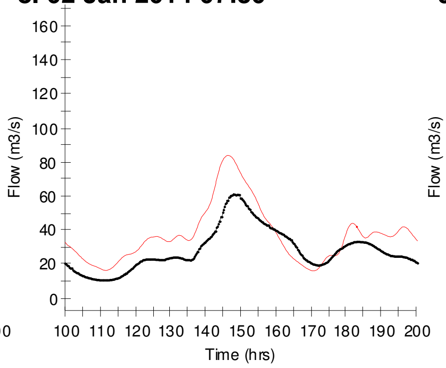
6. 10 Feb 2009 10:30



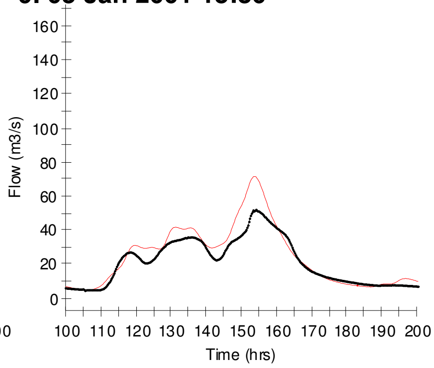
7. 16 Jan 2008 01:30



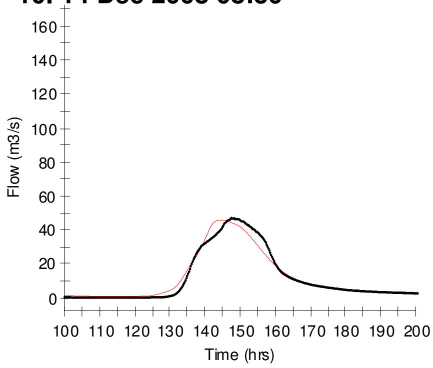
8. 02 Jan 2014 07:30



9. 05 Jan 2001 15:30

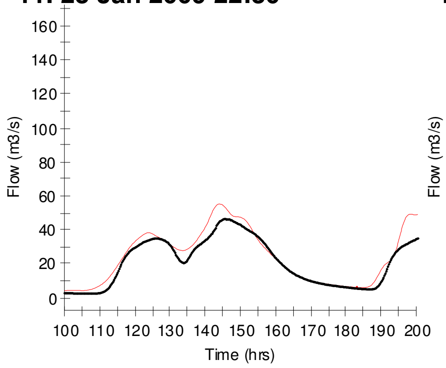


10. 14 Dec 2008 08:30

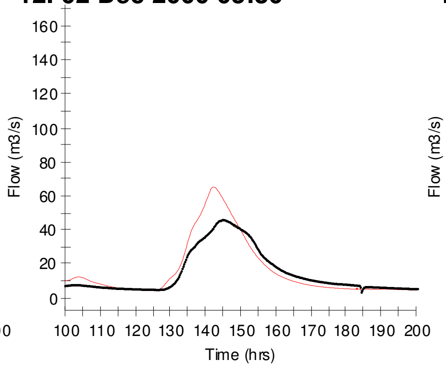


Key
Modelled
Observed

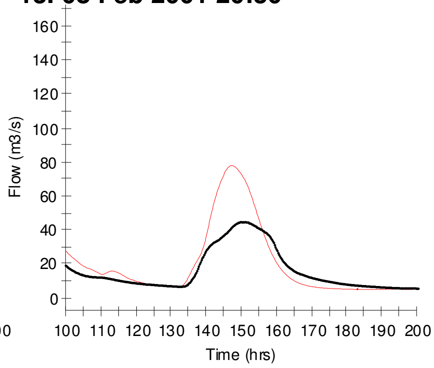
11. 23 Jan 2009 22:30



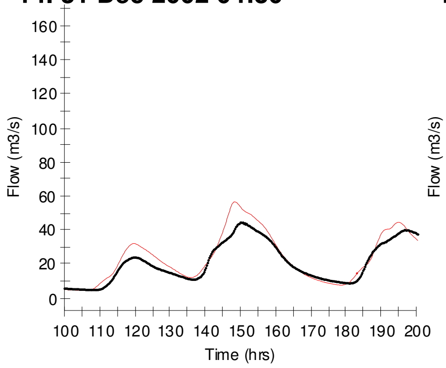
12. 02 Dec 2000 05:30



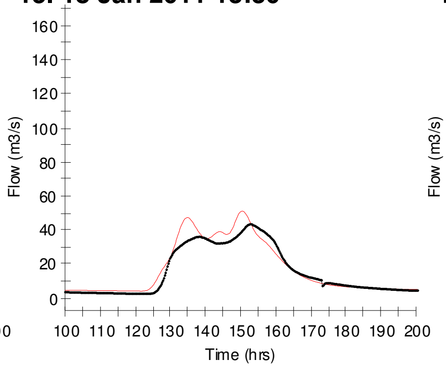
13. 08 Feb 2001 20:30



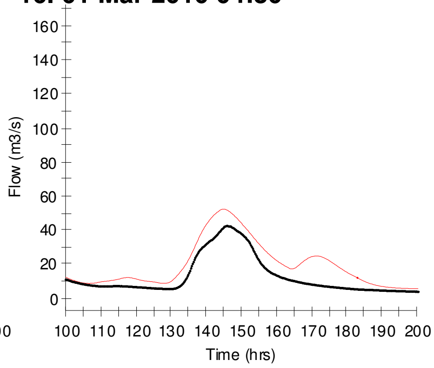
14. 31 Dec 2002 04:30



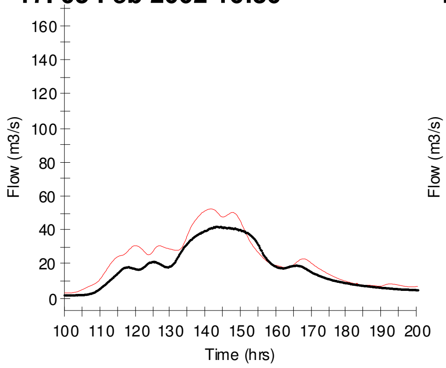
15. 18 Jan 2011 13:30



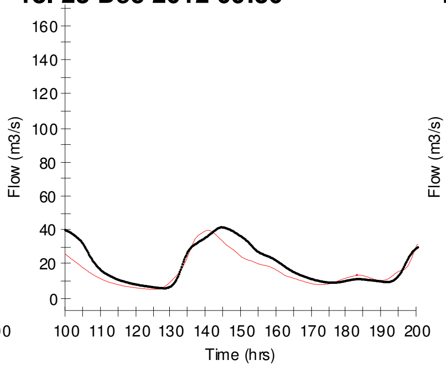
16. 01 Mar 2010 04:30



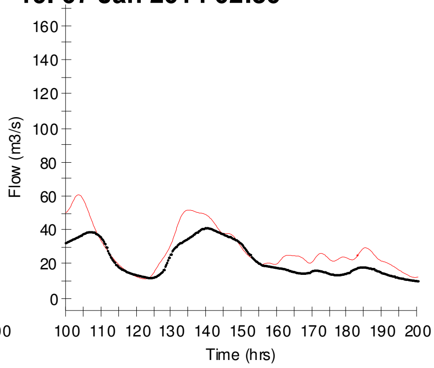
17. 05 Feb 2002 16:30



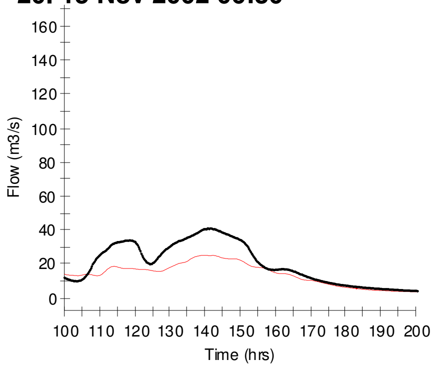
18. 23 Dec 2012 09:30



19. 07 Jan 2014 02:30

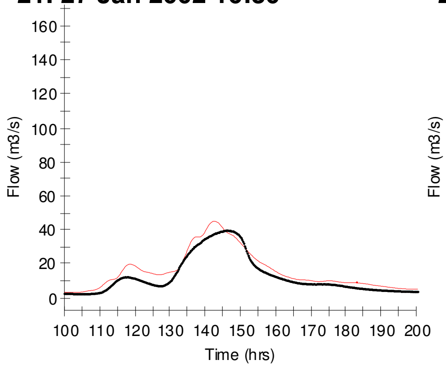


20. 15 Nov 2002 06:30

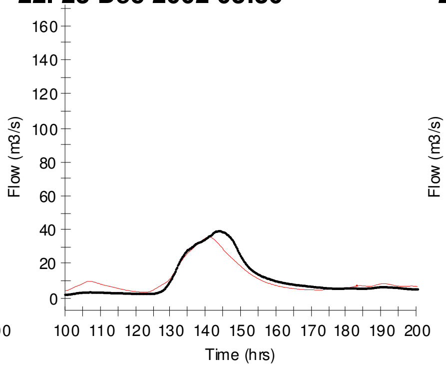


Key
Modelled
Observed

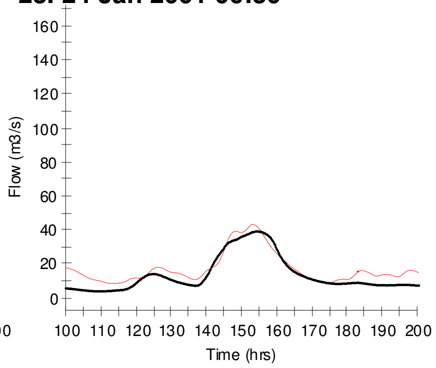
21. 27 Jan 2002 16:30



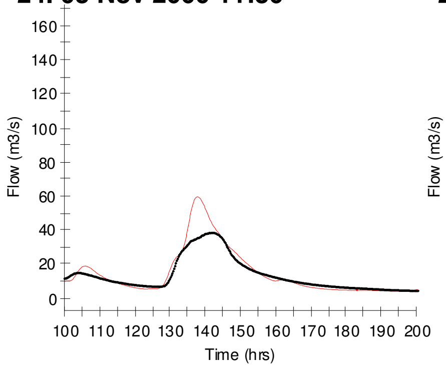
22. 23 Dec 2002 03:30



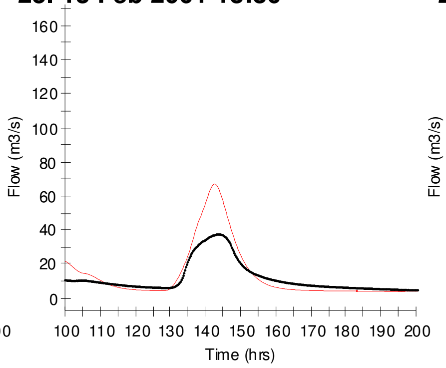
23. 24 Jan 2001 06:30



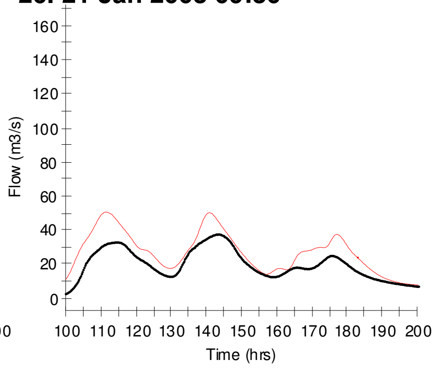
24. 03 Nov 2000 11:30



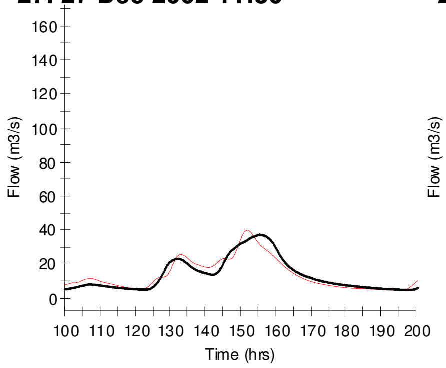
25. 13 Feb 2001 13:30



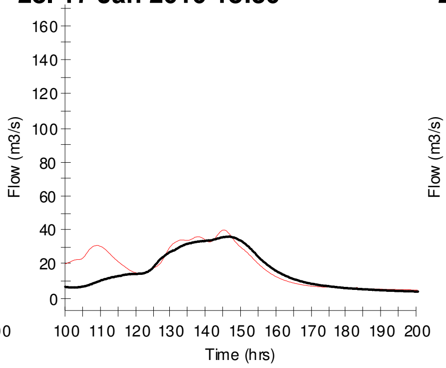
26. 21 Jan 2003 09:30



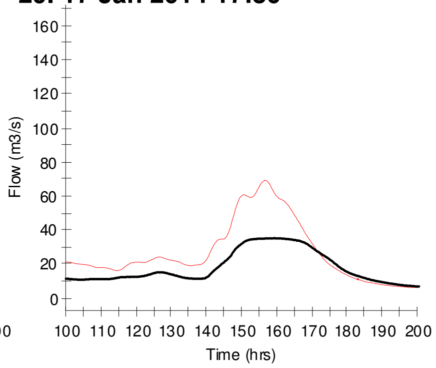
27. 27 Dec 2002 11:30



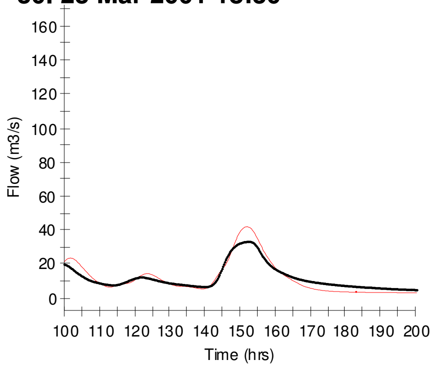
28. 17 Jan 2010 18:30



29. 17 Jan 2014 17:30



30. 23 Mar 2001 18:30



Key
Modelled
Observed

Forest Row

Data summary

40 peaks analysed at ForestRow between 0.0m3/s and 41.7m3/s, for period 30 Oct 2000 to 01 Feb 2014 from :

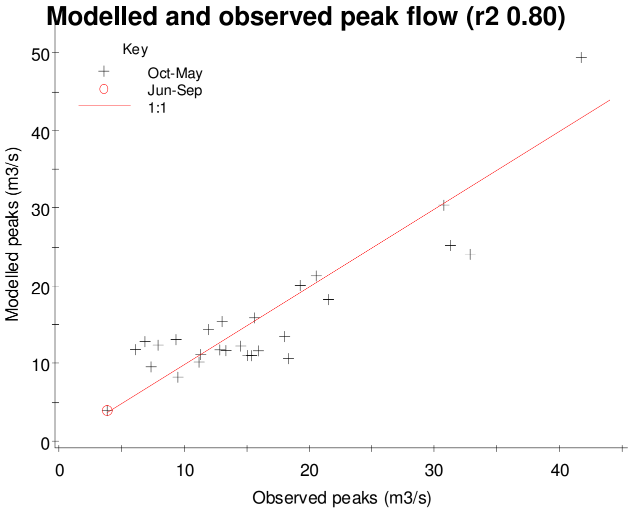
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\09 Cascade

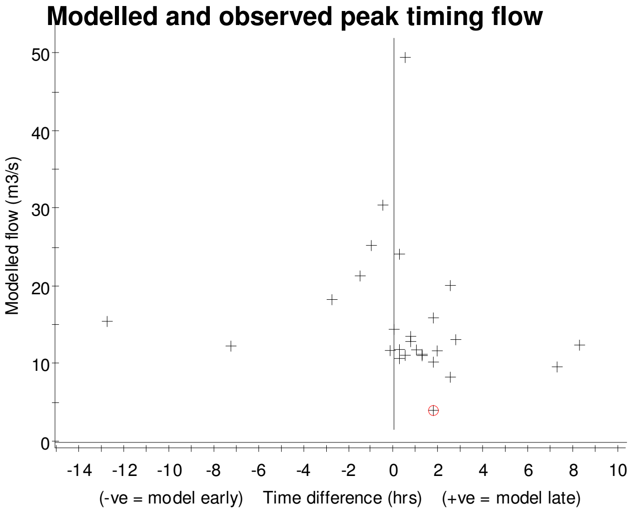
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	41.67	49.45	7.8	19%	0.5	0.820	0.936	3.27
2	10 Feb 2009 10:30	32.80	24.21	-8.6	-26%	0.3	0.818	0.970	2.40
3	17 Jan 2014 17:30	31.22	25.31	-5.9	-19%	-1.0	0.853	0.898	1.89
4	01 Feb 2014 12:30	30.71	30.47	-0.2	-1%	-0.5	-0.11	0.338	6.25
5	23 Jan 2009 22:30	21.48	18.33	-3.1	-15%	-2.8	0.763	0.841	2.04
6	02 Jan 2014 07:30	20.51	21.40	0.9	4%	-1.5	0.478	0.727	2.33
7	14 Dec 2008 08:30	19.25	20.17	0.9	5%	2.5	0.495	0.902	2.06
8	17 Jan 2010 18:30	18.30	10.78	-7.5	-41%	0.3	0.264	0.667	2.78
9	31 Dec 2002 04:30	17.99	13.63	-4.4	-24%	0.8	0.579	0.895	2.24
10	27 Dec 2002 11:30	15.89	11.78	-4.1	-26%	1.9	0.596	0.918	2.32

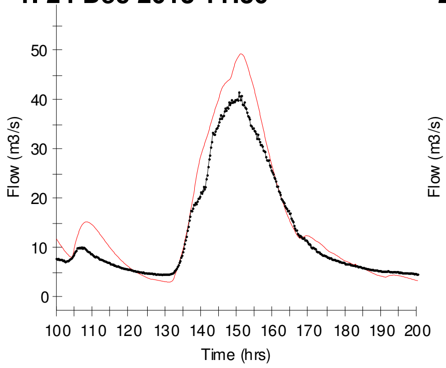
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.01	1.42	1.16	2.47	2.37	4.00	2.70	2.30

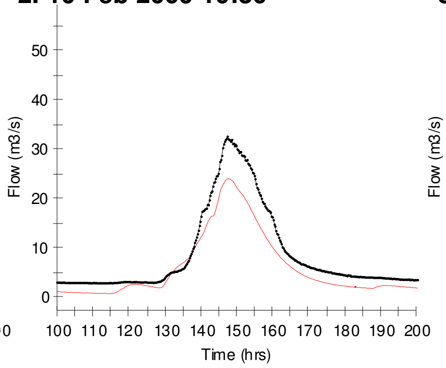




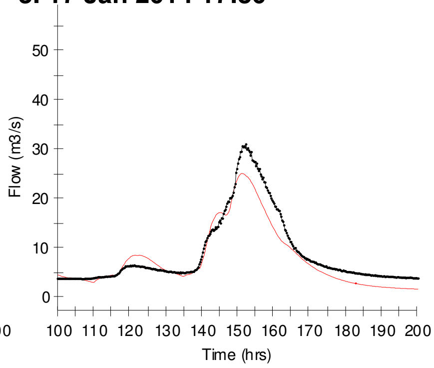
1. 24 Dec 2013 11:30



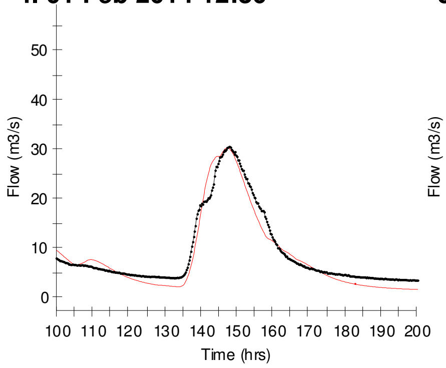
2. 10 Feb 2009 10:30



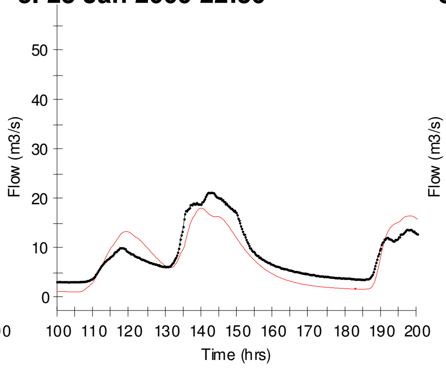
3. 17 Jan 2014 17:30



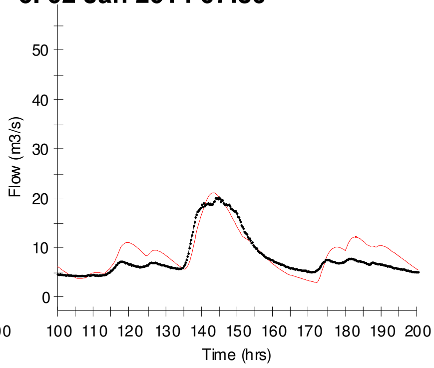
4. 01 Feb 2014 12:30



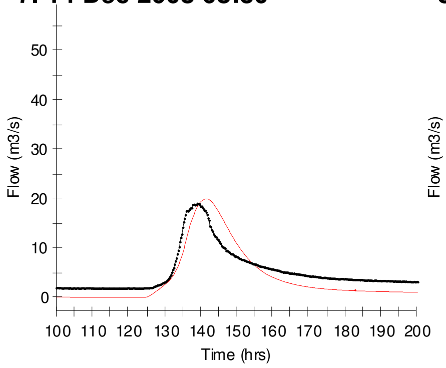
5. 23 Jan 2009 22:30



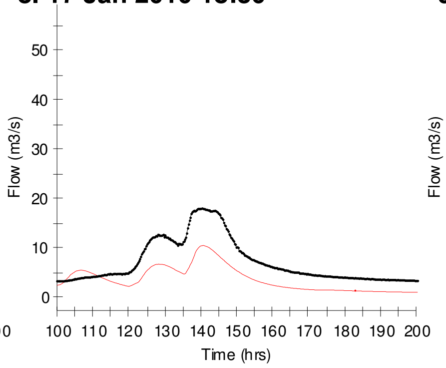
6. 02 Jan 2014 07:30



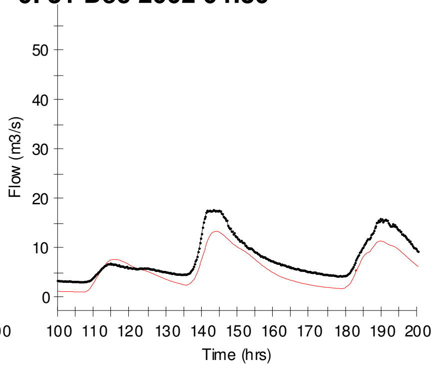
7. 14 Dec 2008 08:30



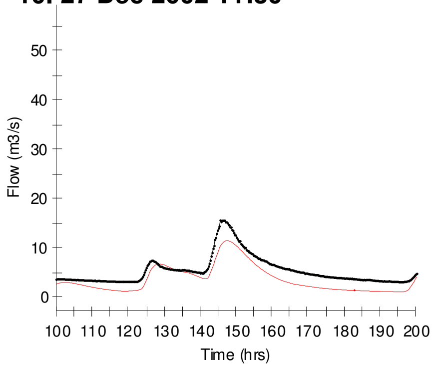
8. 17 Jan 2010 18:30



9. 31 Dec 2002 04:30



10. 27 Dec 2002 11:30

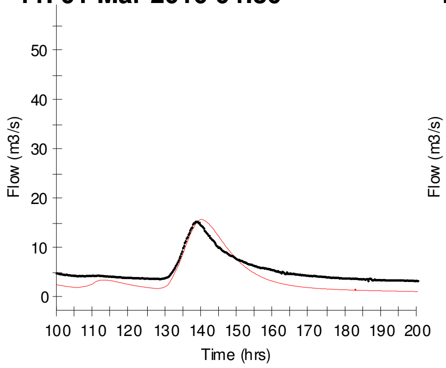


Key

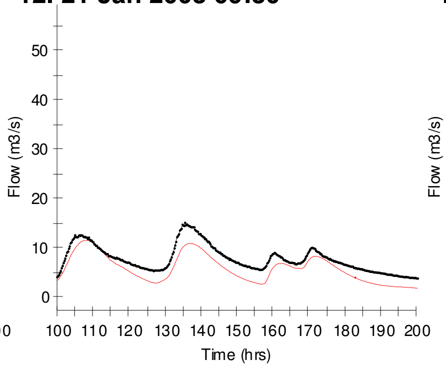
Modelled

Observed

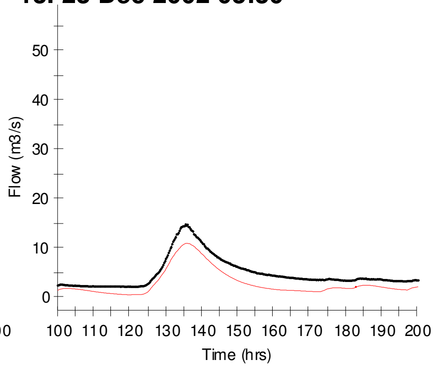
11. 01 Mar 2010 04:30



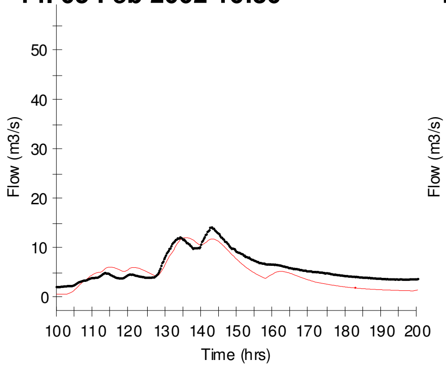
12. 21 Jan 2003 09:30



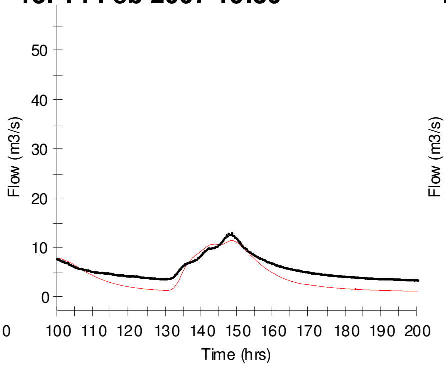
13. 23 Dec 2002 03:30



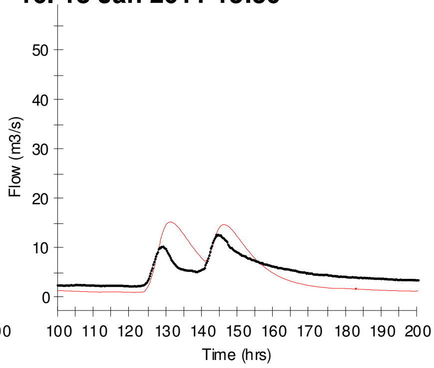
14. 05 Feb 2002 16:30



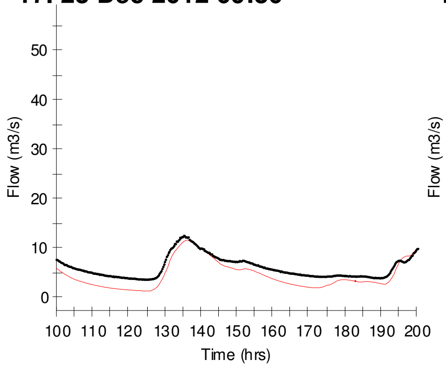
15. 14 Feb 2007 19:30



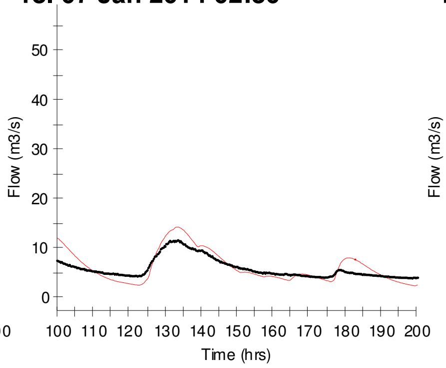
16. 18 Jan 2011 13:30



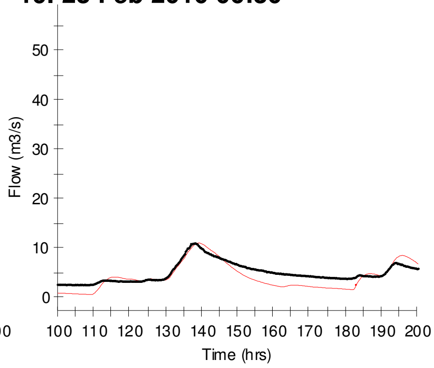
17. 23 Dec 2012 09:30



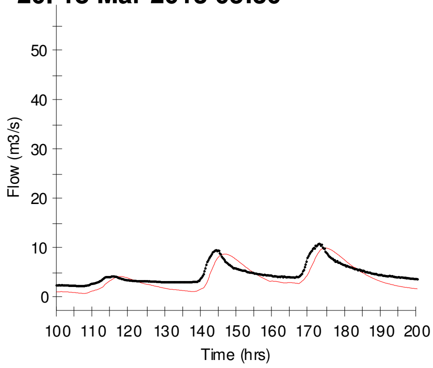
18. 07 Jan 2014 02:30



19. 23 Feb 2010 06:30

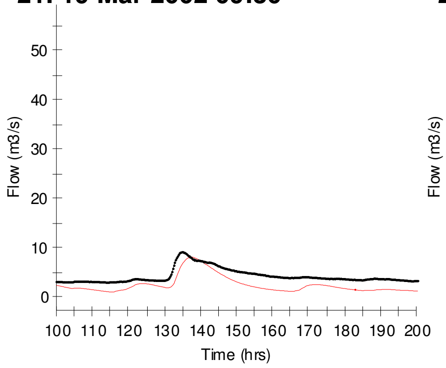


20. 18 Mar 2013 05:30

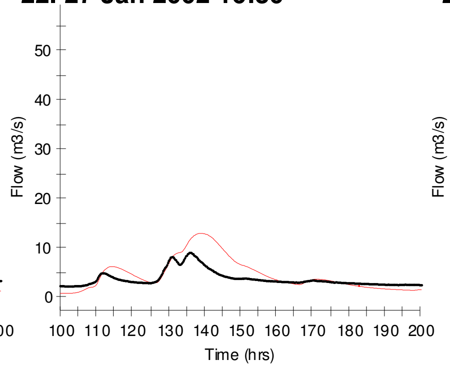


Key
Modelled
Observed

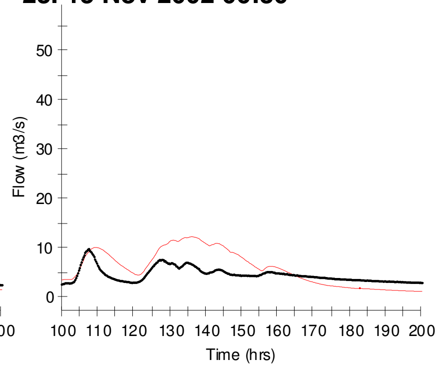
21. 19 Mar 2002 09:30



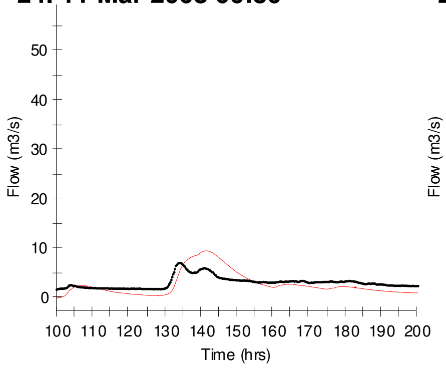
22. 27 Jan 2002 16:30



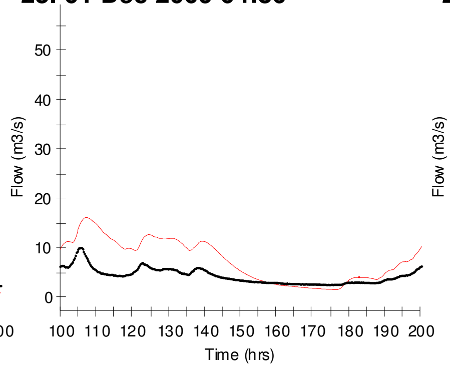
23. 15 Nov 2002 06:30



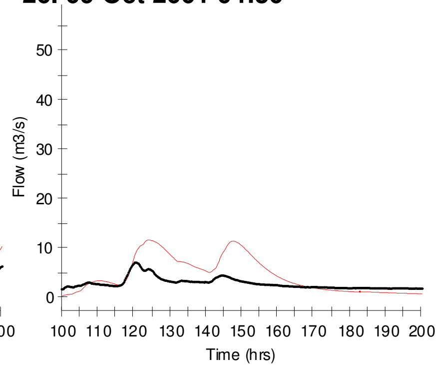
24. 11 Mar 2008 06:30



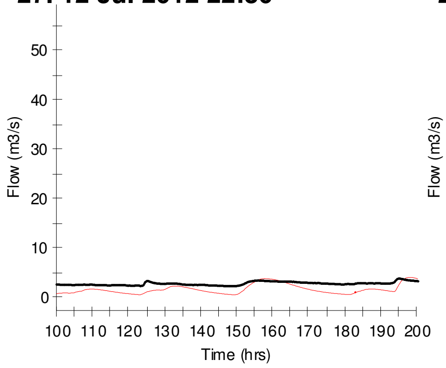
25. 01 Dec 2009 04:30



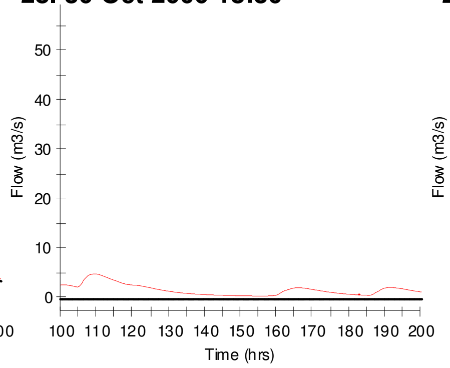
26. 09 Oct 2001 04:30



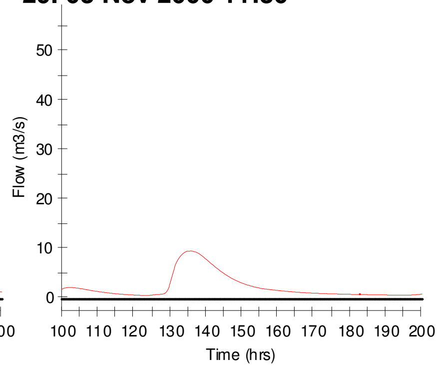
27. 12 Jul 2012 22:30



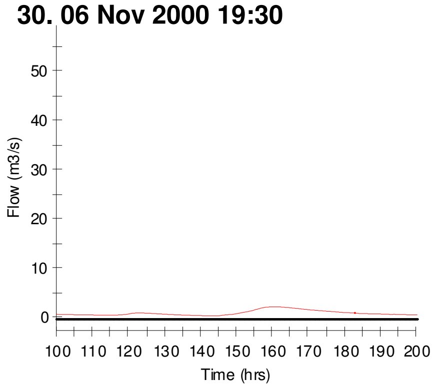
28. 30 Oct 2000 18:30



29. 03 Nov 2000 11:30



30. 06 Nov 2000 19:30



Key
Modelled
Observed

Leigh Barrier Inflow (observed is Colliers + Vexour)

Data summary

40 peaks analysed at MEDWAY13 between 35.7m3/s and 228.4m3/s, for period 30 Oct 2000 to 01 Feb 2014 from :

```
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\09 Cascade
```

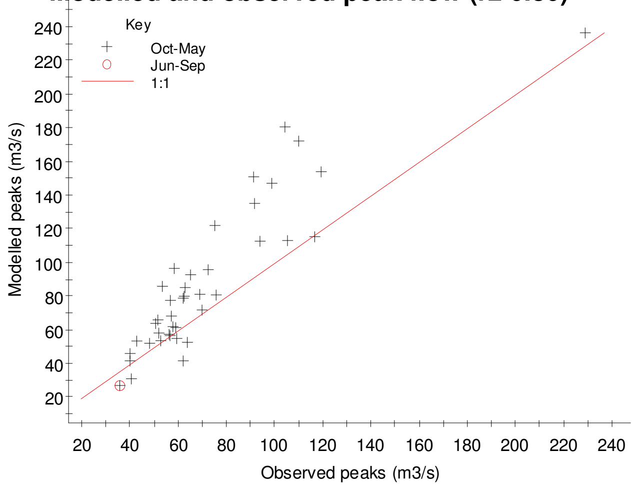
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	228.43	236.41	8.0	3%	6.9	0.850	0.870	17.03
2	17 Jan 2014 17:30	119.08	154.10	35.0	29%	4.6	0.712	0.936	12.46
3	30 Oct 2000 18:30	116.38	115.71	-0.7	-1%	2.7	0.885	0.887	8.53
4	01 Feb 2014 12:30	109.75	172.44	62.7	57%	3.0	0.317	0.921	19.86
5	16 Jan 2008 01:30	105.14	113.51	8.4	8%	4.8	0.902	0.917	7.06
6	06 Nov 2000 19:30	104.12	180.79	76.7	74%	3.7	0.580	0.808	15.71
7	10 Feb 2009 10:30	98.63	147.41	48.8	49%	4.6	0.699	0.951	11.32
8	31 Dec 2002 04:30	93.81	113.05	19.2	21%	3.3	0.735	0.852	10.20
9	02 Jan 2014 07:30	91.57	135.36	43.8	48%	1.7	0.349	0.846	14.35
10	13 Dec 2000 10:30	91.16	151.19	60.0	66%	3.0	0.476	0.925	14.96

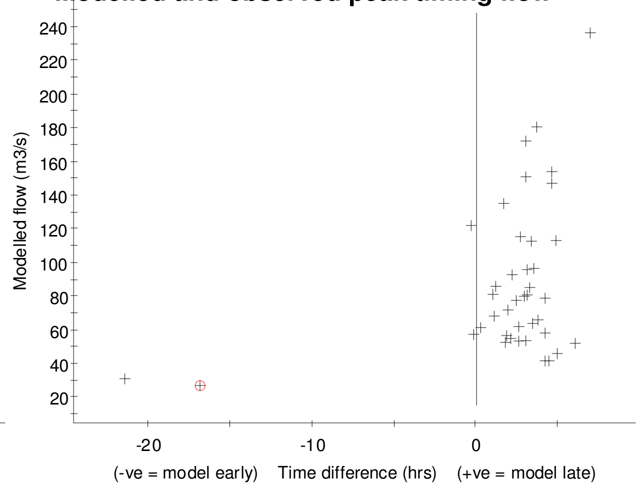
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.00	2.53	1.69	1.54	1.42	0.40	4.00	1.96

Modelled and observed peak flow (r2 0.80)

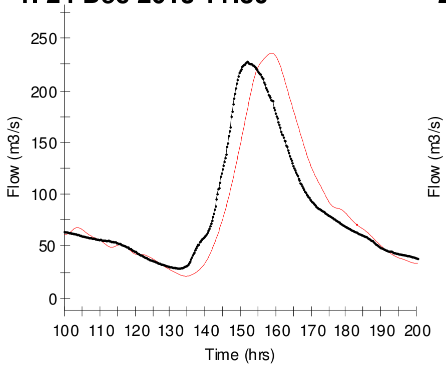


Modelled and observed peak timing flow

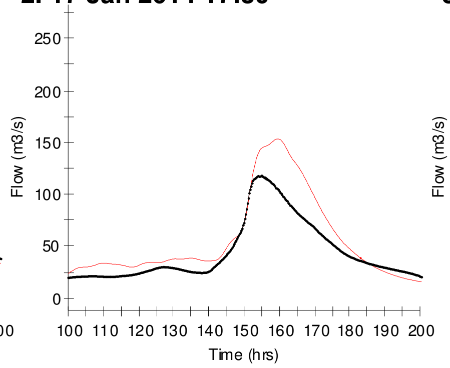


Leigh Barrier Inflow (observed is Colliers + Vexour)

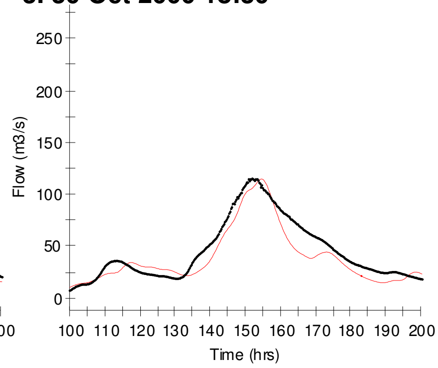
1. 24 Dec 2013 11:30



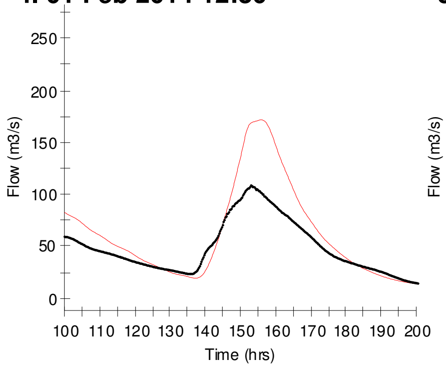
2. 17 Jan 2014 17:30



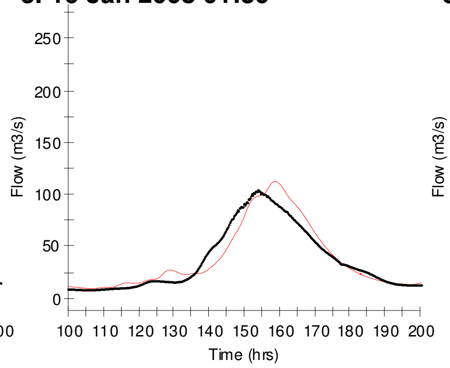
3. 30 Oct 2000 18:30



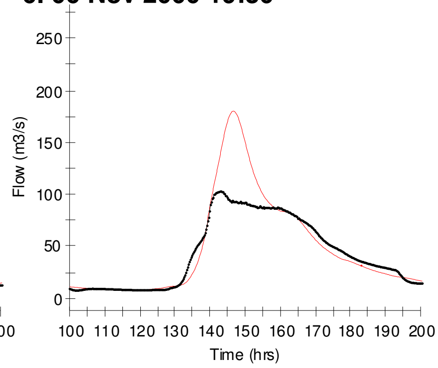
4. 01 Feb 2014 12:30



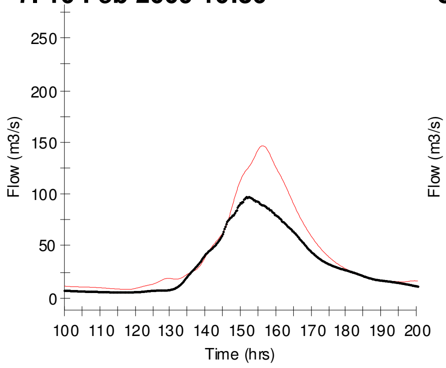
5. 16 Jan 2008 01:30



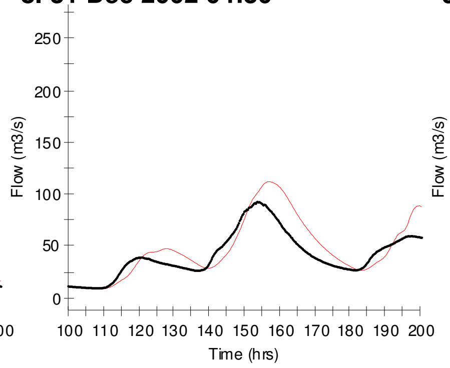
6. 06 Nov 2000 19:30



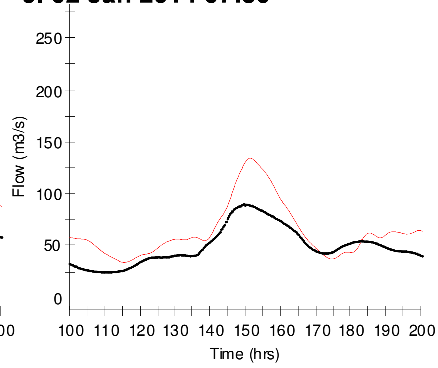
7. 10 Feb 2009 10:30



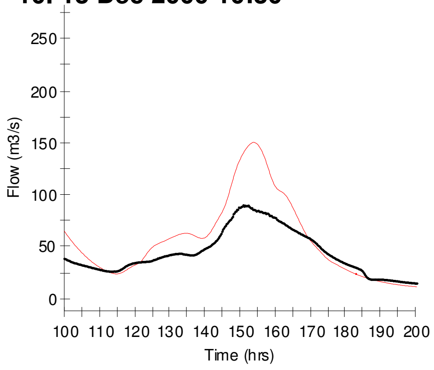
8. 31 Dec 2002 04:30



9. 02 Jan 2014 07:30



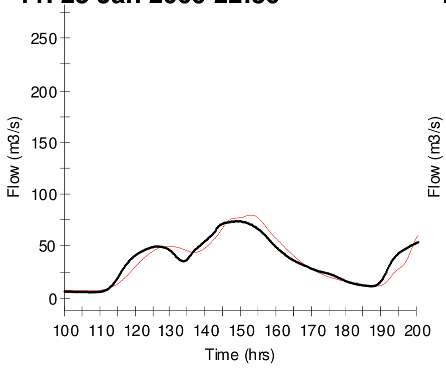
10. 13 Dec 2000 10:30



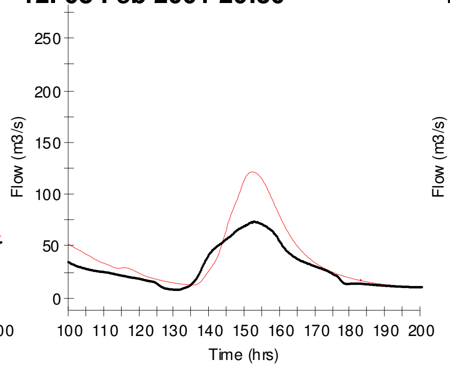
Key
Modelled
Observed

Leigh Barrier Inflow (observed is Colliers + Vexour)

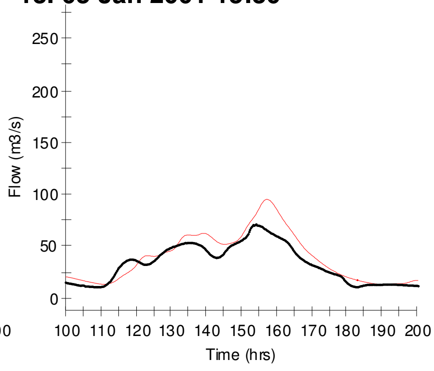
11. 23 Jan 2009 22:30



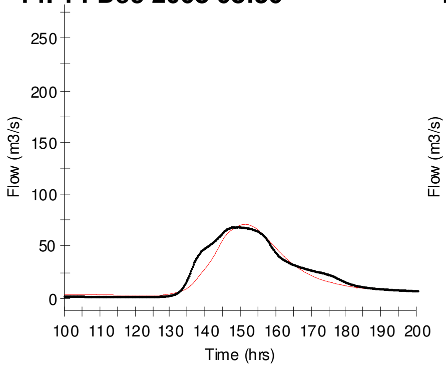
12. 08 Feb 2001 20:30



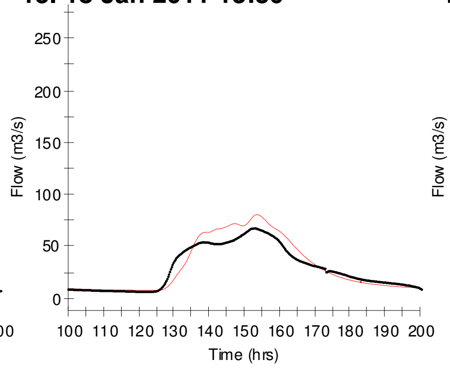
13. 05 Jan 2001 15:30



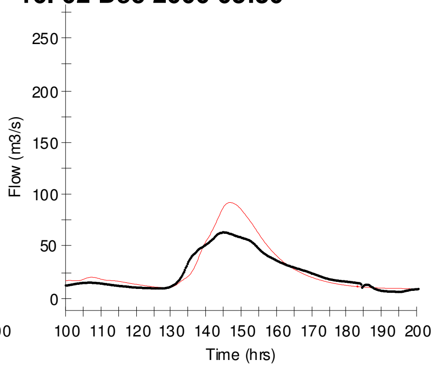
14. 14 Dec 2008 08:30



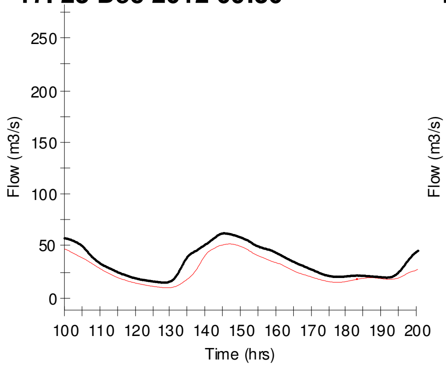
15. 18 Jan 2011 13:30



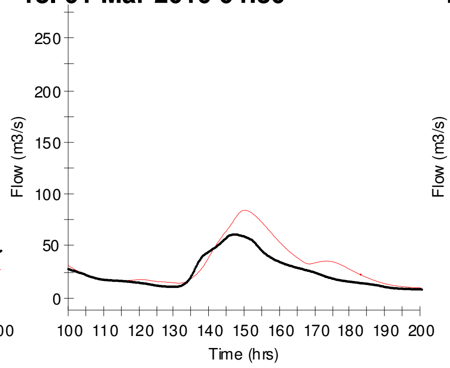
16. 02 Dec 2000 05:30



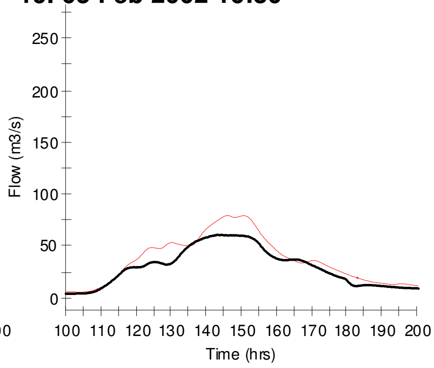
17. 23 Dec 2012 09:30



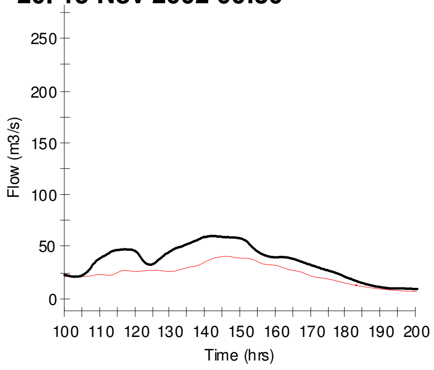
18. 01 Mar 2010 04:30



19. 05 Feb 2002 16:30



20. 15 Nov 2002 06:30



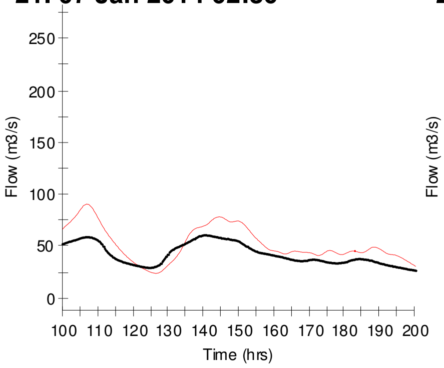
Key

Modelled

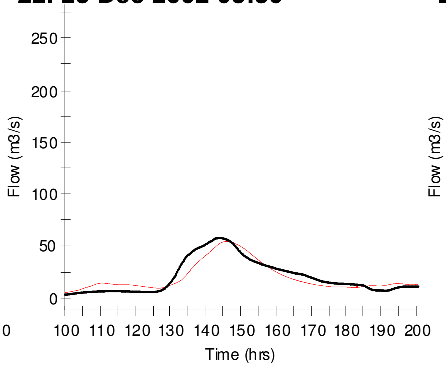
Observed

Leigh Barrier Inflow (observed is Colliers + Vexour)

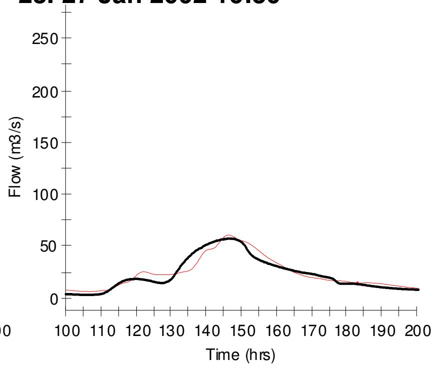
21. 07 Jan 2014 02:30



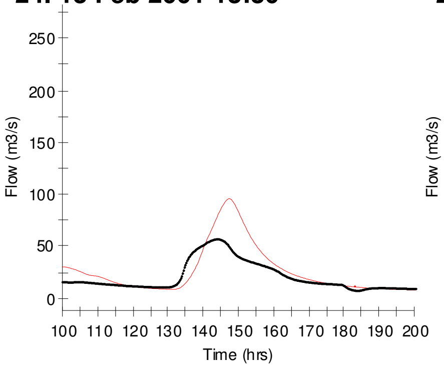
22. 23 Dec 2002 03:30



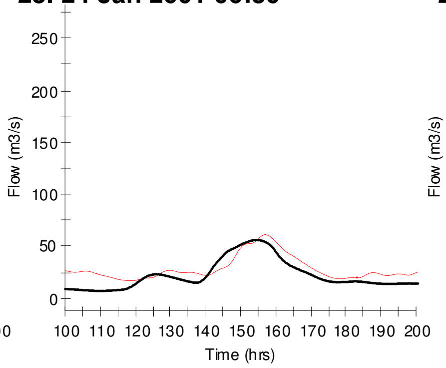
23. 27 Jan 2002 16:30



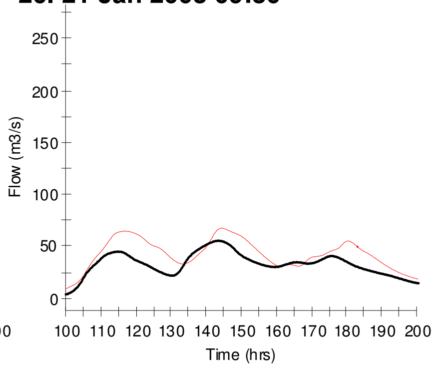
24. 13 Feb 2001 13:30



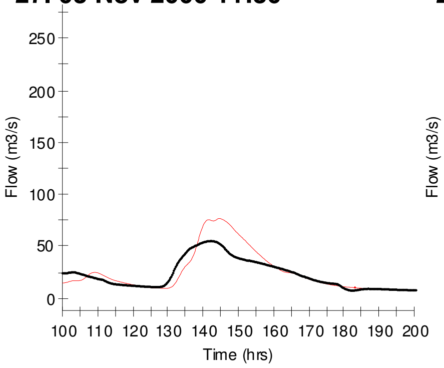
25. 24 Jan 2001 06:30



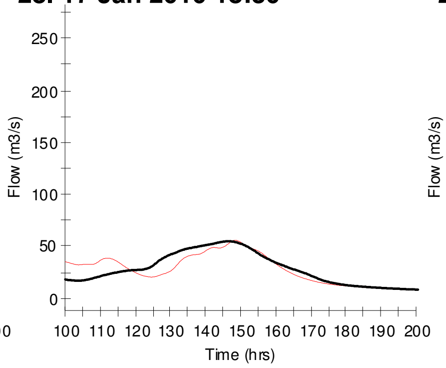
26. 21 Jan 2003 09:30



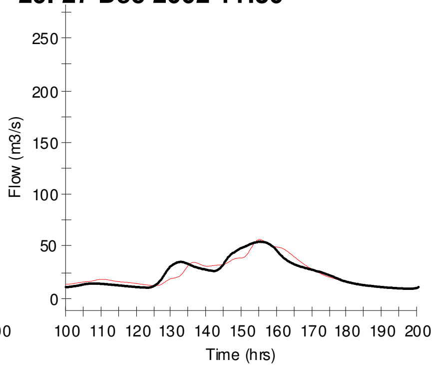
27. 03 Nov 2000 11:30



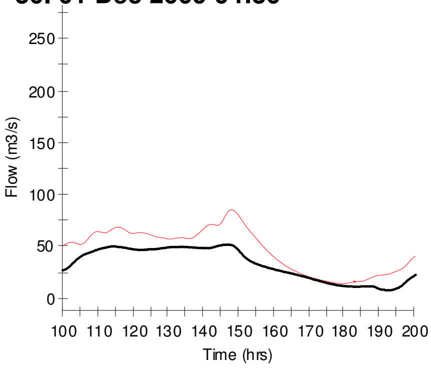
28. 17 Jan 2010 18:30



29. 27 Dec 2002 11:30



30. 01 Dec 2009 04:30



Key
Modelled
Observed

Leigh FSA Level

Data summary

40 peaks analysed at CSM61 between 0.0m and 27.6m, for period 30 Oct 2000 to 01 Feb 2014 from :

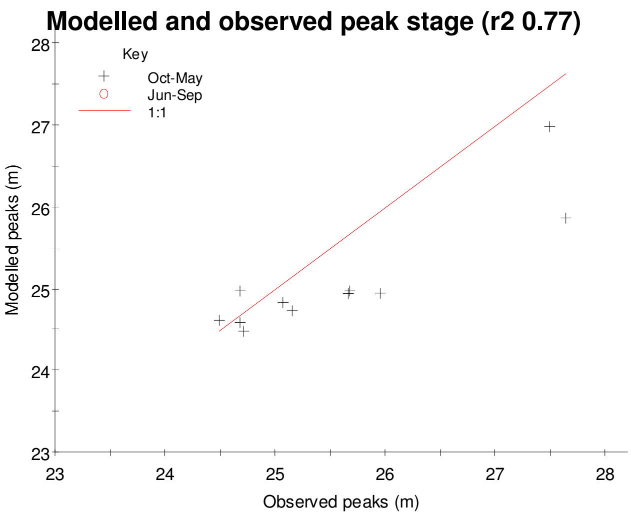
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\09 Cascade

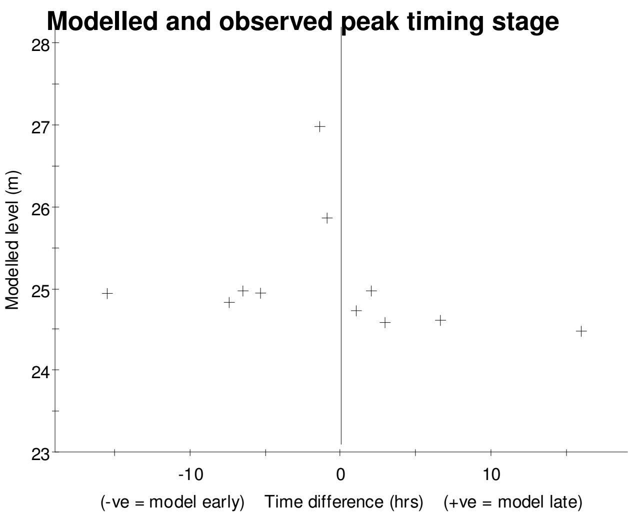
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m)	Mod. (m)	Diff. (m)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	16 Jan 2008 01:30	27.63	25.87	-1.76	-6%	-0.9	0.312	0.558	0.89
2	10 Feb 2009 10:30	27.48	26.99	-0.50	-2%	-1.4	0.710	0.798	0.53
3	23 Jan 2009 22:30	25.95	24.96	-0.99	-4%	-5.3	-0.30	0.516	0.48
4	01 Mar 2010 04:30	25.67	24.98	-0.69	-3%	-6.5	0.462	0.571	0.27
5	18 Jan 2011 13:30	25.66	24.95	-0.71	-3%	-15.5	0.008	0.127	0.34
6	14 Feb 2007 19:30	25.15	24.74	-0.41	-2%	1.0	0.564	0.618	0.14
7	14 Dec 2008 08:30	25.07	24.84	-0.22	-1%	-7.4	0.199	0.285	0.24
8	11 Mar 2008 06:30	24.71	24.49	-0.22	-1%	15.9	-0.09	0.096	0.19
9	01 Dec 2009 04:30	24.68	24.98	0.31	1%	2.0	0.332	0.517	0.22
10	17 Jan 2010 18:30	24.68	24.59	-0.08	0%	2.9	0.022	0.282	0.16

Model scores

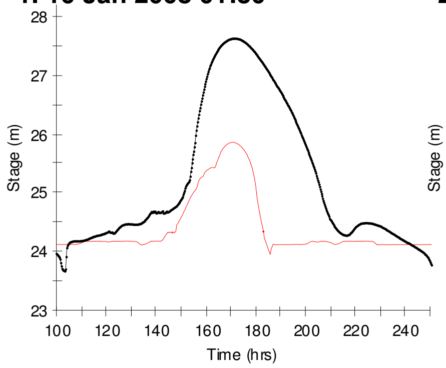
	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.18	3.49	4.04	0.00	3.51	4.00	3.33	2.58



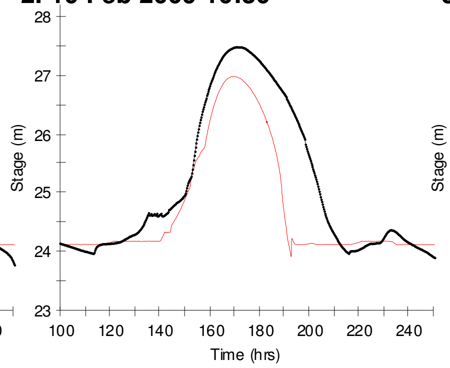


Leigh FSA Level

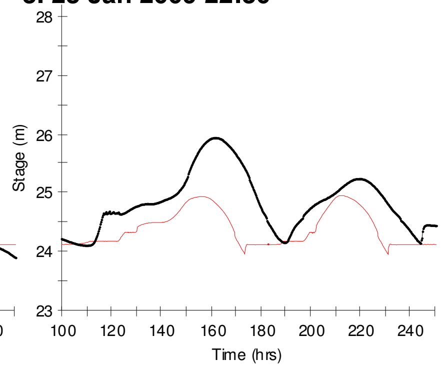
1. 16 Jan 2008 01:30



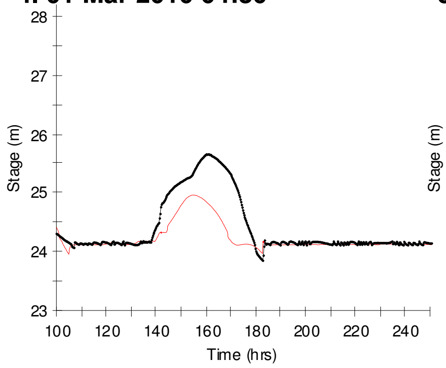
2. 10 Feb 2009 10:30



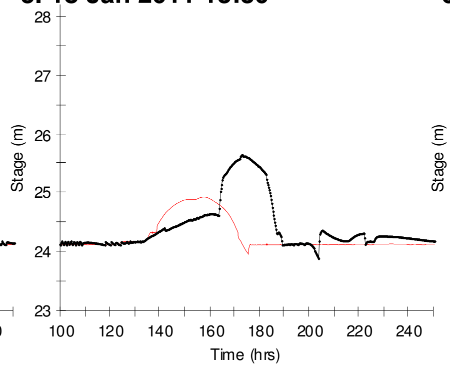
3. 23 Jan 2009 22:30



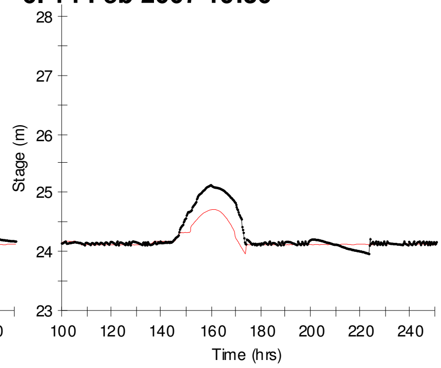
4. 01 Mar 2010 04:30



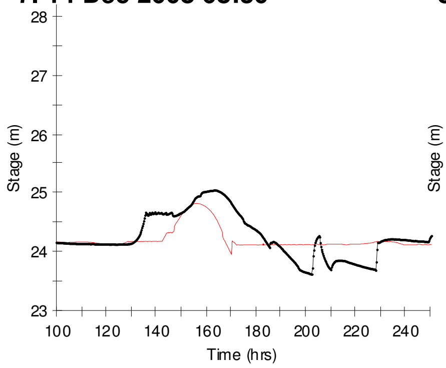
5. 18 Jan 2011 13:30



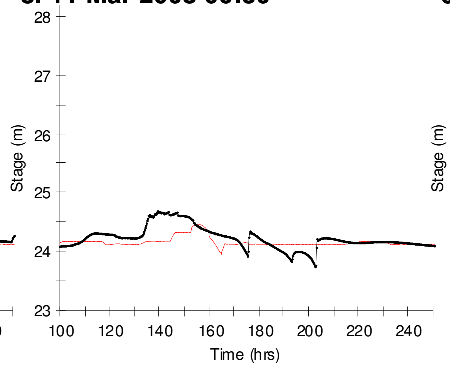
6. 14 Feb 2007 19:30



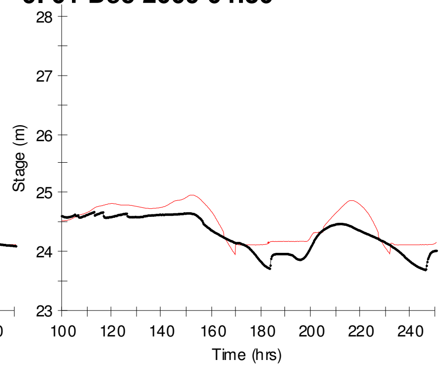
7. 14 Dec 2008 08:30



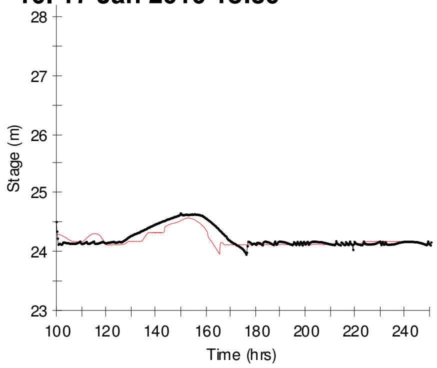
8. 11 Mar 2008 06:30



9. 01 Dec 2009 04:30

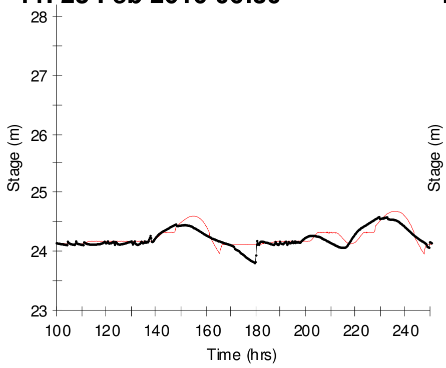


10. 17 Jan 2010 18:30

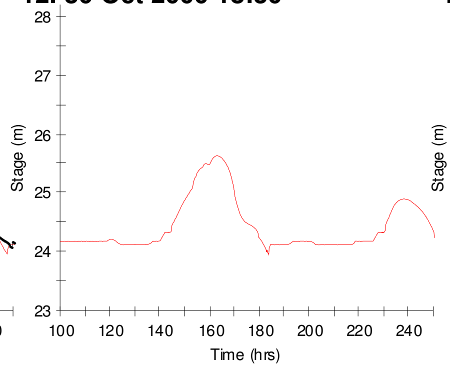


Key
Modelled
Observed

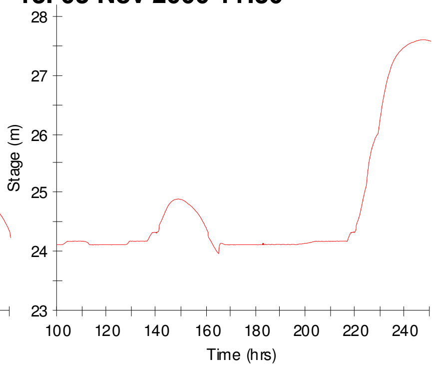
11. 23 Feb 2010 06:30



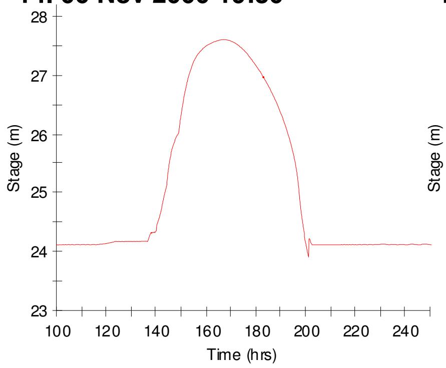
12. 30 Oct 2000 18:30



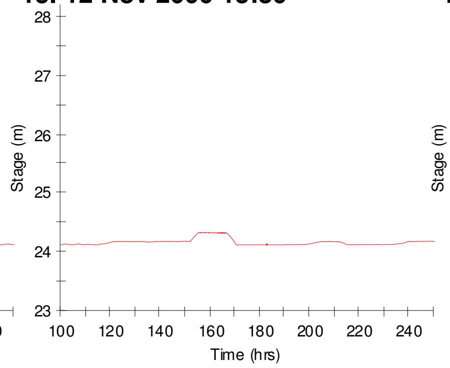
13. 03 Nov 2000 11:30



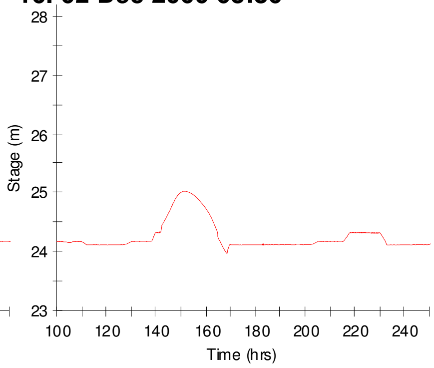
14. 06 Nov 2000 19:30



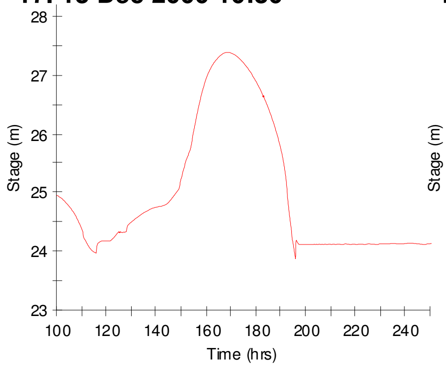
15. 12 Nov 2000 15:30



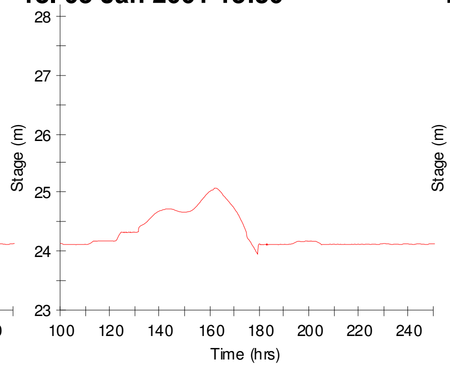
16. 02 Dec 2000 05:30



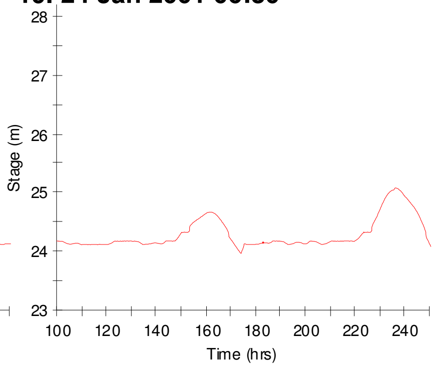
17. 13 Dec 2000 10:30



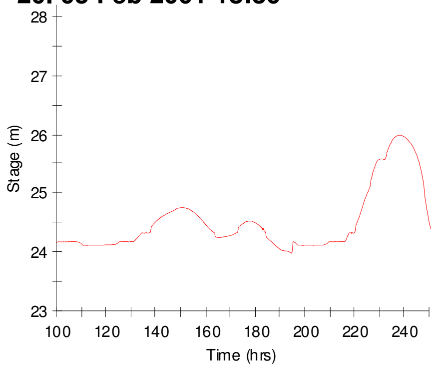
18. 05 Jan 2001 15:30



19. 24 Jan 2001 06:30

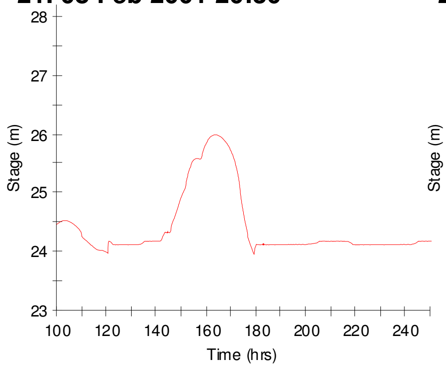


20. 05 Feb 2001 18:30

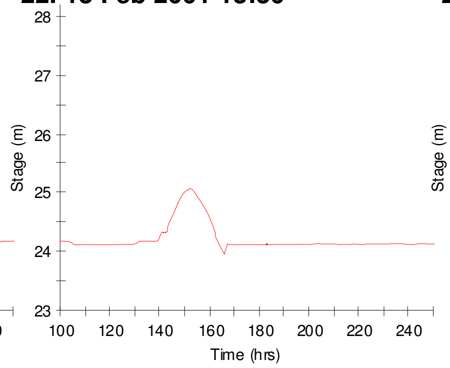


Key
Modelled
Observed

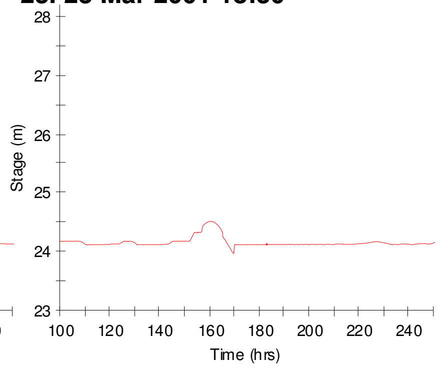
21. 08 Feb 2001 20:30



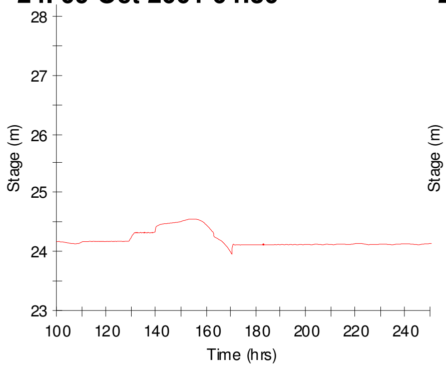
22. 13 Feb 2001 13:30



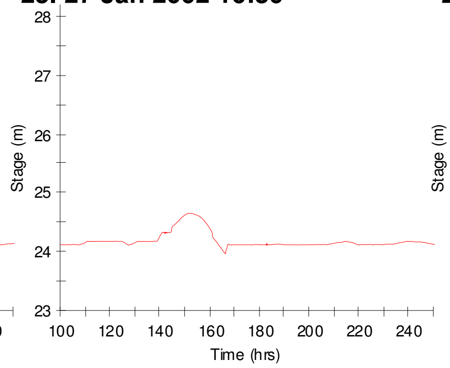
23. 23 Mar 2001 18:30



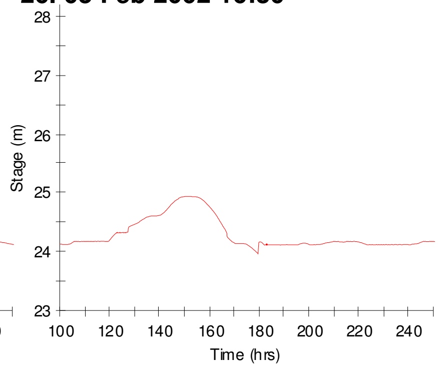
24. 09 Oct 2001 04:30



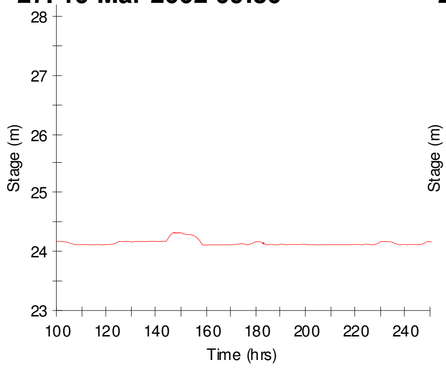
25. 27 Jan 2002 16:30



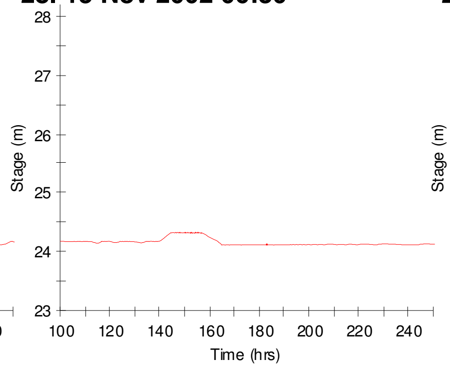
26. 05 Feb 2002 16:30



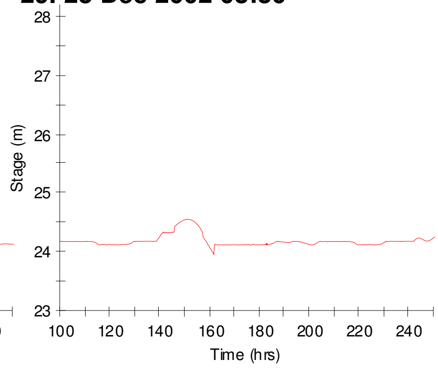
27. 19 Mar 2002 09:30



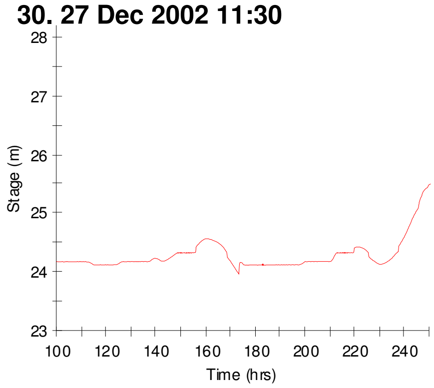
28. 15 Nov 2002 06:30



29. 23 Dec 2002 03:30



30. 27 Dec 2002 11:30



Key
Modelled
Observed

Data summary

40 peaks analysed at CS10 between 0.0m3/s and 161.1m3/s, for period 30 Oct 2000 to 01 Feb 2014 from :

N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\09 Cascade

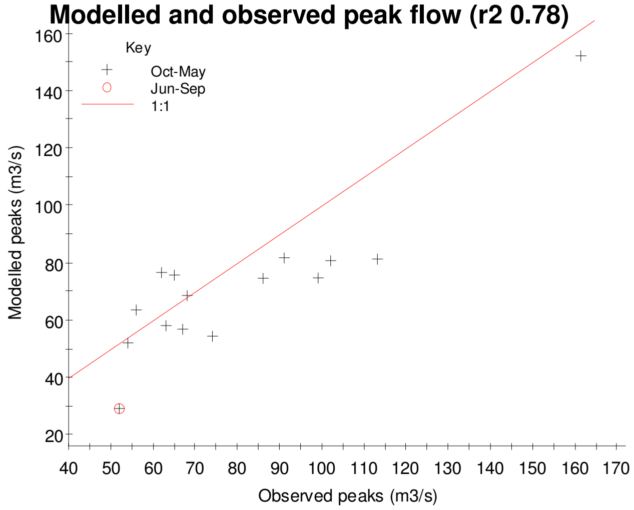
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	161.14	152.14	-9.0	-6%	7.8	0.253	0.824	37.50
2	10 Feb 2009 10:30	113.00	81.46	-31.5	-28%	8.4	0.802	0.818	12.63
3	16 Jan 2008 01:30	102.00	80.94	-21.1	-21%	3.8	0.466	0.603	19.27
4	23 Jan 2009 22:30	99.00	74.91	-24.1	-24%	-3.3	0.701	0.751	13.29
5	01 Feb 2014 12:30	91.00	81.99	-9.0	-10%	8.0	-0.05	0.238	29.93
6	18 Jan 2011 13:30	86.00	74.78	-11.2	-13%	-1.0	0.712	0.717	10.41
7	23 Dec 2012 09:30	74.00	54.72	-19.3	-26%	-13.0	0.297	0.747	16.62
8	14 Dec 2008 08:30	68.00	68.82	0.8	1%	-0.5	0.686	0.706	11.08
9	17 Jan 2010 18:30	67.00	57.07	-9.9	-15%	3.1	0.695	0.705	9.82
10	01 Mar 2010 04:30	65.00	75.89	10.9	17%	-6.7	0.421	0.524	14.65

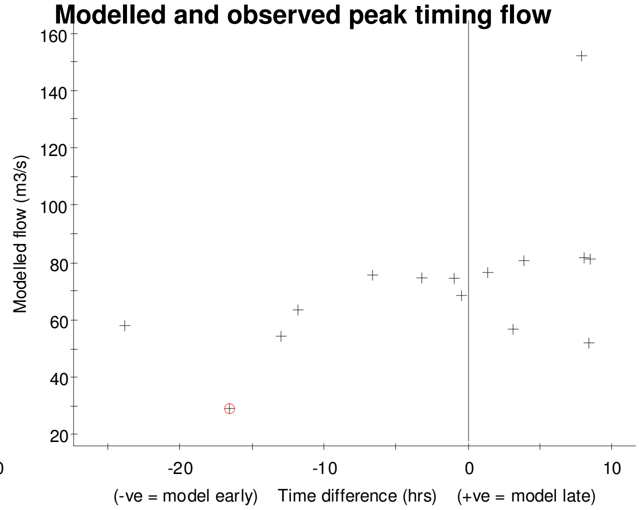
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.11	2.90	3.35	0.00	3.20	4.00	4.00	2.51

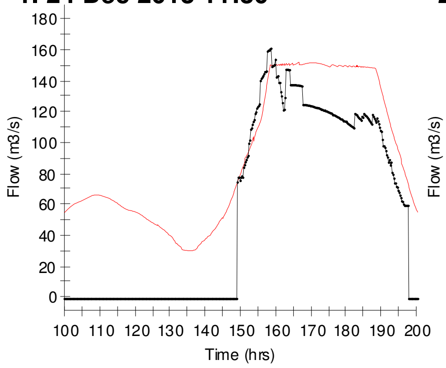
Modelled and observed peak flow (r2 0.78)



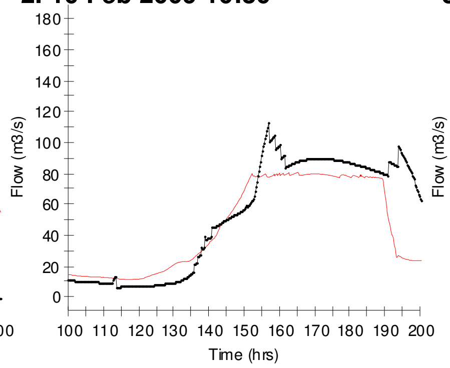
Modelled and observed peak timing flow



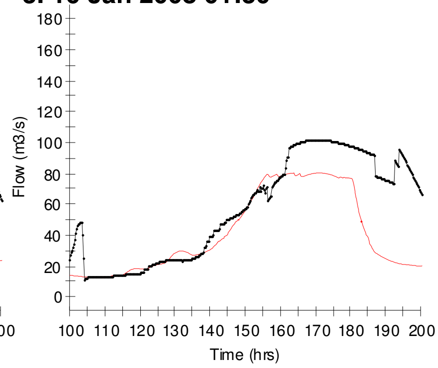
1. 24 Dec 2013 11:30



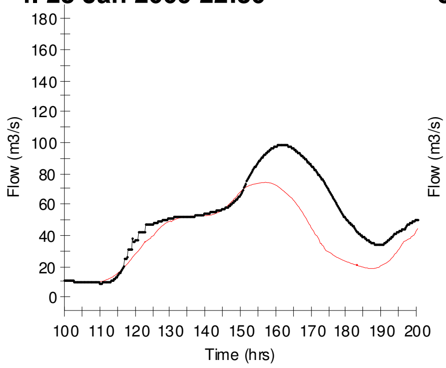
2. 10 Feb 2009 10:30



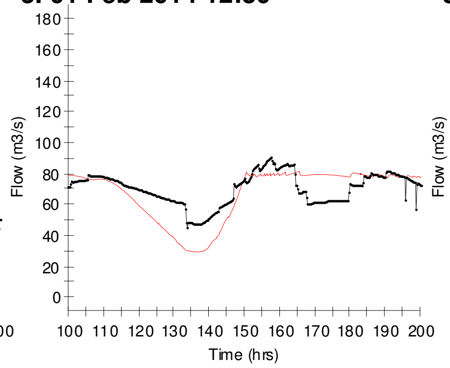
3. 16 Jan 2008 01:30



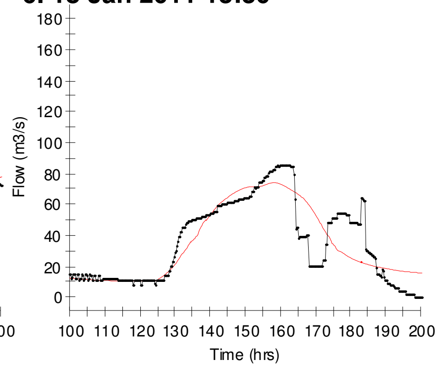
4. 23 Jan 2009 22:30



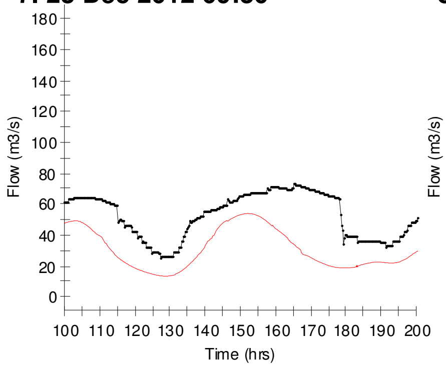
5. 01 Feb 2014 12:30



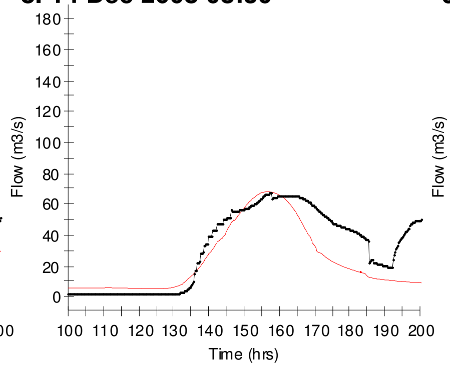
6. 18 Jan 2011 13:30



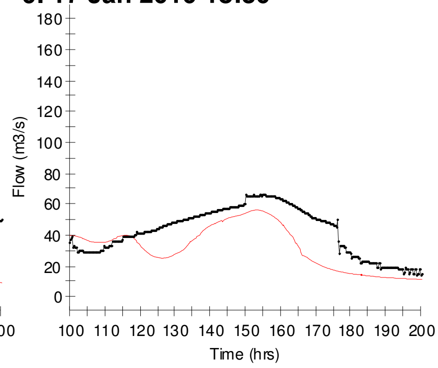
7. 23 Dec 2012 09:30



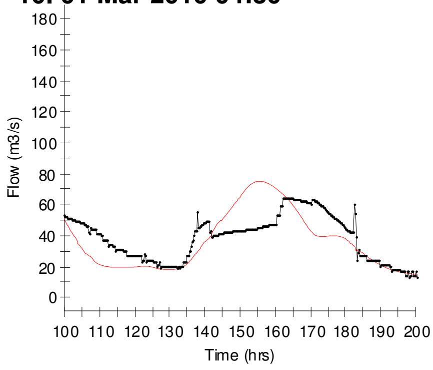
8. 14 Dec 2008 08:30



9. 17 Jan 2010 18:30

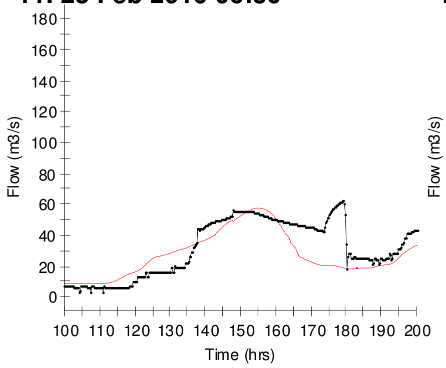


10. 01 Mar 2010 04:30

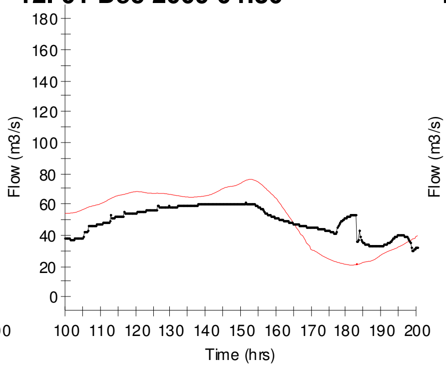


Key
Modelled
Observed

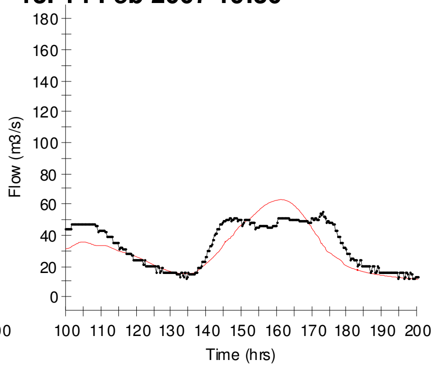
11. 23 Feb 2010 06:30



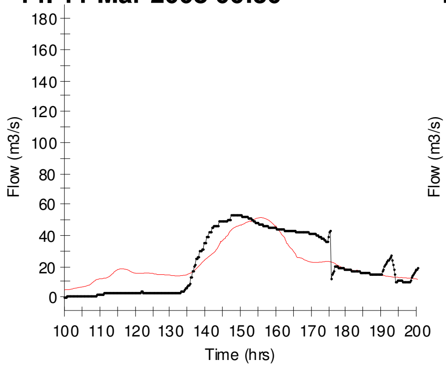
12. 01 Dec 2009 04:30



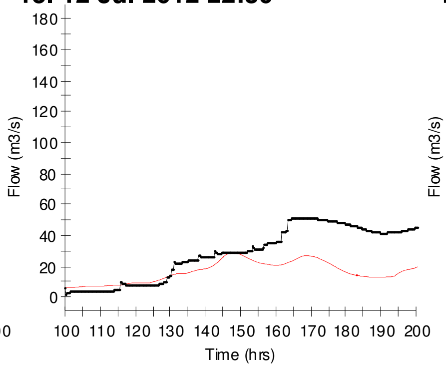
13. 14 Feb 2007 19:30



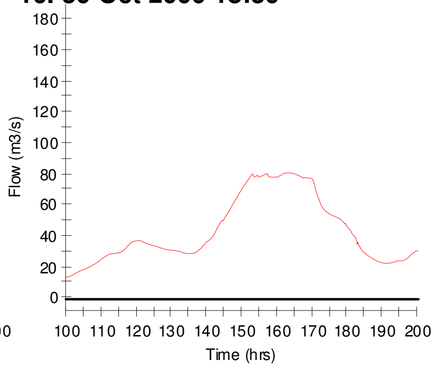
14. 11 Mar 2008 06:30



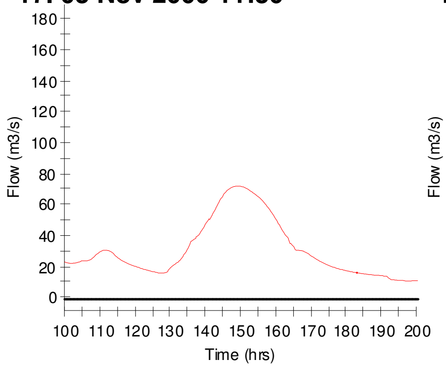
15. 12 Jul 2012 22:30



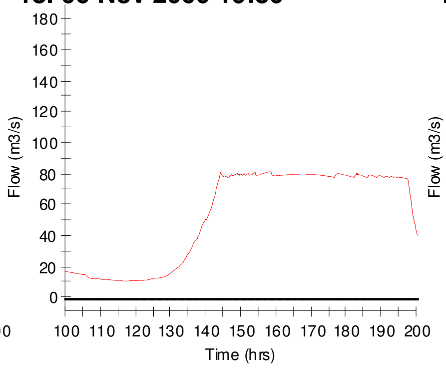
16. 30 Oct 2000 18:30



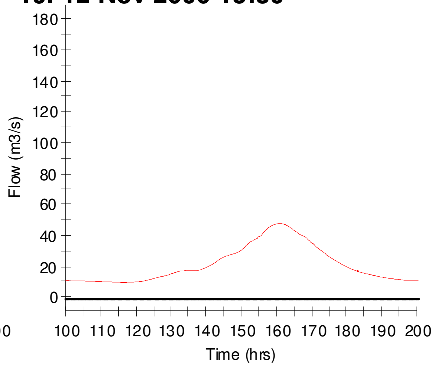
17. 03 Nov 2000 11:30



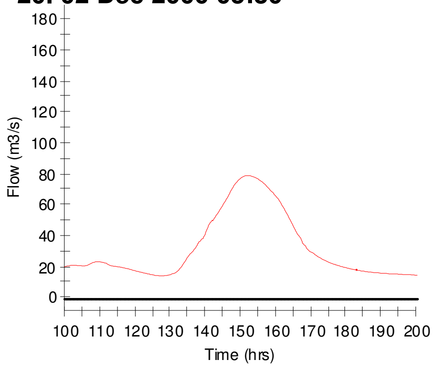
18. 06 Nov 2000 19:30



19. 12 Nov 2000 15:30

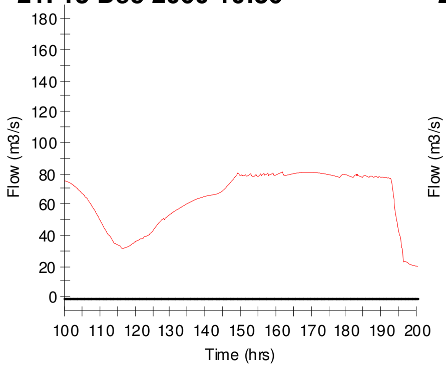


20. 02 Dec 2000 05:30

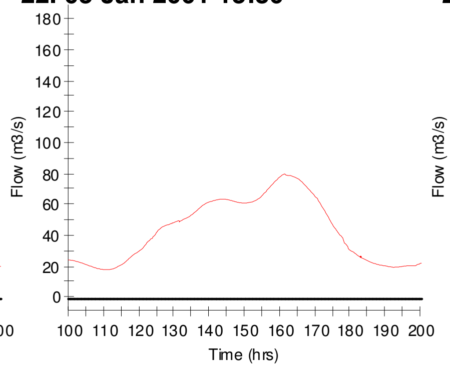


Key
Modelled
Observed

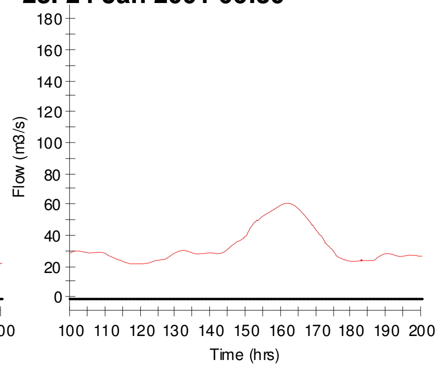
21. 13 Dec 2000 10:30



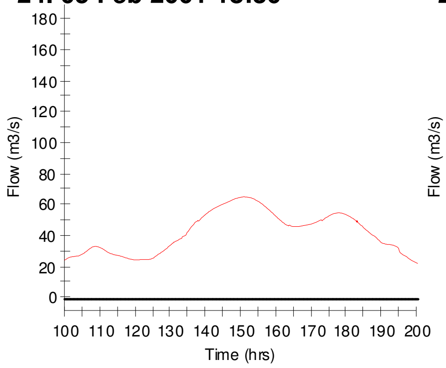
22. 05 Jan 2001 15:30



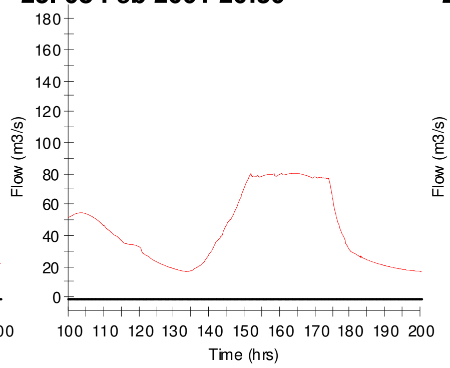
23. 24 Jan 2001 06:30



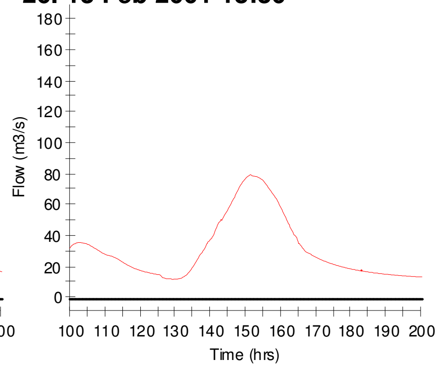
24. 05 Feb 2001 18:30



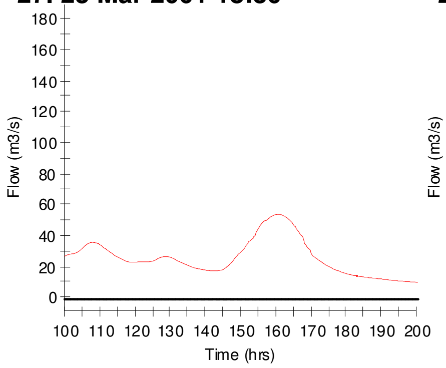
25. 08 Feb 2001 20:30



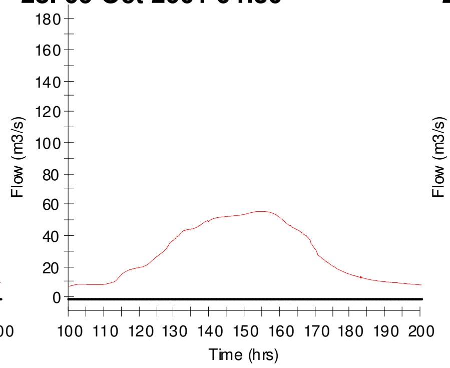
26. 13 Feb 2001 13:30



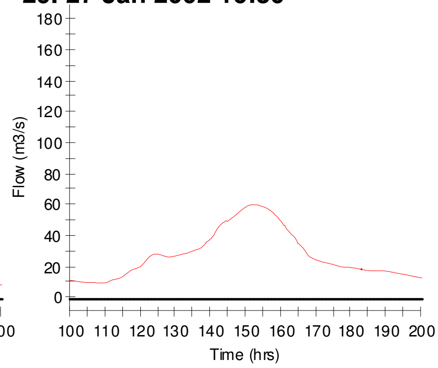
27. 23 Mar 2001 18:30



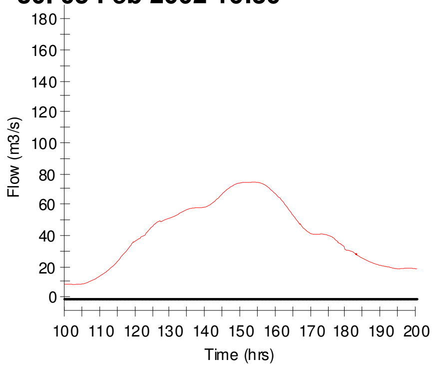
28. 09 Oct 2001 04:30



29. 27 Jan 2002 16:30



30. 05 Feb 2002 16:30



Key

Modelled

Observed

Summerford Bridge

Data summary

40 peaks analysed at Summerfd between 7.7m3/s and 74.0m3/s, for period 30 Oct 2000 to 01 Feb 2014 from :

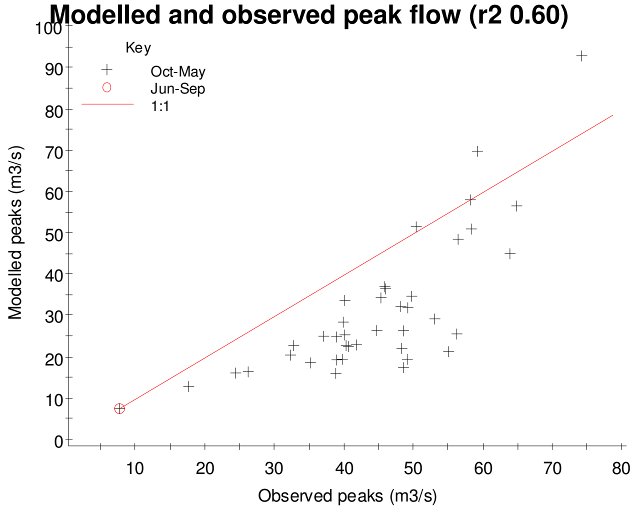
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\09 Cascade

Peak magnitude and timing for the top ten observed events (09 Cascade)

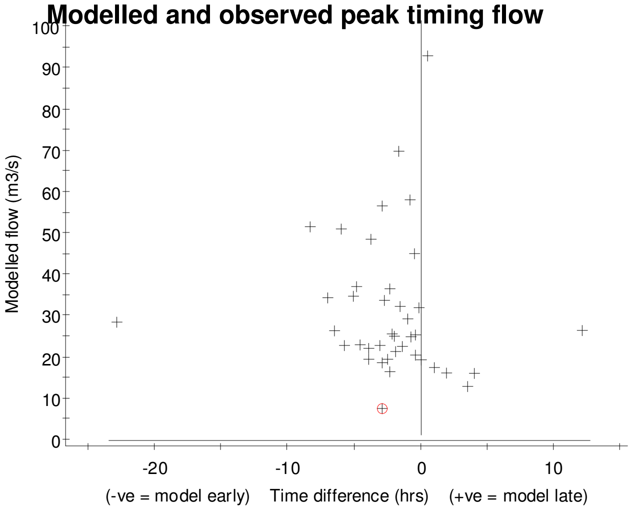
	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	74.05	92.86	18.8	25%	0.5	0.652	0.763	11.53
2	06 Nov 2000 19:30	64.75	56.61	-8.1	-13%	-2.9	0.292	0.574	13.03
3	16 Jan 2008 01:30	63.75	45.15	-18.6	-29%	-0.5	0.663	0.891	9.12
4	01 Feb 2014 12:30	59.10	69.84	10.7	18%	-1.7	0.166	0.313	15.32
5	13 Dec 2000 10:30	58.22	51.11	-7.1	-12%	-6.0	0.442	0.667	11.36
6	10 Feb 2009 10:30	58.05	58.07	0.0	0%	-0.8	0.853	0.879	5.21
7	02 Jan 2014 07:30	56.32	48.56	-7.8	-14%	-3.8	0.616	0.754	8.65
8	05 Feb 2002 16:30	56.15	25.77	-30.4	-54%	-2.2	0.512	0.852	8.93
9	27 Jan 2002 16:30	54.96	21.51	-33.5	-61%	-1.9	0.553	0.863	6.24
10	14 Dec 2008 08:30	52.95	29.37	-23.6	-45%	-1.0	0.698	0.963	6.31

Model scores								
	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	3.14	3.21	2.96	1.97	2.00	0.53	4.00	2.64

Modelled and observed peak flow (r2 0.60)

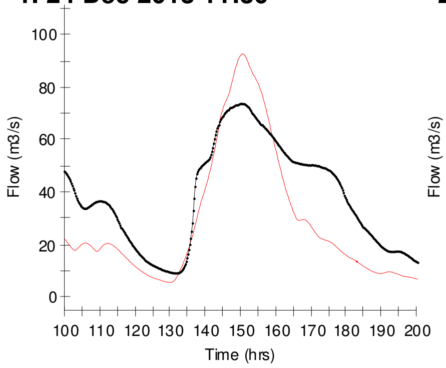


Modelled and observed peak timing flow

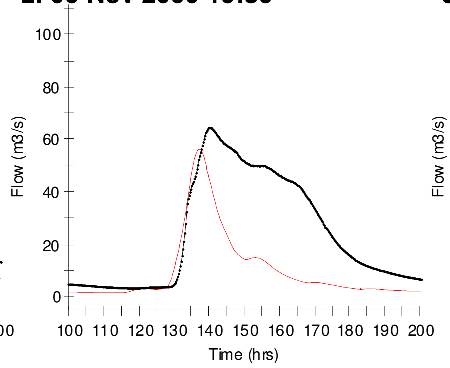


Summerford Bridge

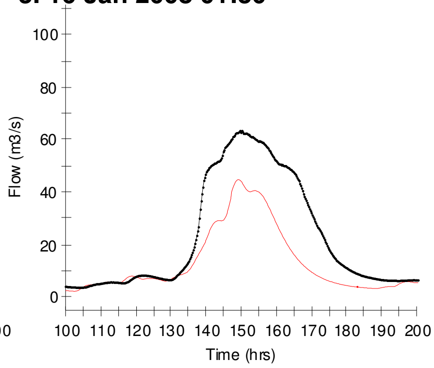
1. 24 Dec 2013 11:30



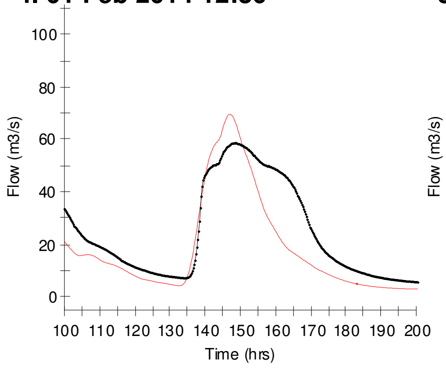
2. 06 Nov 2000 19:30



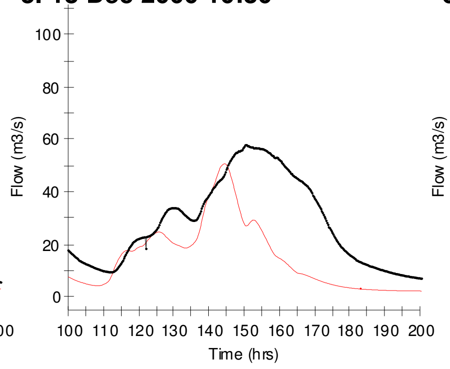
3. 16 Jan 2008 01:30



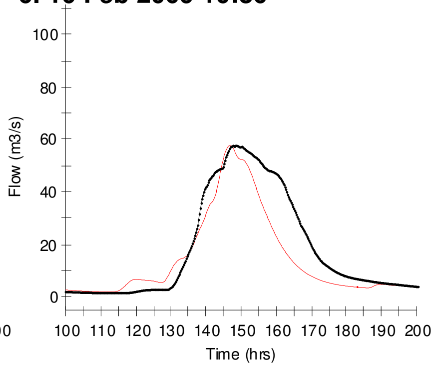
4. 01 Feb 2014 12:30



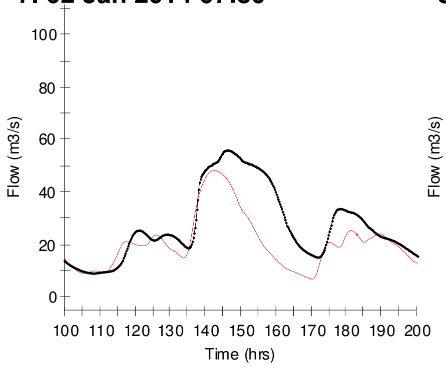
5. 13 Dec 2000 10:30



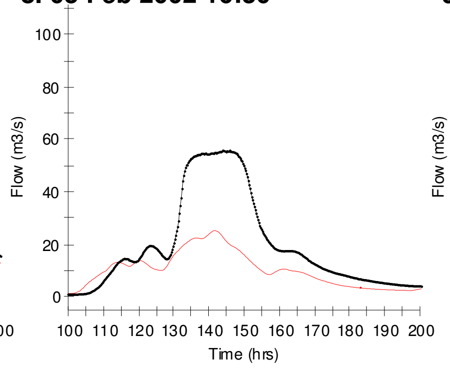
6. 10 Feb 2009 10:30



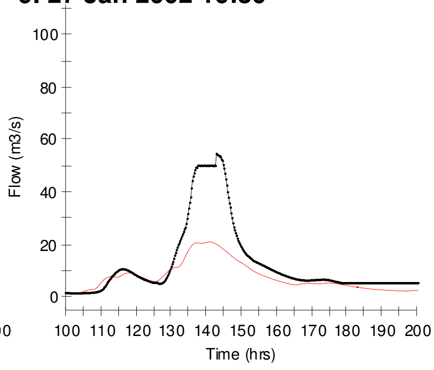
7. 02 Jan 2014 07:30



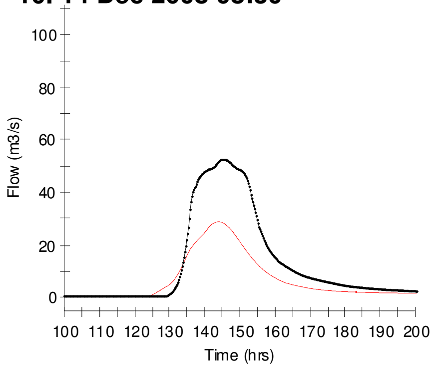
8. 05 Feb 2002 16:30



9. 27 Jan 2002 16:30



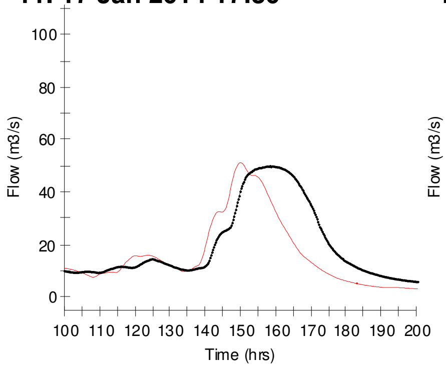
10. 14 Dec 2008 08:30



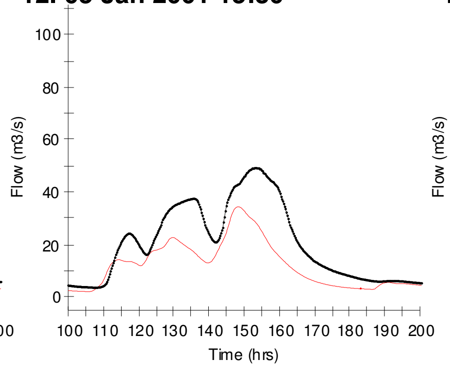
Key
Modelled
Observed

JBA consulting

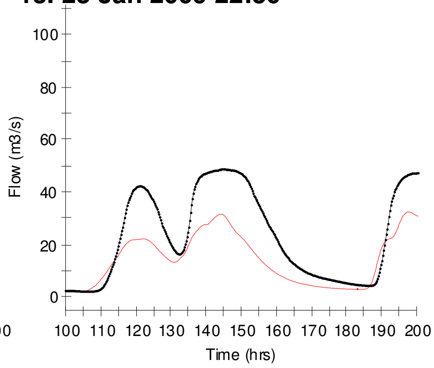
11. 17 Jan 2014 17:30



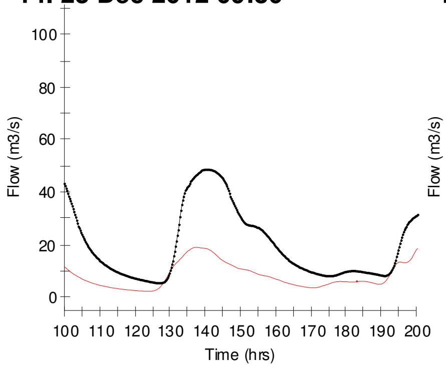
12. 05 Jan 2001 15:30



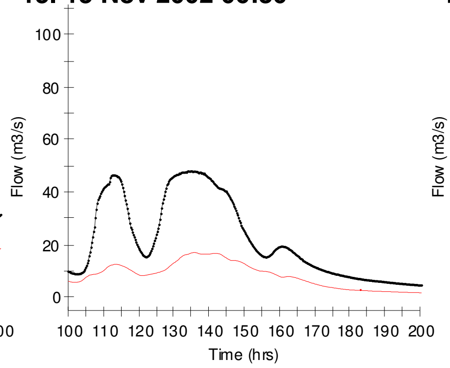
13. 23 Jan 2009 22:30



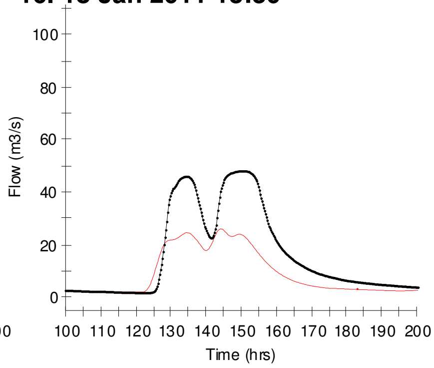
14. 23 Dec 2012 09:30



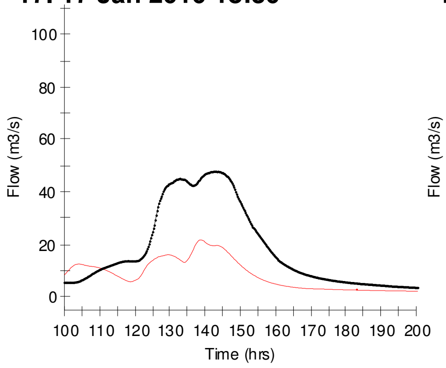
15. 15 Nov 2002 06:30



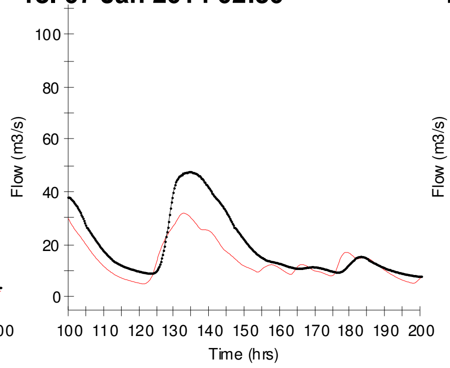
16. 18 Jan 2011 13:30



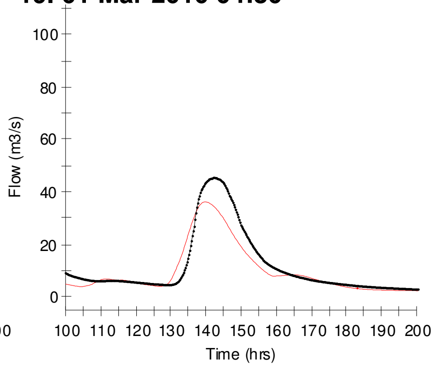
17. 17 Jan 2010 18:30



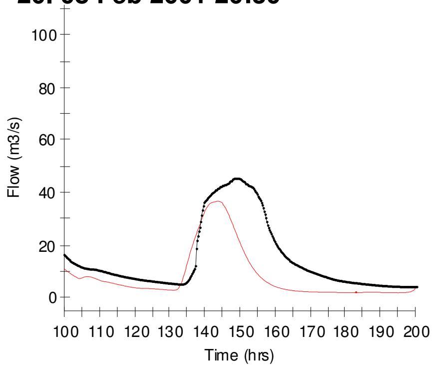
18. 07 Jan 2014 02:30



19. 01 Mar 2010 04:30

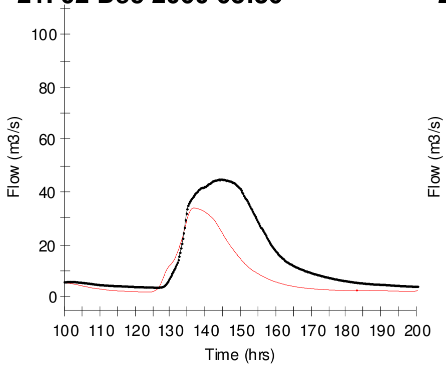


20. 08 Feb 2001 20:30

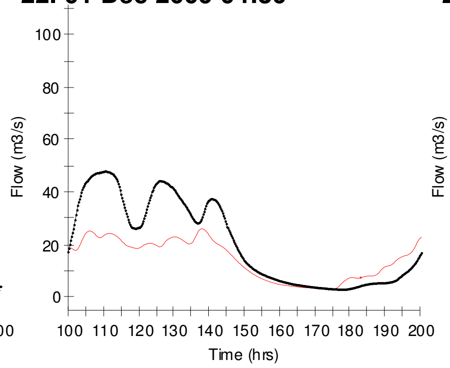


Key
Modelled
Observed

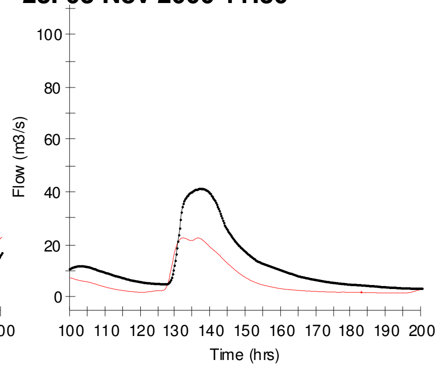
21. 02 Dec 2000 05:30



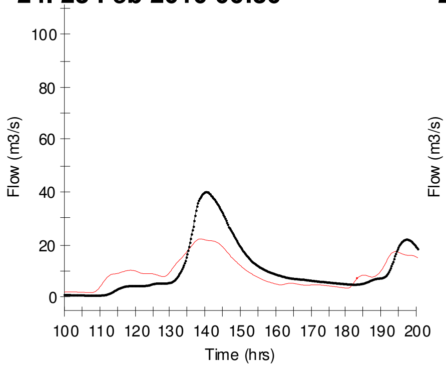
22. 01 Dec 2009 04:30



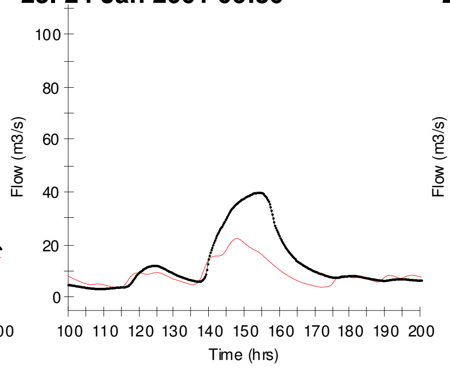
23. 03 Nov 2000 11:30



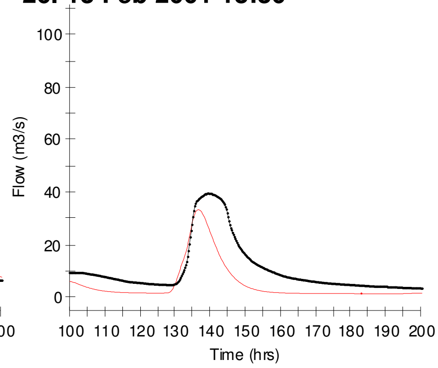
24. 23 Feb 2010 06:30



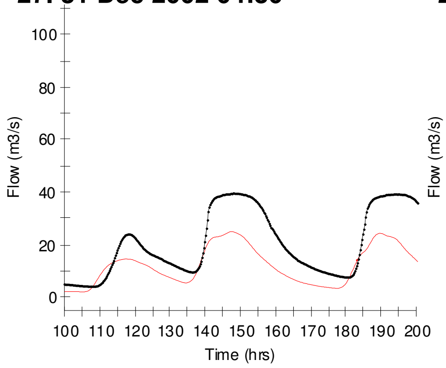
25. 24 Jan 2001 06:30



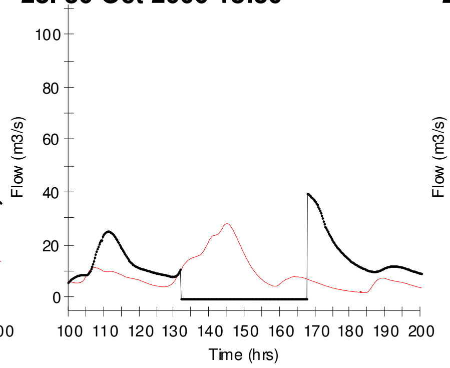
26. 13 Feb 2001 13:30



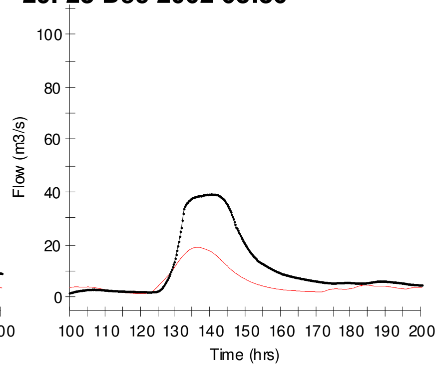
27. 31 Dec 2002 04:30



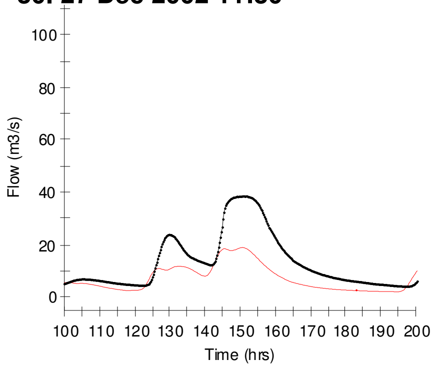
28. 30 Oct 2000 18:30



29. 23 Dec 2002 03:30



30. 27 Dec 2002 11:30



Key
Modelled
Observed

Data summary

39 peaks analysed at Hendal between 0.0m3/s and 31.1m3/s, for period 30 Oct 2000 to 01 Feb 2014 from :

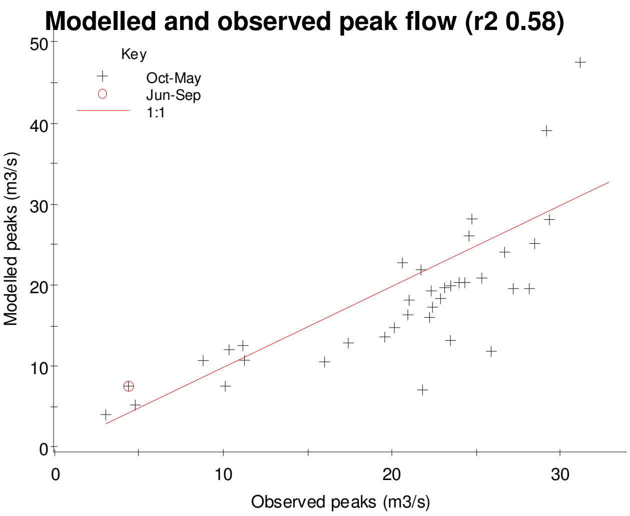
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\09 Cascade

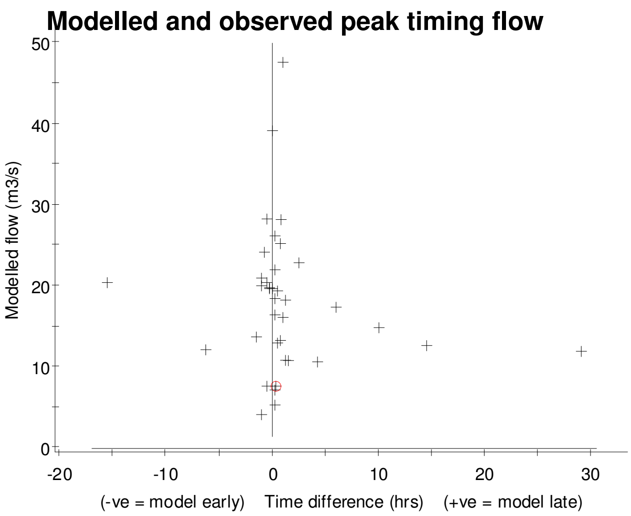
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	06 Nov 2000 19:30	31.09	47.54	16.5	53%	1.0	0.869	0.924	2.24
2	05 Jan 2001 15:30	29.27	28.20	-1.1	-4%	0.8	0.158	0.267	5.71
3	30 Oct 2000 18:30	29.11	39.11	10.0	34%	0.0	0.929	0.938	1.77
4	10 Feb 2009 10:30	28.40	25.22	-3.2	-11%	0.8	0.924	0.956	1.44
5	01 Feb 2014 12:30	28.07	19.70	-8.4	-30%	-0.3	0.225	0.307	4.91
6	02 Jan 2014 07:30	27.14	19.70	-7.4	-27%	0.0	0.759	0.846	2.90
7	16 Jan 2008 01:30	26.63	24.16	-2.5	-9%	-0.8	0.905	0.925	1.64
8	01 Mar 2010 04:30	25.83	11.96	-13.9	-54%	29.0	0.230	0.259	3.58
9	02 Dec 2000 05:30	25.28	20.99	-4.3	-17%	-1.0	0.861	0.878	1.50
10	03 Nov 2000 11:30	24.69	28.28	3.6	15%	-0.5	0.881	0.920	2.65

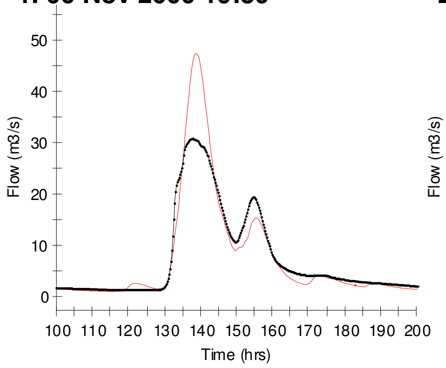
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	3.19	0.46	0.60	1.95	1.07	2.48	2.68	2.15

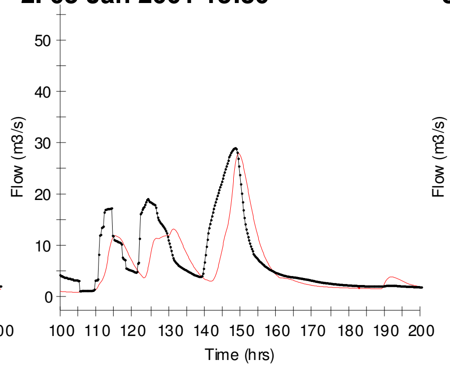




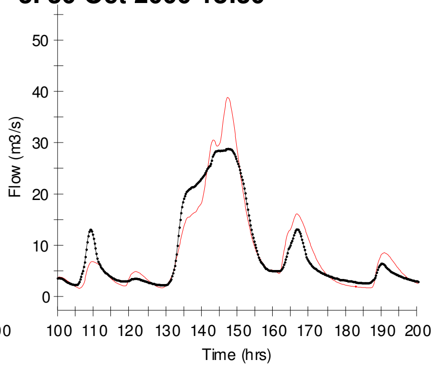
1. 06 Nov 2000 19:30



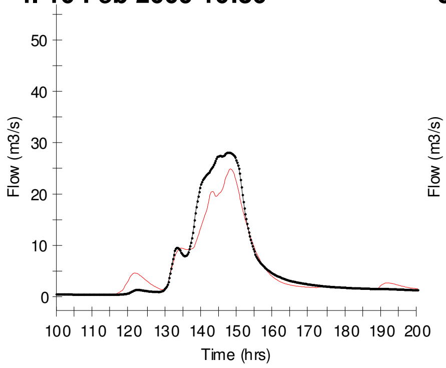
2. 05 Jan 2001 15:30



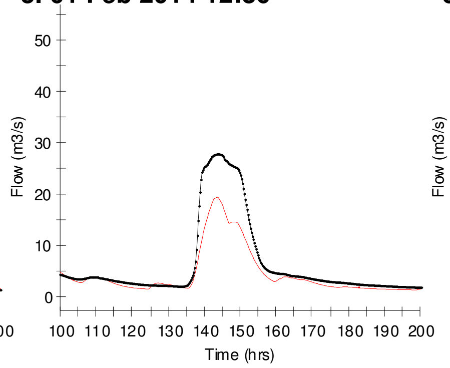
3. 30 Oct 2000 18:30



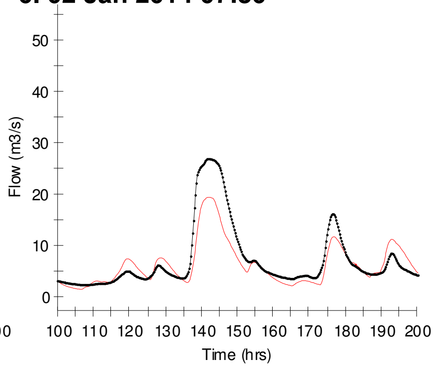
4. 10 Feb 2009 10:30



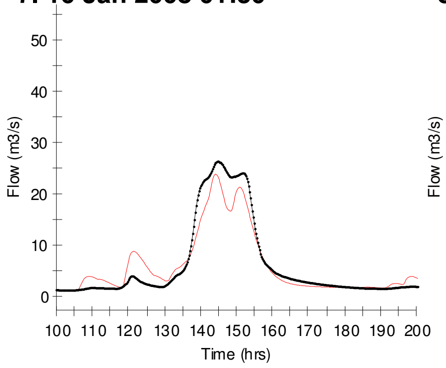
5. 01 Feb 2014 12:30



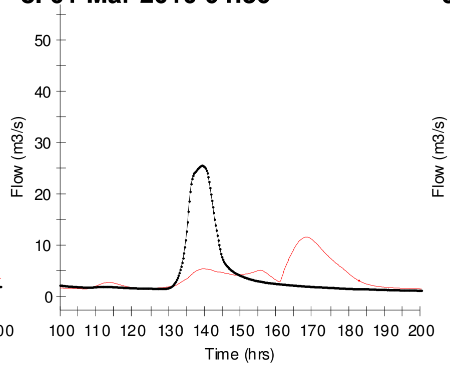
6. 02 Jan 2014 07:30



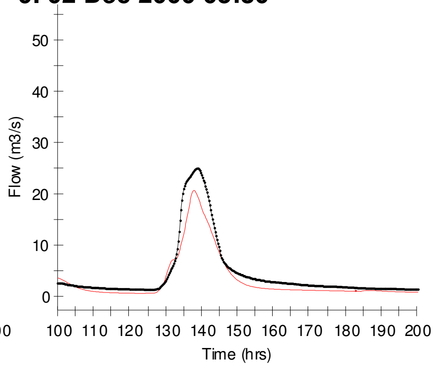
7. 16 Jan 2008 01:30



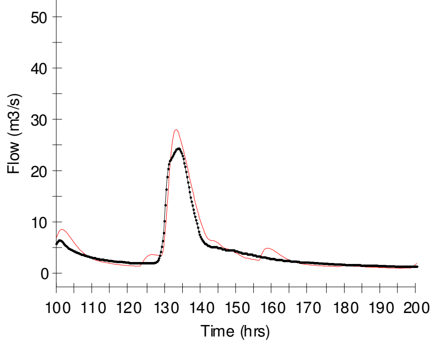
8. 01 Mar 2010 04:30



9. 02 Dec 2000 05:30

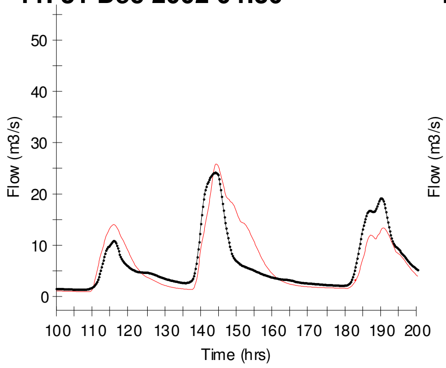


10. 03 Nov 2000 11:30

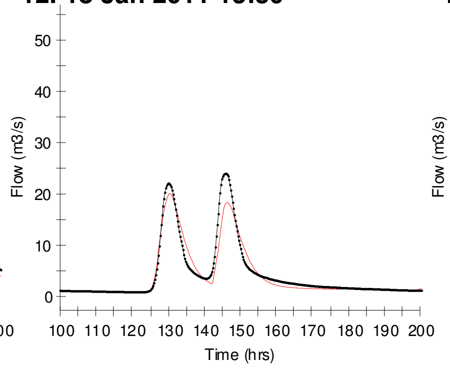


Key
Modelled
Observed

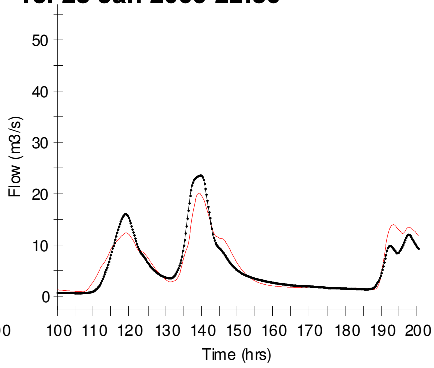
11. 31 Dec 2002 04:30



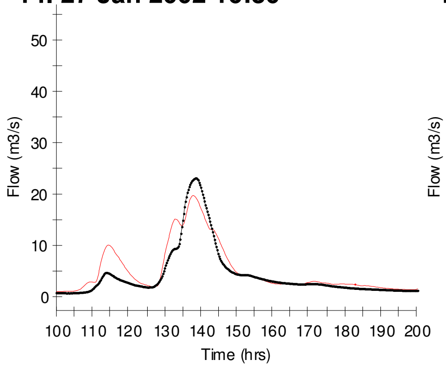
12. 18 Jan 2011 13:30



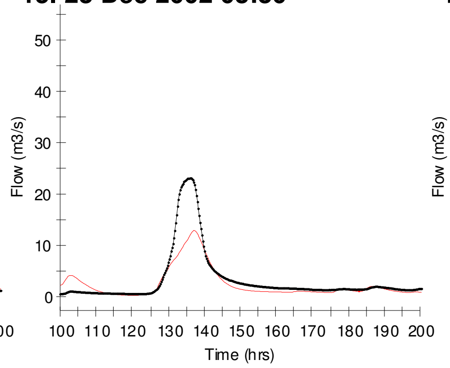
13. 23 Jan 2009 22:30



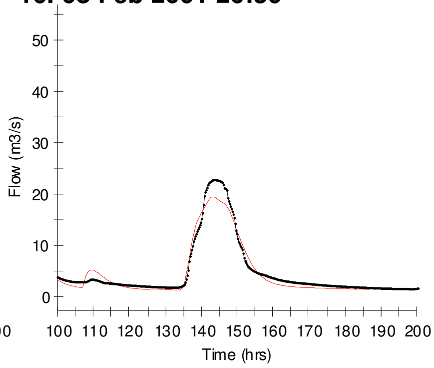
14. 27 Jan 2002 16:30



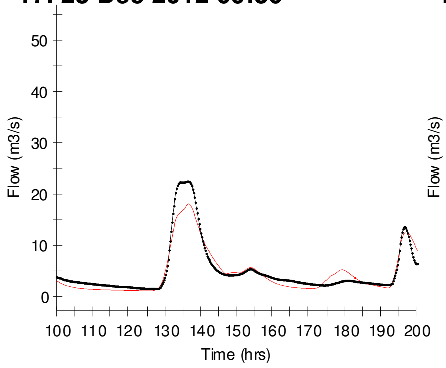
15. 23 Dec 2002 03:30



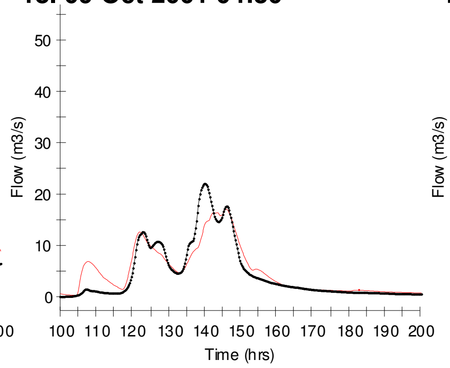
16. 08 Feb 2001 20:30



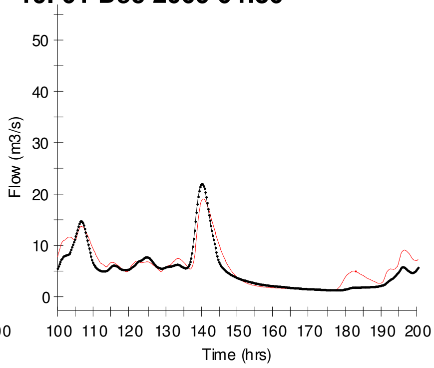
17. 23 Dec 2012 09:30



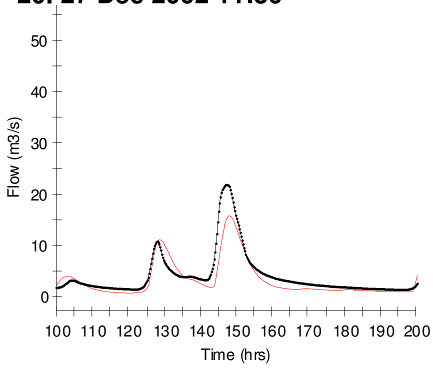
18. 09 Oct 2001 04:30



19. 01 Dec 2009 04:30



20. 27 Dec 2002 11:30

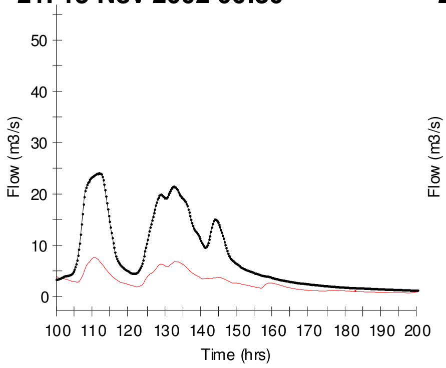


Key

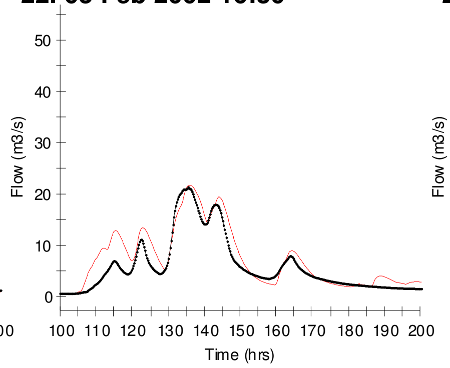
Modelled

Observed

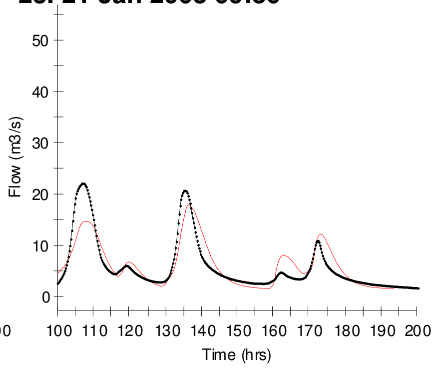
21. 15 Nov 2002 06:30



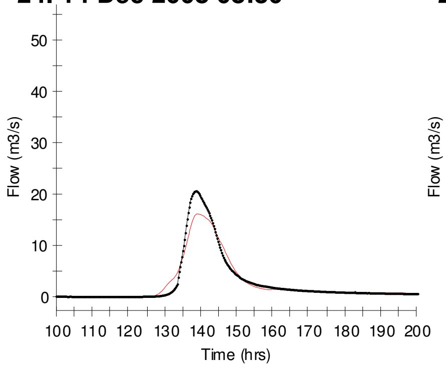
22. 05 Feb 2002 16:30



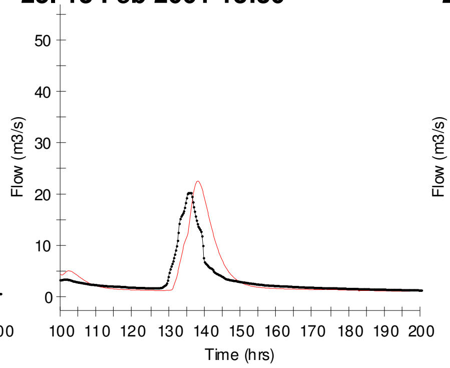
23. 21 Jan 2003 09:30



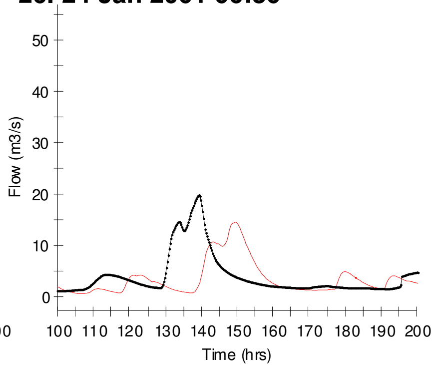
24. 14 Dec 2008 08:30



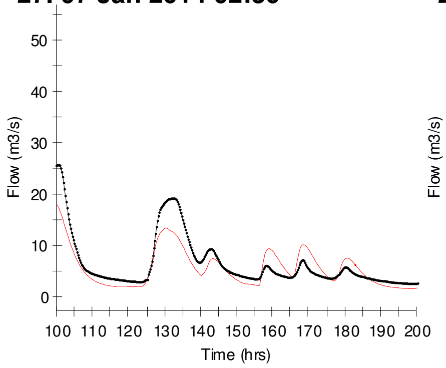
25. 13 Feb 2001 13:30



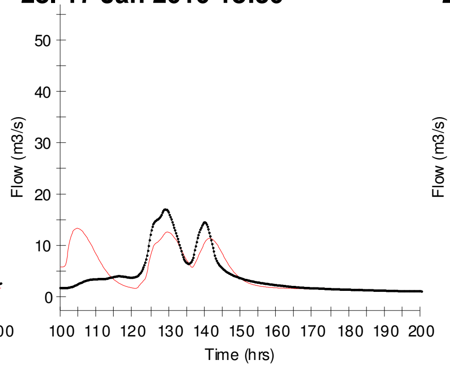
26. 24 Jan 2001 06:30



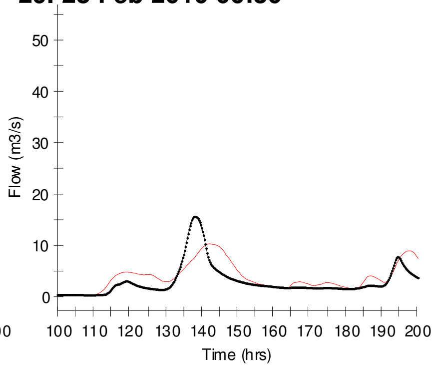
27. 07 Jan 2014 02:30



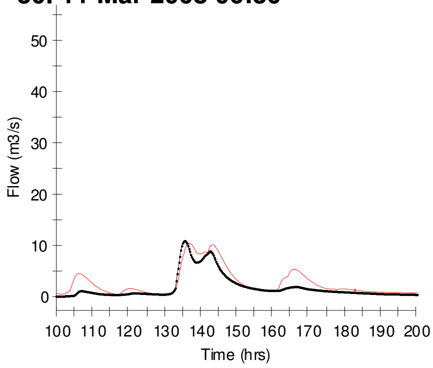
28. 17 Jan 2010 18:30



29. 23 Feb 2010 06:30

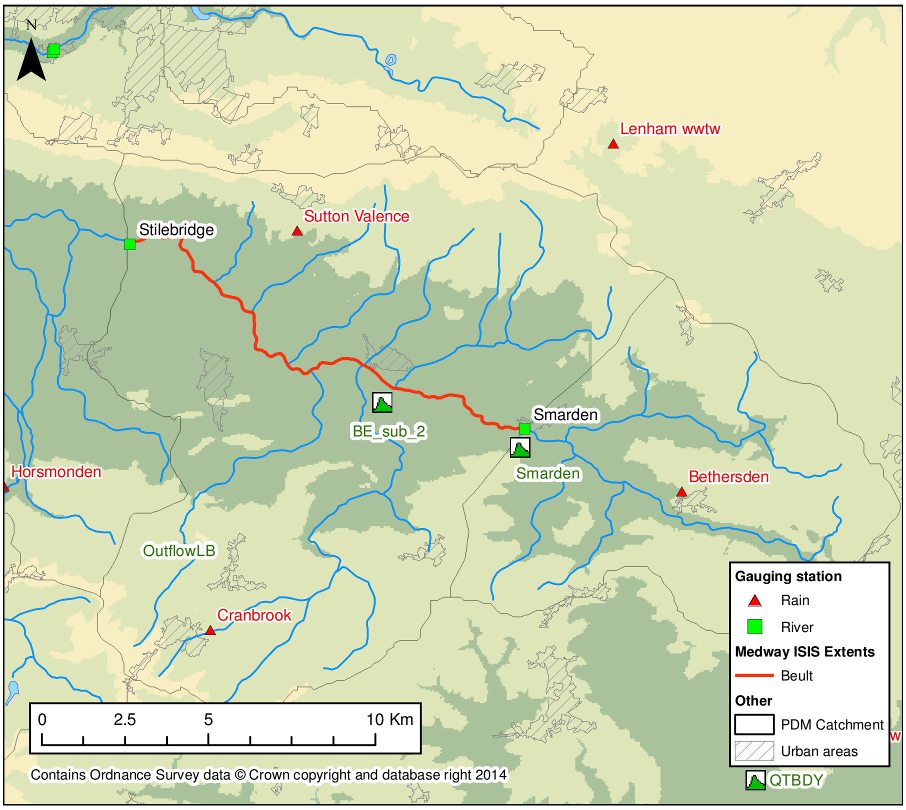


30. 11 Mar 2008 06:30



Key
Modelled
Observed

Catchment map



1 River model documentation

1.1 Background

1.1.1 Context

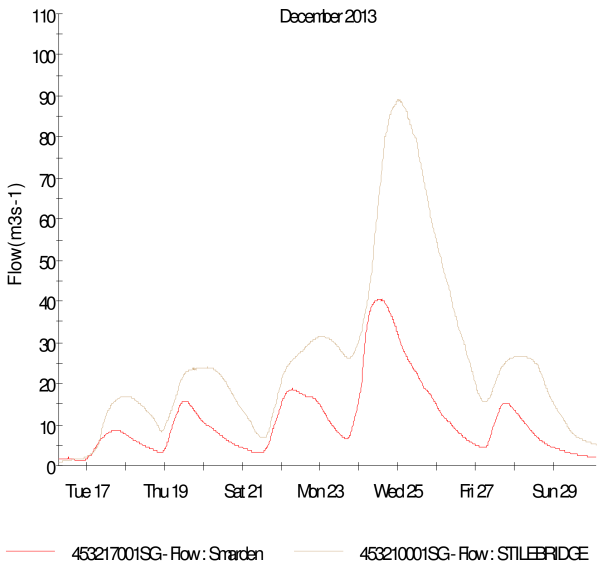
This catchment model (combination of ISIS 1d/routing and PDM rainfall runoff models) is needed to identify design events from a continuously simulated (CS) flow series. The Beult section is the third model in a network reaching from the headwaters of the Beult, Eden and Medway to East Farleigh. This model extends from Smarden to Stilebridge (where flows cascade into the Middle Medway model).

Rainfall is continuously simulated at an hourly interval over a 5,000 year period. Two PDM models representing the upper and intervening catchments (see Table "PDM Parameters" below in report template) are executed using the rainfall. Outputs from these PDMs are then fed into the ISIS model via QTBDYs (see Table "Boundaries for ISIS model Beult01.DAT").

A set of the largest events from lumped PDM simulations at Colliers Land Bridge, Vexour, Stonebridge and Stilebridge are then simulated using the ISIS model. Results at any particular node are then be ranked and the event that gives a design flow identified (using the Gringorton formula). The ISIS IED file giving rise to that event may then be simulated in the fully hydraulic ISIS-TUFLOW model to give flood extents for that return period.

1.1.2 Key hydraulic features

The main feature of the Beult is its low gradient and significant floodplain. The effect is to attenuate and delay flows entering the reach from upstream and laterally. The Figure below shows flows for Smarden and Stilebridge in December 2013. The shapes of the hydrographs are similar, but there is a 12 hour delay between the two and the rate of rise at Stilebridge is slower.



There are numerous bridges and culverts in the reach, but no significant moving structures.

1.1.3 Hydrological features

The hydrology of the Beult is similar to the rest of the Medway, only more low lying with lower rainfall totals and higher summer soil moisture deficits. High summer evaporation rates combine with deep soils and low rainfall to accumulate a large soil moisture deficit. Floods tend to be seasonal therefore - occuring most often in the winter months. The catchment area of the Beult increases significantly downstream of Smarden (from 97km2 to 279km2), meaning the lateral catchment is more influential than that at Smarden.

1.1.4 Available data

There are two significant river gauges on the Beult: Smarden and Stilebridge. The model reach is bounded by these gauges and both have ratings that give reasonable rates of runoff and are sensibly compatible with one another. The catchment contains three rain gauges (see Table "Rain gauge weights" and map) and there are others around the fringe. The reach is therefore well served with hydrometric data.

An existing 1D mapping model was available to form the basis for the river reach.

1.2 River model development

1.2.1 Model Type

An ISIS 1D model exists for the reach of the Beult being considered. It was tested and gave good results so there was no need to consider alternatives.

1.2.2 Model Development

The model is based on an existing Beult 1D Mapping model (UBE_100yr_design_final.dat) and the only changes were to:

- Replace the hydrological boundaries (FEH RR) with QTBDYs; and
- Extend the rating curve at the downstream boundary to cope with larger flows (this was done by simple extrapolation).

1.3 Model boundaries

1.3.1 Flow boundaries

The two FEH RR boundaries, now replaced with QTBDYs, were substituted for PDMs: one for Smarden and one for the lateral catchment. Table "PDM Parameters" (below) lists the PDM parameters used for each catchment and Table "Boundaries for ISIS model Beult01.DAT" shows how they are fed to the ISIS model.

A PDM was initially calibrated for Smarden directly against observed data. The same model parameters (with adjustments to catchment area and rain gauge weights) were then transferred to the PDM representing the lateral inflows. Further adjustements to b and Cmin were made to improve the fit at Stilebridge.

1.3.2 Downstream boundary

A rating curve provides the downstream boundary at Stilebridge. It was extrapolated for this version of the model to ensure the model would run with all continuously simulated events.

1.4 Simulation performance

1.4.1 Calibration points

The table "Model calibration points" lists the two nodes (Smarden and Stilebridge) in the model having useful observed data for comparison against stimulations. Smarden represents the performance of the PDM and Stilebridge the combined performance of the two PDMs and ISIS model.

Although 47 events were simultated between November 1998 and April 2014, the first nine were discarded because the rainfall could not be corrected. Rainfall is only considered properly reliable after April 2006. Unfortunately this excludes the largest event on record: 12 October 2000.

Model results are presented as 'model evaluation sheets' and an explanation of their layout and contents is available at the begining of this Appendix.

1.4.2 Accuracy

The main points from each model evaluation sheet are outlined below.

Beult @ Smarden

Other than for a couple of events where observed data are suspicious, Smarden PDM simulates flows very consistenly, with little scatter and good hydrograph shape and timing. Flows are highly seasonal, mostly confined to the autumn and winter months. The PDM consistently predicts lower flows than the rating suggests. This may be a fault of the rating (which is not supported by gaugings). The bias is not evident at Stilebridge.

Beult @ Stilebridge

Model performance at Stilebridge is also good in terms of consistency, timing and hydrograph shape. The results here are also unbiased (and this rating is supported by gaugings). This suggests the overall Beult network is reasonable and fit for purpose.

1.4.3 Predominant sources of error

Like other parts of the Medway catchment, runoff rates and observed data are the main likely sources of error.

Runoff from the Beult is highly seasonal and modelling this is a challenge (althoug the PDM appears to be quite successful once observed rainfall is good).

Observed rainfall prior to April 2006 is known to be suspect in places (although a significant effort wenmt into cleaning these data up). This limits the accuracy of the PDM in the early record. The observed level series at Smarden has some erroneous data and the rating curve may well over estimate flow.

1.4.4 Potential for model improvement

This model is fit for the purpose for this project. If it were to be used as a forecasting tool, it would be sensible to adjust the rating at Smarden to be more consistent with the PDM's predictions (if it were being used to error correct flows).

ISIS model documentation for Beult01.dat

Boundaries for ISIS model Beult01.dat						
Type	**Node**	**Source**	**Name**	**Scale or offset**	**Lag**	**PDM Area (km2)**
QTBDY	BE_sub_2	PDM	BE_sub_2_JBA01			182
QTBDY	Smarden	PDM	Smarden_JBA01			97
					Total	**279.0**

Model calibration points			
Type	**Node**	**Source**	**Name**
Flow	Stilebridge	Observed	453210001SG (Flow) - STILEBRIDGE
Flow	Smarden	Observed	453217001SG (Flow) - Smarden

Notes:

Model run with 47 events from the period 01 Nov 1998 to 01 Feb 2014; see individual model evaluation sheets for results

An asterisk (*) indicates scaling in the 'scale' column, otherwise the value is an offset (e.g. datum) - added or subtracted from the raw time series

The area calculated for boundaries is the product of PDM Area and scaling factor

Rain gauge weights							
Name	**Area (km2)**	**BETHERSDEN STW tbr**	**Bybrook**	**Cranbrook**	**RUCKINGE TBR**	**Sutton Valence**	**WAREHORNE STW RTS**
BE_sub_2_JBA01	182	0.25	0.125	0.374	0.001	0.25	0.001
Smarden_JBA01	97	0.664	0.332		0.002		0.002

PDM parameters													
Area	**Fc**	**Cmin**	**Cmax**	**b**	**Be**	**Kg**	**Bg**	**St**	**K1**	**K2**	**Kb**	**QConst**	**Tdly**
Km^2		**mm**	**mm**					**mm**	**hrs**	**hrs**	**hmm^2**	**m^3/s**	**hrs**
BE_sub_2_JBA01			**Surf.**	Identical linear cascad			**Base**	Cubic store		**Drainage**		Gravity	
182	1	20	150	0.4	5	60000	1.6	0	6	n/a	5.8	0	0
Smarden_JBA01			**Surf.**	Identical linear cascad			**Base**	Cubic store		**Drainage**		Gravity	
97	1	30	150	0.6	5	60000	1.6	50	8	n/a	5.8	0	3

Notes:

Please refer to PDM documentation for a definition of parameters

Rating details								
Gauge Ref		453210001SG	**Name**	STILEBRIDGE (tabular rating)				
Gauge Ref		453217001SG	**Name**	Smarden				
No.	**Limb**	**Description**	**K**	**a**	**p**	**Max.**	**Start**	**End**
99	a	XML	3.322	-18.000	2.926	18.30	01 Jan 1970	01 Jan 2100
99	b	XML	3.322	-18.000	2.926	18.75	01 Jan 1970	01 Jan 2100
99	c	XML	2.280	-18.000	1.618	19.45	01 Jan 1970	01 Jan 2100
99	d	XML	0.000	-11.148	7.068	20.88	01 Jan 1970	01 Jan 2100

99	e	XML	0.008	-16.219	4.795	21.29	01 Jan 1970	01 Jan 2100
99	f	XML	2.336	-19.255	3.012	22.10	01 Jan 1970	01 Jan 2100

Notes:

Rating equation has the form Q=K*(Stage+a)^p

Stations where flows are stored, and not calculated from a rating, may be listed without a rating

General notes:

Ratings database used: N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\00 Ratings Database\2013s7661 - Medway Rating DB Modelled Ratings Active.accdb

Form settings: N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\05 Beult\Beult_Sim_02 - Cascade.BTD

Data summary

38 peaks analysed at Smarden between 0.6m3/s and 42.4m3/s, for period 06 Nov 2000 to 01 Feb 2014 from :

`N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\05 Beult\09 Cascade`

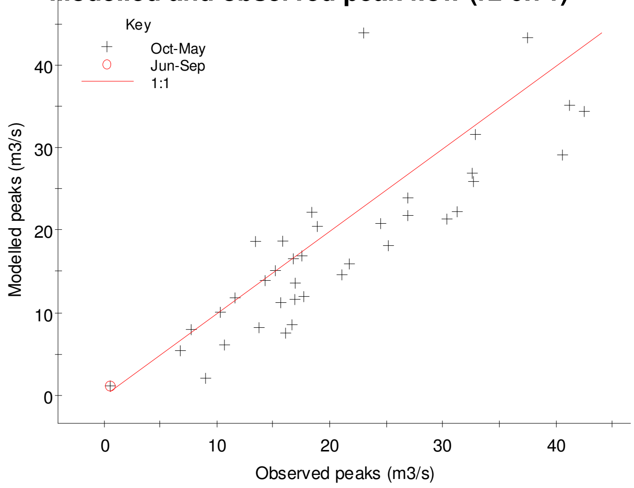
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	16 Jan 2008 01:30	42.40	34.48	-7.9	-19%	-0.3	0.951	0.970	2.16
2	01 Dec 2009 04:30	41.10	35.21	-5.9	-14%	-0.5	0.791	0.805	4.08
3	24 Dec 2013 11:30	40.48	29.20	-11.3	-28%	3.8	0.706	0.965	5.06
4	08 Feb 2001 20:30	37.40	43.41	6.0	16%	3.3	0.161	0.502	6.81
5	06 Nov 2000 19:30	32.80	31.70	-1.1	-3%	23.0	0.798	0.824	4.03
6	10 Feb 2009 10:30	32.63	25.97	-6.7	-20%	-0.8	0.910	0.962	2.14
7	23 Jan 2009 22:30	32.51	26.98	-5.5	-17%	-0.5	0.893	0.962	2.60
8	01 Feb 2014 12:30	31.18	22.34	-8.8	-28%	-0.8	0.251	0.294	7.91
9	02 Jan 2014 07:30	30.28	21.46	-8.8	-29%	0.3	0.565	0.882	4.33
10	23 Feb 2010 06:30	26.83	21.86	-5.0	-19%	-1.3	0.895	0.955	2.55

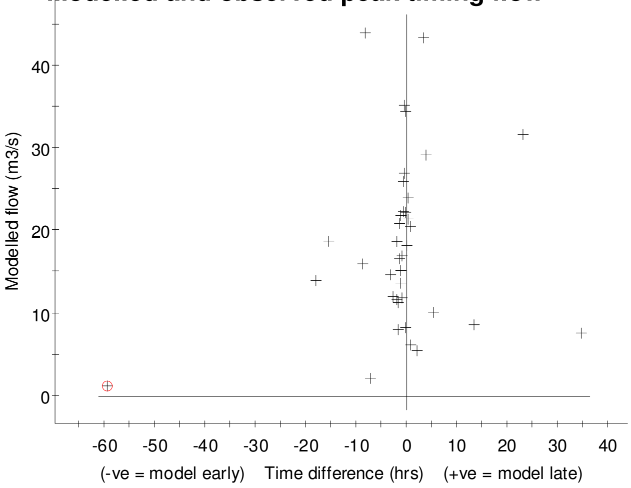
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.60	1.75	1.19	1.46	0.45	0.32	3.57	1.87

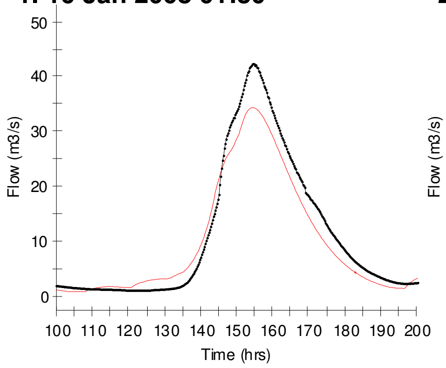
Modelled and observed peak flow (r2 0.71)



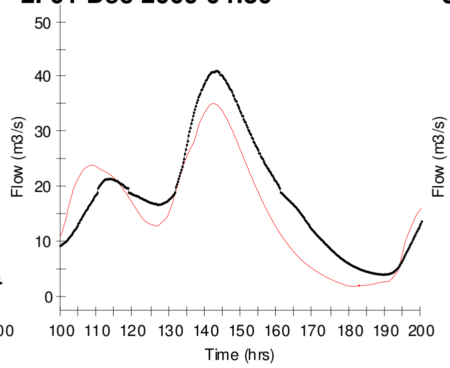
Modelled and observed peak timing flow



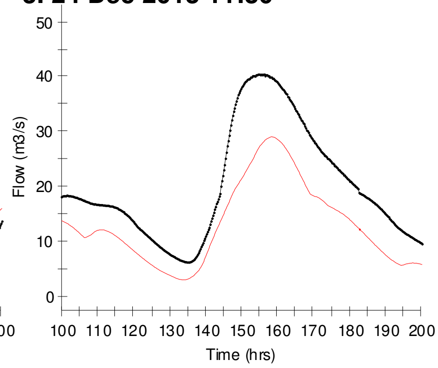
1. 16 Jan 2008 01:30



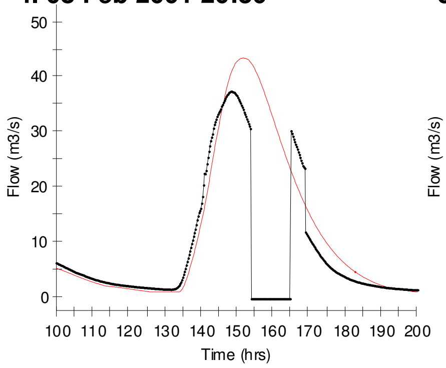
2. 01 Dec 2009 04:30



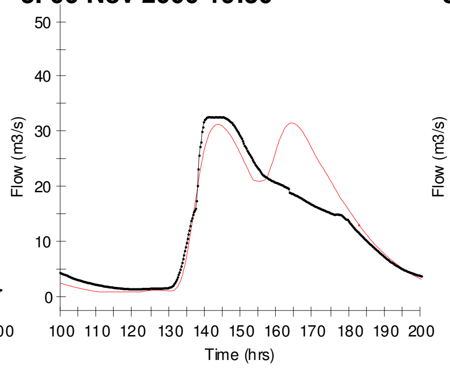
3. 24 Dec 2013 11:30



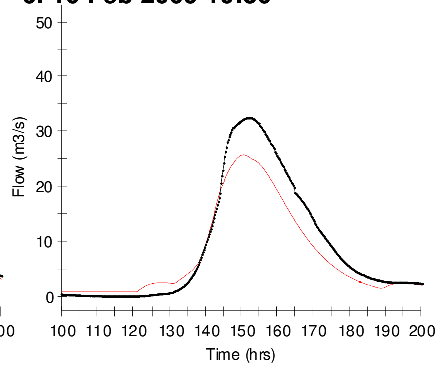
4. 08 Feb 2001 20:30



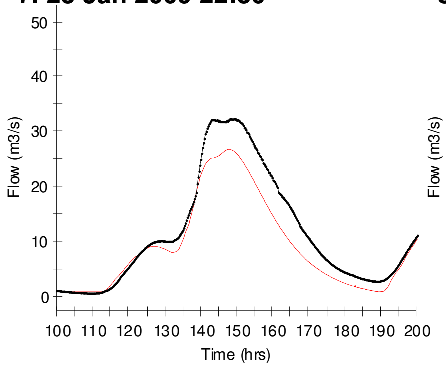
5. 06 Nov 2000 19:30



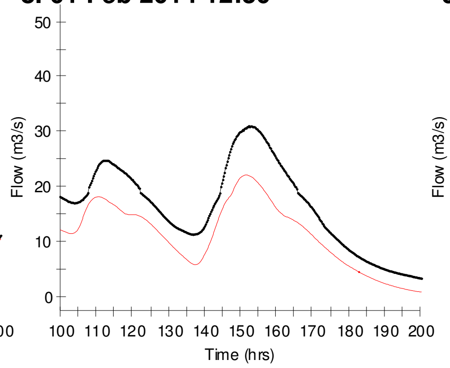
6. 10 Feb 2009 10:30



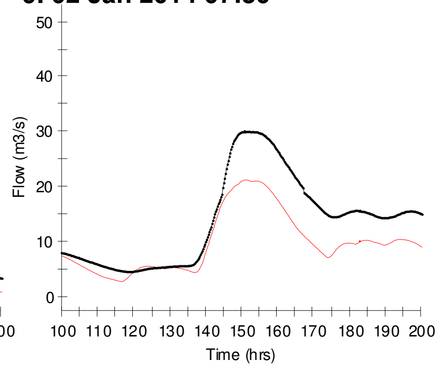
7. 23 Jan 2009 22:30



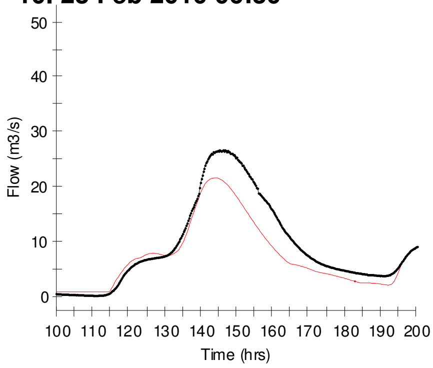
8. 01 Feb 2014 12:30



9. 02 Jan 2014 07:30

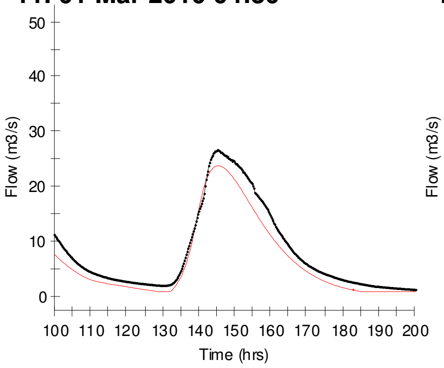


10. 23 Feb 2010 06:30

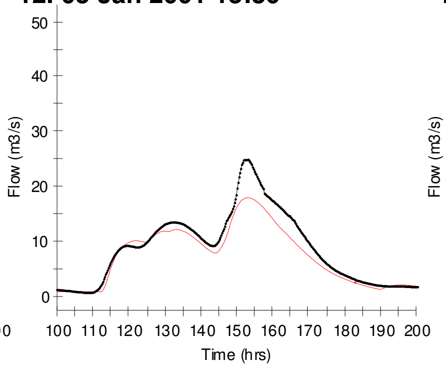


Key
Modelled
Observed

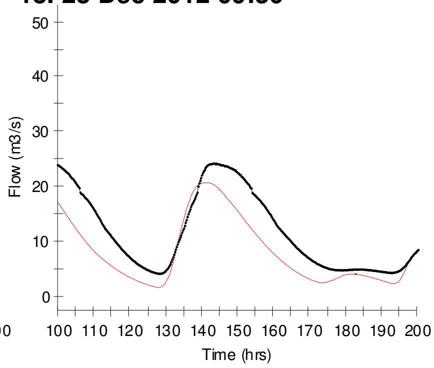
11. 01 Mar 2010 04:30



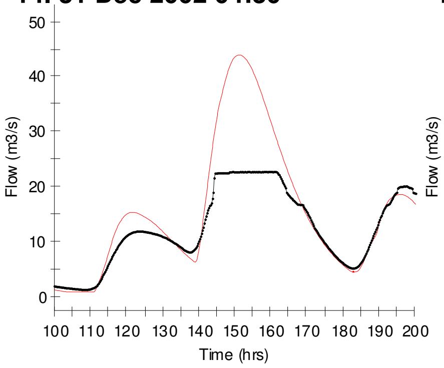
12. 05 Jan 2001 15:30



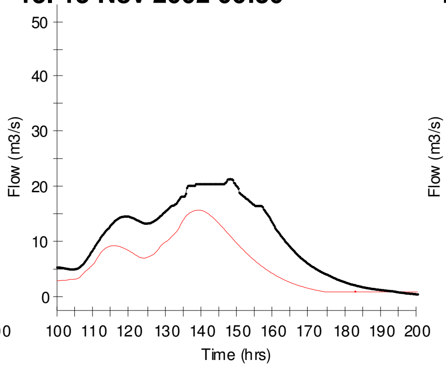
13. 23 Dec 2012 09:30



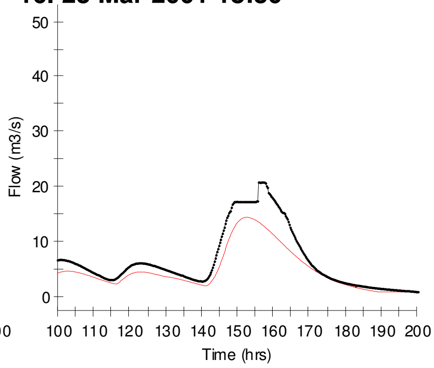
14. 31 Dec 2002 04:30



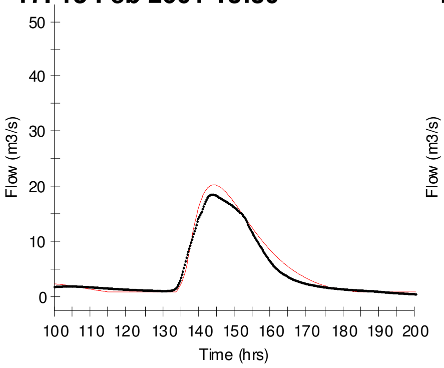
15. 15 Nov 2002 06:30



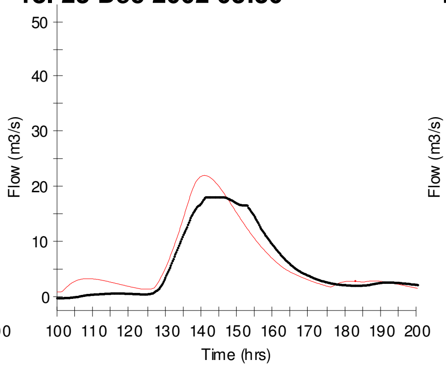
16. 23 Mar 2001 18:30



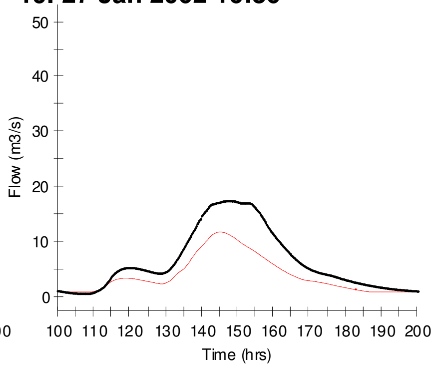
17. 13 Feb 2001 13:30



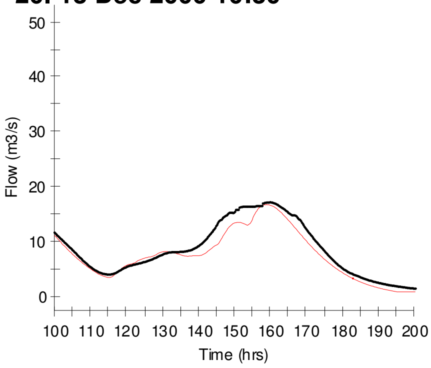
18. 23 Dec 2002 03:30



19. 27 Jan 2002 16:30

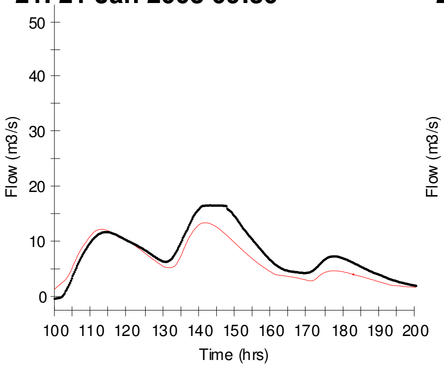


20. 13 Dec 2000 10:30

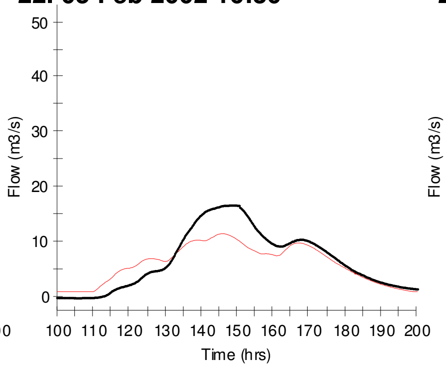


Key
Modelled
Observed

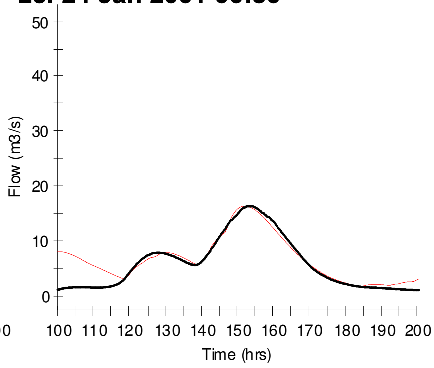
21. 21 Jan 2003 09:30



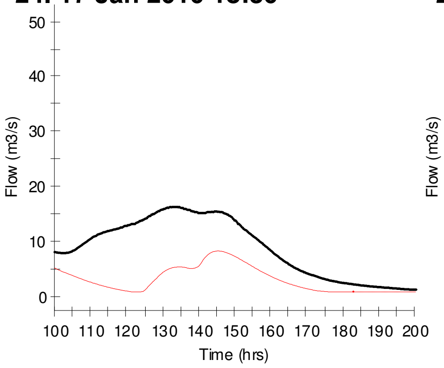
22. 05 Feb 2002 16:30



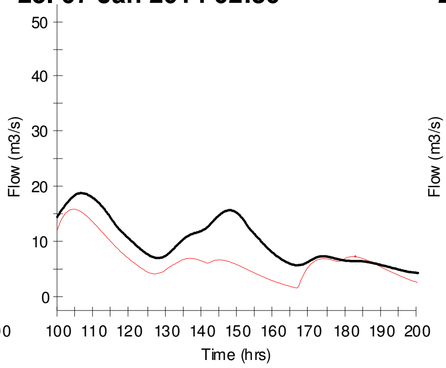
23. 24 Jan 2001 06:30



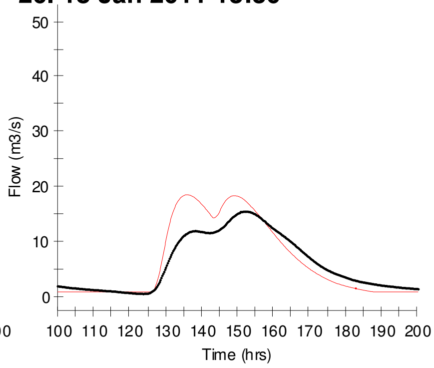
24. 17 Jan 2010 18:30



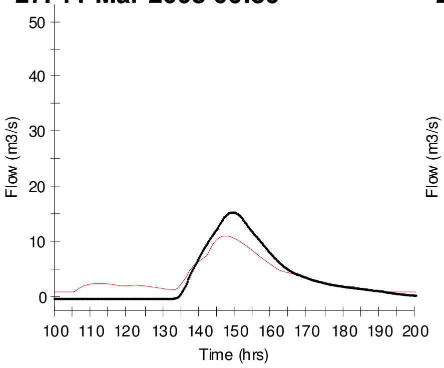
25. 07 Jan 2014 02:30



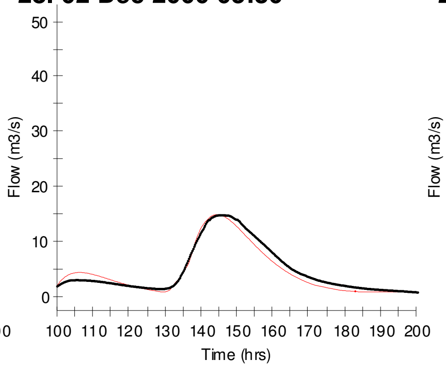
26. 18 Jan 2011 13:30



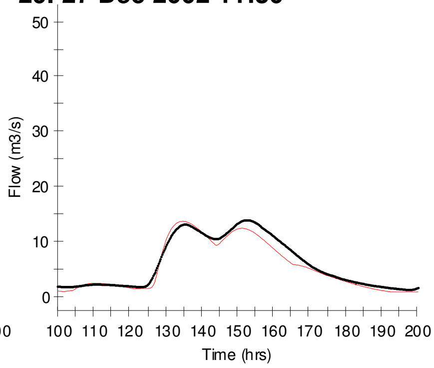
27. 11 Mar 2008 06:30



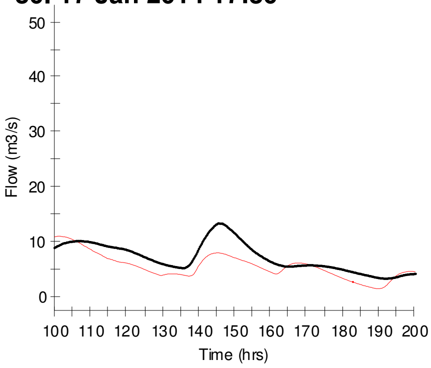
28. 02 Dec 2000 05:30



29. 27 Dec 2002 11:30



30. 17 Jan 2014 17:30



Key
Modelled
Observed

Stilebridge

Data summary

38 peaks analysed at Stilebridge between 0.0m3/s and 89.0m3/s, for period 06 Nov 2000 to 01 Feb 2014 from :

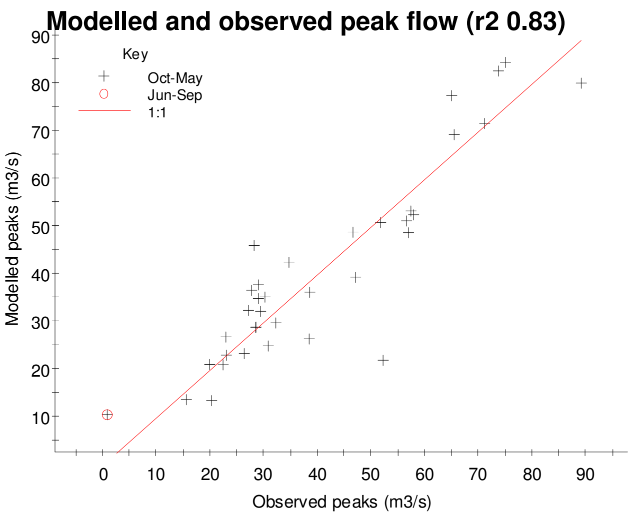
```
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and
Modelling\Calculations\04 Routing\05 Beult\09 Cascade
```

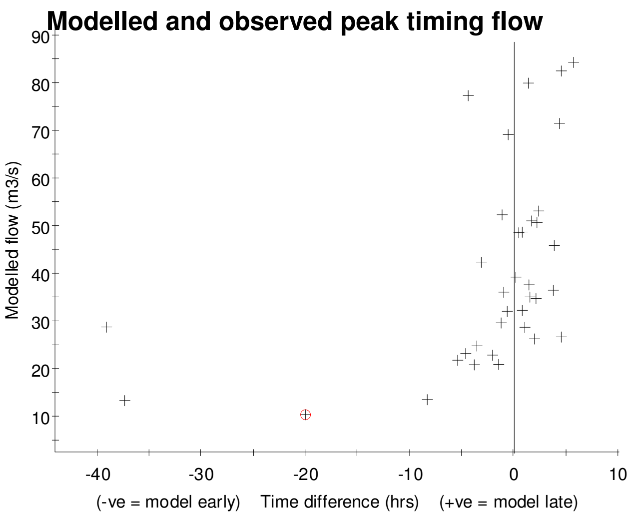
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	88.97	80.10	-8.9	-10%	1.3	0.905	0.930	6.57
2	08 Feb 2001 20:30	74.90	84.41	9.5	13%	5.7	0.583	0.839	9.37
3	31 Dec 2002 04:30	73.53	82.60	9.1	12%	4.5	0.864	0.947	6.51
4	06 Nov 2000 19:30	71.02	71.62	0.6	1%	4.3	0.318	0.546	15.09
5	16 Jan 2008 01:30	65.38	69.29	3.9	6%	-0.6	0.943	0.957	4.05
6	01 Dec 2009 04:30	64.88	77.48	12.6	19%	-4.4	0.413	0.748	12.01
7	02 Jan 2014 07:30	57.81	52.51	-5.3	-9%	-1.2	0.824	0.856	5.01
8	10 Feb 2009 10:30	57.31	53.32	-4.0	-7%	2.3	0.927	0.929	3.64
9	01 Feb 2014 12:30	56.81	48.74	-8.1	-14%	0.4	0.916	0.920	4.64
10	23 Jan 2009 22:30	56.48	51.22	-5.3	-9%	1.7	0.907	0.916	4.12

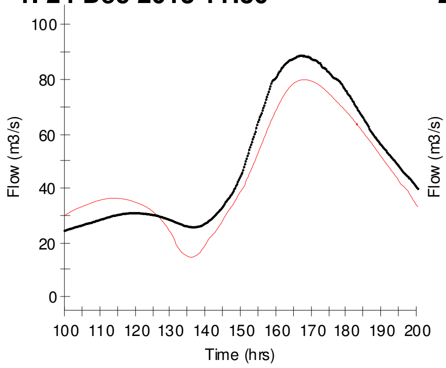
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	1.81	0.58	0.30	1.79	0.57	1.17	3.07	1.55

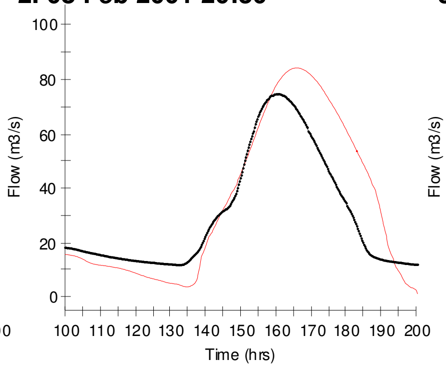




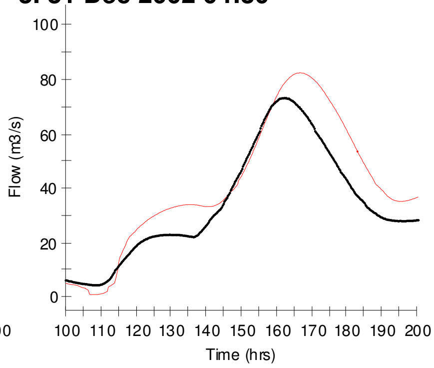
1. 24 Dec 2013 11:30



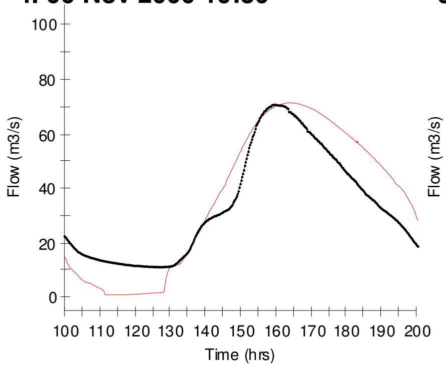
2. 08 Feb 2001 20:30



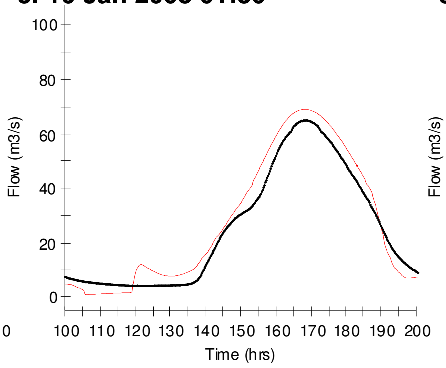
3. 31 Dec 2002 04:30



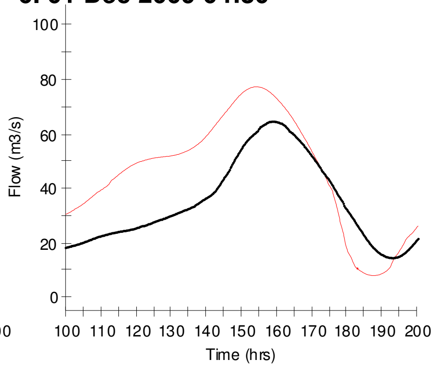
4. 06 Nov 2000 19:30



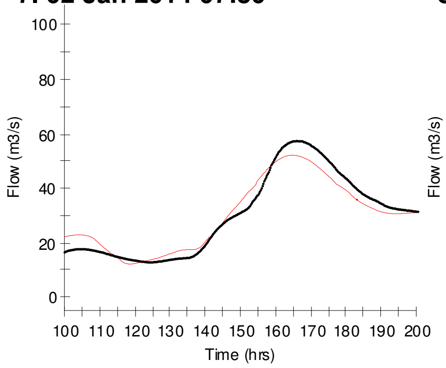
5. 16 Jan 2008 01:30



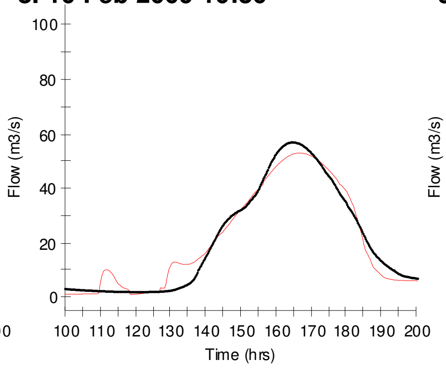
6. 01 Dec 2009 04:30



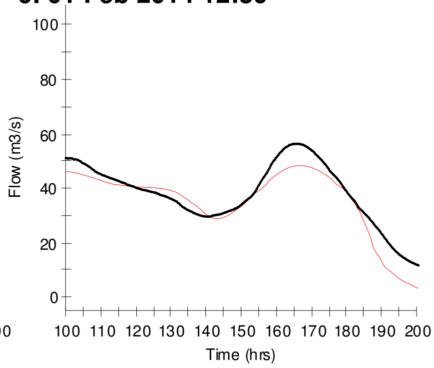
7. 02 Jan 2014 07:30



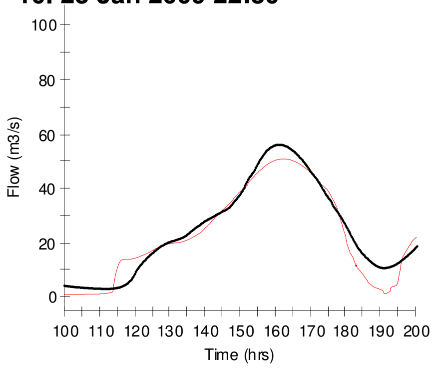
8. 10 Feb 2009 10:30



9. 01 Feb 2014 12:30

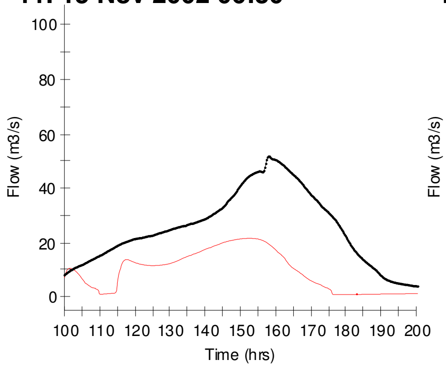


10. 23 Jan 2009 22:30

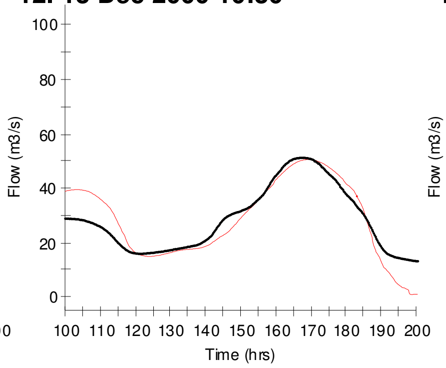


Key
Modelled
Observed

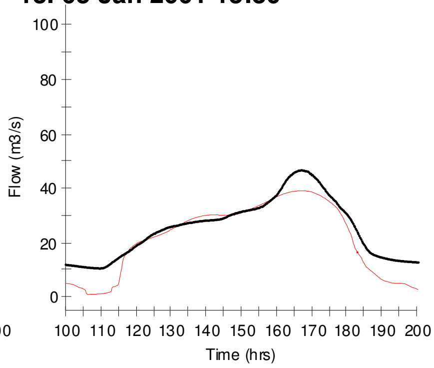
11. 15 Nov 2002 06:30



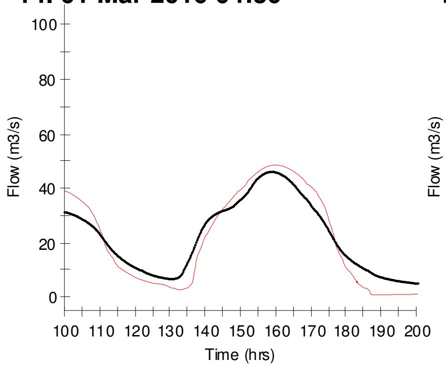
12. 13 Dec 2000 10:30



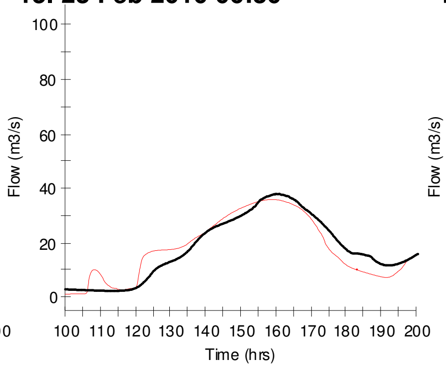
13. 05 Jan 2001 15:30



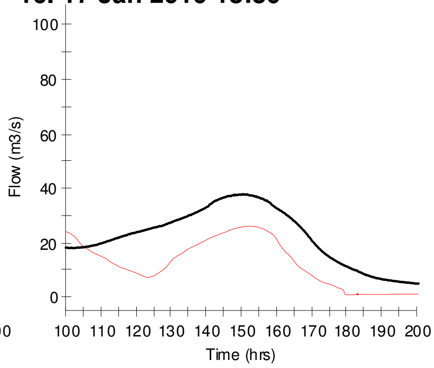
14. 01 Mar 2010 04:30



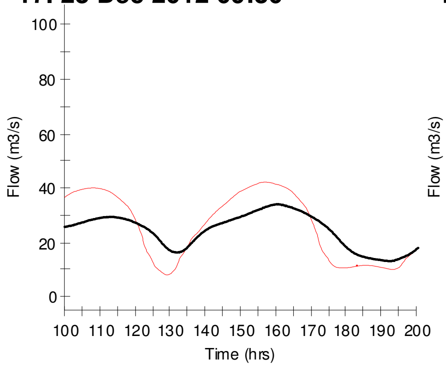
15. 23 Feb 2010 06:30



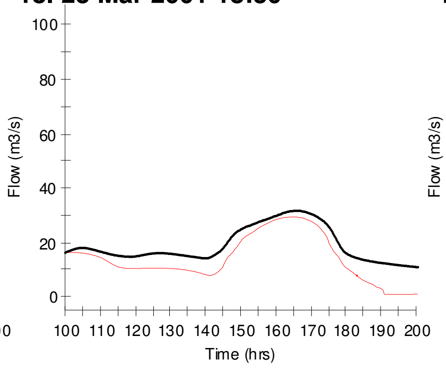
16. 17 Jan 2010 18:30



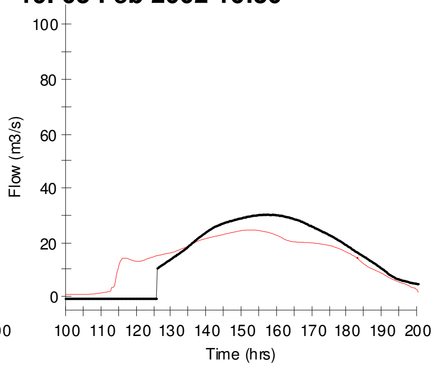
17. 23 Dec 2012 09:30



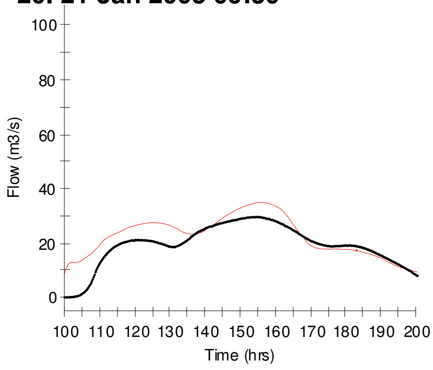
18. 23 Mar 2001 18:30



19. 05 Feb 2002 16:30

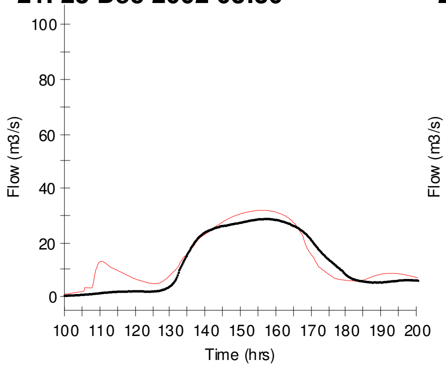


20. 21 Jan 2003 09:30

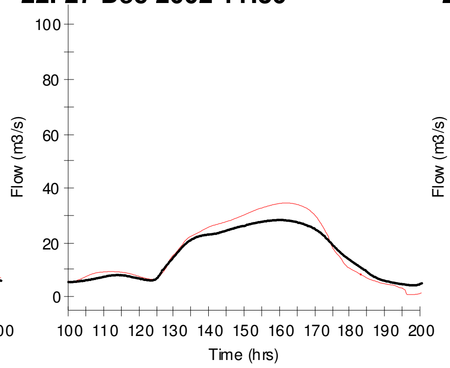


Key
Modelled
Observed

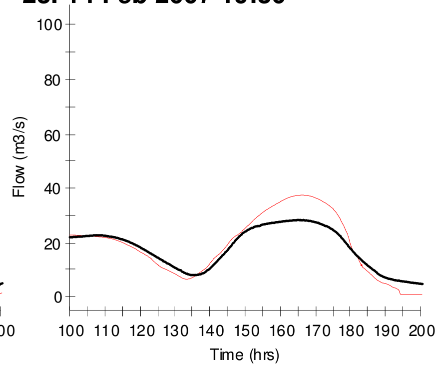
21. 23 Dec 2002 03:30



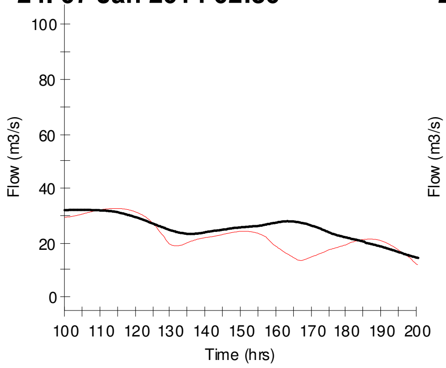
22. 27 Dec 2002 11:30



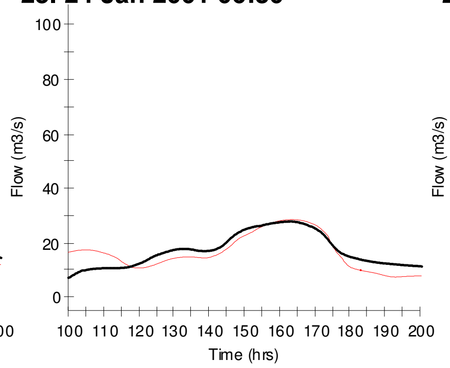
23. 14 Feb 2007 19:30



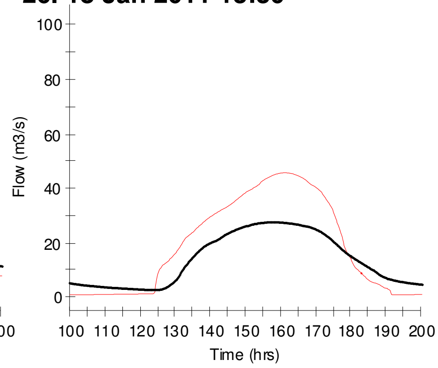
24. 07 Jan 2014 02:30



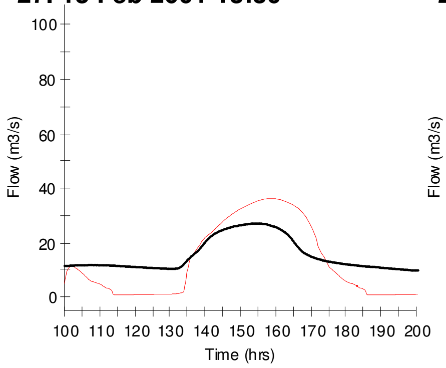
25. 24 Jan 2001 06:30



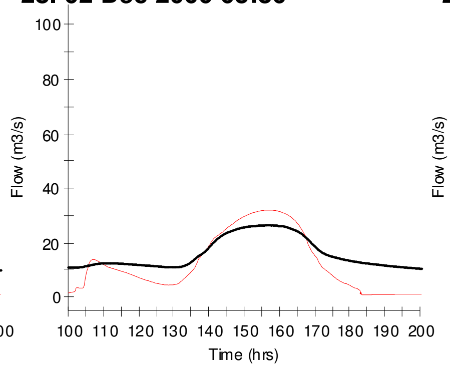
26. 18 Jan 2011 13:30



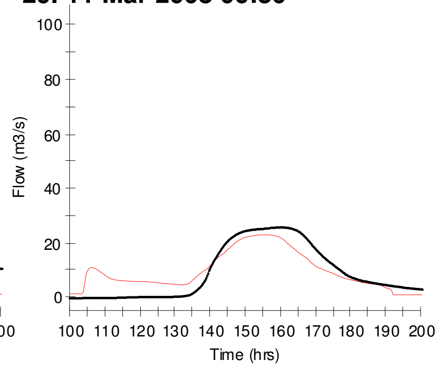
27. 13 Feb 2001 13:30



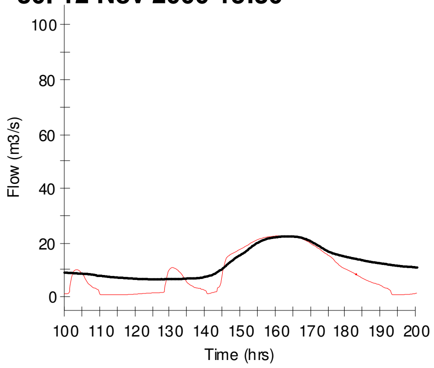
28. 02 Dec 2000 05:30



29. 11 Mar 2008 06:30

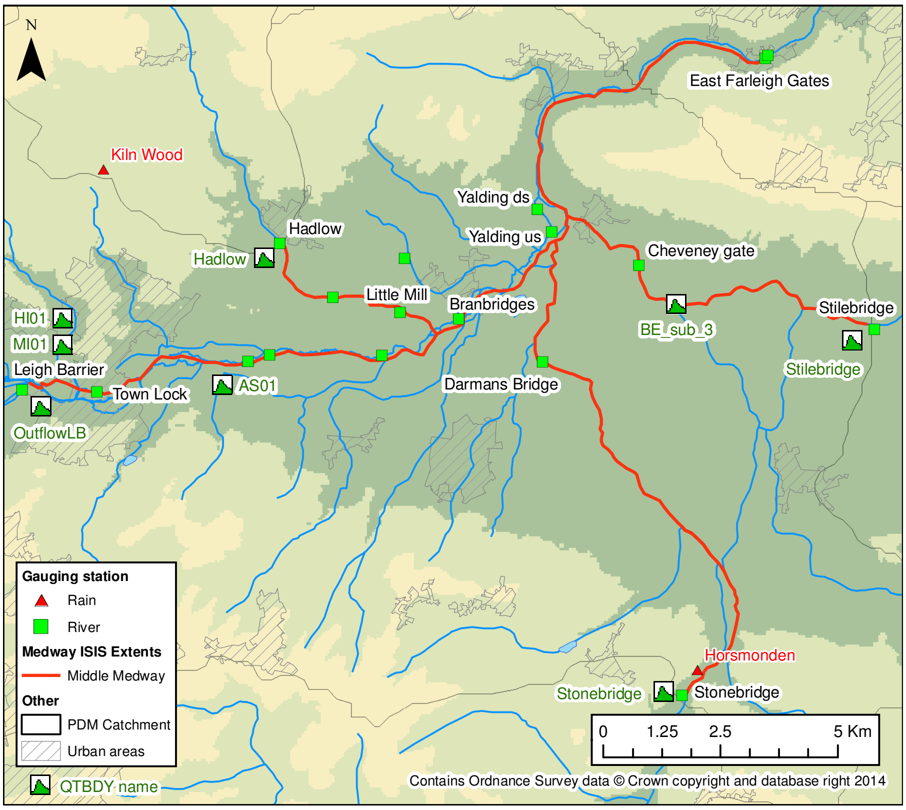


30. 12 Nov 2000 15:30



Key
Modelled
Observed

Catchment map



1 River model documentation

1.1 Background

1.1.1 Context

This catchment model (combination of ISIS 1d/routing and PDM rainfall runoff models) is needed to identify design events from a continuously simulated (CS) flow series. The Middle Medway section is the second model in a network reaching from the headwaters of the Eden and Medway to East Farleigh. It extends to East Farleigh Gates (the location of the last flow gauging station on the Medway before the tidal boundary).

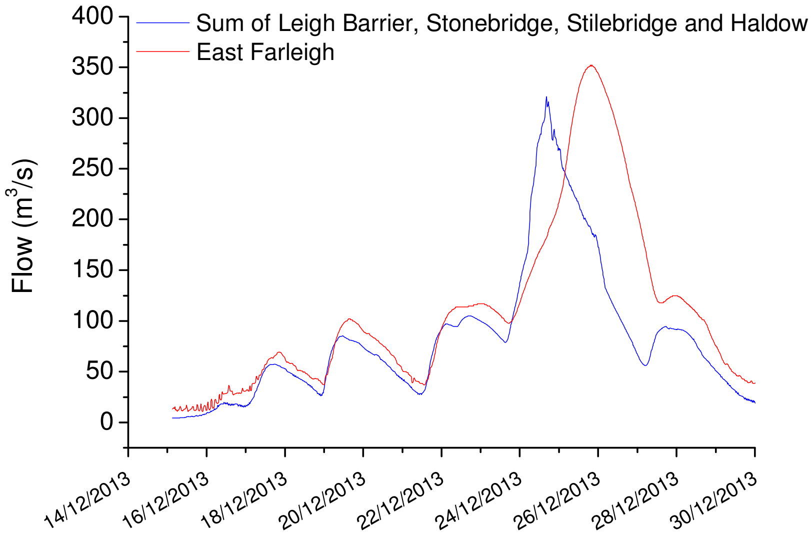
Rainfall is continuously simulated at an hourly interval over a 5,000 year period. PDM models representing each sub catchment (see Table "PDM Parameters" below in report template) are executed using the rainfall. Outputs from these PDMs are then fed into the ISIS model via QTBDYs (see Table "Boundaries for ISIS model MidMedway.DAT"). Two of this model's boundaries take flows from the other ISIS models in the catchment network: Outflows from Leigh Barrier come from LeighBarrier01.DAT; and Stilebridge flows come from Beult01.DAT.

A set of the largest events from lumped PDM simulations at Colliers Land Bridge, Vexour, Stonebridge and Stilebridge are then simulated using the ISIS model. Results at any particular node are then be ranked and the event that gives a design flow identified (using the Gringorton formula). The ISIS IED file giving rise to that event may then be simulated in the fully hydraulic ISIS-TUFLOW model to give flood extents for that return period.

1.1.2 Key hydraulic features

Between the Leigh FSA and East Farleigh, the Medway has a gentle gradient and an extensive floodplain (which also affects the lower parts of tributaries like the Teise and Beult). These features delay the hydrograph and attenuate peak flows. There are also many hydraulic structures and gates, designed to control local water levels but having little impact on flows passed downstream.

The Medway's floodplain is the key feature affecting how flows translate the reach. Inflows are smoothed, delayed and significantly attenuated, as shown by the figure below. It shows combined inflows from the FSA, Stonebridge, Stilebridge and Hadlow compared to East Farleigh observed for the December 2013 event.



While the many hydraulic structures control water levels locally, they have only a small effect on the flows translating the reach.

1.1.3 Hydrological features

Most inflows to the reach are measured at gauging stations (Bourne at Hadlow, Teise at Stonebridge and Beult at Stilebridge) or at the Leigh FSA. Hydrological characteristics are similar to the Upper Medway. Other than the Teise, which has steeper headwaters and a quicker response to rainfall, the remainder of inflows downstream of the FSA are somewhat attenuated and low lying. Deeper soils in these areas combine with low annual rainfall totals to give a large soil moisture deficit and seasonal runoff regime.

1.1.4 Available data

The catchment map at the begining of this document shows the hydrometric stations in the catchment. The only flow measurement points are at the model's boundaries: Leigh FSA outflow, Stonebridge, Stilebridge and Hadlow on the upstream and East Farleigh on the downstream. There are several level measurement locations within the river network however. Rain gauge coverage is fairly good across the catchment's headwaters, but the Middle Medway itself lacks a rain gauge.

A 1D model already exists that covers the entire reach. It is in current use in the forecasting system and was used as the basis for the catchment flow routing model.

1.2 River model development

1.2.1 Model Type

This hydraulic model is based on the Environment Agency's Medway forecasting model. That model covers the required reaches and had been reviewed as part of a performance testing project (Environment agency 2012) which seemed to show that it gave reasonable results. No other model type was considered as this model was readily available. It is an ISIS 1D hydraulic model with some flow routing reaches.

The file name is MidMedway.DAT

1.2.2 Model Development

The only model development carried out was stabilisation to enable our simulations to run. A summary of the edits made is given below:

Inflow apportioned correctly at the Stonebridge boundary (a corrected proportion is applied to each channel).

Moving structures that were not controlled by logical rules were made time controlled and set to be fully open.

Short Muskingum reaches on the Beult and Teise were removed and hydraulic units connected directly to the nearest available hydraulic junction/node.

SPILL T20-BJU added as tributary bed is above main channel bed, and water level was being drawn down below XS bed. Although automatic Preissman slot meant that it didn't complain directly about this, it meant that the average conveyance calculation for the reach upstream returned a very small conveyance, pushing up the water levels at the XS upstream and leading to a super-steep WS which eventually led to instabilities.

SPILL B13-D1-LJU added. Although no evidence of instabilities, the potential for same issue as at T20 was there (hanging tributary) so spill added for precautionary reasons

ZERO area in BERNOULLI Loss CS176 changed to 0.01 to remove warning message

Reach T27-SD to T20-BJU: floodplain geometry simplified, panels added, T21-SD replaced with interpolate

SPILL T30-D2-WU added as bypass around sluice gate at high flows (to stop water levels getting unrealistically high, geometry invented as required to stabilise)

SPILL B20-D1-SU added as bypass around sluice gate at high flows (to stop water levels getting unrealistically high, geometry invented as required to stabilise)

MI01 added upstream of reach CSJ1-CSJ2 rather than downstream so acts as sweetening flow

Reach CS96 - CS114 panels added

ARCH BRIDGE BU09: section data curtailed and orifice mode activated. As section data extended beyond bank top, at high flows the error that blockage ratio was outside expected range occurred, but since bypass spill means that embankment not completely holding up flow, a blockage ratio based on full wetted width is not really appropriate/necessary, so section data curtailed to banktop. Orifice mode activated with transition distance 0.2m below soffit.

SPILL BO9SPU: flat parts of geometry removed and given slight slope

USPBR B016BU: section data curtailed and orifice mode activated (transition distance 0.1m below soffit)

USPBR B038BU: section data curtailed and orifice mode activated (transition distance 0.1m below soffit)

CS-121 converted to interpolated section

Bypass spill B20-D1-SU extended

MUSK-XSEC units LT44-WD, LT21-BD and LT1-JU turned into VPMC so parameters can be smoothed

Very short hydrodynamic reaches (0.5m) LT44-WU-D1 and SplitT deleted. Lateral inflow from Stilebridge instead added at LT44-WU which has been turned into a MUSK-VPMC using a copy of LT44-WD.

Orifice coefficient at BU038 increased to 1.15 for smoother transition

Model failed for one simulation at the Bridge B09BU. this was fixed by changing lower transition distance for orifice flow from 0.2 to 0.3

1.3 Model boundaries and error correction

1.3.1 Flow boundaries

We re-used the same flow boundary locations and PDMs as the forecasting model, except for:

- Outflow from the Leigh FSA, which cascades from our Upper Medway ISIS model;
- Flow at Stonebridge, which is simulated using new PDM parameters; and
- Flow at Stilebridge, which cascades from our Beult ISIS model.

Table "PDM Parameters" (above) lists the PDM parameters used for each catchment and Table "Boundaries for ISIS model MidMedway.DAT" shows how they are fed to the ISIS model.

1.3.2 Downstream boundary

The model's downstream boundary is unchanged from the forecasting model (except extended to a high flow). It uses the rating curve for East Farleigh gauging station.

1.4 Simulation performance

1.4.1 Calibration points

The table "Model calibration points" lists all the nodes in the model configured to exprot data in NFFS and having useful observed data for comparison against stimulations. There are 13 of these, but only one is a flow gauge not at an upstream boundary (East Farleigh). Only simulated level can be compared at the remaining nodes.

Of the 47 simulated events since 1998, only 38 could be used for comparison (those since 6 Nov 2000) because of limitations on rainfall data. Rainfall is only considered properly reliable after April 2006.

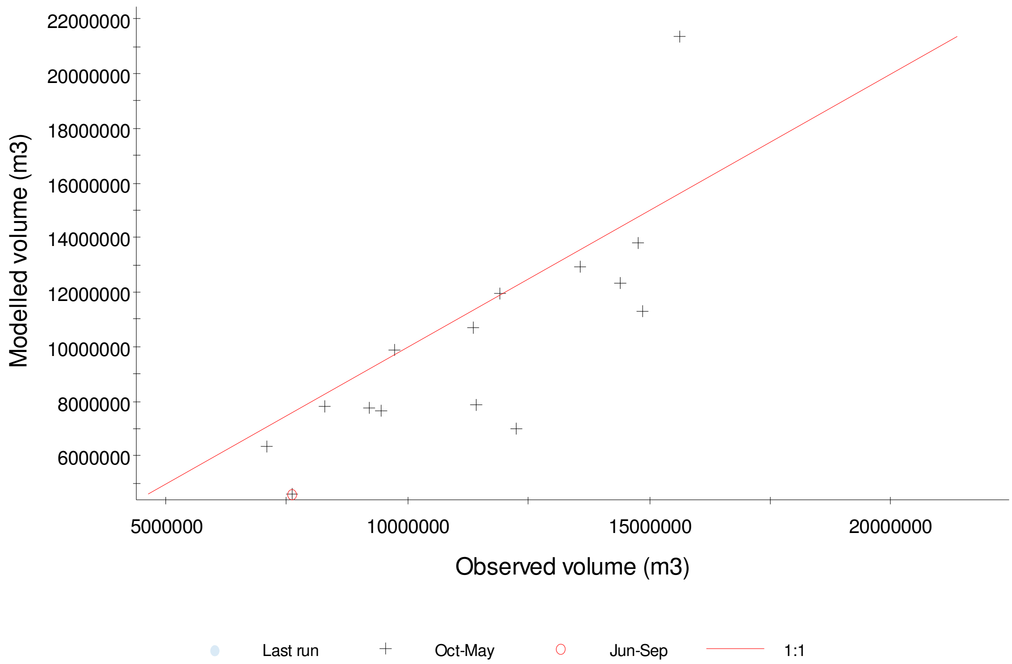
Model results are presented as 'model evaluation sheets' and an explanation of their layout and contents is available at the begining of this Appendix.

1.4.2 Accuracy

The main points from each model evaluation sheet are outlined below. Many of the structures have gates set to 'open' in the simulation, impacting the accuracy of level measurements in some events. The level data are therefore of limited usefulness. Our main concern was to show how the model performs in terms of flow prediction at East Farleigh.

Medway @ Leigh FSA outflow

Flows at the Medway boundary are cascaded from the Upper Medway model. Observed flows are calculated for the barrier based on levels in the impoundment and the gate openings. Observations therefore depend on how the gates have been operated. Observed flow data out of the barrier are only availble for 15 of the 38 events. Model performance is reaonable in terms of volume (see below), although there is a tendency to under predict for some events. December 2013 observations are incomplete, so the volume comparison is not valid (but the hydrograph shapes look reasonable).



Medway @ Leigh Barrier DS

Levels are monitored downstream of the barrier, giving the equivelant of the outflow, but as level. There are 18 events recorded here, including December 2013. Water levels tend to be under predicted by the model. This is partly a result of the gates being operated differently in reality to the model rules and partly due to local channel hydraulics.

Medway @ Town Lock

There is a strong tendency to over predict levels at Town Lock. This is more likely to be a fault of the local hydraulics than the flow in the model. Flows here are dominated by releases from the Barrier.

Bourne @ Little Mill

Observed river levels are available at Little Mill from 2008 and are affected by backwater from the Medway in high flows. Simulated river levels are quite variable between events, but the two largest (December 2013 and February 2009) are well matched. The timing and shape of the hydrographs tends to be good.

Medway @ Branbridges

Water levels at Branbridges are controlled by a structure downstream. The model assumes this is kept open while in reality it is sometimes closed. The model nearly always predicts higher water levels than the observed, but the timing of the hydrograph (and often the shape) are reasonable.

Teise @ Stonebridge

Stonebridge is a boundary of the model and takes flow from the PDM there. The PDM's peak flows are highly correlated with the observed, but tend to be higher. This is partly due to the impact of flood plain storage upstream of the boundary, not represented in the PDM model. Its effect is to store water on the rising limb of the hydrograph, reducing the eventual observed peak (see top ten hydrograph thumbnail plots). This process is not modelled by the PDM.

Teise @ Darmans Bridge

Darmans Bridge is on the Teise, just upstream of the Medway confluence. Water levels are controlled locally by a moving structure. Simulated levels are much higher than observed, but the timing of the peak is reasonable.

Medway @Yalding US

Yalding US is just upstream of the Teise and Beult confluence. Water levels are again controlled by a moving structure (navgable lock). We have observations for events up to 2012. The model reproduces the hydrograph shape and timing reasonably well but predicts higher water levels than observed. At this structure, the model does seem to maintain the correct water level between events.

Beult @ Stilebridge

Flows and levels are monitored at Stilebridge - another boundary of the ISIS model. Simulated flows are cascaded from the Beult ISIS model (described elsewhere). Simulated and observed flows are a good match at this location, with good magnitude, shape and timing.

Beult @ Cheveney Gate

Water levels are recorded on the Beult at Cheveney Gate. The site is influenced by levels in the Medway at high flows. The model strongly over predicts levels here and does not reproduce the impact of the structure. December 2013 is the best fit in terms of peak level but is still 1m too high. Comparisons at this location are not very helpful.

Medway @ Yalding DS

Yalding downstream includes the influence of the Teise and the Beult, which join the Medway in between the gates at Yaldking Upstream and Downstream. Nearly all of the inflows to the Medway are therefore included at this point. The site is close enough to the downstream boundary (a rating curve) to be influenced by it - probably helping the accuracy of level prediction. Simulated levels match the observed well at this location and there is a complete level series available. The four largest events are under predicted slightly and the model peaks earlier than the observed series for those.

Medway @ East Farleigh

Flows and levels are available at East Farleigh. As levels come from a rating curve (the model boundary) we will only consider flows. Like at Yalding Downstream, the model fit is good at this location, particularly so for all but the three largest (and a couple of earlier events which seem to have data issues, e.g. Dec 2009 and Mar 2001). In the largest events, the model's behaviour begins to diverge from the observed slightly. Observed river levels are attenuated at first (so the model rises first), but later in the event they rise more quickly (not replicated well by the model, which has a steady rate of rise from the begining of the event). We hypothesise that this is the impact of the floodplain becoming full to the point that attenuation is reduced. This feature of the hydrograph is not well replicated by the 1D model. However, the model is still sufficient to identify the correct design event to apply to the full mapping model (its primary purpose).

1.4.3 Predominant sources of error

The purpose of the Middle Medway model is to route flows through the system from Leigh Barrier, the Teise and Beult. How the model is being used here, to identify which continuous simulation event is the design for a given return period, is critical in the assessment of error. There are three main sources of error seen at individual locations, but not all are relevant to the overall task:

Runoff. Although the Upper Medway and Beult models account for a large proportion of the area to East Farleigh, there are still significant lateral inflows. Correctly simulating runoff rates (as indicated by the performance of the PDM models at Stonebridge, Stilebridge and Hadlow) is still an important factor in model accuracy, although attenuation means that peak flows tend to be less of an issue.

Floodplain attenuation. There is a lot of attenuation in the middle reaches of the Medway and its tributaries. This was seen in the Figure earlier in this section. The model does not always simulate this correctly. The observed data shows initial storage attenuation lessening as the flow rises to an extreme (like December 2013) and the flood plain fills. As the model simulates the floodplain as extended 1D sections, this process is not well reproduced by the model. The impact is to over-attenuate in the largest events. As a result, flows outputted from the model are probably less than they would be in reality (given the same inputs). Design flows from the model should not be cascaded to the Lower Medway without accounting for this bias.

Local hydraulics. Simulated water levels are quite different to observed at several of the river locations. This may not be important for the routing of flows through the Medway (the local effects tend to be related to structure operation or local channel hydraulics) but they should be of concern for the forecasting model.

1.4.4 Potential for model improvement

The Middle Medway model is already a forecasting tool. We have altered several aspects to make it run for the continuous simulation events, but this was done without much regard for level prediction at the key forecast locations (our main aim was to route flows to East Farleigh). The Middle Medway model would benefit from the stabilisation adjustments being implemented ALONGSIDE improvements to its prediction of water levels at key locations. This may also involve replacing the removed routing reaches with river reached.

Lateral inflows to the model were retained unchanged. There was no obvious need to change the PDM parameters underlying these, but improvements in accuracy may be possible by investigating this aspect of the model.

Boundaries for ISIS model MidMedway.DAT

Type	Node	Source	Name	Scale or offset	Lag	PDM Area (km2)
QTBDY	Hadlow	PDM	Hadlow			51
QTBDY	AS01	PDM	A_sub_1 v1			37.816
QTBDY	HI01	PDM	H_sub_1			53
QTBDY	MI01	PDM	M_sub_1			27
QTBDY	BE_sub_3	PDM	BE_sub_3			157
QTBDY	OutflowLB	Other model	... Routing\04 LeighBarrier\09 Cascade			
QTBDY	Stonebridge	PDM	Stonebridge			134
QTBDY	Stilebridge	Other model	...ions\04 Routing\05 Beult\09 Cascade			
					Total	**459.8**

Model calibration points

Type	Node	Source	Name
Flow	OutflowLB	Observed	453400018FQ (Flow) - LEIGH BARRIER
Level		Observed	453400004SG (Stage) - Lucifer Bridge
Level	CS36	Observed	453400003SG (Stage) - Town Lock
Flow	Hadlow	Observed	453310001SG (Flow) - Hadlow
Level	BO9-WJD	Observed	453300005SG (Stage) - LITTLE MILL RL
Level	CS114	Observed	453300006SG (Stage) - Branbridges
Level	CS28	Observed	453400009SG (Stage) - STONBRIDGE
Flow	Stonebridge	Observed	453230001SG (Flow) - STONEBRIDGE
Level	T30-BJDc	Observed	453220001SG (Stage) - Darmans Bridge
Level	CS147	Observed	E1910SG (Stage) - Yalding US
Level	CS161JD	Observed	453202003SG (Stage) - Yalding D/S
Flow	Stilebridge	Observed	453210001SG (Flow) - STILEBRIDGE
Level	B21-LJU	Observed	453203002SG (Stage) - Cheveney Gate
Flow	CS189	Observed	453101001HFQ (Flow) - East Farleigh
Level		Observed	453101003SG (Stage) - East Farleigh Gate

Notes:

Model run with 47 events from the period 01 Nov 1998 to 01 Feb 2014; see individual model evaluation sheets for results

An asterisk (*) indicates scaling in the 'scale' column, otherwise the value is an offset (e.g. datum) - added or subtracted from the raw time series

The area calculated for boundaries is the product of PDM Area and scaling factor

Where two PDMs are indicated for a boundary, their flows are summed to give a combined input

Rain gauge weights										
Name	**Area (km2)**	**BEWL BRIDGE RES tbr**	**HAM HILL STW tbr**	**HORSMONDEN STW tbr**	**Kiln Wood**	**LEIGH TBR**	**Lamberhurst WWTW**	**REDGATE MILL tbr**	**Saints Mill**	**Sutton Valence**
Hadlow	51		0.01		0.89	0.1				
A_sub_1 v1	37.816			0.1	0.4	0.3	0.2			
H_sub_1	53		0.01		0.25	0.75				
M_sub_1	27				0.3	0.6			0.1	
BE_sub_3	157		0.25	0.25	0.001	0.375	0.001			0.125
Stonebridge	134	0.4					0.4	0.2		

PDM parameters													
Area	**Fc**	**Cmin**	**Cmax**	**b**	**Be**	**Kg**	**Bg**	**St**	**K1**	**K2**	**Kb**	**QConst**	**Tdly**
Km^2		**mm**	**mm**					**mm**	**hrs**	**hrs**	**hmm^2**	**m^3/s**	**hrs**
Hadlow			**Surf.**	Linear Cascade			**Base**	Cubic store		**Drainage**		Gravity	
51	0.9	0	150	0.25	0.9	50000	2	71.936	4.045	6	120.0	0	0.129
A_sub_1 v1			**Surf.**	Identical linear cascad			**Base**	Cubic store		**Drainage**		Gravity	
37.816	1	20	200	1.1	2	75000	1.8	10	5	n/a	4.6	0	3.5
H_sub_1			**Surf.**	Linear Cascade			**Base**	Cubic store		**Drainage**		Gravity	
53	0.9	0	150	0.25	0.9	50000	2	71.936	4.045	6	120.0	0	0.129
M_Sub_1			**Surf.**	Linear Cascade			**Base**	Cubic store		**Drainage**		Gravity	
27	0.9	0	150	0.25	0.9	50000	2	71.936	4.045	6	120.0	0	0.129
BE_sub_3			**Surf.**	Linear Cascade			**Base**	Cubic store		**Drainage**		Gravity	
157	1.1	0	120	0.25	1.1	100000	1.8	0	9	12	20.0	0	3
Stonebridge			**Surf.**	Identical linear cascad			**Base**	Cubic store		**Drainage**		Gravity	
134	1	30	230	0.5	4	30000	1.7	60	4	n/a	5.8	0	2

Notes:

Please refer to PDM documentation for a definition of parameters

Rating details									
Gauge Ref		453400018FQ	**Name**	LEIGH BARRIER (no rating identifier)					
Gauge Ref		453310001SG	**Name**	Hadlow					
No.	**Limb**	**Description**		**K**	**a**	**p**	**Max.**	**Start**	**End**
1	a	HiFlows UK		2.957	0.002	1.860	0.31	01 Jan 1970	01 Jan 2100
1	b	HiFlows UK		2.757	0.110	2.348	1.21	01 Jan 1970	01 Jan 2100
1	c	HiFlows UK		5.443	-0.226	1.762	1.99	01 Jan 1970	01 Jan 2100
1	d	HiFlows UK		0.217	0.959	3.901	2.25	01 Jan 1970	01 Jan 2100
1	e	HiFlows UK		22.874	-1.318	1.496	3.65	01 Jan 1970	01 Jan 2100
1	f	HiFlows UK		4.121	0.165	2.237	3.85	01 Jan 1970	01 Jan 2100
Gauge Ref		453230001SG	**Name**	STONEBRIDGE (tabular rating)					
Gauge Ref		453210001SG	**Name**	STILEBRIDGE (tabular rating)					

Gauge Ref	453101001HFQ	Name	East Farleigh (no rating identifier)

Notes:

Rating equation has the form Q=K*(Stage+a)^p

Stations where flows are stored, and not calculated from a rating, may be listed without a rating

General notes:

Ratings database used: N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\00 Ratings Database\2013s7661 - Medway Rating DB Modelled Ratings Active.accdb

Form settings: N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\MiddleMedway_SIM_01 - Cascade.BTD

Cheveney Gate Level

Data summary

38 peaks analysed at B21-LJU between 0.0m and 12.5m, for period 06 Nov 2000 to 01 Feb 2014 from :

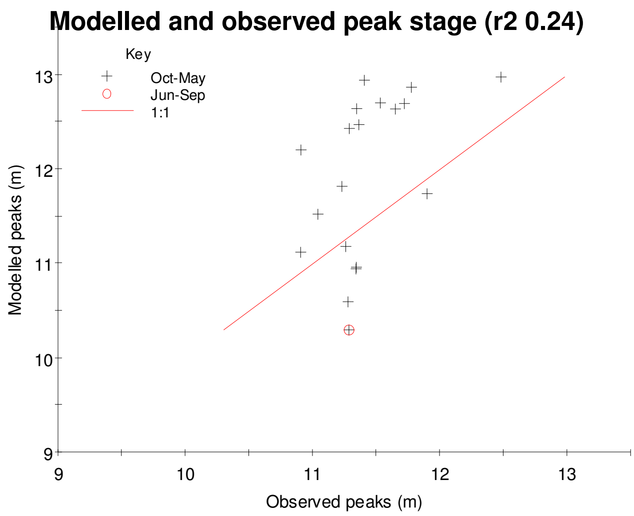
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade

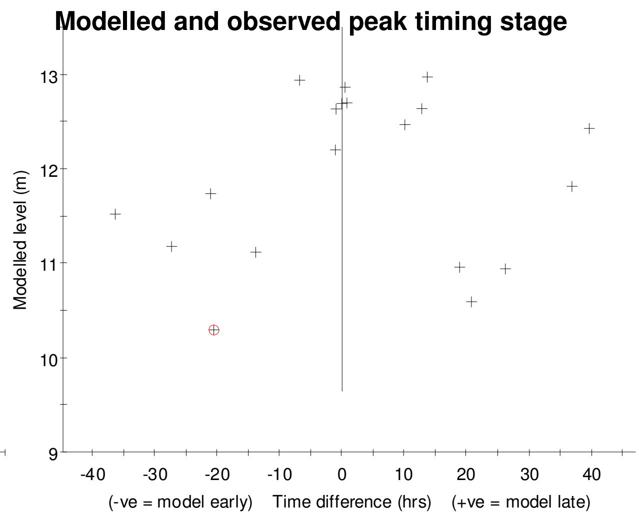
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m)	Mod. (m)	Diff. (m)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	12.48	12.98	0.50	4%	13.6	-1.05	0.445	0.70
2	23 Feb 2010 06:30	11.90	11.74	-0.15	-1%	-21.1	-6.22	-999.	0.93
3	16 Jan 2008 01:30	11.77	12.86	1.09	9%	0.4	-10.2	-999.	1.05
4	10 Feb 2009 10:30	11.72	12.69	0.97	8%	-0.1	-21.5	-999.	1.05
5	01 Feb 2014 12:30	11.65	12.64	0.99	8%	-1.0	-0.36	0.002	5.36
6	02 Jan 2014 07:30	11.53	12.70	1.17	10%	0.8	-6.51	0.006	0.81
7	01 Dec 2009 04:30	11.40	12.94	1.54	13%	-6.8	-12.3	-999.	1.18
8	01 Mar 2010 04:30	11.36	12.47	1.11	10%	10.0	-7.00	-999.	0.97
9	23 Jan 2009 22:30	11.34	12.64	1.30	11%	12.8	-6.50	-999.	0.94
10	14 Dec 2008 08:30	11.34	10.96	-0.38	-3%	18.8	-34.9	-999.	1.19

Model scores

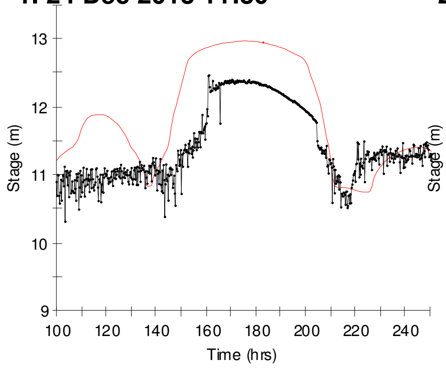
	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	4.21	3.04	4.02	0.00	2.95	4.00	4.00	3.19



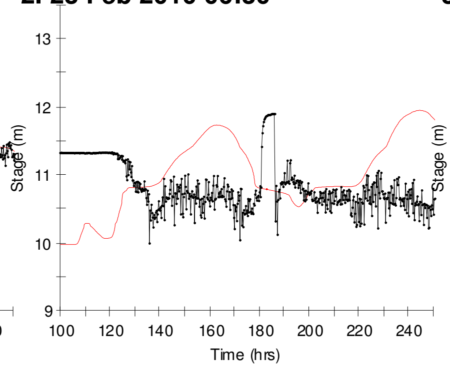


Cheveney Gate Level

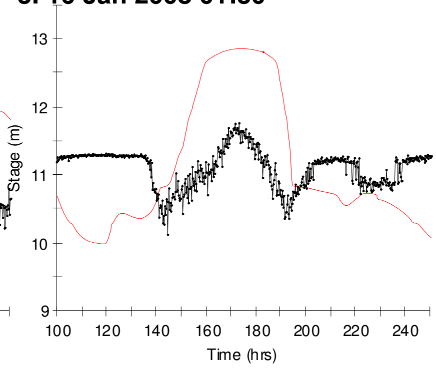
1. 24 Dec 2013 11:30



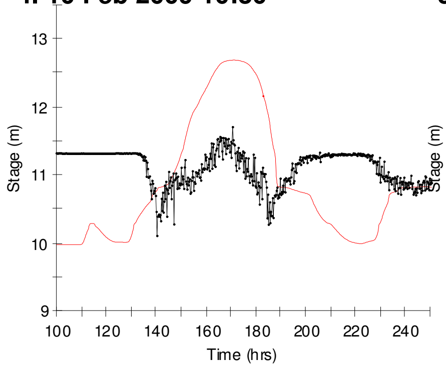
2. 23 Feb 2010 06:30



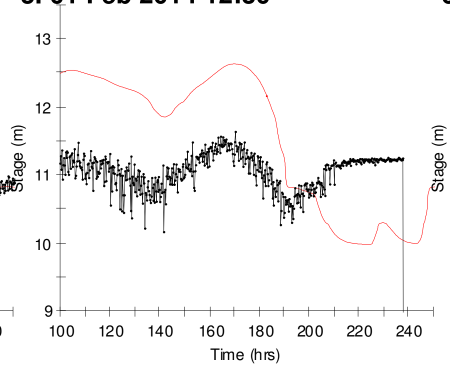
3. 16 Jan 2008 01:30



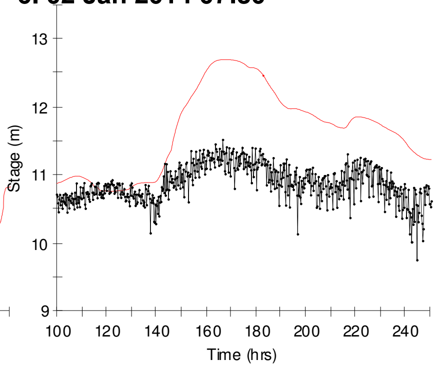
4. 10 Feb 2009 10:30



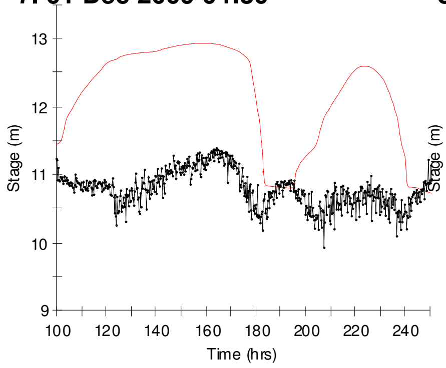
5. 01 Feb 2014 12:30



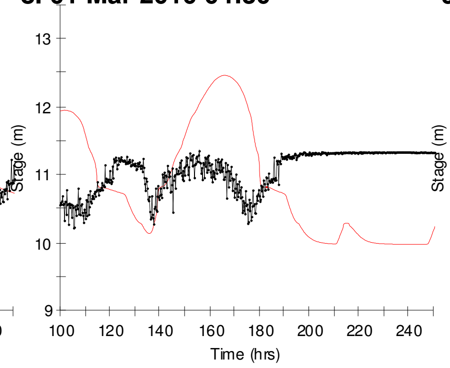
6. 02 Jan 2014 07:30



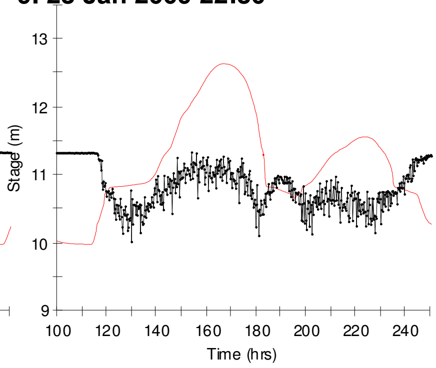
7. 01 Dec 2009 04:30



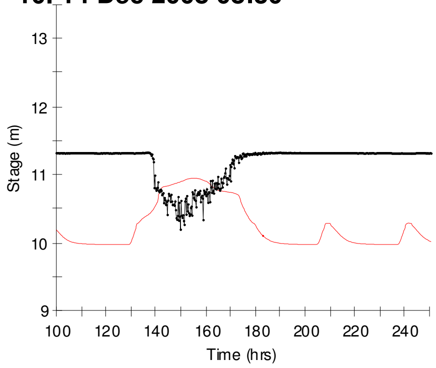
8. 01 Mar 2010 04:30



9. 23 Jan 2009 22:30

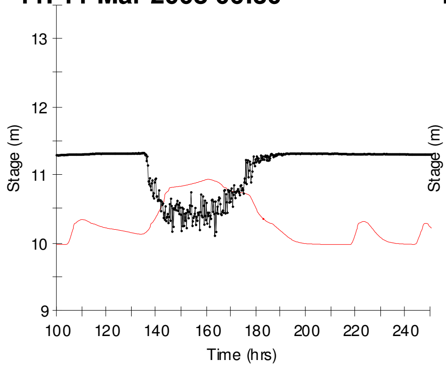


10. 14 Dec 2008 08:30

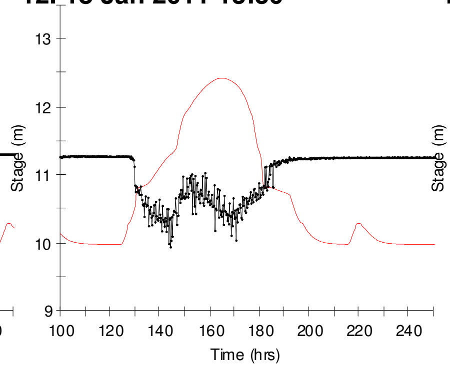


Key
Modelled
Observed

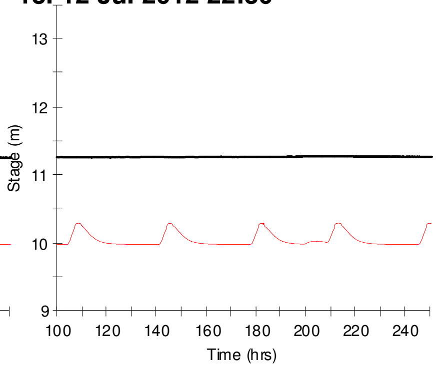
11. 11 Mar 2008 06:30



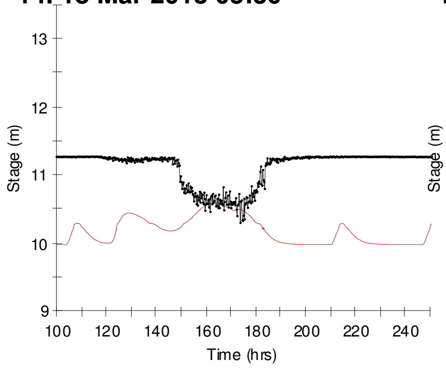
12. 18 Jan 2011 13:30



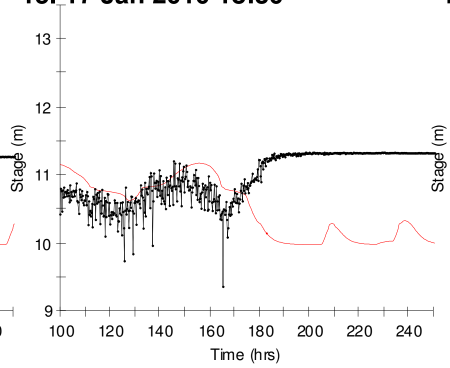
13. 12 Jul 2012 22:30



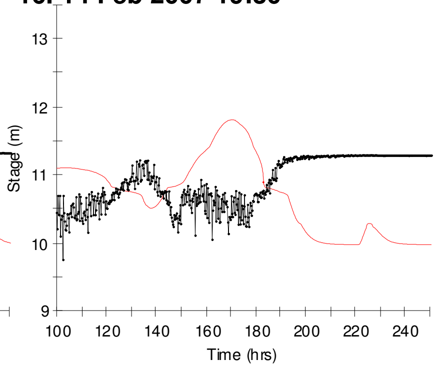
14. 18 Mar 2013 05:30



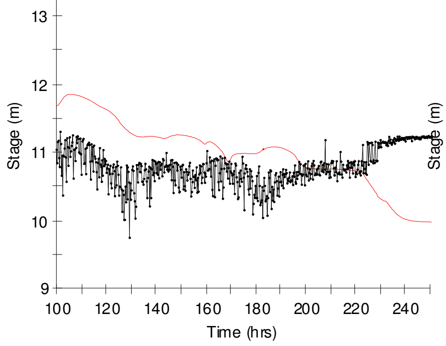
15. 17 Jan 2010 18:30



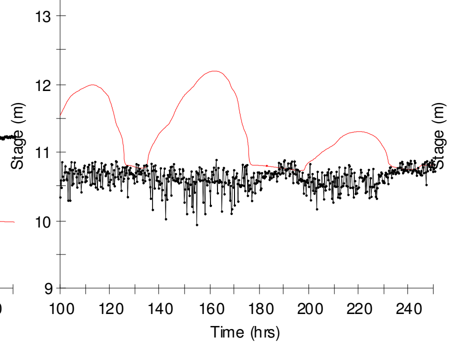
16. 14 Feb 2007 19:30



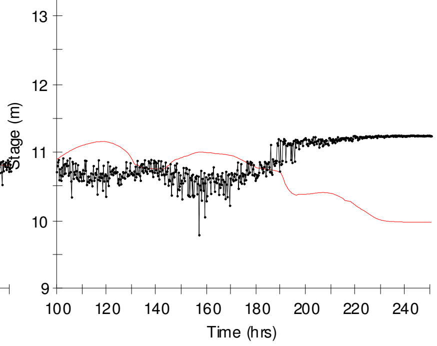
17. 07 Jan 2014 02:30



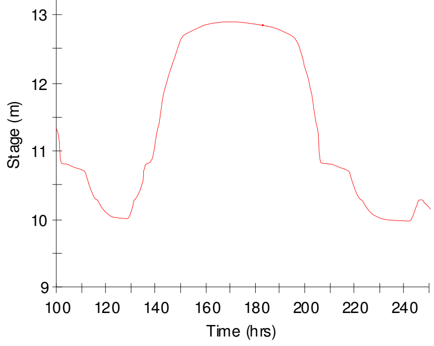
18. 23 Dec 2012 09:30



19. 17 Jan 2014 17:30

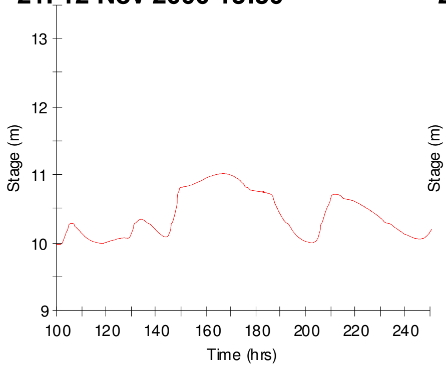


20. 06 Nov 2000 19:30

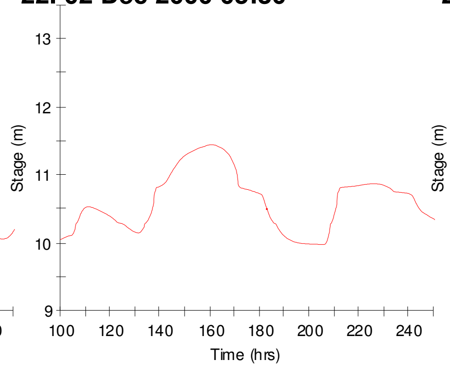


Key
Modelled
Observed

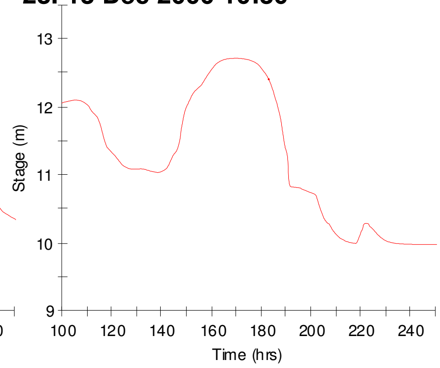
21. 12 Nov 2000 15:30



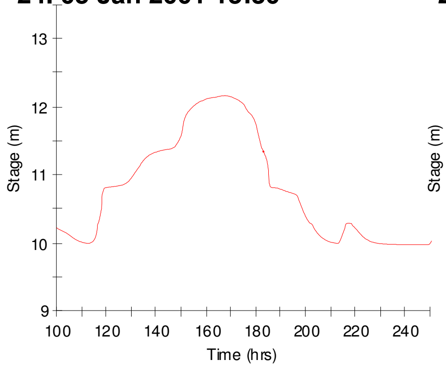
22. 02 Dec 2000 05:30



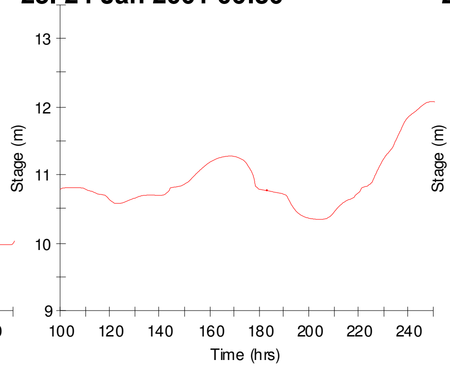
23. 13 Dec 2000 10:30



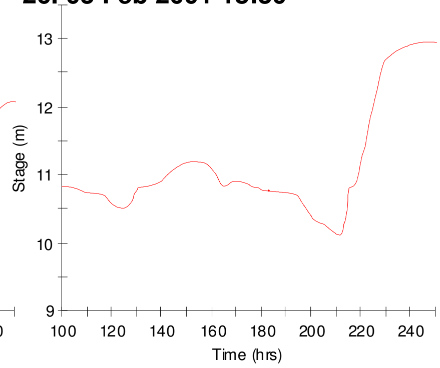
24. 05 Jan 2001 15:30



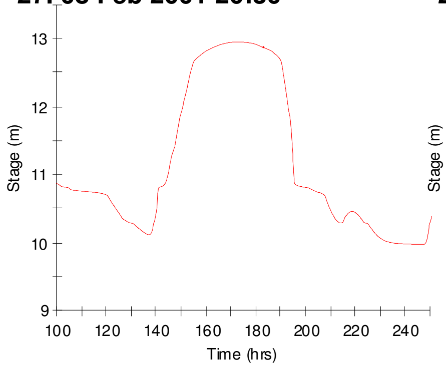
25. 24 Jan 2001 06:30



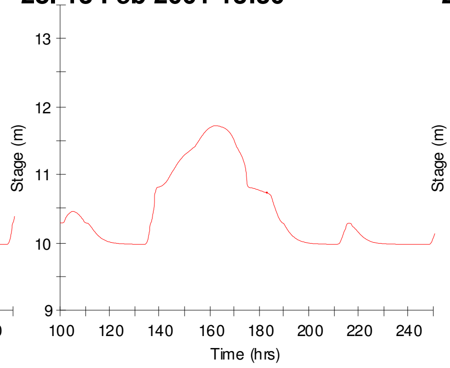
26. 05 Feb 2001 18:30



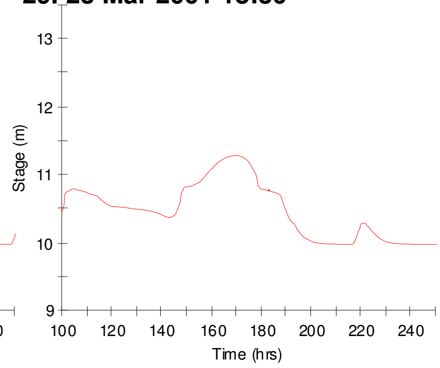
27. 08 Feb 2001 20:30



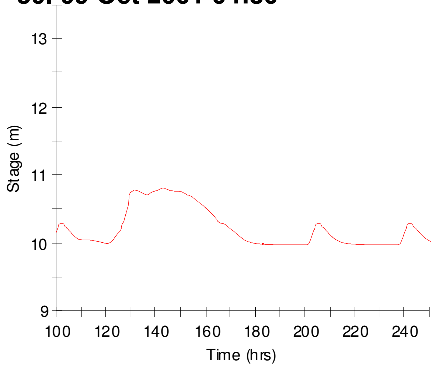
28. 13 Feb 2001 13:30



29. 23 Mar 2001 18:30



30. 09 Oct 2001 04:30



Key
Modelled
Observed

Stilebridge

Data summary

38 peaks analysed at Stilebridge between 0.0m3/s and 89.0m3/s, for period 06 Nov 2000 to 01 Feb 2014 from :

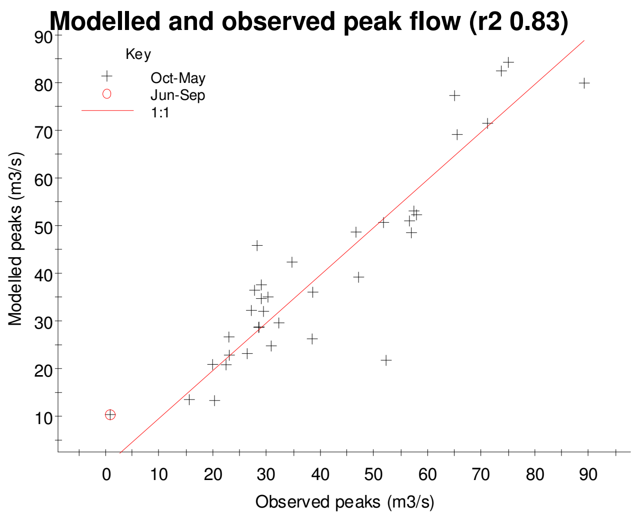
```
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade
```

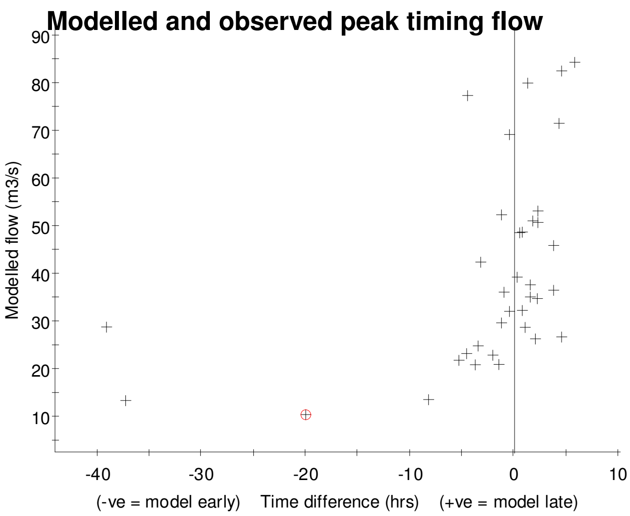
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		**Modelled and differences**				**Event statistics**		
	Date	**Obs. (m3/s)**	**Mod. (m3/s)**	**Diff. (m3/s)**	**Diff (%)**	**Time Diff. (hrs)**	**NSE**	**r^2**	**RMSE**
1	24 Dec 2013 11:30	88.97	80.10	-8.9	-10%	1.3	0.909	0.932	6.42
2	08 Feb 2001 20:30	74.90	84.41	9.5	13%	5.8	0.605	0.844	9.12
3	31 Dec 2002 04:30	73.53	82.60	9.1	12%	4.5	0.867	0.948	6.44
4	06 Nov 2000 19:30	71.02	71.62	0.6	1%	4.3	0.360	0.554	14.62
5	16 Jan 2008 01:30	65.38	69.29	3.9	6%	-0.5	0.947	0.960	3.88
6	01 Dec 2009 04:30	64.88	77.48	12.6	19%	-4.5	0.416	0.749	11.98
7	02 Jan 2014 07:30	57.81	52.51	-5.3	-9%	-1.3	0.834	0.859	4.86
8	10 Feb 2009 10:30	57.31	53.32	-4.0	-7%	2.3	0.934	0.935	3.46
9	01 Feb 2014 12:30	56.81	48.74	-8.1	-14%	0.5	0.924	0.925	4.41
10	23 Jan 2009 22:30	56.48	51.22	-5.3	-9%	1.8	0.917	0.919	3.90

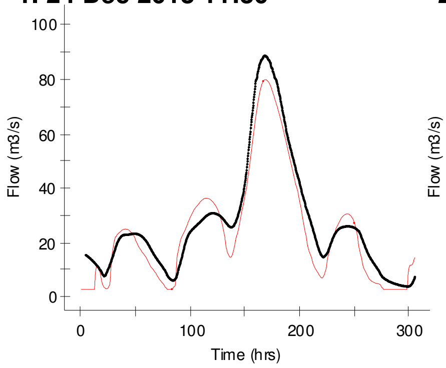
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	1.81	0.58	0.30	1.72	0.58	1.18	3.07	1.54

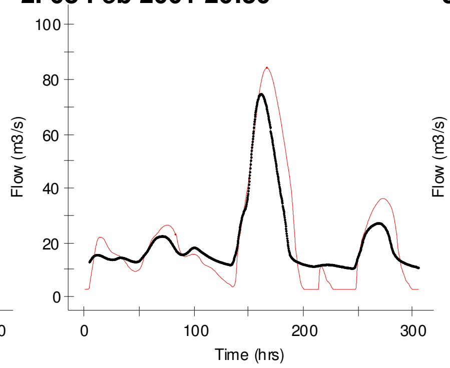




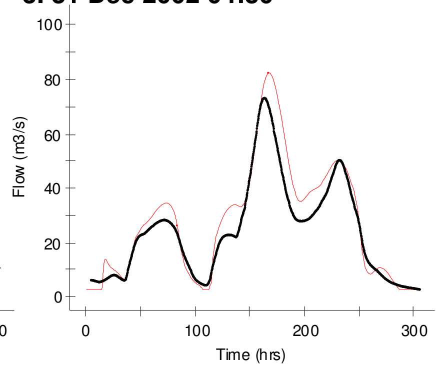
1. 24 Dec 2013 11:30



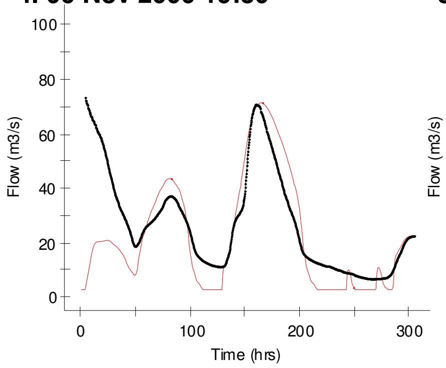
2. 08 Feb 2001 20:30



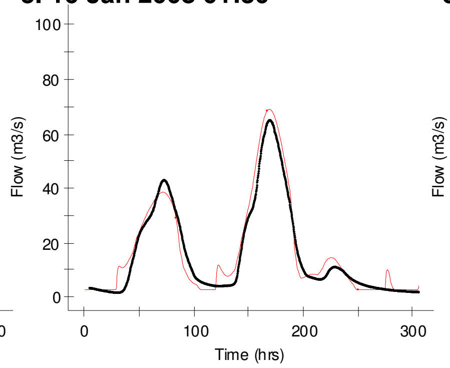
3. 31 Dec 2002 04:30



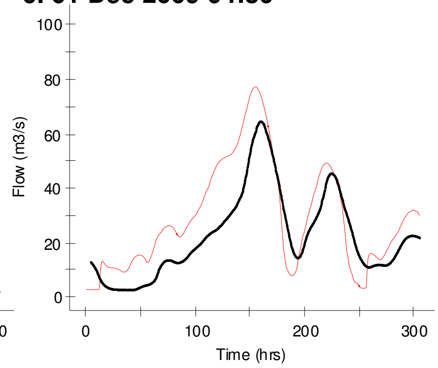
4. 06 Nov 2000 19:30



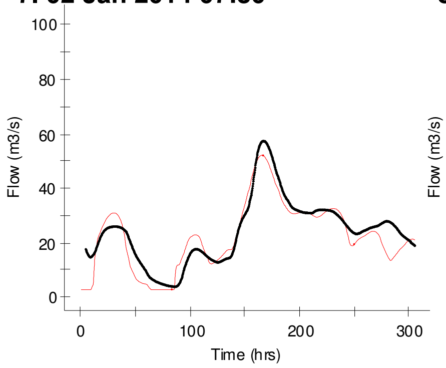
5. 16 Jan 2008 01:30



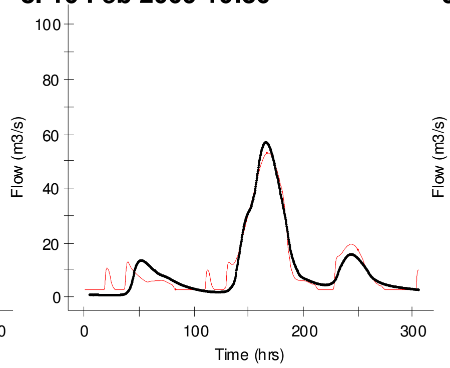
6. 01 Dec 2009 04:30



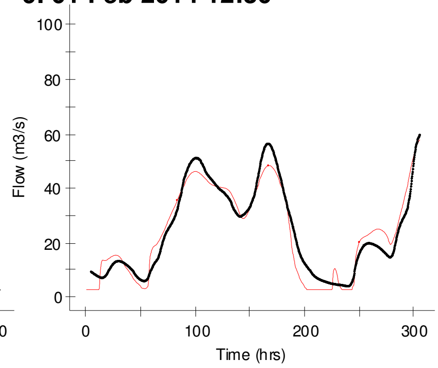
7. 02 Jan 2014 07:30



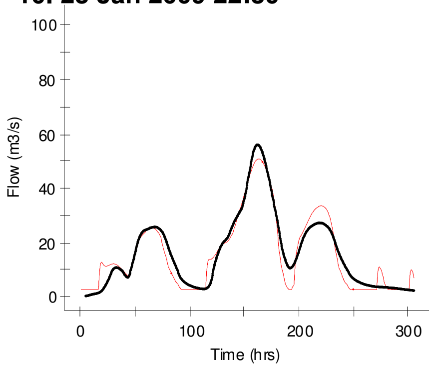
8. 10 Feb 2009 10:30



9. 01 Feb 2014 12:30



10. 23 Jan 2009 22:30

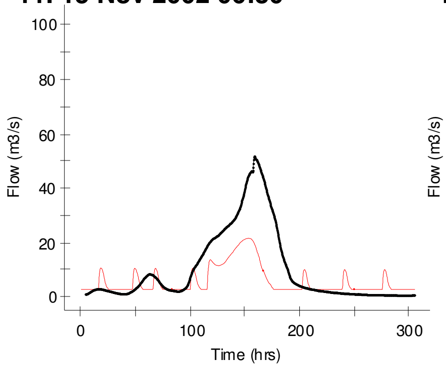


Key

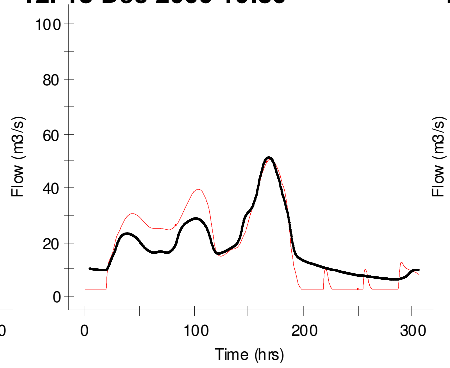
Modelled

Observed

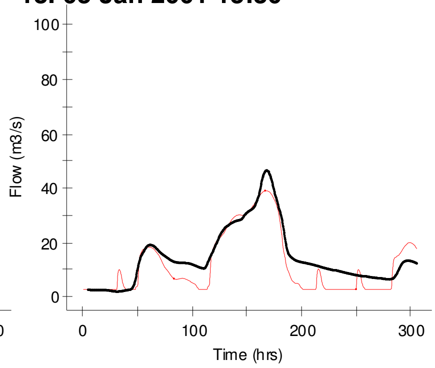
11. 15 Nov 2002 06:30



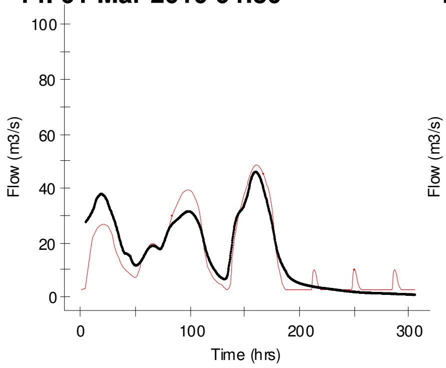
12. 13 Dec 2000 10:30



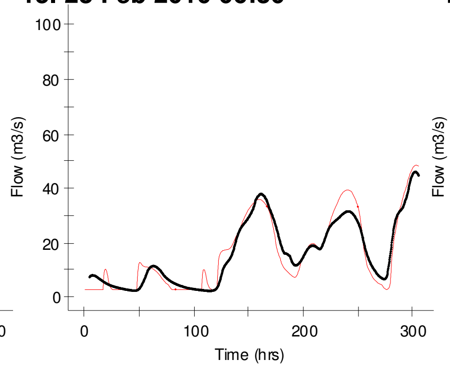
13. 05 Jan 2001 15:30



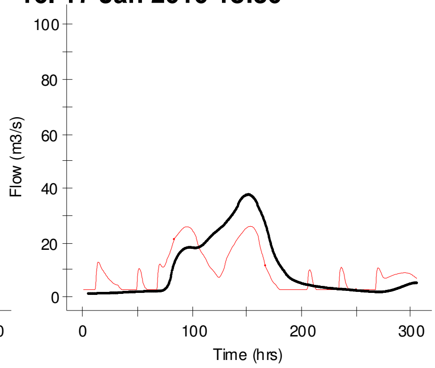
14. 01 Mar 2010 04:30



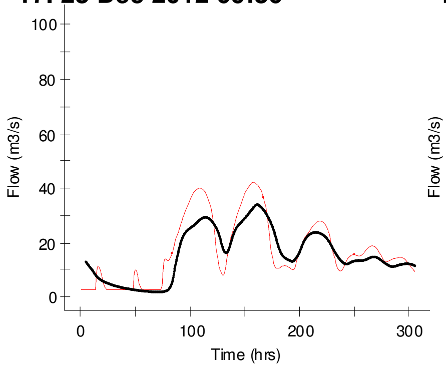
15. 23 Feb 2010 06:30



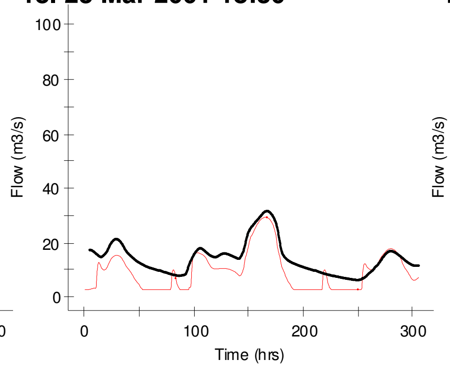
16. 17 Jan 2010 18:30



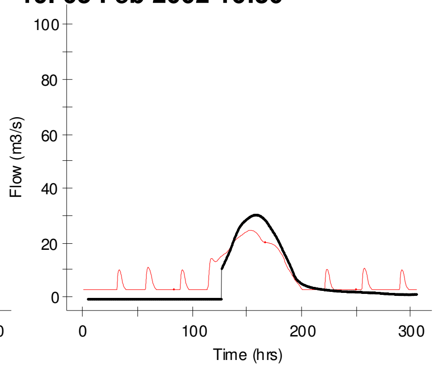
17. 23 Dec 2012 09:30



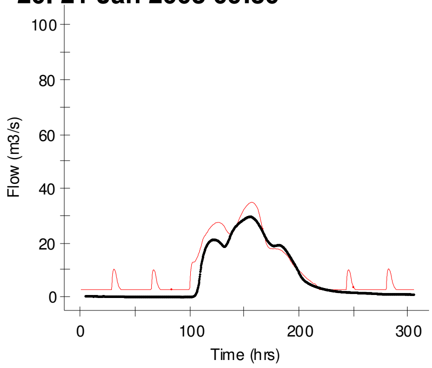
18. 23 Mar 2001 18:30



19. 05 Feb 2002 16:30

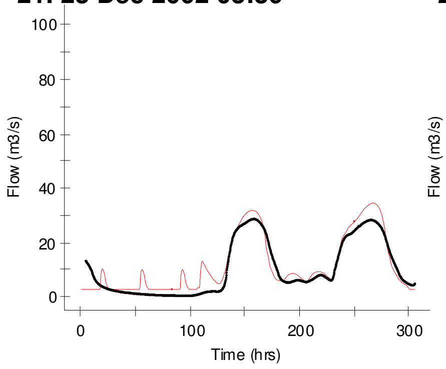


20. 21 Jan 2003 09:30

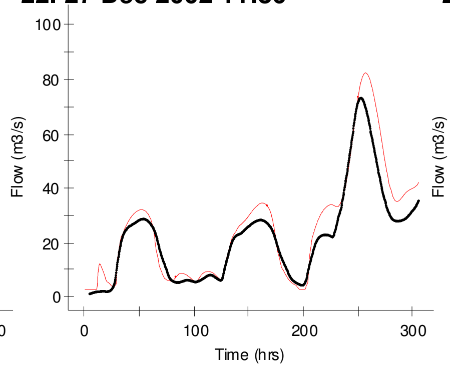


Key
Modelled
Observed

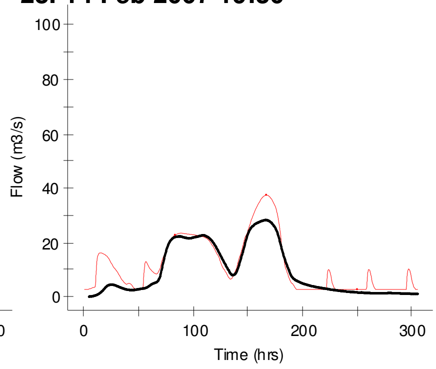
21. 23 Dec 2002 03:30



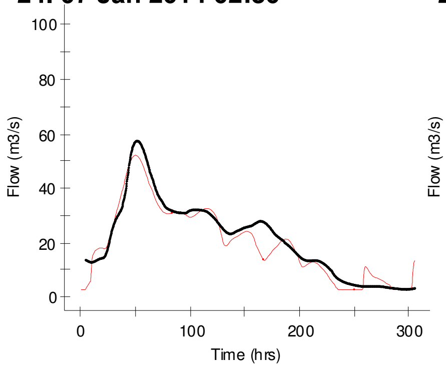
22. 27 Dec 2002 11:30



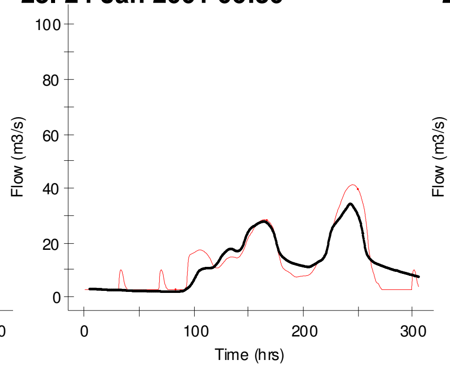
23. 14 Feb 2007 19:30



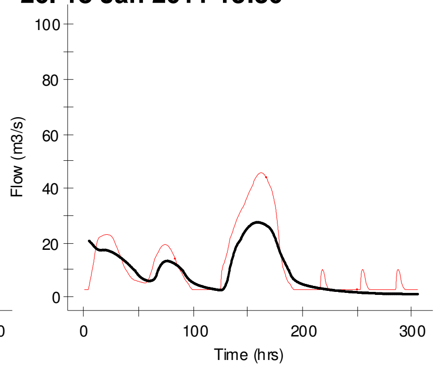
24. 07 Jan 2014 02:30



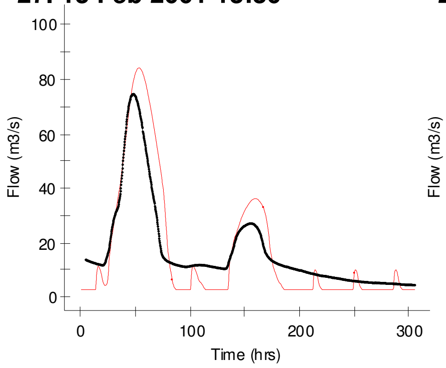
25. 24 Jan 2001 06:30



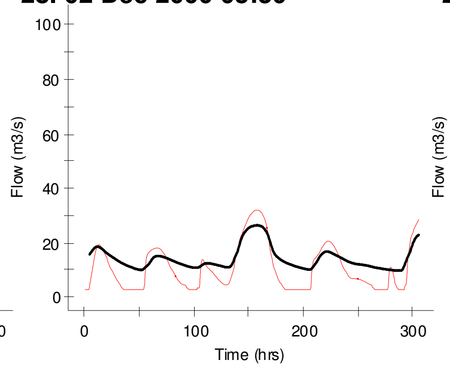
26. 18 Jan 2011 13:30



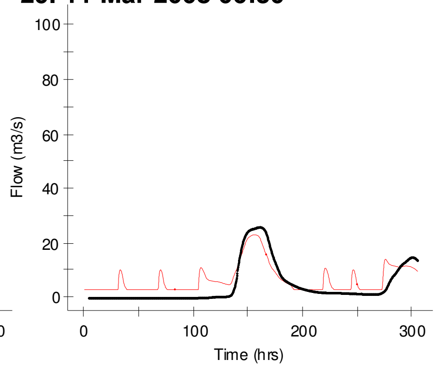
27. 13 Feb 2001 13:30



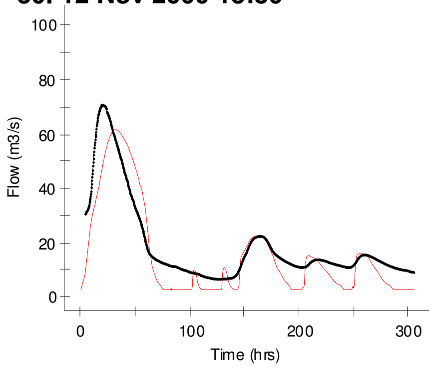
28. 02 Dec 2000 05:30



29. 11 Mar 2008 06:30



30. 12 Nov 2000 15:30



Key
Modelled
Observed

Data summary

38 peaks analysed at BO9-WJD between 0.0m and 15.2m, for period 06 Nov 2000 to 01 Feb 2014 from :

N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade

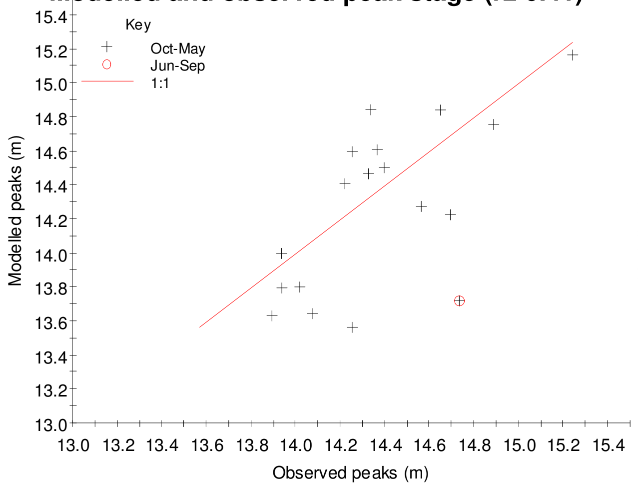
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m)	Mod. (m)	Diff. (m)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	15.24	15.17	-0.07	0%	3.5	0.908	0.944	0.12
2	10 Feb 2009 10:30	14.88	14.76	-0.13	-1%	4.3	0.802	0.873	0.11
3	12 Jul 2012 22:30	14.73	13.72	-1.01	-7%	-6.0	0.024	0.551	0.23
4	01 Mar 2010 04:30	14.69	14.23	-0.46	-3%	0.9	0.507	0.825	0.16
5	17 Jan 2014 17:30	14.65	14.84	0.20	1%	-0.6	0.690	0.942	0.12
6	23 Jan 2009 22:30	14.56	14.28	-0.28	-2%	2.2	0.656	0.873	0.12
7	01 Feb 2014 12:30	14.40	14.51	0.11	1%	-2.1	-0.25	0.024	6.41
8	02 Jan 2014 07:30	14.36	14.61	0.25	2%	6.0	0.382	0.839	0.14
9	18 Jan 2011 13:30	14.34	14.84	0.51	4%	0.3	0.368	0.926	0.14
10	16 Jan 2008 01:30	14.33	14.47	0.14	1%	0.4	0.868	0.883	0.07

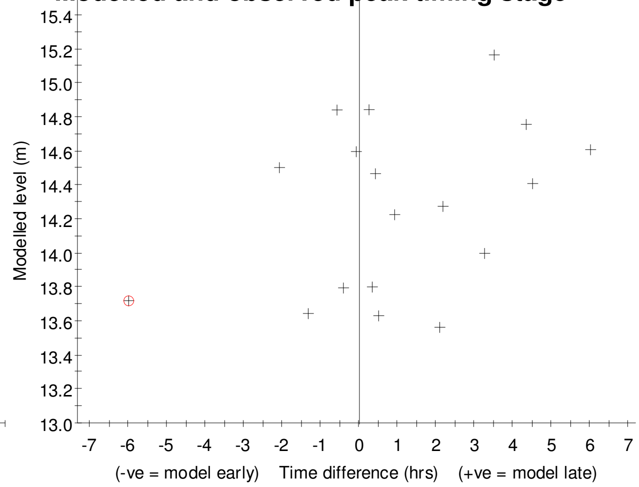
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	3.68	3.00	4.02	0.00	3.02	4.00	4.00	3.05

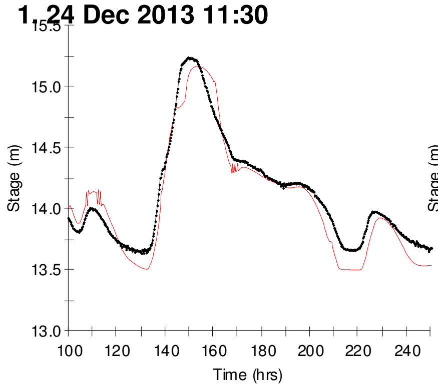
Modelled and observed peak stage (r2 0.41)



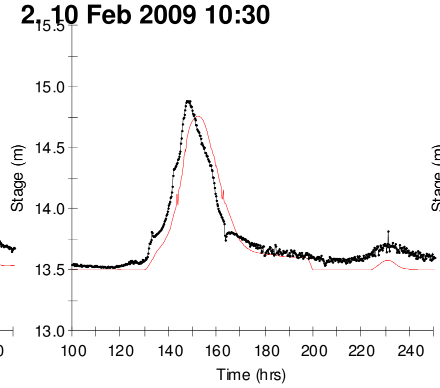
Modelled and observed peak timing stage



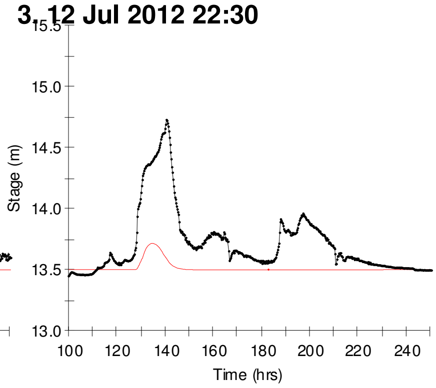
1, 24 Dec 2013 11:30



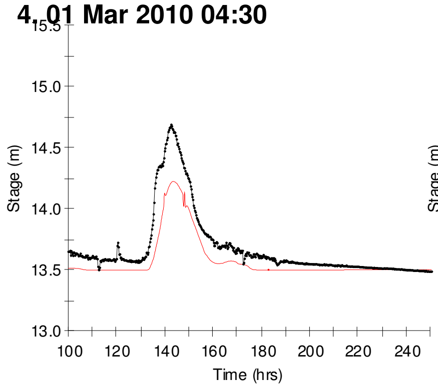
2, 10 Feb 2009 10:30



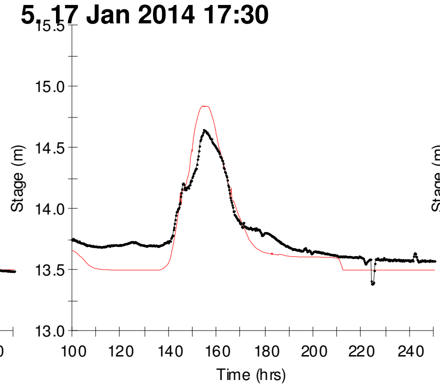
3, 12 Jul 2012 22:30



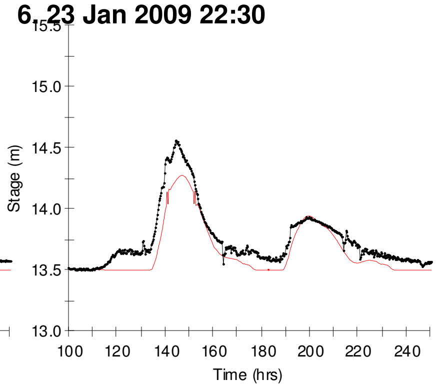
4, 01 Mar 2010 04:30



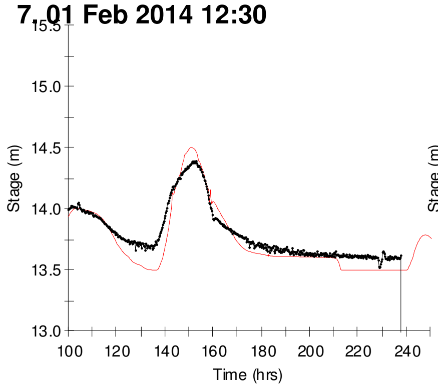
5, 17 Jan 2014 17:30



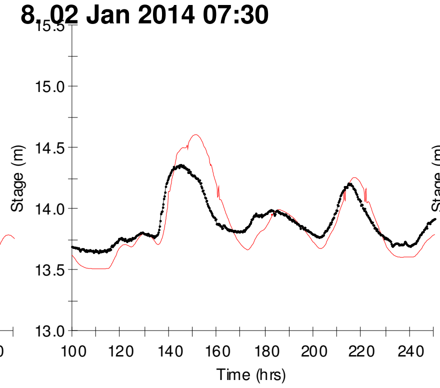
6, 23 Jan 2009 22:30



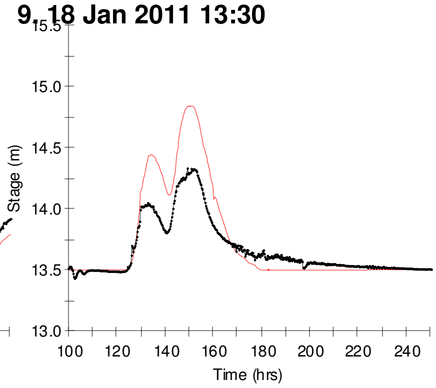
7, 01 Feb 2014 12:30



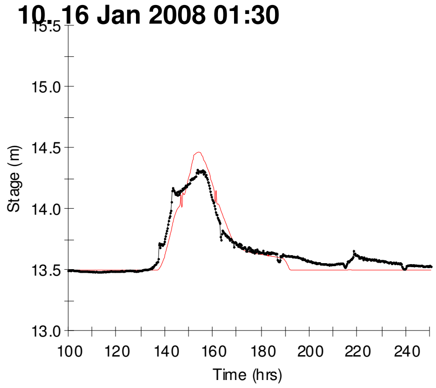
8, 02 Jan 2014 07:30



9, 18 Jan 2011 13:30

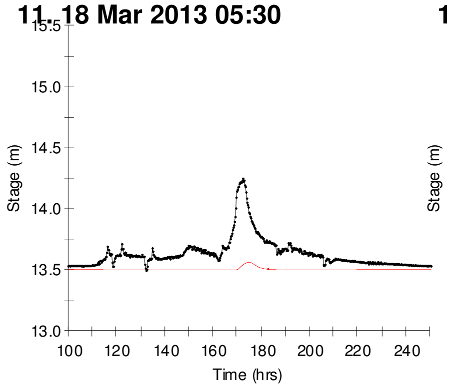


10, 16 Jan 2008 01:30

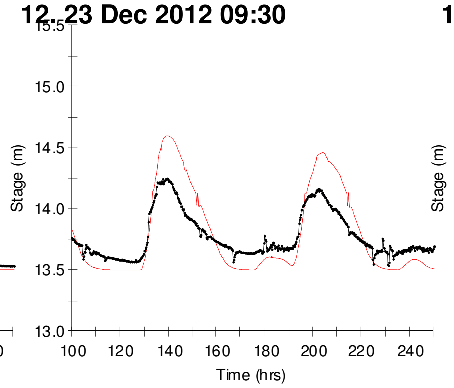


Key
Modelled
Observed

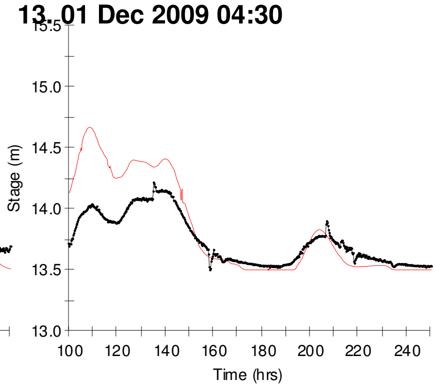
11. 18 Mar 2013 05:30



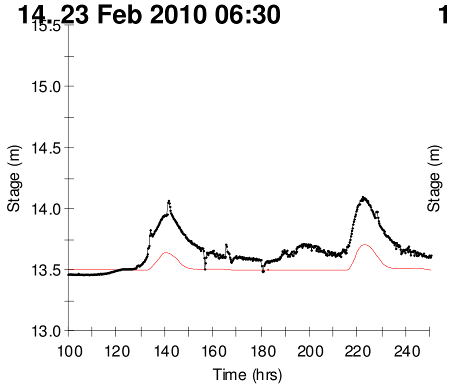
12. 23 Dec 2012 09:30



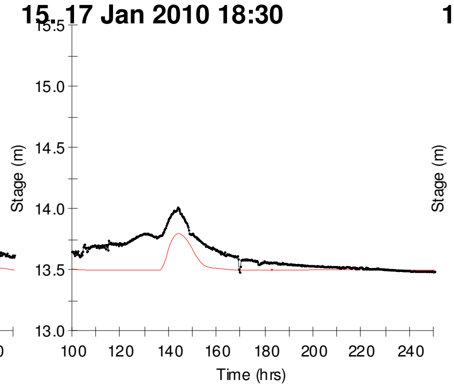
13. 01 Dec 2009 04:30



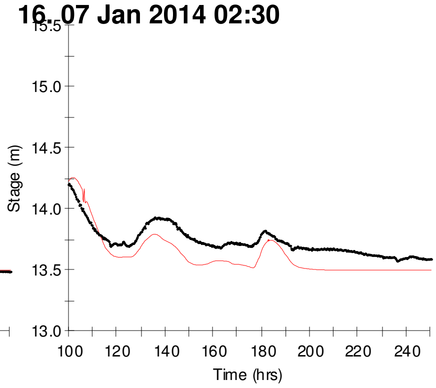
14. 23 Feb 2010 06:30



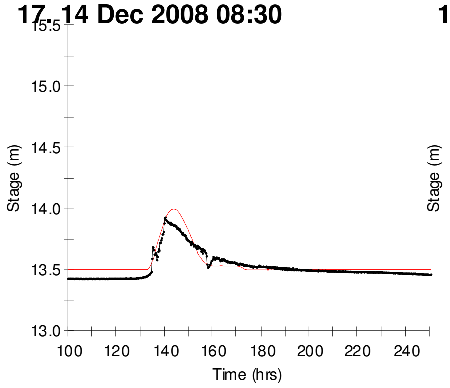
15. 17 Jan 2010 18:30



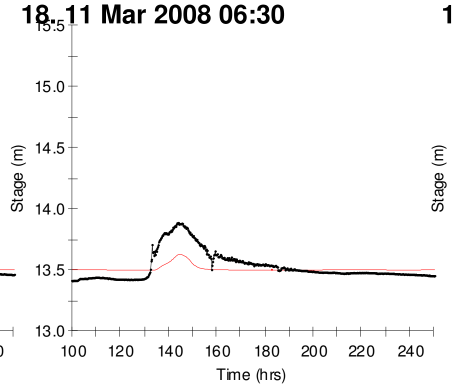
16. 07 Jan 2014 02:30



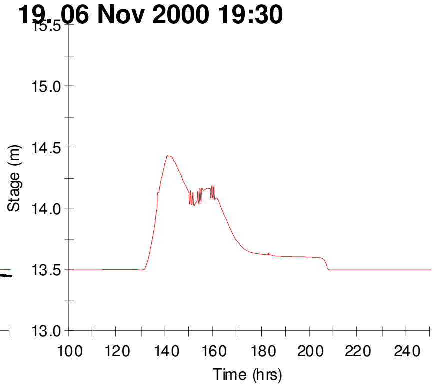
17. 14 Dec 2008 08:30



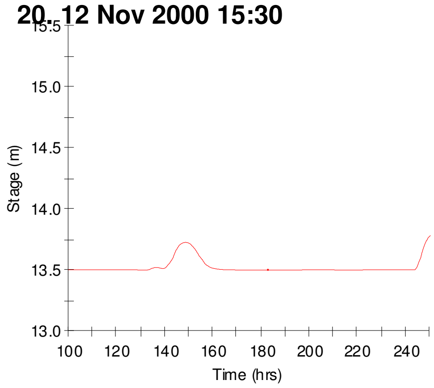
18. 11 Mar 2008 06:30



19. 06 Nov 2000 19:30

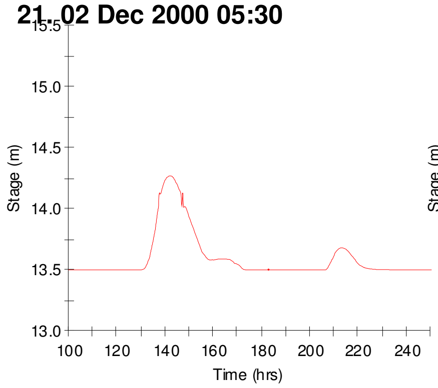


20. 12 Nov 2000 15:30

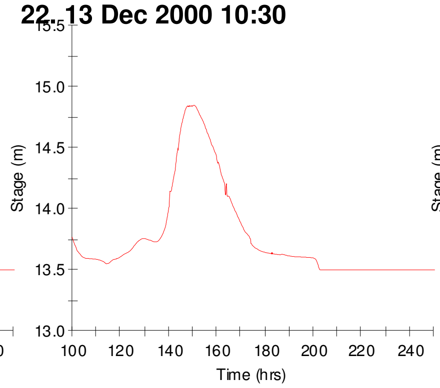


Key
Modelled
Observed

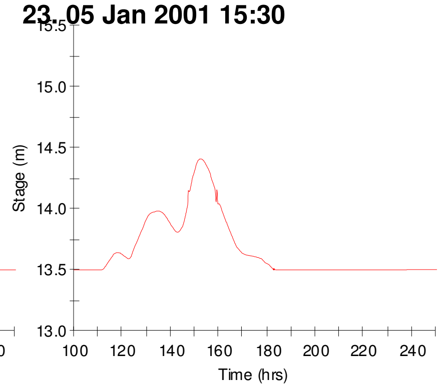
21. 02 Dec 2000 05:30



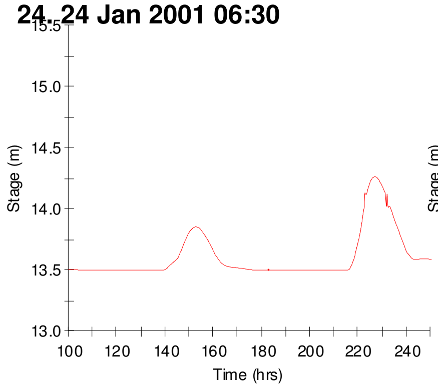
22. 13 Dec 2000 10:30



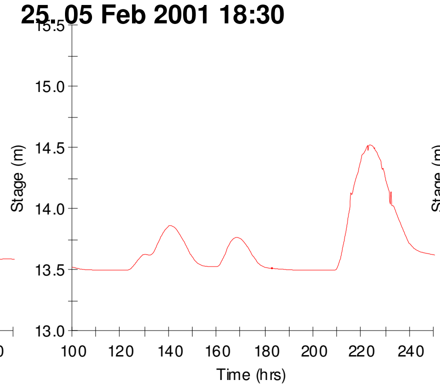
23. 05 Jan 2001 15:30



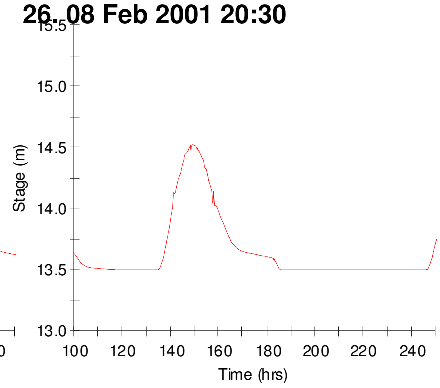
24. 24 Jan 2001 06:30



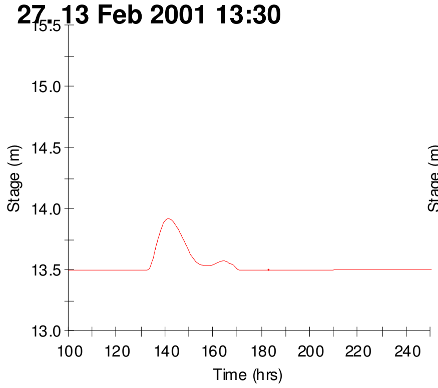
25. 05 Feb 2001 18:30



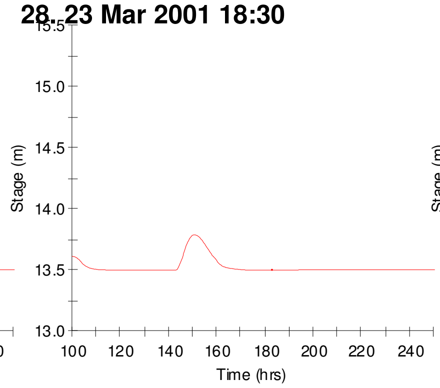
26. 08 Feb 2001 20:30



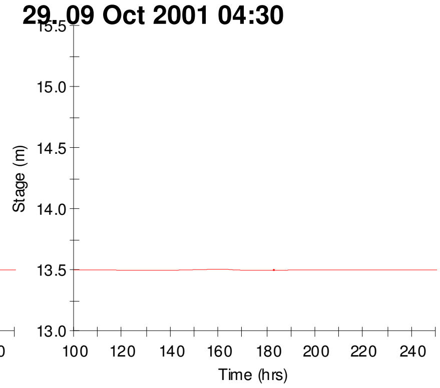
27. 13 Feb 2001 13:30



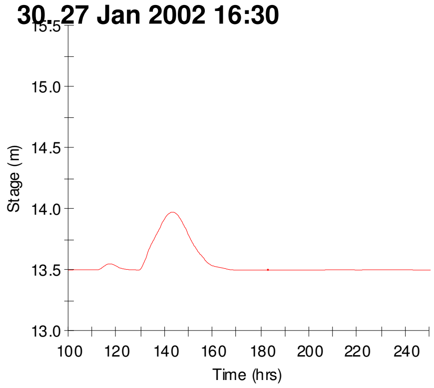
28. 23 Mar 2001 18:30



29. 09 Oct 2001 04:30



30. 27 Jan 2002 16:30



Key
Modelled
Observed

Branbridges Level

Data summary

38 peaks analysed at CS114 between 0.0m and 13.6m, for period 06 Nov 2000 to 01 Feb 2014 from :

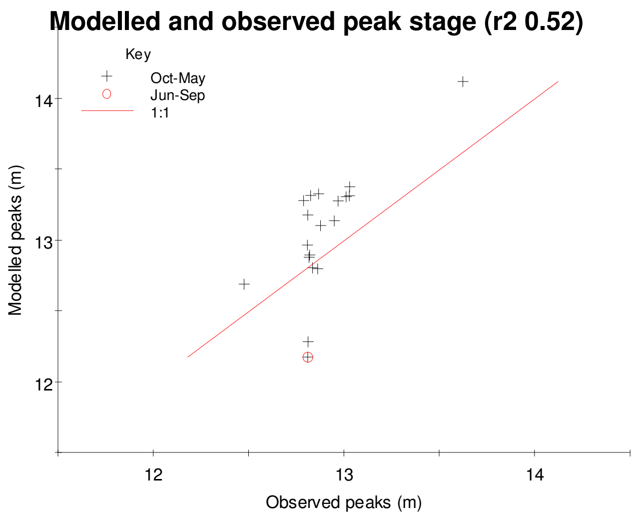
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade

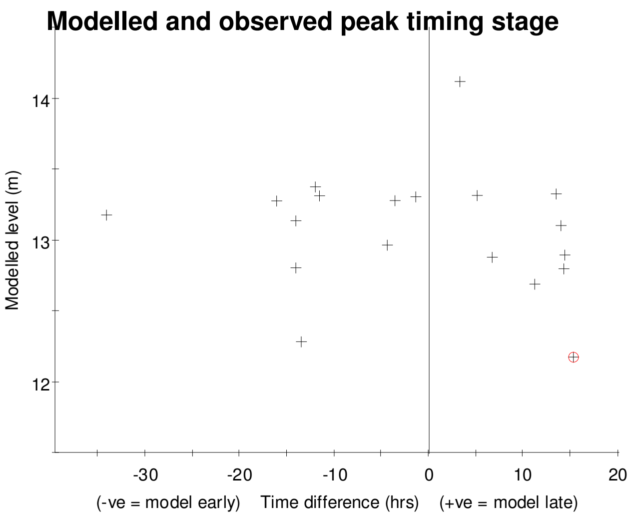
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m)	Mod. (m)	Diff. (m)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	13.62	14.12	0.50	4%	3.3	-3.17	0.713	0.55
2	02 Jan 2014 07:30	13.03	13.38	0.35	3%	-12.0	-57.6	0.169	0.48
3	17 Jan 2014 17:30	13.03	13.31	0.29	2%	-11.6	-0.57	0.231	0.56
4	10 Feb 2009 10:30	13.01	13.31	0.30	2%	-1.4	-174.	0.807	0.83
5	16 Jan 2008 01:30	12.97	13.28	0.31	2%	-16.1	0.693	0.741	0.29
6	23 Jan 2009 22:30	12.95	13.14	0.19	1%	-14.1	-463.	0.378	0.69
7	01 Mar 2010 04:30	12.87	13.10	0.23	2%	13.9	-2119	0.592	0.85
8	18 Jan 2011 13:30	12.86	13.33	0.46	4%	13.4	-6113	0.484	0.91
9	23 Feb 2010 06:30	12.86	12.80	-0.06	0%	14.3	-2711	0.668	0.81
10	17 Jan 2010 18:30	12.83	12.81	-0.02	0%	-14.1	-1.05	-999.	9.08

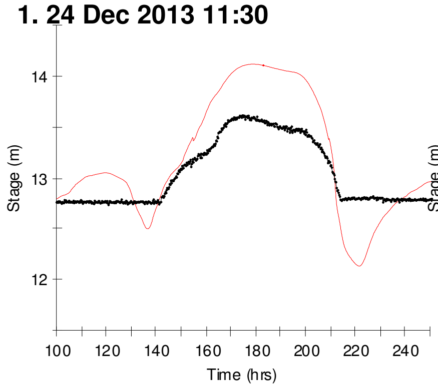
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	3.38	2.97	4.02	0.00	2.87	4.00	4.00	2.95

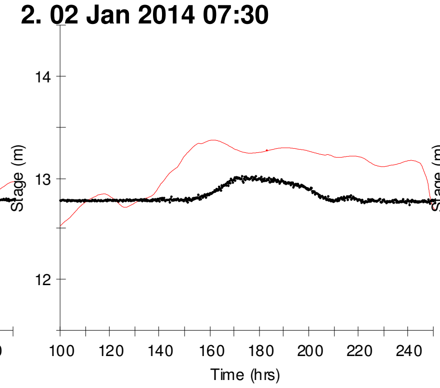




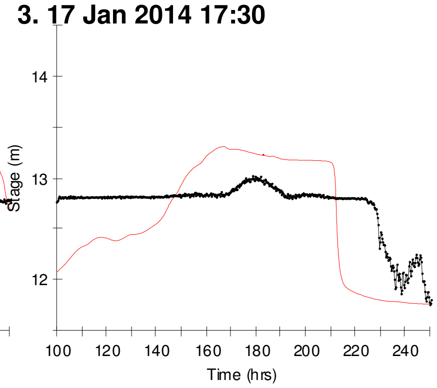
1. 24 Dec 2013 11:30



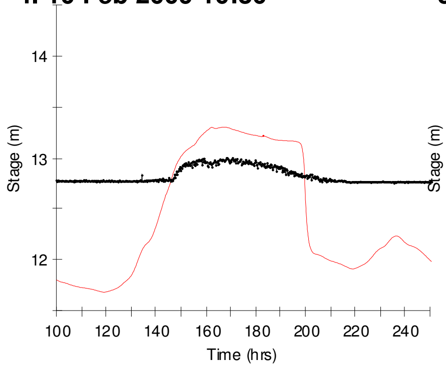
2. 02 Jan 2014 07:30



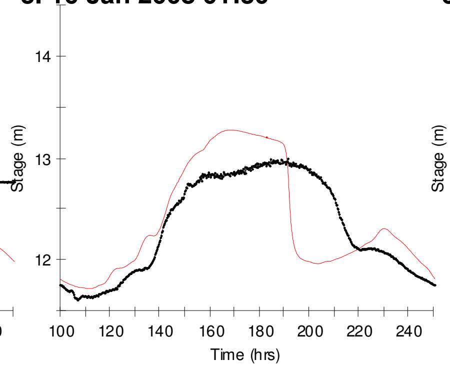
3. 17 Jan 2014 17:30



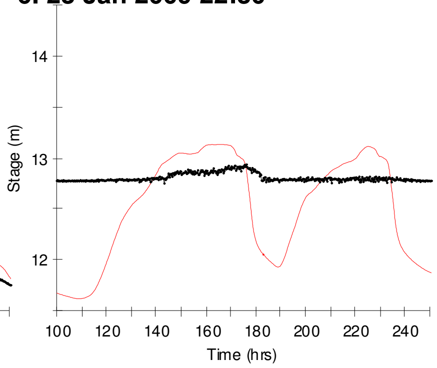
4. 10 Feb 2009 10:30



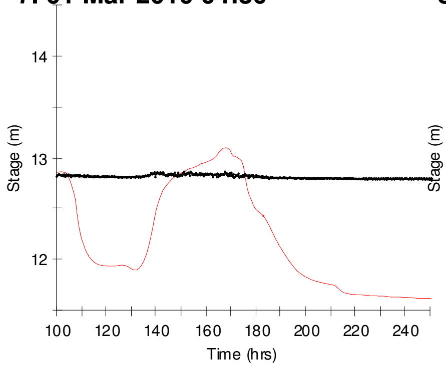
5. 16 Jan 2008 01:30



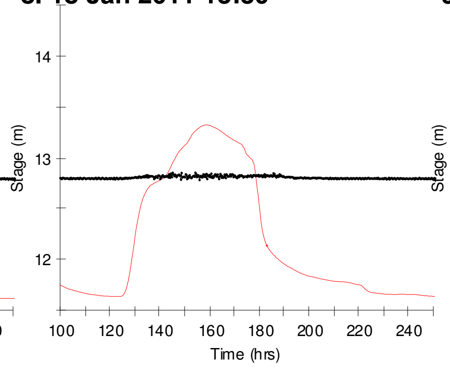
6. 23 Jan 2009 22:30



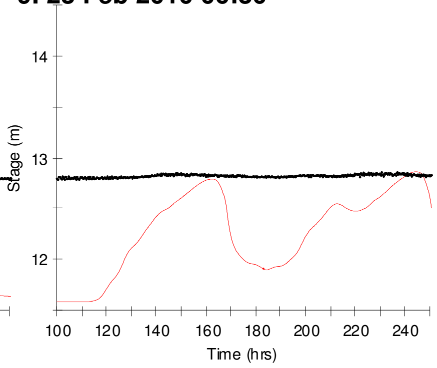
7. 01 Mar 2010 04:30



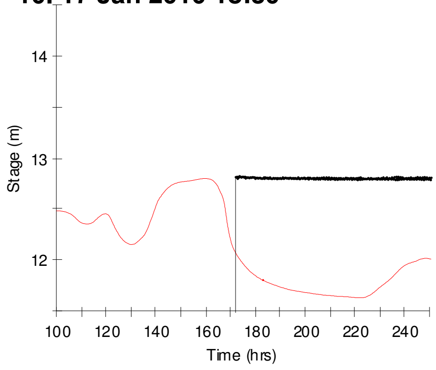
8. 18 Jan 2011 13:30



9. 23 Feb 2010 06:30

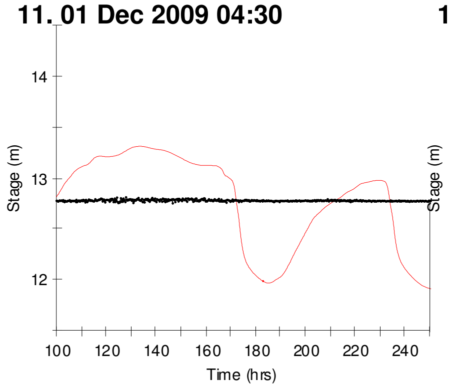


10. 17 Jan 2010 18:30

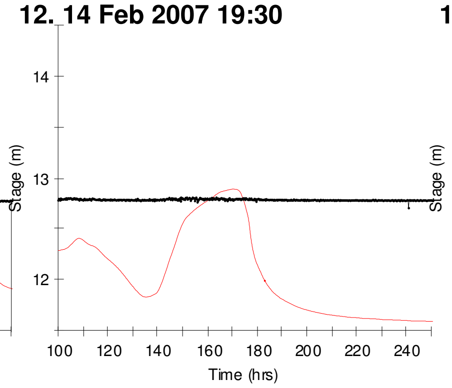


Key
Modelled
Observed

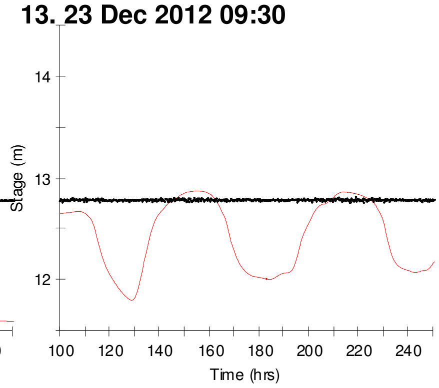
11. 01 Dec 2009 04:30



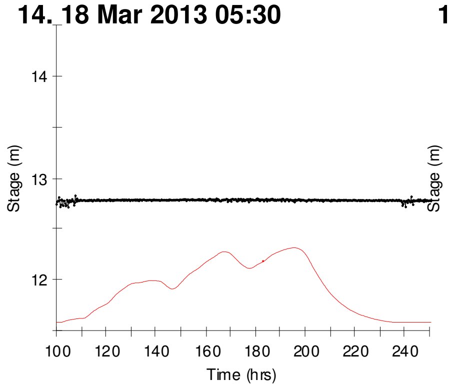
12. 14 Feb 2007 19:30



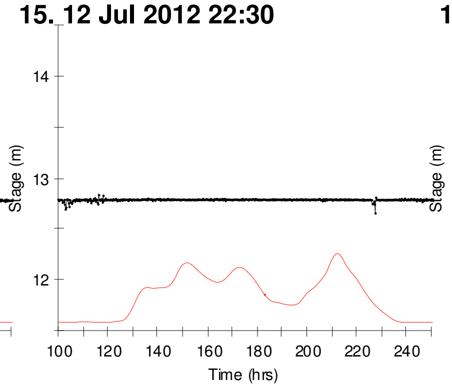
13. 23 Dec 2012 09:30



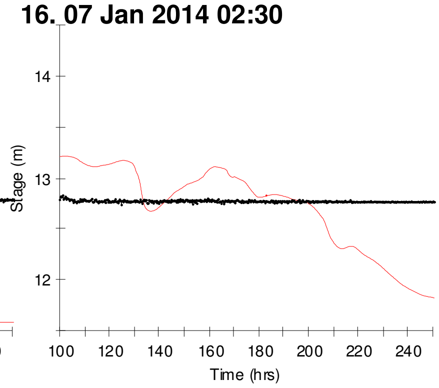
14. 18 Mar 2013 05:30



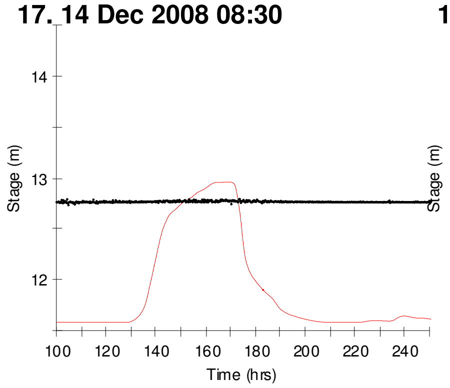
15. 12 Jul 2012 22:30



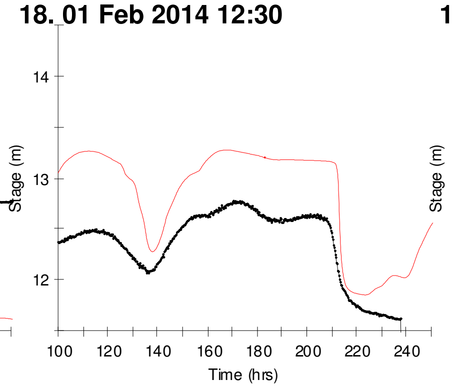
16. 07 Jan 2014 02:30



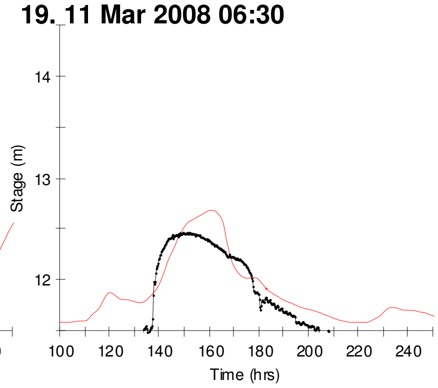
17. 14 Dec 2008 08:30



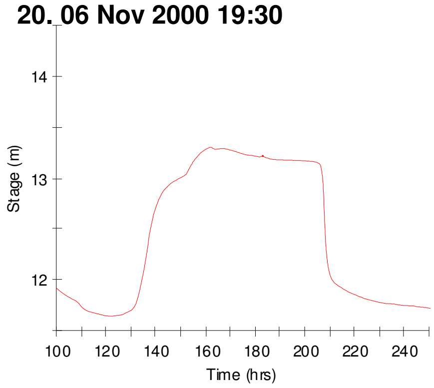
18. 01 Feb 2014 12:30



19. 11 Mar 2008 06:30



20. 06 Nov 2000 19:30



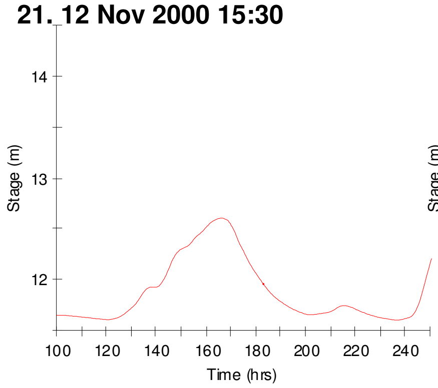
Key

Modelled

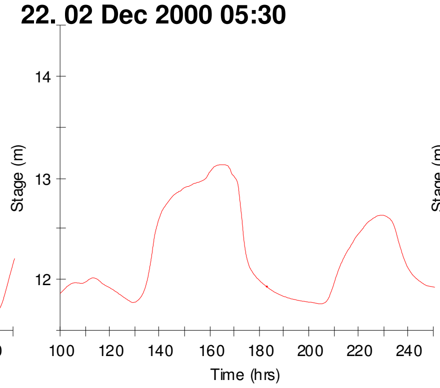
Observed

Branbridges Level

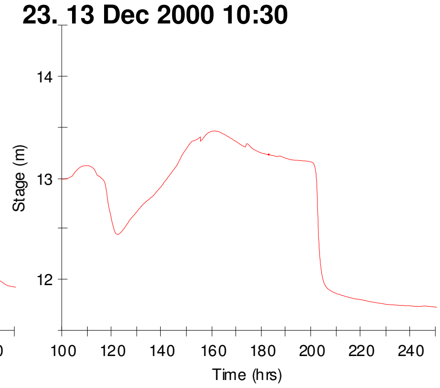
21. 12 Nov 2000 15:30



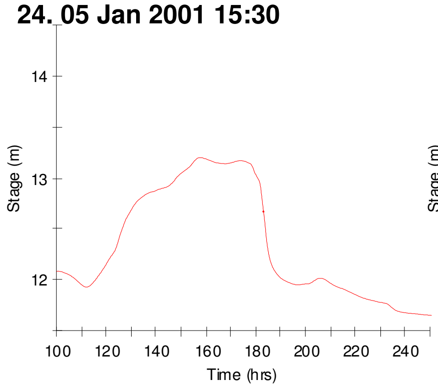
22. 02 Dec 2000 05:30



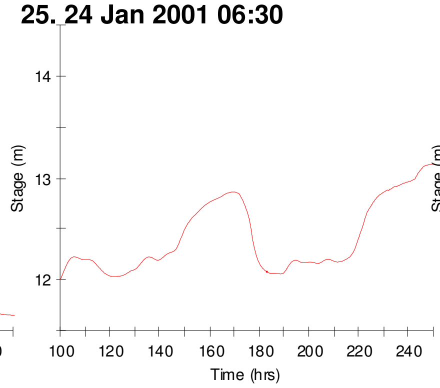
23. 13 Dec 2000 10:30



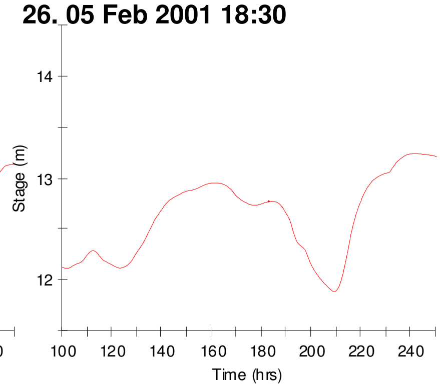
24. 05 Jan 2001 15:30



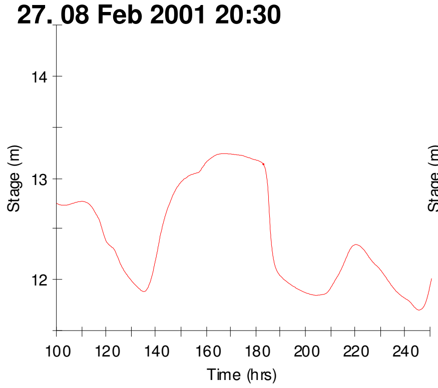
25. 24 Jan 2001 06:30



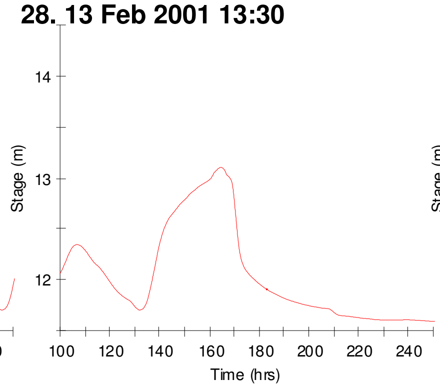
26. 05 Feb 2001 18:30



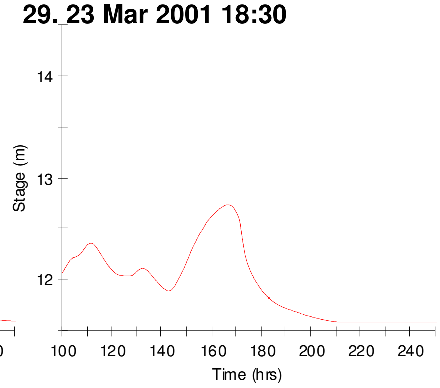
27. 08 Feb 2001 20:30



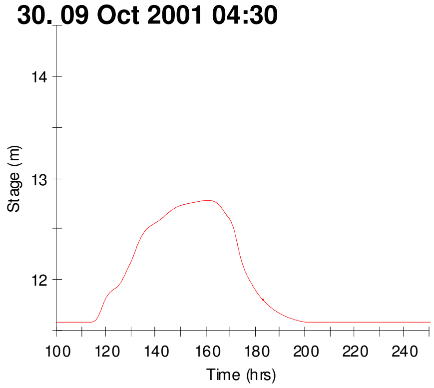
28. 13 Feb 2001 13:30



29. 23 Mar 2001 18:30



30. 09 Oct 2001 04:30



Key
Modelled
Observed

East Farleigh

Data summary

38 peaks analysed at CS189 between 47.6m3/s and 350.0m3/s, for period 06 Nov 2000 to 01 Feb 2014 from :

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N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade
```

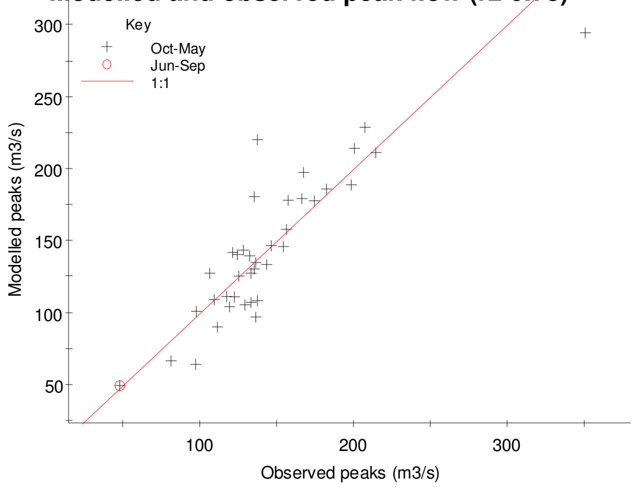
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	350.00	294.33	-55.7	-16%	-2.5	0.865	0.866	31.75
2	06 Nov 2000 19:30	214.00	211.53	-2.5	-1%	-4.5	0.280	0.471	54.88
3	13 Dec 2000 10:30	207.00	228.90	21.9	11%	-10.9	0.768	0.791	27.80
4	31 Dec 2002 04:30	200.00	214.26	14.3	7%	-0.1	0.926	0.942	14.71
5	08 Feb 2001 20:30	198.00	189.12	-8.9	-4%	0.0	0.830	0.862	18.29
6	10 Feb 2009 10:30	182.00	186.11	4.1	2%	-6.9	0.938	0.941	12.26
7	01 Feb 2014 12:30	174.00	177.93	3.9	2%	-7.8	0.228	0.388	52.44
8	02 Jan 2014 07:30	167.00	197.60	30.6	18%	-13.8	0.553	0.670	26.18
9	16 Jan 2008 01:30	166.00	179.43	13.4	8%	-6.3	0.886	0.887	15.99
10	05 Jan 2001 15:30	157.00	178.36	21.4	14%	5.4	0.913	0.922	13.44

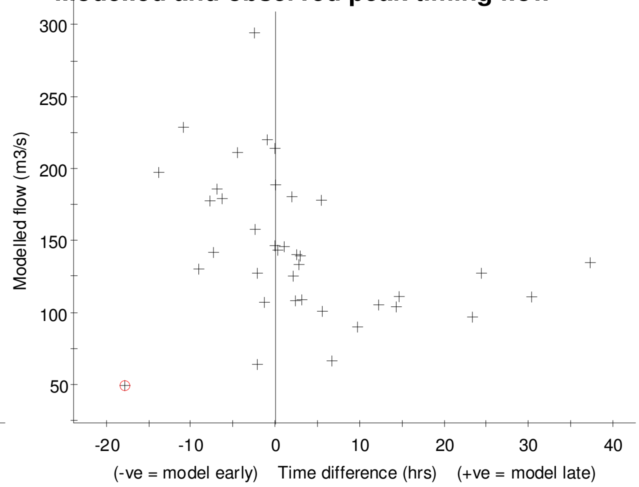
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.15	0.11	0.04	1.48	0.97	0.61	0.17	1.07

Modelled and observed peak flow (r2 0.78)

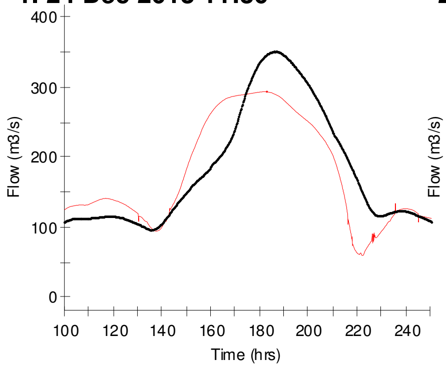


Modelled and observed peak timing flow

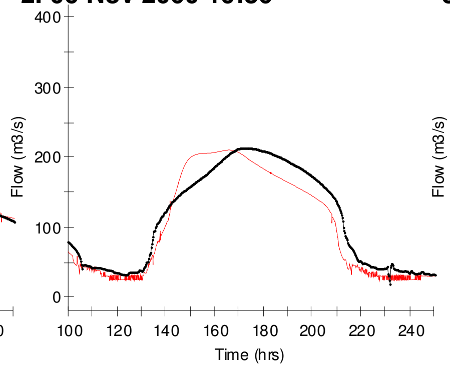


East Farleigh

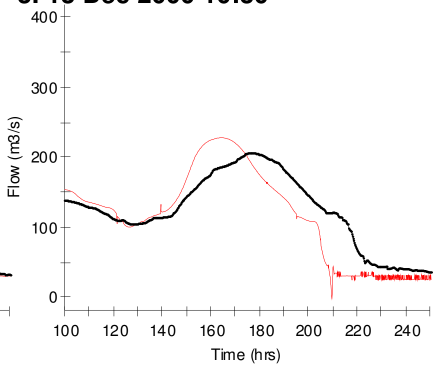
1. 24 Dec 2013 11:30



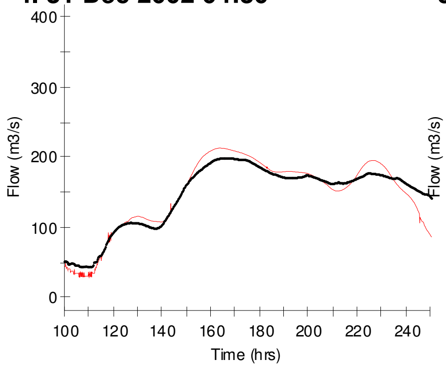
2. 06 Nov 2000 19:30



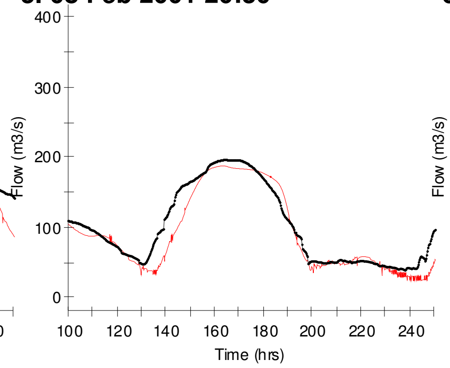
3. 13 Dec 2000 10:30



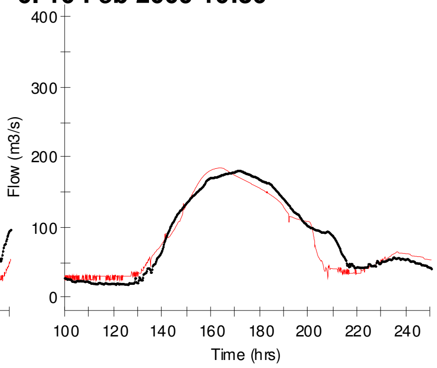
4. 31 Dec 2002 04:30



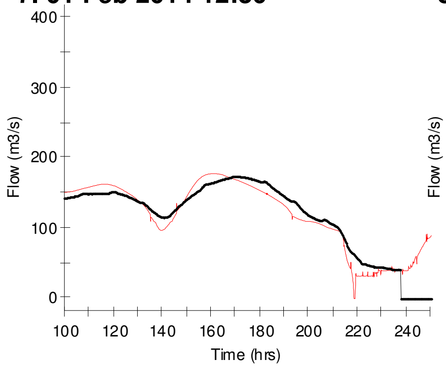
5. 08 Feb 2001 20:30



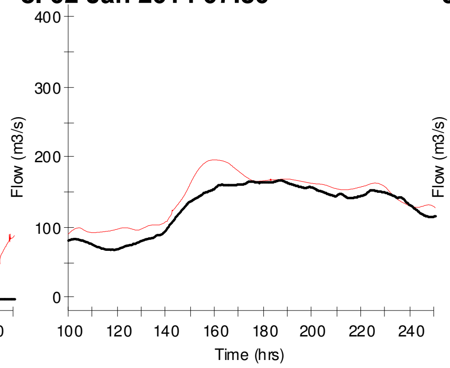
6. 10 Feb 2009 10:30



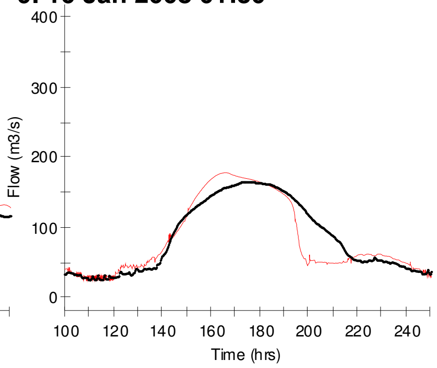
7. 01 Feb 2014 12:30



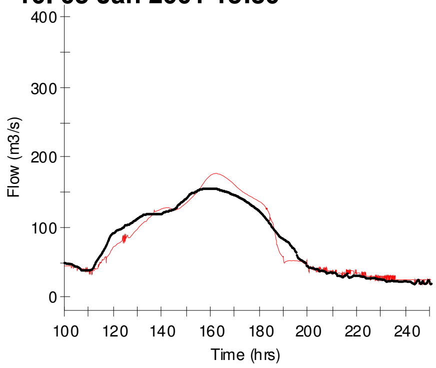
8. 02 Jan 2014 07:30



9. 16 Jan 2008 01:30

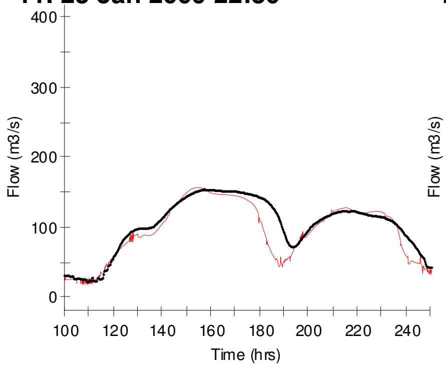


10. 05 Jan 2001 15:30

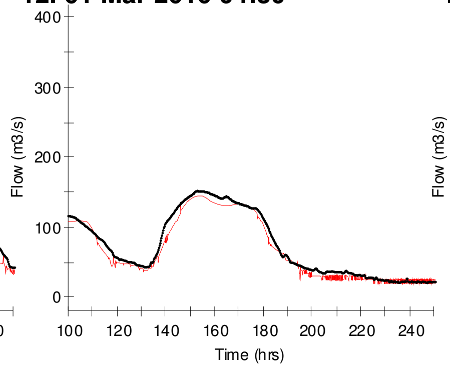


Key
Modelled
Observed

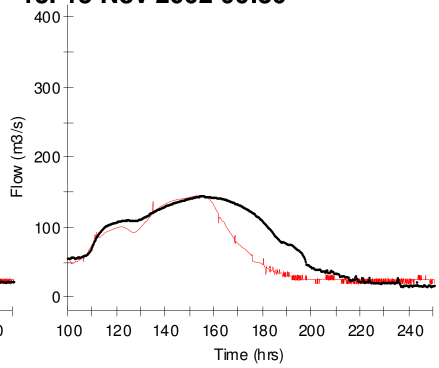
11. 23 Jan 2009 22:30



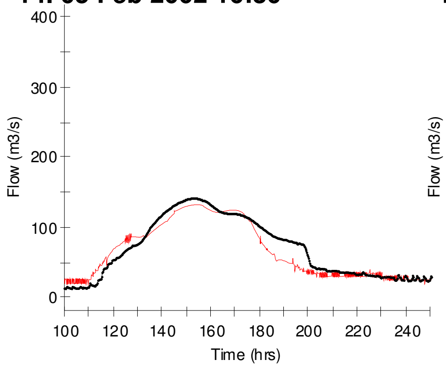
12. 01 Mar 2010 04:30



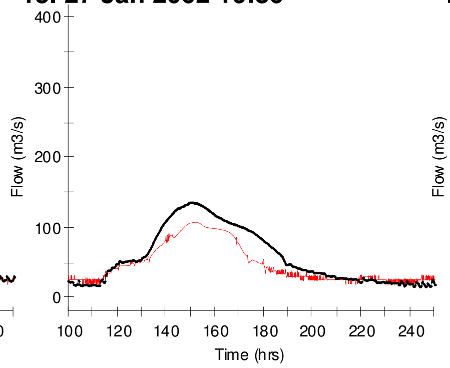
13. 15 Nov 2002 06:30



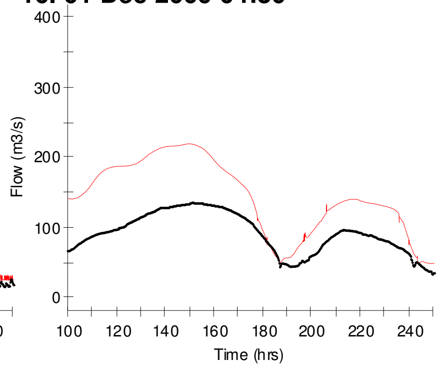
14. 05 Feb 2002 16:30



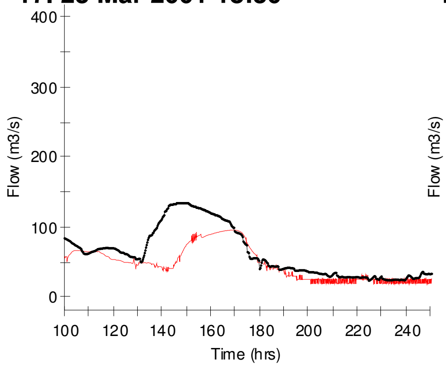
15. 27 Jan 2002 16:30



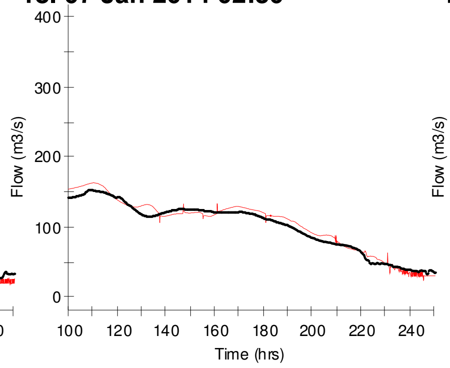
16. 01 Dec 2009 04:30



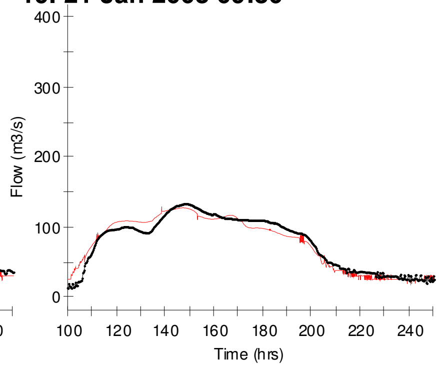
17. 23 Mar 2001 18:30



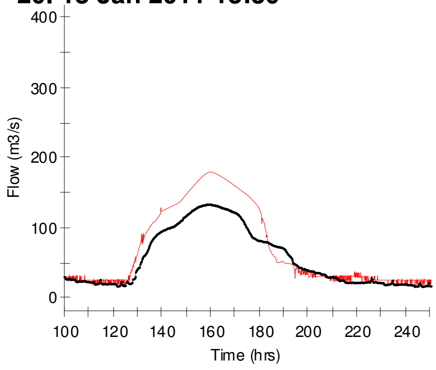
18. 07 Jan 2014 02:30



19. 21 Jan 2003 09:30



20. 18 Jan 2011 13:30

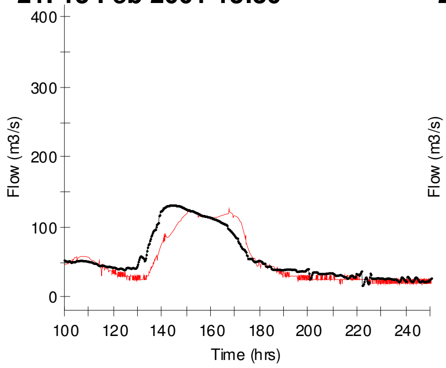


Key

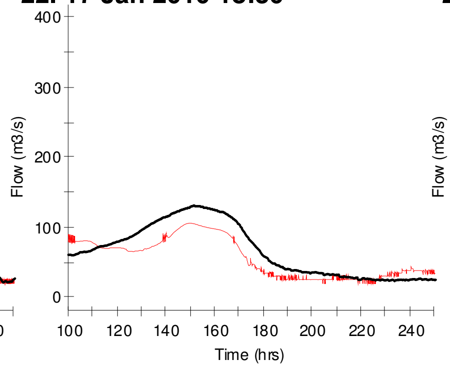
Modelled

Observed

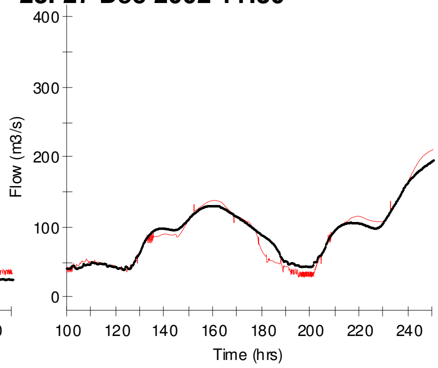
21. 13 Feb 2001 13:30



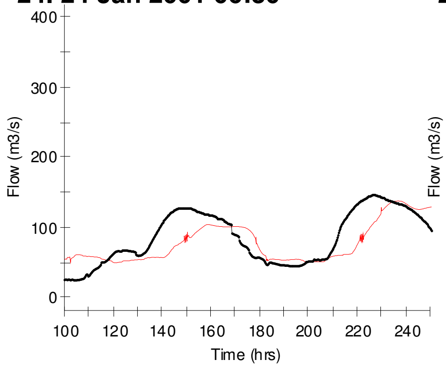
22. 17 Jan 2010 18:30



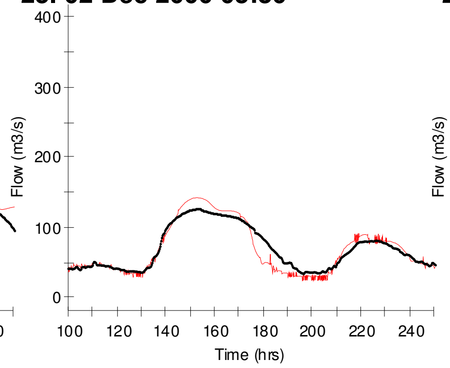
23. 27 Dec 2002 11:30



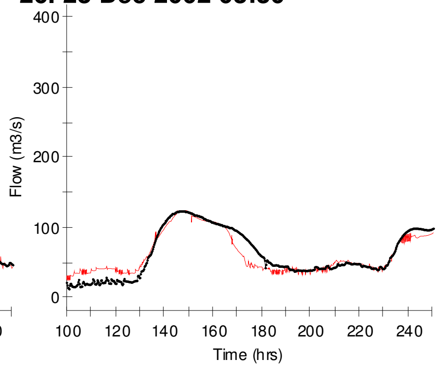
24. 24 Jan 2001 06:30



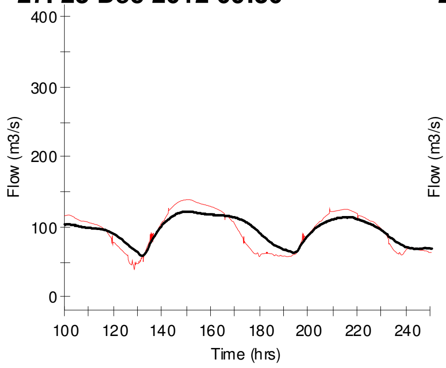
25. 02 Dec 2000 05:30



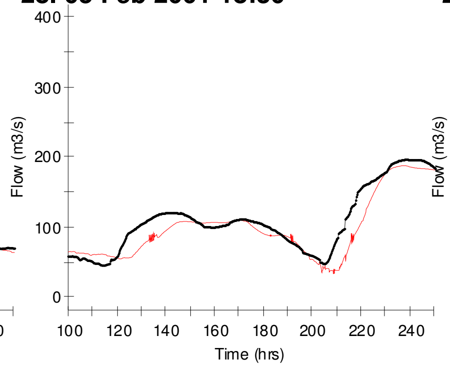
26. 23 Dec 2002 03:30



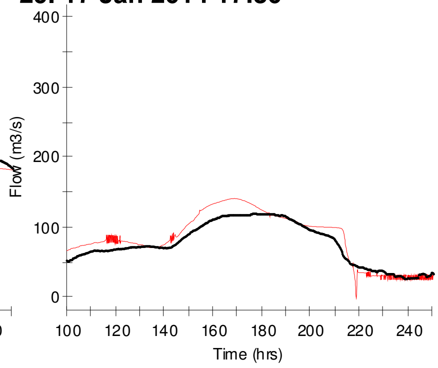
27. 23 Dec 2012 09:30



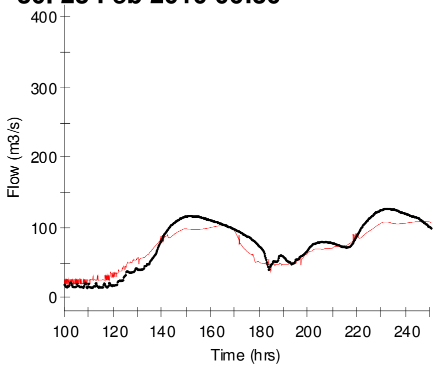
28. 05 Feb 2001 18:30



29. 17 Jan 2014 17:30



30. 23 Feb 2010 06:30



Key
Modelled
Observed

East Farleigh Gate Level

Data summary

38 peaks analysed at CS189 between 5.4m and 8.0m, for period 06 Nov 2000 to 01 Feb 2014 from :

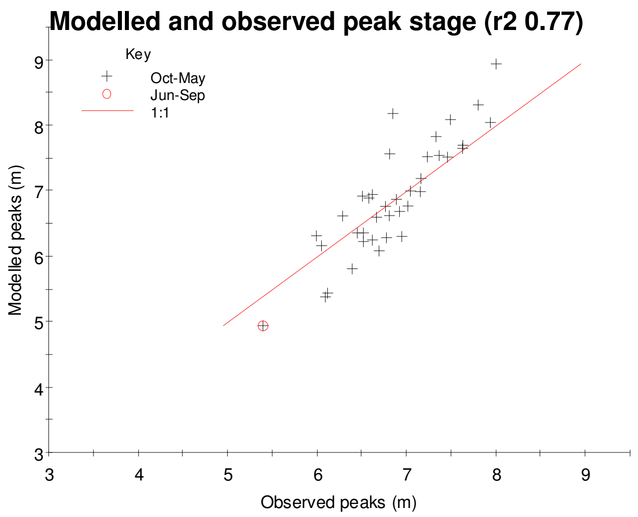
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade

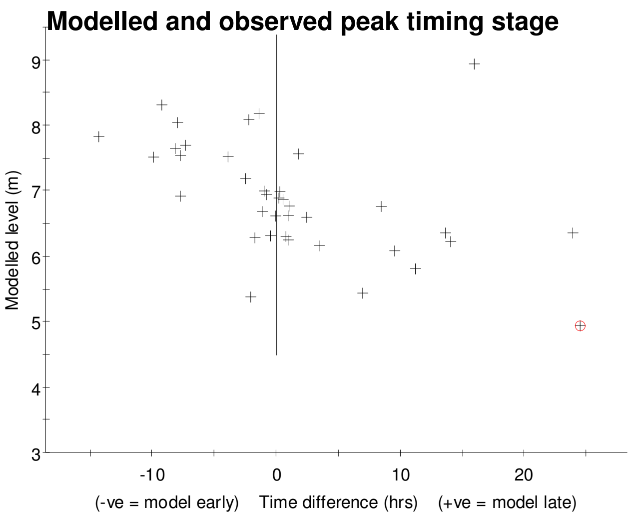
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m)	Mod. (m)	Diff. (m)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	8.00	8.94	0.94	12%	15.9	0.655	0.879	0.57
2	06 Nov 2000 19:30	7.93	8.05	0.12	1%	-8.0	-0.12	0.442	1.10
3	13 Dec 2000 10:30	7.79	8.31	0.52	7%	-9.3	0.477	0.857	0.59
4	08 Feb 2001 20:30	7.62	7.70	0.08	1%	-7.3	0.880	0.925	0.27
5	10 Feb 2009 10:30	7.62	7.65	0.03	0%	-8.2	0.301	0.900	0.61
6	31 Dec 2002 04:30	7.48	8.09	0.61	8%	-2.3	0.608	0.905	0.51
7	01 Feb 2014 12:30	7.45	7.52	0.07	1%	-9.9	-0.22	0.033	2.96
8	16 Jan 2008 01:30	7.36	7.55	0.19	3%	-7.8	0.136	0.850	0.63
9	02 Jan 2014 07:30	7.32	7.83	0.51	7%	-14.3	0.295	0.627	0.56
10	05 Jan 2001 15:30	7.23	7.53	0.30	4%	-3.9	0.493	0.888	0.48

Model scores

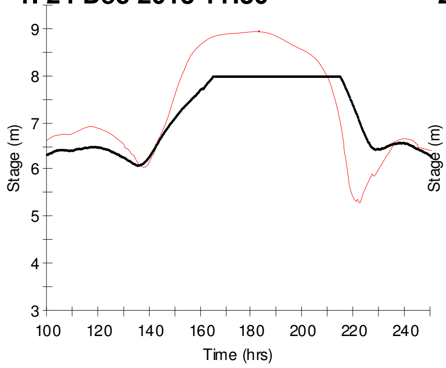
	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.22	0.36	0.31	1.87	0.59	0.28	4.00	1.72



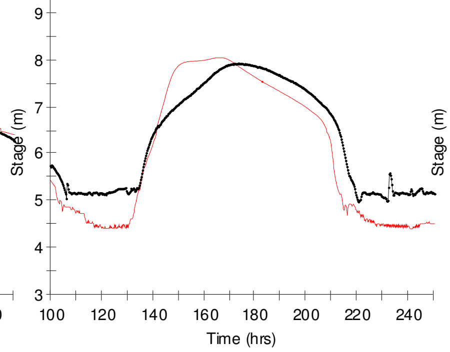


East Farleigh Gate Level

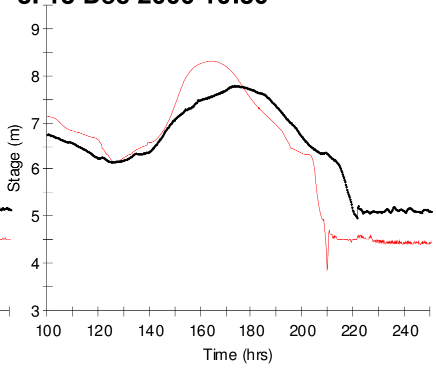
1. 24 Dec 2013 11:30



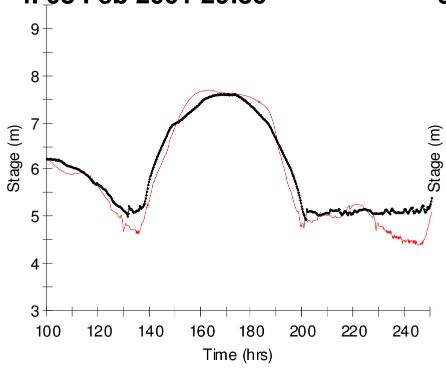
2. 06 Nov 2000 19:30



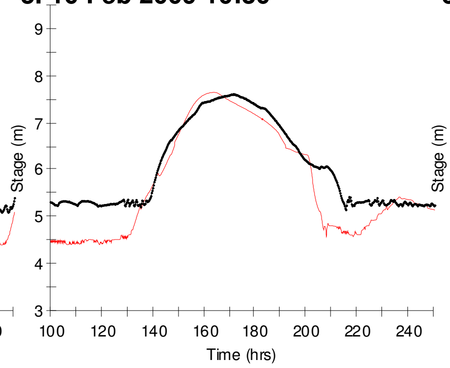
3. 13 Dec 2000 10:30



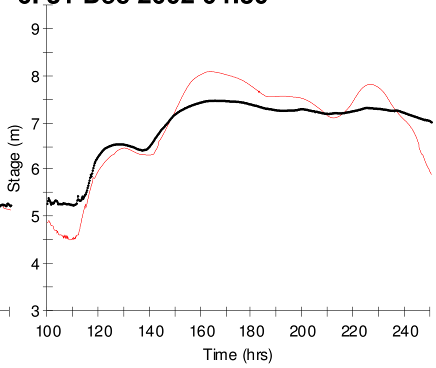
4. 08 Feb 2001 20:30



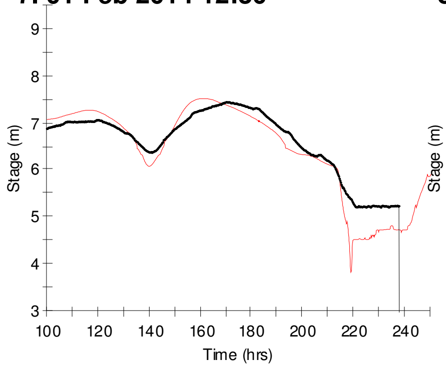
5. 10 Feb 2009 10:30



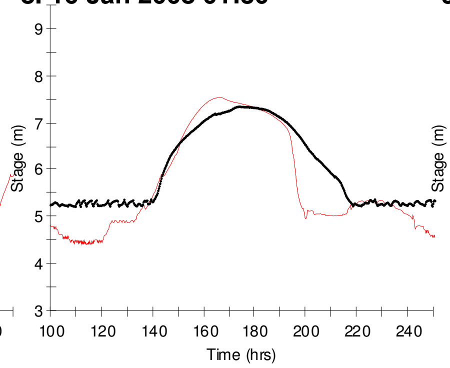
6. 31 Dec 2002 04:30



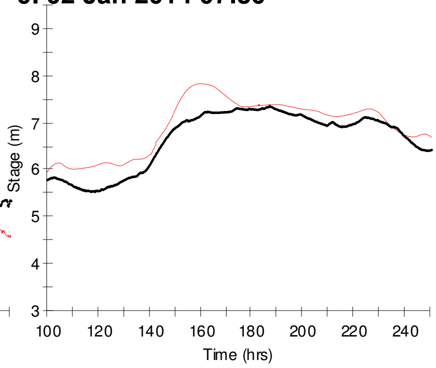
7. 01 Feb 2014 12:30



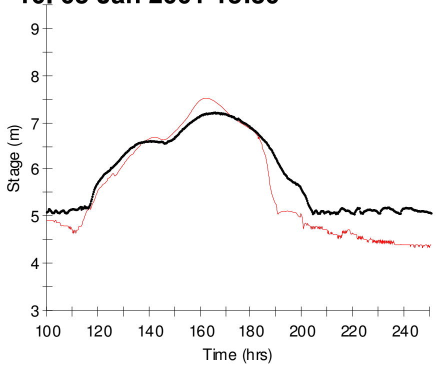
8. 16 Jan 2008 01:30



9. 02 Jan 2014 07:30



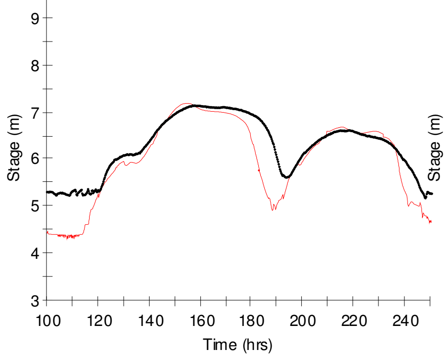
10. 05 Jan 2001 15:30



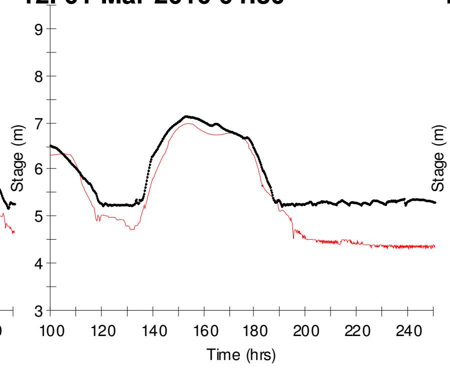
Key
Modelled
Observed

East Farleigh Gate Level

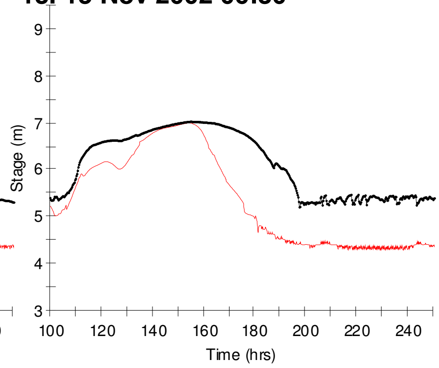
11. 23 Jan 2009 22:30



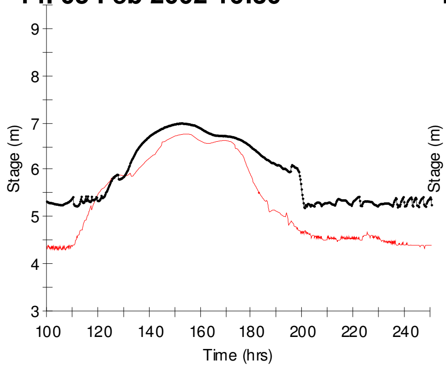
12. 01 Mar 2010 04:30



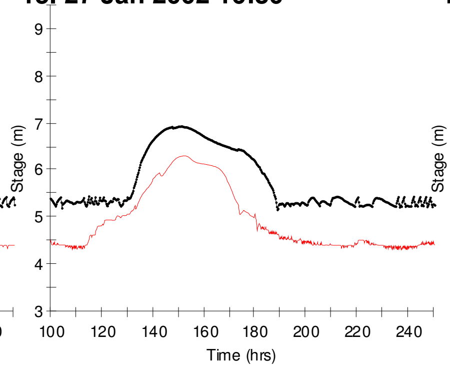
13. 15 Nov 2002 06:30



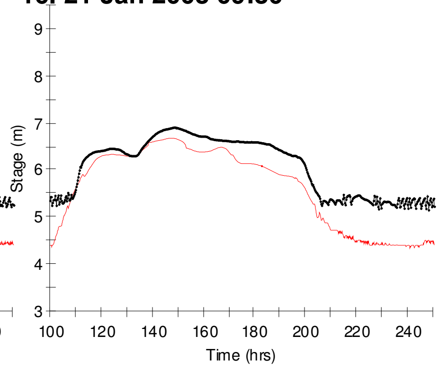
14. 05 Feb 2002 16:30



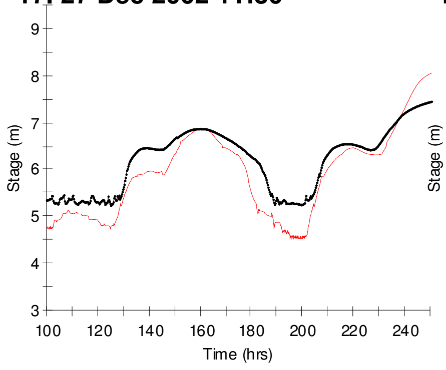
15. 27 Jan 2002 16:30



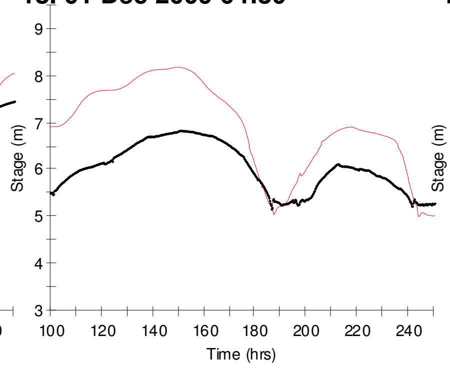
16. 21 Jan 2003 09:30



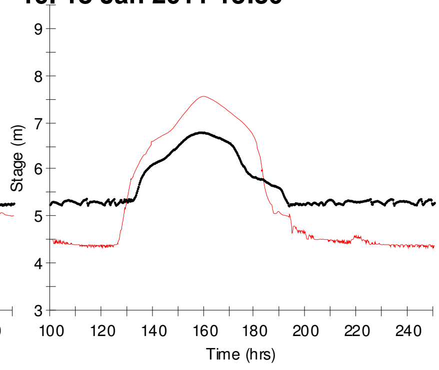
17. 27 Dec 2002 11:30



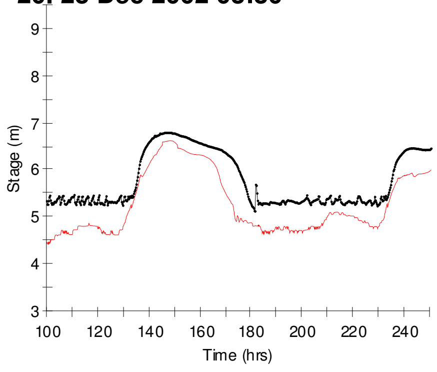
18. 01 Dec 2009 04:30



19. 18 Jan 2011 13:30

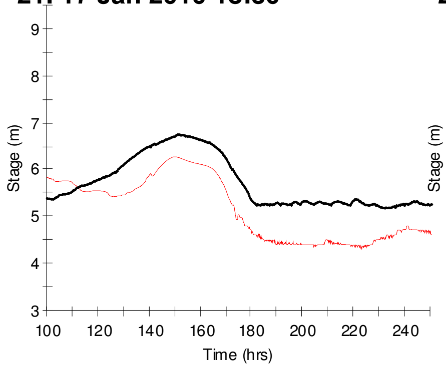


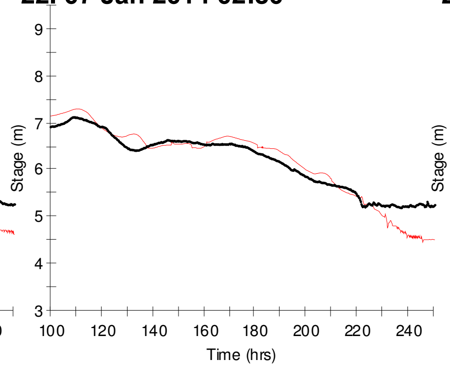
20. 23 Dec 2002 03:30

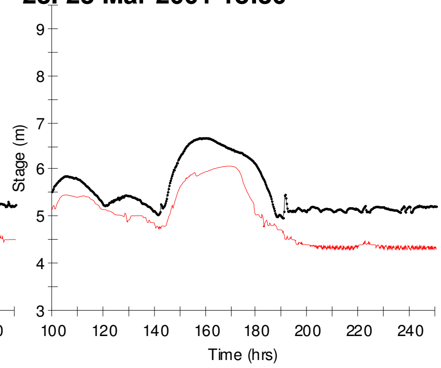


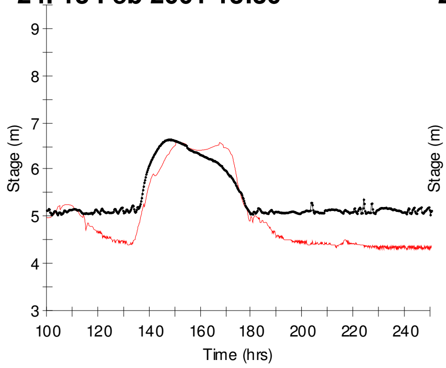
Key
Modelled
Observed

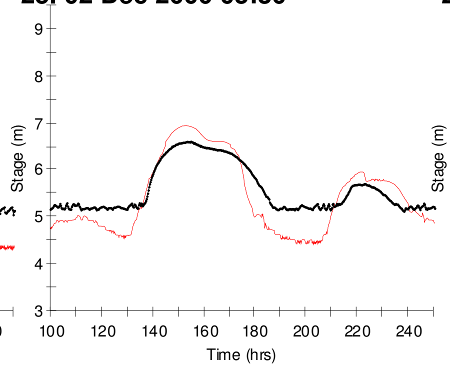
East Farleigh Gate Level

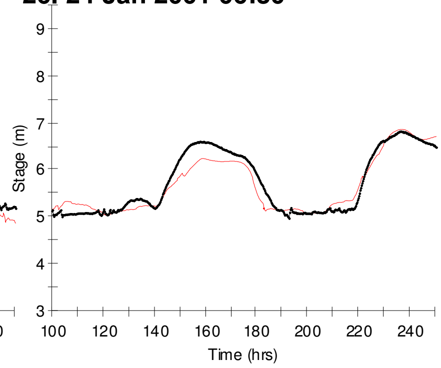
21. 17 Jan 2010 18:30


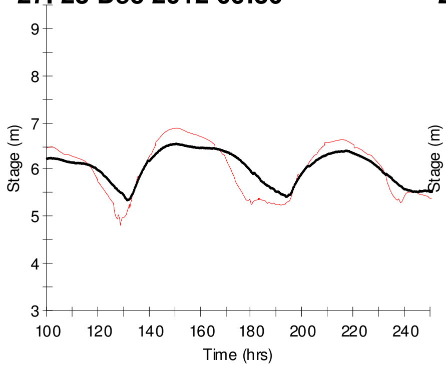
22. 07 Jan 2014 02:30


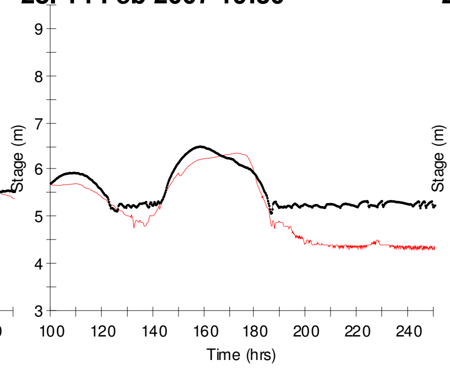
23. 23 Mar 2001 18:30


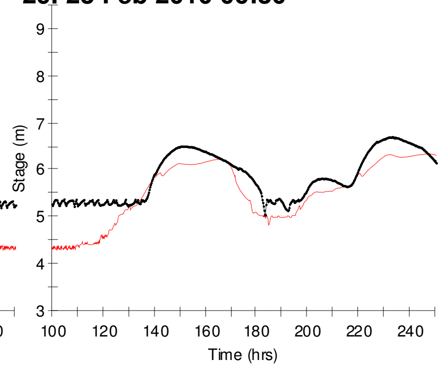
24. 13 Feb 2001 13:30


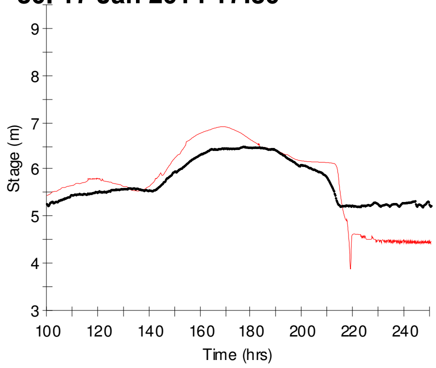
25. 02 Dec 2000 05:30


26. 24 Jan 2001 06:30


27. 23 Dec 2012 09:30


28. 14 Feb 2007 19:30


29. 23 Feb 2010 06:30


30. 17 Jan 2014 17:30


Key
Modelled
Observed

Leigh FSA downstream

Data summary

47 peaks analysed at CS10 between 0.0m and 23.9m, for period 01 Nov 1998 to 01 Feb 2014 from :

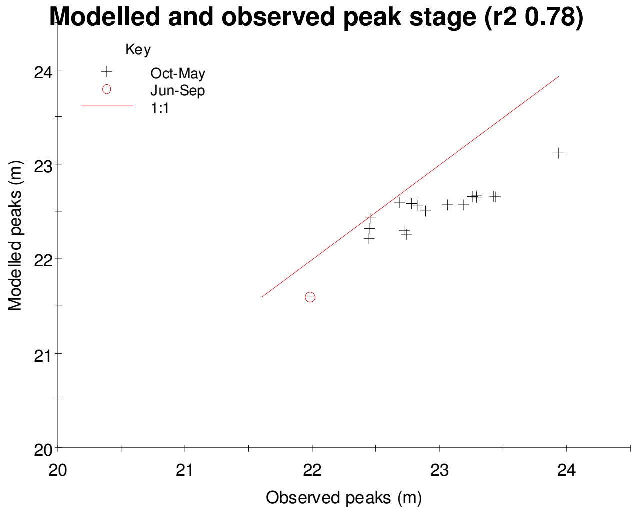
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\04 LeighBarrier\09 Cascade

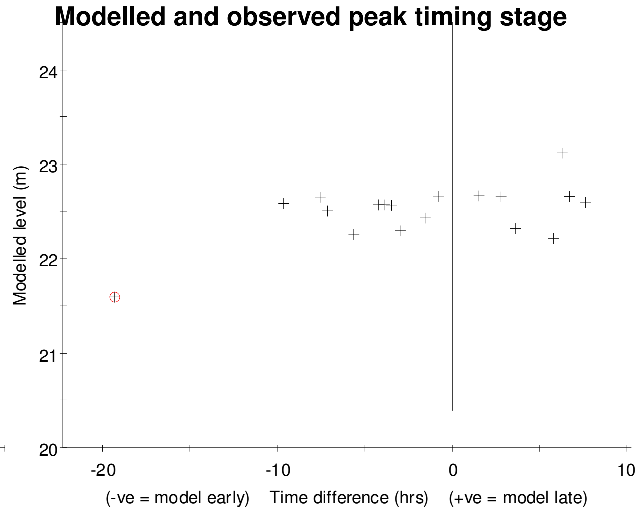
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m)	Mod. (m)	Diff. (m)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	23.93	23.12	-0.81	-3%	6.3	0.283	0.750	0.60
2	02 Jan 2014 07:30	23.43	22.66	-0.77	-3%	2.8	-0.03	0.566	0.49
3	17 Jan 2014 17:30	23.42	22.67	-0.75	-3%	-0.8	0.596	0.711	0.37
4	01 Feb 2014 12:30	23.29	22.67	-0.62	-3%	1.5	-0.28	-999.	10.51
5	16 Jan 2008 01:30	23.28	22.66	-0.63	-3%	-7.6	0.271	0.560	0.59
6	10 Feb 2009 10:30	23.25	22.66	-0.59	-3%	6.7	0.528	0.631	0.46
7	23 Jan 2009 22:30	23.18	22.58	-0.60	-3%	-4.3	0.265	0.667	0.52
8	18 Jan 2011 13:30	23.06	22.58	-0.48	-2%	-3.9	0.147	0.514	0.43
9	14 Dec 2008 08:30	22.89	22.51	-0.37	-2%	-7.2	-0.68	0.618	0.63
10	07 Jan 2014 02:30	22.83	22.57	-0.25	-1%	-3.5	0.500	0.755	0.42

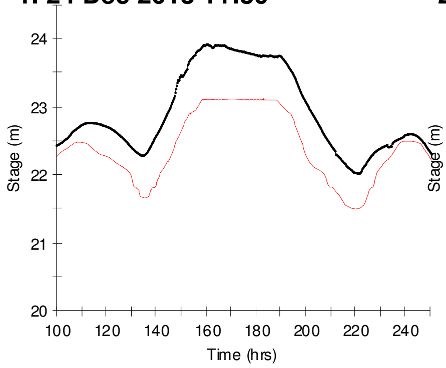
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.16	3.19	4.03	0.00	3.20	4.00	2.02	2.34

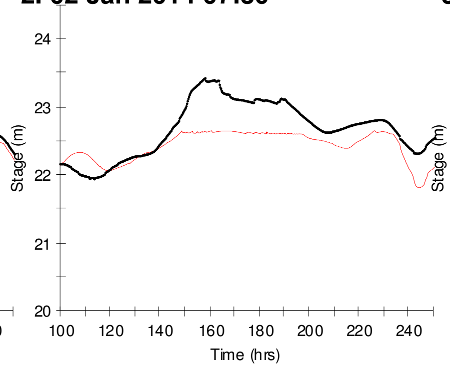




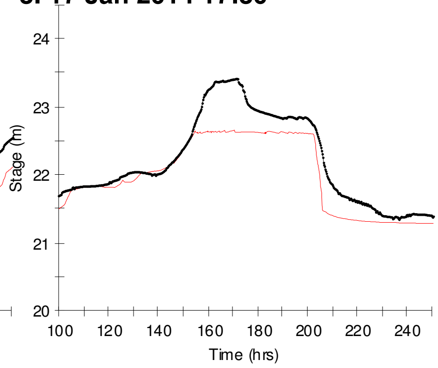
1. 24 Dec 2013 11:30



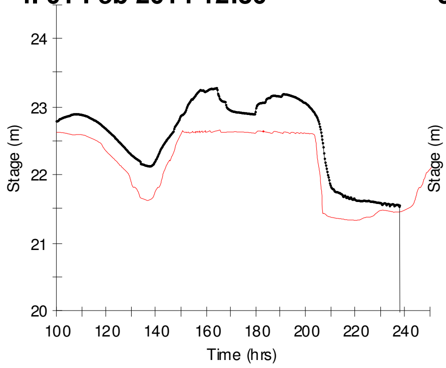
2. 02 Jan 2014 07:30



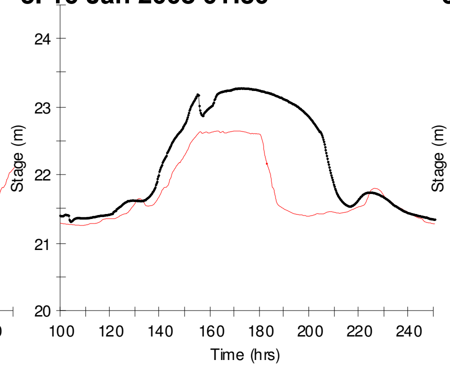
3. 17 Jan 2014 17:30



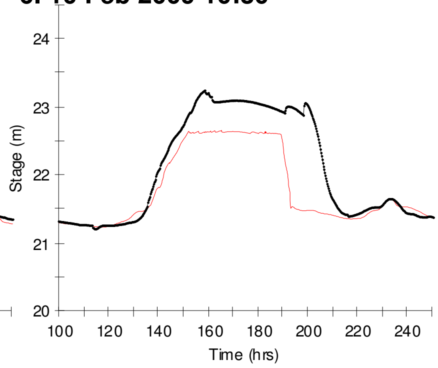
4. 01 Feb 2014 12:30



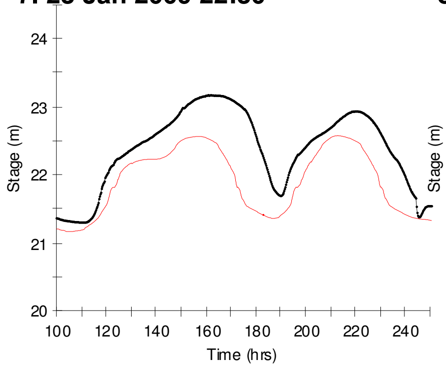
5. 16 Jan 2008 01:30



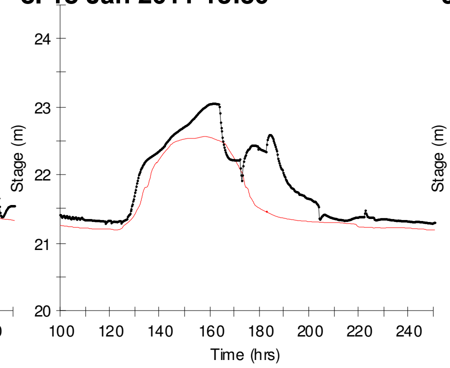
6. 10 Feb 2009 10:30



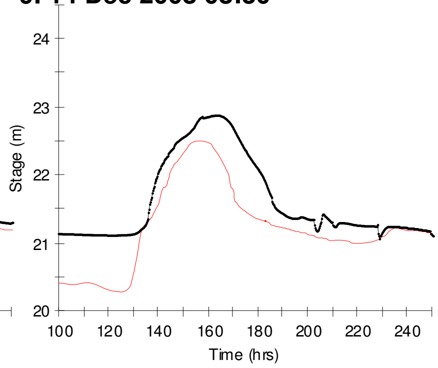
7. 23 Jan 2009 22:30



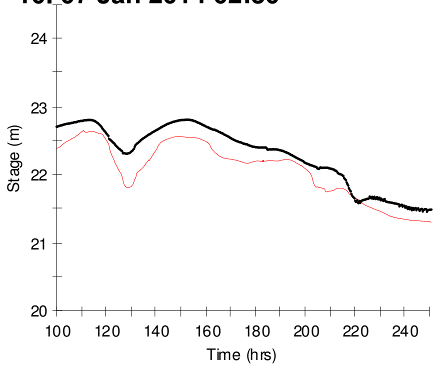
8. 18 Jan 2011 13:30



9. 14 Dec 2008 08:30



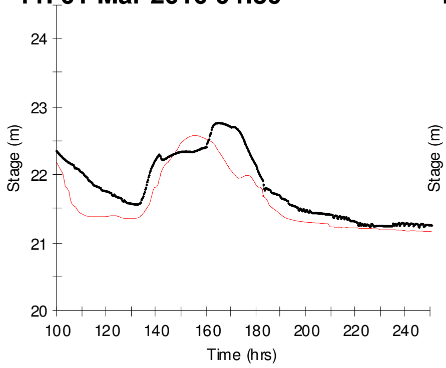
10. 07 Jan 2014 02:30



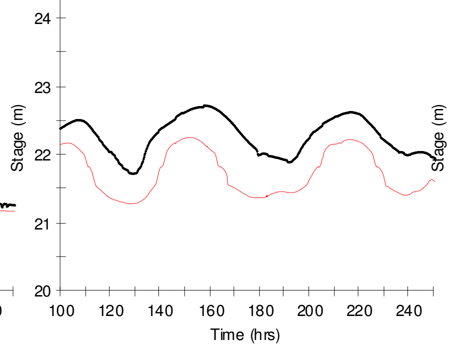
Key
Modelled
Observed

JBA consulting

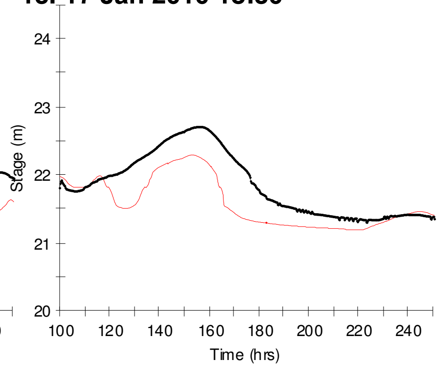
11. 01 Mar 2010 04:30



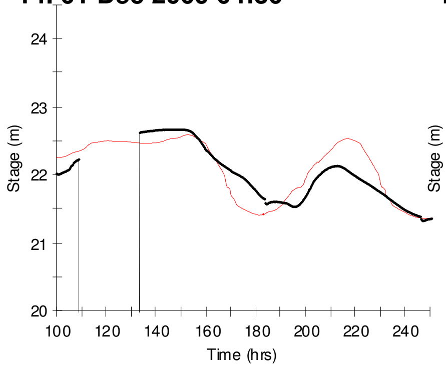
12. 23 Dec 2012 09:30



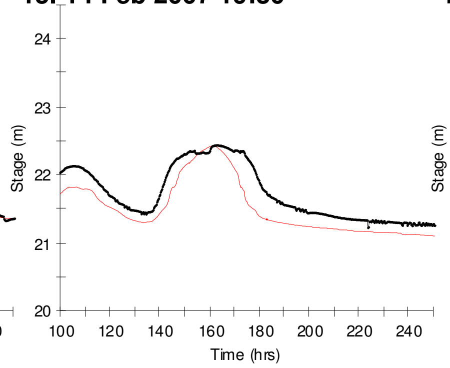
13. 17 Jan 2010 18:30



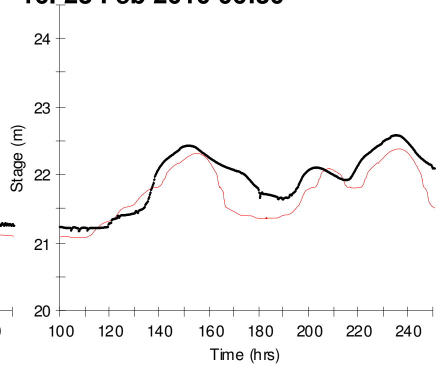
14. 01 Dec 2009 04:30



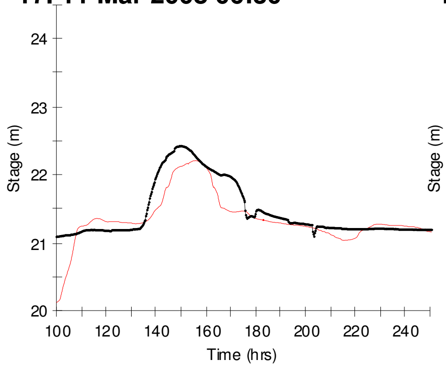
15. 14 Feb 2007 19:30



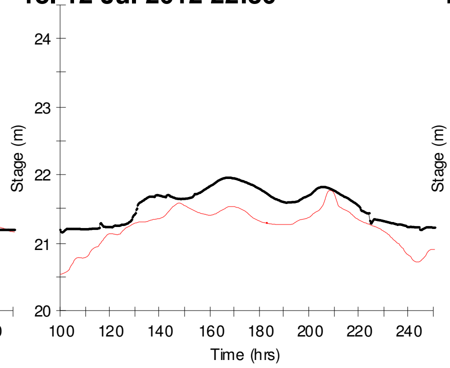
16. 23 Feb 2010 06:30



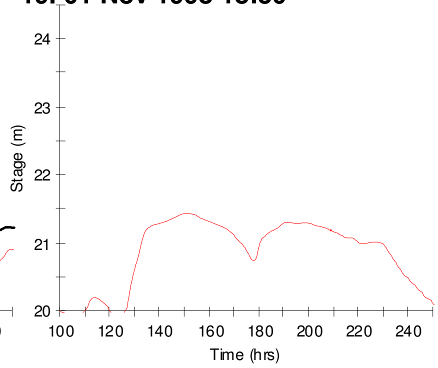
17. 11 Mar 2008 06:30



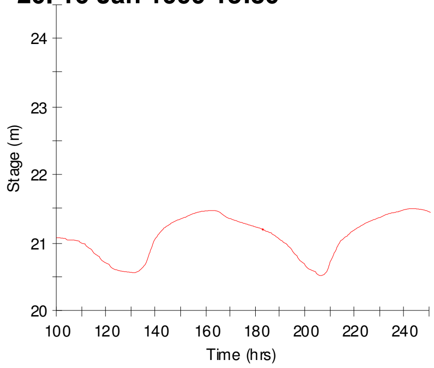
18. 12 Jul 2012 22:30



19. 01 Nov 1998 18:30

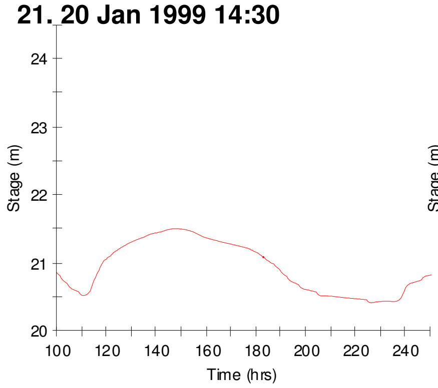


20. 16 Jan 1999 15:30

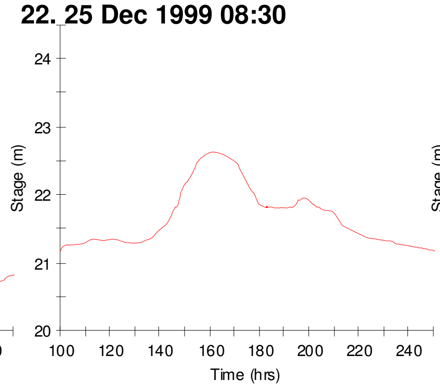


Key
Modelled
Observed

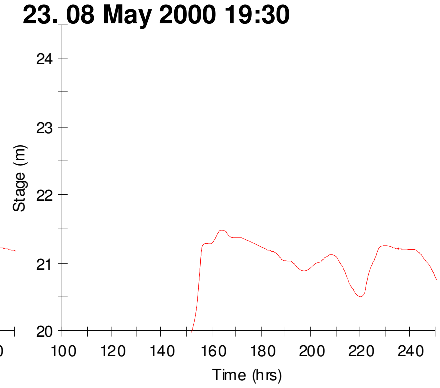
21. 20 Jan 1999 14:30



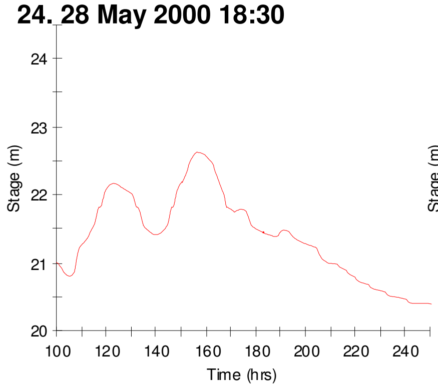
22. 25 Dec 1999 08:30



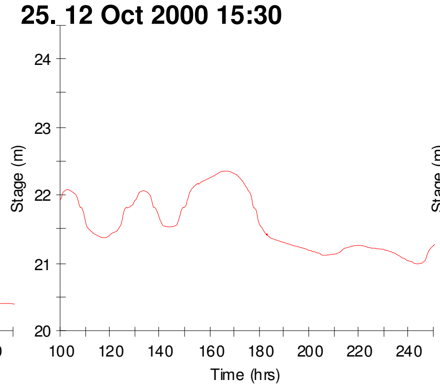
23. 08 May 2000 19:30



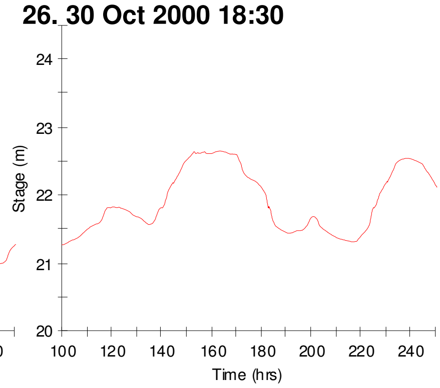
24. 28 May 2000 18:30



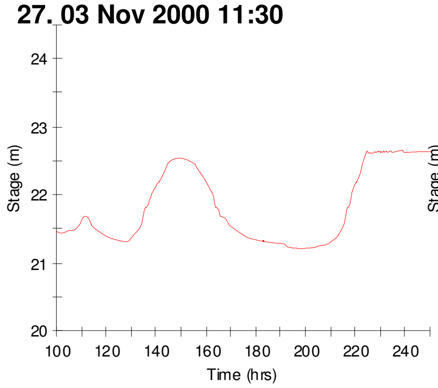
25. 12 Oct 2000 15:30



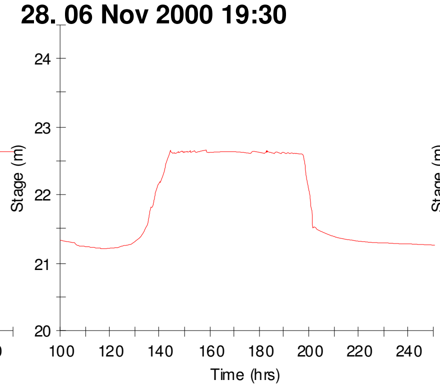
26. 30 Oct 2000 18:30



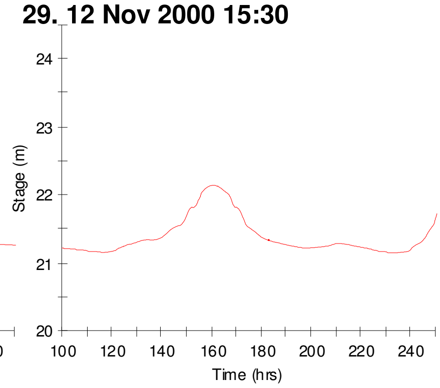
27. 03 Nov 2000 11:30



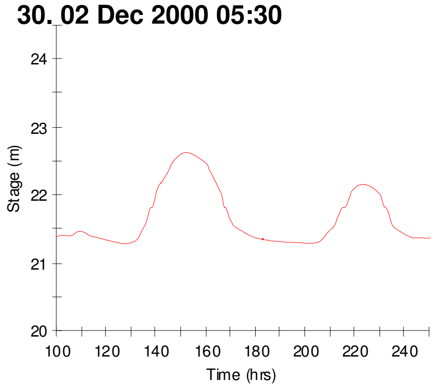
28. 06 Nov 2000 19:30



29. 12 Nov 2000 15:30



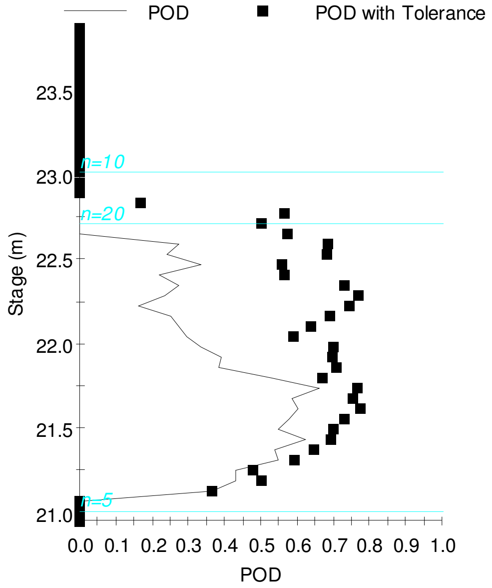
30. 02 Dec 2000 05:30

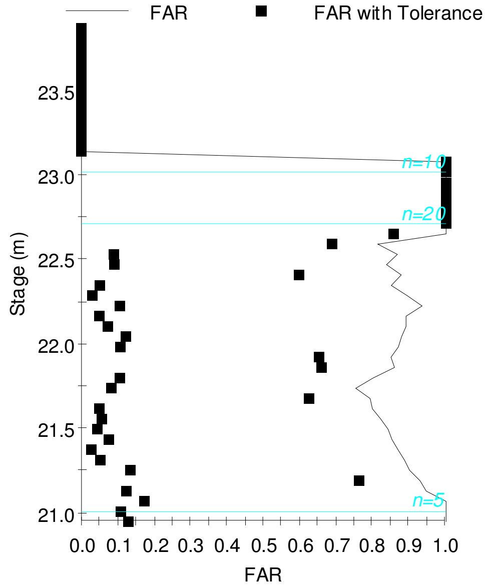


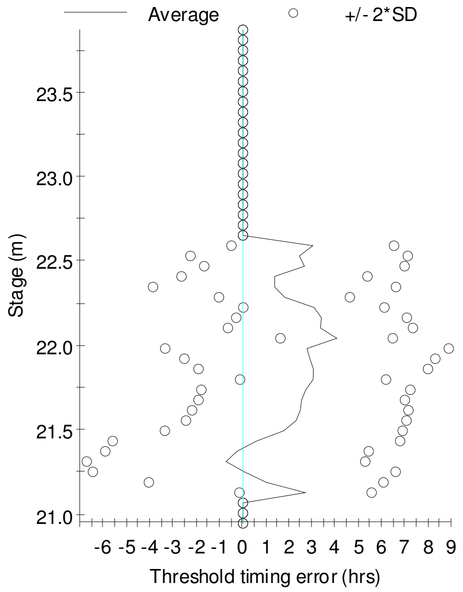
Key
Modelled
Observed

Leigh FSA downstream

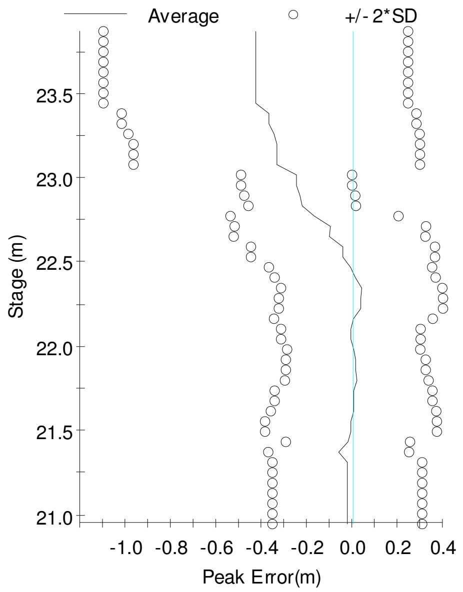
POD, FAR and peak matching statistics over full range of observations

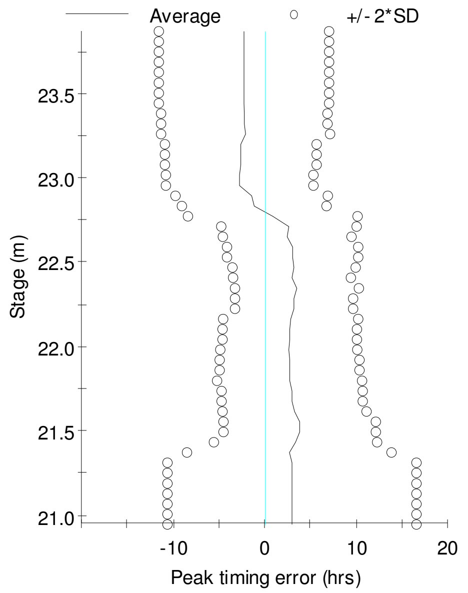






Notes: Moving average of 20 peaks used in peak calculation. Tolerance of 0.2 used in POD and FAR. Threshold crossing window is 5 to 5 hrs





Leigh FSA Outflow (Cascaded)

Data summary

38 peaks analysed at OutflowLB between 0.0m3/s and 161.1m3/s, for period 06 Nov 2000 to 01 Feb 2014 from :

N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade

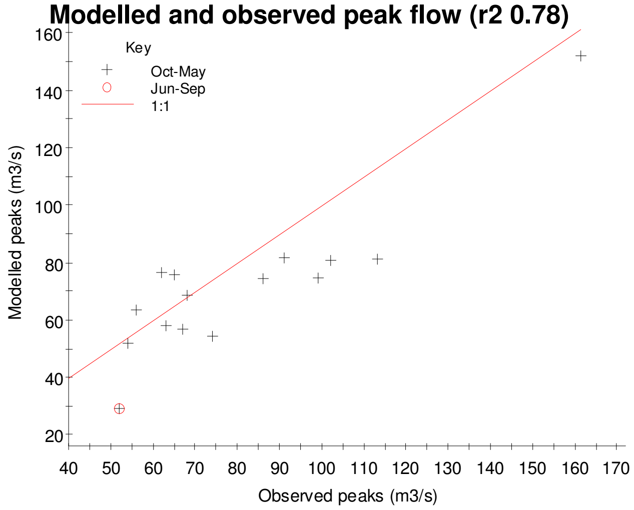
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	161.14	152.03	-9.1	-6%	7.8	0.251	0.831	37.55
2	10 Feb 2009 10:30	113.00	81.41	-31.6	-28%	8.3	0.802	0.820	12.65
3	16 Jan 2008 01:30	102.00	81.03	-21.0	-21%	3.8	0.464	0.589	19.31
4	23 Jan 2009 22:30	99.00	74.90	-24.1	-24%	-3.3	0.700	0.748	13.31
5	01 Feb 2014 12:30	91.00	81.90	-9.1	-10%	8.3	-0.05	0.238	29.86
6	18 Jan 2011 13:30	86.00	74.65	-11.4	-13%	-1.0	0.734	0.737	10.01
7	23 Dec 2012 09:30	74.00	54.70	-19.3	-26%	-13.0	0.314	0.751	16.42
8	14 Dec 2008 08:30	68.00	68.88	0.9	1%	-0.5	0.650	0.663	11.69
9	17 Jan 2010 18:30	67.00	57.06	-9.9	-15%	3.0	0.690	0.705	9.90
10	01 Mar 2010 04:30	65.00	75.97	11.0	17%	-6.8	0.459	0.548	14.17

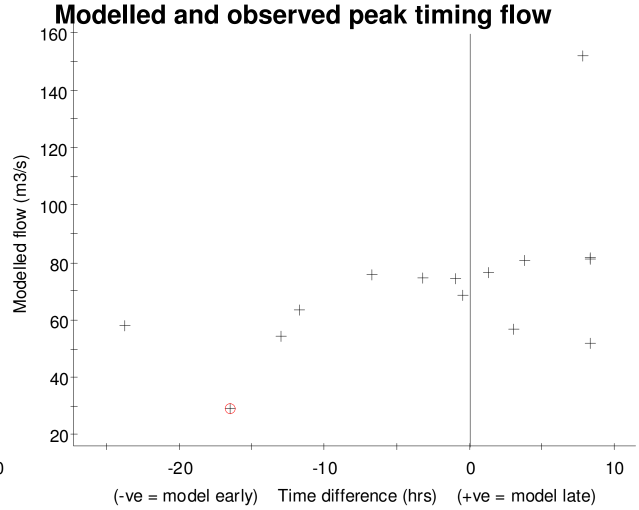
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.12	2.80	3.22	0.00	3.15	4.00	4.00	2.49

Modelled and observed peak flow (r2 0.78)

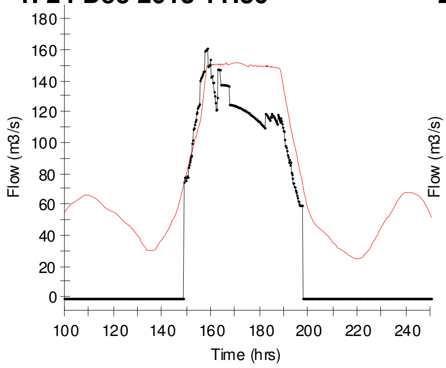


Modelled and observed peak timing flow

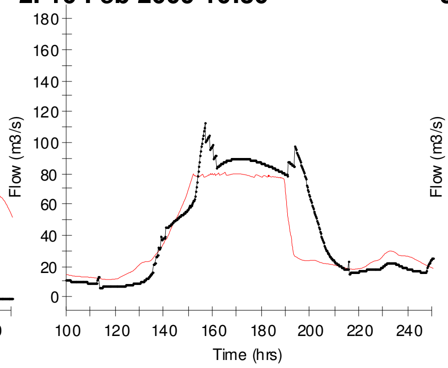


Leigh FSA Outflow (Cascaded)

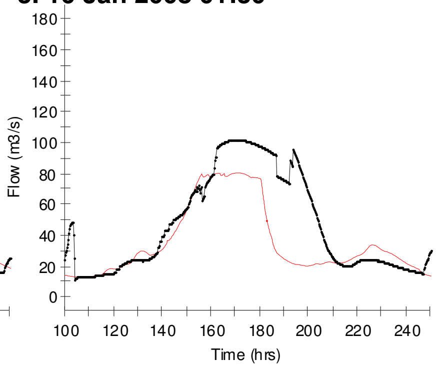
1. 24 Dec 2013 11:30



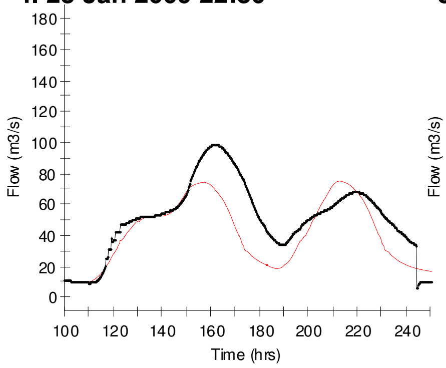
2. 10 Feb 2009 10:30



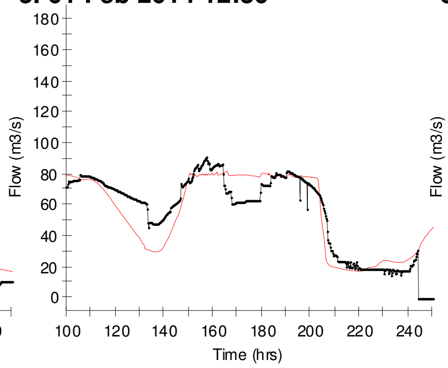
3. 16 Jan 2008 01:30



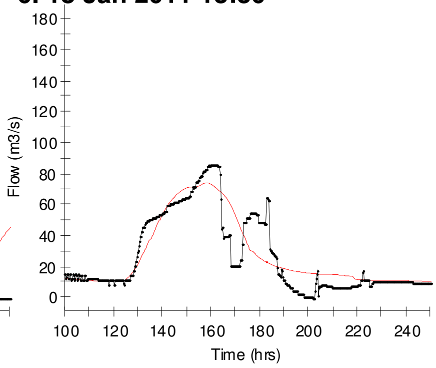
4. 23 Jan 2009 22:30



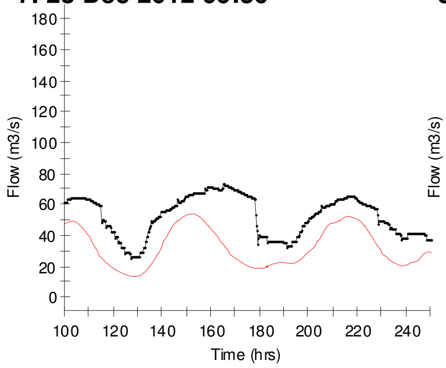
5. 01 Feb 2014 12:30



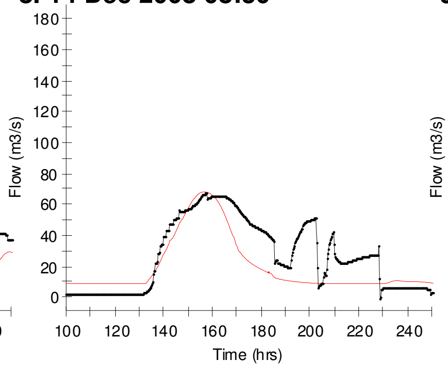
6. 18 Jan 2011 13:30



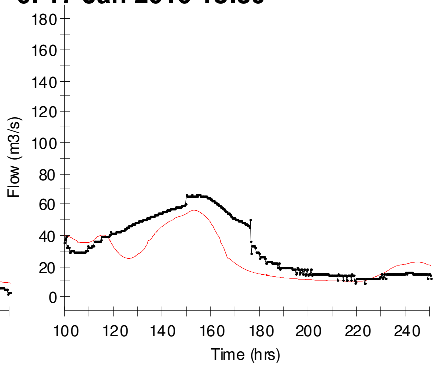
7. 23 Dec 2012 09:30



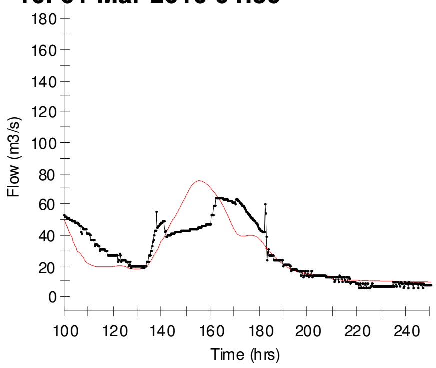
8. 14 Dec 2008 08:30



9. 17 Jan 2010 18:30

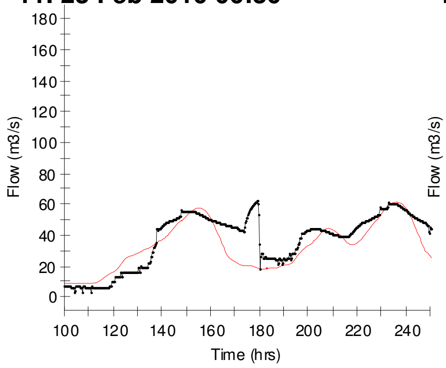


10. 01 Mar 2010 04:30

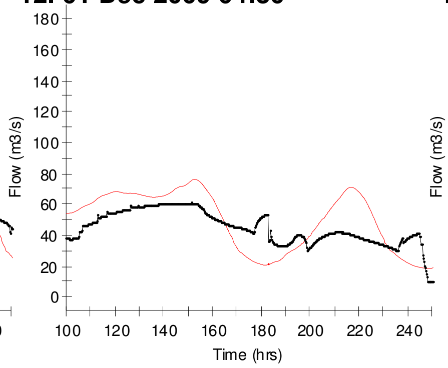


Key
Modelled
Observed

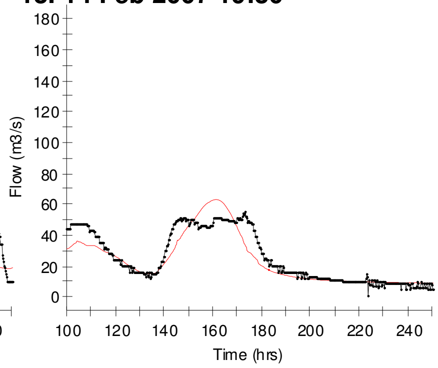
11. 23 Feb 2010 06:30



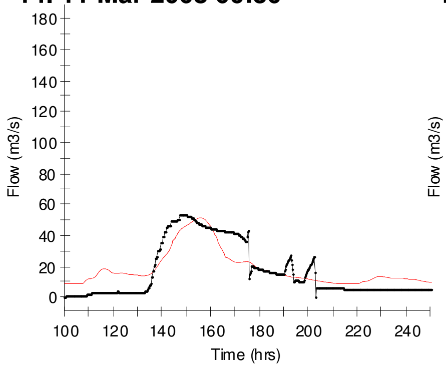
12. 01 Dec 2009 04:30



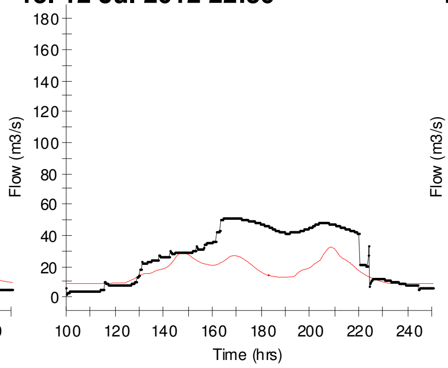
13. 14 Feb 2007 19:30



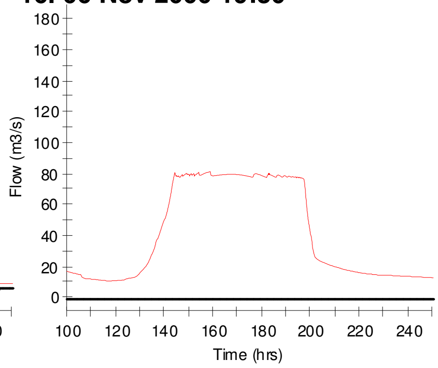
14. 11 Mar 2008 06:30



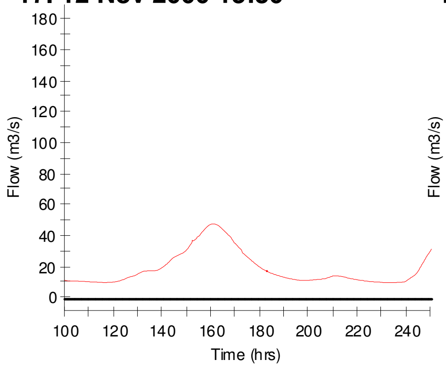
15. 12 Jul 2012 22:30



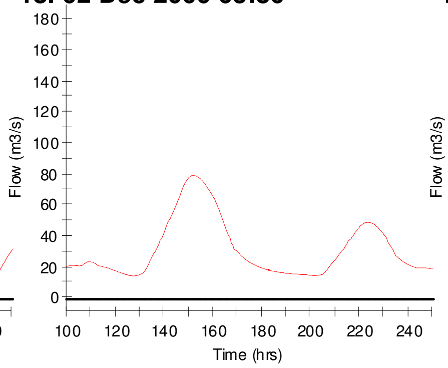
16. 06 Nov 2000 19:30



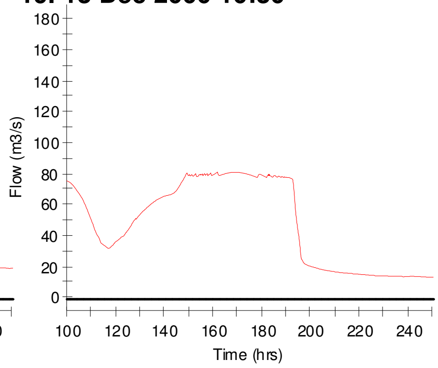
17. 12 Nov 2000 15:30



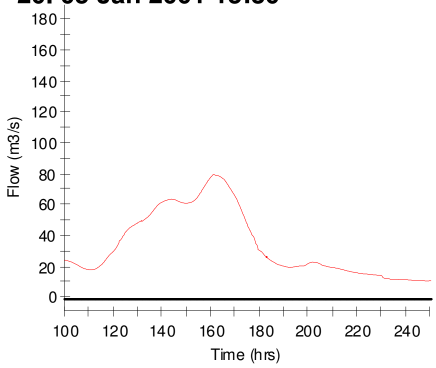
18. 02 Dec 2000 05:30



19. 13 Dec 2000 10:30



20. 05 Jan 2001 15:30



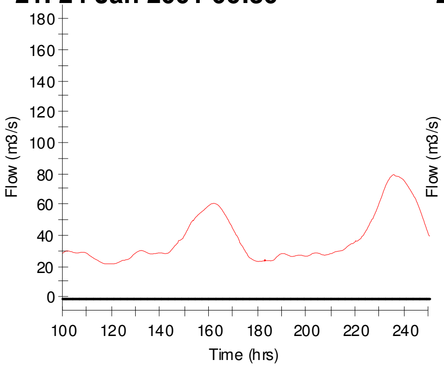
Key

Modelled

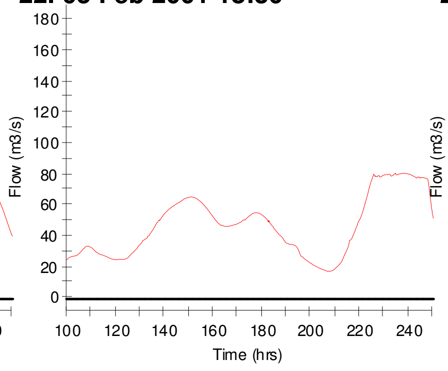
Observed

Leigh FSA Outflow (Cascaded)

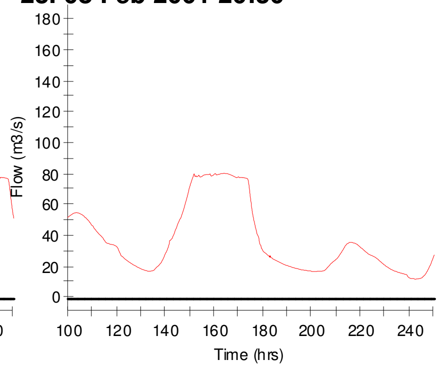
21. 24 Jan 2001 06:30



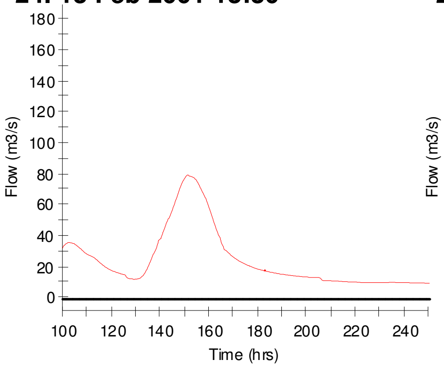
22. 05 Feb 2001 18:30



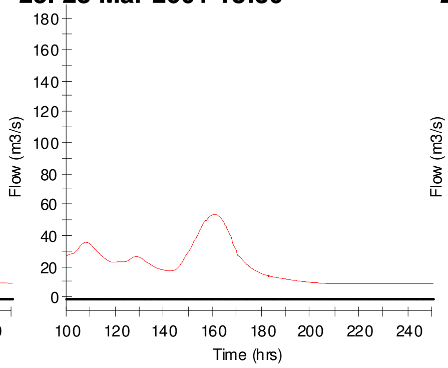
23. 08 Feb 2001 20:30



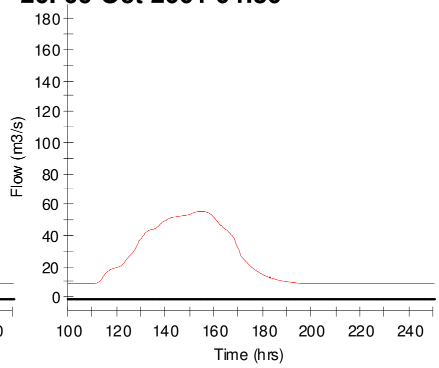
24. 13 Feb 2001 13:30



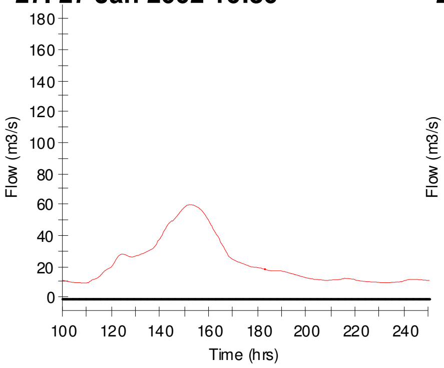
25. 23 Mar 2001 18:30



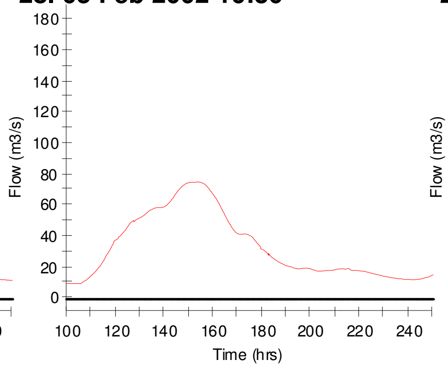
26. 09 Oct 2001 04:30



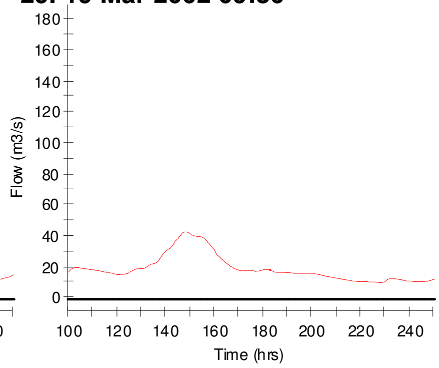
27. 27 Jan 2002 16:30



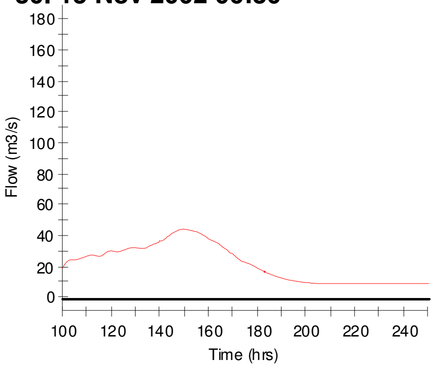
28. 05 Feb 2002 16:30



29. 19 Mar 2002 09:30



30. 15 Nov 2002 06:30



Key

Modelled

Observed

Town Lock Level

Data summary

38 peaks analysed at CS36 between 20.2m and 22.2m, for period 06 Nov 2000 to 01 Feb 2014 from :

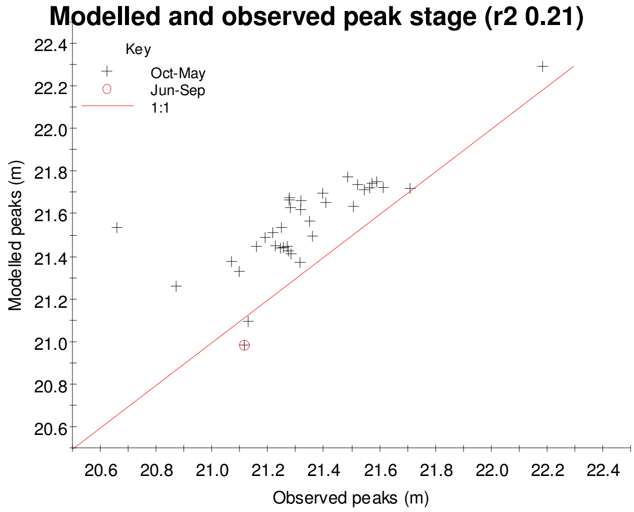
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade

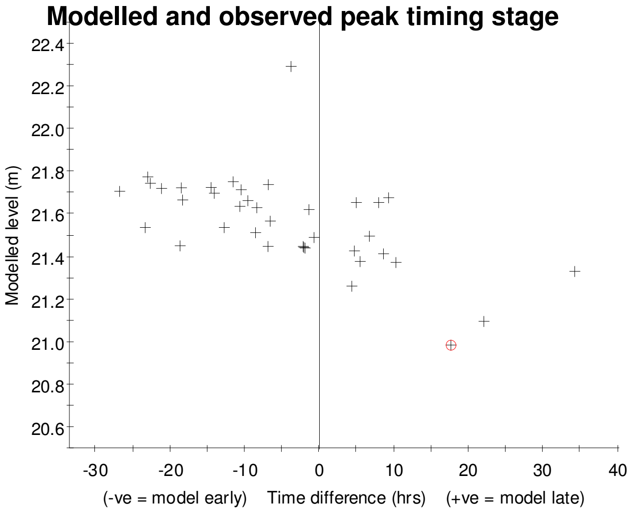
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m)	Mod. (m)	Diff. (m)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	22.18	22.29	0.11	1%	-3.8	-0.30	0.570	0.39
2	06 Nov 2000 19:30	21.71	21.72	0.01	0%	-21.2	-6.17	0.157	0.65
3	17 Jan 2014 17:30	21.61	21.73	0.11	1%	-14.5	-16.9	0.422	0.51
4	02 Jan 2014 07:30	21.59	21.75	0.17	1%	-11.6	-6.15	0.408	0.38
5	31 Dec 2002 04:30	21.57	21.75	0.17	1%	-22.7	-10.9	0.135	0.52
6	16 Jan 2008 01:30	21.56	21.73	0.16	1%	-18.5	-9.46	0.240	0.61
7	01 Feb 2014 12:30	21.54	21.72	0.17	1%	-10.5	-0.31	-999.	10.10
8	10 Feb 2009 10:30	21.52	21.74	0.22	1%	-6.8	-10.3	0.537	0.58
9	23 Jan 2009 22:30	21.51	21.64	0.13	1%	-10.7	-7.70	0.400	0.46
10	13 Dec 2000 10:30	21.48	21.78	0.29	1%	-23.0	-12.8	0.381	0.58

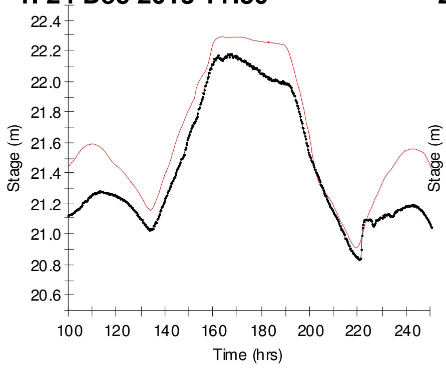
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	4.29	2.83	2.42	4.09	1.30	0.95	4.00	3.27

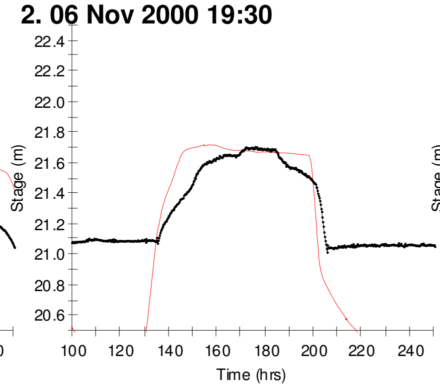




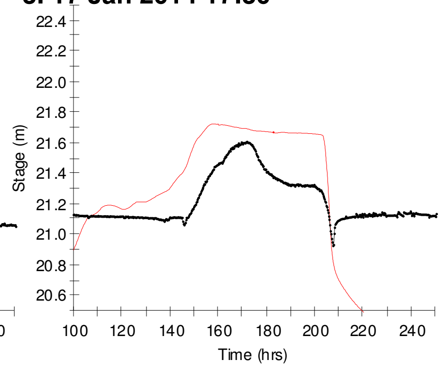
1. 24 Dec 2013 11:30



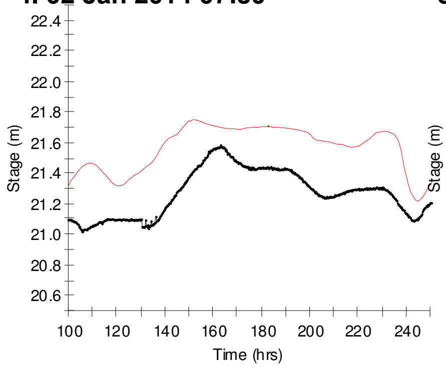
2. 06 Nov 2000 19:30



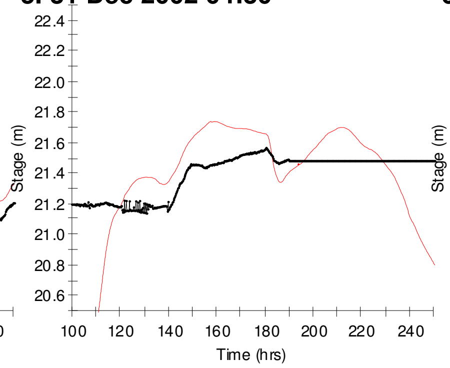
3. 17 Jan 2014 17:30



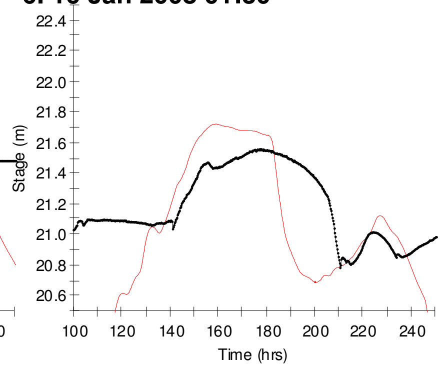
4. 02 Jan 2014 07:30



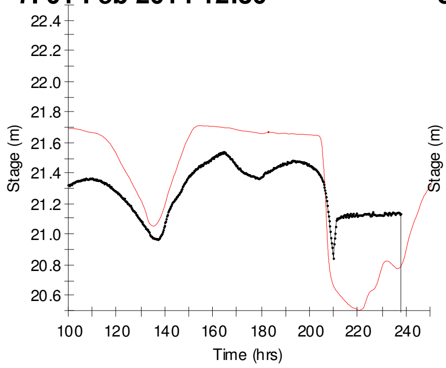
5. 31 Dec 2002 04:30



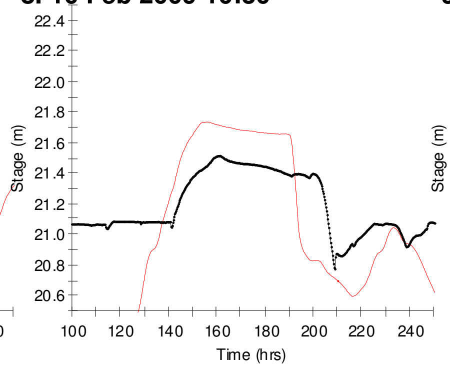
6. 16 Jan 2008 01:30



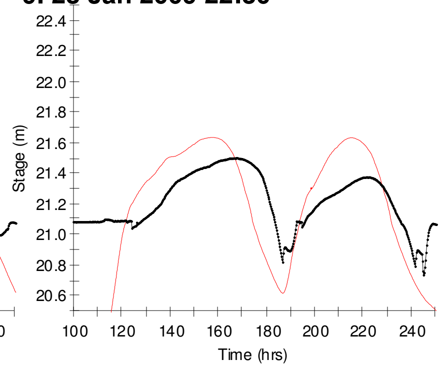
7. 01 Feb 2014 12:30



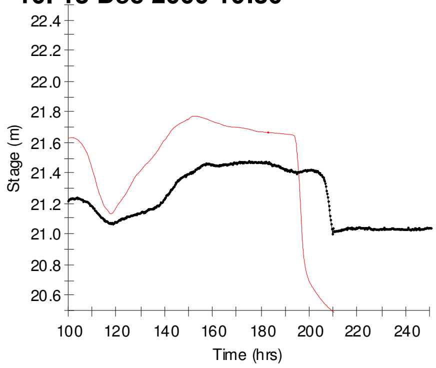
8. 10 Feb 2009 10:30



9. 23 Jan 2009 22:30

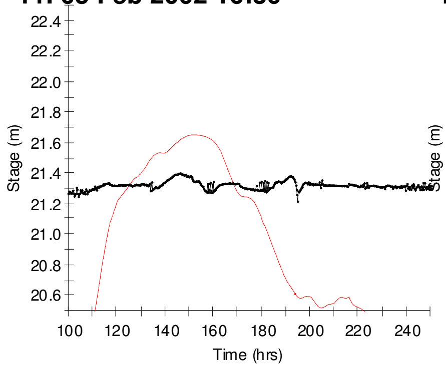


10. 13 Dec 2000 10:30

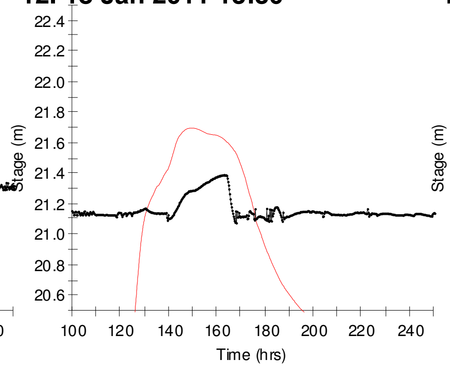


Key
Modelled
Observed

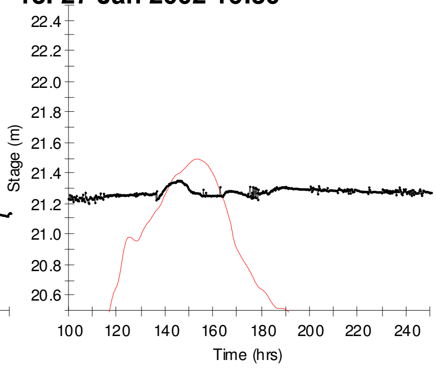
11. 05 Feb 2002 16:30



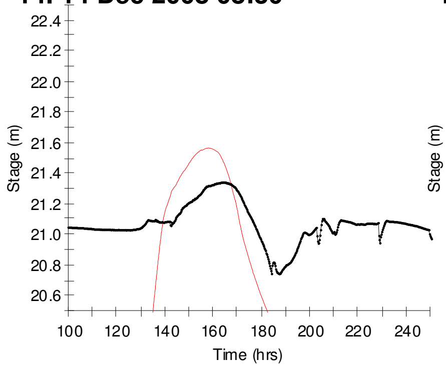
12. 18 Jan 2011 13:30



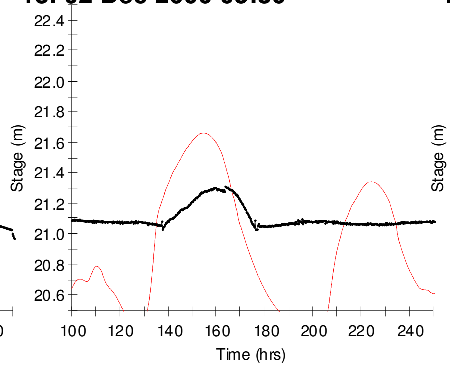
13. 27 Jan 2002 16:30



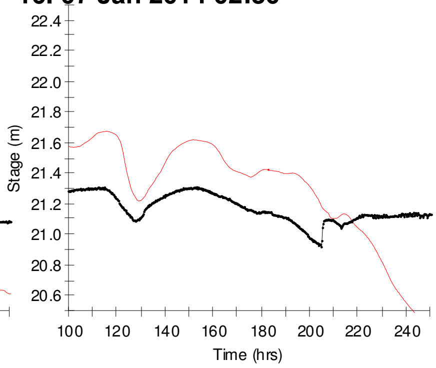
14. 14 Dec 2008 08:30



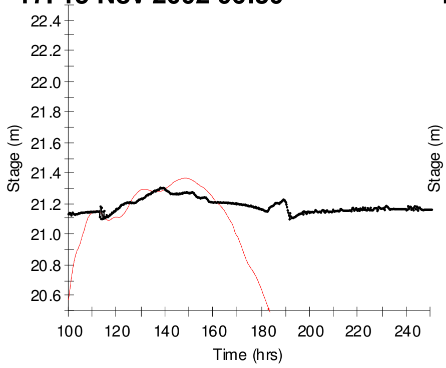
15. 02 Dec 2000 05:30



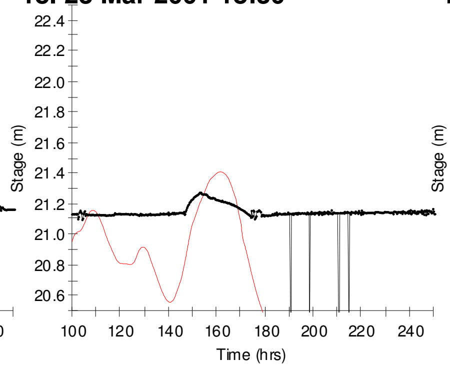
16. 07 Jan 2014 02:30



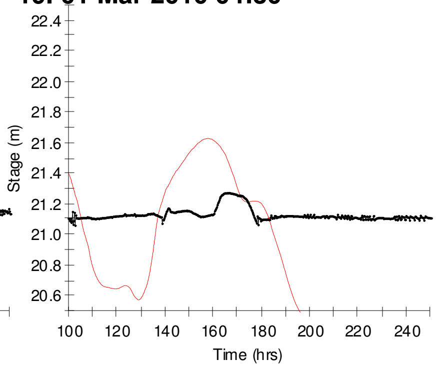
17. 15 Nov 2002 06:30



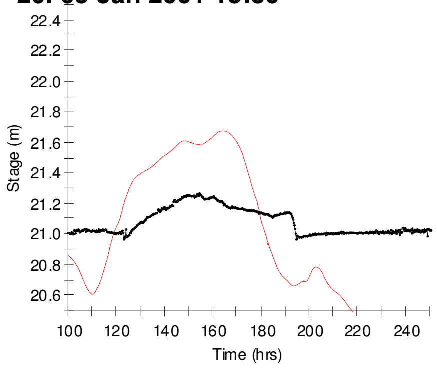
18. 23 Mar 2001 18:30



19. 01 Mar 2010 04:30

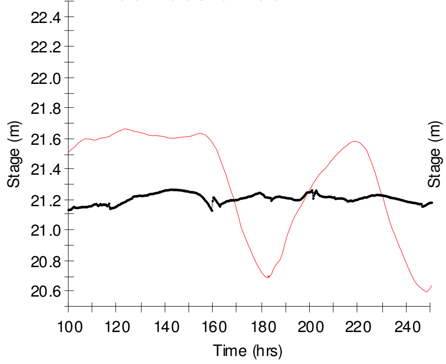


20. 05 Jan 2001 15:30

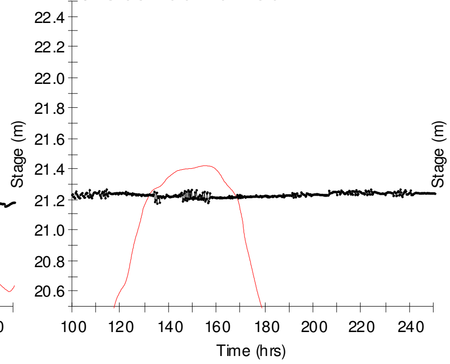


Key
Modelled
Observed

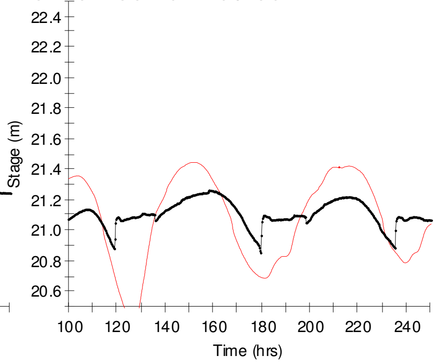
21. 01 Dec 2009 04:30



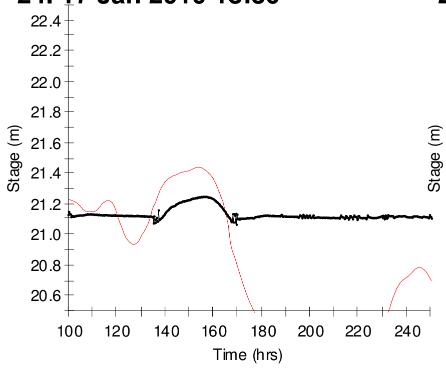
22. 09 Oct 2001 04:30



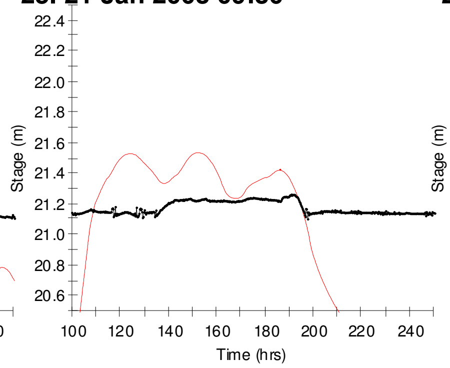
23. 23 Dec 2012 09:30



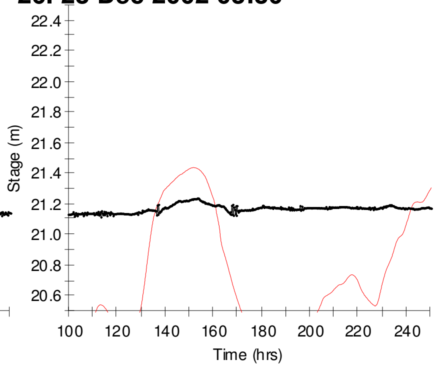
24. 17 Jan 2010 18:30



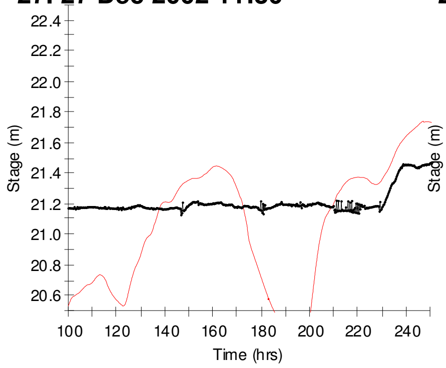
25. 21 Jan 2003 09:30



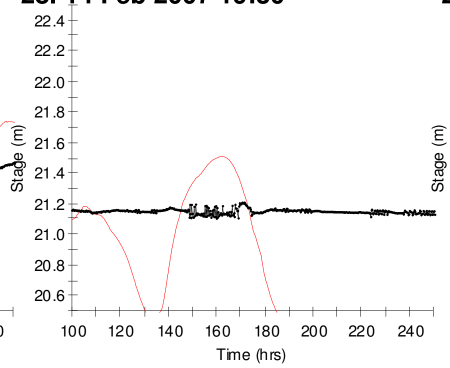
26. 23 Dec 2002 03:30



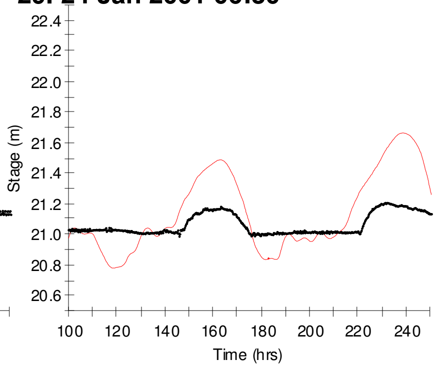
27. 27 Dec 2002 11:30



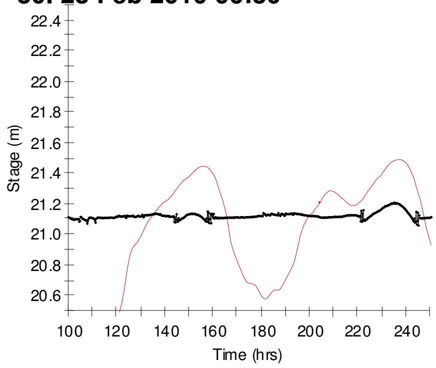
28. 14 Feb 2007 19:30



29. 24 Jan 2001 06:30



30. 23 Feb 2010 06:30



Key
Modelled
Observed

Yalding Downstream Level

Data summary

38 peaks analysed at CS161JD between 8.2m and 12.0m, for period 06 Nov 2000 to 01 Feb 2014 from :

N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade

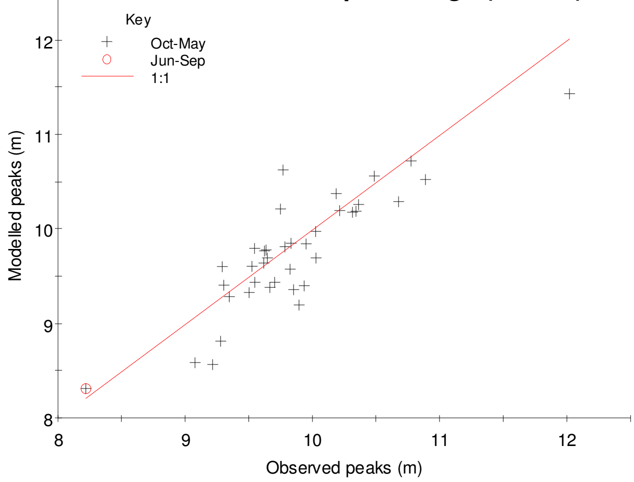
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m)	Mod. (m)	Diff. (m)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	12.01	11.43	-0.58	-5%	-3.9	0.889	0.892	0.38
2	06 Nov 2000 19:30	10.88	10.53	-0.35	-3%	-11.3	0.207	0.235	1.56
3	13 Dec 2000 10:30	10.77	10.73	-0.05	0%	-11.5	0.828	0.856	0.35
4	08 Feb 2001 20:30	10.67	10.30	-0.38	-4%	-3.6	0.853	0.927	0.28
5	31 Dec 2002 04:30	10.48	10.57	0.09	1%	-2.0	0.935	0.936	0.21
6	10 Feb 2009 10:30	10.36	10.27	-0.09	-1%	-5.8	0.891	0.929	0.27
7	05 Jan 2001 15:30	10.34	10.20	-0.14	-1%	-4.2	0.866	0.902	0.29
8	01 Feb 2014 12:30	10.31	10.19	-0.13	-1%	-8.9	-0.28	0.004	4.40
9	16 Jan 2008 01:30	10.21	10.20	-0.01	0%	-10.6	0.851	0.871	0.32
10	02 Jan 2014 07:30	10.18	10.38	0.20	2%	-23.9	0.660	0.694	0.38

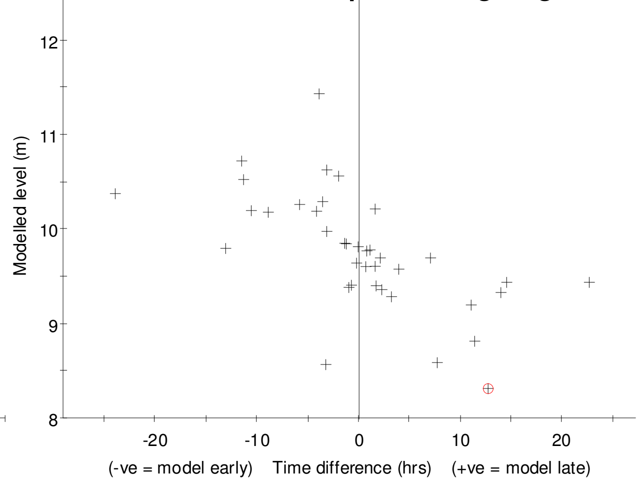
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	2.28	1.15	0.48	1.49	0.07	0.04	3.37	1.56

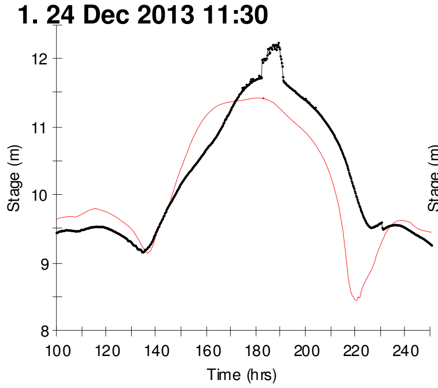
Modelled and observed peak stage (r2 0.76)



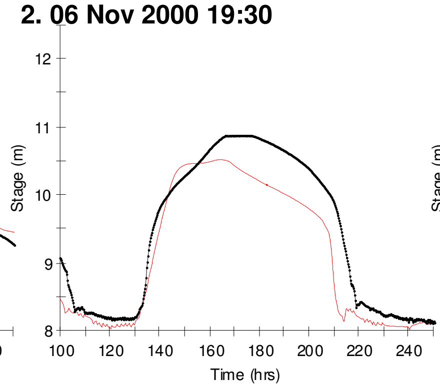
Modelled and observed peak timing stage



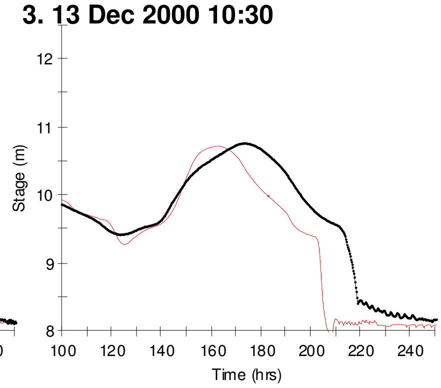
1. 24 Dec 2013 11:30



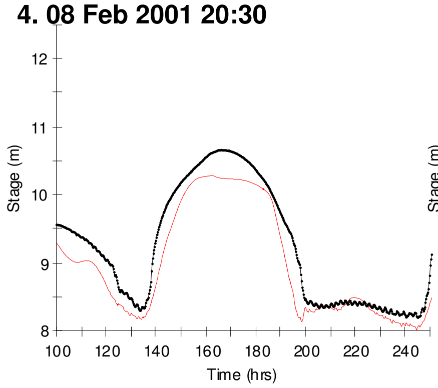
2. 06 Nov 2000 19:30



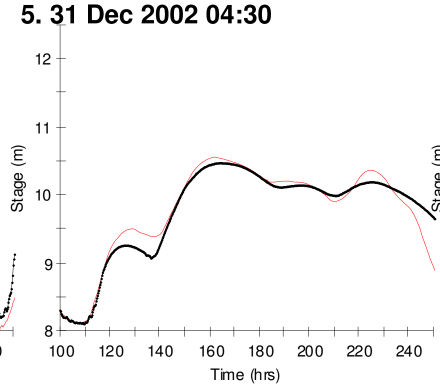
3. 13 Dec 2000 10:30



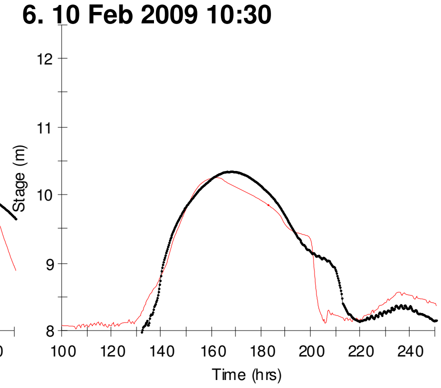
4. 08 Feb 2001 20:30



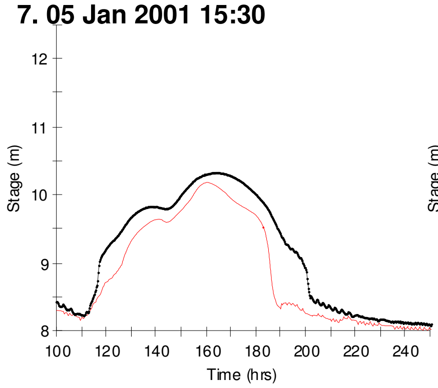
5. 31 Dec 2002 04:30



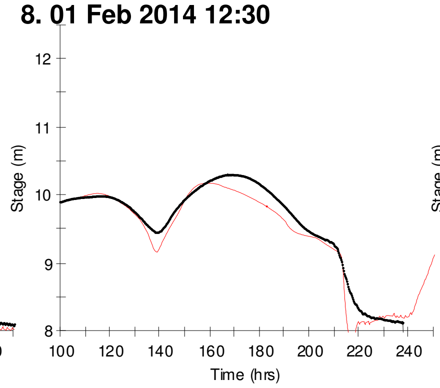
6. 10 Feb 2009 10:30



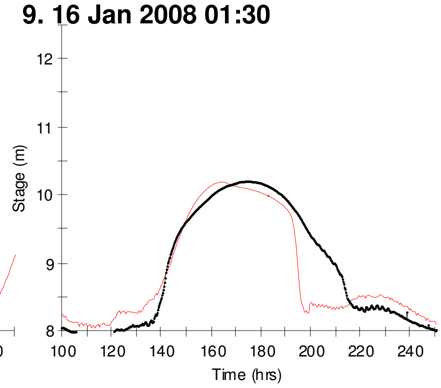
7. 05 Jan 2001 15:30



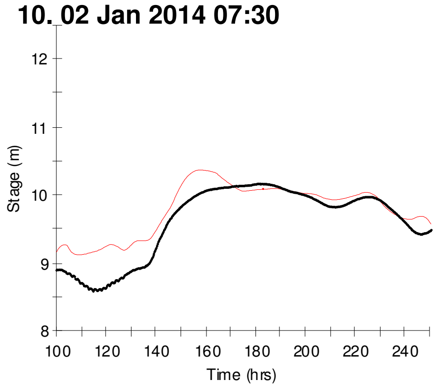
8. 01 Feb 2014 12:30



9. 16 Jan 2008 01:30

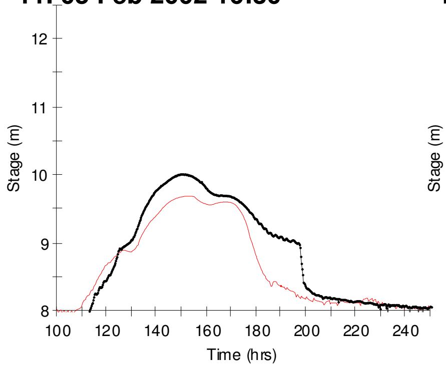


10. 02 Jan 2014 07:30

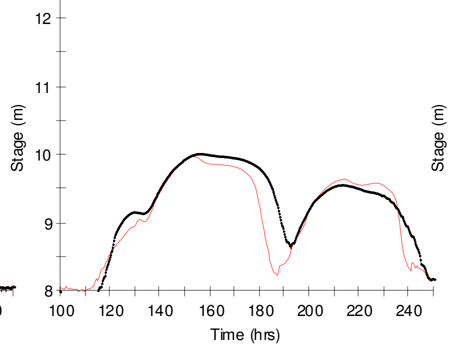


Key
Modelled
Observed

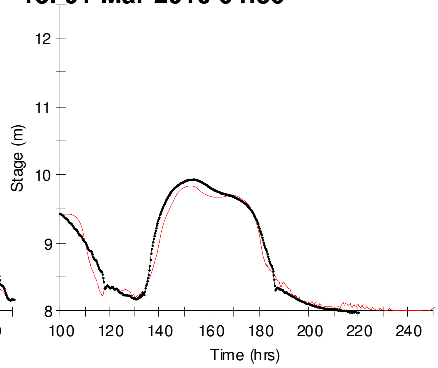
11. 05 Feb 2002 16:30



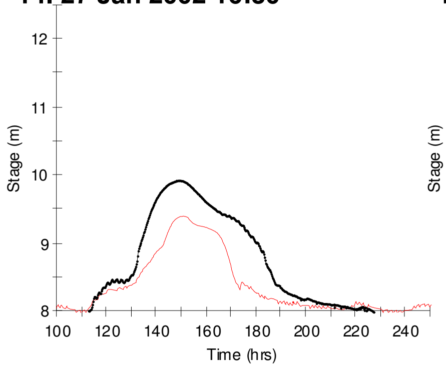
12. 23 Jan 2009 22:30



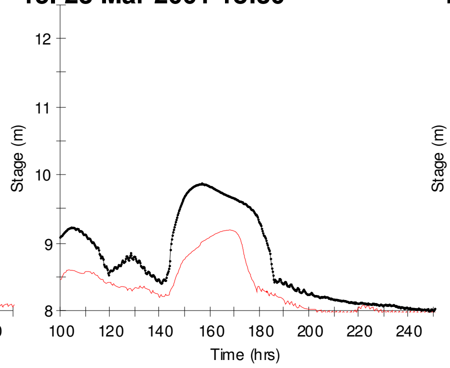
13. 01 Mar 2010 04:30



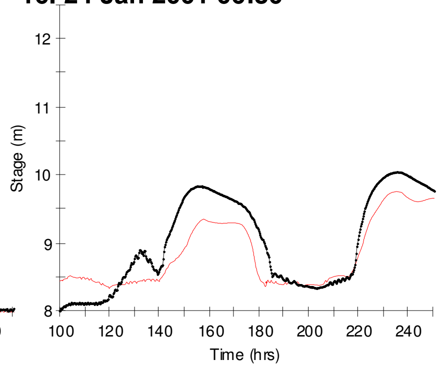
14. 27 Jan 2002 16:30



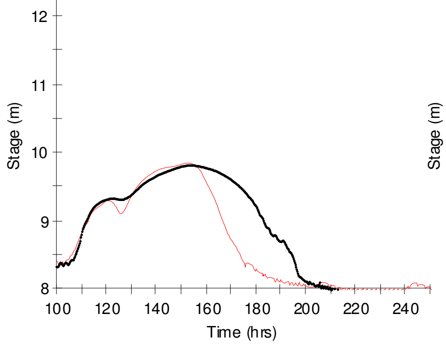
15. 23 Mar 2001 18:30



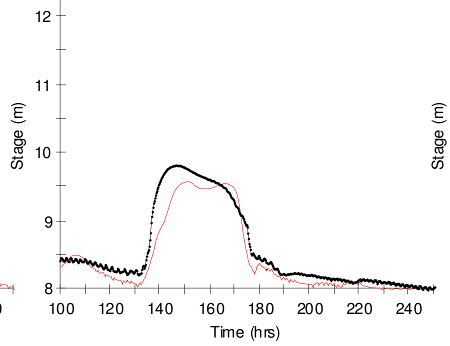
16. 24 Jan 2001 06:30



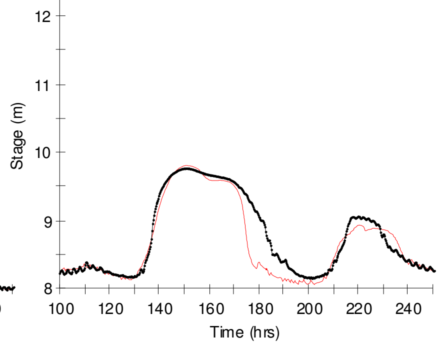
17. 15 Nov 2002 06:30



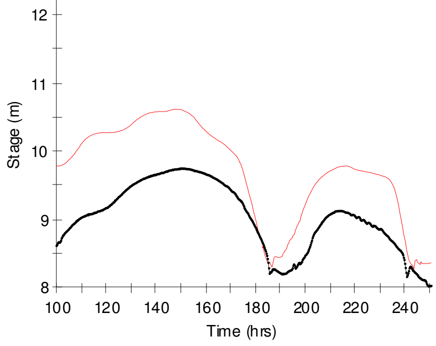
18. 13 Feb 2001 13:30



19. 02 Dec 2000 05:30

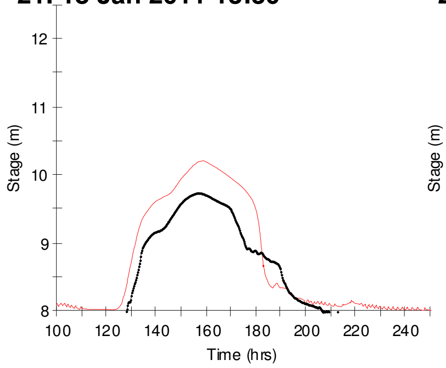


20. 01 Dec 2009 04:30

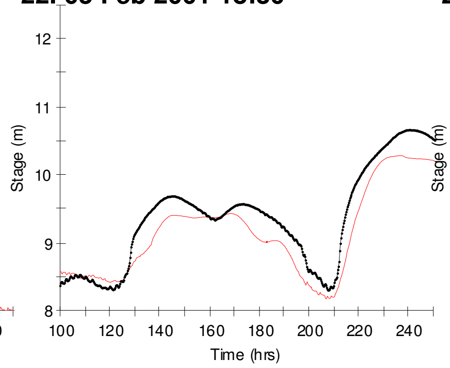


Key
Modelled
Observed

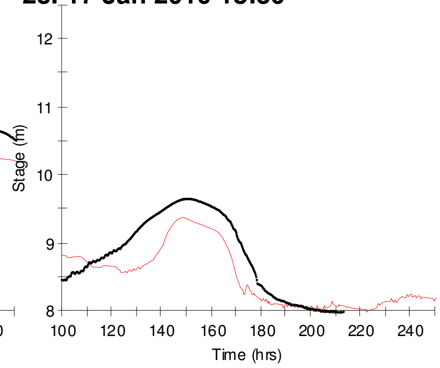
21. 18 Jan 2011 13:30



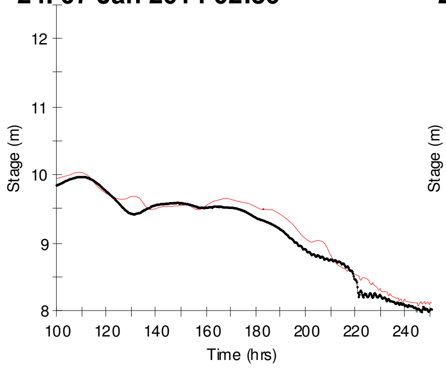
22. 05 Feb 2001 18:30



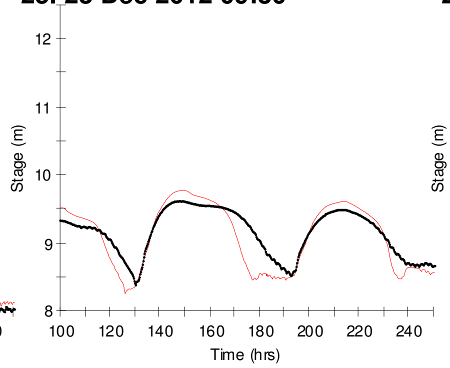
23. 17 Jan 2010 18:30



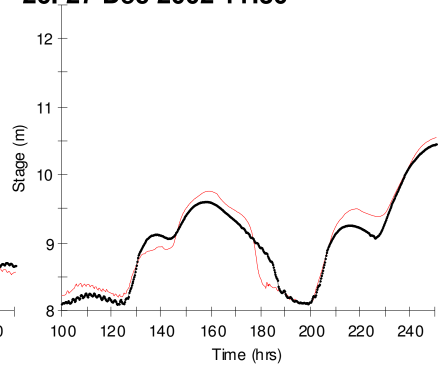
24. 07 Jan 2014 02:30



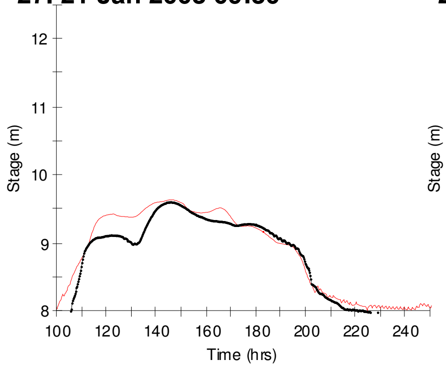
25. 23 Dec 2012 09:30



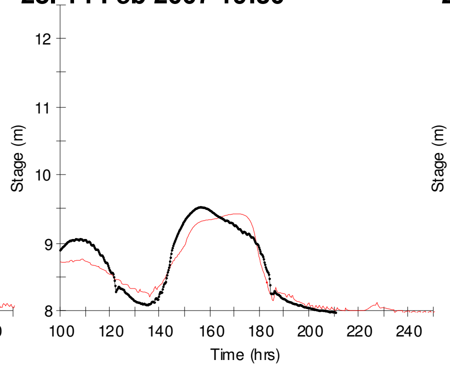
26. 27 Dec 2002 11:30



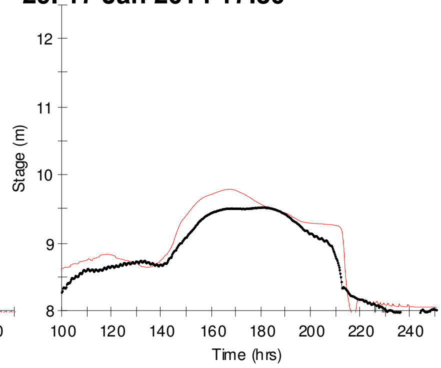
27. 21 Jan 2003 09:30



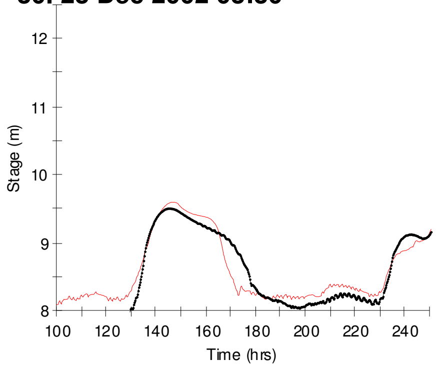
28. 14 Feb 2007 19:30



29. 17 Jan 2014 17:30



30. 23 Dec 2002 03:30



Key
Modelled
Observed

Yalding Upstream Level

Data summary

38 peaks analysed at CS147 between 0.0m and 11.7m, for period 06 Nov 2000 to 01 Feb 2014 from :

N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade

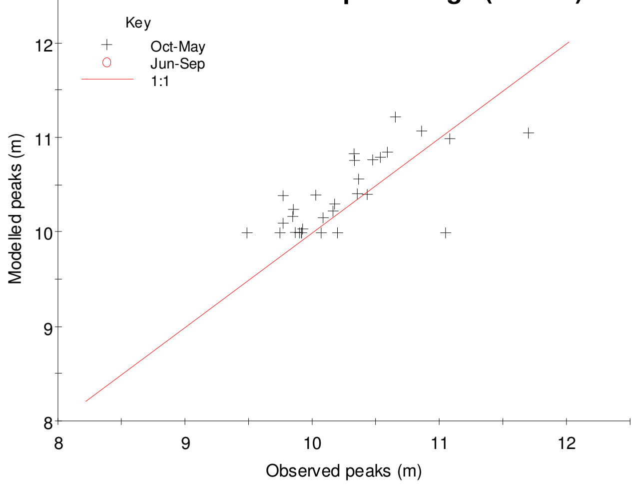
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	**Obs. (m)**	**Mod. (m)**	**Diff. (m)**	**Diff (%)**	**Time Diff. (hrs)**	**NSE**	**r^2**	**RMSE**
1	01 Dec 2009 04:30	11.69	11.05	-0.64	-5%	-6.8	-0.00	0.083	1.26
2	06 Nov 2000 19:30	11.08	10.99	-0.09	-1%	-1.7	0.197	0.336	0.47
3	19 Mar 2002 09:30	11.04	10.00	-1.04	-9%	-50.4	-0.36	0.002	0.29
4	31 Dec 2002 04:30	10.85	11.07	0.22	2%	-0.7	0.764	0.794	0.19
5	13 Dec 2000 10:30	10.65	11.22	0.57	5%	-11.4	-0.69	0.599	0.48
6	10 Feb 2009 10:30	10.59	10.85	0.26	2%	-5.5	0.449	0.919	0.17
7	08 Feb 2001 20:30	10.53	10.79	0.26	2%	-1.9	-0.63	0.685	0.37
8	16 Jan 2008 01:30	10.47	10.77	0.30	3%	-10.8	0.148	0.513	0.26
9	01 Mar 2010 04:30	10.43	10.41	-0.02	0%	0.6	0.207	0.254	0.22
10	23 Jan 2009 22:30	10.36	10.57	0.20	2%	-2.8	-0.32	0.489	0.29

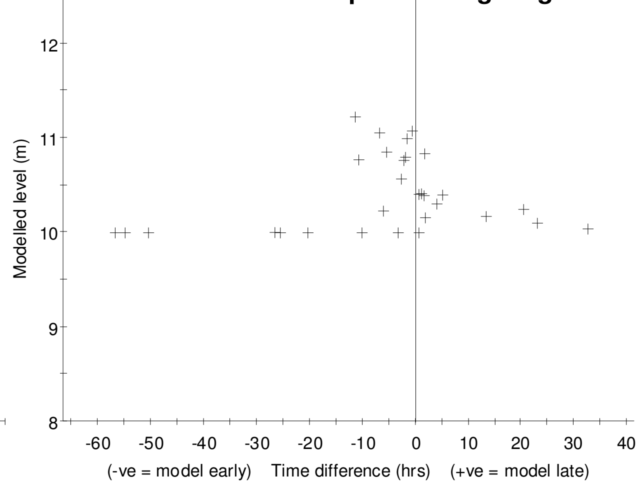
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	3.40	2.06	2.96	4.82	1.54	4.00	4.00	3.57

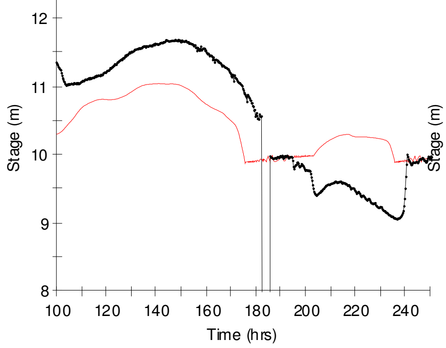
Modelled and observed peak stage (r2 0.51)



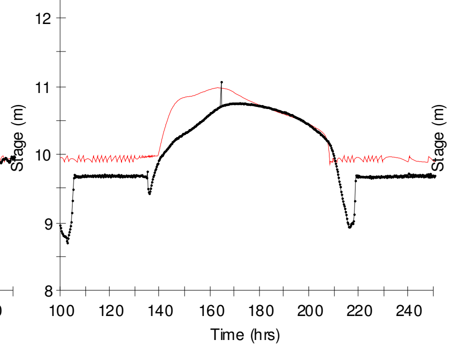
Modelled and observed peak timing stage



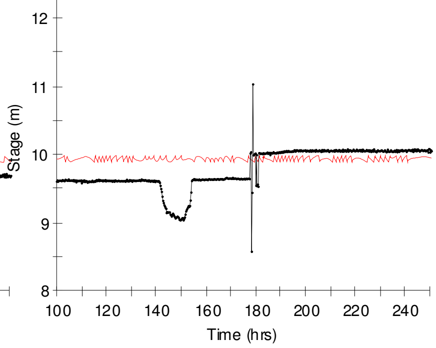
1. 01 Dec 2009 04:30



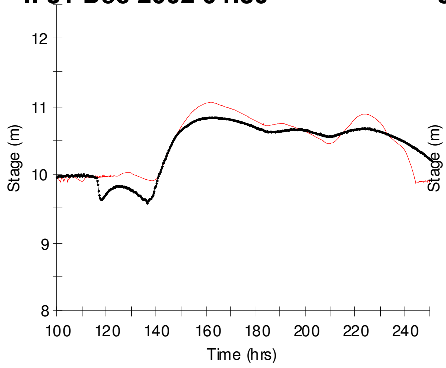
2. 06 Nov 2000 19:30



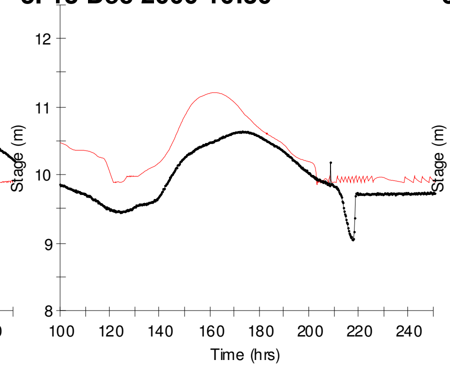
3. 19 Mar 2002 09:30



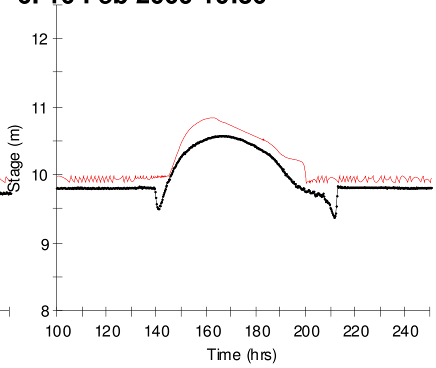
4. 31 Dec 2002 04:30



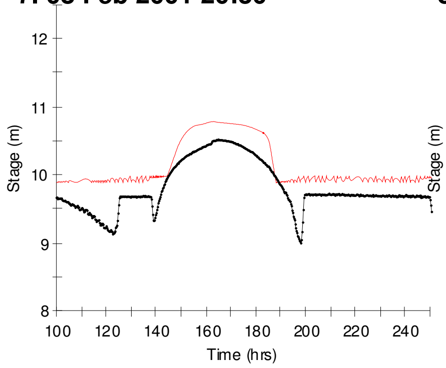
5. 13 Dec 2000 10:30



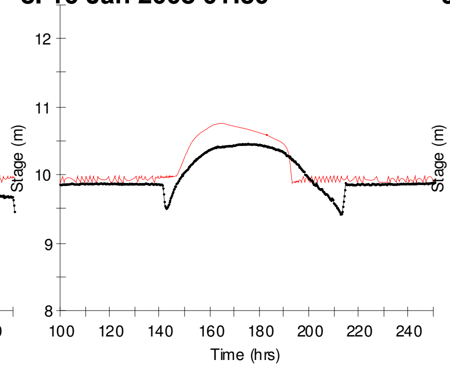
6. 10 Feb 2009 10:30



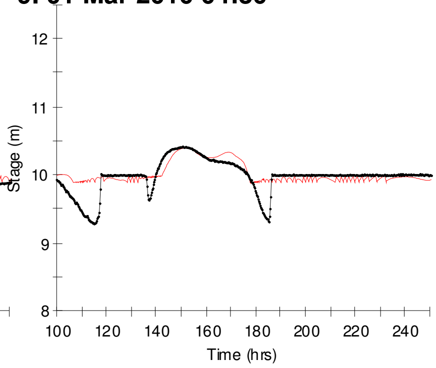
7. 08 Feb 2001 20:30



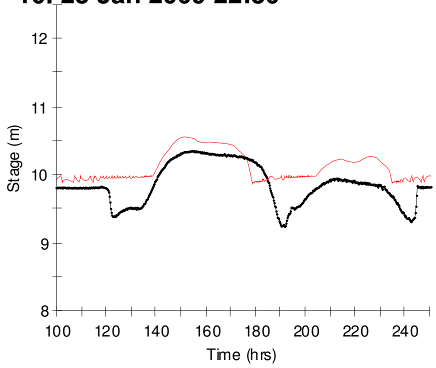
8. 16 Jan 2008 01:30



9. 01 Mar 2010 04:30

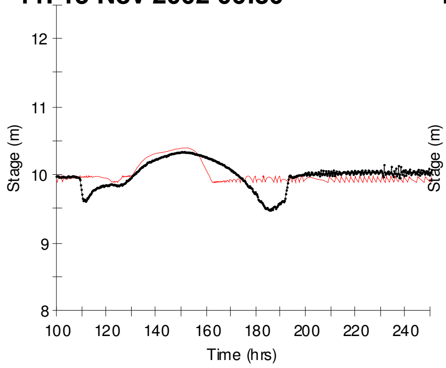


10. 23 Jan 2009 22:30

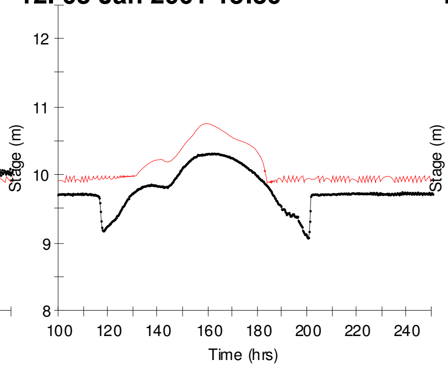


Key
Modelled
Observed

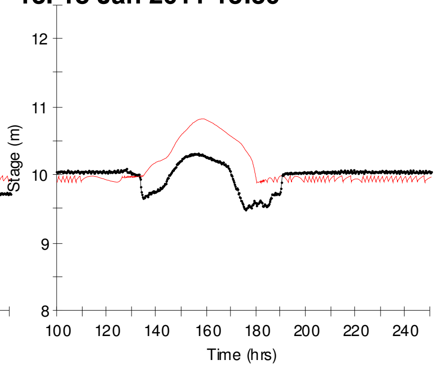
11. 15 Nov 2002 06:30



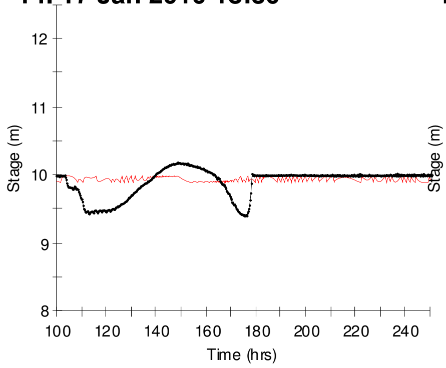
12. 05 Jan 2001 15:30



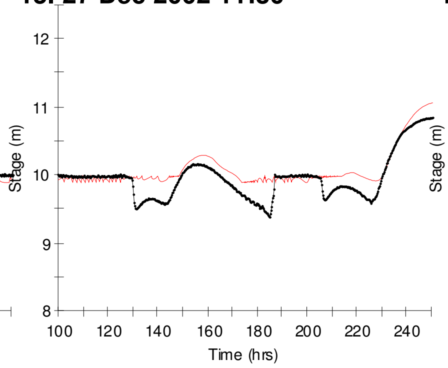
13. 18 Jan 2011 13:30



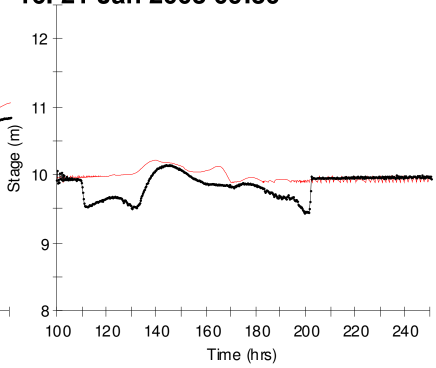
14. 17 Jan 2010 18:30



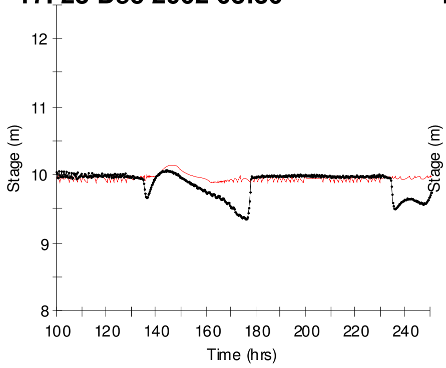
15. 27 Dec 2002 11:30



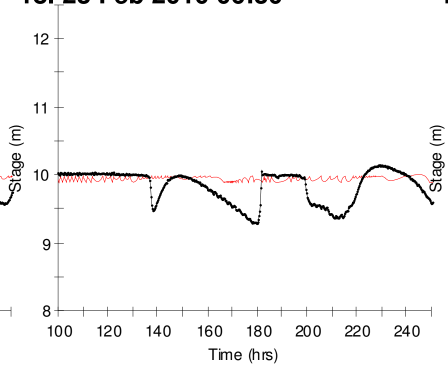
16. 21 Jan 2003 09:30



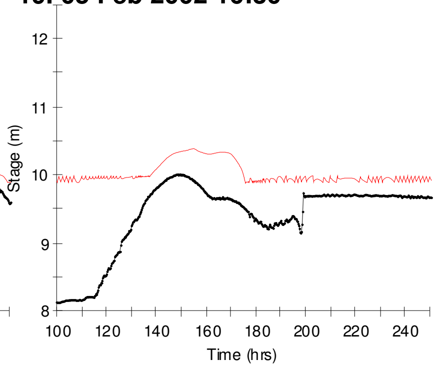
17. 23 Dec 2002 03:30



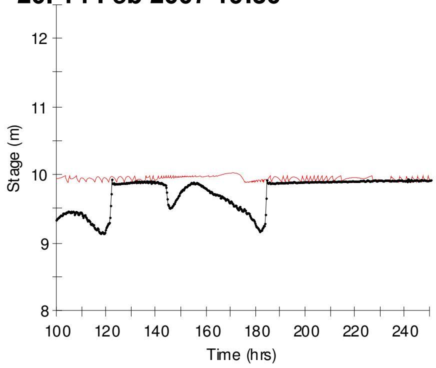
18. 23 Feb 2010 06:30



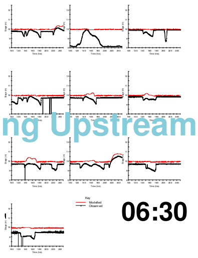
19. 05 Feb 2002 16:30



20. 14 Feb 2007 19:30



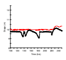
Key
Modelled
Observed



21. 24 06:30

22. 27 Jan 2002 16:30

23. 11 Mar 2008 06:30



24. 23 Mar 2001 18:30

25. 13 Feb 2001 13:30

26. 14 Dec 2008 08:30

27. 02 Dec 2000 05:30

28. 05 Feb 2001 18:30

29. 12 Nov 2000 15:30

30. 09 Oct 2001 04:30

Darmans Bridge

Data summary

47 peaks analysed at T30-BJD between 0.0m and 13.0m, for period 01 Nov 1998 to 01 Feb 2014 from :

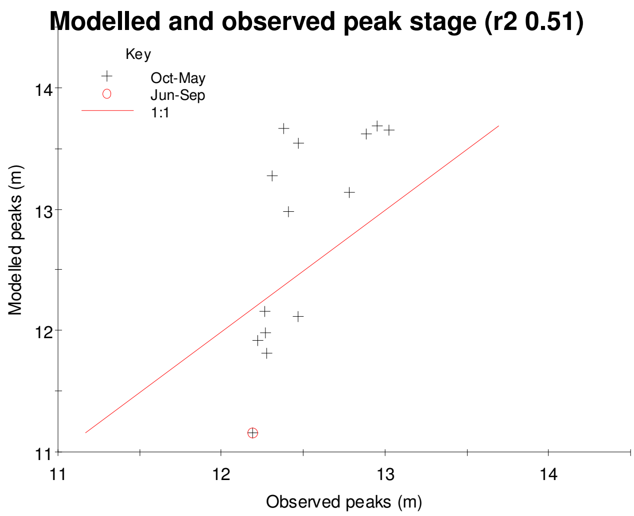
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade

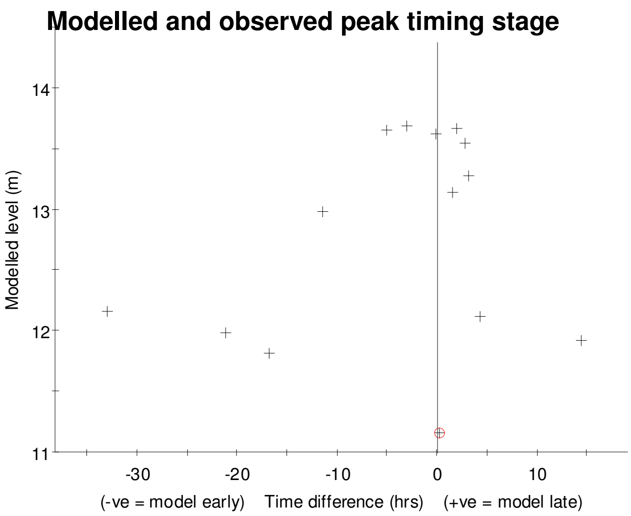
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m)	Mod. (m)	Diff. (m)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	10 Feb 2009 10:30	13.02	13.65	0.64	5%	-5.1	0.013	0.028	3.84
2	16 Jan 2008 01:30	12.95	13.69	0.74	6%	-3.1	-34.5	0.672	0.95
3	01 Mar 2010 04:30	12.88	13.62	0.74	6%	-0.2	-49.4	0.707	0.98
4	23 Jan 2009 22:30	12.78	13.14	0.36	3%	1.5	-0.11	-999.	3.86
5	14 Dec 2008 08:30	12.47	13.55	1.08	9%	2.8	-0.13	-999.	5.14
6	23 Feb 2010 06:30	12.47	12.12	-0.34	-3%	4.3	-43.9	0.645	0.93
7	18 Jan 2011 13:30	12.41	12.98	0.58	5%	-11.5	-463.	-999.	0.96
8	01 Dec 2009 04:30	12.38	13.67	1.29	10%	1.9	0.015	0.057	3.06
9	23 Dec 2012 09:30	12.31	13.28	0.97	8%	3.1	-471.	-999.	0.83
10	11 Mar 2008 06:30	12.27	11.82	-0.45	-4%	-16.8	0.003	0.004	3.31

Model scores

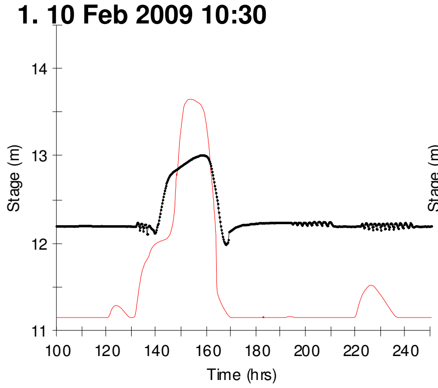
	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	3.39	3.50	4.04	0.00	3.39	4.00	3.92	3.00



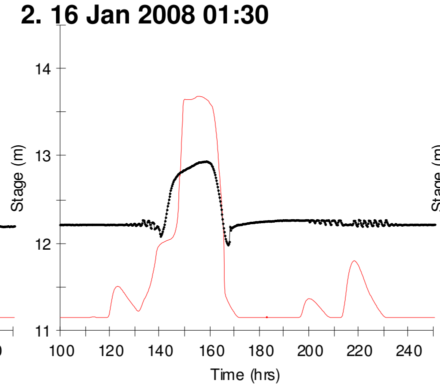


Darmans Bridge

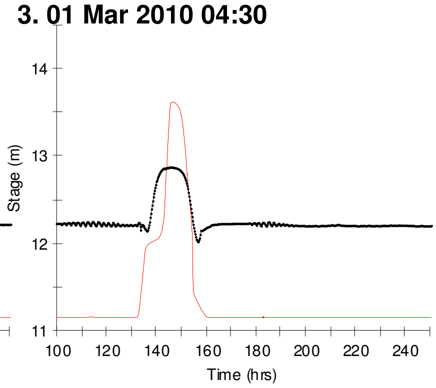
1. 10 Feb 2009 10:30



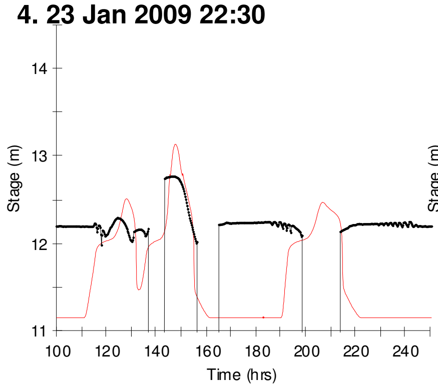
2. 16 Jan 2008 01:30



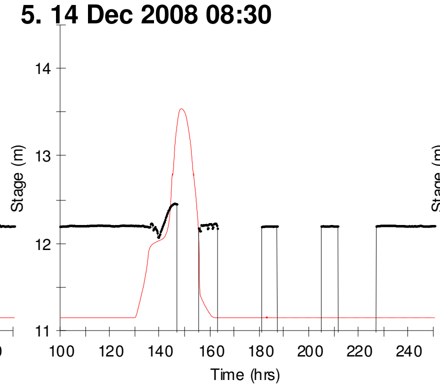
3. 01 Mar 2010 04:30



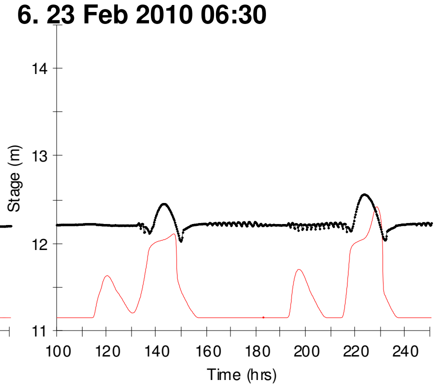
4. 23 Jan 2009 22:30



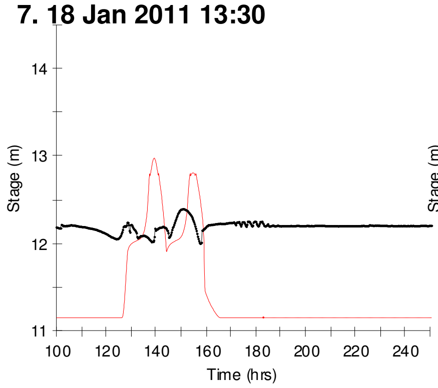
5. 14 Dec 2008 08:30



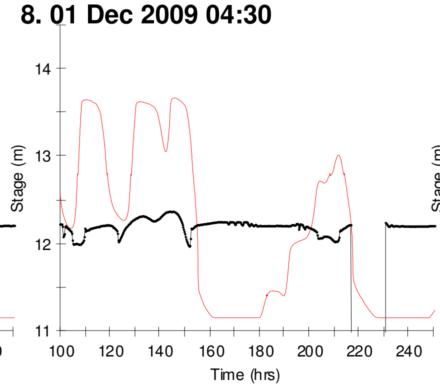
6. 23 Feb 2010 06:30



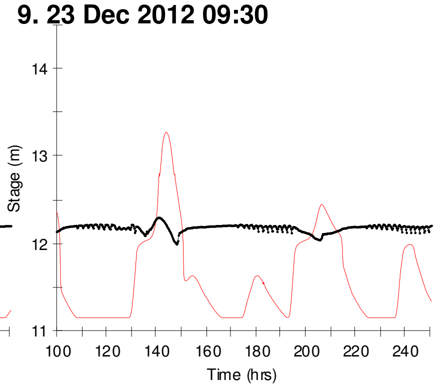
7. 18 Jan 2011 13:30



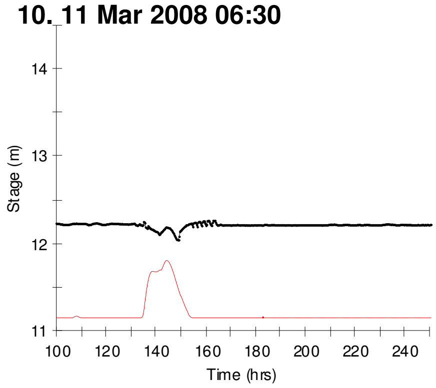
8. 01 Dec 2009 04:30



9. 23 Dec 2012 09:30



10. 11 Mar 2008 06:30

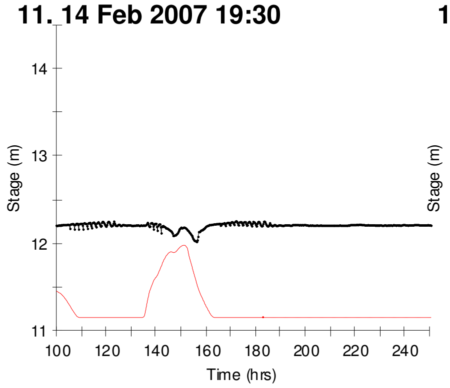


Key

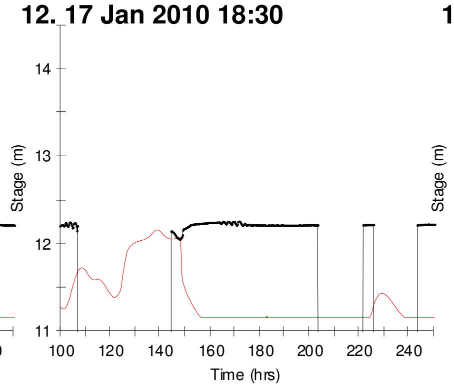
Modelled

Observed

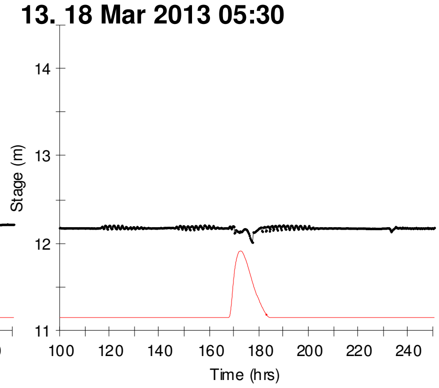
11. 14 Feb 2007 19:30



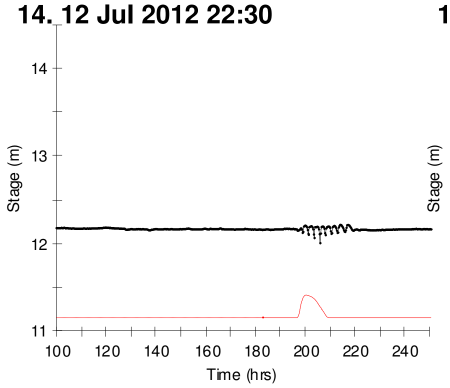
12. 17 Jan 2010 18:30



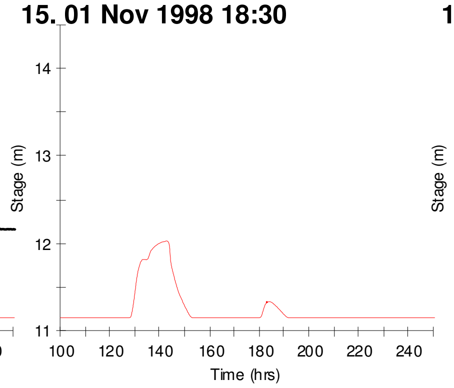
13. 18 Mar 2013 05:30



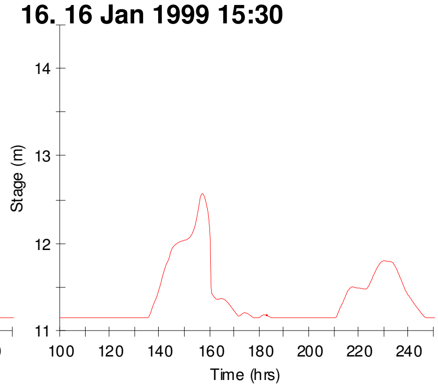
14. 12 Jul 2012 22:30



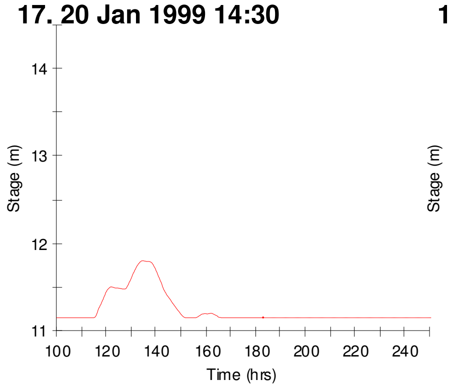
15. 01 Nov 1998 18:30



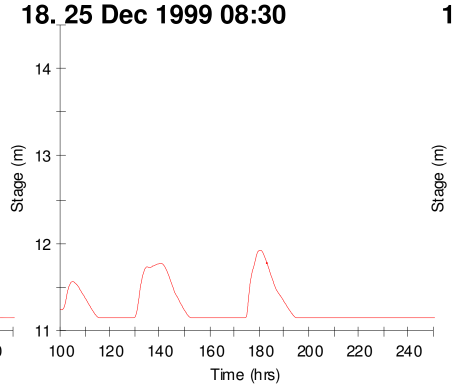
16. 16 Jan 1999 15:30



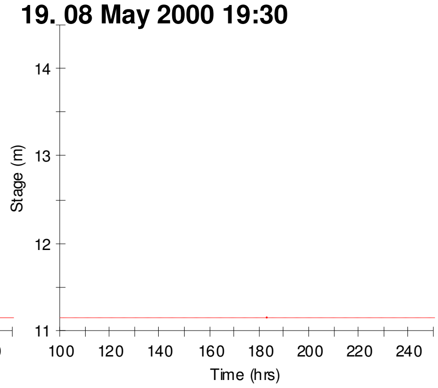
17. 20 Jan 1999 14:30



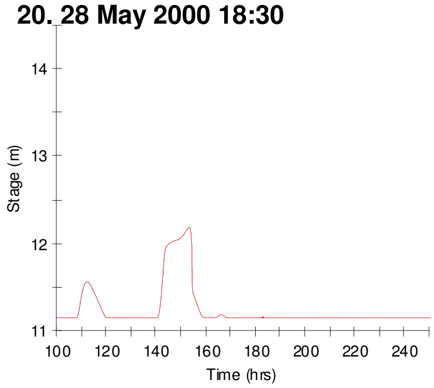
18. 25 Dec 1999 08:30



19. 08 May 2000 19:30



20. 28 May 2000 18:30

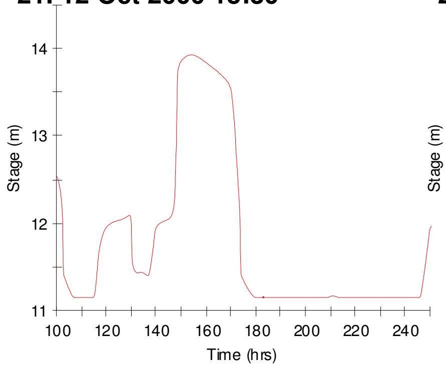


Key

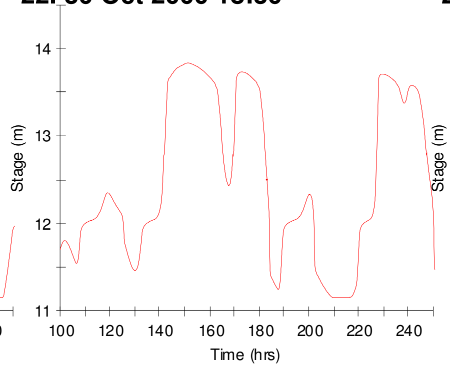
Modelled

Observed

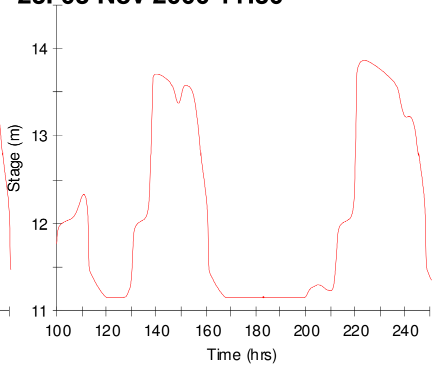
21. 12 Oct 2000 15:30



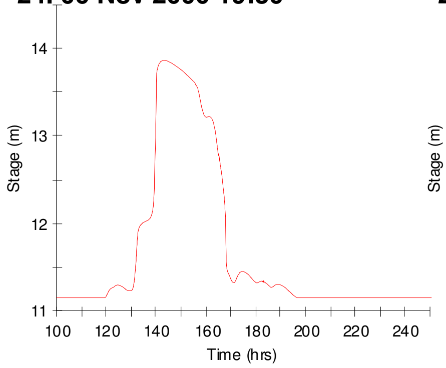
22. 30 Oct 2000 18:30



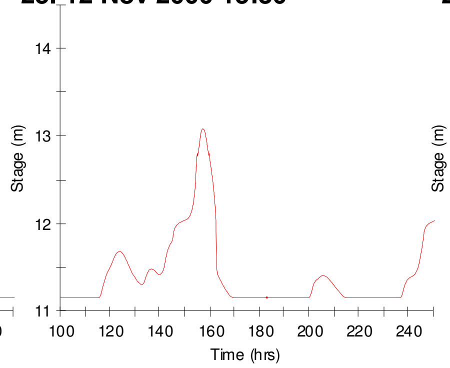
23. 03 Nov 2000 11:30



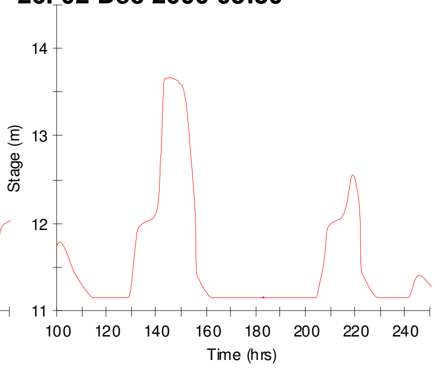
24. 06 Nov 2000 19:30



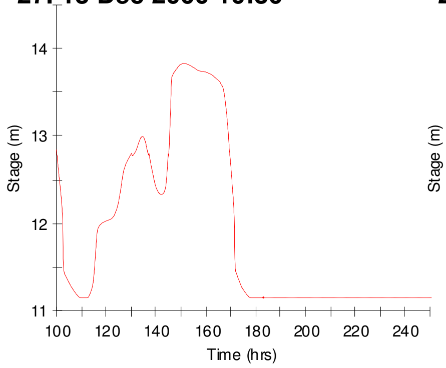
25. 12 Nov 2000 15:30



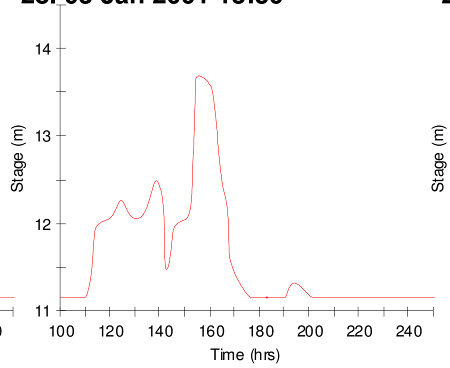
26. 02 Dec 2000 05:30



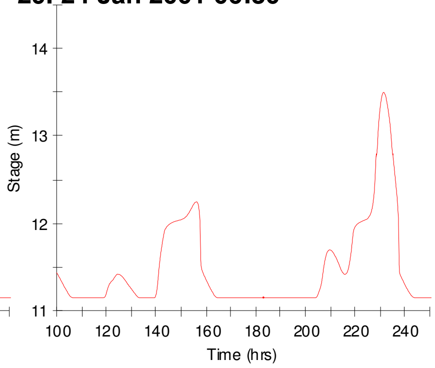
27. 13 Dec 2000 10:30



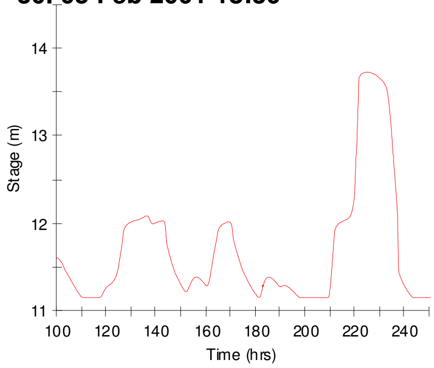
28. 05 Jan 2001 15:30



29. 24 Jan 2001 06:30



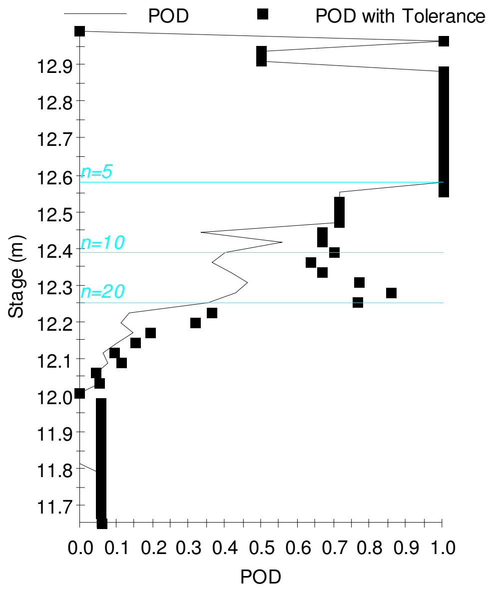
30. 05 Feb 2001 18:30

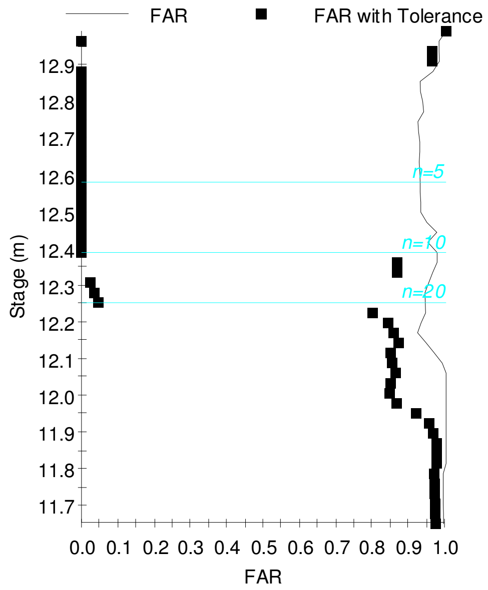


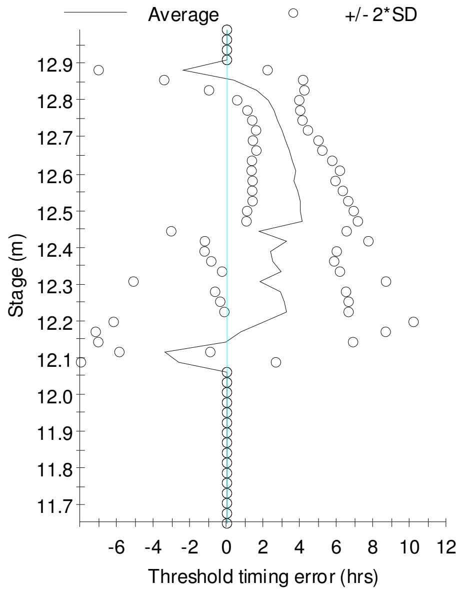
Key
Modelled
Observed

Darmans Bridge

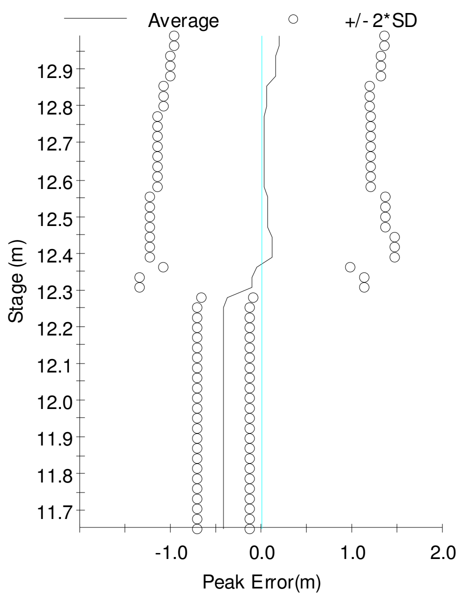
POD, FAR and peak matching statistics over full range of observations

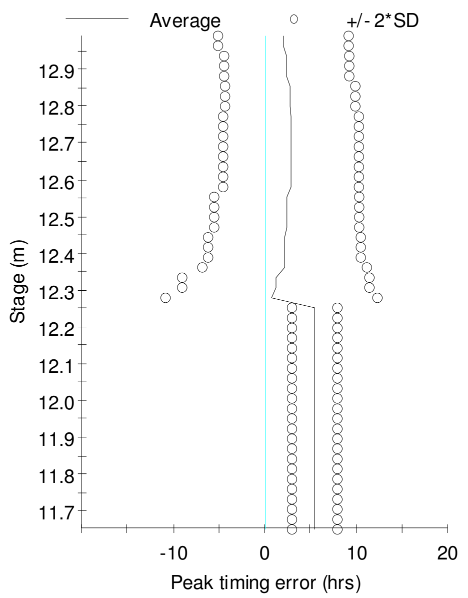






Notes: Moving average of 20 peaks used in peak calculation. Tolerance of 0.2 used in POD and FAR. Threshold crossing window is 5 to 5 hrs





Stonebridge

Data summary

38 peaks analysed at Stonebridge between 1.8m3/s and 96.0m3/s, for period 06 Nov 2000 to 01 Feb 2014 from :

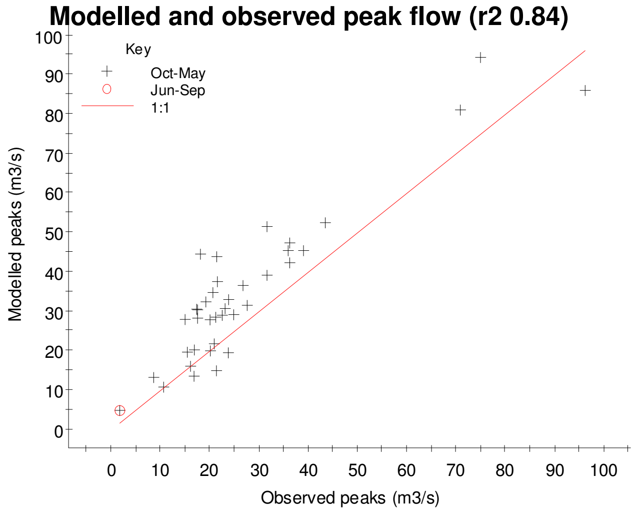
N:\2013\Projects\2013s7661 - Environment Agency - South East Region - Medway Catchment Mapping and Modelling\Calculations\04 Routing\06 MidMedway\09 Cascade

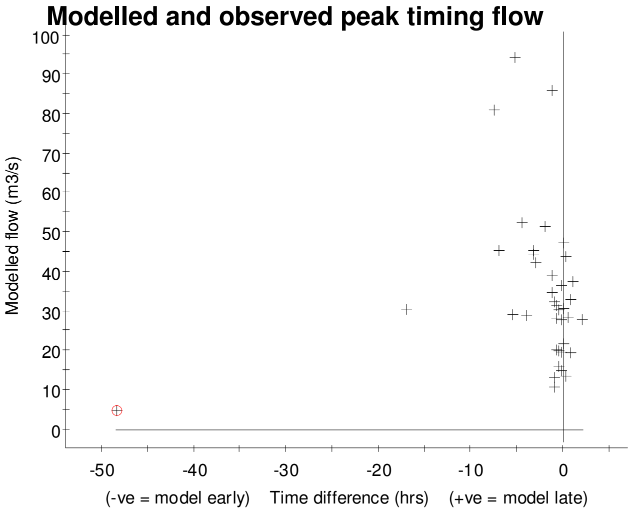
Peak magnitude and timing for the top ten observed events (09 Cascade)

	Observed		Modelled and differences				Event statistics		
	Date	Obs. (m3/s)	Mod. (m3/s)	Diff. (m3/s)	Diff (%)	Time Diff. (hrs)	NSE	r^2	RMSE
1	24 Dec 2013 11:30	96.03	85.97	-10.1	-10%	-1.3	0.791	0.836	7.68
2	06 Nov 2000 19:30	74.87	94.31	19.4	26%	-5.3	0.175	0.731	10.31
3	13 Dec 2000 10:30	70.73	80.99	10.3	15%	-7.5	0.369	0.655	9.33
4	08 Feb 2001 20:30	43.43	52.51	9.1	21%	-4.5	0.778	0.873	3.70
5	16 Jan 2008 01:30	38.96	45.41	6.4	17%	-3.3	0.798	0.919	3.55
6	10 Feb 2009 10:30	36.23	42.32	6.1	17%	-3.0	0.791	0.919	3.33
7	05 Jan 2001 15:30	36.20	47.35	11.2	31%	0.0	0.772	0.860	3.46
8	01 Feb 2014 12:30	35.85	45.40	9.5	27%	-7.0	0.778	0.843	3.94
9	01 Mar 2010 04:30	31.56	39.18	7.6	24%	-1.3	0.828	0.844	2.54
10	02 Jan 2014 07:30	31.56	51.52	20.0	63%	-2.0	-0.31	0.817	7.00

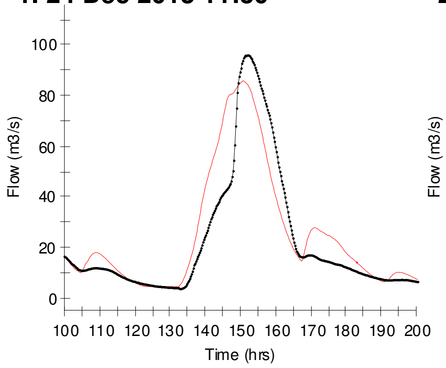
Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This model	1.71	2.94	1.59	1.74	1.53	0.71	4.00	1.96

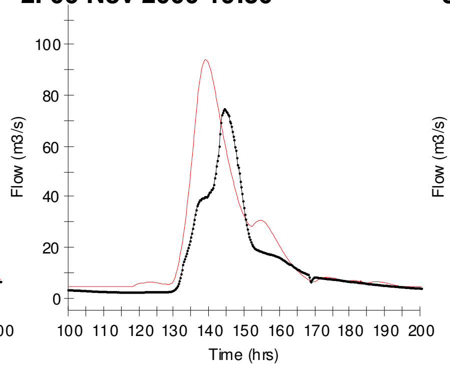




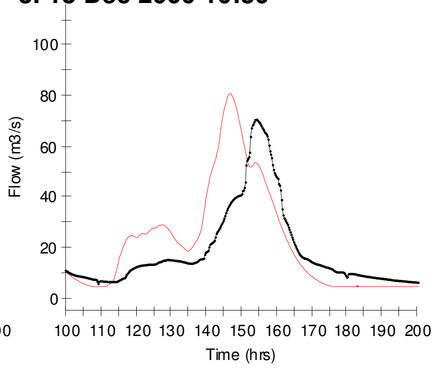
1. 24 Dec 2013 11:30



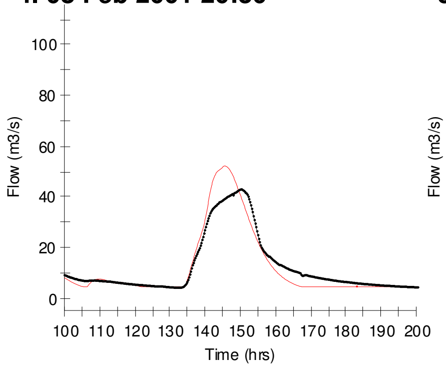
2. 06 Nov 2000 19:30



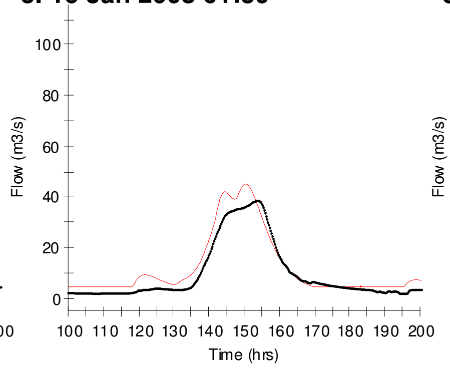
3. 13 Dec 2000 10:30



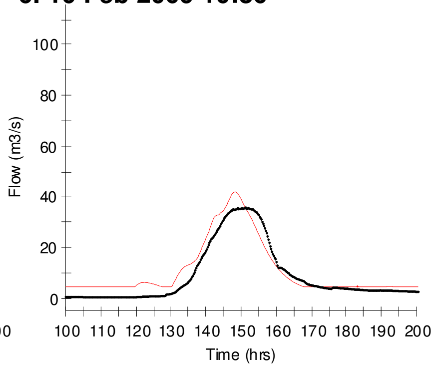
4. 08 Feb 2001 20:30



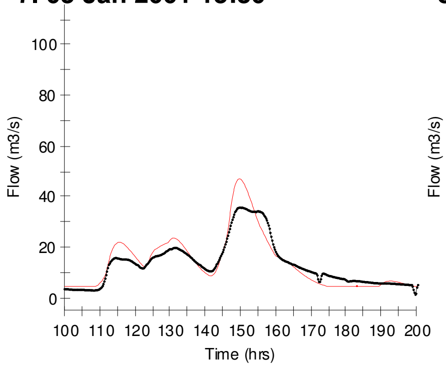
5. 16 Jan 2008 01:30



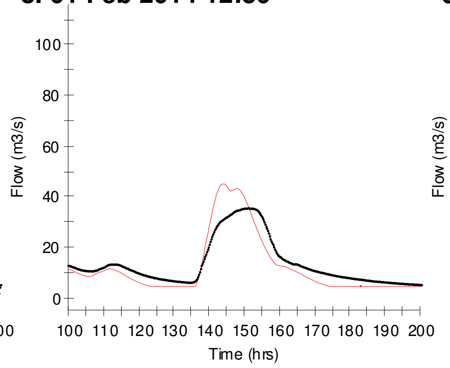
6. 10 Feb 2009 10:30



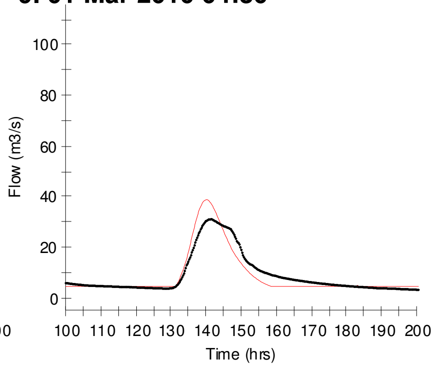
7. 05 Jan 2001 15:30



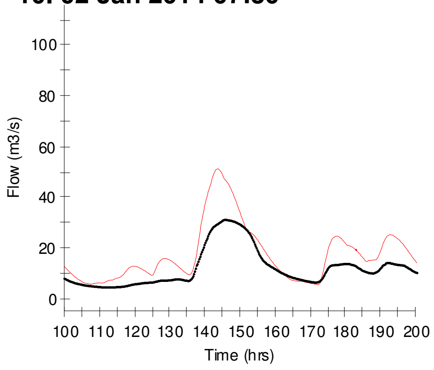
8. 01 Feb 2014 12:30



9. 01 Mar 2010 04:30



10. 02 Jan 2014 07:30



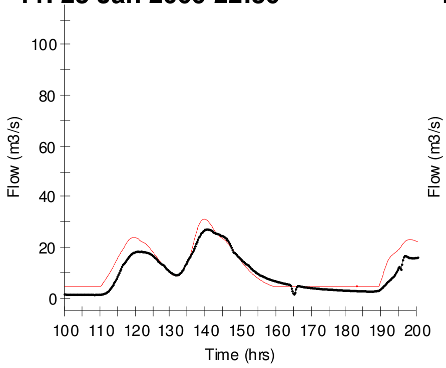
Key

Modelled

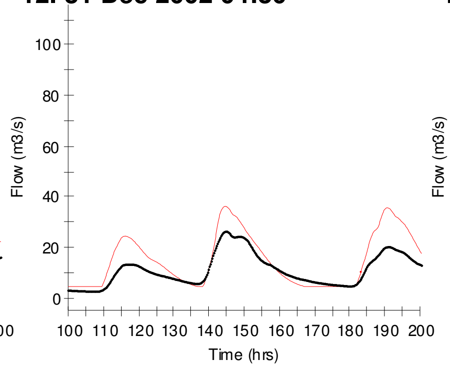
Observed

Stonebridge

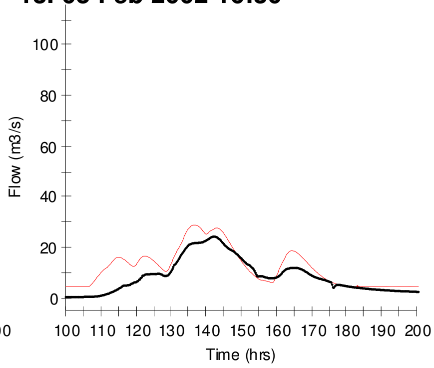
11. 23 Jan 2009 22:30



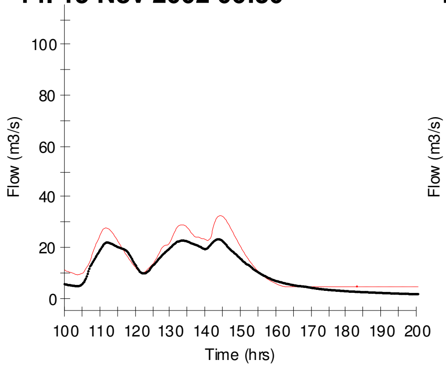
12. 31 Dec 2002 04:30



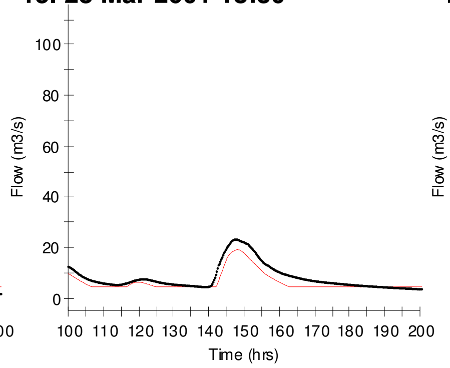
13. 05 Feb 2002 16:30



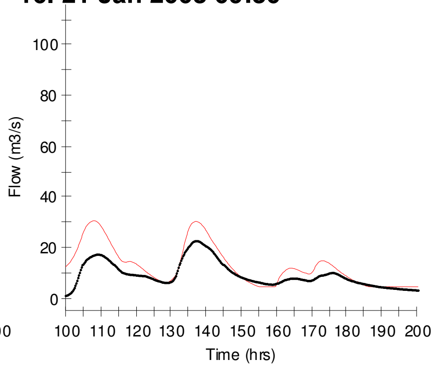
14. 15 Nov 2002 06:30



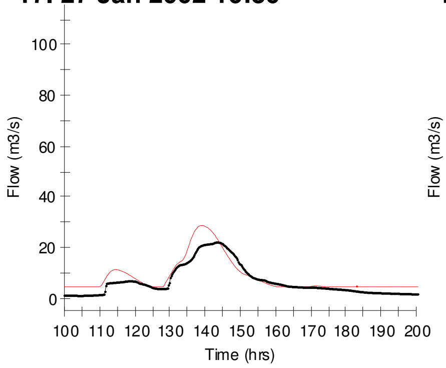
15. 23 Mar 2001 18:30



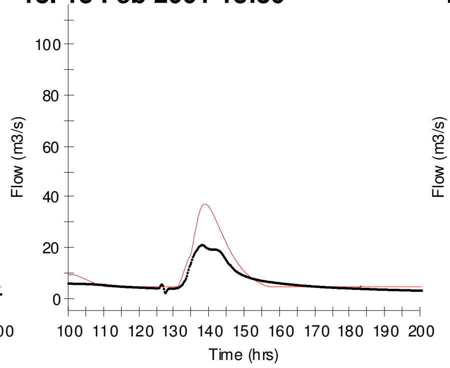
16. 21 Jan 2003 09:30



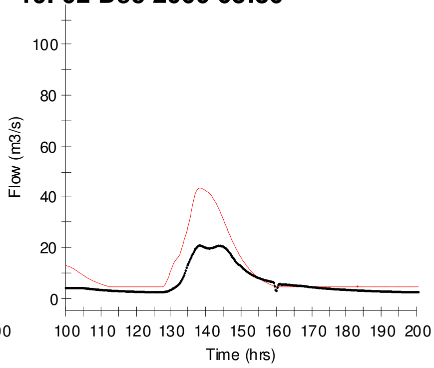
17. 27 Jan 2002 16:30



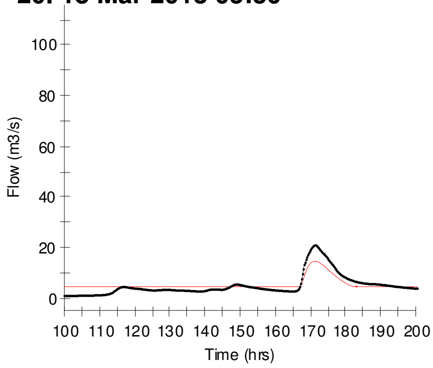
18. 13 Feb 2001 13:30

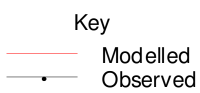


19. 02 Dec 2000 05:30

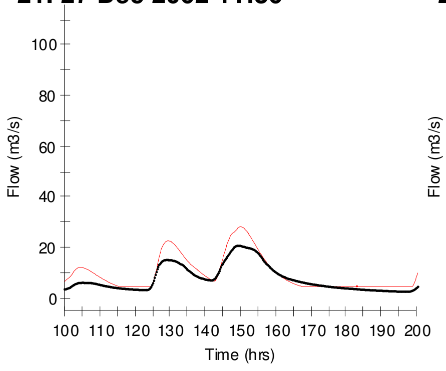


20. 18 Mar 2013 05:30

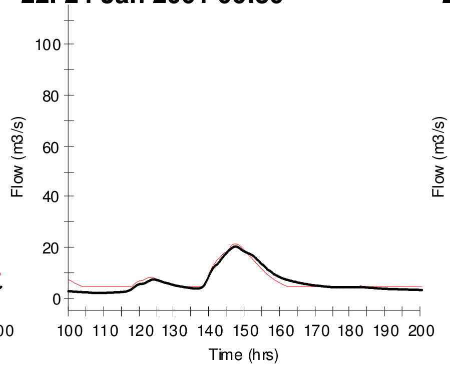




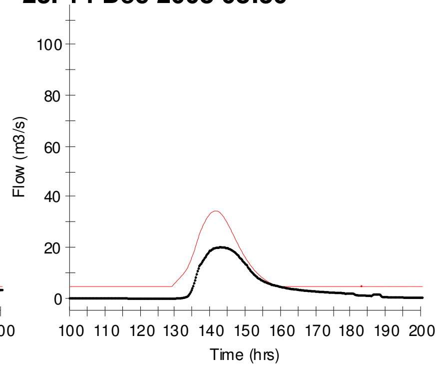
21. 27 Dec 2002 11:30



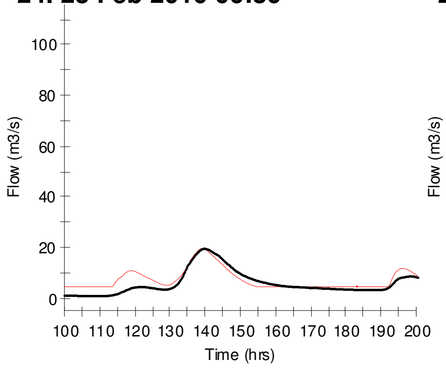
22. 24 Jan 2001 06:30



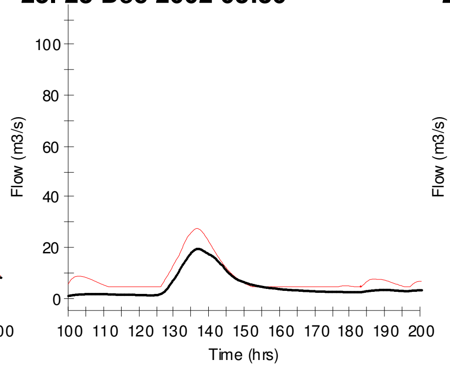
23. 14 Dec 2008 08:30



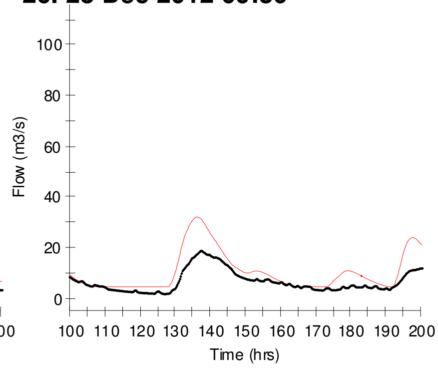
24. 23 Feb 2010 06:30



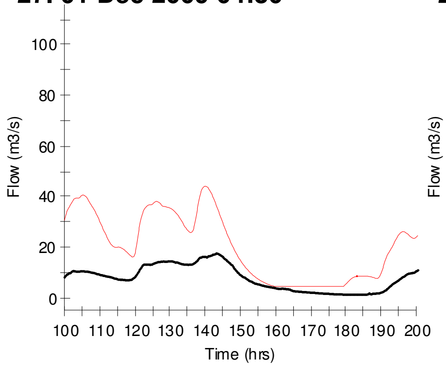
25. 23 Dec 2002 03:30



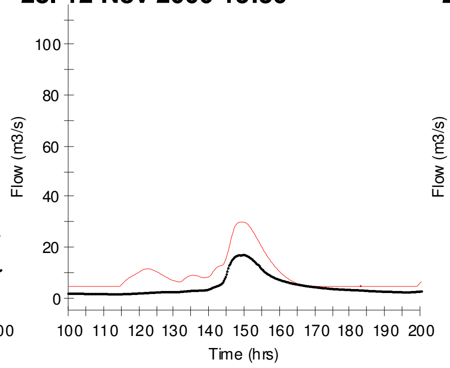
26. 23 Dec 2012 09:30



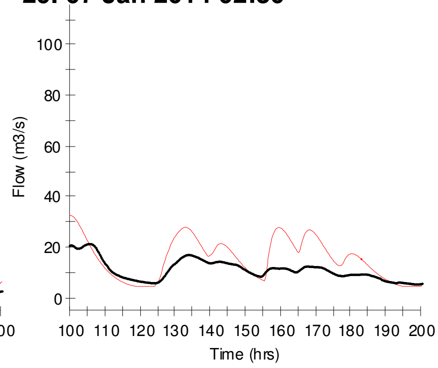
27. 01 Dec 2009 04:30



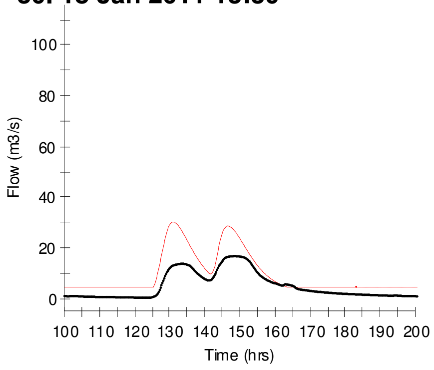
28. 12 Nov 2000 15:30



29. 07 Jan 2014 02:30



30. 18 Jan 2011 13:30



Key

Modelled

Observed

PDM Model Sheet for : Colliers_JBA02

Raingauges used		
TBR Ref	**Name**	**Weight**
463655903REev	EDEN VALE STW RTS	0.2
292554REev	Weir Wood Res RF	0.2
463501506REev	COWDEN LOGGER	0.2
463521512REev	REDGATE MILL tbr	0.2
463400901REev	Saints Mill	0.2
463521918REev	Jarvis Brook	0.2

Potential evaporation data from SINE curve

Min	0 mm/day	**Max**	3.06 mm/day	**Month**	Jul

Period of calibration

From	06 Apr 1993 18:00	**To**	07 Feb 2014 00:00

Level gauge : Not Found - 453400001HSG (No rating - level only)

PDM parameters

Surface		Identical linear cascade			**Base**	Cubic store			**Drainage**		Gravity		
Area	**Fc**	**Cmin**	**Cmax**	**b**	**Be**	**Kg**	**Bg**	**St**	**K1**	**K2**	**Kb**	**QConst**	**Tdly**
Km^2		**mm**	**mm**					**mm**	**hrs**	**hrs**	**hmm^2**	**m^3/s**	**hrs**
255.1	1	70	400	1.5	4	70000	1.75	60	7	n/a	0.5	0	4
Parameters of second PDM plotted (Colliers_NFFS)													
Surface		Linear cascade			**Base**	Cubic store			**Drainage**		Gravity		
255.1	1	0	130	0.5	2.5	80000	1.9	0	8	11	29.0	0	0.001

Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This PDM	1.90	0.67	0.34	1.02	1.16	2.10	3.55	1.67
Other PDM	1.70	2.47	1.02	1.12	0.40	0.51	2.33	1.38

Calibration Notes

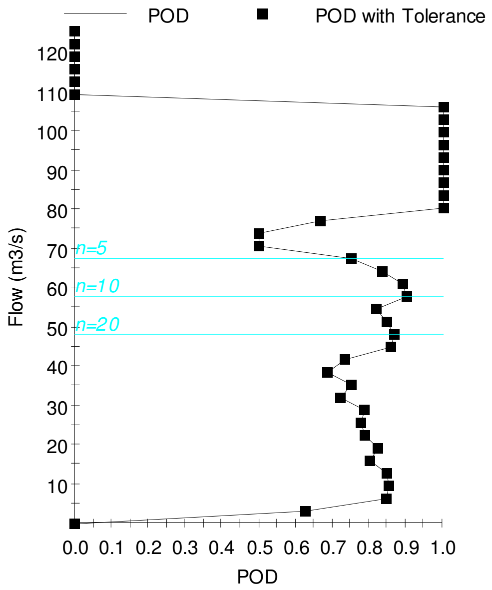
PDM based on Vexour, with small tweak to baseflow drainage to reduce inflow to the baseflow store. K also optimised slightly. Tried optimising rain gauge weights, but didn't improve perforance overall. Rainfall data suspect before 2006, so started model after that date. Mass balance and peak matching reasonable, but the modelled hydrograph can be 'slimmer' than the observed. Good variability though - looks reasonable. NOTE - have used the NFFS rating here.

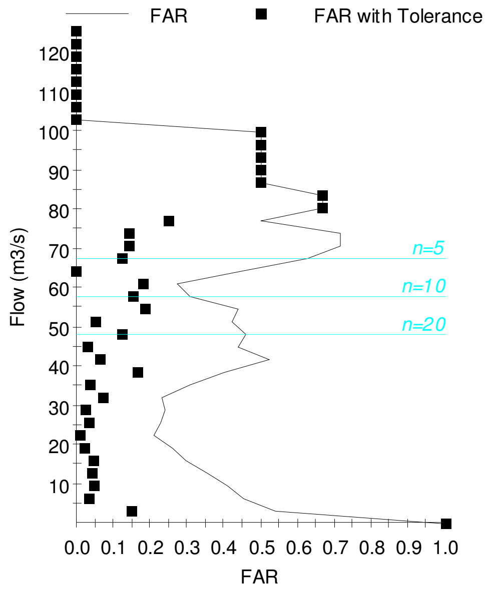
Calibration start date limited by 463400901REev - Saints Mill, end date limited by 463701508REev - WEIR WOOD RES tbr

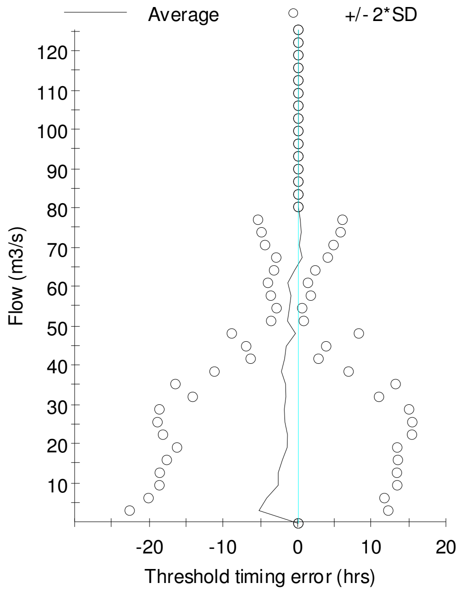
Calibration start date limited by 463400901REev - Saints Mill, end date limited by 463655903REev - EDEN VALE STW RTS

PDM Model Sheet for : Colliers_JBA02

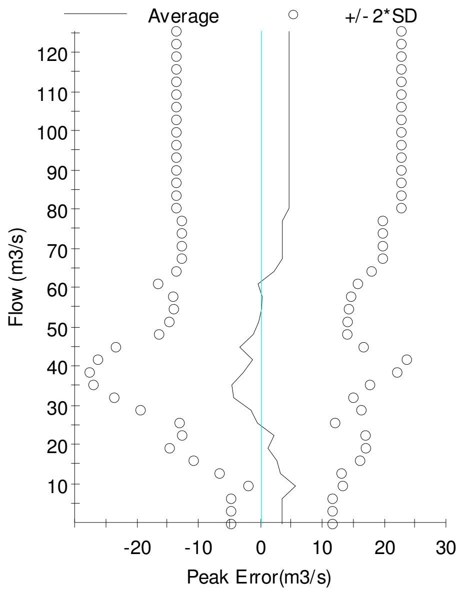
POD, FAR and peak matching statistics over full range of observations

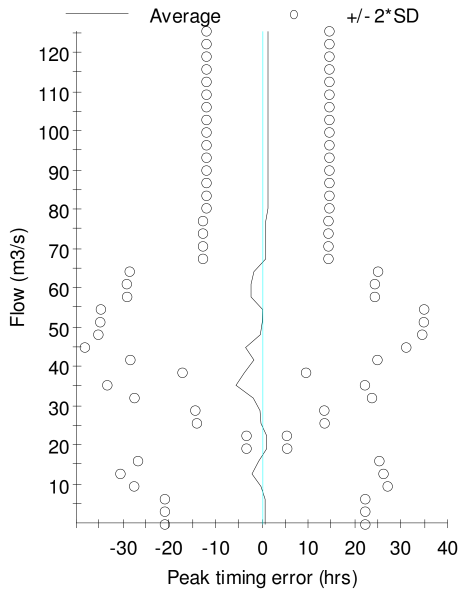






Notes: Peak statistics based on a moving average of 20 peaks. Tolerance of 0 used for POD and FAR. Threshold crossing window is -30 to +30 hrs



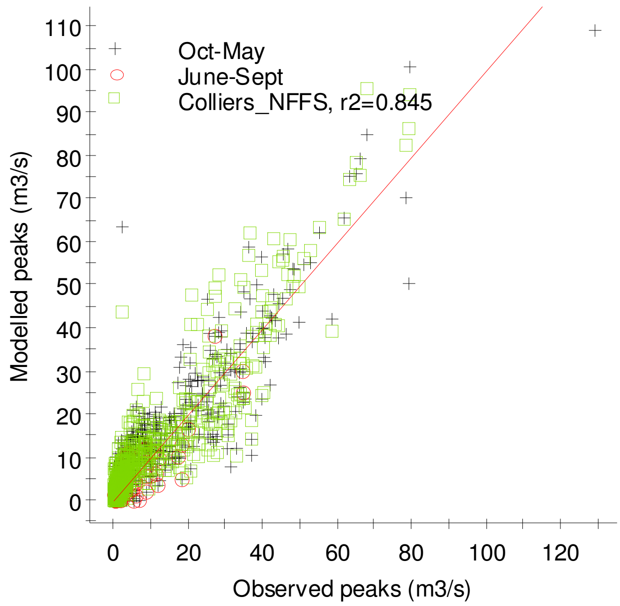


PDM Model Sheet for : Colliers_JBA02

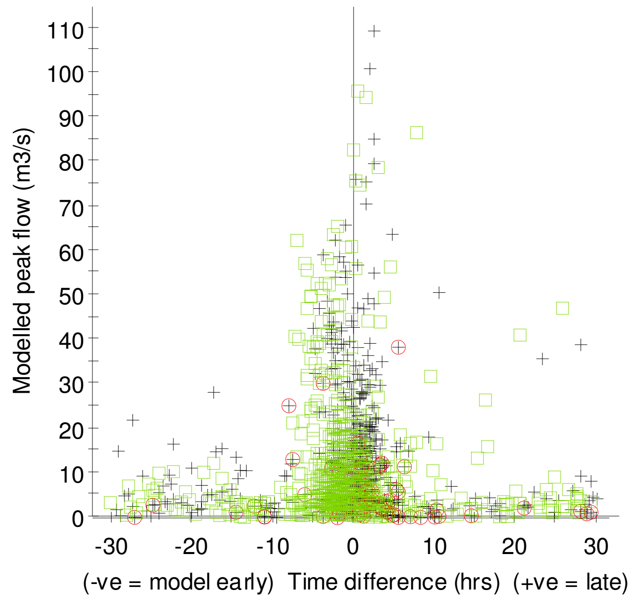
Peak magnitude and timing for the top ten observed events (Colliers_JBA02)

	Observed		Modelled		Difference		Event statistics		
	Date	**Flow (m3/s)**	**Date**	**Flow (m3/s)**	**Q (%)**	**T (hrs)**	**NSE**	**RMSE**	**r^2**
1	24/12/2013 09:15	128.6	24/12/2013 11:45	109.1	-15%	2.5	0.933	7.617	0.962
2	06/11/2000 07:15	79.2	06/11/2000 09:15	100.7	27%	2.0	0.708	9.701	0.950
3	12/10/2000 11:45	79.0	12/10/2000 22:15	50.6	-36%	10.5	0.751	10.627	0.840
4	25/12/1999 04:45	78.2	25/12/1999 06:15	70.4	-10%	1.5	0.933	4.293	0.948
5	30/10/2000 12:15	67.7	30/10/2000 14:45	85.0	25%	2.5	0.888	5.741	0.973
6	01/02/2014 07:15	65.9	01/02/2014 09:45	79.4	20%	2.5	0.900	4.998	0.964
7	13/12/2000 06:15	64.9	13/12/2000 06:30	75.9	17%	0.3	0.871	5.461	0.974
8	10/02/2009 06:30	63.1	10/02/2009 08:00	75.3	19%	1.5	0.877	5.396	0.978
9	02/01/2014 01:30	61.7	02/01/2014 00:30	65.7	7%	-1.0	0.811	5.759	0.911
10	28/05/2000 17:00	58.5	28/05/2000 14:15	42.3	-28%	-2.8	0.784	6.640	0.900

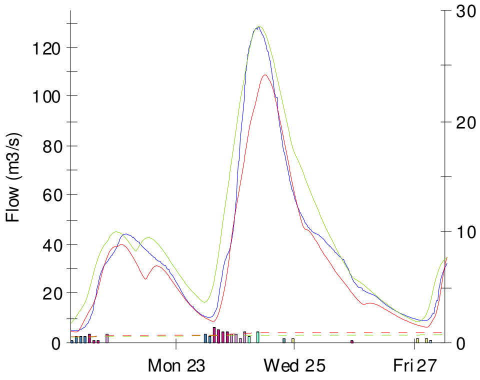
Modelled and observed peak flows, r2=0.815



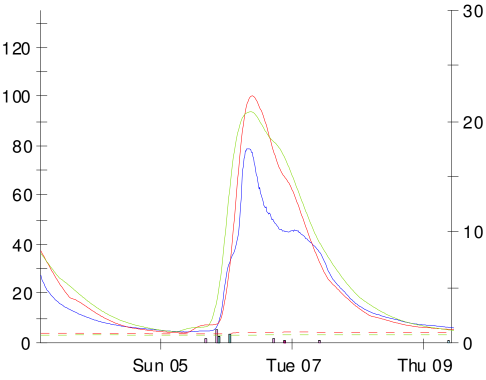
Modelled and observed peak timing



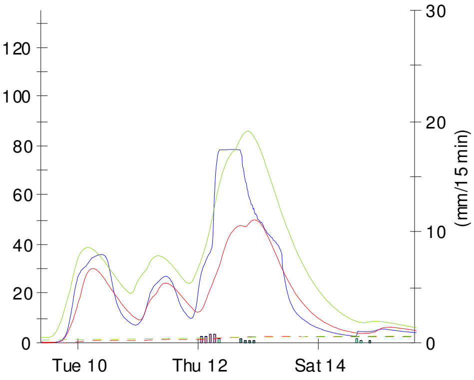
1. 24 Dec 2013 09:15 (81-106-142mm)



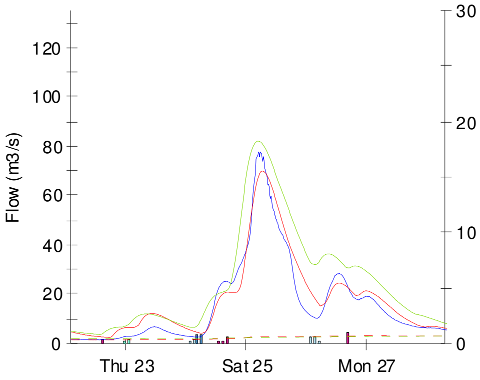
2. 06 Nov 2000 07:15 (11-55-63mm)



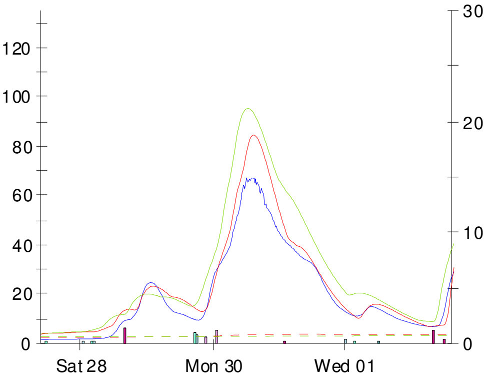
3. 12 Oct 2000 11:45 (27-102-104mm)



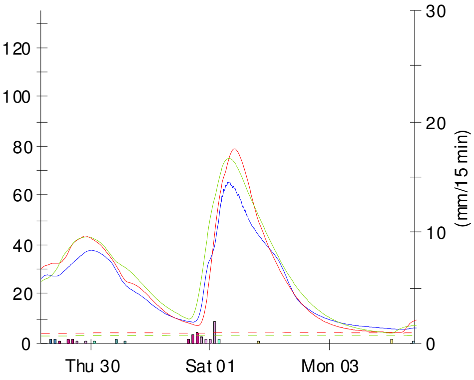
4. 25 Dec 1999 04:45 (14-69-86mm)



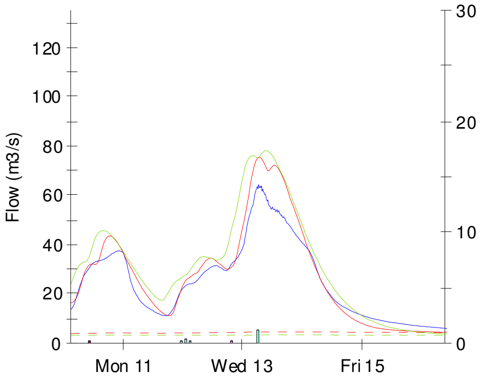
5. 30 Oct 2000 12:15 (4-90-116mm)



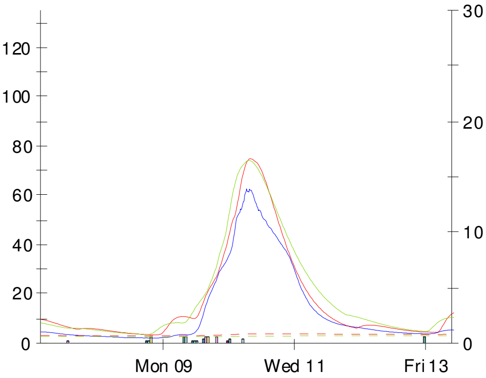
6. 01 Feb 2014 07:15 (42-54-74mm)



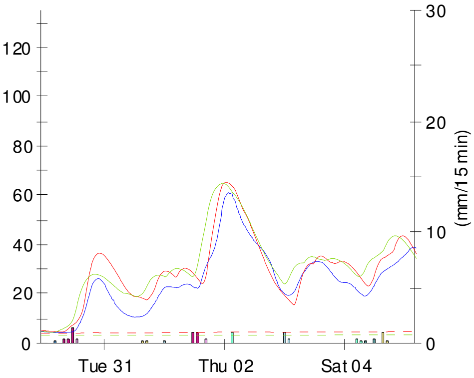
7. 13 Dec 2000 06:15 (27-57-75mm)



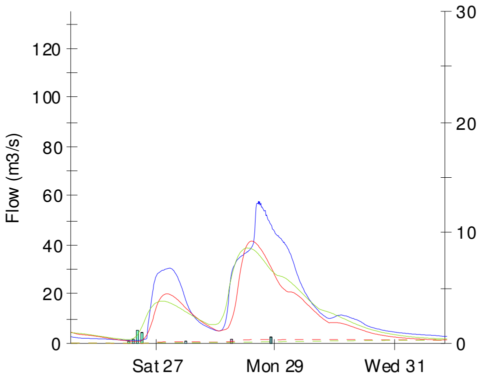
8. 10 Feb 2009 06:30 (42-49-56mm)



9. 02 Jan 2014 01:30 (66-77-97mm)



10. 28 May 2000 17:00 (33-69-80mm)

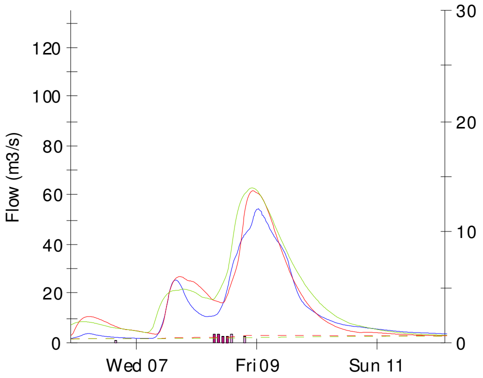


Key

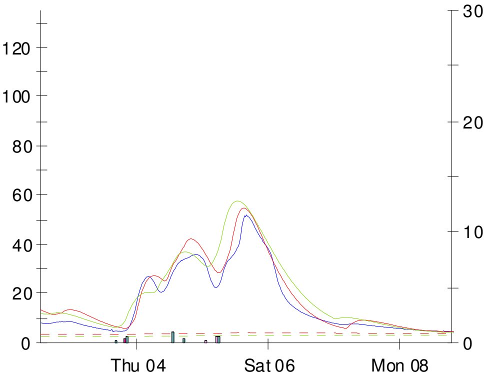
- 453400001HSG - Flow : COLLIERS LAND BRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Colliers_NFFS)
- Qg (Colliers_NFFS)
- 463655903REev - Recording Rain : EDEN VALE STW RTS
- 292554REev - Recording Rain : Weir Wood Res RF
- 463501506REev - Recording Rain : COWDEN LOGGER
- 463521512REev - Recording Rain : REDGATE MILL tbr
- 463400901REev - Recording Rain : Saints Mill
- 463521918REev - Recording Rain : Jarvis Brook
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

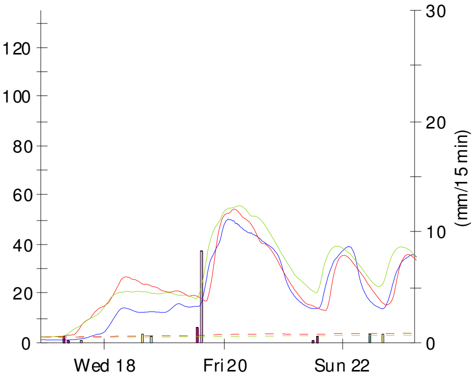
11. 09 Dec 1994 00:30 (50-52-55mm)



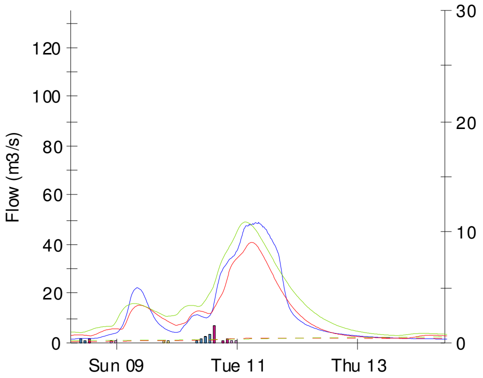
12. 05 Jan 2001 15:45 (36-45-59mm)



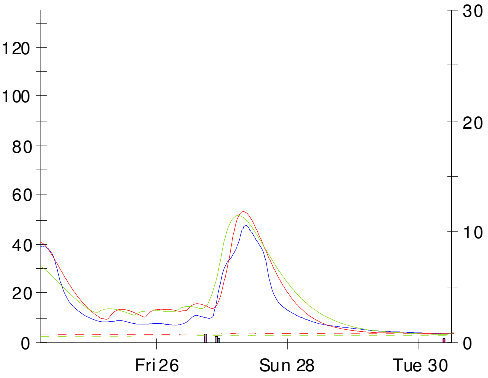
13. 20 Jan 1995 01:45 (80-83-84mm)



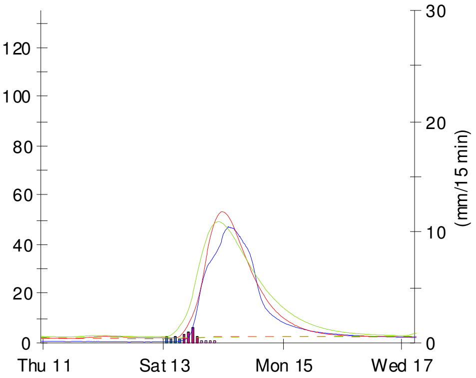
14. 11 Nov 2008 08:15 (27-56-64mm)



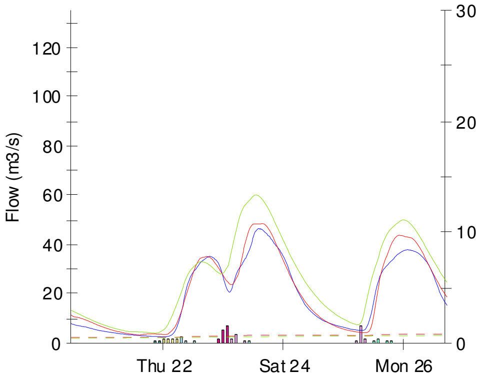
15. 27 Jan 2001 09:00 (25-32-40mm)



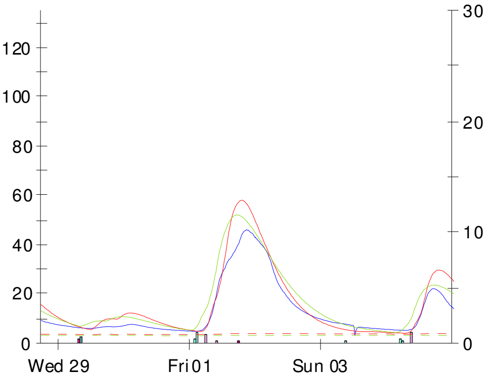
16. 14 Dec 2008 02:00 (30-36-44mm)



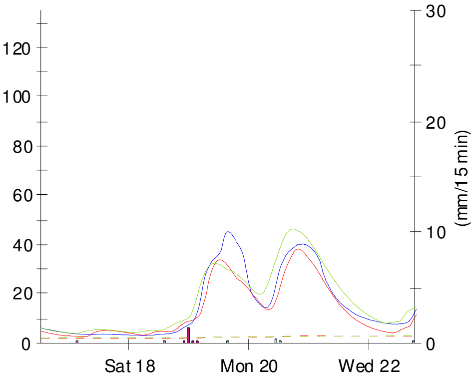
17. 23 Jan 2009 14:00 (54-66-80mm)



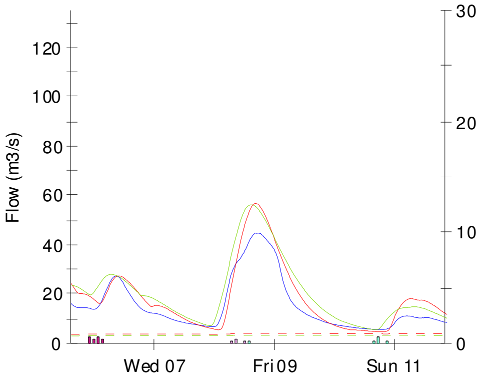
18. 01 Dec 2000 20:30 (30-40-45mm)



19. 19 Dec 1993 15:30 (1-50-55mm)



20. 08 Feb 2001 17:30 (9-42-47mm)



Key

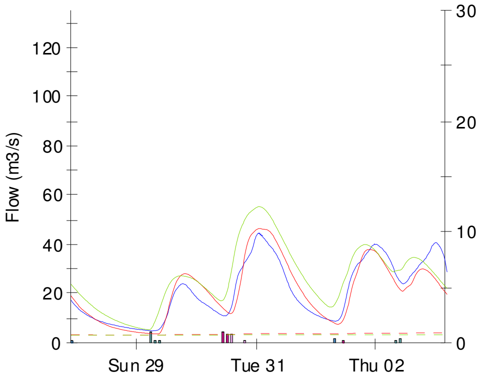
- 453400001HSG - Flow : COLLIERS LAND BRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Colliers_NFFS)
- Qg (Colliers_NFFS)
- 463655903REev - Recording Rain : EDEN VALE STW RTS
- 292554REev - Recording Rain : Weir Wood Res RF
- 463501506REev - Recording Rain : COWDEN LOGGER
- 463521512REev - Recording Rain : REDGATE MILL tbr
- 463400901REev - Recording Rain : Saints Mill
- 463521918REev - Recording Rain : Jarvis Brook
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

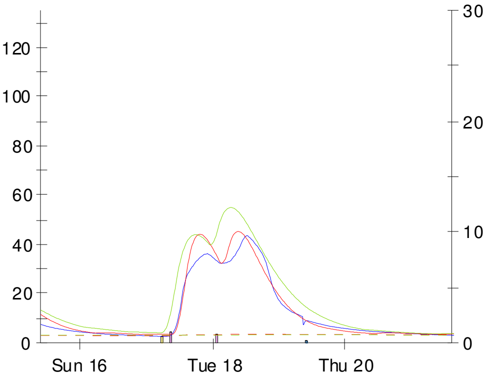
PDM Model Sheet for : Colliers_JBA02

JBA consulting

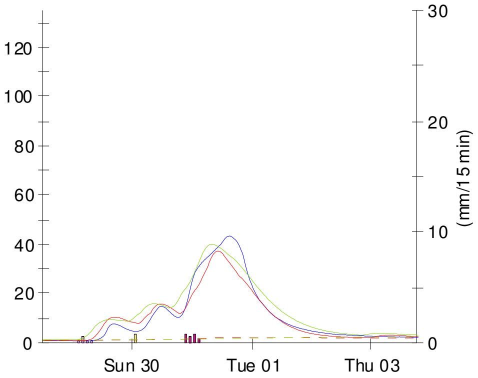
21. 31 Dec 2002 00:45 (57-58-59mm)



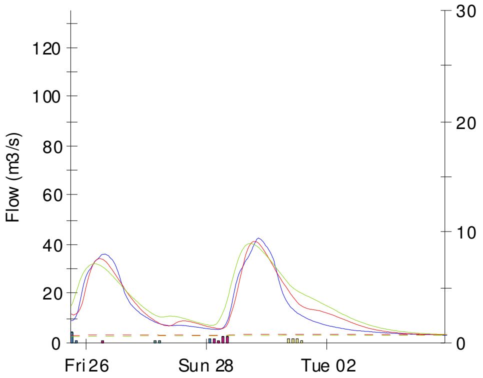
22. 18 Jan 2011 12:15 (6-32-35mm)



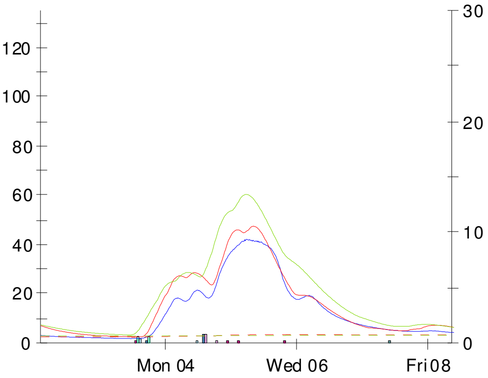
23. 31 Oct 1994 15:00 (2-47-53mm)



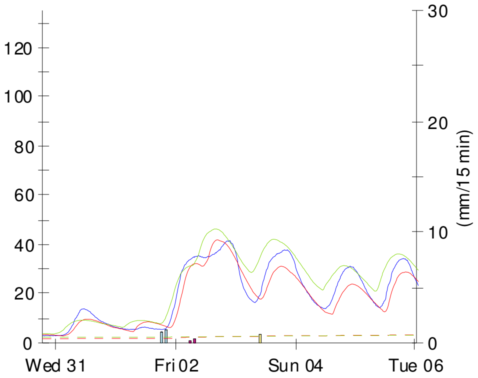
24. 28 Feb 2010 20:30 (32-36-38mm)



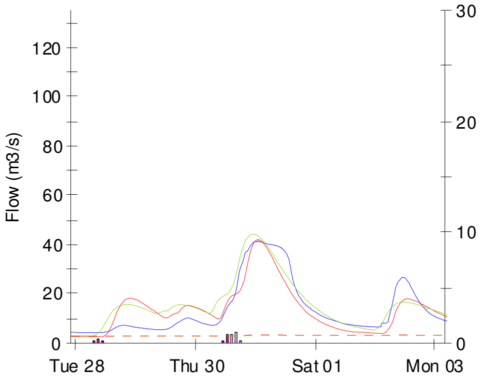
25. 05 Feb 2002 05:45 (7-48-59mm)



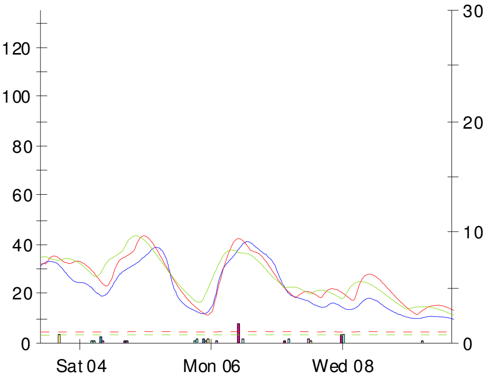
26. 02 Jan 1998 21:30 (18-71-84mm)



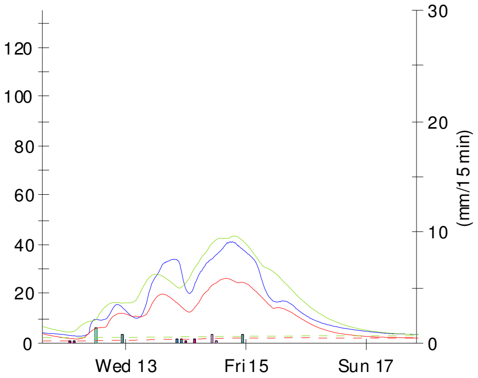
27. 31 Dec 1993 01:00 (11-42-44mm)



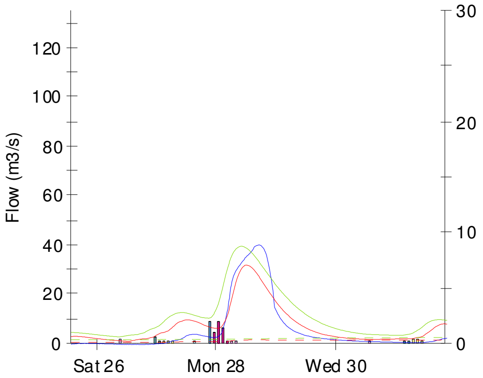
28. 06 Jan 2014 12:30 (37-49-61mm)



29. 14 Nov 2002 17:15 (21-48-59mm)



30. 28 Oct 2013 16:45 (0-45-82mm)



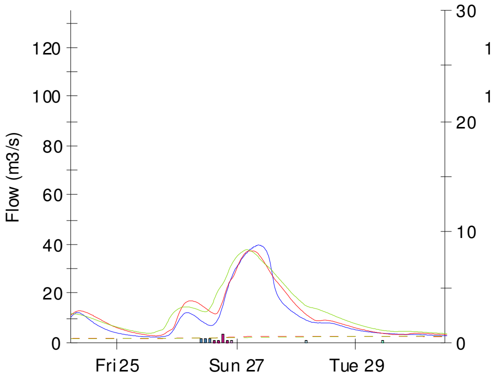
Key

- 453400001HSG - Flow : COLLIERS LAND BRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Colliers_NFFS)
- Qg (Colliers_NFFS)
- 463655903REev - Recording Rain : EDEN VALE STW RTS
- 292554REev - Recording Rain : Weir Wood Res RF
- 463501506REev - Recording Rain : COWDEN LOGGER
- 463521512REev - Recording Rain : REDGATE MILL tbr
- 463400901REev - Recording Rain : Saints Mill
- 463521918REev - Recording Rain : Jarvis Brook
- Average Rain

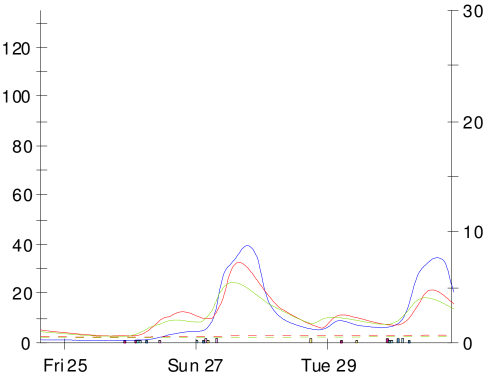
Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

JBA consulting

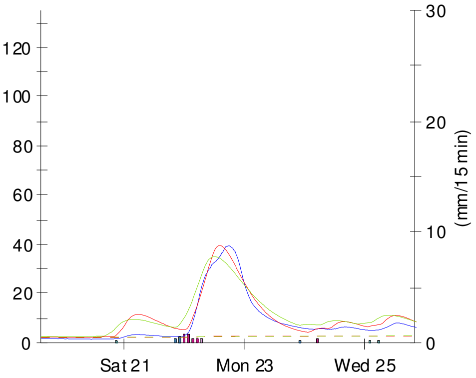
31. 27 Jan 2002 08:45 (8-38-47mm)



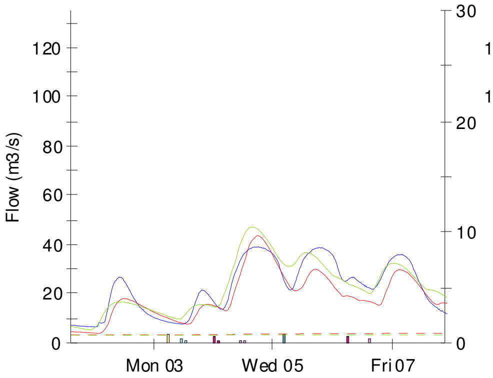
32. 27 Jan 2013 18:15 (29-38-45mm)



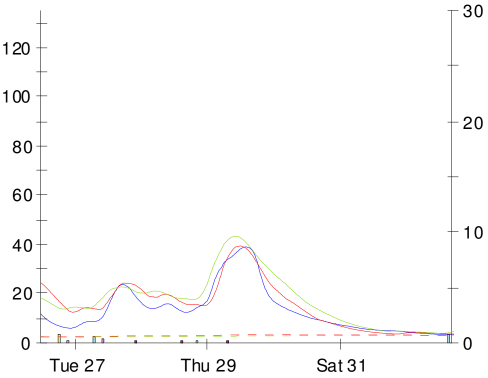
33. 22 Dec 2002 17:15 (31-35-39mm)



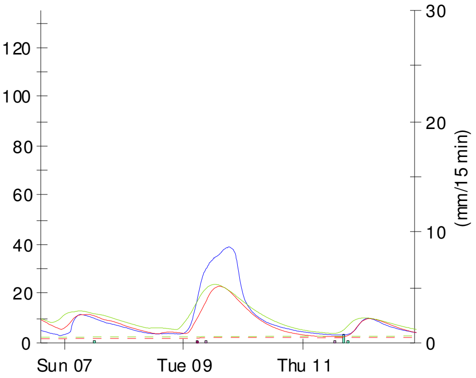
34. 04 Jan 1994 18:00 (14-55-71mm)



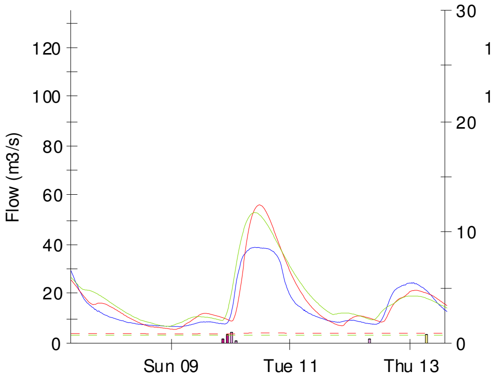
35. 29 Dec 1994 14:00 (2-42-45mm)



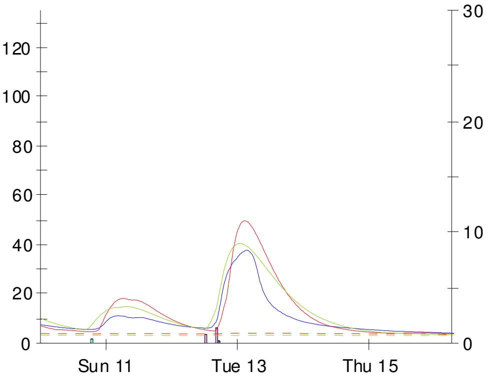
36. 09 Jan 1996 17:45 (1-27-42mm)



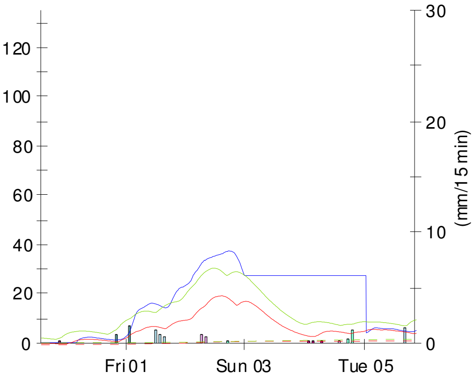
37. 10 Jan 1994 11:00 (6-39-42mm)



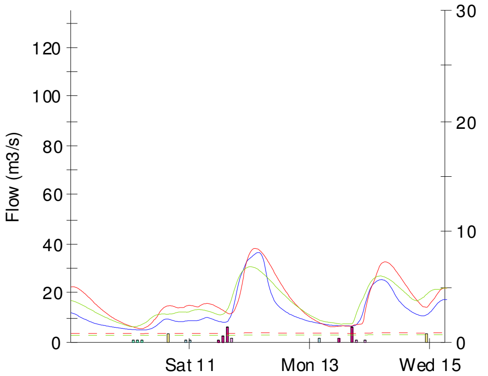
38. 13 Feb 2001 03:15 (17-26-29mm)



39. 02 Oct 1993 17:00 (5-73-89mm)



40. 12 Feb 1995 03:30 (35-43-54mm)



Key

- 453400001HSG - Flow : COLLIERS LAND BRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Colliers_NFFS)
- Qg (Colliers_NFFS)
- 463655903REev - Recording Rain : EDEN VALE STW RTS
- 292554REev - Recording Rain : Weir Wood Res RF
- 463501506REev - Recording Rain : COWDEN LOGGER
- 463521512REev - Recording Rain : REDGATE MILL tbr
- 463400901REev - Recording Rain : Saints Mill
- 463521918REev - Recording Rain : Jarvis Brook
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

PDM Model Sheet for : Lenside v01

Raingauges used

TBR Ref	Name	Weight
301329REev	Lenham RF	0.01
463210512REev	Sutton Valence	0.98
462121501REev	HAM HILL STW tbr	0.01

Potential evaporation data from SINE curve

Min	0 mm/day	Max	3.06 mm/day	Month	Jul

Period of calibration

From	01 Jan 2000 02:30	To	03 Mar 2014 19:30

Level gauge : Not Found - 453120001FQ (No rating - level only)

PDM parameters

Surface		Linear cascade			Base	Cubic store			Drainage		Gravity		
Area	**Fc**	**Cmin**	**Cmax**	**b**	**Be**	**Kg**	**Bg**	**St**	**K1**	**K2**	**Kb**	**QConst**	**Tdly**
Km^2		**mm**	**mm**					**mm**	**hrs**	**hrs**	**hmm^2**	**m^3/s**	**hrs**
69.7	1	30	500	0.6	3	10000	1.6	50	4	20	1259.9	0	3

Model scores

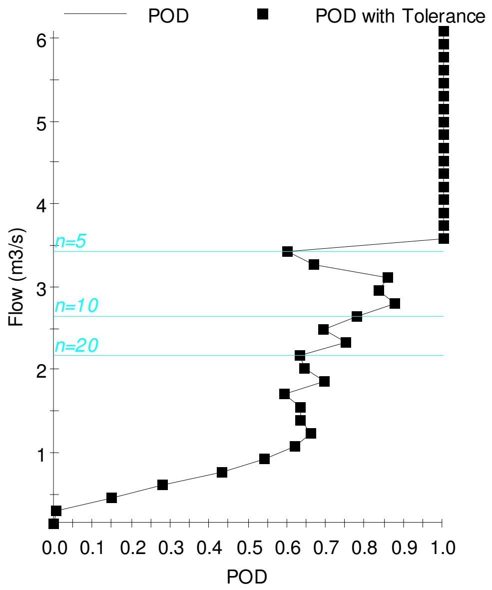
	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This PDM	1.90	1.39	0.63	3.22	1.78	2.39	0.60	1.79

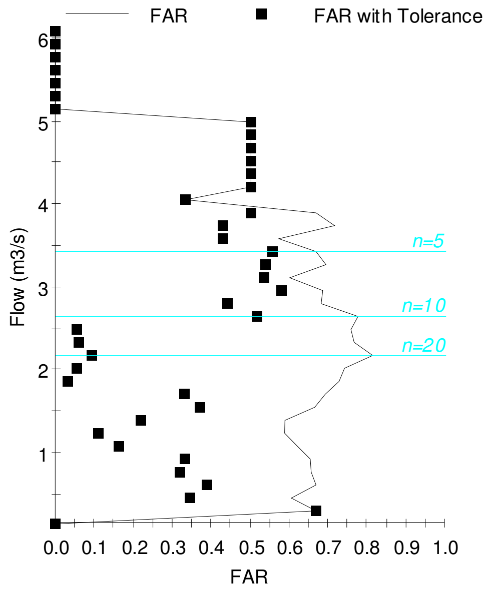
Calibration Notes

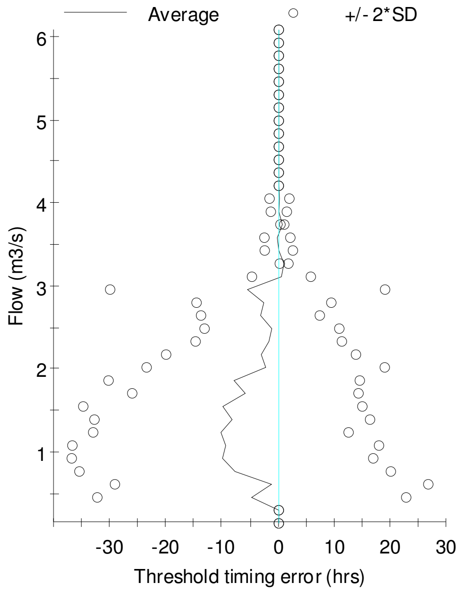
This PDM represents the River Len at Lenside gauging station. This is a chalk catchment and highly permeable. It is a right bank tributary of the Medway. The PDM has been developed to provide lateral inflows to the Lower Medway mapping study. It will be run in continuous simulation to generate the appropriate flow series. Parameters reflect the chalky nature of the catchment (large soil store, small drainage constant, very long baseflow time constant). Results are very good when the model is run with sutton Valance rainfall. Data are not available for Lenham and Ham Hill (not provided as outside the Medway catchment). There does not appear to be any need ti use these - and the long response time of the catchment means it is not particularly sensitive to short duration fluctuations in rainfall intensity.

PDM Model Sheet for : Lenside v01

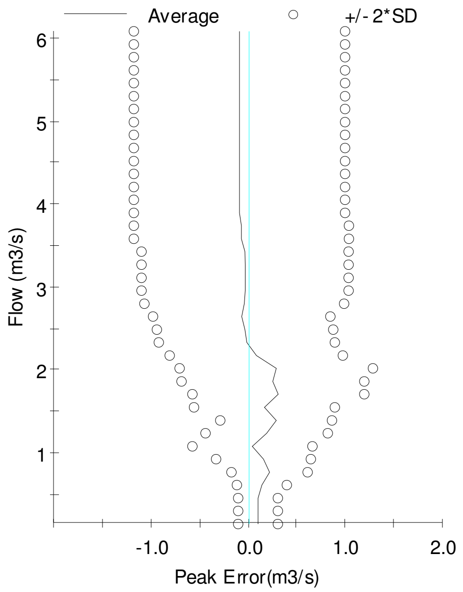
POD, FAR and peak matching statistics over full range of observations

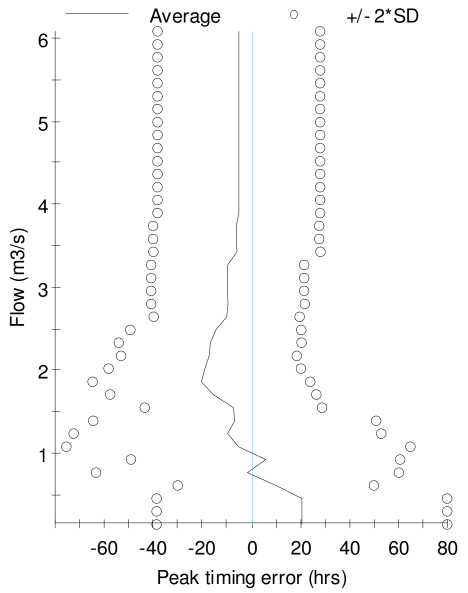






Notes: Peak statistics based on a moving average of 20 peaks. Tolerance of 0 used for POD and FAR. Threshold crossing window is -30 to +30 hrs



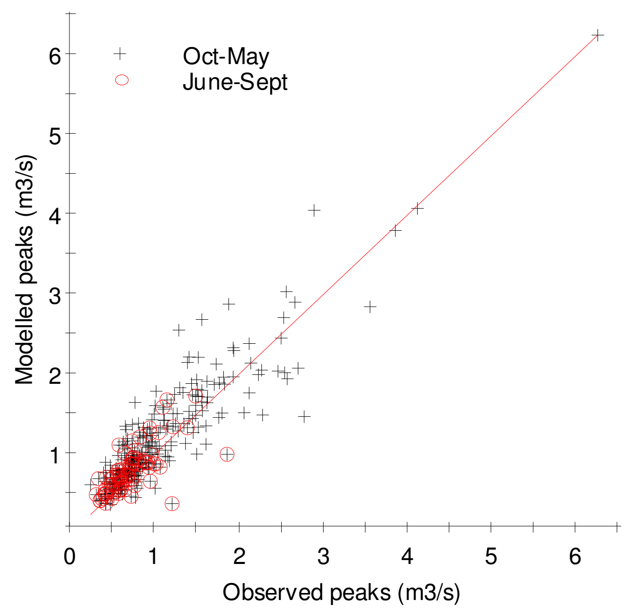


PDM Model Sheet for : Lenside v01

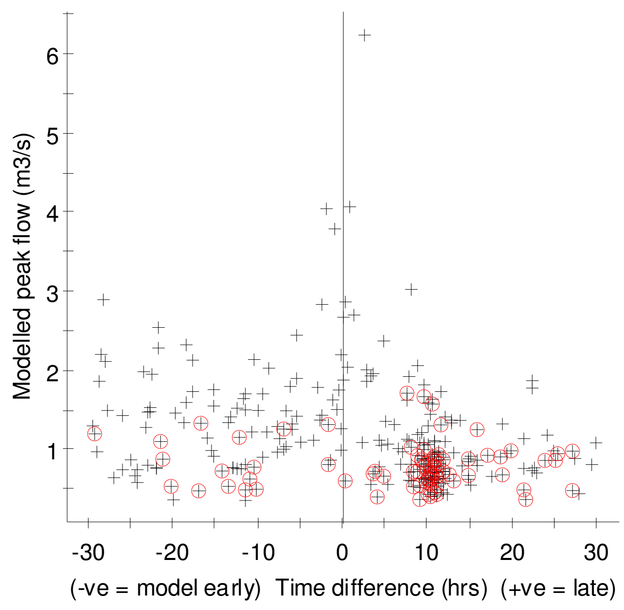
Peak magnitude and timing for the top ten observed events

	Observed		Modelled		Difference		Event statistics		
	Date	**Flow (m3/s)**	**Date**	**Flow (m3/s)**	**Q (%)**	**T (hrs)**	**NSE**	**RMSE**	**r^2**
1	31/12/2002 01:30	6.2	31/12/2002 04:00	6.2	0%	2.5	0.860	0.468	0.937
2	24/12/2013 13:00	4.1	24/12/2013 13:45	4.1	-1%	0.8	0.872	0.320	0.885
3	28/02/2010 21:00	3.9	28/02/2010 20:00	3.8	-1%	-1.0	0.588	0.412	0.781
4	10/02/2009 13:15	3.6	10/02/2009 10:45	2.8	-20%	-2.5	0.458	0.537	0.783
5	30/11/2009 17:15	2.9	30/11/2009 15:15	4.1	40%	-2.0	-0.548	0.862	0.328
6	30/04/2012 12:15	2.8	29/04/2012 16:30	1.5	-47%	-19.7	0.124	0.619	0.204
7	17/01/2010 01:30	2.7	17/01/2010 10:15	2.1	-23%	8.8	0.264	0.557	0.331
8	31/12/2009 12:30	2.7	30/12/2009 08:15	2.9	9%	-28.3	-0.885	0.605	0.073
9	04/01/2003 15:00	2.6	04/01/2003 18:15	1.9	-24%	3.2	0.374	0.654	0.796
10	28/05/2000 06:45	2.6	28/05/2000 14:45	3.0	19%	8.0	0.385	0.472	0.448

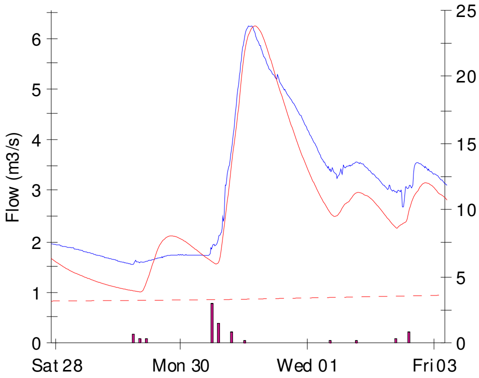
Modelled and observed peak flows, r2=0.814



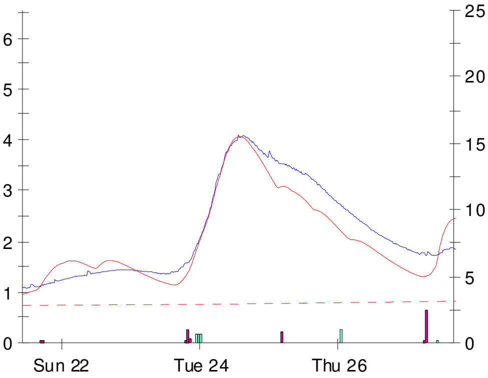
Modelled and observed peak timing



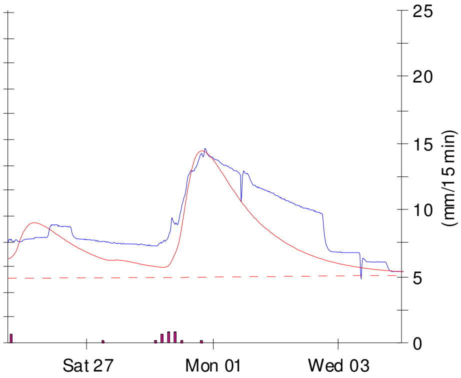
1. 31 Dec 2002 01:30 (0-84-85mm)



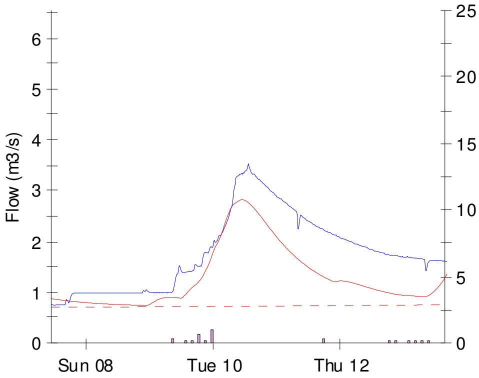
2. 24 Dec 2013 13:00 (77mm)



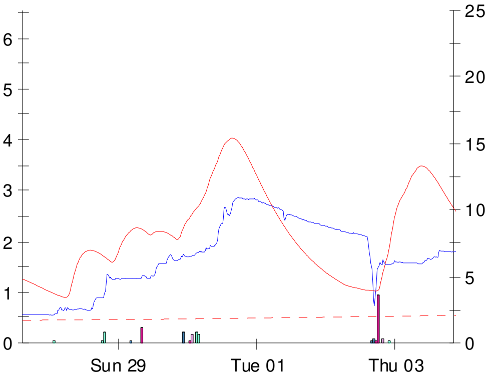
3. 28 Feb 2010 21:00 (35-35-40mm)



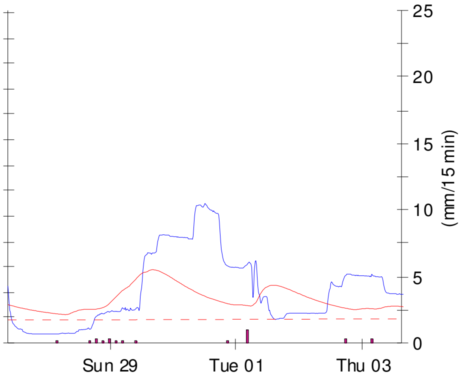
4. 10 Feb 2009 13:15 (42-42-44mm)



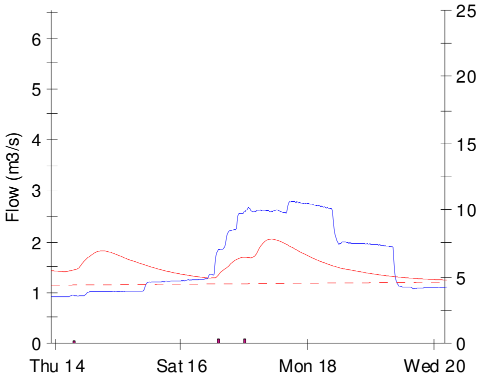
5. 30 Nov 2009 17:15 (63-82-83mm)



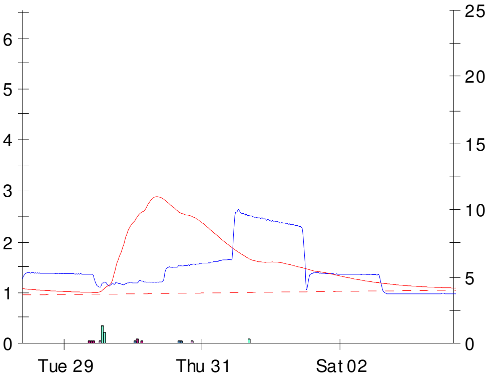
6. 30 Apr 2012 12:15 (32mm)



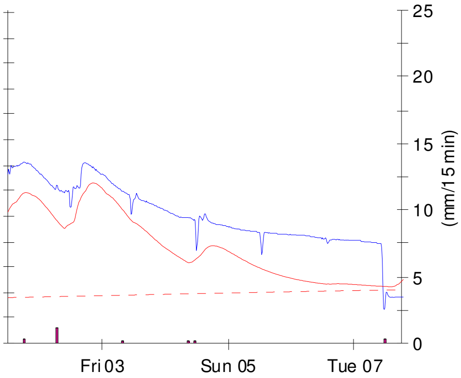
7. 17 Jan 2010 01:30 (18-18-18mm)



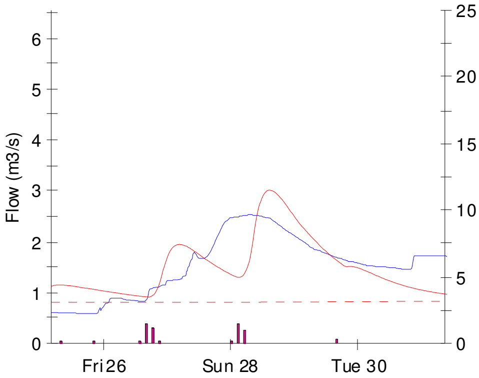
8. 31 Dec 2009 12:30 (20-28-28mm)



9. 04 Jan 2003 15:00 (24-25-28mm)



10. 28 May 2000 06:45 (51-52-62mm)



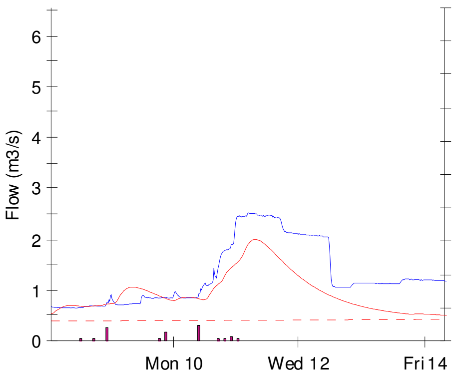
Key

- 453120001FQ - Flow : LENSIDE
- Modelled Q
- Modelled Qg
- 301329REev - Recording Rain : Lenham RF
- 463210512REev - Recording Rain : Sutton Valence
- 462121501REev - Recording Rain : HAM HILL STW tbr
- Average Rain

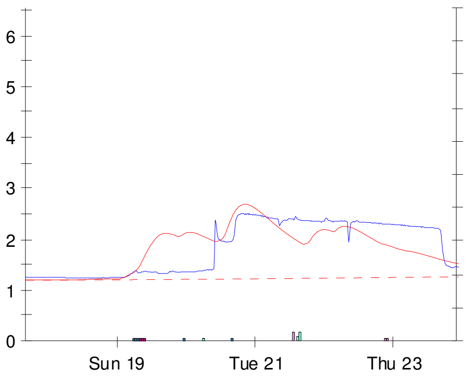
Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

PDM Model Sheet for : Lenside v01

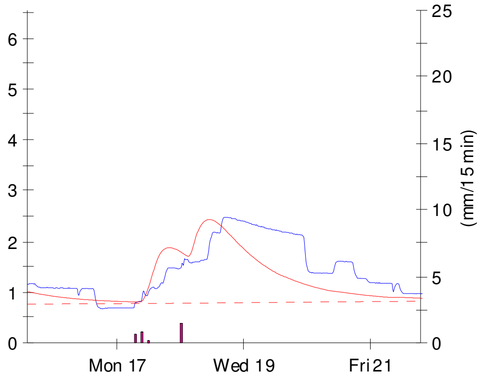
11. 11 Nov 2008 04:30 (35-35-37mm)



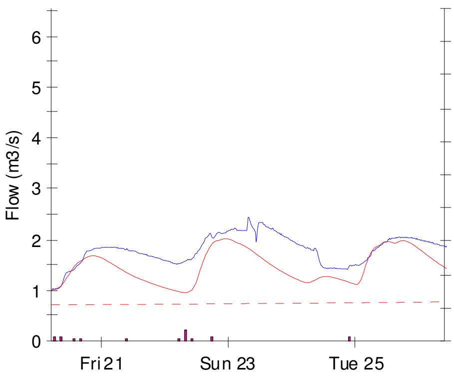
12. 20 Jan 2003 19:00 (18-35-36mm)



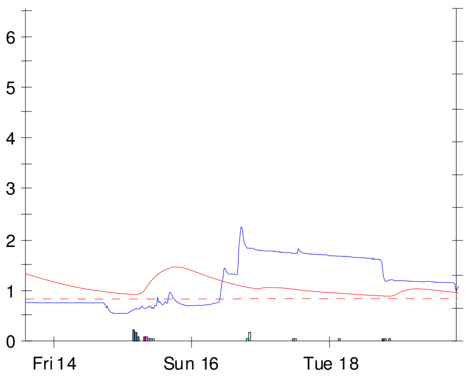
13. 18 Jan 2011 16:30 (21-25-34mm)



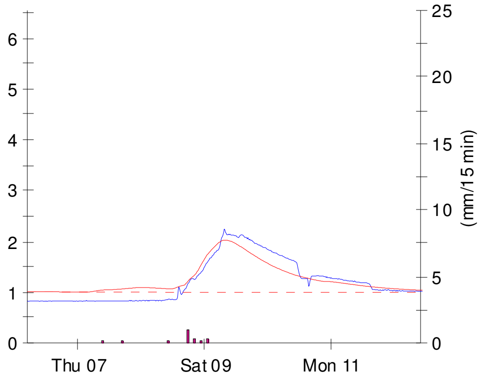
14. 23 Dec 2012 07:30 (44mm)



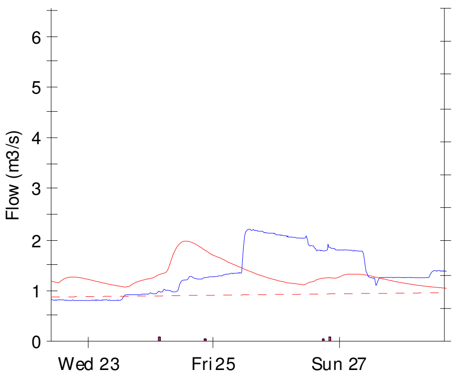
15. 16 Apr 2000 17:15 (16-16-33mm)



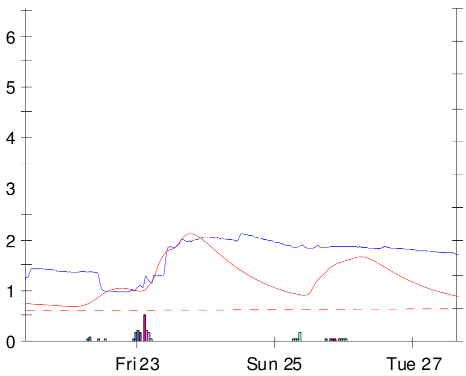
16. 09 Mar 2013 07:30 (24mm)



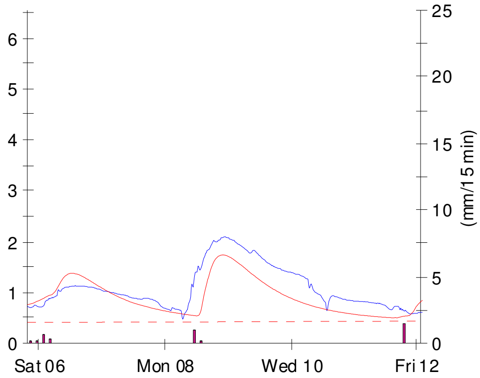
17. 25 Dec 2009 13:00 (13-18-18mm)



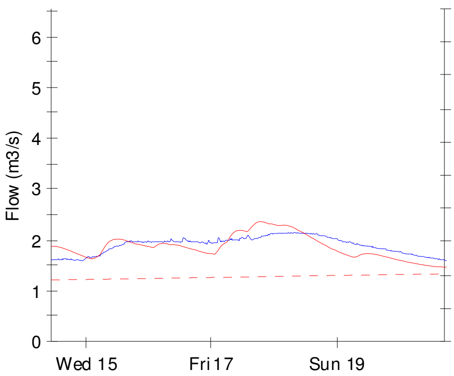
18. 24 Jan 2009 12:00 (43-43-50mm)



19. 08 Oct 2012 22:30 (36mm)



20. 17 Jan 2014 14:00 (24mm)



Key

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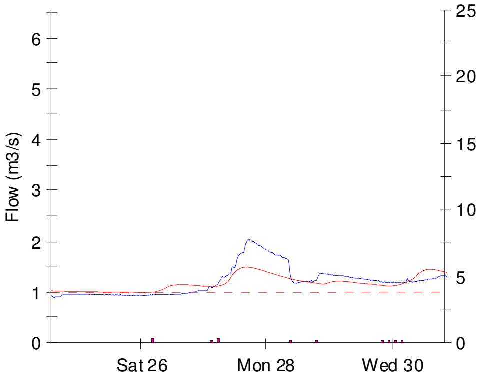
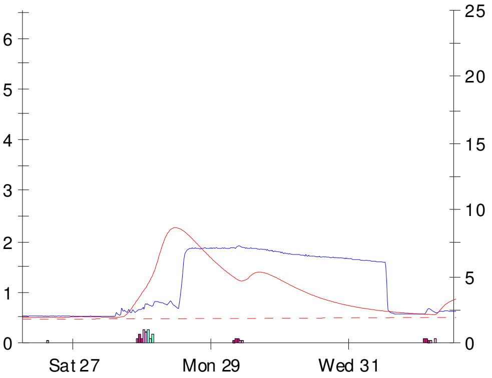
- 463210512REev - Recording Rain : Sutton Valence
- 462121501REev - Recording Rain : HAM HILL STW tbr
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

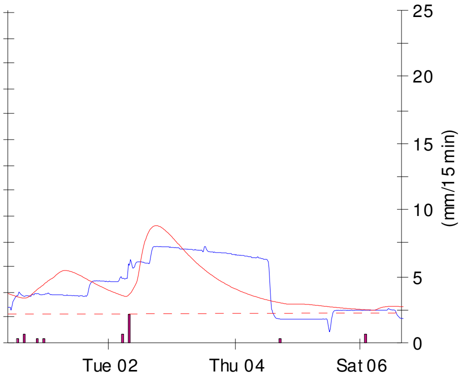
21. 27 Jan 2013 17:15 (17mm)



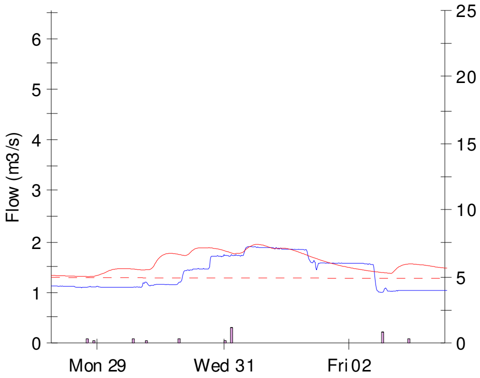
22. 29 Dec 2003 09:45 (0-38-42mm)



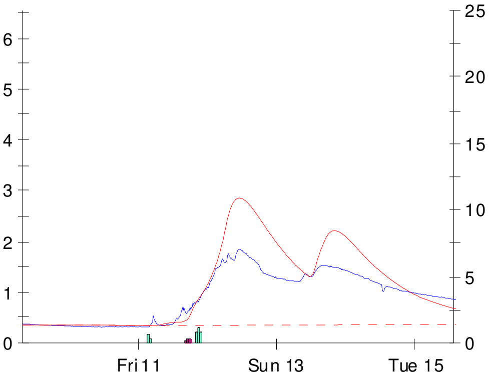
23. 03 Oct 2001 12:45 (35-40-40mm)



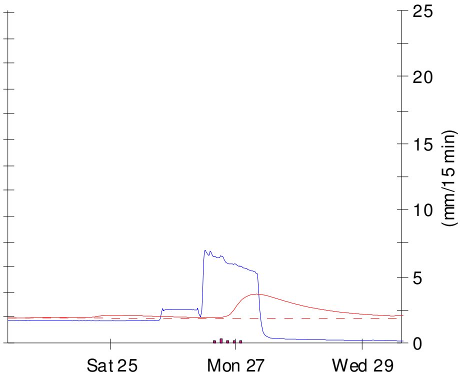
24. 31 Mar 2010 09:30 (24-29-37mm)



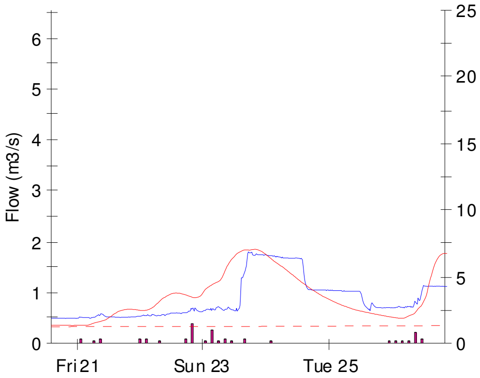
25. 12 Oct 2013 10:30 (75mm)



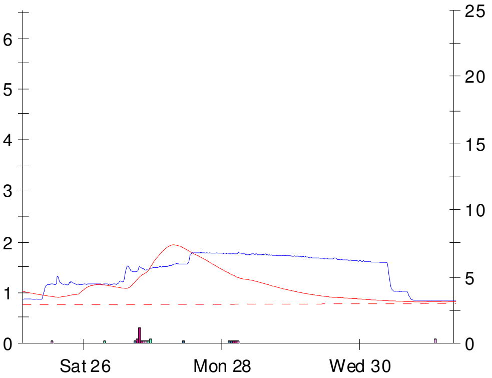
26. 26 Sep 2010 12:00 (11-15-25mm)



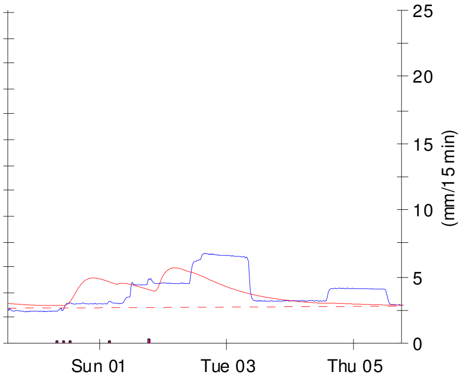
27. 23 Nov 2003 17:15 (33-63-73mm)



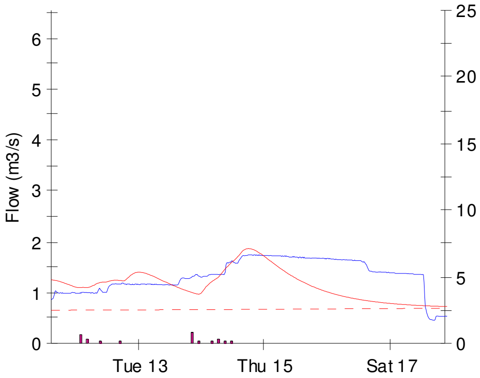
28. 28 Jan 2002 05:45 (24-25-27mm)



29. 02 Feb 2004 15:45 (17-17-17mm)



30. 14 Feb 2007 18:00 (0-27-27mm)



Key

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- Modelled Qg
- 301329REev - Recording Rain : Lenham RF
- 463210512REev - Recording Rain : Sutton Valence
- 462121501REev - Recording Rain : HAM HILL STW tbr
- Average Rain

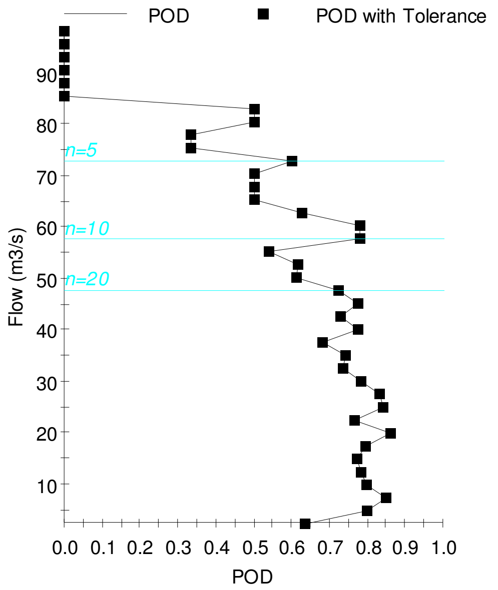
Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

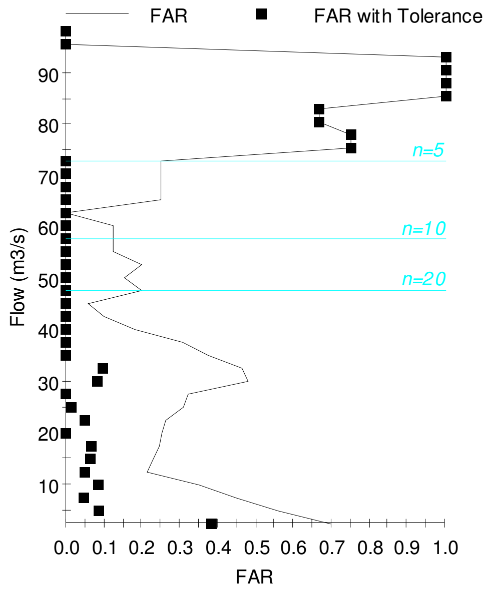
JBA consulting

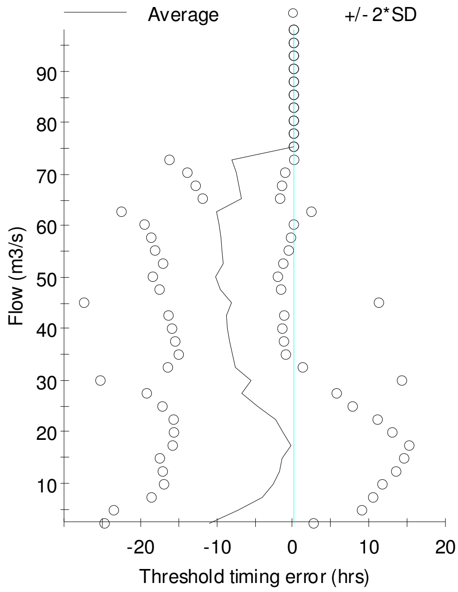
Raingauges used													
TBR Ref			**Name**					**Weight**					
463214509REev			BETHERSDEN STW tbr					0.353					
664306908REev			Bybrook					0.024					
565113902REev			WAREHORNE STW RTS					0.015					
664232501REev			RUCKINGE TBR					0.059					
463215906REev			Cranbrook					0.235					
463210512REev			Sutton Valence					0.4					
Potential evaporation data from SINE curve													
Min	0 mm/day			**Max**	3.06 mm/day			**Month**	Jul				
Period of calibration													
From	01 May 2000 02:00			**To**	04 Apr 2014 22:00								
Level gauge : Not Found - 453210001SG (No rating - level only)													
PDM parameters													
Surface		Identical linear cascade			**Base**	Cubic store			**Drainage**		Gravity		
Area	**Fc**	**Cmin**	**Cmax**	**b**	**Be**	**Kg**	**Bg**	**St**	**K1**	**K2**	**Kb**	**QConst**	**Tdly**
Km^2		**mm**	**mm**					**mm**	**hrs**	**hrs**	**hmm^2**	**m^3/s**	**hrs**
283	1	20	150	0.8	4	60000	1.6	0	12	n/a	13.6	0	3
Parameters of second PDM plotted (Stilebridge_NFFS)													
Surface		Linear cascade			**Base**	Cubic store			**Drainage**		Gravity		
283	1	0	120	0.5	2.5	99940	1.7	0	11	14.004	13.7	0	3
Model scores													
		Variability	**bias -absolute**	**bias -significance**	**shape**	**Timing bias - abs.**	**Timing bias - sign.**	**Seasonaility**	**Overall Score**				
This PDM		2.14	1.06	1.30	2.18	4.00	4.00	2.17	2.33				
Other PDM		2.11	0.68	0.84	1.94	4.00	4.00	1.10	2.04				
Calibration Notes													
PDM works well with similar parameters to Smarden. Had to shift PE maxima to July & put rainfall weight on Sutton Valance. That makes for a v good PDM in most events except Oct 2000 (soil not wet enough). Therefore hard to confirm/refute the rating curve at the top end. Looks a LOT more sensible than the exiting NFFS one though.													

PDM Model Sheet for : Stilebridge_JBA01

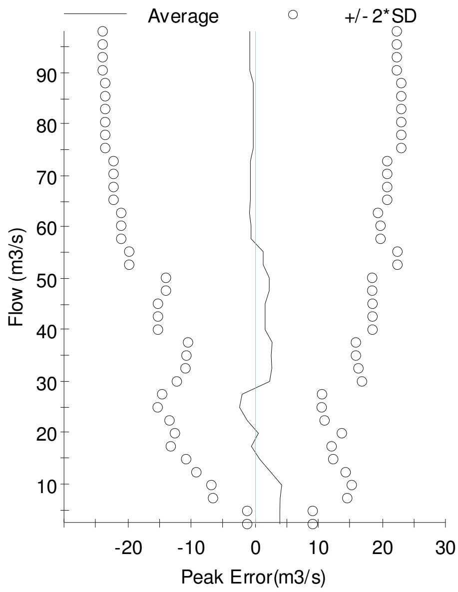
POD, FAR and peak matching statistics over full range of observations

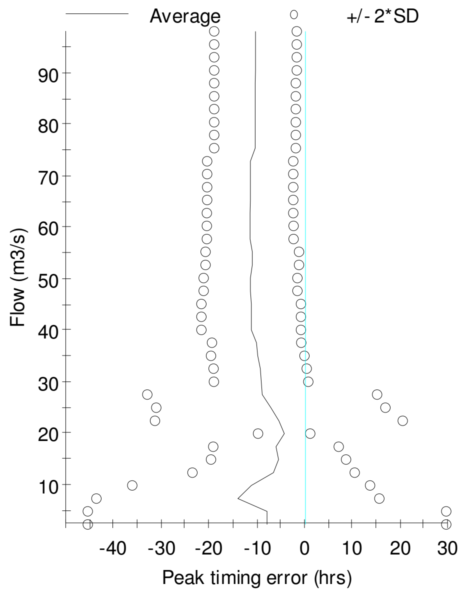






Notes: Peak statistics based on a moving average of 20 peaks. Tolerance of 0 used for POD and FAR. Threshold crossing window is -30 to +30 hrs

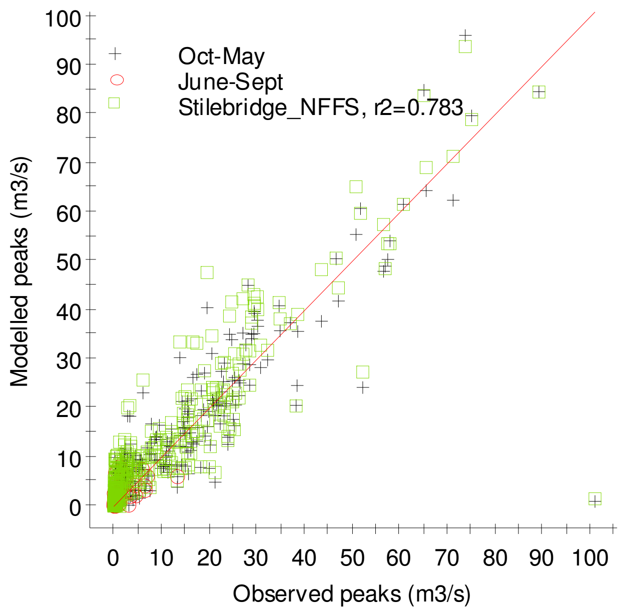




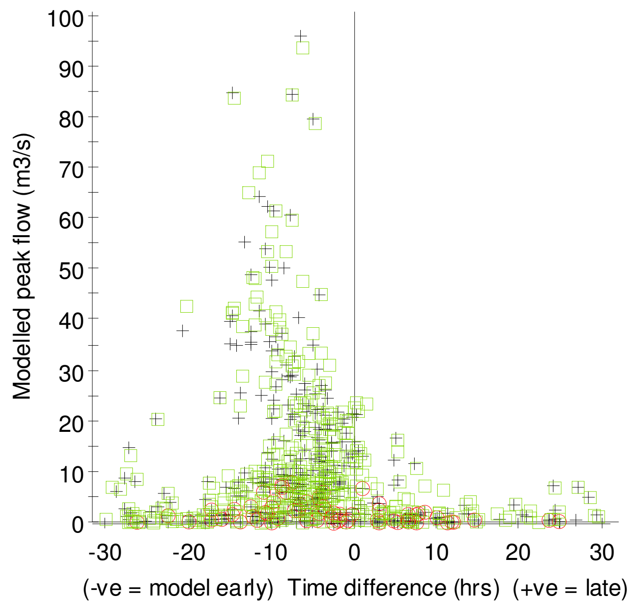
Peak magnitude and timing for the top ten observed events (Stilebridge_JBA01)

	Observed		Modelled		Difference		Event statistics		
	Date	Flow (m3/s)	Date	Flow (m3/s)	Q (%)	T (hrs)	NSE	RMSE	r^2
1	13/10/2000 03:30	100.6	12/10/2000 17:15	1.1	-99%	-10.3	-0.874	39.277	0.423
2	25/12/2013 00:15	89.0	24/12/2013 16:45	84.5	-5%	-7.5	0.801	10.100	0.828
3	09/02/2001 02:45	74.9	08/02/2001 21:45	79.6	6%	-5.0	0.826	7.464	0.894
4	31/12/2002 12:45	73.5	31/12/2002 06:15	95.9	30%	-6.5	0.542	11.670	0.778
5	07/11/2000 01:15	71.0	06/11/2000 14:45	62.4	-12%	-10.5	0.621	10.949	0.786
6	16/01/2008 16:15	65.4	16/01/2008 04:45	64.3	-2%	-11.5	0.720	9.562	0.727
7	01/12/2009 09:15	64.9	30/11/2009 18:30	84.8	31%	-14.7	-0.538	18.095	0.281
8	07/02/2014 20:15	60.6	07/02/2014 10:30	61.5	1%	-9.8	0.741	8.343	0.754
9	02/01/2014 19:30	57.8	02/01/2014 08:45	54.1	-6%	-10.7	0.673	7.800	0.679
10	10/02/2009 21:00	57.3	10/02/2009 12:30	50.3	-12%	-8.5	0.839	6.394	0.846

Modelled and observed peak flows, r2=0.779



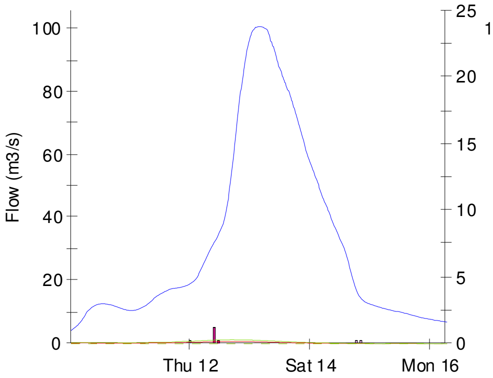
Modelled and observed peak timing



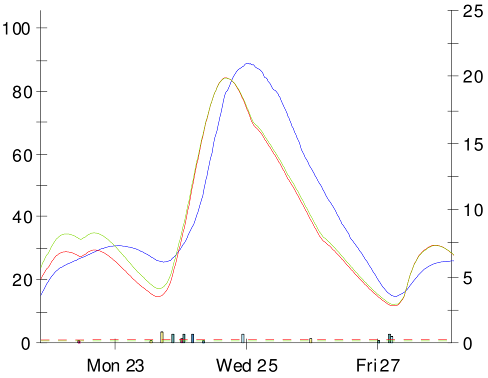
PDM Model Sheet for : Stilebridge_JBA01

JBA consulting

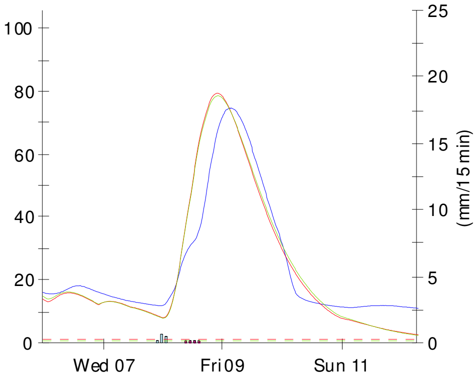
1. 13 Oct 2000 03:30 (0-6-76mm)



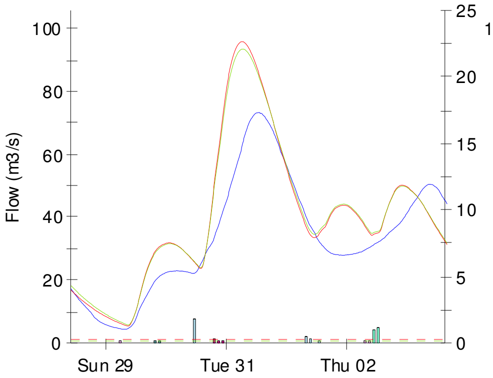
2. 25 Dec 2013 00:15 (56-69-89mm)



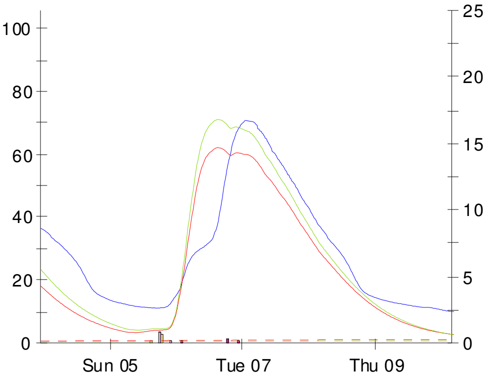
3. 09 Feb 2001 02:45 (0-43-49mm)



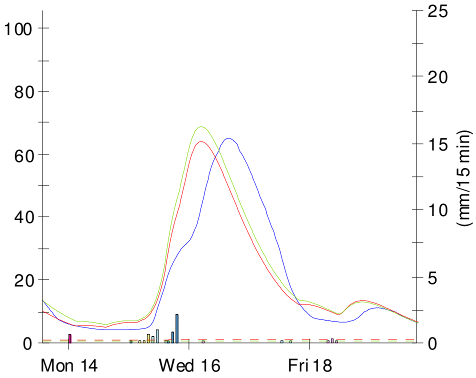
4. 31 Dec 2002 12:45 (29-82-86mm)



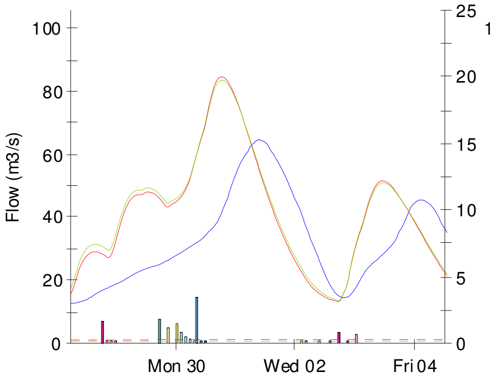
5. 07 Nov 2000 01:15 (38-48-54mm)



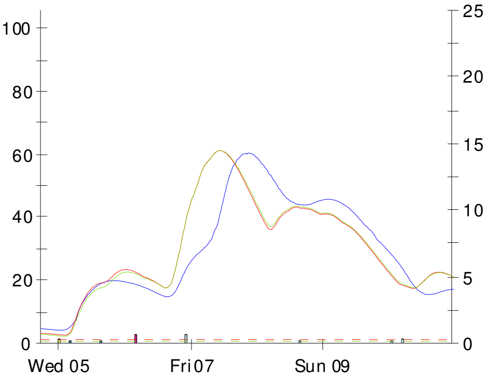
6. 16 Jan 2008 16:15 (32-41-51mm)



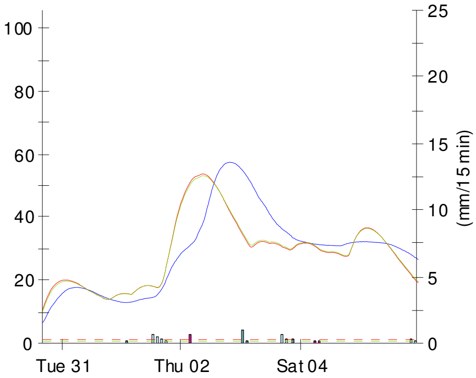
7. 01 Dec 2009 09:15 (12-74-85mm)



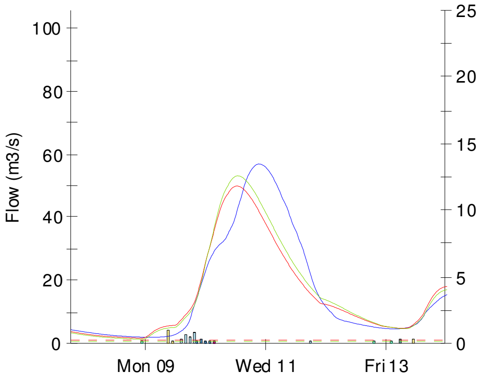
8. 07 Feb 2014 20:15 (10-67-66mm)



9. 02 Jan 2014 19:30 (51-55-66mm)



10. 10 Feb 2009 21:00 (17-41-44mm)

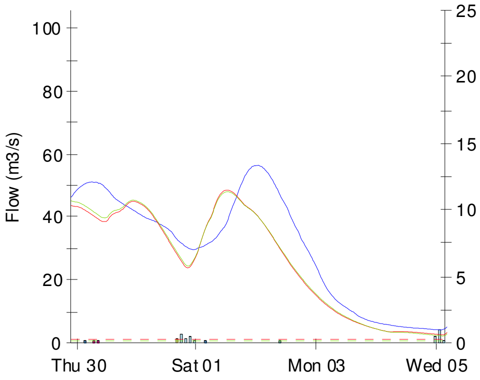


Key

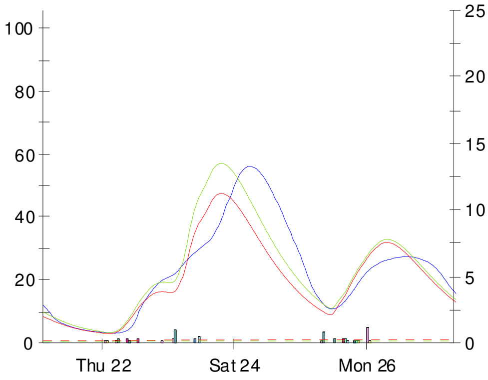
- 453210001SG - Flow : STILEBRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Stilebridge_NFFS)
- Qg (Stilebridge_NFFS)
- 463214509REev - Recording Rain : BETHERSDEN STW tbr
- 664306908REev - Recording Rain : Bybrook
- 565113902REev - Recording Rain : WAREHORNE STW RTS
- 664232501REev - Recording Rain : RUCKINGE TBR
- 463215906REev - Recording Rain : Cranbrook
- 463210512REev - Recording Rain : Sutton Valence
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

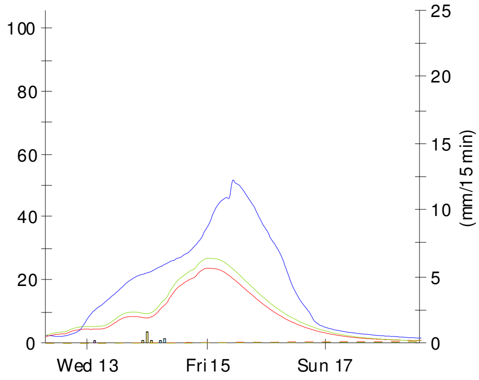
11. 02 Feb 2014 00:45 (39-44-49mm)



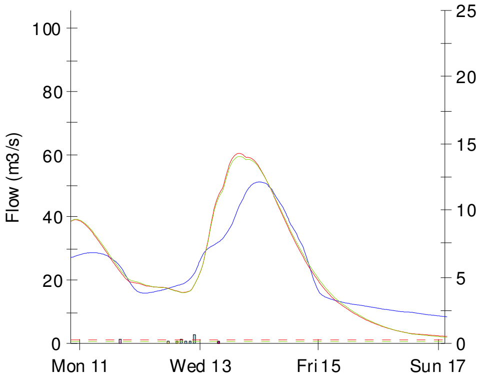
12. 24 Jan 2009 05:15 (43-48-56mm)



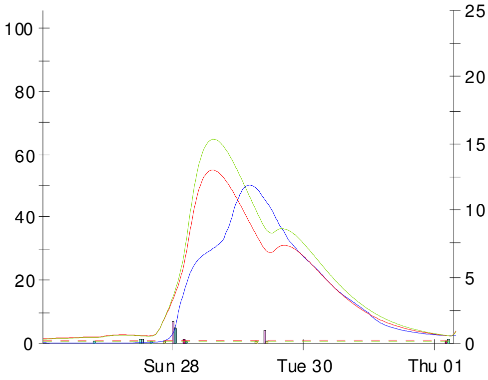
13. 15 Nov 2002 10:30 (1-39-52mm)



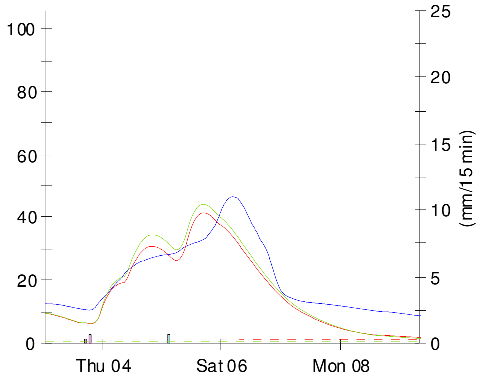
14. 13 Dec 2000 23:30 (23-34-35mm)



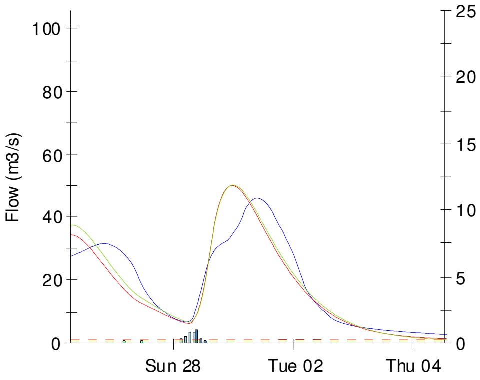
15. 29 Dec 2003 04:15 (37-45-56mm)



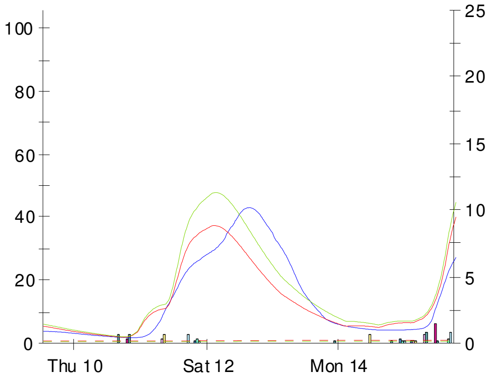
16. 06 Jan 2001 04:30 (26-32-32mm)



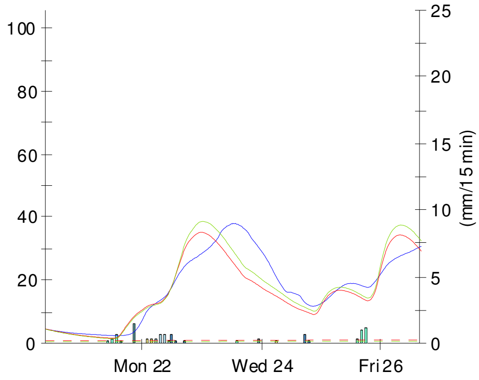
17. 01 Mar 2010 09:45 (19-25-29mm)



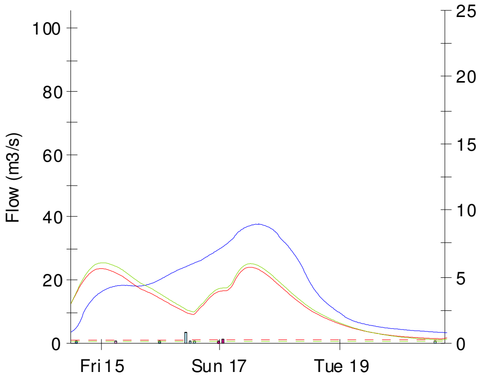
18. 12 Jan 2008 15:30 (51-61-74mm)



19. 23 Feb 2010 12:30 (38-50-63mm)



20. 17 Jan 2010 15:00 (11-17-33mm)

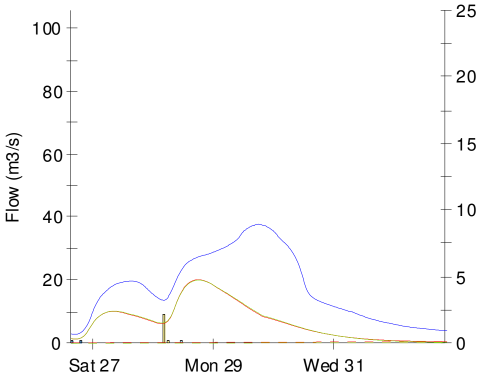


Key

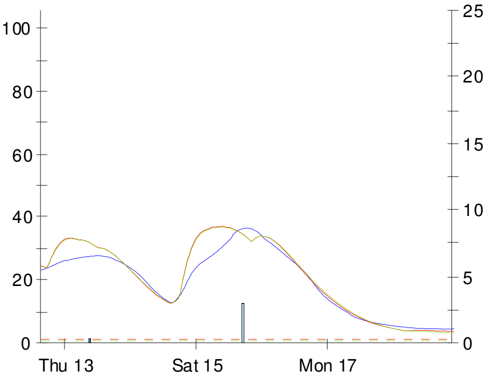
- 453210001SG - Flow : STILEBRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Stilebridge_NFFS)
- Qg (Stilebridge_NFFS)
- 463214509REev - Recording Rain : BETHERSDEN STW tbr
- 664306908REev - Recording Rain : Bybrook
- 565113902REev - Recording Rain : WAREHORNE STW RTS
- 664232501REev - Recording Rain : RUCKINGE TBR
- 463215906REev - Recording Rain : Cranbrook
- 463210512REev - Recording Rain : Sutton Valence
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

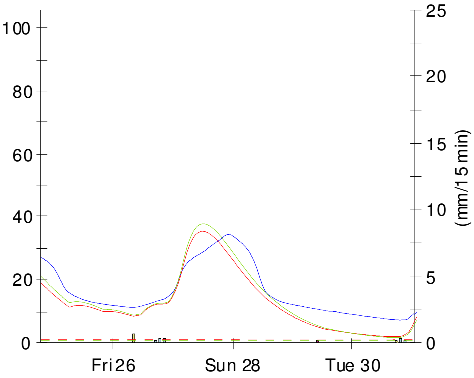
21. 29 May 2000 18:00 (31-40-49mm)



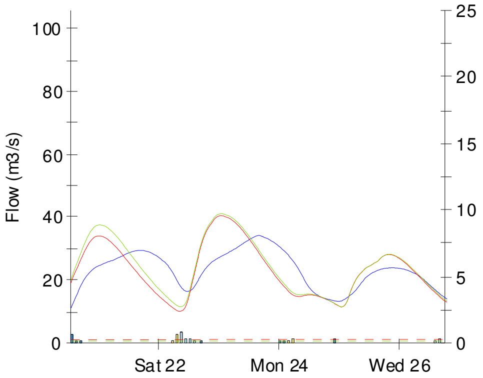
22. 15 Feb 2014 18:15 (32-32-32mm)



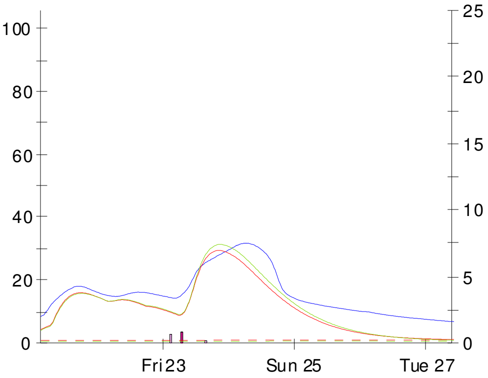
23. 27 Jan 2001 22:00 (6-28-30mm)



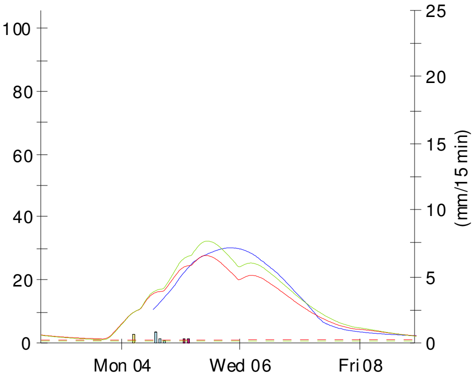
24. 23 Dec 2012 15:45 (39-42-46mm)



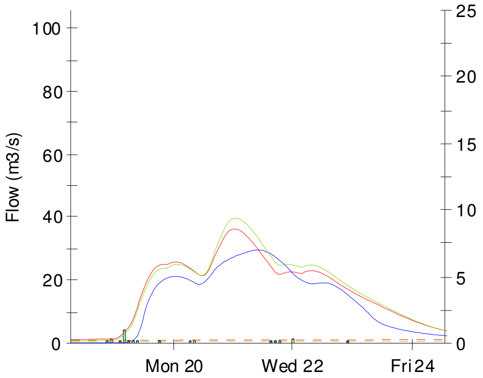
25. 24 Mar 2001 06:30 (29-29-33mm)



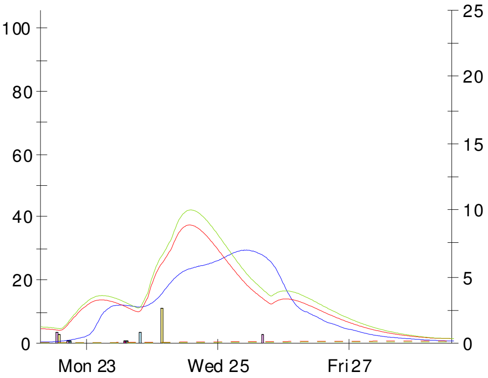
26. 05 Feb 2002 18:45 (28-28-29mm)



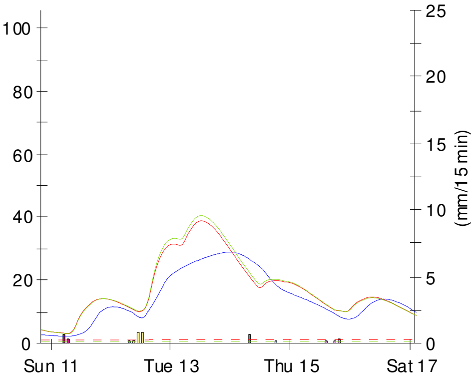
27. 21 Jan 2003 10:00 (30-40-51mm)



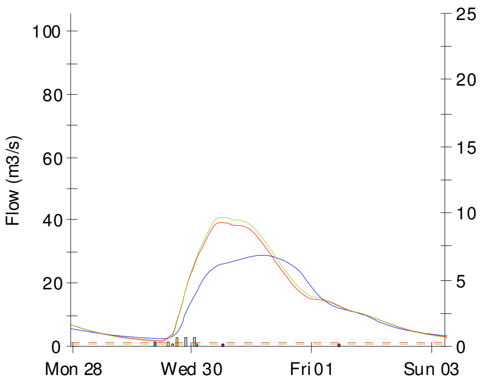
28. 25 Oct 2006 10:30 (40-49-61mm)



29. 13 Jan 2004 23:00 (29-37-48mm)



30. 31 Dec 2009 02:30 (24-28-30mm)



Key

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- Modelled Qg
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- Qg (Stilebridge_NFFS)
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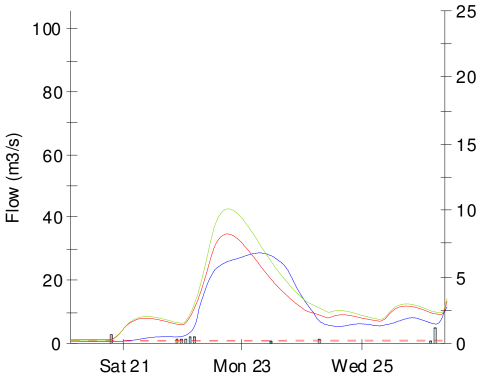
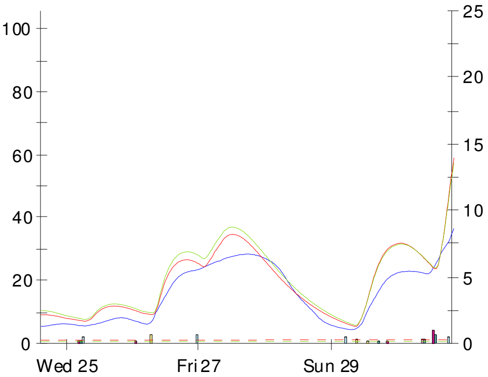
- 664306908REev - Recording Rain : Bybrook
- 565113902REev - Recording Rain : WAREHORNE STW RTS
- 664232501REev - Recording Rain : RUCKINGE TBR
- 463215906REev - Recording Rain : Cranbrook
- 463210512REev - Recording Rain : Sutton Valence
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

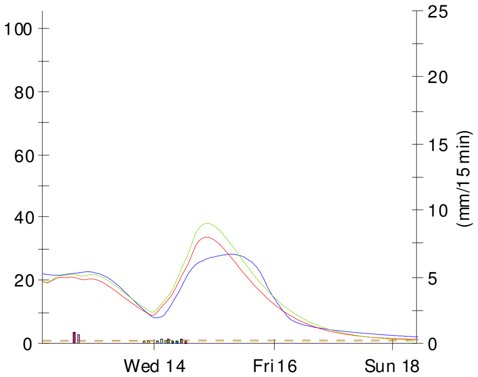
31. 23 Dec 2002 06:15 (39-42-47mm)



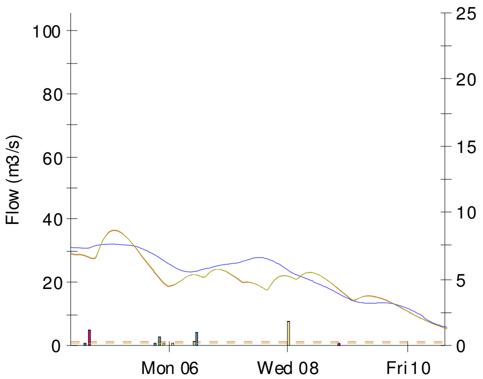
32. 27 Dec 2002 17:15 (62-74-82mm)



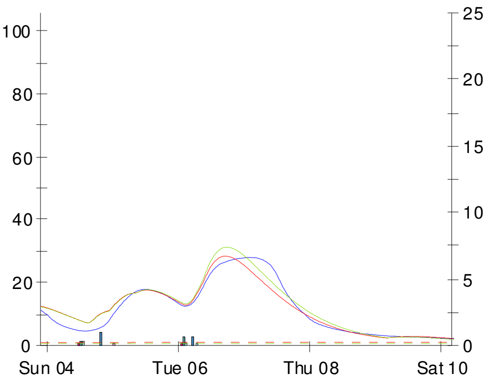
33. 15 Feb 2007 06:15 (22-23-27mm)



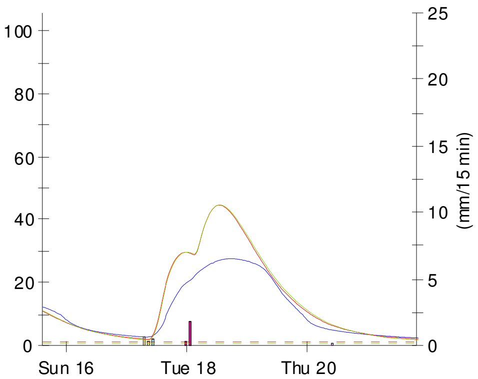
34. 07 Jan 2014 11:45 (24-31-37mm)



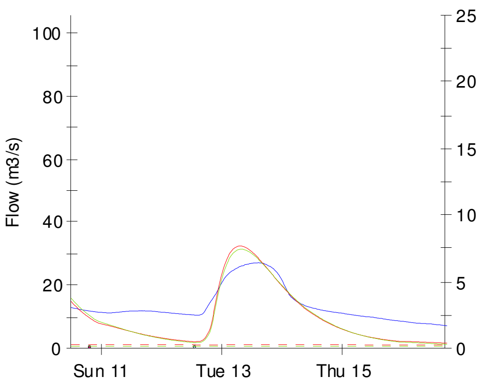
35. 07 Mar 2007 01:00 (20-25-33mm)



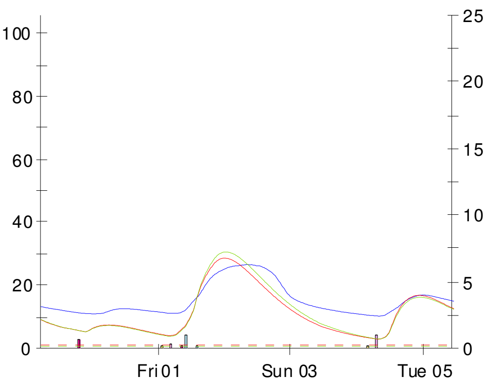
36. 18 Jan 2011 17:00 (0-25-27mm)



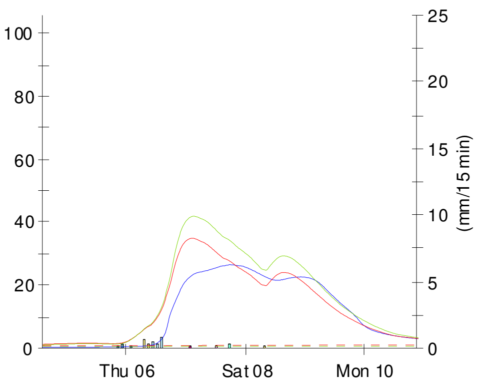
37. 13 Feb 2001 14:30 (11-17-21mm)



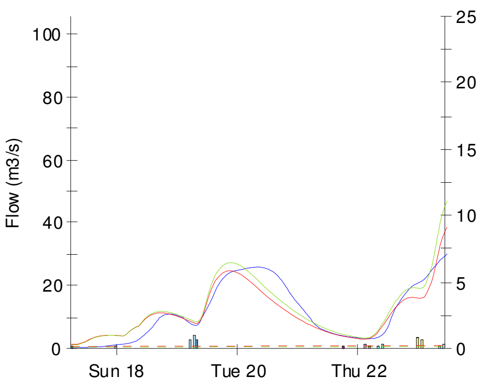
38. 02 Dec 2000 07:45 (25-26-27mm)



39. 07 Jan 2011 17:45 (28-35-38mm)



40. 20 Jan 2009 08:15 (31-55-68mm)



Key

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- Modelled Qg
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- Qg (Stilebridge_NFFS)
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- 565113902REev - Recording Rain : WAREHORNE STW RTS
- 664232501REev - Recording Rain : RUCKINGE TBR
- 463215906REev - Recording Rain : Cranbrook
- 463210512REev - Recording Rain : Sutton Valence
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

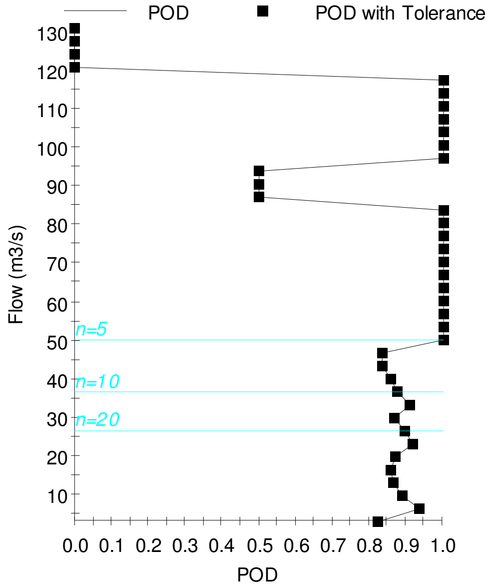
PDM Model Sheet for : Stonebridge_JBA_01

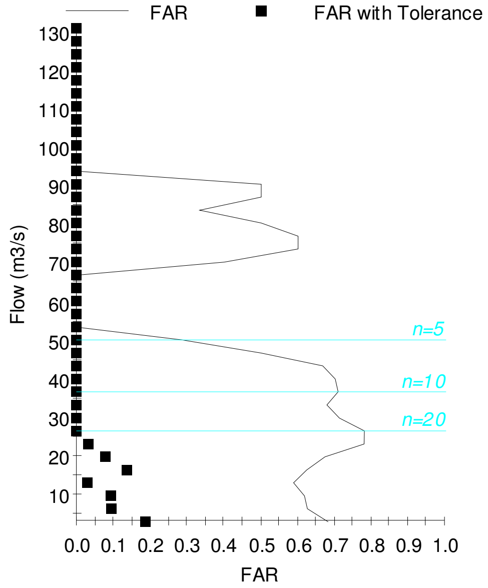
Raingauges used													
TBR Ref			**Name**					**Weight**					
463230905REev			Lamberhurst WWTW					0.4					
463521512REev			REDGATE MILL tbr					0.2					
463234504REev			BEWL BRIDGE RES tbr					0.4					
Potential evaporation data from SINE curve													
Min	0 mm/day				**Max**	3.06 mm/day		**Month**	Jun				
Period of calibration													
From	29 Sep 1998 04:00				**To**	01 Apr 2014 00:00							
Level gauge : Not Found - 453230001SG (No rating - level only)													
PDM parameters													
Surface		Identical linear cascade			**Base**	Cubic store			**Drainage**		Gravity		
Area	**Fc**	**Cmin**	**Cmax**	**b**	**Be**	**Kg**	**Bg**	**St**	**K1**	**K2**	**Kb**	**QConst**	**Tdly**
Km^2		**mm**	**mm**					**mm**	**hrs**	**hrs**	**hmm^2**	**m^3/s**	**hrs**
134	1	30	230	0.5	4	30000	1.7	60	4	n/a	5.8	0	2
Parameters of second PDM plotted (Stonebridge_NFFS)													
Surface		Linear cascade			**Base**	Cubic store			**Drainage**		Gravity		
114	1	0	120	0.6	2.5	80000	1.9	0.026	6	8.405	20.0	0	0
Model scores													
		Variability	**bias -absolute**	**bias -significance**	**shape**	**Timing bias - abs.**	**Timing bias - sign.**	**Seasonaility**	**Overall Score**				
This PDM		2.01	2.62	1.16	1.39	2.82	3.33	4.00	2.30				
Other PDM		2.50	2.27	1.17	1.10	2.35	3.66	2.32	2.12				
Calibration Notes													

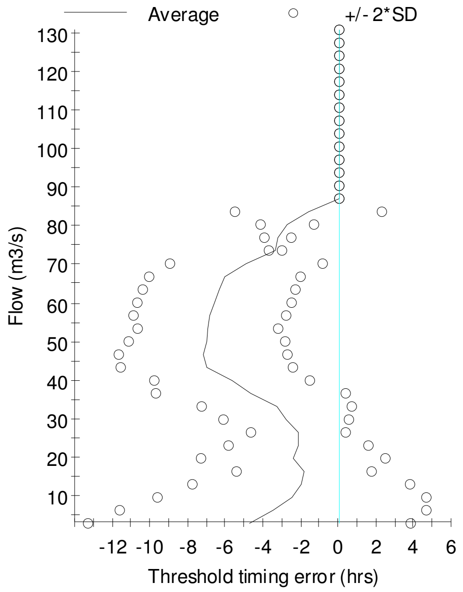
PDM, loosely based on Vexour parameters. Did a lot of rainfall cleaning to eradicate missing data entered as zeros. Performance is now good - matching a range of event magnitudes. One biggish parameter change is to reduce the maximum size of the soil store (Cmax), reduce b and increase St. The effect of all this is to increase peak flows while supressing lower flows. Further increasing St means lower flowsd start to be over estimated.

PDM Model Sheet for : Stonebridge_JBA_01

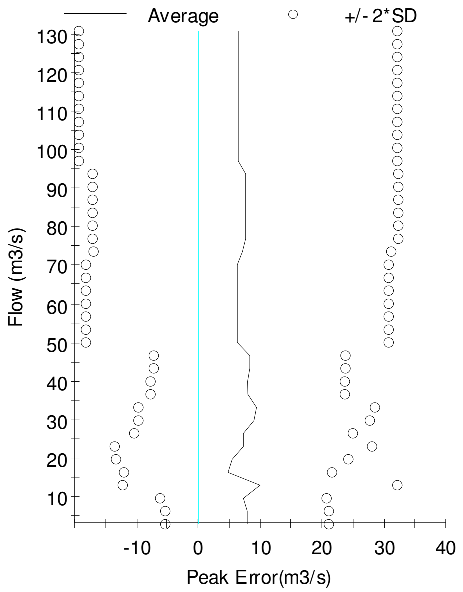
POD, FAR and peak matching statistics over full range of observations

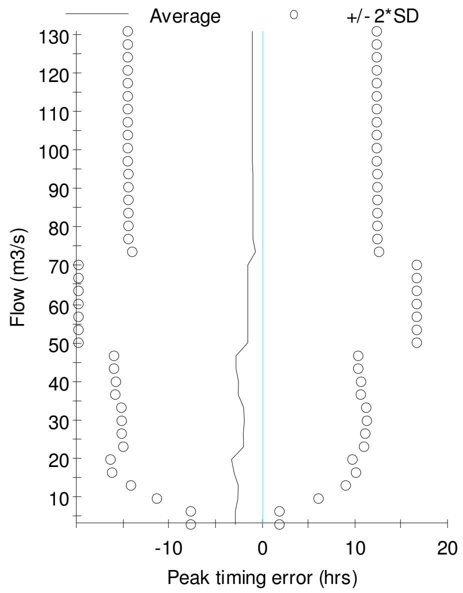






Notes: Peak statistics based on a moving average of 20 peaks. Tolerance of 0 used for POD and FAR. Threshold crossing window is -16 to +16 hrs



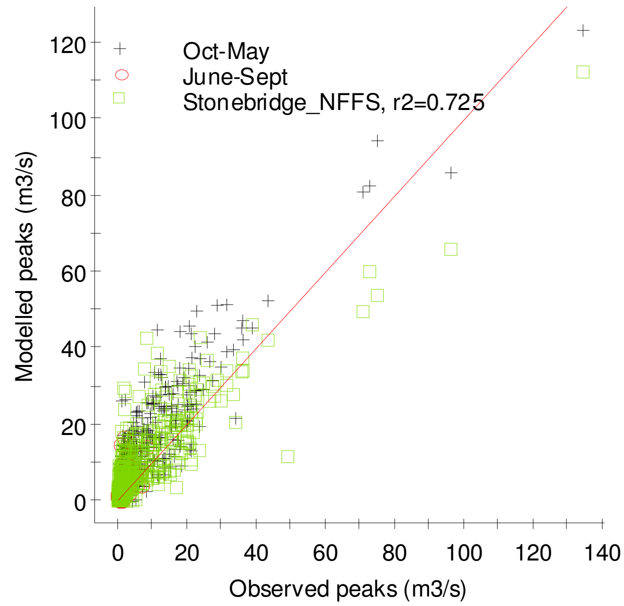


PDM Model Sheet for : Stonebridge_JBA_01

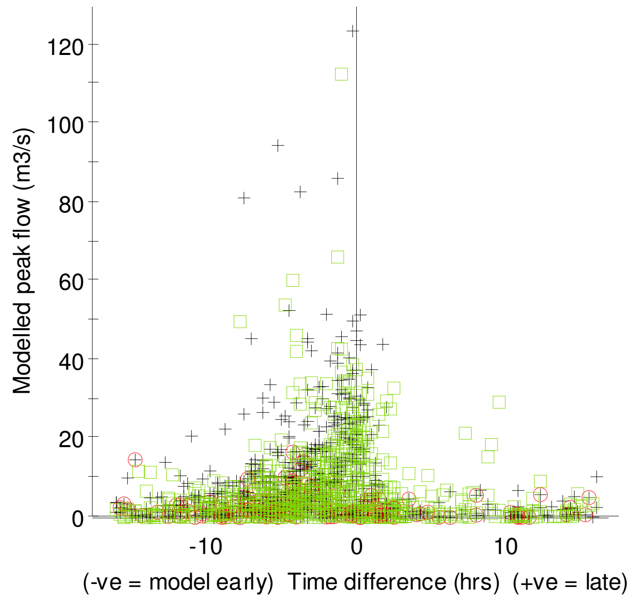
Peak magnitude and timing for the top ten observed events (Stonebridge_JBA_01)

	Observed		Modelled		Difference		Event statistics		
	Date	Flow (m3/s)	Date	Flow (m3/s)	Q (%)	T (hrs)	NSE	RMSE	r^2
1	12/10/2000 12:30	134.0	12/10/2000 12:15	123.2	-8%	-0.3	0.866	12.933	0.870
2	24/12/2013 09:30	96.0	24/12/2013 08:15	86.0	-10%	-1.3	0.804	11.171	0.817
3	06/11/2000 10:00	74.9	06/11/2000 04:45	94.3	26%	-5.3	0.390	13.661	0.714
4	30/10/2000 15:15	72.7	30/10/2000 11:30	82.6	14%	-3.8	0.175	15.054	0.721
5	13/12/2000 11:00	70.7	13/12/2000 03:30	81.0	15%	-7.5	0.237	14.449	0.554
6	08/02/2001 16:45	43.4	08/02/2001 12:15	52.5	21%	-4.5	0.859	4.339	0.935
7	16/01/2008 01:15	39.0	15/01/2008 22:00	45.4	17%	-3.3	0.891	3.800	0.937
8	10/02/2009 07:45	36.2	10/02/2009 04:45	42.3	17%	-3.0	0.907	3.437	0.919
9	05/01/2001 11:15	36.2	05/01/2001 11:15	47.3	31%	0.0	0.828	3.661	0.903
10	01/02/2014 09:45	35.8	01/02/2014 02:45	45.4	27%	-7.0	0.704	4.962	0.893

Modelled and observed peak flows, r2=0.799

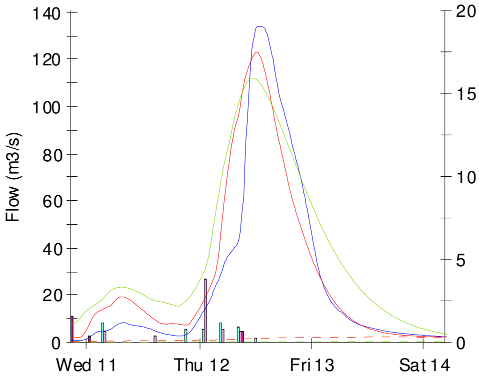


Modelled and observed peak timing

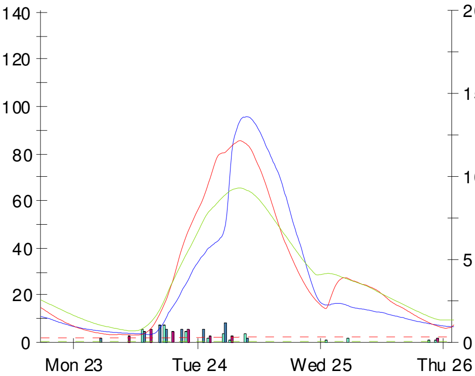


PDM Model Sheet for : Stonebridge_JBA_01

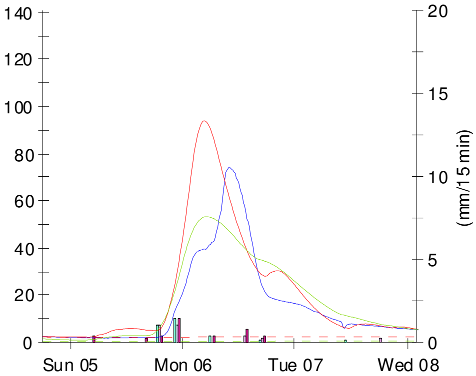
1. 12 Oct 2000 12:30 (34-100-96mm)



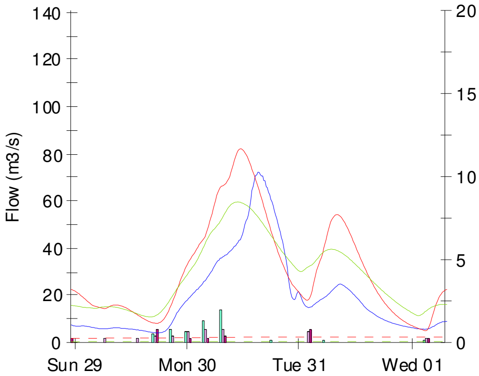
2. 24 Dec 2013 09:30 (68-69-69mm)



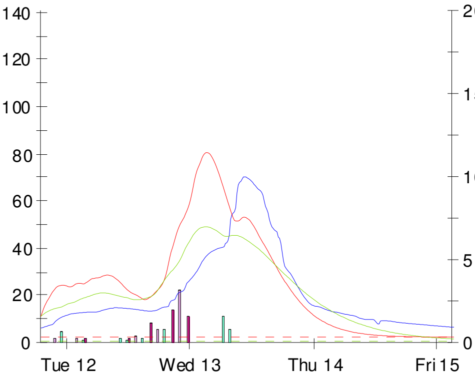
3. 06 Nov 2000 10:00 (45-51-62mm)



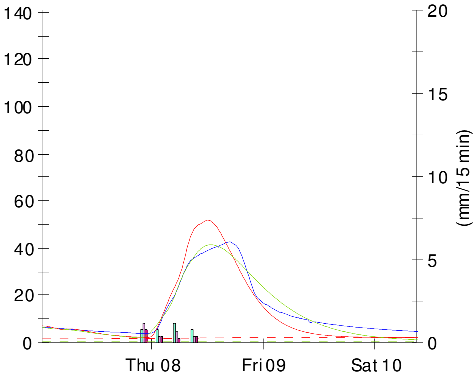
4. 30 Oct 2000 15:15 (69-76-79mm)



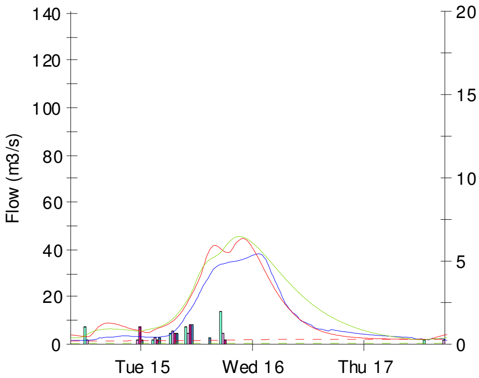
5. 13 Dec 2000 11:00 (46-48-51mm)



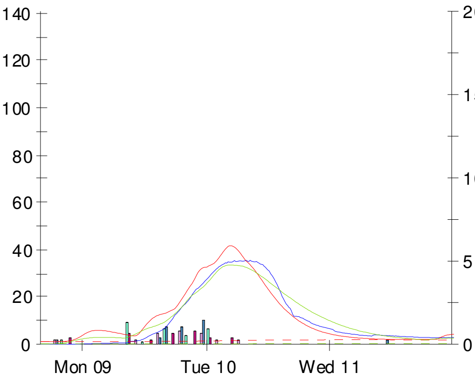
6. 08 Feb 2001 16:45 (26-35-39mm)



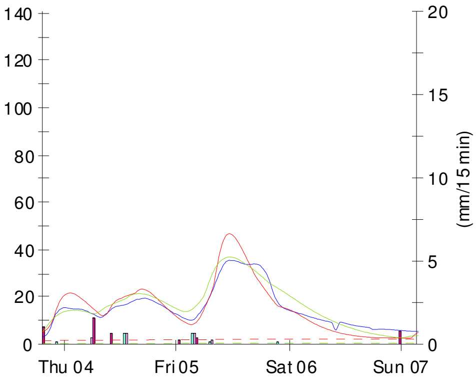
7. 16 Jan 2008 01:15 (41-45-50mm)



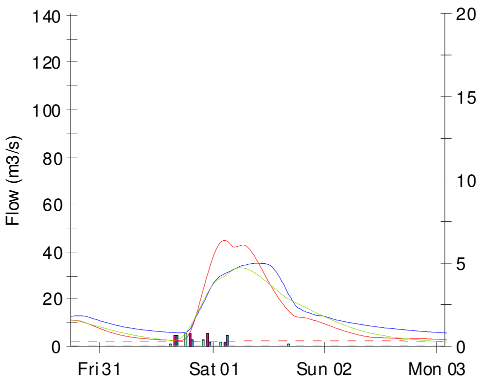
8. 10 Feb 2009 07:45 (42-45-52mm)



9. 05 Jan 2001 11:15 (43-44-48mm)



10. 01 Feb 2014 09:45 (28-29-30mm)

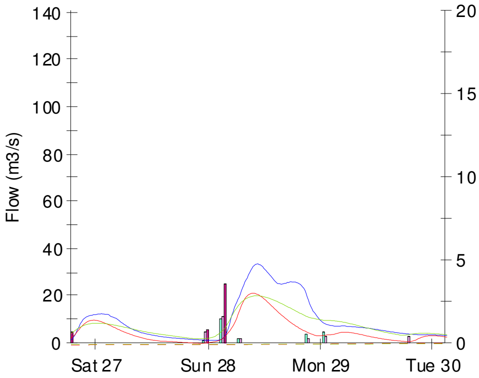


Key

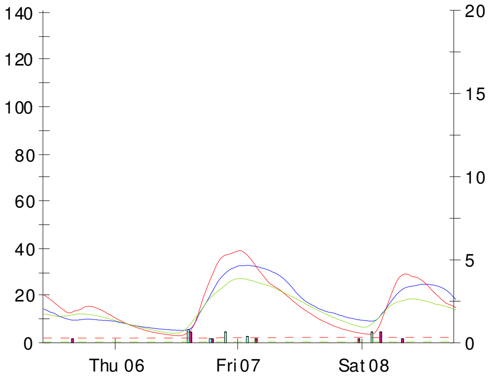
- 453230001SG - Flow : STONEBRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Stonebridge_NFFS)
- Qg (Stonebridge_NFFS)
- 463230905REev - Recording Rain : Lamberhurst WWTW
- 463521512REev - Recording Rain : REDGATE MILL tbr
- 463234504REev - Recording Rain : BEWL BRIDGE RES tbr
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

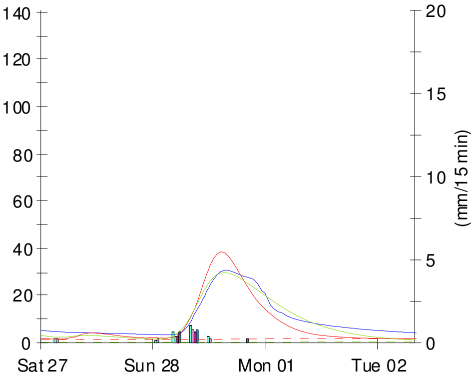
11. 28 May 2000 10:45 (42-47-57mm)



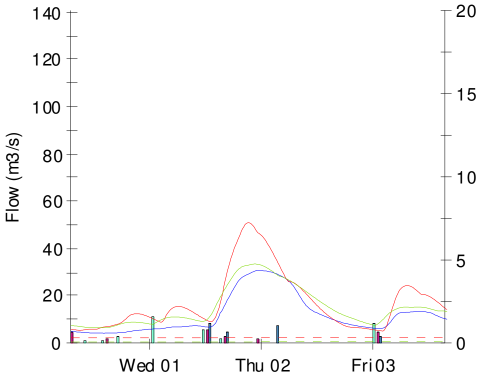
12. 07 Feb 2014 02:00 (43mm)



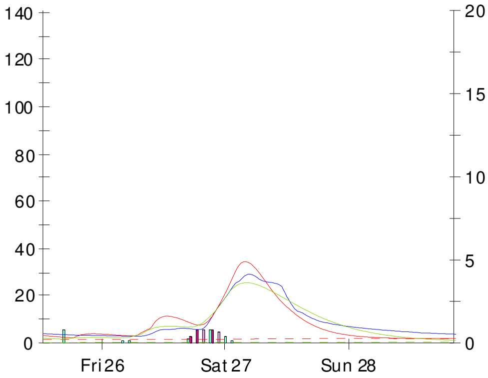
13. 28 Feb 2010 16:00 (29-29-29mm)



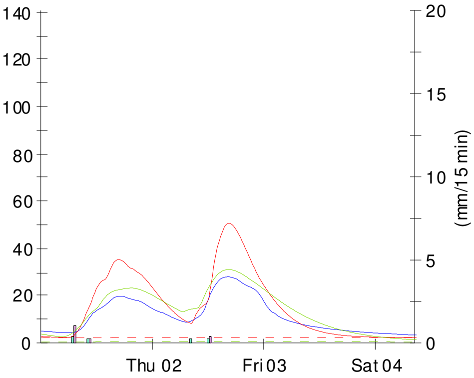
14. 01 Jan 2014 23:15 (45-45-46mm)



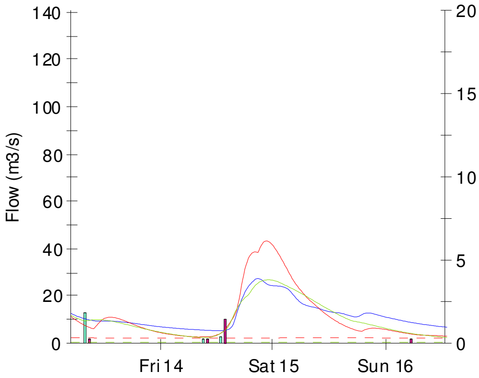
15. 27 Jan 2001 04:30 (25-28-35mm)



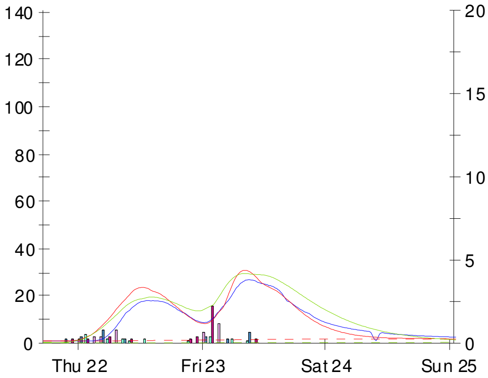
16. 02 Jan 2003 16:15 (36mm)



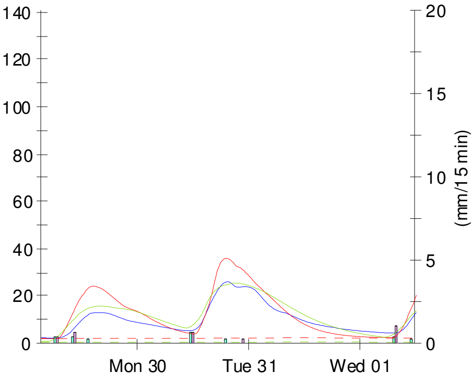
17. 14 Feb 2014 20:45 (27mm)



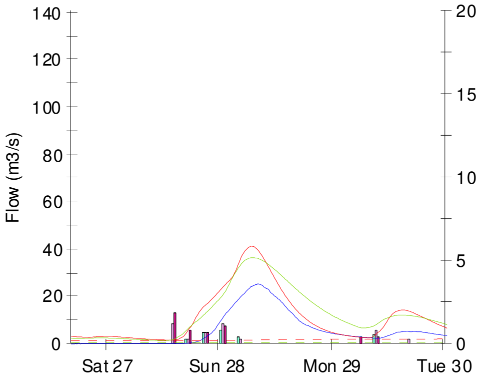
18. 23 Jan 2009 09:00 (38-43-48mm)



19. 30 Dec 2002 19:30 (43mm)



20. 28 Dec 2003 08:30 (42-44-48mm)

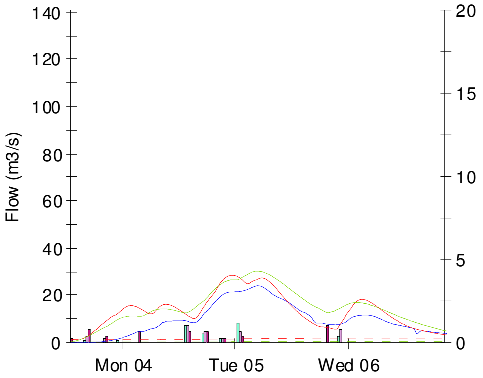


Key

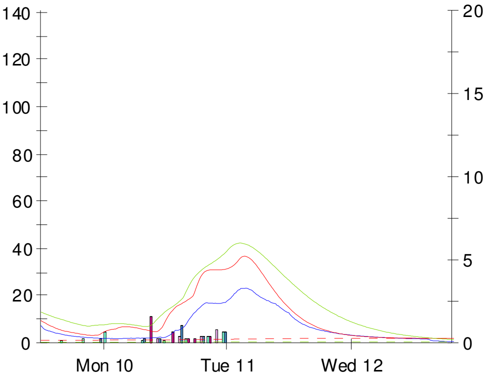
- 453230001SG - Flow : STONEBRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Stonebridge_NFFS)
- Qg (Stonebridge_NFFS)
- 463230905REev - Recording Rain : Lamberhurst WWTW
- 463521512REev - Recording Rain : REDGATE MILL tbr
- 463234504REev - Recording Rain : BEWL BRIDGE RES tbr
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

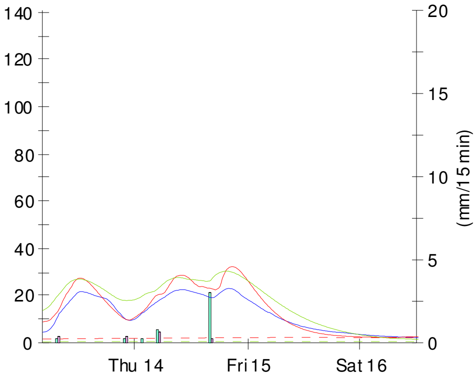
21. 05 Feb 2002 04:45 (48-51-56mm)



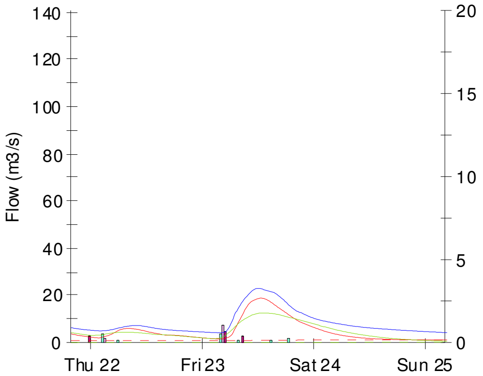
22. 11 Nov 2008 03:45 (34-37-41mm)



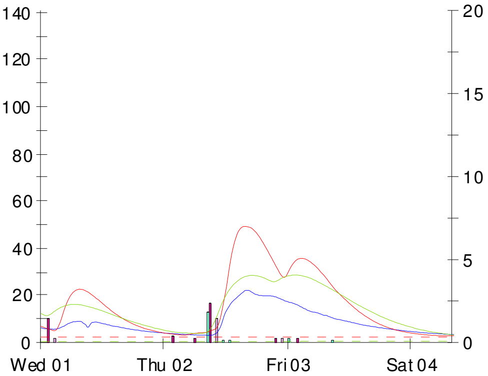
23. 14 Nov 2002 20:15 (2-38-55mm)



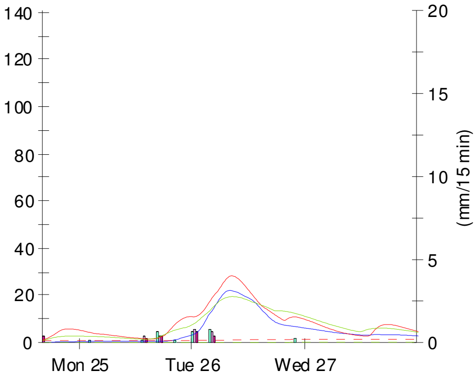
24. 23 Mar 2001 12:00 (22-23-23mm)



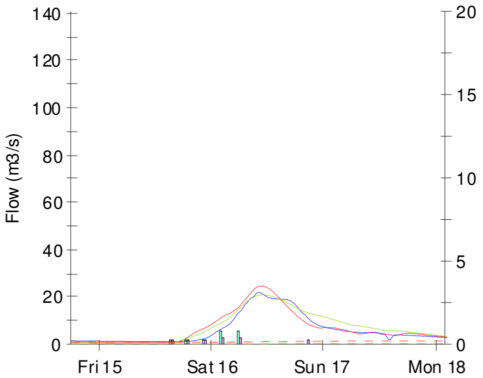
25. 02 Nov 2000 16:00 (33-36-37mm)



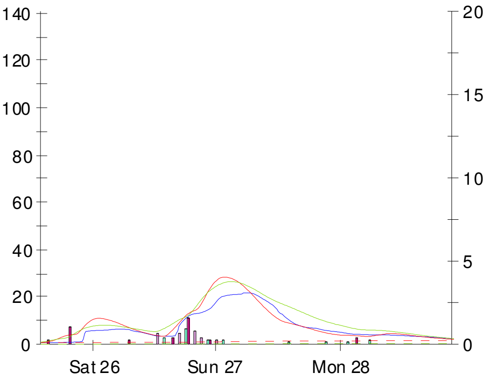
26. 26 Feb 2002 08:00 (37-38-39mm)



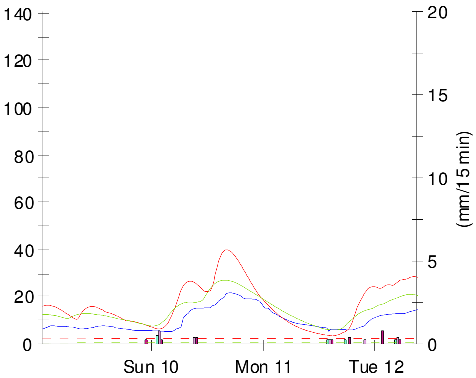
27. 16 Jan 1999 10:00 (30mm)



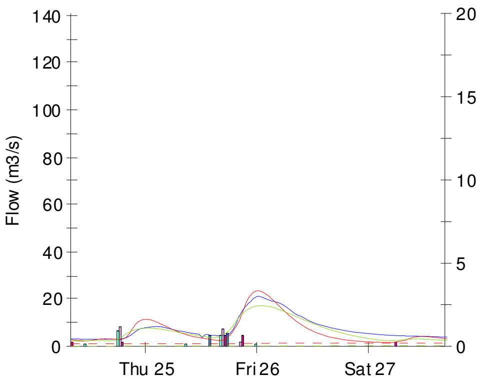
28. 27 Jan 2002 05:45 (38-40-44mm)



29. 10 Dec 2000 16:45 (38-41-49mm)



30. 26 Feb 2010 00:15 (27-28-29mm)



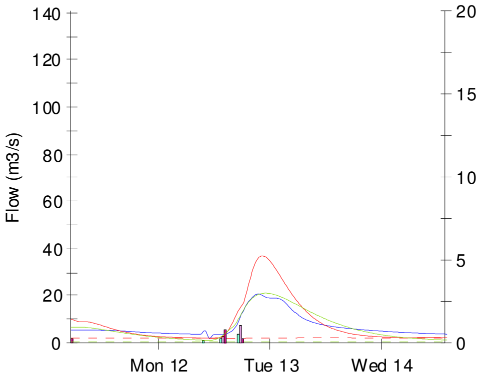
Key

- 453230001SG - Flow : STONEBRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Stonebridge_NFFS)
- Qg (Stonebridge_NFFS)
- 463230905REev - Recording Rain : Lamberhurst WWTW
- 463521512REev - Recording Rain : REDGATE MILL tbr
- 463234504REev - Recording Rain : BEWL BRIDGE RES tbr
- Average Rain

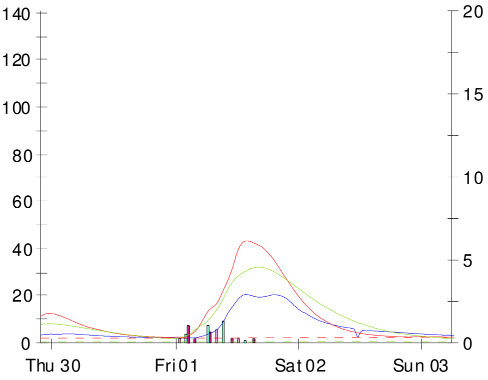
Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

JBA consulting

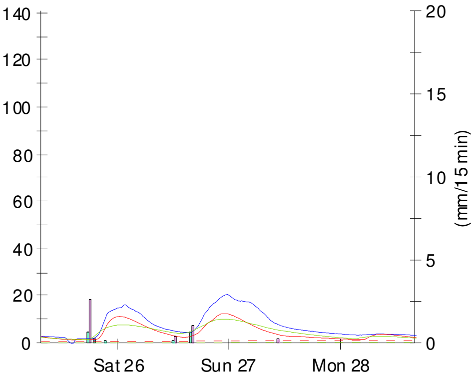
31. 12 Feb 2001 21:30 (19-19-20mm)



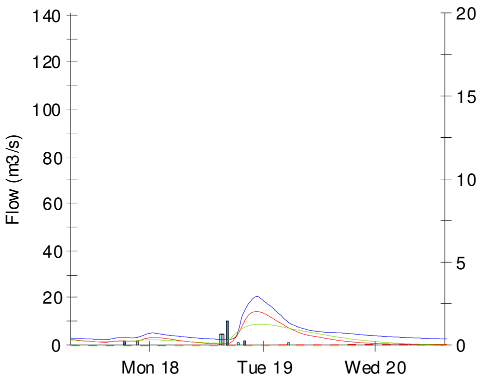
32. 01 Dec 2000 13:45 (24-25-28mm)



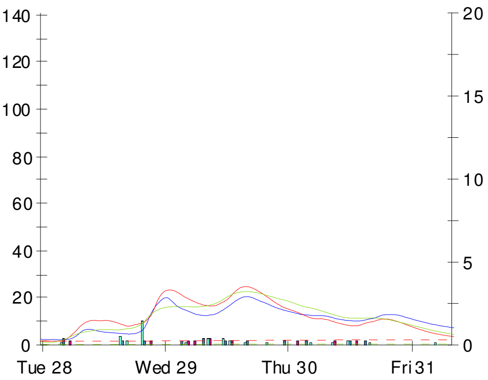
33. 26 Dec 1998 23:45 (7-21-36mm)



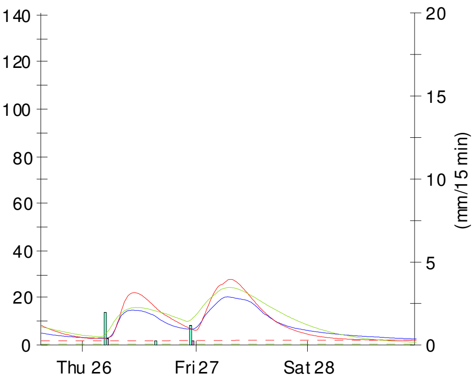
34. 18 Mar 2013 23:00 (16-23-26mm)



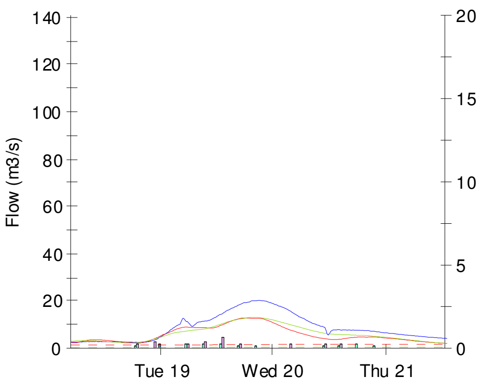
35. 29 Jan 2014 15:45 (33-41-46mm)



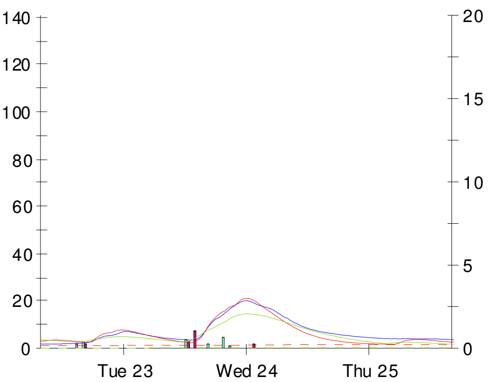
36. 27 Dec 2002 07:00 (26mm)



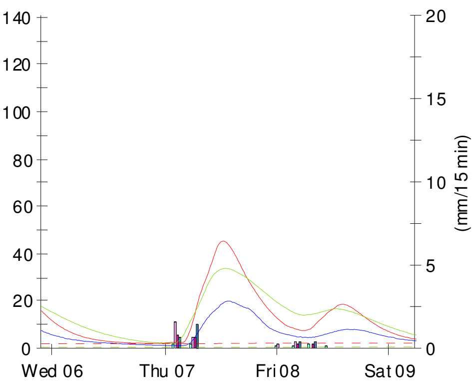
37. 19 Jan 1999 20:45 (6-20-35mm)



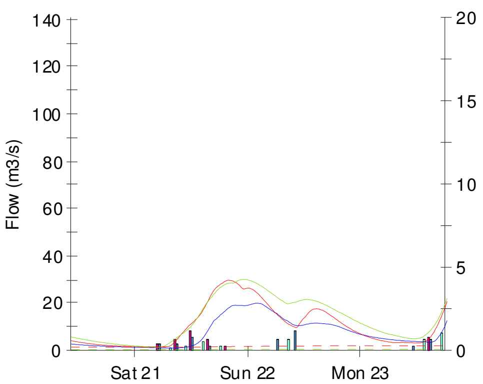
38. 24 Jan 2001 00:00 (21-23-29mm)



39. 07 Dec 2006 13:30 (29-32-34mm)



40. 22 Dec 2013 02:15 (50-52-57mm)



Key

- 453230001SG - Flow : STONEBRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Stonebridge_NFFS)
- Qg (Stonebridge_NFFS)
- 463230905REev - Recording Rain : Lamberhurst WWTW
- 463521512REev - Recording Rain : REDGATE MILL tbr
- 463234504REev - Recording Rain : BEWL BRIDGE RES tbr
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

PDM Model Sheet for : vexour_JBA_01

River Medway at Vexour. Rough calibration of PDM based on a PDM developed for Lingfield Bridge (upper catchment). Only area, rain gauges and K adjusted (by calibration). Developed to test rating curve and for continuous simulation. Model performance appears to confirm something like the existing rating curve. Model has more baseflow than the observed, but otherwise works well.

Raingauges used

TBR Ref	Name	Weight
463655903REev	EDEN VALE STW RTS	0.07
292554REev	Weir Wood Res RF	0.07
463630901REev	PAINS HILL RES RTS	0.13
463622502REev	KENT HATCH RES tbr	0.13
463641904REev	GODSTONE STW RTS	0.141
463610906REev	EDENBRIDGE STW RTS	0.419

Potential evaporation data from SINE curve

Min	0 mm/day	Max	3 mm/day	Month	Jul

Period of calibration

From	04 Apr 1993 08:00	To	06 Feb 2014 00:00

Level gauge : Not Found - 453600002HSG (No rating - level only)

PDM parameters

Surface		Linear cascade			**Base**	Cubic store			**Drainage**		Gravity		
Area	**Fc**	**Cmin**	**Cmax**	**b**	**Be**	**Kg**	**Bg**	**St**	**K1**	**K2**	**Kb**	**QConst**	**Tdly**
Km^2		**mm**	**mm**					**mm**	**hrs**	**hrs**	**hmm^2**	**m^3/s**	**hrs**
223	1	30	250	0.6	4	120000	1.8	40	8	14	0.5	0	4

Parameters of second PDM plotted (Vexour_NFFS)

Surface		Linear cascade			**Base**	Cubic store			**Drainage**		Gravity		
223	0.78	0	169	0.25	2.5	60000	1.8	87.064	13.961	21.593	48.6	0	0.002

Model scores

	Variability	bias -absolute	bias -significance	shape	Timing bias - abs.	Timing bias - sign.	Seasonaility	Overall Score
This PDM	1.73	0.69	0.33	1.23	1.28	2.13	4.00	1.74
Other PDM	3.35	2.52	2.63	1.51	0.29	0.30	2.35	2.14

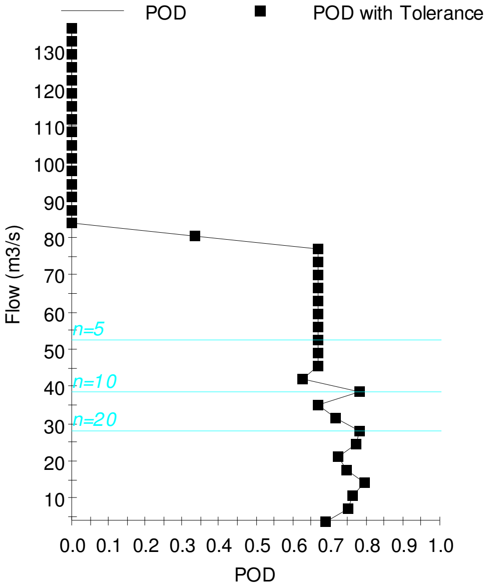
Calibration Notes

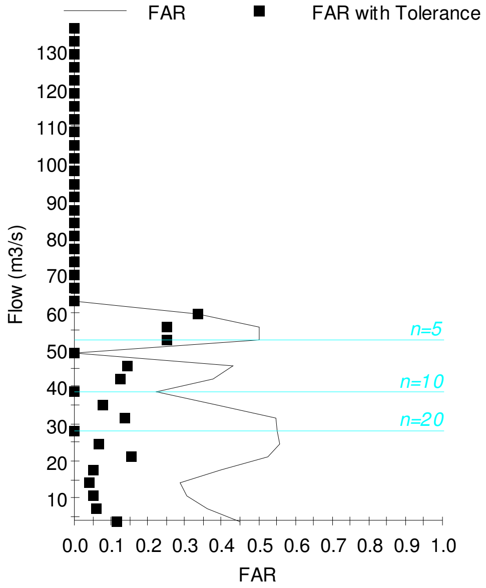
Calibration start date limited by 463655903REev - EDEN VALE STW RTS, end date limited by 453600003FQ (Flow) - VEXOUR_PENSHURST

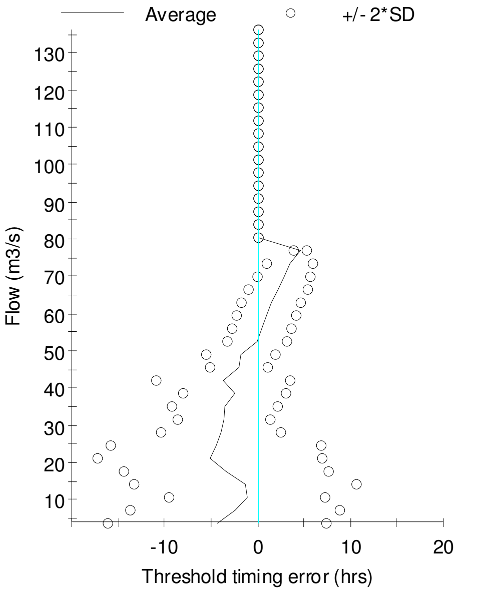
Calibration start date limited by 463655903REev - EDEN VALE STW RTS, end date limited by 463630901REev - PAINS HILL RES RTS

PDM Model Sheet for : vexour_JBA_01

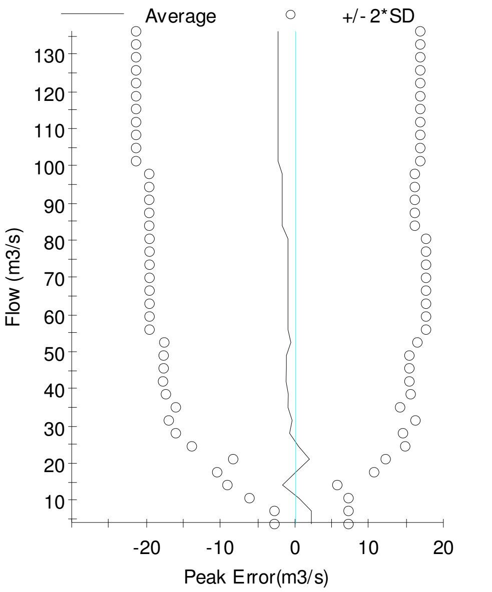
POD, FAR and peak matching statistics over full range of observations

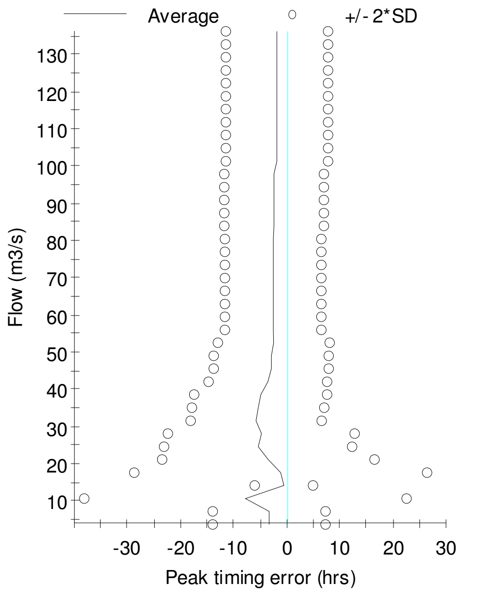






Notes: Peak statistics based on a moving average of 20 peaks. Tolerance of 0 used for POD and FAR. Threshold crossing window is -24 to +24 hrs





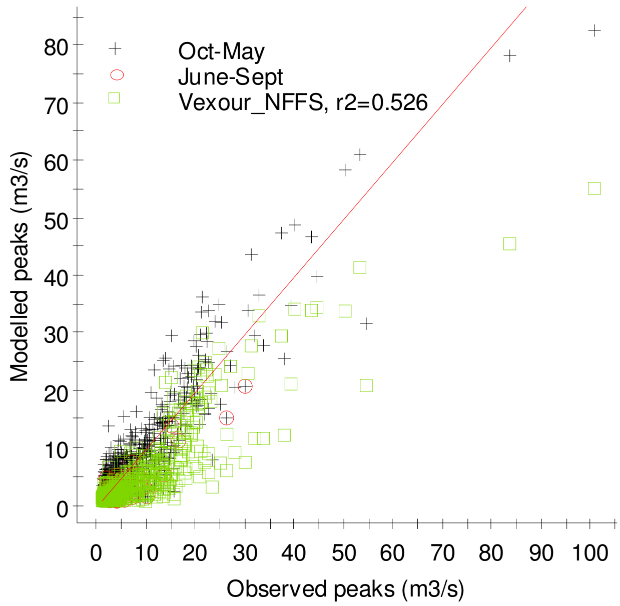
PDM Model Sheet for : vexour_JBA_01

JBA consulting

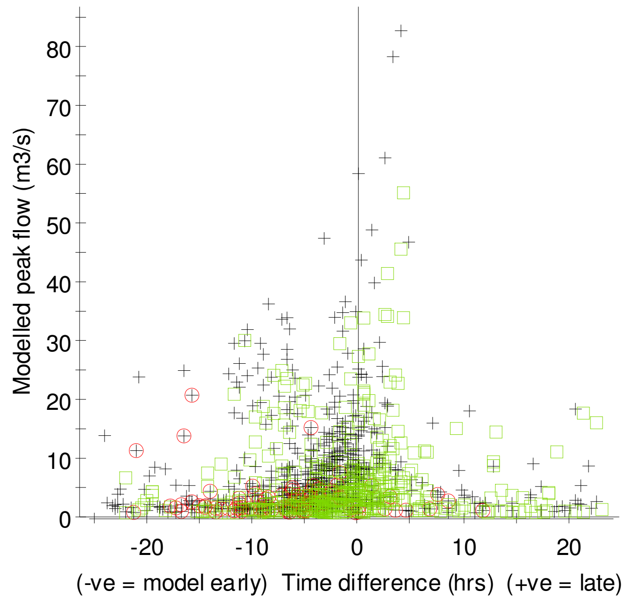
Peak magnitude and timing for the top ten observed events (vexour_JBA_01)

	Observed		Modelled		Difference		Event statistics		
	Date	Flow (m3/s)	Date	Flow (m3/s)	Q (%)	T (hrs)	NSE	RMSE	r^2
1	24/12/2013 10:45	100.4	24/12/2013 14:45	82.6	-18%	4.0	0.861	8.755	0.863
2	17/01/2014 18:30	83.3	17/01/2014 21:45	78.2	-6%	3.2	0.833	7.792	0.912
3	30/10/2000 18:45	54.4	30/10/2000 17:15	31.8	-42%	-1.5	0.769	6.167	0.919
4	31/12/2002 05:00	53.1	31/12/2002 07:30	61.1	15%	2.5	0.349	8.600	0.898
5	01/02/2014 13:15	50.1	01/02/2014 13:15	58.4	17%	0.0	0.639	6.406	0.928
6	16/01/2008 02:30	44.4	16/01/2008 04:00	39.9	-10%	1.5	0.975	1.741	0.981
7	06/11/2000 19:45	43.3	07/11/2000 00:30	46.8	8%	4.8	0.896	4.070	0.949
8	10/02/2009 11:15	40.0	10/02/2009 12:30	48.9	22%	1.3	0.804	4.607	0.984
9	09/12/1994 03:15	39.1	09/12/1994 01:45	34.9	-11%	-1.5	0.943	2.395	0.945
10	25/12/1999 10:30	37.8	25/12/1999 08:30	25.7	-32%	-2.0	0.829	3.986	0.962

Modelled and observed peak flows, r2=0.841

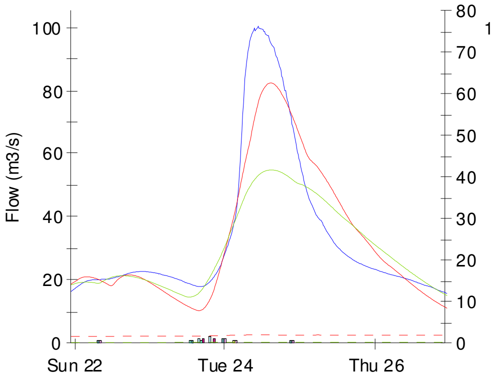


Modelled and observed peak timing

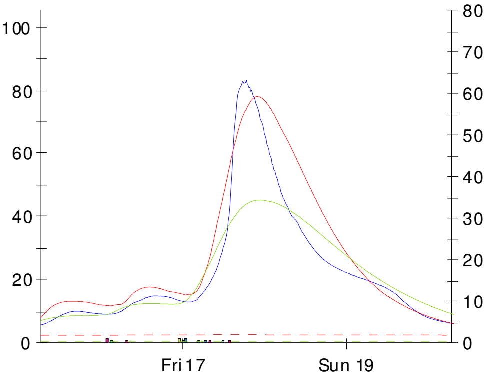


PDM Model Sheet for : vexour_JBA_01

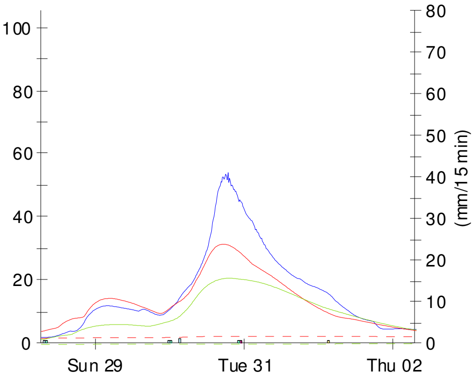
1. 24 Dec 2013 10:45 (62-68-99mm)



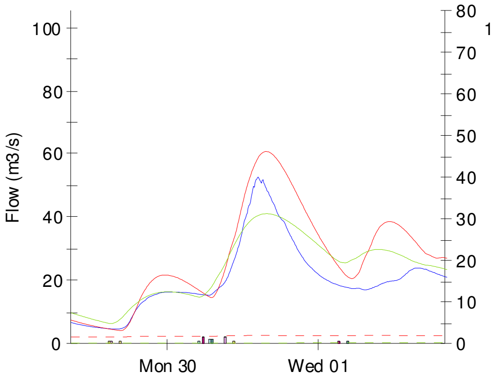
2. 17 Jan 2014 18:30 (42-52-60mm)



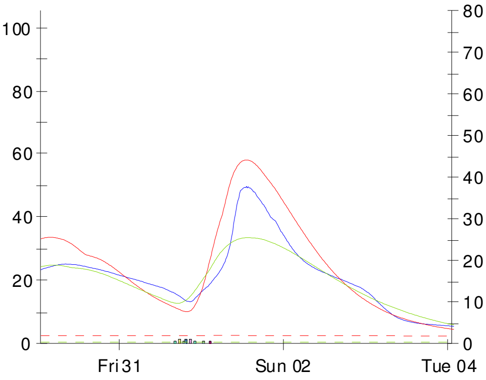
3. 30 Oct 2000 18:45 (23-42-60mm)



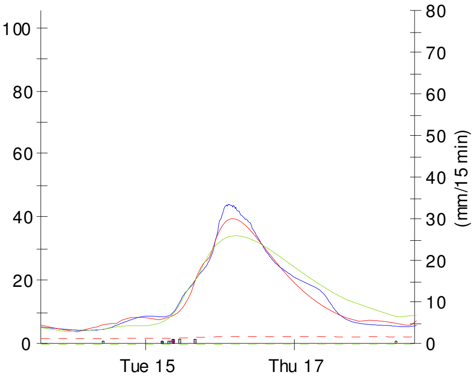
4. 31 Dec 2002 05:00 (56-71-86mm)



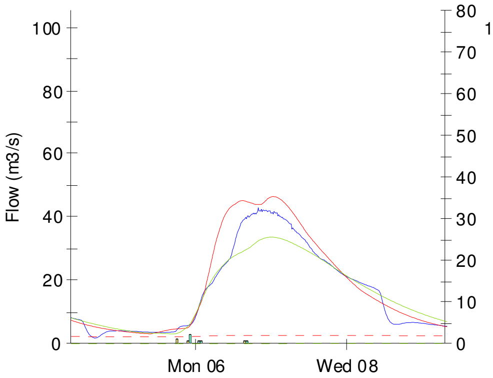
5. 01 Feb 2014 13:15 (31-35-52mm)



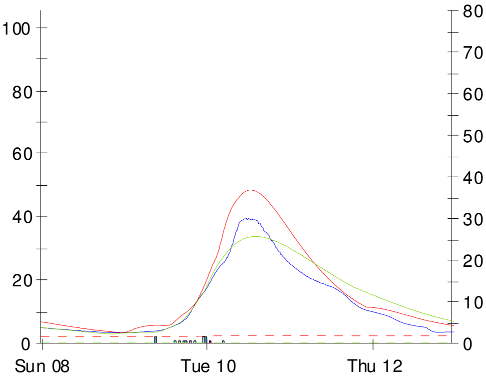
6. 16 Jan 2008 02:30 (40-47-63mm)



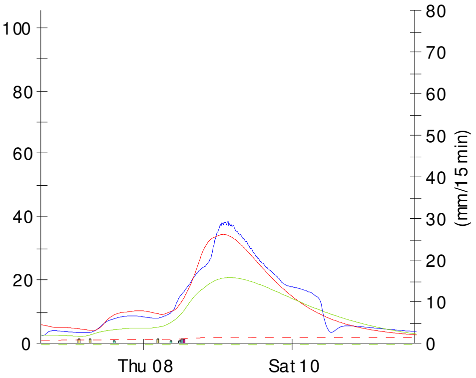
7. 06 Nov 2000 19:45 (10-46-50mm)



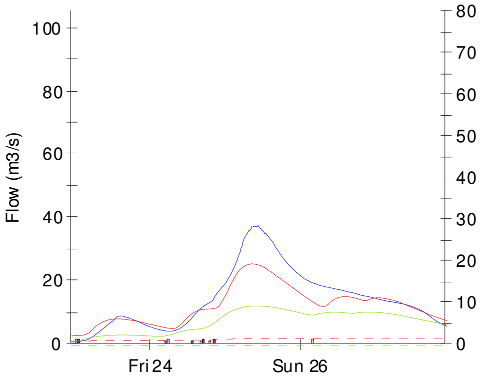
8. 10 Feb 2009 11:15 (35-40-48mm)



9. 09 Dec 1994 03:15 (30-45-55mm)



10. 25 Dec 1999 10:30 (30-51-80mm)

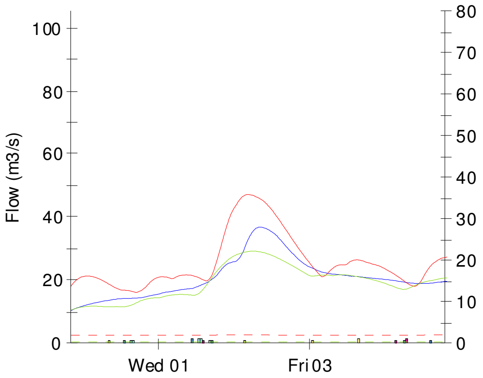


Key

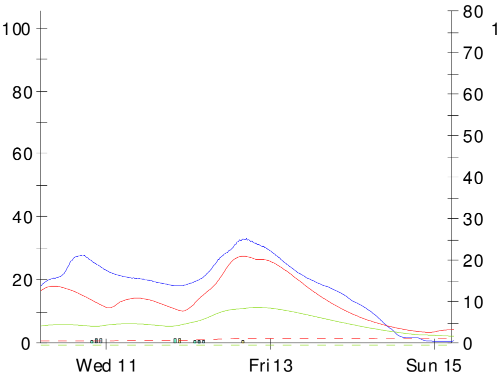
- 453600002HSG - Flow : VEXOUR BRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Vexour_NFFS)
- Qg (Vexour_NFFS)
- 463655903REev - Recording Rain : EDEN VALE STW RTS
- 292554REev - Recording Rain : Weir Wood Res RF
- 463630901REev - Recording Rain : PAINS HILL RES RTS
- 463622502REev - Recording Rain : KENT HATCH RES tbr
- 463641904REev - Recording Rain : GODSTONE STW RTS
- 463610906REev - Recording Rain : EDENBRIDGE STW RTS
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

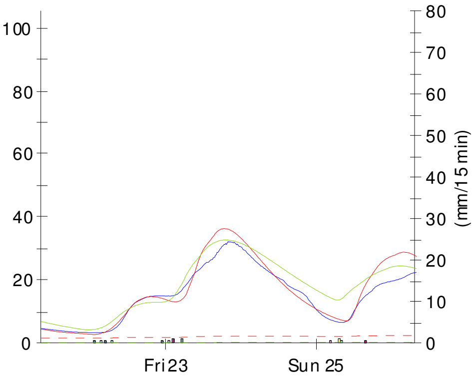
11. 02 Jan 2014 07:45 (46-55-82mm)



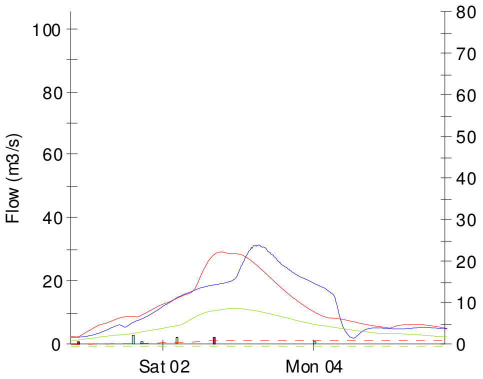
12. 12 Oct 2000 17:00 (27-50-55mm)



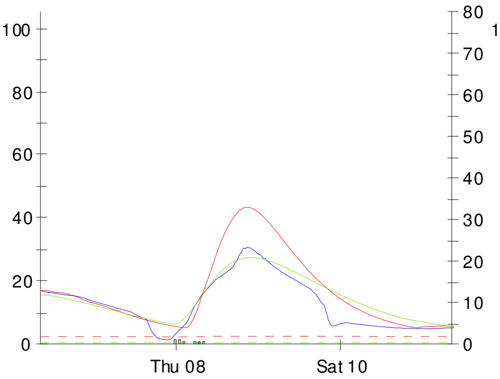
13. 23 Jan 2009 19:45 (48-60-80mm)



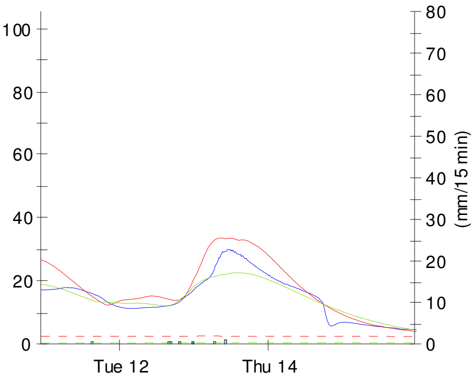
14. 03 Oct 1993 06:15 (32-71-81mm)



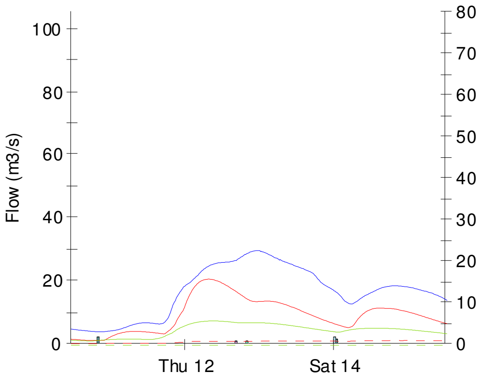
15. 08 Feb 2001 20:15 (1-30-35mm)



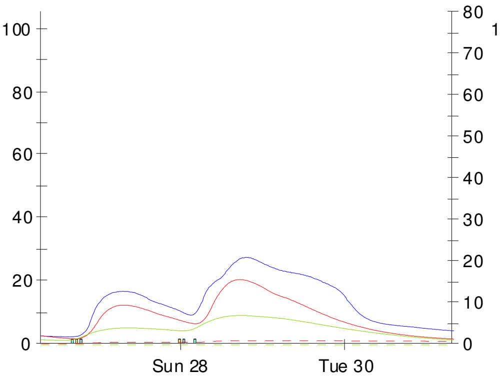
16. 13 Dec 2000 10:45 (20-26-34mm)



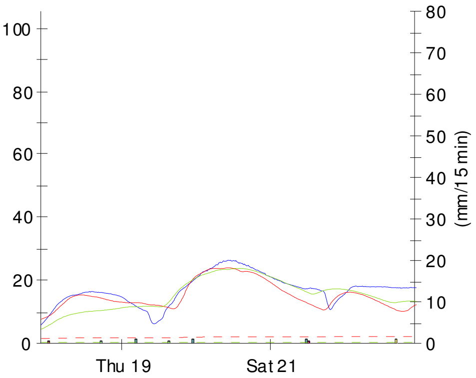
17. 12 Jul 2012 23:30 (29-67-74mm)



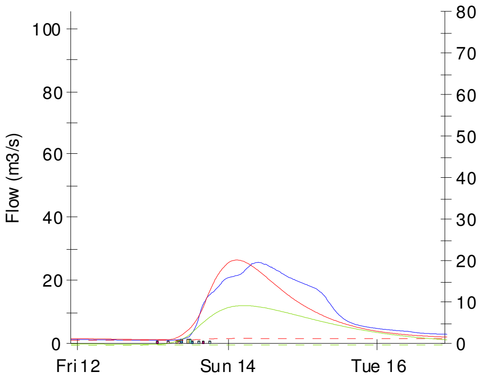
18. 28 May 2000 19:00 (32-56-60mm)



19. 20 Jan 1995 10:15 (0-45-73mm)



20. 14 Dec 2008 09:45 (27-30-42mm)



Key

- 453600002HSG - Flow : VEXOUR BRIDGE
- Modelled Q
- Modelled Qg
- Qtot (Vexour_NFFS)
- Qg (Vexour_NFFS)
- 463655903REev - Recording Rain : EDEN VALE STW RTS
- 292554REev - Recording Rain : Weir Wood Res RF
- 463630901REev - Recording Rain : PAINS HILL RES RTS
- 463622502REev - Recording Rain : KENT HATCH RES tbr
- 463641904REev - Recording Rain : GODSTONE STW RTS
- 463610906REev - Recording Rain : EDENBRIDGE STW RTS
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

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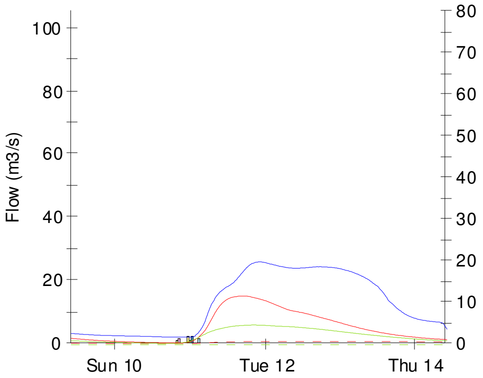
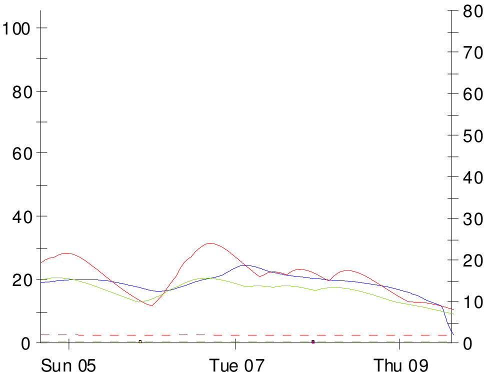
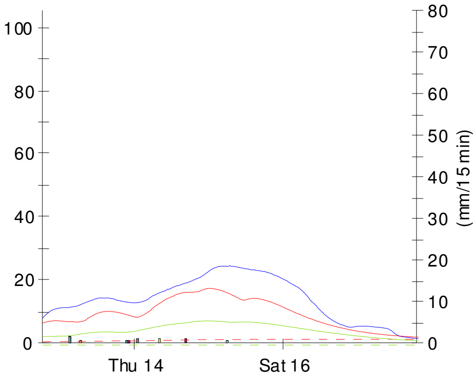
21. 11 Jun 2012 21:45 (39-43-59mm)



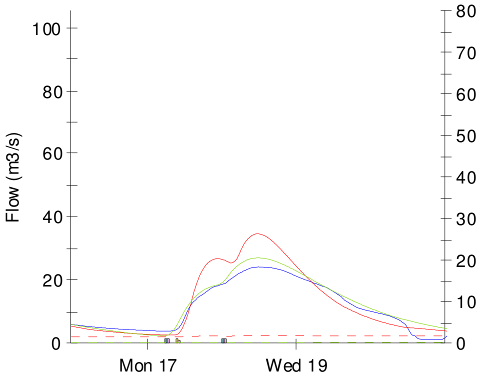
22. 07 Jan 2014 03:30 (29-33-41mm)



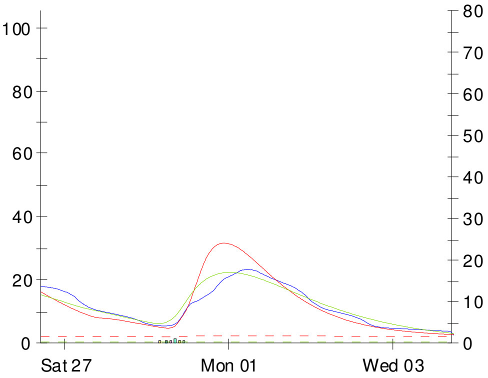
23. 15 Nov 2002 06:45 (32-41-49mm)



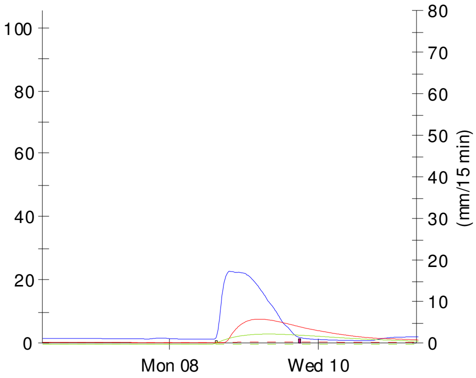
24. 18 Jan 2011 11:45 (30-32-36mm)



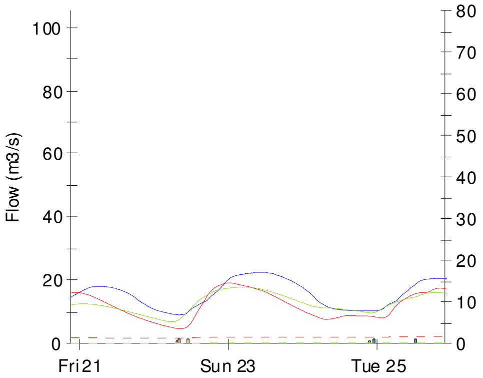
25. 01 Mar 2010 05:00 (22-24-26mm)



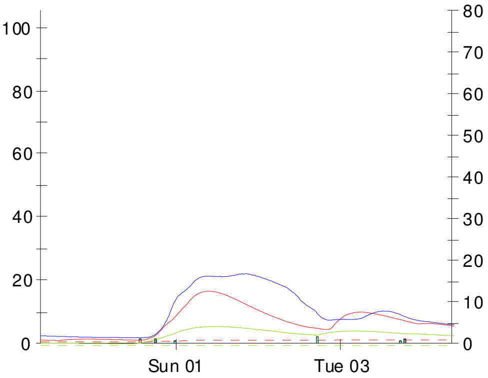
26. 08 May 2000 19:15 (8-17-29mm)



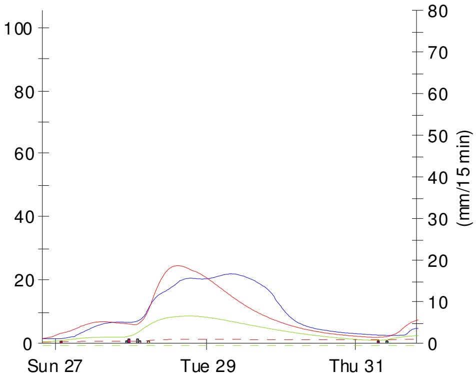
27. 23 Dec 2012 09:30 (7-34-45mm)



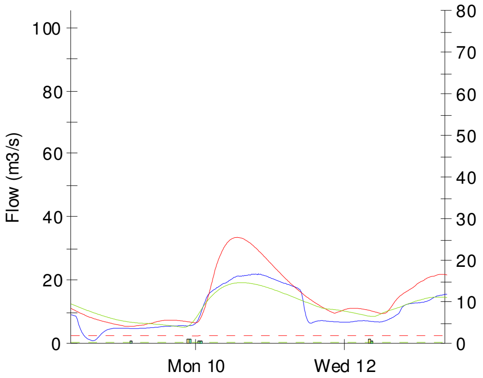
28. 01 Nov 1998 20:15 (4-38-52mm)



29. 29 Oct 2013 07:30 (40-45-73mm)



30. 10 Jan 1994 20:15 (23-35-42mm)



Key

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- Modelled Qg
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- Qg (Vexour_NFFS)
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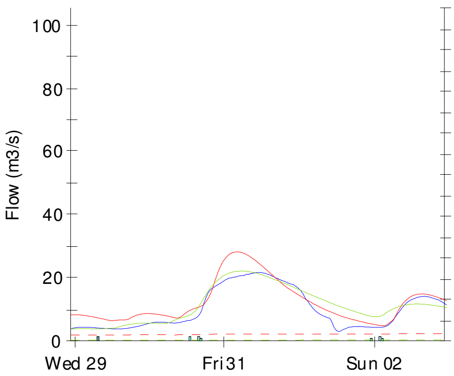
- 292554REev - Recording Rain : Weir Wood Res RF
- 463630901REev - Recording Rain : PAINS HILL RES RTS
- 463622502REev - Recording Rain : KENT HATCH RES tbr
- 463641904REev - Recording Rain : GODSTONE STW RTS
- 463610906REev - Recording Rain : EDENBRIDGE STW RTS
- Average Rain

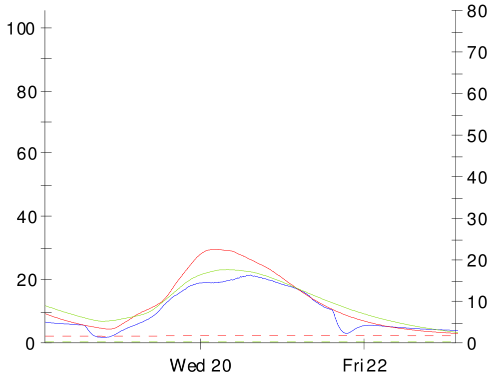
Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

JBA consulting

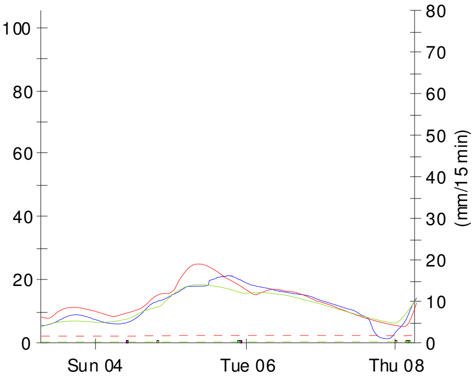
31. 31 Dec 1993 10:45 (26-33-34mm)



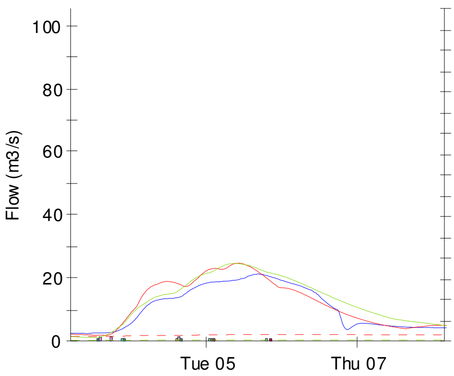
32. 20 Jan 1999 14:45 (18-28-34mm)



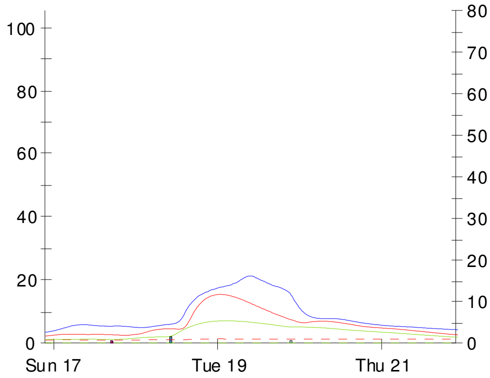
33. 05 Feb 2001 18:15 (31-46-55mm)



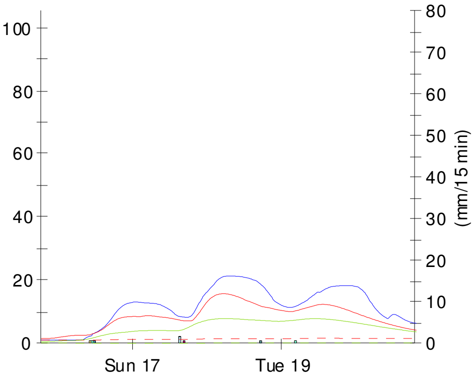
34. 05 Feb 2002 16:15 (16-39-69mm)



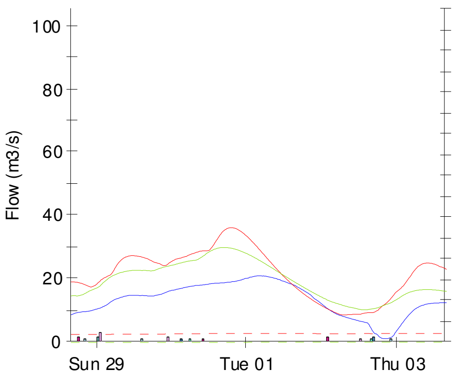
35. 19 Mar 2002 09:45 (0-24-28mm)



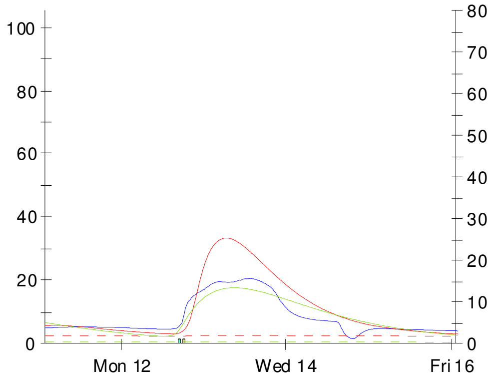
36. 18 Mar 2013 06:30 (35-38-44mm)



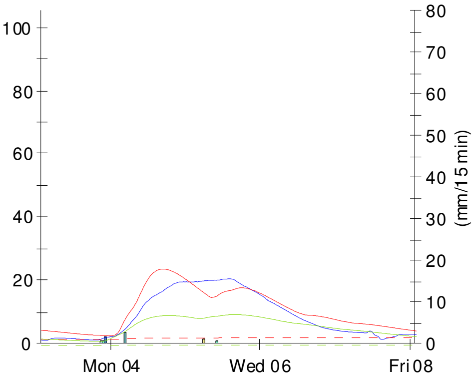
37. 01 Dec 2009 03:45 (29-52-66mm)



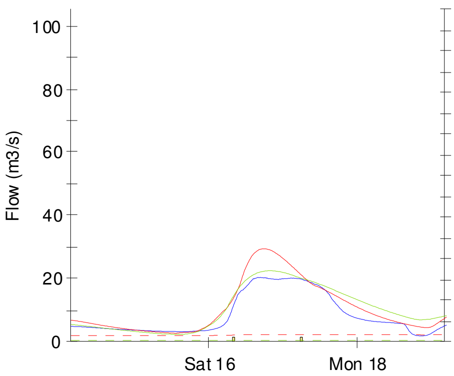
38. 13 Feb 2001 13:30 (18-20-24mm)



39. 05 Nov 2013 13:30 (32-36-46mm)



40. 16 Jan 1999 15:45 (4-32-36mm)



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- Modelled Qg
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- 463610906REev - Recording Rain : EDENBRIDGE STW RTS
- Average Rain

Rainfall accumulations shown as minimum-average-maximum for the plot period, using the rain gauges selected

C Additional rating curves used by this project

C.1 General

Rating curves used by the project but not covered in the Model Summary Reports (e.g. because they are tabular) are included in this Appendix. Other than Forest Row (tabular rating extracted from the hydraulic model), tabular ratings are those developed by JBA for this project.

East Farleigh rating is not included because flows were provided by the Environment Agency direct.

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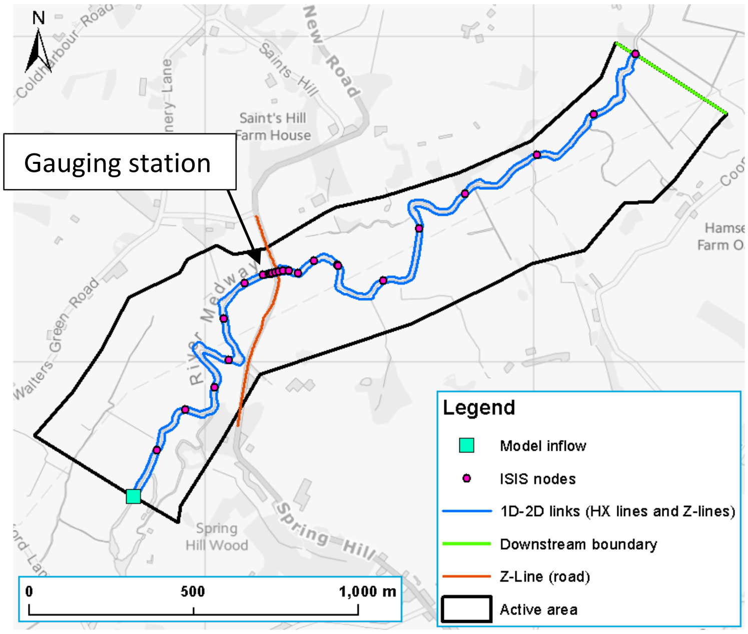
MEDWAY CATCHMENT MAPPING AND MODELLING

COLLIERS LAND BRIDGE RATING SHEET

Station Details	
Station Name	Colliers Land Bridge
Site ID	453400001SG
Structure Type:	Bridge
Model Node:	COLL01_0170u
Watercourse:	River Medway
Site Datum:	29.0mAOD

Photograph

Model Representation – NEW Standalone ISIS-TUFLOW model

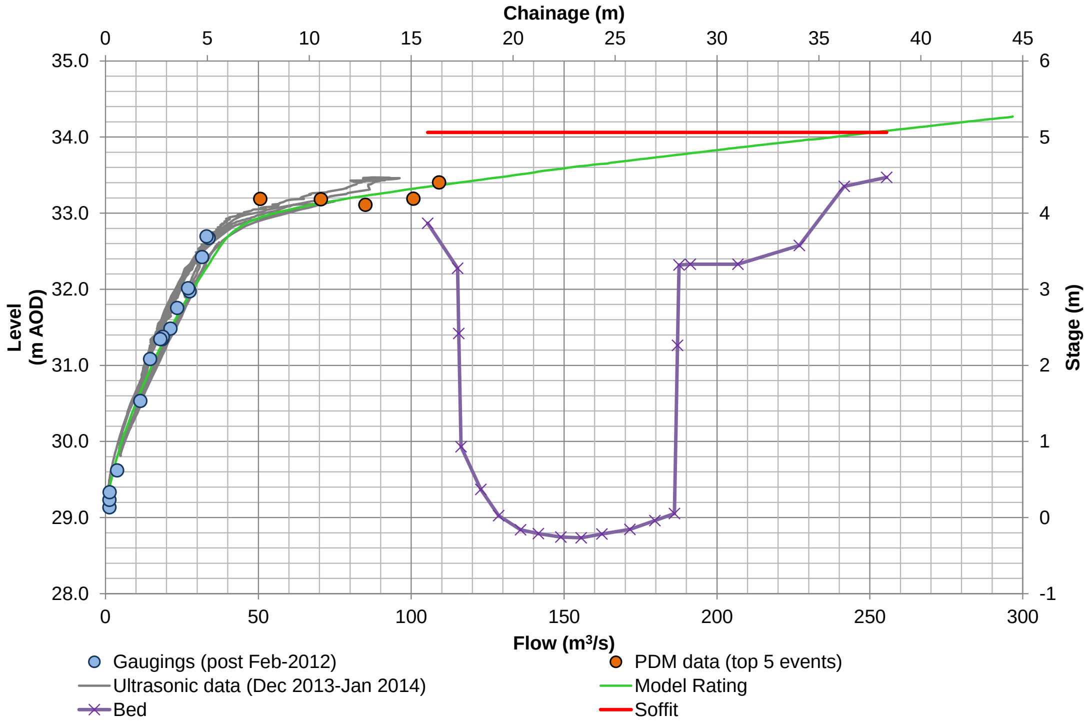


MEDWAY CATCHMENT MAPPING AND MODELLING

COLLIERS LAND BRIDGE RATING SHEET

Unit(s)	Node Labels	Key dimensions	Coefficients	Data source	Comments
BERNOULLI LOSS	COLL_0170bu	Soffit 34.09mAOD Areas from Maltby survey (=46.287sqm at soffit)	K values increase from 0 – 2.5 at soffit	Maltby Land Surveys Ltd 2014	Bernoulli loss allowed more calibration control than arch bridge unit
SPILL	COLL_0170su	Min level 33.9mAOD	Mod limit 0.9, Coeff 1.1		No flow over headwall until flows in excess of 225m^3/s
TUFLOW domain		4m grid Critical levels for bypass over road: left bank 32.8mAOD; right bank	Dominant roughness class n= 0.1	LiDAR	Bypass flow in 2D domain above 44m^3/s (left bank)

Rating Curve Graph



Notes

- **Datum:** The internal reference level within the measurement hut for stage measurement is 35.035mAOD following the recent (2014) Maltby Land Survey.
- **Flooding of road:** Flow over the road downstream (right bank) occurs above water levels at the gauge of 32.8mAOD (stage 3.8m) when flows are in excess of 44m^3/s. No bypassing across the road over the left bank is predicted.

- **Historic Events:** Spot gaugings are only shown post-2012 when the ultrasonics were installed. The highest gauged flow in this period was 33.7m^3/s for a stage of 3.70m, taken in October 2013. The model predicts a slightly higher flow for this stage, possibly due to the gauging measurement missing a small amount of bypassing flow either side of the channel section where the ultrasonics are situated. The model rating fits well with lower spot gaugings and with the ultrasonic measurements. Recent high flow events are also shown in the graph above, along with their flow predicted by rainfall-runoff modelling (PDM). The highest is a level of 33.47m at the peak of the December 2013 event.
- **Hysteresis**: The ultrasonic data shows some minor hysteresis. The model rating fits the rising limb.
- **Ultrasonics**: The ultrasonics should be reliable up to the berm level of 32.3mAOD (stage 3.3m). Then the model rating is preferred to capture bypass flow effects.

Rating Table (Quality flags QF: A=Model calibrated to spot gaugings; B=Extended calibrated model or well defined structure; C= Model calibrated only by correlation or to runoff calculations, D=hysteresis or other source of natural variability

Stage	Flow	QF	Stage	Flow	QF	Stage	Flow	QF	Stage	Flow	QF
0.20	0.0	A	1.30	8.0	A	2.40	20.1	A	3.50	36.5	B
0.30	0.7	A	1.40	9.0	A	2.50	21.5	A	3.60	38.2	B
0.40	1.4	A	1.50	10.0	A	2.60	22.8	A	3.80	43.3	B
0.50	2.0	A	1.60	11.0	A	2.70	24.2	A	4.00	55.4	B
0.60	2.5	A	1.70	12.0	A	2.80	25.6	A	4.20	80.4	B
0.70	3.2	A	1.80	13.0	A	2.90	27.1	A	4.40	115.5	B
0.80	3.8	A	1.90	14.1	A	3.00	28.6	A	4.60	151.9	B
0.90	4.6	A	2.00	15.2	A	3.10	30.2	A	4.80	194.1	B
1.00	5.3	A	2.10	16.3	A	3.20	31.7	A	5.00	238.0	B
1.10	6.2	A	2.20	17.5	A	3.30	33.4	A	5.20	281.5	B
1.20	7.1	A	2.30	18.8	A	3.40	34.9	B	5.27	296.7	B

NOTE TO FILE

JBA Project Code	2013s7661
Contract	Medway Catchment Mapping and Modelling
Client	Environment Agency – South East Region
Day, Date and Time	September 2014
Author	Ben Gibson
Subject	Model Operation Manual: Colliers Land Bridge Rating Review model

1 Introduction

This document accompanies the ISIS-TUFLOW model developed to inform a rating at Colliers Land Bridge gauging station on the River Medway, commissioned under the Medway Catchment Mapping and Modelling study.

It notes the model files required to re-simulate the hydraulic model, provides a description of the hydraulic model and schematisation, as well as a brief summary of testing that was completed to inform the rating model.

1.1 Model files

Files for the final rating model are supplied.

The model files needed to run the Colliers Land Bridge rating ISIS-TUFLOW model are listed in the table below:

File type	File name
ISIS Data file (.DAT)	COLLIERS_013_050h_BernoulliAdjustment(K2-5)
ISIS Event run form (.IEF)	COLLIERS_015_050h_BernoulliAdjustment(K2-5)_noFLC
TUFLOW Control File (.TCF)	COLLIERS_015_050h_BernoulliAdjustment(K2-5)_noFLC
TUFLOW Geometry Control File (.TGC)	Medway_Colliers_005_NoFLC
TUFLOW Boundary Control File (.TBC)	Medway_Colliers_002
TUFLOW Materials File (.TMF)	Rating_Models_005

TUFLOW model files which define the geometry of the hydraulic model and 1D-2D linking etc are linked within the relevant TUFLOW control files and are maintained in the *TUFLOW > Model > gis* folder.

Results files are also provided.

Within ISIS these have the same stem and *.zzl, *.zzu, *.zzn, *.zzd, *.exy, *.mmm, .bmp extensions.

Within TUFLOW these have the same stem and *.csv, *.dat, *.sup extensions

1.2 Re-running the model

In order to re-simulate hydraulic model, it is recommended that the folder structure within which the hydraulic model data was supplied is retained.

It is recommended that the same versions of ISIS and TUFLOW software used in the simulation of models for this study are retained. These are summarised below. If different versions of either software are used then it is recommended that the corresponding baseline models are re-simulated and results compared in order to appreciate any differences in modelled predictions that have arisen as a result of using a different software package.

- ISIS version: 3.7.1 64-bit single precision
- TUFLOW build: 2013-12-AC-iSP-w64

The model data bundle should be moved to a suitable location, from where the model can be re-simulated. Relative references have been used in both the ISIS and TUFLOW run files, so only the relative path file should need to be updated to re-simulate the model. Currently the default file path (*Path* =) is as follows:

- N:\2013\Projects\2013s7661 - EA SE – Medway Catchment\Calculations\04_Rating_Review_Models\01_Colliers\ISIS\Runs

To update the default file path complete the following steps:

- The ISIS Event Run Form (.ief) for the given baseline or option model should be identified and opened either in ISIS or a text editor (e.g. Notepad, Notepad++, UltraEdit). Replace the ISIS > Runs destination folder with the same location on the users server.

Note: If original model outputs (e.g. ISIS Results files, TUFLOW Results files, TUFLOW Check files, TUFLOW Log files) are not copied from the output folder location, then the outputs will be over-written. It is recommended that these are either copied to a safe location prior to re-simulating the model, or suitable version control is applied to the model files so that these are not over-written.

1.2.1 Model run parameters

With the exception of *dflood* which was increased from the default of 3 to 5, to stabilise the model if water levels rise more than 3m above the highest data point in a given section, all other parameters remain as default.

1.2.2 Model inflows

The inflow into the model is a triangular hydrograph which is input into the ISIS 1D model at the most upstream cross-section. The inflow has the form displayed in the table below – this accounts for the range of flows required and provides greater time at lower flows when these are most critical (e.g. at the point of bank exceedance). Testing on durations of 100h and 200h showed very little difference in the predicted rating so the 50h hydrograph was retained.

Time (h)	Flow (m^3/s)
0	0.1
15	70.0
25	300.0
35	70.0
50	0.1

2 Model history and schematisation

2.1 Existing model and data

An existing 1D ISIS model of the River Medway developed for flood risk mapping purposes was updated in 2008 by Mott MacDonald (River Medway Catchment Modelling and Flood Mapping Updates, 2008), developed before this in the River Medway Flood Risk Mapping Phase 3 Study (2003). Additionally an ISIS-TUFLOW model was developed by Halcrow in 2012 to assist in the derivation of a rating at the gauging site. Survey information used to inform these models was collected in 2001/2002 by Longdin & Browning and in 1995 by Flynn & Rothwell. In addition to this information, survey at the gauging site was collected in 2013 by EDI Surveys Ltd (EA survey reference 11655), which included section data at the ultrasonic gauge as well as topographic survey of various parts of the gauging site.

At the request of the Environment Agency new survey information was specified and collected for the current commission to inform the rating review at the site. This was collected in June 2014 by Maltby Land Surveys Ltd. This was in part driven by the age of the previous survey in addition to damage sustained at the gauging site during the flooding of December 2013 and January 2014. Given the age of the previous survey, new survey was collected at the gauging site and some distance upstream and downstream of the gauge, including Colliers Land Bridge and bank top levels. Other information available to inform the model development was 1m LIDAR data (both filtered and unfiltered) which was flown in April 2009 (note: 2m filtered LIDAR data is used in a few locations within the channel where the 1m data contained null values).

2.2 Model development

Given the age of the information used to inform the previous modelling and the extent of survey data collected to inform the rating study, a model was developed from new to inform the rating investigation at the site.

The 1D hydraulic model was developed with the Maltby Land Surveys Ltd 2014 survey data as the base information. This was supplemented with data from the 2013 EDI Surveys Ltd data where this could add value. To extend the hydraulic model upstream and downstream to provide suitable boundary locations the 1995 and 2001/2002 survey data was used in these areas.

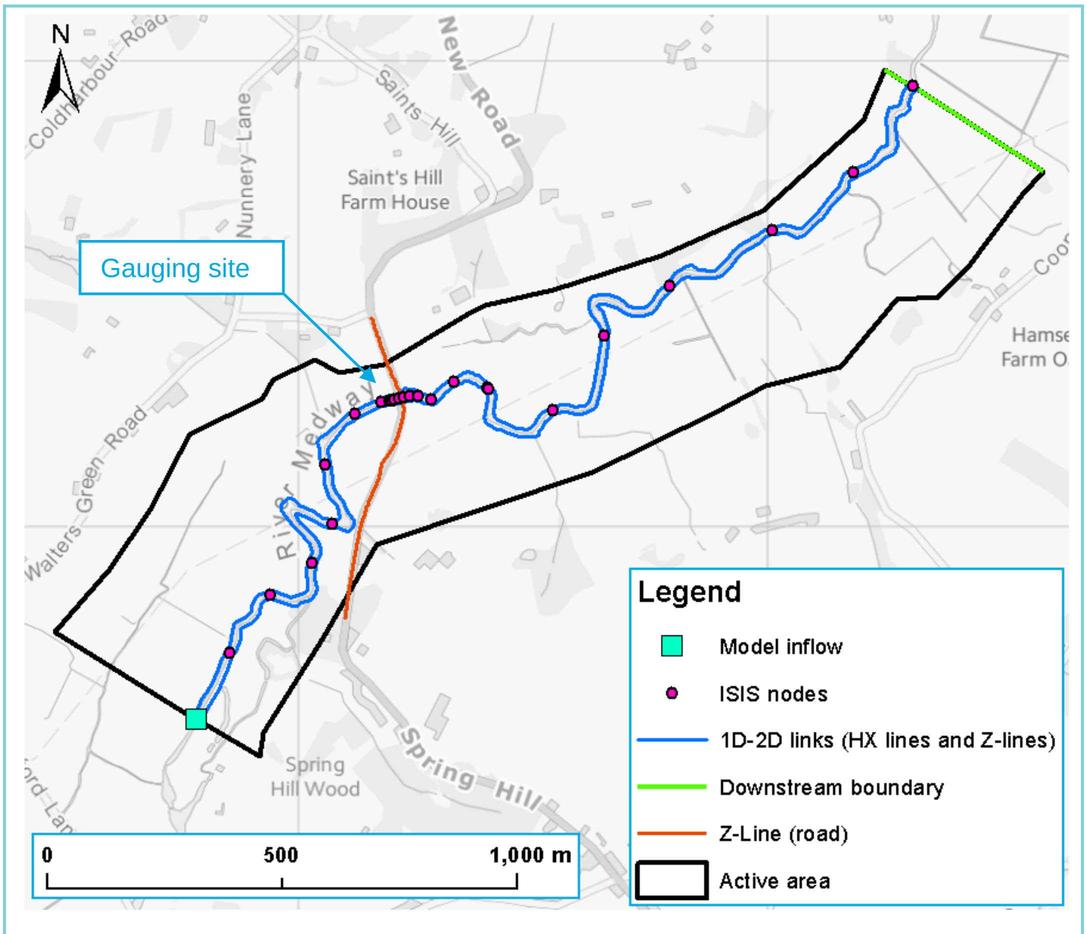
The 2D hydraulic model was developed with the 1m filtered LIDAR data providing the elevations for the base grid which is at a resolution of 4m. Bank levels were informed from the bank top level information collected as part of the 2014 survey and where this was not available bank level were derived from the 2013 survey data collected by EDI Surveys Ltd (where applicable) or filtered LIDAR data. The level of Spring Hill road was also enforced via the use of a Z-Line.

Roughness values for the 1D domain were initially informed from site and survey photographs, and latterly updated during the model and results checking process. Roughness values for the 2D domain were assigned according to land cover classes in OS MasterMap Topography Layer data.

A normal depth boundary is implemented at the downstream boundary of the model in both the 1D and 2D domains with the slope informed from the average slope of the river sections upstream. Sensitivity testing indicates that this does not influence model predictions at the gauging site.

A schematic of the model indicating key model features and extents can be found in Figure 2-1.

Figure 2-1: Model schematic



2.2.1 Model refinement

During the model and results checking process, spot gauging information as well as historic flood event information and sensibility checks on rating performance against PDM model performance were used to make adjustments to the model. From initial model development the following adjustments were made:

- Increased 1D roughness for all sections by 0.015, increasing by a further 0.015 at notable bends in the channel.
- Increased 2D roughness for land cover classes by 0.04 (see discussion in section 3).
- Implemented a roughness value of 0.2 at bank cells where dense vegetation is recorded in site photos or satellite imagery including Spring Hill (see discussion in section 3).
- Implemented a roughness value of 0.2 at isolated along banks to improve model stability at 1D-2D links.
- Filled in a channel recorded in the LIDAR data on the level bank of the channel upstream of the gauging site, as it was considered this would be full with water during a flood event.
- Input a value of 1 within the A parameter of the HX Lines (this increased the form loss coefficient)

2.3 Model testing

The following tests were completed on the model to understand its sensitivity and during the model and rating testing phase (impacts on model predictions are listed below each of these tests in blue). Please also refer to section 3 for further detail regarding model refinements and testing to achieve water levels expected for a given stage once flows spill onto the floodplain.

- Downstream boundary (normal depth slope multiplied by 5)
  Negligible impact on model predictions at the area of interest.
- Downstream boundary (normal depth slope halved)
  Negligible impact on model predictions at the area of interest.
- Spring Hill road raised to level implemented within 2012 rating study (approximately 200mm higher than indicated by 1m filtered LIDAR data)
  Increase in water level for a given flow, but not a direct 200mm increase. Source of data unclear so existing LIDAR information retained as data seems sensible.
- 1D and 2D roughness increased by 20%
  Completed using an earlier version of the model, before increased roughness of 0.015 applied globally to the 1D domain and roughness values were increased in the 2D domain. Increased water levels resulted which are expected. Current roughness values are thought best to represent reality and match well with data from spot flow gaugings. Testing of 1D only and 2D only adjustments suggest 2D roughness adjustments have less notable impacts on predicted water levels at a given flow compared with these combined.
- 1D and 2D roughness decreased by 20%
  Completed using an earlier version of the model, before increased roughness of 0.015 applied globally to the 1D domain and roughness values were increased in the 2D domain. Decreased water levels resulted which are expected. Current roughness values taken forward are thought best to represent reality and match well with data from spot flow gaugings. Testing of 1D only and 2D only adjustments suggest 2D roughness adjustments have less notable impacts on predicted water levels at a given flow compared with these combined.
- Arch Bridge unit used in place of a Bernoulli Loss unit
  Low in-bank and out of bank water levels for a given flow (similar to USBPR 1978 unit). These match less well with the recorded information, so Bernoulli Loss unit taken forward.
- USBPR unit used in place of a Bernoulli Loss unit
  Low in-bank and out of bank water levels for a given flow (similar to Arch Bridge unit). These match less well with the recorded information, so Bernoulli Loss unit taken forward.

JBA Project Code	2013s7661
Contract	Medway Catchment Mapping and Modelling
Client	Environment Agency – South East Region
Day, Date and Time	September 2014
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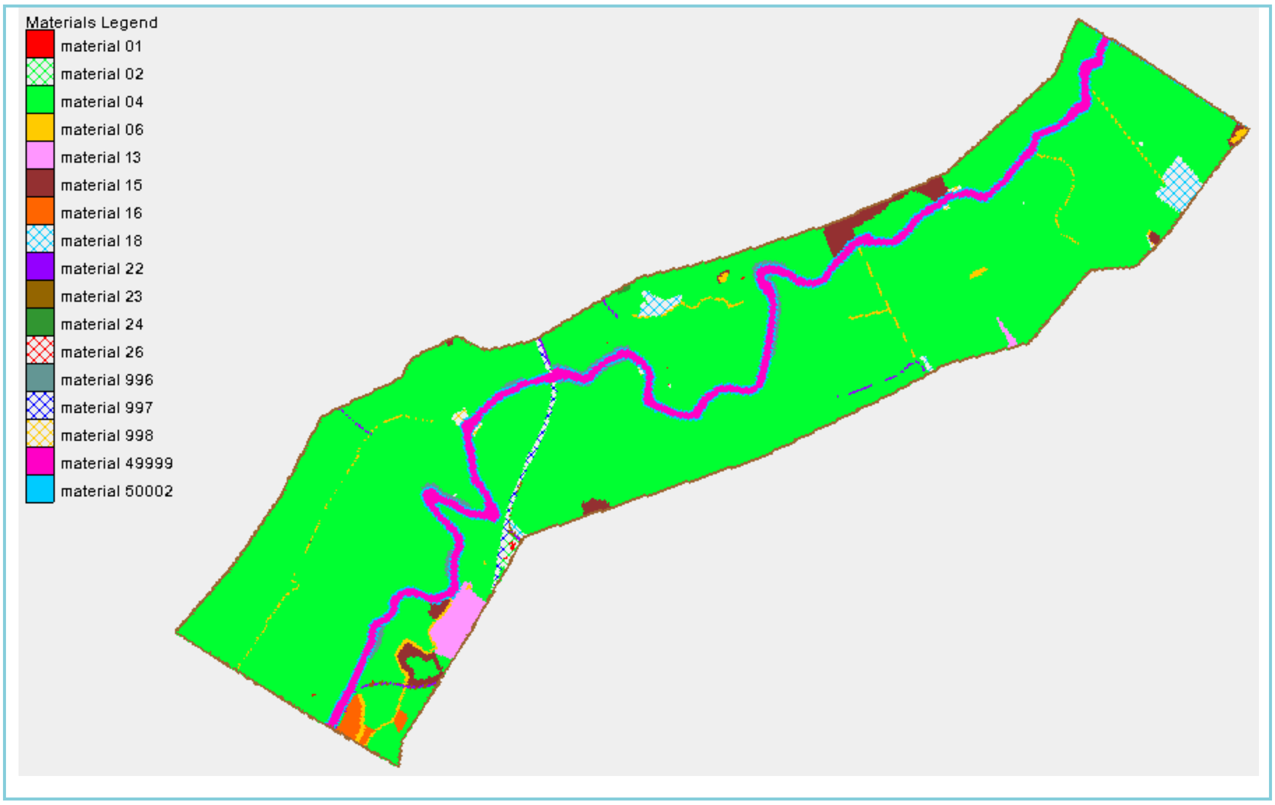
Subject	Model Operation Manual: Colliers Land Bridge Rating Review model

3 Floodplain flow testing

3.1 Initial simulations

Initial simulations implemented roughness values of 0.04 for the TMF class 4 (OS MasterMap class: General surface, code 10056). It can be seen within Figure 3-1 that this generally covers the majority of the modelled area. In addition to the roughness classes below (refer to Table 3-2), a roughness value of 0.10 was applied where dense vegetation was noted from satellite imagery or unfiltered LIDAR data at the banks. Roughness for Spring Hill road remained as per the TMF road class.

Figure 3-1: Model domain and land cover classes (TMF) codes



3.2 Probability Distributed Moisture (PDM) model outputs

On comparison of the initial outputs with predictions of a PDM model developed of the area, it became apparent that whilst in-channel flows were matching well (with spot gaugings too), notably too much out of bank flow was being predicted for a given water level recorded at the gauging site. Assessment of rainfall, gauged information and percentage runoff for the catchment above both for this site and others completed at the same time in the catchment indicated that excessive runoff (in some cases above 100% runoff) would be required to achieve the predicted flows for the events tested.

Consequently it was considered that increasing material roughness of the 2D domain should be tested, as well as testing form loss applied to represent losses at the road intersecting the floodplain, to assess whether this would better match expected flows for the determined runoff rates.

3.3 Testing completed

Three scenarios were tested and comparison made between these and the initial baseline. These are summarised in Table 3-1 below. Note: TMF code 4 is used as a reference point for roughness, refer to Table 3-2 for a full overview of the different roughness values tested.

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Table 3-1: Testing completed to produce more realistic flows once bank levels are exceeded

Model	Material roughness (class 4)	Bank vegetation roughness	Road roughness	Road form loss (1.0)
Initial baseline	0.05	0.10	Default	No
v014	0.08	0.20	0.20	No
v015_FLC	0.10	0.20	Default	Yes
v015_noFLC	0.10	0.20	0.20	No

Table 3-2: Roughness values tested for TMF classes
Note: not all land cover types are necessarily located within the model domain

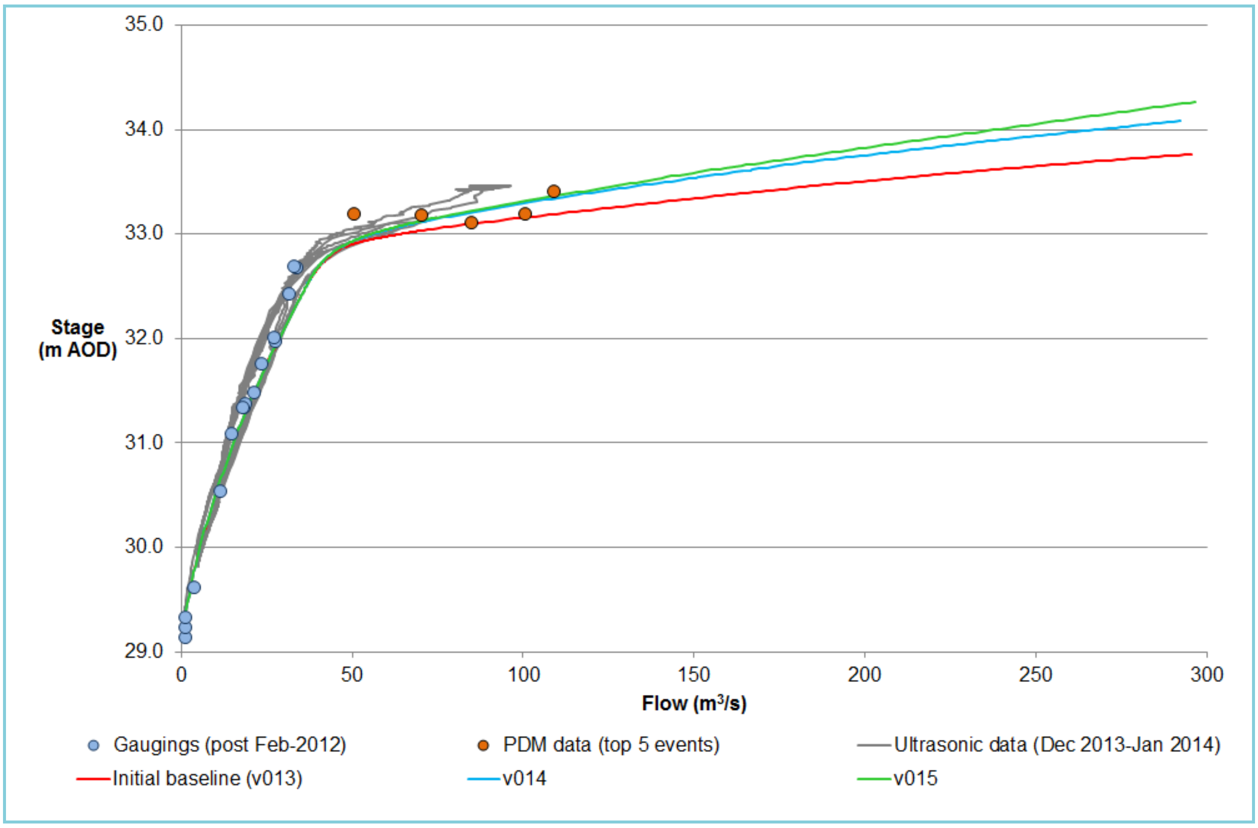
TMF code	OS MasterMap land cover type and (code)	Initial baseline roughness	v014 roughness	v015 roughness
1	Building (10021)	0.300	0.300	0.300
2	General surface – multi surface (10053)	0.050	0.070	0.090
3	General surface – step (10054)	0.050	0.070	0.090
4	General surface (10056)	0.060	0.080	0.100
5	Glasshouse (10062)	0.200	0.200	0.200
6	Inland water (10089)	0.055	0.075	0.095
7	Landform (10093)	0.060	0.080	0.100
8	Landform – slope (10096)	0.060	0.080	0.100
9	Landform – cliff (10099)	0.060	0.080	0.100
10	Boulders (10111)	0.065	0.085	0.105
11	Coniferous trees (10111)	0.120	0.140	0.160
12	Coniferous trees – scattered / Orchard (10111)	0.070	0.090	0.110
13	Coppice or osiers (10111)	0.090	0.110	0.130
14	Marsh Reeds or Saltmarsh (10111)	0.060	0.080	0.100
15	Non coniferous trees (10111)	0.090	0.110	0.130
16	Non-coniferous trees – scattered (10111)	0.060	0.080	0.100
17	Rough grassland (10111)	0.060	0.080	0.100
18	Scrub (10111)	0.070	0.090	0.110
19	Path – step (10119)	0.050	0.070	0.090
20	Path (10123)	0.050	0.070	0.090
21	Rail (10167)	0.040	0.060	0.080
22	Road (10172)	0.040	0.060	0.080
23	Roadside (10183)	0.050	0.070	0.090
24	Structure (10185)	0.300	0.300	0.300
25	Structure – upper level of communication (10187)	0.300	0.300	0.300
26	Structure – pylon (10193)	0.060	0.080	0.100
27	Tidal water – foreshore (10203)	0.055	0.075	0.095
28	Tidal water (10210)	0.055	0.075	0.095
29	Unclassified (10217)	0.060	0.080	0.100
30	Rock (10111)	0.070	0.090	0.110
31	Heath (10111)	0.090	0.110	0.130

3.4 Results and final simulation

Increasing the roughness of the 2D domain floodplain domain increased water levels, which is expected. Comparison of the modelled rating curves for the initial baseline, v014 and v015 are displayed in Figure 3-2. The test with a form loss coefficient implemented at the road intersecting the floodplain has not been plotted as the results were very similar to the case without this applied. Comparison was made between these outputs and those from the PDM. In channel data matches spot gaugings in each case, but v015 outputs were considered to best reflect the observed case, particularly for the largest of flows. *Consequently v015 was taken forward for the derivation of the final rating curve.*

The modelled rating curve data also matches closely with the stage-flow information recorded by the ultrasonic gauging site during the period December 2013-January 2014. At the uppermost data points on the ultrasonic measurement, model predictions suggests that bypassing of the site across Spring Hill road would occur, meaning under prediction of the event flow is expected.

Figure 3-2: Comparison of model rating curves from initial baseline, v014 and v015 tests



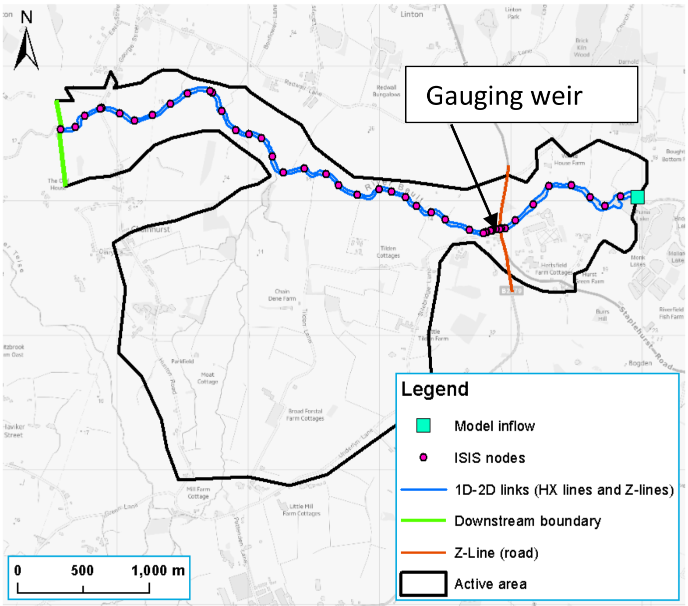
MEDWAY CATCHMENT MAPPING AND MODELLING

STILE BRIDGE RATING SHEET

Station Details	
Station Name	Stile Bridge
Site ID	453210001SG
Structure Type:	Flat-V weir
Model Node:	STIL01_0135
Watercourse:	River Beult
Site Datum:	11.42mAOD

Photograph

Model Representation – NEW Standalone ISIS-TUFLOW model



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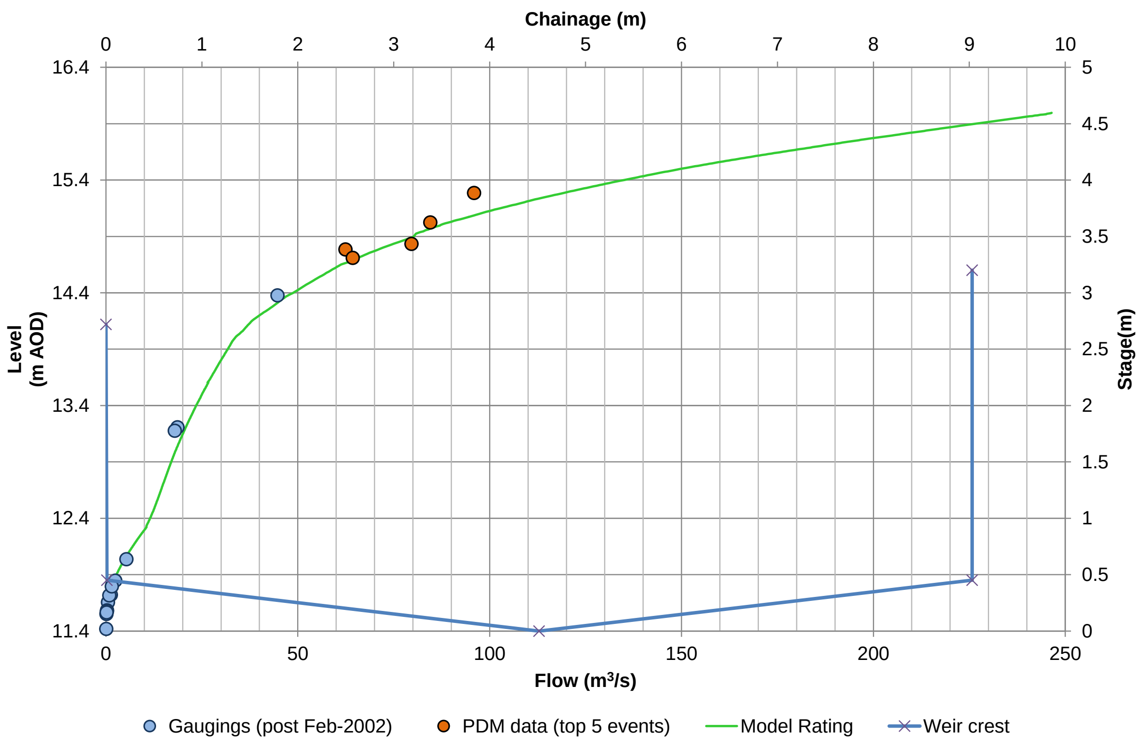
MEDWAY CATCHMENT MAPPING AND MODELLING

STILE BRIDGE RATING SHEET

Unit(s)	Node Labels	Key dimensions	Coefficients	Data source	Comments
FLAT-V WEIR	STIL_0133wu	Crest 11.402mAOD	Defaults	Maltby Land Surveys Ltd 2014	Non-modular above 12.34mAOD (10.5m^3/s)
SPILL	STIL_0133su	Min level 13.0mAOD	Mod limit 0.9, Coeff 1.5		Bypass flow starts at 18.5m^3/s
TUFLOW domain		8m grid Left bank critical level 14.12mAOD; Right bank: 14.6mAOD	Dominant roughness class n= 0.1	LiDAR	Bypass flow in 2D domain above 37.5m^3/s (left bank)

Rating Curve Graph



Notes

- **Datum:** The reference level for stage measurement is 11.402mAOD following the recent (2014) Maltby Land Survey.
- **Flooding of road:** Flow over the road upstream (left bank) occurs above water levels at the gauge of 15.1mAOD (stage 2.91m) when flows are in excess of 99m^3/s.
- **Historic Events:** Spot gaugings are only shown post-2002 when the weir was reconstructed. The highest gauged flow in this period was 44.7m^3/s for a stage of 2.96m, taken in February 2009. However the weir reconstruction is likely to have a reduced impact in very high flows and it is therefore instructive to note that a number of spot gaugings during the October 2000 event at a stage of 3.44-3.47m indicated flows of 75-79m^3/s. These fit very well with

the model rating. Recent high flow events are also shown in the graph above, along with their flow predicted by rainfall-runoff modelling (PDM). The highest is a level of 15.3m at the peak of the December 2012 event.

- **Hysteresis**: The model indicates significant hysteresis due to filling of the large area of floodplain downstream of the gauge. This can lead to much higher stages for a given level on the falling limb than on the rising limb. The rating curve has been fitted to the rising limb.

Rating Table (Quality flags QF: A=Model calibrated to spot gaugings; B=Extended calibrated model or well defined structure; C= Model calibrated only by correlation or to runoff calculations, D=hysteresis or other source of natural variability

Stage	Flow	QF	Stage	Flow	QF	Stage	Flow	QF	Stage	Flow	QF
0.00	0.0	A	1.10	12.9	A	2.20	26.8	A	3.30	66.3	A
0.13	0.1	A	1.20	14.0	A	2.30	28.6	A	3.40	73.8	A
0.20	0.3	A	1.30	15.1	A	2.40	30.3	A	3.50	80.7	A
0.30	0.9	A	1.40	16.1	A	2.50	32.1	A	3.60	88.9	B
0.40	1.8	A	1.50	17.2	A	2.60	34.2	A	3.70	99.3	B
0.50	3.0	A	1.60	18.4	A	2.70	37.2	A	3.80	110.9	B
0.60	4.6	A	1.70	19.7	A	2.80	40.9	A	3.90	123.8	B
0.70	6.4	A	1.80	21.0	A	2.90	45.0	A	4.00	137.8	B
0.80	8.4	A	1.90	22.4	A	3.00	49.8	A	4.20	170.7	B
0.90	10.6	A	2.00	23.8	A	3.10	54.6	A	4.40	209.8	B
1.00	11.8	A	2.10	25.3	A	3.20	59.7	A	4.58	246.5	B

MODEL USER GUIDE

JBA Project Code	2013s7661
Contract	Medway Catchment Mapping and Modelling
Client	Environment Agency – South East Region
Day, Date and Time	September 2014
Author	Ben Gibson
Subject	Model Operation Manual: Stile Bridge Rating Review model

1 Introduction

This document accompanies the ISIS-TUFLOW model developed to inform a rating at Stile Bridge gauging station on the River Beult, commissioned under the Medway Catchment Mapping and Modelling study.

It notes the model files required to re-simulate the hydraulic model, provides a description of the hydraulic model and schematisation, as well as a brief summary of testing that was completed to inform the rating model.

1.1 Model files

Files for the final rating model are supplied.

The model files needed to run the Stile Bridge rating ISIS-TUFLOW model are listed in the table below:

File type	File name
ISIS Data file (.DAT)	STILEBRIDGE_014_100h
ISIS Event run form (.IEF)	STILEBRIDGE_015_100h
TUFLOW Control File (.TCF)	STILEBRIDGE_015_100h
TUFLOW Geometry Control File (.TGC)	Medway_Stilebridge_006
TUFLOW Boundary Control File (.TBC)	Medway_Stilebridge_004
TUFLOW Materials File (.TMF)	Rating_Models_005

TUFLOW model files which define the geometry of the hydraulic model and 1D-2D linking etc are linked within the relevant TUFLOW control files and are maintained in the *TUFLOW* > *Model* > *gis* folder.

Results files are also provided.

Within ISIS these have the same stem and *.zzl, *.zzu, *.zzn, *.zzd, *.exy, *.mmm, .bmp extensions.

Within TUFLOW these have the same stem and *.csv, *.dat, *.sup extensions

1.2 Re-running the model

In order to re-simulate hydraulic model, it is recommended that the folder structure within which the hydraulic model data was supplied is retained.

It is recommended that the same versions of ISIS and TUFLOW software used in the simulation of models for this study are retained. These are summarised below. If different versions of either software are used then it is recommended that the corresponding baseline models are re-simulated and results compared in order to appreciate any differences in modelled predictions that have arisen as a result of using a different software package.

- ISIS version: 3.7.1 64-bit single precision
- TUFLOW build: 2013-12-AC-iSP-w64

The model data bundle should be moved to a suitable location, from where the model can be re-simulated. Relative references have been used in both the ISIS and TUFLOW run files, so only the relative path file should need to be updated to re-simulate the model. Currently the default file path (*Path* =) is as follows:

- N:\2013\Projects\2013s7661 - EA SE – Medway Catchment\Calculations\04_Rating_Review_Models\04_Stilebridge\ISIS\Runs

To update the default file path complete the following steps:

- The ISIS Event Run Form (.ief) for the given baseline or option model should be identified and opened either in ISIS or a text editor (e.g. Notepad, Notepad++, UltraEdit). Replace the ISIS > Runs destination folder with the same location on the users server.

Note: If original model outputs (e.g. ISIS Results files, TUFLOW Results files, TUFLOW Check files, TUFLOW Log files) are not copied from the output folder location, then the outputs will be over-written. It is recommended that these are either copied to a safe location prior to re-simulating the model, or suitable version control is applied to the model files so that these are not over-written.

1.2.1 Model run parameters

With the exception of *dflood* which was increased from the default of 3 to 10, to stabilise the model if water levels rise more than 3m above the highest data point in a given section, all other parameters remain as default.

1.2.2 Model inflows

The inflow into the model is a triangular hydrograph which is input into the ISIS 1D model at the most upstream cross-section. The inflow has the form displayed in the table below – this accounts for the range of flows required and provides greater time at lower flows when these are most critical (e.g. at the point of bank exceedance). Testing on durations of 50h and 200h showed some difference in the predicted rating, particularly on the recession limb so the 100h hydrograph was retained as it is considered that this more closely relates to a typical hydrograph duration at the site.

Time (h)	Flow (m^3/s)
0	0.1
25	40.0
50	250.0
75	40.0
100	0.1

2 Model history and schematisation

2.1 Existing model and data

Existing 1D and 1D-2D ISIS and ISIS-TUFLOW models of the River Beult upstream and downstream of Stile Bridge, respectively were developed for flood risk mapping purposes in 2007 by Mott MacDonald (Upper Teise/Beult & Bourne Modelling and Mapping, 2007 and Teise and Beult 2D Modelling and Mapping, 2007, respectively). Survey information used to inform these models was collected in 2002 for the Middle Medway Strategy Survey by Cartographical Surveys Ltd. In addition to this information, survey at the gauging site was collected in 2013 by EDI Surveys Ltd (EA survey reference 116581), which included section data at the ultrasonic gauge as well as topographic survey of various parts of the gauging site. Survey collected in 2001 by Longdin & Browning at the gauging site and various other channel sections, was also available.

At the request of the Environment Agency new survey information was specified and collected for the current commission to inform the rating review at the site. This was collected in June 2014 by Maltby Land Surveys Ltd. This was driven by the age of the previous survey in addition to the need to collect more detailed information at particular locations to inform model build. Given the age of the previous survey, new survey was collected at the gauging site and some distance upstream and downstream of the gauge, including Stile Bridge and bank top levels. Other information available to inform the model development was 1m LIDAR data (both filtered and unfiltered) which was flown in April 2009 where no more higher resolution LIDAR data is available (note: 2m filtered LIDAR data is used in a few locations within the channel where the 1m data contained null values), where the is available the higher resolution data appears to have re-sampled to produce the 1m data. The 25cm LIDAR data available from

January/May 2008 and November 2010 was not used as it was considered the 1m data provided sufficient detail.

2.2 Model development

Given the age of the information used to inform the previous modelling and the extent of survey data collected to inform the rating study, a model was developed from new to inform the rating investigation at the site.

The 1D hydraulic model was developed with the Maltby Land Surveys Ltd 2014 survey data as the base information. This was supplemented with data from the 2013 EDI Surveys Ltd data where this could add value. To extend the hydraulic model upstream and downstream to provide suitable boundary locations the 2001 and 2002 survey data was used in these areas.

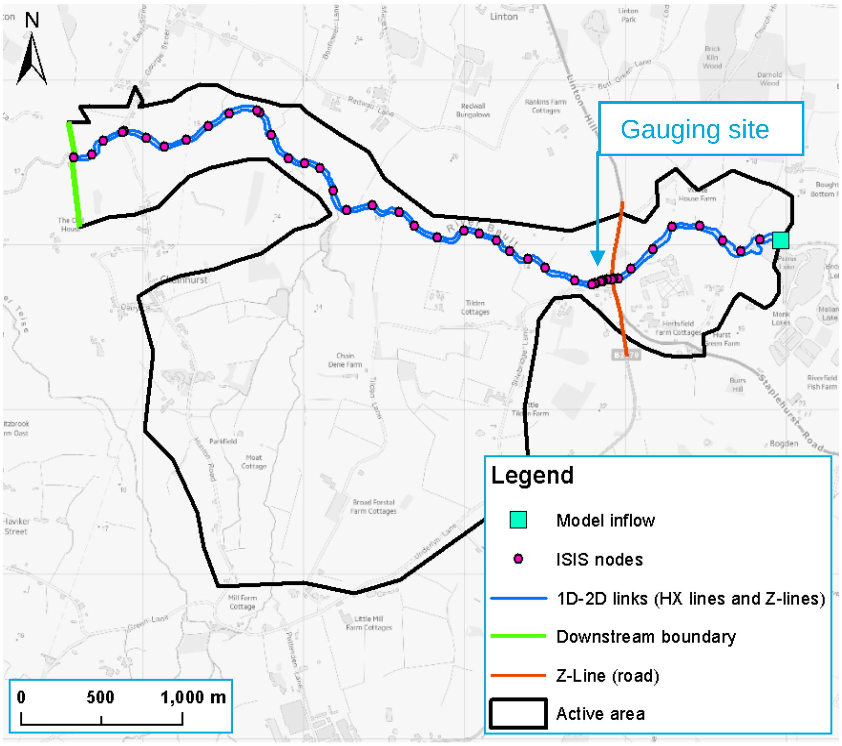
The 2D hydraulic model was developed with the 1m filtered LIDAR data providing the elevations for the base grid which is at a resolution of 8m. Bank levels were informed from the bank top level information collected as part of the 2014 survey and where this was not available bank level were derived from the filtered LIDAR data. The level of the A229 was also enforced via the use of a Z-Line.

Roughness values for the 1D domain were initially informed from site and survey photographs, and latterly updated during the model and results checking process. Roughness values for the 2D domain were assigned according to land cover classes in OS MasterMap Topography Layer data.

A normal depth boundary is implemented at the downstream boundary of the model in both the 1D and 2D domain with the slope informed from the average slope of the river sections upstream. This was increased from its original values of 0.000875 to 0.002 to remove non-convergence at the downstream boundary. Sensitivity testing (completed prior to these adjustments but using more extreme slope ranges) indicates that this does not influence model predictions at the gauging site.

A schematic of the model indicating key model features and extents can be found in Figure 2-1.

Figure 2-1: Model schematic



2.2.1 Model refinement

During the model and results checking process, spot gauging information as well as historic flood event information and sensibility checks on rating performance against PDM model performance were used to make adjustments to the model. From initial model development the following adjustments were made:

- Increased 1D roughness for all sections by 0.010
- Increased 2D roughness for all land cover classes by 0.06 (see discussion in section 3).
- Implemented a roughness value of 0.2 at bank cells where dense vegetation is recorded in site photos or satellite imagery, including the A229 where dense vegetation lines the road (see discussion in section 3).
- Implemented a roughness value of 0.2 at isolated along banks to improve model stability at 1D-2D links.
- Input a value of 1 within the A parameter of the HX Lines (this increased the form loss coefficient)

2.3 Model testing

The following tests were completed on the model to understand its sensitivity and during the model and rating testing phase (impacts on model predictions are listed below each of these tests in blue). Please also refer to section 3 for further detail regarding model refinements and testing to achieve water levels expected for a given stage once flows spill onto the floodplain.

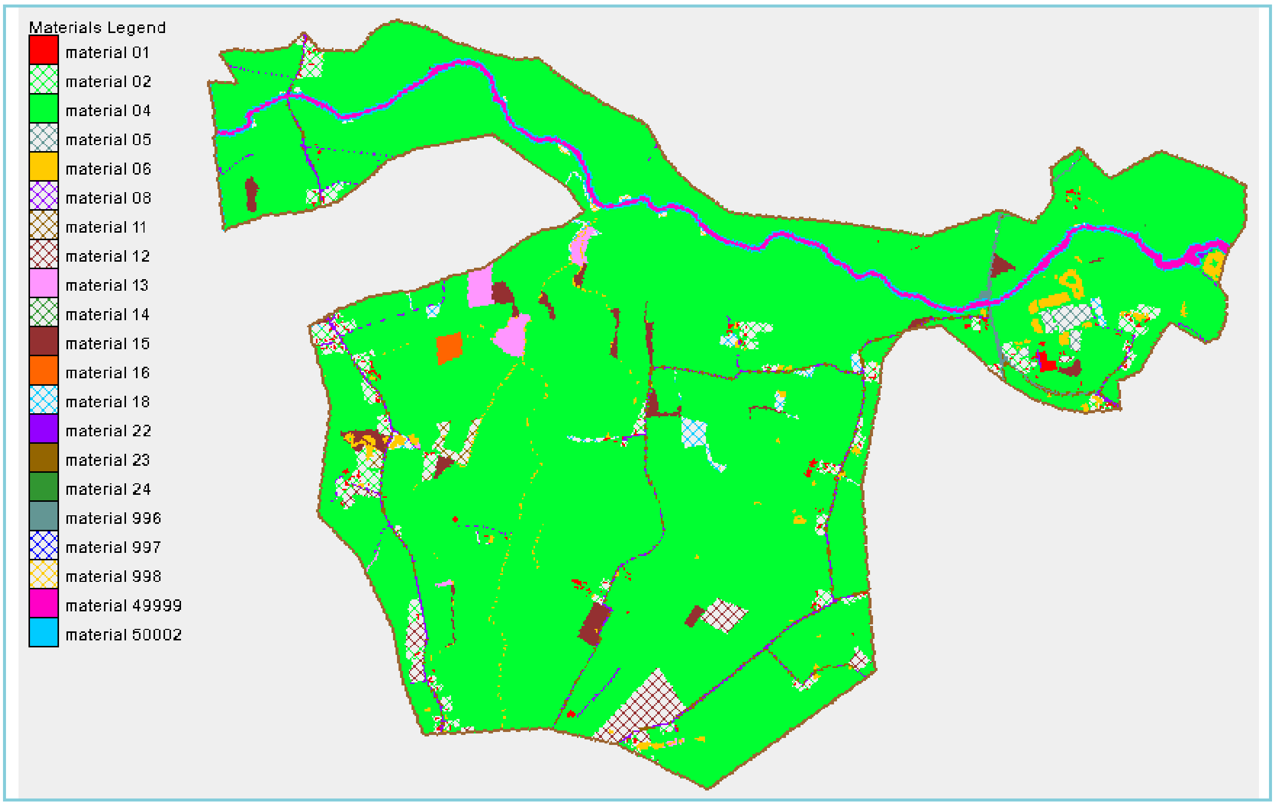
- Downstream boundary (normal depth slope multiplied by 5)
  Negligible impact on model predictions at the area of interest.
- Downstream boundary (normal depth slope halved)
  Negligible impact on model predictions at the area of interest.
- 1D and 2D roughness increased by 20%
  Completed using an earlier version of the model, before increased roughness of 0.010 applied globally to the 1D domain and roughness values were increased in the 2D domain. Increased water levels resulted which are expected. Current roughness values are thought best to represent reality and match well with data from spot flow gaugings. Testing of 1D only and 2D only adjustments suggest 2D roughness adjustments have less notable impacts on predicted water levels at a given flow compared with these combined.
- 1D and 2D roughness decreased by 20%
  Completed using an earlier version of the model, before increased roughness of 0.010 applied globally to the 1D domain and roughness values were increased in the 2D domain. Decreased water levels resulted which are expected. Current roughness values are thought best to represent reality and match well with data from spot flow gaugings. Testing of 1D only and 2D only adjustments suggest 2D roughness adjustments have less notable impacts on predicted water levels at a given flow compared with these combined.
- Removed weir boards which are modelled at the upstream face of Stile Bridge in the baseline case
  Negligible impact on model predictions at the area of interest.
- Crump unit used in place of V-Weir unit
  Negligible impact on model predictions at the area of interest.
- Spill unit used in place of V-Weir unit
  Negligible impact on model predictions at the area of interest.

3 Floodplain flow testing

3.1 Initial simulations

Initial simulations implemented roughness values of 0.04 for the TMF class 4 (OS MasterMap class: General surface, code 10056). It can be seen within Figure 3-1 that this generally covers the majority of the modelled area. In addition to the roughness classes below (refer to Table 3-2), a roughness value of 0.10 was applied where dense vegetation was noted from satellite imagery or unfiltered LIDAR data at the banks. Roughness for the A229 road remained as per the TMF road class.

Figure 3-1: Model domain and land cover classes (TMF) codes



3.2 Probability Distributed Moisture (PDM) model outputs

On comparison of the initial outputs with predictions of a PDM model developed of the area, it became apparent that whilst in-channel flows were matching well (with spot gaugings too), notably too much out of bank flow was being predicted for a given water level recorded at the gauging site. Assessment of rainfall, gauged information and percentage runoff for the catchment above both for this site and others completed at the same time in the catchment indicated that excessive runoff (in some cases above 100% runoff) would be required to achieve the predicted flows for the events tested.

Consequently it was considered that increasing material roughness of the 2D domain should be tested to assess whether this would better match expected flows for the determined runoff rates.

3.3 Testing completed

Three scenarios were tested and comparison made between these and the initial baseline. These are summarised in Table 3-1 below. Note: TMF code 4 is used as a reference point for roughness, refer to Table 3-2 for a full overview of the different roughness values tested.

Table 3-1: Testing completed to produce more realistic flows once bank levels are exceeded

Model	Material roughness (class 4)	Bank vegetation roughness	Road roughness
Initial baseline	0.04	0.10	Default
v014	0.08	0.20	0.20
v015	0.10	0.20	Default

Table 3-2: Roughness values tested for TMF classes
Note: not all land cover types are necessarily located within the model domain

TMF code	OS MasterMap land cover type and (code)	Initial baseline roughness	v014 roughness	v015 roughness
1	Building (10021)	0.300	0.300	0.300
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3	General surface – step (10054)	0.040	0.070	0.090
4	General surface (10056)	0.050	0.080	0.100
5	Glasshouse (10062)	0.200	0.200	0.200
6	Inland water (10089)	0.045	0.075	0.095
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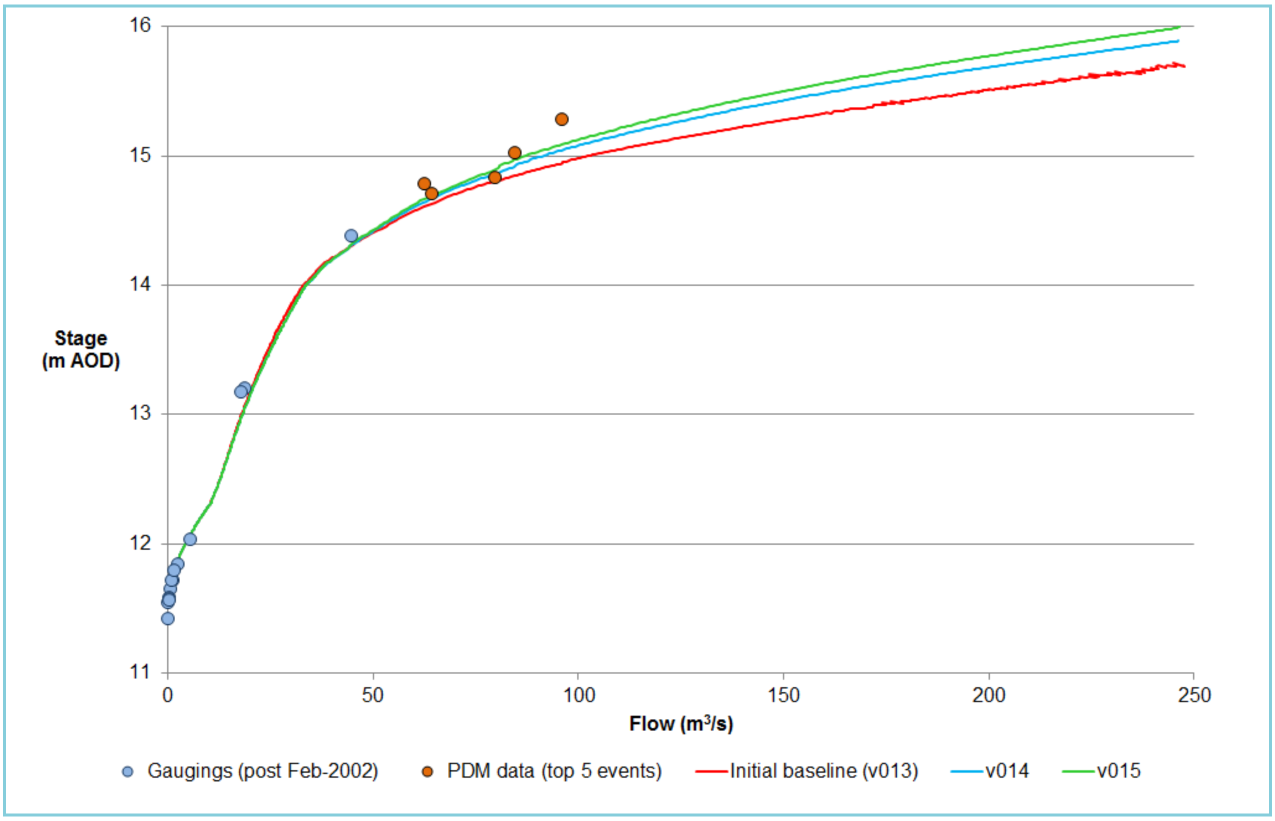
8	Landform – slope (10096)	0.050	0.080	0.100
9	Landform – cliff (10099)	0.050	0.080	0.100
10	Boulders (10111)	0.055	0.085	0.105
11	Coniferous trees (10111)	0.110	0.140	0.160
12	Coniferous trees – scattered / Orchard (10111)	0.060	0.090	0.110
13	Coppice or osiers (10111)	0.080	0.110	0.130
14	Marsh Reeds or Saltmarsh (10111)	0.050	0.080	0.100
15	Non coniferous trees (10111)	0.080	0.110	0.130
16	Non-coniferous trees – scattered (10111)	0.050	0.080	0.100
17	Rough grassland (10111)	0.050	0.080	0.100
18	Scrub (10111)	0.060	0.090	0.110
19	Path – step (10119)	0.040	0.070	0.090
20	Path (10123)	0.040	0.070	0.090
21	Rail (10167)	0.030	0.060	0.080
22	Road (10172)	0.030	0.060	0.080
23	Roadside (10183)	0.040	0.070	0.090
24	Structure (10185)	0.300	0.300	0.300
25	Structure – upper level of communication (10187)	0.300	0.300	0.300
26	Structure – pylon (10193)	0.050	0.080	0.100
27	Tidal water – foreshore (10203)	0.045	0.075	0.095
28	Tidal water (10210)	0.045	0.075	0.095
29	Unclassified (10217)	0.050	0.080	0.100
30	Rock (10111)	0.060	0.090	0.110
31	Heath (10111)	0.080	0.110	0.130

3.4 Results and final simulation

Increasing the roughness of the 2D domain floodplain domain increased water levels, which is expected. Comparison of the modelled rating curves for the initial baseline, v014 and v015 are displayed in Figure 3-2. Comparison was made between these outputs and those from the PDM. In channel data matches spot gaugings well in each case, but v015 outputs were considered to best reflect the observed case. *Consequently v015 was taken forward for the derivation of the final rating curve.*

Figure 3-2: Comparison of model rating curves from initial baseline, v014 and v015 tests



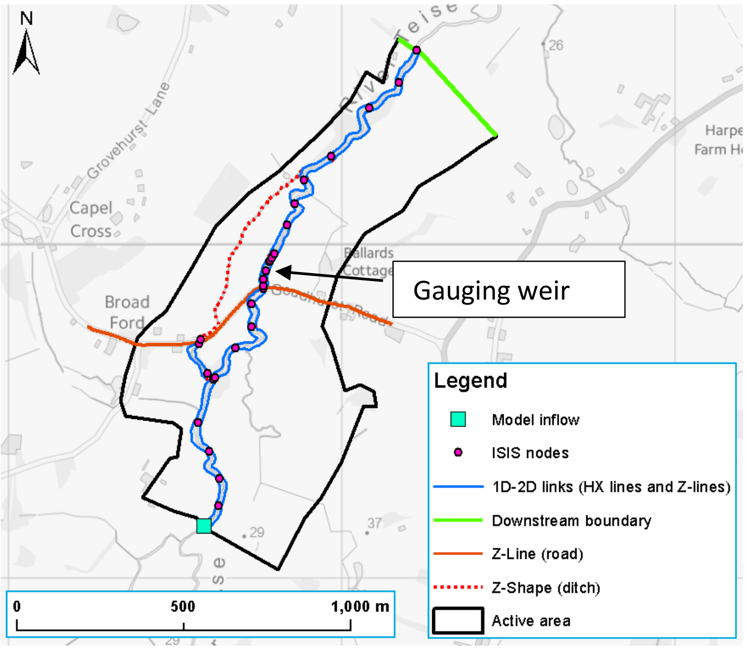
MEDWAY CATCHMENT MAPPING AND MODELLING

STONE BRIDGE RATING SHEET

Station Details	
Station Name	Stone Bridge
Site ID	453230001SG
Structure Type:	Flat-V weir
Model Node:	STON_0117
Watercourse:	River Teise
Site Datum:	24.42mAOD

Photograph

Model Representation – NEW Standalone ISIS-TUFLOW model



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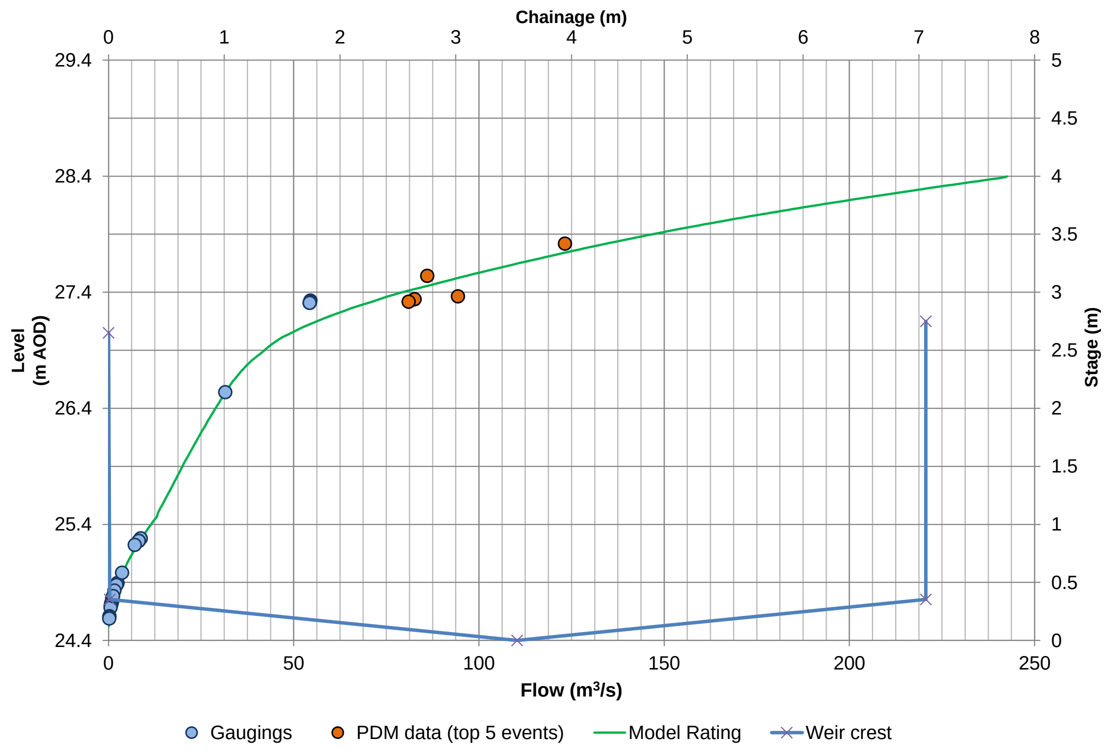
MEDWAY CATCHMENT MAPPING AND MODELLING

STONE BRIDGE RATING SHEET

Unit(s)	Node Labels	Key dimensions	Coefficients	Data source	Comments
FLAT-V WEIR	STON_0117wu	Crest 24.45mAOD	Defaults	Maltby Land Surveys Ltd 2014	Non-modular above 25.52mAOD ($13m^3/s$)
SPILL	STON_0117su	Min level 26.318mAOD	Mod limit 0.9, Coeff 1.5		Bypass flow starts at $27m^3/s$
TUFLOW domain	N/A	5m grid Left bank critical level 27.08mAOD; Right bank 27.18mAOD	Dominant roughness class n= 0.1	1m LiDAR (2009)	Bypass flow in 2D domain above $50m^3/s$ (left bank)

Rating Curve Graph



Notes

- **Datum:** The reference level for stage measurement is 24.45mAOD following the recent (2014) Maltby Land Survey.
- **Flooding of road:** Flow over the road upstream (left bank) occurs above water levels at the gauge of 27.3mAOD (stage 2.88m) when flows are in excess of $65m^3/s$. Some bypassing through the culvert to the west occurs at all flows but sensitivity testing shows that this is never a significant proportion of the total flow.
- **Historic Events:** The highest spot gauging was $55m^3/s$ for a stage of 2.94m, taken in October 2000. The model rating predicts higher flows here due to bypassing that may not have been

fully accounted for in the gauging. A spot gauging in February 2009 of 31.5m^3/s for a stage of 2.15m is well predicted. Recent high flow events are also shown in the graph above, along with their flow predicted by rainfall-runoff modelling (PDM). The highest is a stage of 3.43mALD at the peak of the October 2000 event.

- **Hysteresis**: The model does not indicate any significant hysteresis.

Rating Table (Quality flags QF: A=Model calibrated to spot gaugings; B=Extended calibrated model or well defined structure; C= Model calibrated only by correlation or to runoff calculations, D=hysteresis or other source of natural variability

Stage	Flow	QF	Stage	Flow	QF	Stage	Flow	QF	Stage	Flow	QF
0.00	0.0	A	1.10	13	A	2.20	33	B	3.30	116	B
0.13	0.1	A	1.20	15	A	2.30	35	B	3.40	130	B
0.20	0.3	A	1.30	17	A	2.40	38	B	3.50	145	B
0.30	0.8	A	1.40	18	A	2.50	42	B	3.60	162	B
0.40	1.6	A	1.50	20	A	2.60	46	B	3.70	180	B
0.50	2.7	A	1.60	21	A	2.70	52	B	3.80	199	B
0.60	4.0	A	1.70	23	A	2.80	59	B	3.90	220	B
0.70	5.6	A	1.80	25	A	2.90	68	B	4.00	242	B
0.80	7.4	A	1.90	27	A	3.00	78	B			
0.90	9.3	A	2.00	29	A	3.10	90	B			
1.00	11	A	2.10	31	A	3.20	103	B			

MODEL USER GUIDE

JBA Project Code	2013s7661
Contract	Medway Catchment Mapping and Modelling
Client	Environment Agency – South East Region
Day, Date and Time	September 2014
Author	Ben Gibson
Subject	Model Operation Manual: Stone Bridge Rating Review model

JBA consulting

1 Introduction

This document accompanies the ISIS-TUFLOW model developed to inform a rating at Stone Bridge gauging station on the River Teise, commissioned under the Medway Catchment Mapping and Modelling study.

It notes the model files required to re-simulate the hydraulic model, provides a description of the hydraulic model and schematisation, as well as a brief summary of testing that was completed to inform the rating model.

1.1 Model files

Files for the final rating model are supplied.

The model files needed to run the Stone Bridge rating ISIS-TUFLOW model are listed in the table below:

File type	File name
ISIS Data file (.DAT)	STONEBRIDGE_016_050h
ISIS Event run form (.IEF)	STONEBRIDGE_016_050h
TUFLOW Control File (.TCF)	STONEBRIDGE_016_050h
TUFLOW Geometry Control File (.TGC)	Medway_Stonebridge_004
TUFLOW Boundary Control File (.TBC)	Medway_Stonebridge_002
TUFLOW Materials File (.TMF)	Rating_Models_005

TUFLOW model files which define the geometry of the hydraulic model and 1D-2D linking etc are linked within the relevant TUFLOW control files and are maintained in the *TUFLOW > Model > gis* folder.

Results files are also provided.

Within ISIS these have the same stem and *.zzl, *.zzu, *.zzn, *.zzd, *.exy, *.mmm, .bmp extensions.

Within TUFLOW these have the same stem and *.csv, *.dat, *.sup extensions

1.2 Re-running the model

In order to re-simulate hydraulic model, it is recommended that the folder structure within which the hydraulic model data was supplied is retained.

It is recommended that the same versions of ISIS and TUFLOW software used in the simulation of models for this study are retained. These are summarised below. If different versions of either software are used then it is recommended that the corresponding baseline models are re-simulated and results compared in order to appreciate any differences in modelled predictions that have arisen as a result of using a different software package.

- ISIS version: 3.7.1 64-bit single precision
- TUFLOW build: 2013-12-AC-iSP-w64

The model data bundle should be moved to a suitable location, from where the model can be re-simulated. Relative references have been used in both the ISIS and TUFLOW run files, so only the relative path file should need to be updated to re-simulate the model. Currently the default file path (*Path* =) is as follows:

- N:\2013\Projects\2013s7661 - EA SE – Medway Catchment\Calculations\04_Rating_Review_Models\05_Stonebridge\ISIS\Runs

To update the default file path complete the following steps:

- The ISIS Event Run Form (.ief) for the given baseline or option model should be identified and opened either in ISIS or a text editor (e.g. Notepad, Notepad++, UltraEdit). Replace the ISIS > Runs destination folder with the same location on the users server.

Note: If original model outputs (e.g. ISIS Results files, TUFLOW Results files, TUFLOW Check files, TUFLOW Log files) are not copied from the output folder location, then the outputs will be over-written. It is recommended that these are either copied to a safe location prior to re-simulating the model, or suitable version control is applied to the model files so that these are not over-written.

1.2.1 Model run parameters

With the exception of *dflood* which was increased from the default of 3 to 5, to stabilise the model if water levels rise more than 3m above the highest data point in a given section, all other parameters remain as default.

1.2.2 Model inflows

The inflow into the model is a triangular hydrograph which is input into the ISIS 1D model at the most upstream cross-section. The inflow has the form displayed in the table below – this accounts for the range of flows required and provides greater time at lower flows when these are most critical (e.g. at the point of bank exceedance). Testing on durations of 100h and 200h showed very little difference in the predicted rating so the 50h hydrograph was retained.

Time (h)	Flow (m^3/s)
0	0.1
12.5	40.0
25	250.0
37.5	40.0
50	0.1

2 Model history and schematisation

2.1 Existing model and data

Existing 1D and 1D-2D ISIS and ISIS-TUFLOW models of the River Beult upstream and downstream of Stone Bridge, respectively were developed for flood risk mapping purposes in 2007 by Mott MacDonald (Upper Teise/Beult & Bourne Modelling and Mapping, 2007 and Teise and Beult 2D Modelling and Mapping, 2007, respectively). Survey information used to inform these models was collected in 2002 for the Middle Medway Strategy Survey by Cartographical Surveys Ltd. In addition to this survey collected in 2001 by Longdin & Browning at the gauging site and various other channel sections, was also available.

At the request of the Environment Agency new survey information was specified and collected for the current commission to inform the rating review at the site. This was collected in June 2014 by Maltby Land Surveys Ltd. This was driven by the age of the previous survey in addition to the need to collect more detailed information at particular locations to inform model build. Given the age of the previous survey, new survey was collected at the gauging site and some distance upstream and downstream of the gauge, including Stone Bridge and bank top levels. Other information available to inform the model development was 1m LIDAR data (both filtered and unfiltered) which was flown in February 2009.

2.2 Model development

Given the age of the information used to inform the previous modelling and the extent of survey data collected to inform the rating study, a model was developed from new to inform the rating investigation at the site.

The 1D hydraulic model was developed with the Maltby Land Surveys Ltd 2014 survey data as the base information. This was supplemented with data from the 2002 and 2001 datasets where this could add value e.g. in extending the hydraulic model upstream and downstream to provide suitable boundary locations.

The 2D hydraulic model was developed with the 1m filtered LIDAR data providing the elevations for the base grid which is at a resolution of 5m. Bank levels were informed from the bank top level information collected as part of the 2014 survey and where this was not available bank level were derived from the filtered LIDAR data. The level of Goudhurst Road was also enforced via the use of a Z-Line.

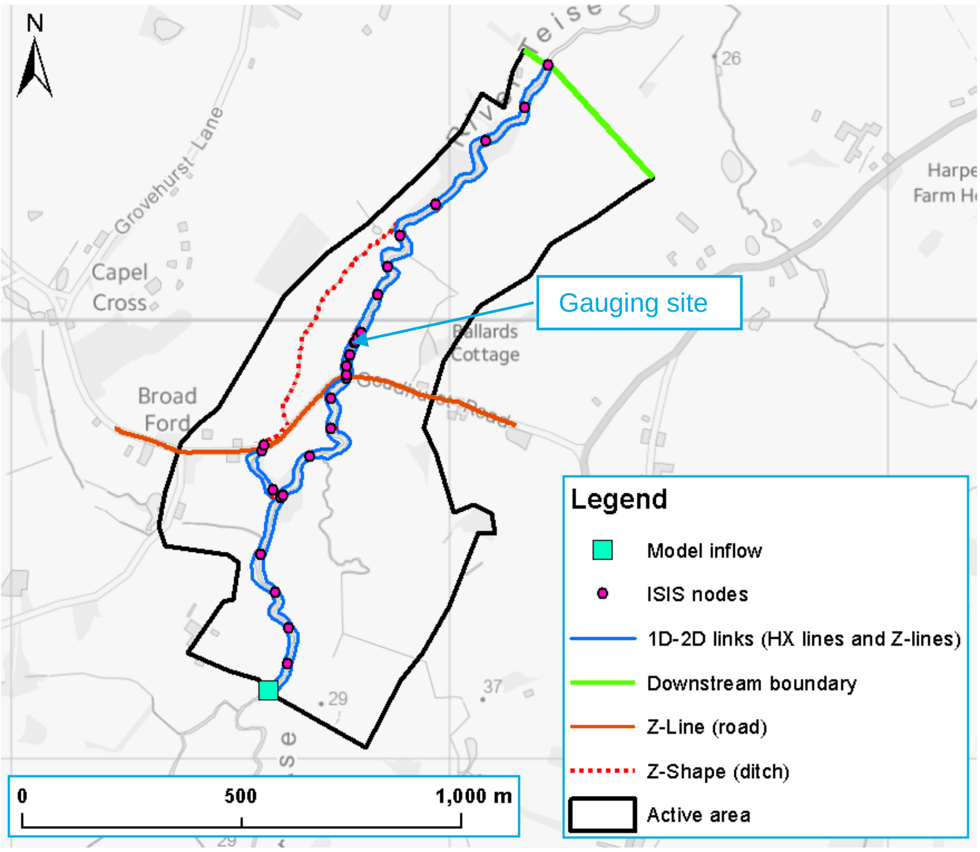
Roughness values for the 1D domain were initially informed from site and survey photographs, and latterly updated during the model and results checking process. Roughness values for the 2D domain were assigned according to land cover classes in OS MasterMap Topography Layer data.

The bypass culvert and channel under Goudhurst Road to the west of the gauging site and main channel was represented within the model. The channel upstream of the road is represented in the 1D domain which transitions to a 2D representation implemented with a Z-Shape which carves a channel into the floodplain. Testing of a scenario in which the connection under Goudhurst Road was removed had limited impact on model predictions.

A normal depth boundary is implemented at the downstream boundary of the model in both the 1D and 2D domain with the slope informed from the average slope of the river sections upstream. Sensitivity testing (completed prior to these adjustments but using more extreme slope ranges) indicates that this does not influence model predictions at the gauging site.

A schematic of the model indicating key model features and extents can be found in Figure 2-1.

Figure 2-1: Model schematic



2.2.1 Model refinement

During the model and results checking process, spot gauging information as well as historic flood event information and sensibility checks on rating performance against PDM model performance were used to make adjustments to the model. From initial model development the following adjustments were made:

- Increased 1D roughness for all sections by 0.010, increasing by a further 0.015 at notable bends in the channel.
- Increased 2D roughness for all land cover classes by 0.01.
- Implemented a roughness value of 0.1 at bank cells where dense vegetation is recorded in site photos or satellite imagery, including Goudhurst Road where dense vegetation lines the road.
- Implemented a roughness value of 0.2 at isolated along banks to improve model stability at 1D-2D links.
- Input a value of 1 within the A parameter of the HX Lines (this increased the form loss coefficient)

2.3 Model testing

The following tests were completed on the model to understand its sensitivity and during the model and rating testing phase (impacts on model predictions are listed below each of these tests in blue). Please also refer to section 3 for further detail regarding model refinements and testing to achieve water levels expected for a given stage once flows spill onto the floodplain.

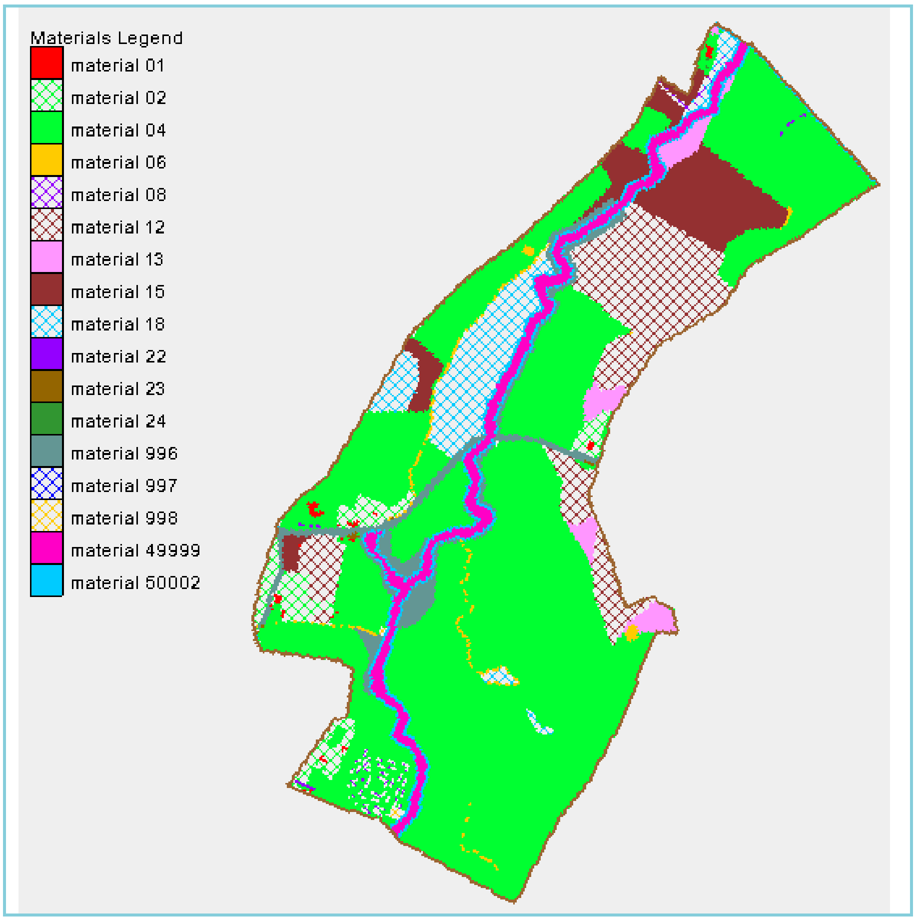
- Downstream boundary (normal depth slope multiplied by 5)
  Negligible impact on model predictions at the area of interest.
- Downstream boundary (normal depth slope halved)
  Limited impact on model predictions at the area of interest.
- 1D and 2D roughness increased by 20%
  Completed using an earlier version of the model, before increased roughness of 0.010 applied globally to the 1D domain and roughness values were increased in the 2D domain. Increased water levels resulted which are expected. Current roughness values are thought best to represent reality and match well with data from spot flow gaugings. Testing of 1D only and 2D only adjustments suggest 2D roughness adjustments have less notable impacts on predicted water levels at a given flow compared with these combined.
- 1D and 2D roughness decreased by 20%
  Completed using an earlier version of the model, before increased roughness of 0.010 applied globally to the 1D domain and roughness values were increased in the 2D domain. Decreased water levels resulted which are expected. Current roughness values are thought best to represent reality and match well with data from spot flow gaugings. Testing of 1D only and 2D only adjustments suggest 2D roughness adjustments have less notable impacts on predicted water levels at a given flow compared with these combined.
- Removal of bypass culvert connection under Goudhurst Road
  Limited impact on model predictions – a slight increase in water level for a given flow when water levels are between 27.3 and 27.5m AOD at the gauging site
- Crump unit used in place of V-Weir unit
  Generally lowered water levels for a given flow e.g. c. 10cm lower water levels at 100m^3/s. V-weir unit implemented within the baseline case considered most suitable to take forward, so retained.
- Spill unit used in place of V-Weir unit
  Generally raised water levels for a given flow e.g. c. 10cm higher water levels at 100m^3/s. V-weir unit implemented within the baseline case considered most suitable to take forward, so retained.

3 Floodplain flow testing

3.1 Initial simulations

Initial simulations implemented roughness values of 0.04 for the TMF class 4 (OS MasterMap class: General surface, code 10056). It can be seen within Figure 3-1 that this generally covers the majority of the modelled area. In addition to the roughness classes below (refer to Table 3-2), a roughness value of 0.10 was applied where dense vegetation was noted from satellite imagery or unfiltered LIDAR data at the banks. Roughness for Goudhurst Road remained as per the TMF road class.

Figure 3-1: Model domain and land cover classes (TMF) codes



3.2 Probability Distributed Moisture (PDM) model outputs

On comparison of the initial outputs with predictions of a PDM model developed of the area, it became apparent that whilst in-channel flows were matching well (with spot gaugings too), notably too much out of bank flow was being predicted for a given water level recorded at the gauging site. Assessment of rainfall, gauged information and percentage runoff for the catchment above both for this site and others completed at the same time in the catchment indicated that excessive runoff (in some cases above 100% runoff) would be required to achieve the predicted flows for the events tested.

Consequently it was considered that increasing material roughness of the 2D domain should be tested to assess whether this would better match expected flows for the determined runoff rates.

3.3 Testing completed

Three scenarios were tested and comparison made between these and the initial baseline. These are summarised in Table 3-1 below. Note: TMF code 4 is used as a reference point for roughness, refer to Table 3-2 for a full overview of the different roughness values tested.

Table 3-1: Testing completed to produce more realistic flows once bank levels are exceeded

Model	Material roughness (class 4)	Bank vegetation roughness	Road roughness
Initial baseline	0.04	0.10	Default
v014	0.08	0.20	0.20
v015	0.10	0.20	Default

Table 3-2: Roughness values tested for TMF classes
Note: not all land cover types are necessarily located within the model domain

TMF code	OS MasterMap land cover type and (code)	Initial baseline roughness	v014 roughness	v015 roughness
1	Building (10021)	0.300	0.300	0.300
2	General surface – multi surface (10053)	0.040	0.070	0.090
3	General surface – step (10054)	0.040	0.070	0.090
4	General surface (10056)	0.050	0.080	0.100
5	Glasshouse (10062)	0.200	0.200	0.200
6	Inland water (10089)	0.045	0.075	0.095
7	Landform (10093)	0.050	0.080	0.100
8	Landform – slope (10096)	0.050	0.080	0.100
9	Landform – cliff (10099)	0.050	0.080	0.100
10	Boulders (10111)	0.055	0.085	0.105
11	Coniferous trees (10111)	0.110	0.140	0.160
12	Coniferous trees – scattered / Orchard (10111)	0.060	0.090	0.110
13	Coppice or osiers (10111)	0.080	0.110	0.130
14	Marsh Reeds or Saltmarsh (10111)	0.050	0.080	0.100
15	Non coniferous trees (10111)	0.080	0.110	0.130
16	Non-coniferous trees – scattered (10111)	0.050	0.080	0.100
17	Rough grassland (10111)	0.050	0.080	0.100
18	Scrub (10111)	0.060	0.090	0.110
19	Path – step (10119)	0.040	0.070	0.090
20	Path (10123)	0.040	0.070	0.090
21	Rail (10167)	0.030	0.060	0.080
22	Road (10172)	0.030	0.060	0.080
23	Roadside (10183)	0.040	0.070	0.090
24	Structure (10185)	0.300	0.300	0.300
25	Structure – upper level of communication (10187)	0.300	0.300	0.300
26	Structure – pylon (10193)	0.050	0.080	0.100
27	Tidal water – foreshore (10203)	0.045	0.075	0.095
28	Tidal water (10210)	0.045	0.075	0.095
29	Unclassified (10217)	0.050	0.080	0.100
30	Rock (10111)	0.060	0.090	0.110
31	Heath (10111)	0.080	0.110	0.130

3.4 Results and final simulation

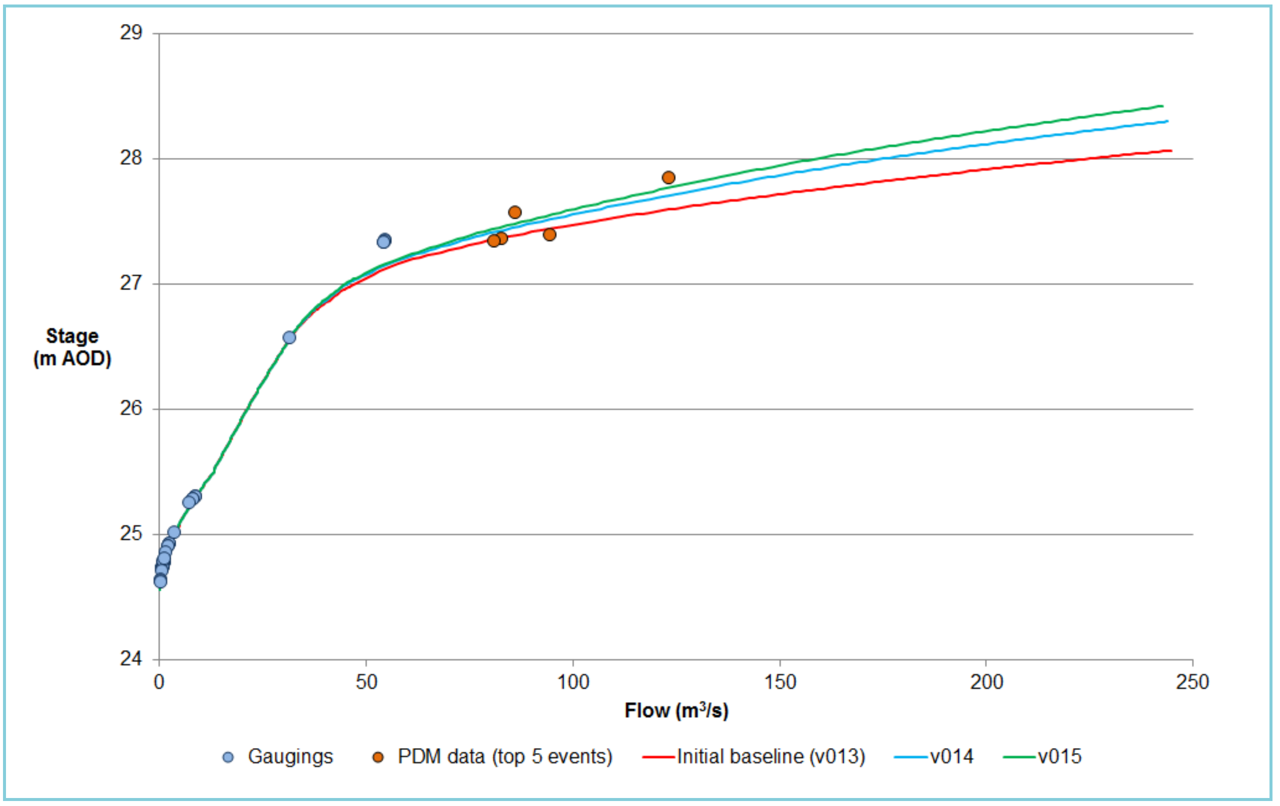
Increasing the roughness of the 2D domain floodplain domain increased water levels, which is expected. Comparison of the modelled rating curves for the initial baseline, v014 and v015 are displayed in Figure 3-2. Comparison was made between these outputs and those from the PDM. In channel data matches spot gaugings well in each case, but v015 outputs were considered to best reflect the observed case.

Version 15 of the model was initially taken forward.

At EA review stage a slight discrepancy was noted with the elevation of the weir section due to two sets of survey collected for this section in 2014. It was determined that the weir crest should be raised by 19mm (raising the centre of the 'V' from 24.431m AOD to 24.450m AOD) to reflect the latter checks during the 2014 survey. Consequently a version 16 simulation was carried out with this adjustment made. On understanding impacts to the rating changes were limited to flows up to approximately 10m^3/s, above which the influence of the minor adjustment to weir crest has minimal impact. Version 16 can be considered to reflect v015 when interpreting the figure below.

Consequently v016 was taken forward for the derivation of the final rating curve.

Figure 3-2: Comparison of model rating curves from initial baseline, v014 and v015 tests



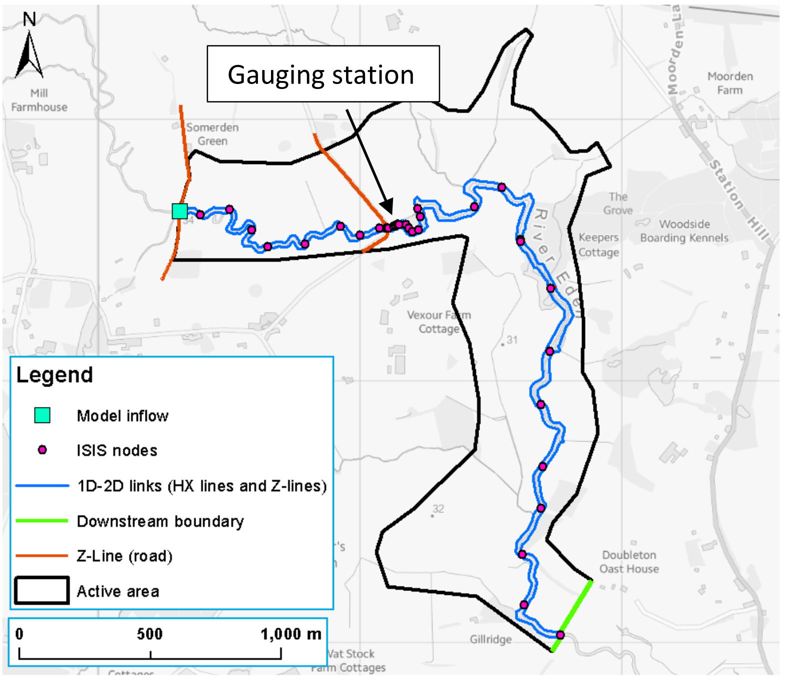
MEDWAY CATCHMENT MAPPING AND MODELLING

VEXOUR RATING SHEET

Station Details	
Station Name	Vexour
Site ID	453600002SG
Structure Type:	Open channel
Model Node:	VEXO01_0230
Watercourse:	River Eden
Site Datum:	29.0mAOD

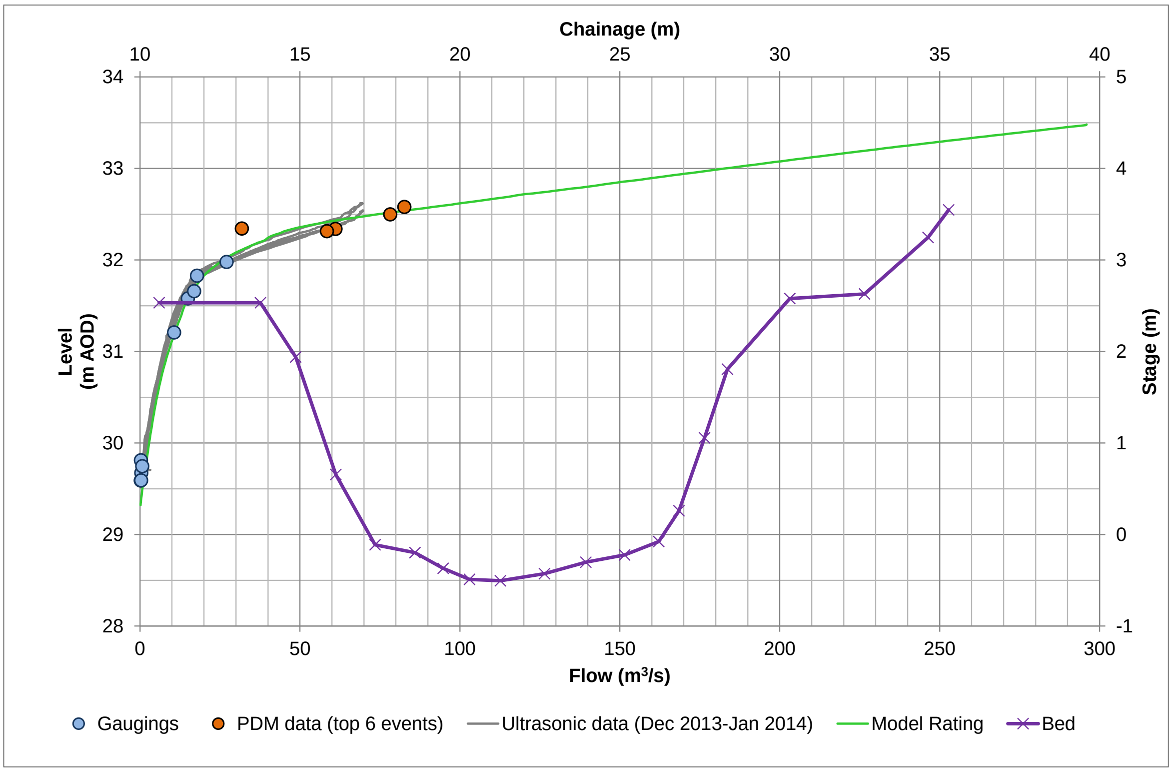
Photograph

Model Representation – NEW Standalone ISIS-TUFLOW model



Unit(s)	Node Labels	Key dimensions	Coefficients	Data source	Comments
RIVER	VEX001_0230	Left bank 31.5mAOD, right bank 32.5mAOD	Manning's n = 0.05	Maltby Survey 2014	
TUFLOW domain		5m grid Minimum level of 32.0m applied along left bank in TUFLOW to prevent rating curve flattening off too soon. Critical road level 32.5mAOD	Dominant roughness class n= 0.1	LiDAR	Due to embankments along gauging reach (LHS 32.6mAOD, RHS 32.8mAOD), bypassing occurs when road upstream overtops

Rating Curve Graph



Notes

- **Datum:** The internal reference level within the measurement hut for stage measurement is 34.286mAOD following the recent (2014) Maltby Land Survey.
- **Flooding of road:** Flow over the road upstream (left bank) occurs above water levels at the gauge of 32.3AOD (stage 3.3m) when flows are in excess of 55m^3/s.
- **Historic Events:** The highest gauged flow is 27.0m^3/s for a stage of 2.98m, taken in January 2014. The model fits well with spot gaugings and with the ultrasonic measurements. Recent

high flow events are also shown in the graph above, along with their flow predicted by rainfall-runoff modelling (PDM). The highest is a level of 32.62m at the peak of the December 2013 event.

- **Hysteresis**: The ultrasonic data shows some very minor hysteresis. The model rating fits the rising limb.
- **Ultrasonics**: The ultrasonics will be reliable up to the level of 32.3mAOD (stage 3.3m). Then the model rating is preferred to capture bypass flow over the road.

Rating Table (Quality flags QF: A=Model calibrated to spot gaugings; B=Extended calibrated model or well defined structure; C= Model calibrated only by correlation or to runoff calculations, D=hysteresis or other source of natural variability

Stage	Flow	QF	Stage	Flow	QF	Stage	Flow	QF	Stage	Flow	QF
0.30	0.0	A	1.40	4.8	A	2.50	13.9	A	3.60	96.0	B
0.40	0.4	A	1.50	5.3	A	2.60	15.4	A	3.70	116.8	B
0.50	0.8	A	1.60	5.9	A	2.70	17.1	A	3.80	139.6	B
0.60	1.2	A	1.70	6.5	A	2.80	19.2	A	3.90	161.2	B
0.70	1.6	A	1.80	7.2	A	2.90	22.1	A	4.00	182.9	B
0.80	2.0	A	1.90	8.0	A	3.00	25.9	B	4.10	205.1	B
0.90	2.4	A	2.00	8.9	A	3.10	31.1	B	4.20	228.0	B
1.00	2.8	A	2.10	9.8	A	3.20	37.8	B	4.30	251.9	B
1.10	3.3	A	2.20	10.8	A	3.30	44.2	B	4.40	276.8	B
1.20	3.8	A	2.30	11.8	A	3.40	56.1	B	4.48	295.9	B
1.30	4.2	A	2.40	12.9	A	3.50	74.5	B			

MODEL USER GUIDE

JBA Project Code	2013s7661
Contract	Medway Catchment Mapping and Modelling
Client	Environment Agency – South East Region
Day, Date and Time	September 2014
Author	Ben Gibson
Subject	Model Operation Manual: Vexour Bridge Rating Review model

1 Introduction

This document accompanies the ISIS-TUFLOW model developed to inform a rating at Vexour Bridge gauging station on the River Eden, commissioned under the Medway Catchment Mapping and Modelling study.

It notes the model files required to re-simulate the hydraulic model, provides a description of the hydraulic model and schematisation, as well as a brief summary of testing that was completed to inform the rating model.

1.1 Model files

Files for the final rating model are supplied.

The model files needed to run the Vexour Bridge rating ISIS-TUFLOW model are listed in the table below:

File type	File name
ISIS Data file (.DAT)	VEXOUR_011_050h_WC1-3_ML0-7
ISIS Event run form (.IEF)	VEXOUR_015_050h_LB_32-0mAOD_NoFLC
TUFLOW Control File (.TCF)	VEXOUR_015_050h_LB_32-0mAOD_NoFLC
TUFLOW Geometry Control File (.TGC)	Medway_Vexour_004_LB_32-0mAOD_NoFLC
TUFLOW Boundary Control File (.TBC)	Medway_Vexour_003
TUFLOW Materials File (.TMF)	Rating_Models_005

TUFLOW model files which define the geometry of the hydraulic model and 1D-2D linking etc are linked within the relevant TUFLOW control files and are maintained in the *TUFLOW > Model > gis* folder.

Results files are also provided.

Within ISIS these have the same stem and *.zzl, *.zzu, *.zzn, *.zzd, *.exy, *.mmm, .bmp extensions.

Within TUFLOW these have the same stem and *.csv, *.dat, *.sup extensions

1.2 Re-running the model

In order to re-simulate hydraulic model, it is recommended that the folder structure within which the hydraulic model data was supplied is retained.

It is recommended that the same versions of ISIS and TUFLOW software used in the simulation of models for this study are retained. These are summarised below. If different versions of either software are used then it is recommended that the corresponding baseline models are re-simulated and results compared in order to appreciate any differences in modelled predictions that have arisen as a result of using a different software package.

- ISIS version: 3.7.1 64-bit single precision
- TUFLOW build: 2013-12-AC-iSP-w64

The model data bundle should be moved to a suitable location, from where the model can be re-simulated. Relative references have been used in both the ISIS and TUFLOW run files, so only the relative path file should need to be updated to re-simulate the model. Currently the default file path (*Path* =) is as follows:

- N:\2013\Projects\2013s7661 - EA SE – Medway Catchment\Calculations\04_Rating_Review_Models\02_Vexour\ISIS\Runs

To update the default file path complete the following steps:

- The ISIS Event Run Form (.ief) for the given baseline or option model should be identified and opened either in ISIS or a text editor (e.g. Notepad, Notepad++, UltraEdit). Replace the ISIS > Runs destination folder with the same location on the users server.

Note: If original model outputs (e.g. ISIS Results files, TUFLOW Results files, TUFLOW Check files, TUFLOW Log files) are not copied from the output folder location, then the outputs will be over-written. It is recommended that these are either copied to a safe location prior to re-simulating the model, or suitable version control is applied to the model files so that these are not over-written.

1.2.1 Model run parameters

With the exception of *dflood* which was increased from the default of 3 to 5, to stabilise the model if water levels rise more than 3m above the highest data point in a given section, all other parameters remain as default.

1.2.2 Model inflows

The inflow into the model is a triangular hydrograph which is input into the ISIS 1D model at the most upstream cross-section. The inflow has the form displayed in the table below – this accounts for the range of flows required and provides greater time at lower flows when these are most critical (e.g. at the point of bank exceedance). Testing on durations of 100h and 200h showed very little difference in the predicted rating so the 50h hydrograph was retained.

Time (h)	Flow (m^3/s)
0	0.2
12.5	40.0
25	300.0
37.5	40.0
50	0.2

2 Model history and schematisation

2.1 Existing model and data

An existing 1D ISIS model of the River Eden developed for flood risk mapping purposes was updated in 2008 by Mott MacDonald (River Medway Catchment Modelling and Flood Mapping Updates, 2008), developed before this in the River Medway Flood Risk Mapping Phase 3 Study (2003). Survey information used to inform this model was collected in 2001/2002 by Longdin & Browning and in 1995 by Flynn & Rothwell. In addition to this information, survey at the gauging site was collected in 2013 by EDI Surveys Ltd (EA survey reference 11658), which included section data at the ultrasonic gauge as well as topographic survey of various parts of the gauging site.

At the request of the Environment Agency new survey information was specified and collected for the current commission to inform the rating review at the site. This was collected in June 2014 by Maltby Land Surveys Ltd. This was driven by the age of the previous survey in addition to the need to collect more detailed information at particular locations to inform model build. Given the age of the previous survey, new survey was collected at the gauging site and some distance upstream and downstream of the gauge, including Vexour Bridge and bank top levels. Other information available to inform the model development was 1m LIDAR data (both filtered and unfiltered) which was flown in April 2009.

2.2 Model development

Given the age of the information used to inform the previous modelling and the extent of survey data collected to inform the rating study, a model was developed from new to inform the rating investigation at the site.

The 1D hydraulic model was developed with the Maltby Land Surveys Ltd 2014 survey data as the base information. This was supplemented with data from the 2013 EDI Surveys Ltd data where this could add value. To extend the hydraulic model upstream and downstream to provide suitable boundary locations the 1995 and 2001/2002 survey data was used in these areas.

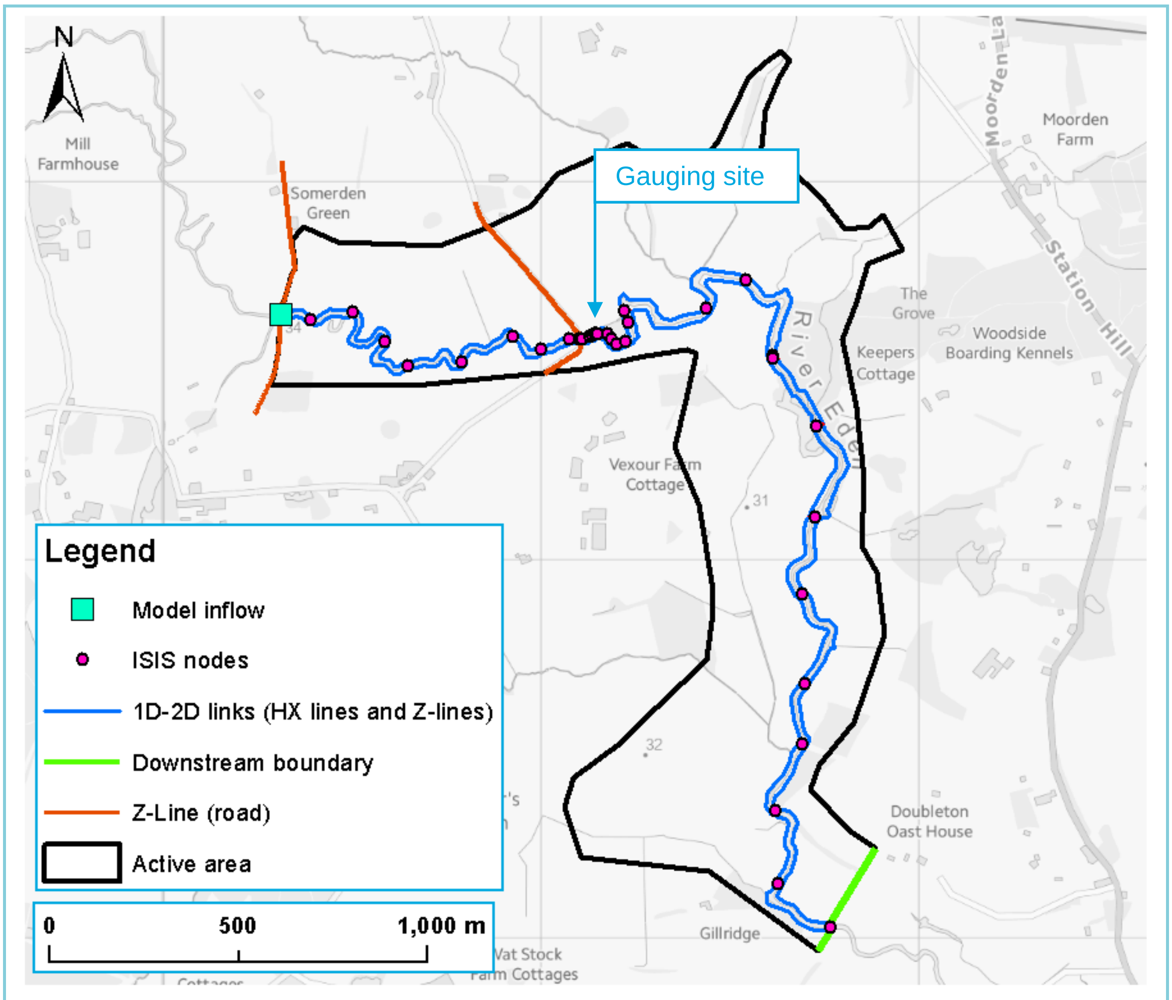
The 2D hydraulic model was developed with the 1m filtered LIDAR data providing the elevations for the base grid which is at a resolution of 5m. Bank levels were informed from the bank top level information collected as part of the 2014 survey and where this was not available bank level were derived from the 2013 survey data collected by EDI Surveys Ltd (where applicable) or filtered LIDAR data. The level of Hampkins Hill road was also enforced via the use of a Z-Line.

Roughness values for the 1D domain were initially informed from site and survey photographs, and latterly updated during the model and results checking process. Roughness values for the 2D domain were assigned according to land cover classes in OS MasterMap Topography Layer data.

A normal depth boundary is implemented at the downstream boundary of the model in both the 1D and 2D domains with the slope informed from the average slope of the river sections upstream. Sensitivity testing indicates that this does not influence model predictions at the gauging site.

A schematic of the model indicating key model features and extents can be found in Figure 2-1.

Figure 2-1: Model schematic



2.2.1 Model refinement

During the model and results checking process, spot gauging information as well as historic flood event information and sensibility checks on rating performance against PDM model performance were used to make adjustments to the model. From initial model development the following adjustments were made:

- Increased 1D roughness for all sections by 0.010, increasing by a further 0.015 at notable bends in the channel.
- Increased 2D roughness for all land cover classes by 0.06 (see discussion in section 3).
- Implemented a roughness value of 0.2 at bank cells where dense vegetation is recorded in site photos or satellite imagery, including along Hampkins Hill road where dense vegetation lines the road (see discussion in section 3).
- Implemented a roughness value of 0.2 at isolated along banks to improve model stability at 1D-2D links.
- Raised the level of the left bank downstream of the gauging site within the 2D domain (implemented as Z-Lines) to 32m AOD. The previous low point of 31.4m AOD is lower than the banks upstream/downstream, which does not appear to be the case in survey photos, and it is assumed that the bank level survey collected here did not pick up the high point in this location
- An in-channel spill was added at CSE11 around 1km downstream of the gauge site as data inspection suggested something holding up low water levels and satellite imagery showed a broken water surface at this location with ponding upstream.
- Input a value of 1 within the A parameter of the HX Lines (this increased the form loss coefficient)

2.3 Model testing

The following tests were completed on the model to understand its sensitivity and during the model and rating testing phase (impacts on model predictions are listed below each of these tests in blue). Please also refer to section 3 for further detail regarding model refinements and testing to achieve water levels expected for a given stage once flows spill onto the floodplain.

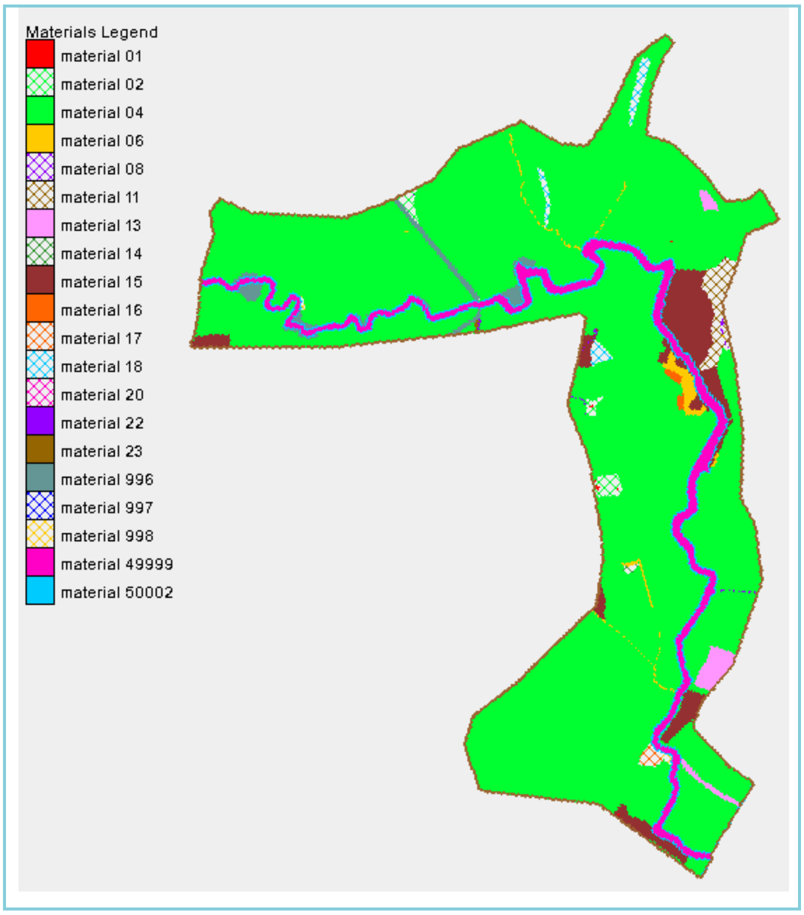
- Downstream boundary (normal depth slope multiplied by 5)
  Negligible impact on model predictions at the area of interest.
- Downstream boundary (normal depth slope halved)
  Negligible impact on model predictions at the area of interest.
- 1D and 2D roughness increased by 20%
  Completed using an earlier version of the model, before increased roughness of 0.010 applied globally to the 1D domain and roughness values were increased in the 2D domain. Increased water levels resulted which are expected. Current roughness values are thought best to represent reality and match well with data from spot flow gaugings. Testing of 1D only and 2D only adjustments suggest 2D roughness adjustments have less notable impacts on predicted water levels at a given flow compared with these combined..
- 1D and 2D roughness decreased by 20%
  Completed using an earlier version of the model, before increased roughness of 0.010 applied globally to the 1D domain and roughness values were increased in the 2D domain. Decreased water levels resulted which are expected. Current roughness values are thought best to represent reality and match well with data from spot flow gaugings. Testing of 1D only and 2D only adjustments suggest 2D roughness adjustments have less notable impacts on predicted water levels at a given flow compared with these combined..
- USBPR unit used in place of Arch Bridge unit
  Negligible impact on model predictions at the area of interest.
- Bernoulli Loss unit used in place of Arch Bridge unit
  Negligible impact on model predictions at the area of interest.

3 Floodplain flow testing

3.1 Initial simulations

Initial simulations implemented roughness values of 0.04 for the TMF class 4 (OS MasterMap class: General surface, code 10056). It can be seen within Figure 3-1 that this generally covers the majority of the modelled area. In addition to the roughness classes below (refer to Table 3-2), a roughness value of 0.10 was applied where dense vegetation was noted from satellite imagery or unfiltered LIDAR data at the banks. Roughness for Hampkins Hill road remained as per the TMF road class.

Figure 3-1: Model domain and land cover classes (TMF) codes



3.2 Probability Distributed Moisture (PDM) model outputs

On comparison of the initial outputs with predictions of a PDM model developed of the area, it became apparent that whilst in-channel flows were matching well (with spot gaugings too), notably too much out of bank flow was being predicted for a given water level recorded at the gauging site. Assessment of rainfall, gauged information and percentage runoff for the catchment above both for this site and others completed at the same time in the catchment indicated that excessive runoff (in some cases above 100% runoff) would be required to achieve the predicted flows for the events tested.

Consequently it was considered that increasing material roughness of the 2D domain should be tested, as well as testing form loss applied to represent losses at the road intersecting the floodplain, to assess whether this would better match expected flows for the determined runoff rates.

3.3 Testing completed

Three scenarios were tested and comparison made between these and the initial baseline. These are summarised in Table 3-1 below. Note: TMF code 4 is used as a reference point for roughness, refer to Table 3-2 for a full overview of the different roughness values tested.

Table 3-1: Testing completed to produce more realistic flows once bank levels are exceeded

Model	Material roughness (class 4)	Bank vegetation roughness	Road roughness	Road form loss (1.0)
Initial baseline	0.05	0.10	Default	No
v014	0.08	0.20	0.20	No
v015_FLC	0.10	0.20	Default	Yes
v015_noFLC	0.10	0.20	0.20	No

Table 3-2: Roughness values tested for TMF classes
Note: not all land cover types are necessarily located within the model domain

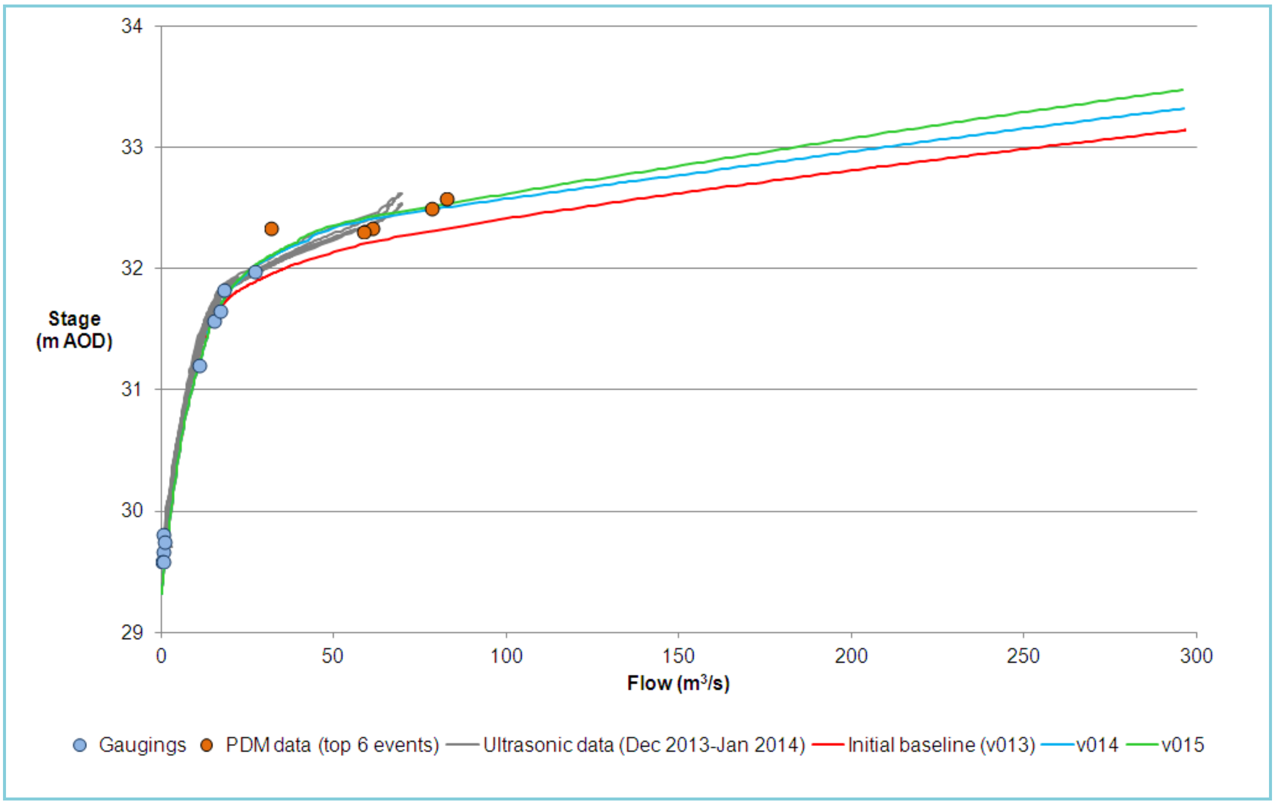
TMF code	OS MasterMap land cover type and (code)	Initial baseline roughness	v014 roughness	v015 roughness
1	Building (10021)	0.300	0.300	0.300
2	General surface – multi surface (10053)	0.050	0.070	0.090
3	General surface – step (10054)	0.050	0.070	0.090
4	General surface (10056)	0.060	0.080	0.100
5	Glasshouse (10062)	0.200	0.200	0.200
6	Inland water (10089)	0.055	0.075	0.095
7	Landform (10093)	0.060	0.080	0.100
8	Landform – slope (10096)	0.060	0.080	0.100
9	Landform – cliff (10099)	0.060	0.080	0.100
10	Boulders (10111)	0.065	0.085	0.105
11	Coniferous trees (10111)	0.120	0.140	0.160
12	Coniferous trees – scattered / Orchard (10111)	0.070	0.090	0.110
13	Coppice or osiers (10111)	0.090	0.110	0.130
14	Marsh Reeds or Saltmarsh (10111)	0.060	0.080	0.100
15	Non coniferous trees (10111)	0.090	0.110	0.130
16	Non-coniferous trees – scattered (10111)	0.060	0.080	0.100
17	Rough grassland (10111)	0.060	0.080	0.100
18	Scrub (10111)	0.070	0.090	0.110
19	Path – step (10119)	0.050	0.070	0.090
20	Path (10123)	0.050	0.070	0.090
21	Rail (10167)	0.040	0.060	0.080
22	Road (10172)	0.040	0.060	0.080
23	Roadside (10183)	0.050	0.070	0.090
24	Structure (10185)	0.300	0.300	0.300
25	Structure – upper level of communication (10187)	0.300	0.300	0.300
26	Structure – pylon (10193)	0.060	0.080	0.100
27	Tidal water – foreshore (10203)	0.055	0.075	0.095
28	Tidal water (10210)	0.055	0.075	0.095
29	Unclassified (10217)	0.060	0.080	0.100
30	Rock (10111)	0.070	0.090	0.110
31	Heath (10111)	0.090	0.110	0.130

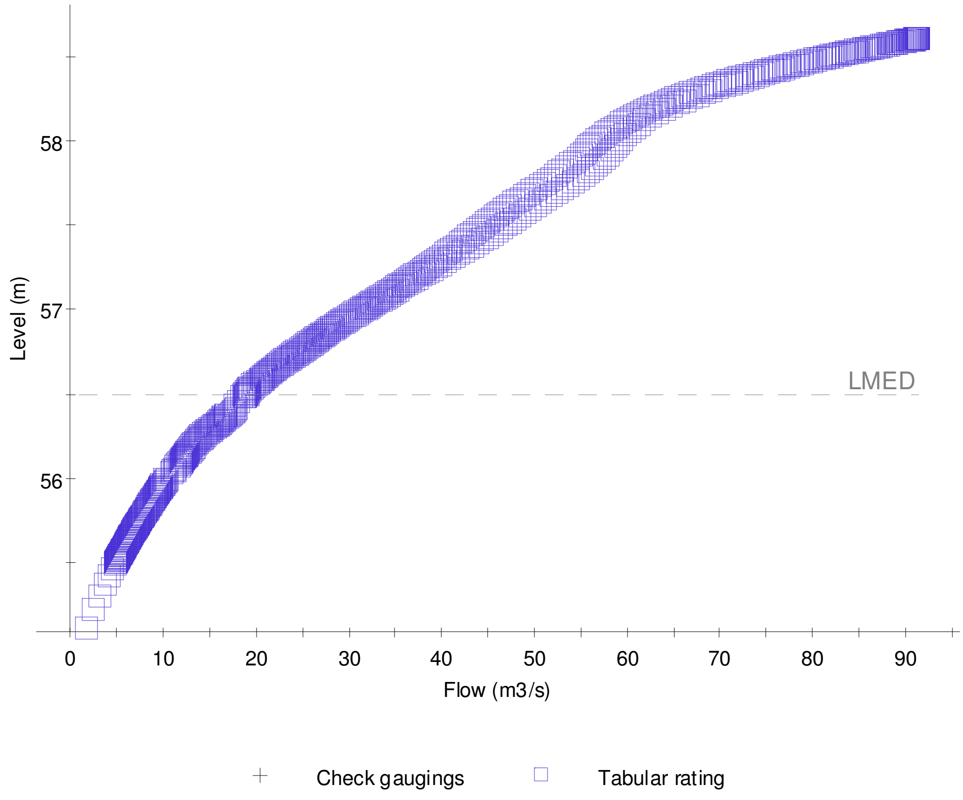
3.4 Results and final simulation

Increasing the roughness of the 2D domain floodplain domain increased water levels, which is expected. Comparison of the modelled rating curves for the initial baseline, v014 and v015 are displayed in Figure 3-2. The test with a form loss coefficient implemented at the road intersecting the floodplain has not been plotted as the results were very similar to the case without this applied. Comparison was made between these outputs and those from the PDM. In channel data matches spot gaugings well in each case, but v015 outputs were considered to best reflect the observed case.
Consequently v015 was taken forward for the derivation of the final rating curve.

The modelled rating curve data also matches closely with the stage-flow information recorded by the ultrasonic gauging site during the period December 2013-January 2014. At the uppermost data points on the ultrasonic measurement, model predictions suggests that bypassing of the site across Hampkins Hill road would occur, meaning under prediction of the event flow is expected.

Figure 3-2: Comparison of model rating curves from initial baseline, v014 and v015 tests





Rating equation is Q = K(H + a)^p, where H is stage

Gauge Ref		453500005SG	Name	FORWARD ROW TELEMETRY RL				
No.	**Limb**	**Description**	**K**	**a**	**p**	**Max stage**	**Start**	**End**
583								

Gauged range

Min	n/a	**Max**	n/a

Rating tabulation:

Stage	Flow
54.99	0.87
55.01	0.96
55.01	0.97
55.01	0.99
54.99	1.16
55.05	1.22
55.12	1.73
55.23	2.44
55.31	3.17
55.38	3.73
55.43	4.16
55.47	4.52
55.5	4.8
55.51	4.84

55.51	4.84
55.51	4.85
55.51	4.86
55.51	4.87
55.51	4.88
55.51	4.89
55.51	4.9
55.51	4.91
55.51	4.93
55.52	4.94
55.52	4.96
55.51	4.96
55.52	4.98
55.52	4.99
55.52	5.02
55.53	5.04
55.53	5.06
55.53	5.09
55.53	5.1
55.53	5.11
55.54	5.14
55.54	5.17
55.54	5.2
55.54	5.21
55.55	5.24
55.55	5.27
55.55	5.29
55.55	5.31
55.56	5.35
55.56	5.36
55.56	5.38
55.56	5.42
55.56	5.42
55.57	5.46
55.57	5.48
55.57	5.5
55.57	5.54
55.58	5.54
55.58	5.58
55.58	5.59
55.58	5.62
55.58	5.64
55.59	5.67

55.59	5.69
55.59	5.72
55.59	5.74
55.6	5.77
55.6	5.79
55.6	5.82
55.6	5.83
55.61	5.88
55.61	5.88
55.61	5.93
55.62	5.94
55.62	5.98
55.62	6.01
55.62	6.02
55.63	6.06
55.63	6.07
55.63	6.11
55.64	6.14
55.63	6.15
55.64	6.19
55.64	6.2
55.64	6.23
55.65	6.27
55.65	6.27
55.65	6.31
55.66	6.34
55.65	6.35
55.66	6.39
55.66	6.4
55.66	6.43
55.67	6.47
55.67	6.47
55.67	6.51
55.67	6.53
55.67	6.55
55.68	6.59
55.68	6.6
55.68	6.64
55.69	6.66
55.69	6.69
55.69	6.72
55.69	6.74
55.7	6.79

55.7	6.79
55.7	6.84
55.71	6.86
55.7	6.89
55.71	6.93
55.71	6.94
55.71	7.0
55.72	7.0
55.72	7.05
55.73	7.08
55.72	7.11
55.73	7.15
55.73	7.16
55.74	7.22
55.73	7.22
55.74	7.28
55.74	7.29
55.74	7.34
55.75	7.36
55.75	7.4
55.76	7.43
55.76	7.46
55.76	7.51
55.76	7.53
55.77	7.58
55.77	7.61
55.78	7.66
55.78	7.69
55.78	7.74
55.78	7.78
55.79	7.81
55.79	7.88
55.8	7.89
55.8	7.97
55.81	7.97
55.81	8.05
55.81	8.07
55.82	8.14
55.82	8.16
55.83	8.23
55.82	8.25
55.84	8.32
55.83	8.35

55.84	8.43
55.85	8.43
55.85	8.52
55.86	8.54
55.85	8.6
55.87	8.66
55.86	8.7
55.88	8.79
55.87	8.79
55.88	8.87
55.89	8.92
55.88	8.95
55.89	9.03
55.9	9.04
55.9	9.09
55.91	9.14
55.9	9.14
55.91	9.2
55.91	9.22
55.91	9.26
55.92	9.3
55.92	9.33
55.93	9.38
55.92	9.41
55.93	9.46
55.93	9.49
55.94	9.52
55.94	9.57
55.94	9.57
55.95	9.6
55.95	9.63
55.94	9.65
55.95	9.65
55.96	9.69
55.95	9.73
55.97	9.79
55.95	9.81
55.96	9.89
55.97	9.97
55.97	10.06
56.0	10.12
55.98	10.15
55.99	10.23

55.99	10.32
56.0	10.41
56.04	10.9
56.05	11.03
56.06	11.18
56.05	11.24
56.08	11.34
56.09	11.5
56.1	11.67
56.08	11.69
56.11	11.83
56.09	11.85
56.1	11.92
56.12	11.96
56.1	11.96
56.11	11.99
56.11	12.02
56.12	12.04
56.11	12.06
56.12	12.1
56.13	12.12
56.12	12.15
56.12	12.2
56.13	12.21
56.13	12.26
56.14	12.28
56.13	12.33
56.15	12.36
56.14	12.39
56.15	12.43
56.14	12.46
56.16	12.5
56.14	12.52
56.16	12.57
56.15	12.59
56.17	12.65
56.16	12.71
56.18	12.76
56.16	12.86
56.19	12.9
56.17	13.01
56.2	13.04
56.18	13.17

56.21	13.17
56.21	13.29
56.19	13.33
56.22	13.41
56.21	13.5
56.23	13.55
56.22	13.67
56.24	13.72
56.23	13.84
56.25	13.86
56.26	13.98
56.24	14.01
56.24	14.13
56.26	14.14
56.25	14.27
56.27	14.3
56.26	14.44
56.28	14.48
56.27	14.6
56.29	14.65
56.28	14.76
56.29	14.81
56.28	14.91
56.3	14.97
56.29	15.05
56.3	15.13
56.29	15.19
56.31	15.29
56.3	15.33
56.32	15.46
56.31	15.48
56.31	15.62
56.32	15.62
56.32	15.76
56.33	15.79
56.32	15.89
56.34	15.94
56.33	16.01
56.35	16.1
56.33	16.14
56.35	16.24
56.34	16.27
56.37	16.37

56.36	16.38
56.35	16.39
56.37	16.49
56.35	16.51
56.37	16.61
56.36	16.64
56.38	16.7
56.38	16.7
56.38	16.75
56.37	16.78
56.37	16.93
56.38	17.07
56.38	17.22
56.39	17.36
56.4	17.48
56.4	17.6
56.44	17.7
56.41	17.72
56.42	17.84
56.46	18.08
56.49	18.42
56.5	18.62
56.49	18.72
56.49	18.73
56.49	18.76
56.51	18.77
56.49	18.82
56.5	18.84
56.49	18.84
56.5	18.89
56.52	18.94
56.5	18.94
56.51	19.02
56.53	19.07
56.51	19.11
56.5	19.12
56.54	19.18
56.52	19.2
56.54	19.29
56.53	19.36
56.56	19.55
56.54	19.56
56.55	19.72

56.57	19.81
56.56	19.97
56.58	20.14
56.57	20.16
56.57	20.29
56.58	20.41
56.59	20.41
56.59	20.51
56.6	20.6
56.59	20.61
56.59	20.71
56.61	20.8
56.6	20.83
56.61	20.97
56.62	21.0
56.61	21.1
56.62	21.24
56.63	21.25
56.63	21.39
56.64	21.49
56.63	21.55
56.64	21.69
56.65	21.73
56.65	21.84
56.66	21.95
56.65	21.99
56.66	22.15
56.67	22.18
56.67	22.3
56.68	22.39
56.67	22.46
56.69	22.61
56.68	22.63
56.68	22.8
56.7	22.82
56.69	22.96
56.71	23.03
56.7	23.13
56.71	23.24
56.7	23.3
56.72	23.45
56.71	23.46
56.71	23.63

56.73	23.66
56.72	23.78
56.74	23.86
56.73	23.94
56.75	24.08
56.73	24.09
56.74	24.26
56.76	24.3
56.74	24.43
56.76	24.52
56.75	24.61
56.77	24.75
56.76	24.78
56.76	24.95
56.78	24.97
56.77	25.1
56.79	25.19
56.77	25.25
56.78	25.4
56.8	25.41
56.79	25.56
56.81	25.63
56.79	25.71
56.81	25.84
56.8	25.86
56.8	26.03
56.82	26.04
56.81	26.19
56.83	26.23
56.82	26.36
56.84	26.42
56.82	26.53
56.84	26.61
56.83	26.7
56.85	26.82
56.84	26.88
56.86	27.02
56.85	27.07
56.86	27.21
56.85	27.28
56.87	27.41
56.86	27.48
56.88	27.61

56.87	27.69
56.89	27.83
56.88	27.9
56.9	28.05
56.89	28.12
56.9	28.28
56.89	28.33
56.91	28.51
56.9	28.56
56.92	28.73
56.91	28.78
56.93	28.97
56.92	29.0
56.94	29.2
56.93	29.22
56.95	29.43
56.93	29.45
56.95	29.66
56.94	29.68
56.96	29.9
56.95	29.9
56.97	30.13
56.96	30.14
56.98	30.36
56.97	30.38
56.99	30.61
56.97	30.62
56.99	30.84
56.98	30.87
57.0	31.08
56.99	31.12
57.01	31.3
57.0	31.37
57.02	31.53
57.01	31.62
57.02	31.77
57.01	31.87
57.03	32.0
57.02	32.13
57.04	32.22
57.03	32.38
57.05	32.44
57.04	32.64

57.05	32.65
57.06	32.87
57.05	32.9
57.07	33.09
57.06	33.17
57.08	33.32
57.06	33.45
57.08	33.53
57.07	33.74
57.09	33.76
57.1	33.98
57.08	34.03
57.11	34.21
57.09	34.32
57.11	34.43
57.1	34.6
57.12	34.65
57.13	34.88
57.11	34.91
57.14	35.1
57.12	35.21
57.15	35.33
57.14	35.52
57.15	35.55
57.16	35.78
57.15	35.85
57.17	36.01
57.16	36.18
57.18	36.25
57.19	36.49
57.17	36.53
57.2	36.73
57.18	36.91
57.21	36.98
57.21	37.24
57.19	37.3
57.22	37.5
57.21	37.69
57.23	37.74
57.24	37.97
57.22	38.07
57.25	38.2
57.26	38.44

57.23	38.48
57.27	38.71
57.24	38.91
57.28	38.98
57.29	39.25
57.26	39.37
57.3	39.53
57.31	39.81
57.27	39.84
57.32	40.1
57.29	40.32
57.34	40.39
57.35	40.69
57.31	40.81
57.36	40.99
57.32	41.29
57.37	41.3
57.38	41.62
57.34	41.78
57.4	41.95
57.41	42.23
57.35	42.28
57.42	42.49
57.37	42.78
57.44	42.82
57.45	43.15
57.38	43.29
57.46	43.47
57.48	43.79
57.4	43.85
57.49	44.12
57.42	44.33
57.5	44.43
57.52	44.73
57.43	44.86
57.53	45.05
57.45	45.37
57.54	45.37
57.56	45.69
57.47	45.89
57.57	46.01
57.58	46.33
57.49	46.4

57.6	46.66
57.51	46.87
57.61	47.0
57.52	47.34
57.62	47.35
57.64	47.71
57.54	47.84
57.65	48.08
57.56	48.35
57.66	48.47
57.68	48.86
57.58	48.89
57.69	49.25
57.6	49.46
57.71	49.67
57.62	50.02
57.72	50.11
57.64	50.55
57.74	50.57
57.75	51.01
57.66	51.12
57.77	51.41
57.68	51.74
57.78	51.79
57.8	52.16
57.7	52.34
57.82	52.56
57.72	52.94
57.83	52.96
57.85	53.39
57.74	53.52
57.87	53.8
57.76	54.09
57.88	54.23
57.9	54.65
57.78	54.66
57.92	54.99
57.8	55.22
57.93	55.31
57.95	55.54
57.82	55.73
57.97	55.76
57.98	56.02

57.84	56.18
57.99	56.34
57.86	56.58
58.01	56.66
58.02	56.98
57.88	57.0
58.03	57.31
57.9	57.43
58.05	57.63
57.92	57.86
58.06	57.96
58.07	58.28
57.95	58.28
58.08	58.61
57.97	58.67
58.09	58.94
57.99	58.97
58.11	59.28
58.01	59.3
58.12	59.63
58.04	59.7
58.13	59.98
58.06	60.18
58.14	60.33
58.15	60.69
58.08	60.71
58.16	61.06
58.1	61.2
58.17	61.42
58.13	61.7
58.18	61.79
58.19	62.16
58.15	62.41
58.2	62.53
58.21	62.9
58.17	63.15
58.21	63.27
58.22	63.64
58.19	63.91
58.23	64.02
58.24	64.39
58.21	64.65
58.25	64.76

58.26	65.13
58.23	65.39
58.26	65.49
58.27	65.85
58.24	66.11
58.28	66.23
58.29	66.66
58.26	66.82
58.29	67.09
58.27	67.52
58.3	67.54
58.31	67.96
58.29	68.22
58.32	68.35
58.32	68.75
58.3	68.91
58.33	69.15
58.34	69.55
58.32	69.61
58.34	69.95
58.35	70.34
58.33	70.39
58.36	70.74
58.34	71.12
58.36	71.15
58.37	71.55
58.35	71.73
58.38	71.95
58.36	72.3
58.38	72.35
58.39	72.76
58.37	72.88
58.39	73.16
58.38	73.45
58.4	73.56
58.4	73.96
58.39	74.02
58.41	74.36
58.4	74.58
58.42	74.76
58.41	75.14
58.42	75.15
58.43	75.55

58.42	75.7
58.43	75.94
58.42	76.24
58.44	76.34
58.44	76.73
58.43	76.78
58.45	77.11
58.44	77.3
58.45	77.5
58.45	77.82
58.46	77.88
58.46	78.25
58.45	78.32
58.47	78.63
58.46	78.81
58.47	79.0
58.47	79.29
58.48	79.37
58.48	79.73
58.47	79.76
58.49	80.09
58.48	80.22
58.49	80.44
58.49	80.68
58.49	80.8
58.49	81.11
58.5	81.14
58.5	81.48
58.5	81.54
58.51	81.82
58.5	81.97
58.51	82.16
58.51	82.39
58.51	82.5
58.51	82.81
58.52	82.83
58.52	83.17
58.52	83.2
58.53	83.49
58.52	83.59
58.53	83.82
58.53	83.97
58.53	84.14

58.53	84.34
58.54	84.45
58.53	84.7
58.54	84.76
58.54	85.05
58.54	85.06
58.55	85.36
58.54	85.39
58.55	85.64
58.55	85.72
58.55	85.93
58.55	86.04
58.56	86.21
58.55	86.35
58.56	86.48
58.56	86.65
58.56	86.74
58.56	86.94
58.56	87.0
58.56	87.22
58.57	87.25
58.57	87.49
58.57	87.49
58.57	87.73
58.57	87.75
58.58	87.96
58.57	88.01
58.58	88.18
58.58	88.25
58.58	88.4
58.58	88.48
58.58	88.61
58.58	88.7
58.58	88.81
58.58	88.92
58.59	89.0
58.59	89.12
58.59	89.19
58.59	89.33
58.59	89.36
58.59	89.51
58.59	89.53
58.59	89.69

Rating report for : FOREST ROW TELEMETRY RL (453500005SG)

58.59	89.7
58.6	89.85
58.59	89.86
58.6	89.99
58.6	90.02
58.6	90.13
58.6	90.17
58.6	90.26
58.6	90.31
58.6	90.38
58.6	90.43
58.6	90.5
58.6	90.55
58.6	90.61
58.6	90.66
58.6	90.71
58.6	90.76
58.61	90.8
58.6	90.85
58.61	90.89
58.61	90.96
58.61	90.97
58.61	91.03
58.61	91.04
58.61	91.09
58.61	91.1
58.61	91.15
58.61	91.15
58.61	91.19
58.61	91.19
58.61	91.22
58.61	91.23
58.61	91.25
58.61	91.25
58.61	91.27
58.61	91.27
58.61	91.28
58.61	91.28

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