River Eden/Carlisle flood forecast modelling

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Abstract

River floods can cause loss of life, devastating damage to properties and adverse economic and environmental impacts. Although flood risks cannot be completely eliminated, real time flood forecasting models can help to provide timely flood warnings with an adequate lead time for the public to minimise flood damages.

Real time flood forecasting is an important and integral part of a flood warning service, and can help to provide more accurate and timely warnings to residents, businesses and emergency services. Depending on catchment characteristics and catchment response to rainfall, various types of flood forecasting models, including correlations, simple trigger flood forecasting and real time catchment-wide integrated hydrological and hydrodynamic models may be adopted. These models provide flow and level forecasts at the selected key locations (known as Flood Forecast Points), which are usually located along major rivers or on streams near urban areas that have a history of flooding. The catchment-wide integrated hydrological and hydrodynamic modelling approach provides a more robust and sophisticated flood forecasting, since hydrological rainfall runoff processes and the interaction of river channel and floodplain hydrodynamic processes are explicitly simulated.

Following severe flooding in January 2005, Atkins have developed a sophisticated and efficient Eden/Carlisle hydrodynamic flood forecasting model for real time use. The Eden/Carlisle flood forecasting model consists of a hydrological component, in which flood discharges are estimated from rainfall measurements and forecasts, and a hydrodynamic component, in which the water levels along the entire river network are calculated. The Eden/Carlisle flood forecasting model (with 1100 nodes), converted from an existing flood defence strategy model originally also developed by Atkins, is robust and stable, incorporates the key hydraulic features of the strategy model, and retains all of the originally modelled floodplains within the required model extents. This paper will describe the development of the Eden/Carlisle flood forecasting model focusing on the hydrodynamic component, its typical model runtime performance and model validations.

1. Introduction

The Environment Agency's River Eden Flood Forecasting model has been in use for several years on the Northwest Regional GeoGUI system. During its operation, the model has performed relatively well. However, during the January 2005 flood event, the model significantly under-predicted flows and levels for the Carlisle area.

The Eden catchment has been subject to several historical flood events. The most significant event in recent years occurred in January 2005 that flooded over 1900 properties in Carlisle city centre and other neighbouring villages in the North West Region. The January 2005 flood event has a flood peak more than 1 metre higher than any other flood events in the previous 200 years (Spencer et. al).

Whilst the existing flood forecasting model has been in operation, a separate strategy / design model has been developed by Atkins for the Carlisle area. The strategy model contains more up-to-date survey information and more realistic flood flow routes than the flood forecasting model and, as a result, is thought to provide more realistic level and flow predictions. Due to the increased detail and model node count in the strategy model, it runs significantly slower than the flood forecasting model.

After reviewing the performance of the existing flood forecast model for the January 2005 flood event, the Environment Agency wished to update and enhance the performance of the existing flood forecasting model. It was proposed that this would take place by converting the strategy model into an improved real-time flood forecasting model. The improved forecast model will then replace the existing model for future operational use.

This paper describes work undertaken to meet the following specific technical requirements:

- To convert the strategy model into a robust and stable real-time hydrodynamic flood forecasting model, with a capability of running stably from base flow to at least $1800m^3$/sec.
- To ensure that the converted model incorporates the key features of the strategy model and the required flood forecasting points are represented by appropriate model nodes.
- To demonstrate the accuracy of the model against at least one large historical event (excluding the January 2005 event) with reliable gauged data. It was proposed that an event that has already been processed would be used so that the ungauged or lateral inflows (represented by FEHBDY nodes) did not require calculating.
- To ensure that the converted model runs for a duration of approximately 60 hours in 7 minutes or less on a PC with a CPU speed of at least 933Mhz. It should be noted that, for NFFS projects, the requirements are usually for a 2.5GHz machine.

The conversion of the Carlisle strategy model for real-time flood forecasting use has been carried out in an iterative manner and included the following tasks:

- Changing the model extents to meet the Environment Agency specification for flood forecasting
- Model simplification in areas where flood forecasting is not required
- Model stabilisation
- Model runtime performance improvement
- Model validation

2. Hydraulic Model Conversion

The Eden/Carlisle strategy model was built using the ISIS (v2.3) software, to be used for the purposes of floodplain mapping, delineation of flood flow routes and the design of flood defences. As a result, a significant amount of detail has been included and the model runtime was not a criterion for model build. The runtime of the strategy model is not fast enough for real-time use.

Flood risk mapping and scheme design models tend to be calibrated primarily for historical flood events, whereas a real time model should be able to operate year round in a range of flow conditions. However, it should be noted that the improved flood forecasting model is optimised for flood forecasting, and not for the more complex task of full flow forecasting, which would require modelling of abstractions, discharges and other complicating factors.

The overall objective of the hydraulic model improvement for real time flood forecasting is to predict flood levels at the defined flood forecast points and to improve the model runtime and convergence/stability for real-time use, thus allowing a ‘slimmer’ model to run on a higher time-step and delivering a shorter model runtime, whilst preserving model accuracy at the Flood Forecast Points. In general, different simplification/modification approaches are required for different features of the models, as follows:

- Significant hydraulic controls for local water levels. These need to be retained within the model to achieve the accuracy specifications.
- Explicitly modelled areas that are not specifically required to deliver accurate simulations at flood forecast points can be removed from the model, or represented in a lumped fashion (typically these are sections of the model upstream of the reach for which forecasts are required).
- Areas known to be potential causes of instability (therefore drivers for low time-steps and more numerical iterations) need to be modified in order to increase the model time-step.

A reduction in the number, and hence increasing the spacing, of channel cross-sections, can also often reduce model runtimes. However, it is sometimes necessary to add cross-sections and spills to improve the model stability and convergence, hence reduce model runtime.

The model simplifications and modifications will need to be determined by experimentation based on catchment characteristics, modelling experience, current best practice and available literature (e.g. Chen, Sene & Hearn (2005), Environment Agency (2005)).

2.1. Flood Forecast Points

There are ten flood forecasting points in the Eden/Carlisle catchment as shown in Figure 1. All flood forecasting points have been represented by a node in the improved flood forecasting model. The main water courses in the model include Rivers Eamont, Eden, Irthing, Petteril and Caldew. It should be noted that two newly proposed flood forecasting points at Armathwaite and Eden Hall exist within a routing reach of the strategy model (represented by Muskingum VPMC units). Routing reaches are able to provide flow and timing information only (no water level). It should also be noted that Duranhill is a flood cell on the floodplain near the confluence of Rivers Eden and Petteril, not in the river.

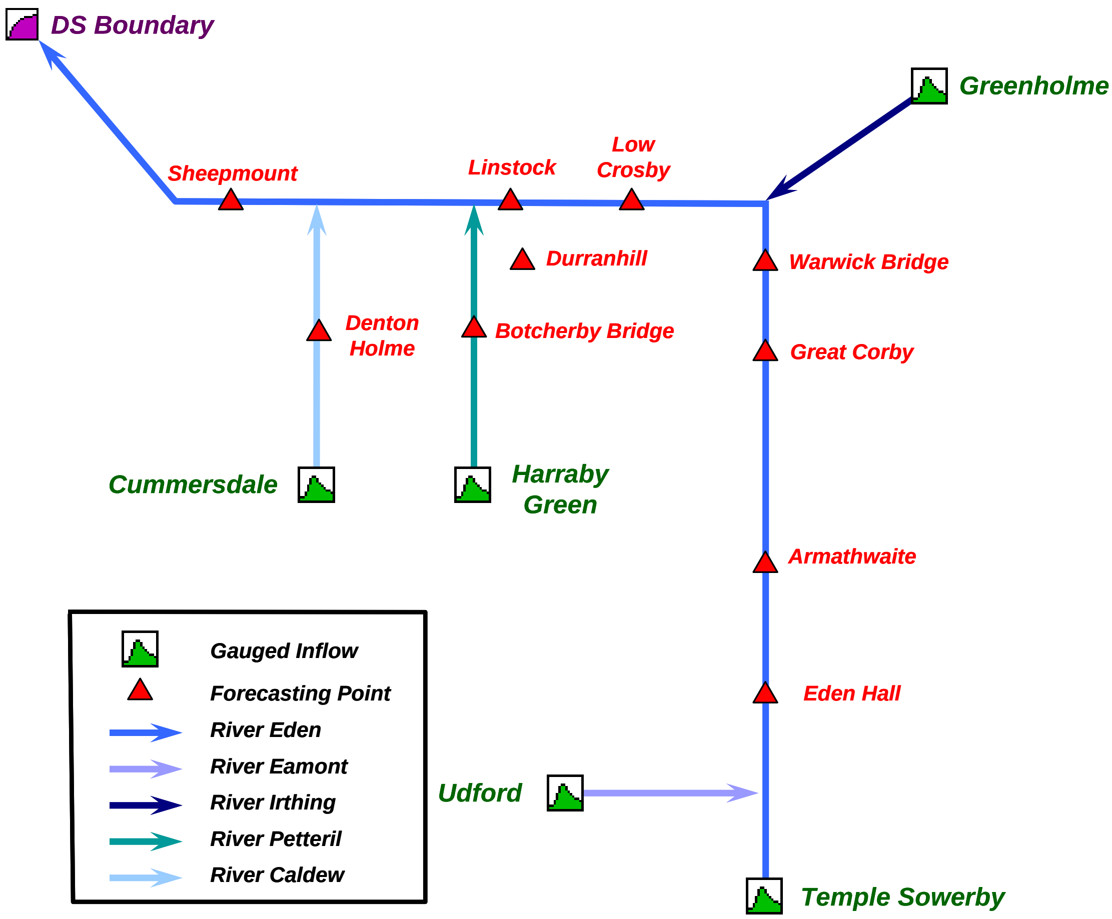


FIGURE 1: Schematic of model extent and flood forecast points for the improved flood forecast model

2.2. Model Extent

As noted above, the purpose of the strategy model was for flood risk mapping and flood defence scheme design. As a result, a significant amount of detail has been included and the model runtime was not a criterion for concern. In addition, the strategy model extends further upstream than the flood forecasting reaches. The effect of the added detail and the extended reach means that the strategy model contains an additional 850 nodes when compared to the existing flood forecasting model.

The model extent that the improved flood forecasting model should cover was specified by the Environment Agency and is detailed in Figure 1. In order to achieve these requirements and to meet the real time runtime requirement, it was necessary to cut down the strategy model and to improve the model convergence/stability.

2.3. Model Simplification, Modification & Stabilisation

Significant reduction in the model node count has been achieved by removing the River Petteril reach upstream of Harraby Green gauge and the entire Little Caldew since there is no flood forecasting requirement in these reaches, reducing the model node count from 1798 to 1269 and the number of hydraulic structures (e.g. bridges, weirs, culverts, flood relief arch, etc) from 78 to 24.

The Little Caldew is an old mill race that runs through the heavily urbanised Denton Holme and Willowholme areas of Carlisle. It extends from Holme Head Weir on the River Caldew (via a sluice) to The Maltings area on the River Caldew. Through much of its 2km length, the Little Caldew flows through small culverts and over steep spills and weirs. The effect of excluding the entire Little Caldew from the improved flood forecasting model can be assessed by a relative comparison of the modelled results at Denton Holme between the improved flood forecasting and the strategy models. The model validation results for the 1990, 1995 and 1999 events indicate the maximum peak water level difference between the two models at Denton Holme is less than 0.09m. It is therefore deem acceptable to exclude the Little Caldew from the flood forecast model.

Once the strategy model had been cut down to cover the required model extent, the spacing between all the river cross-sections was examined reach by reach in a progressive and iterative manner. The strategy model uses small spacing (down to 3m) between cross-sections at many locations. Since small spacing can cause low time steps during the model runs, an improvement to the cross-section spacing has been made throughout the entire model, increasing the minimum spacing between two cross-sections from 3m to 16m. It should be noted that removal of river cross-sections and hydraulic structure units in order to increase the cross-section spacing was undertaken away from key locations and, in particular, the flood forecast points.

A large number of floodplain areas along the river were modelled by the strategy model as flood cells, represented by 61 ISIS reservoir units within the required model extents. These floodplains were connected to the main river through ISIS lateral spill units, with some floodplains being connected to other floodplains using ISIS floodplain units. Some of these floodplain units (spill/reservoir/floodplain units) in the strategy model were not stable at high flows when a large quantity of water, as high as 765 m^3/s for the 1% annual flood probability (i.e. 100 year return frequency) design event, passed through one of the spill units. The configuration of the floodplain connections was carefully examined, with improvements being made to stabilise the model.

The improved flood forecasting model includes hydraulic reaches of the Rivers Eamont, Eden, Irthing, Petteril and Caldew. At the confluences of the Eden and the other tributaries (Irthing, Petteril and Caldew), the flood flow routes were carefully examined and improved. As a result of the re-configuration of the floodplains, the model stability has been improved significantly.

The flow gauging weir at Great Corby is a complex hydraulic structure, consisting of a central low level Crump weir and a higher level Crump weir on either side. The weir was originally modelled as 3 parallel Crump weir units in the strategy model. After checking the dimensions of each Crump weir unit, it was found that the two side weirs were identical. Therefore the two side weirs were merged into one unit in the improved flood forecasting model. There was another weir, consisting of 3 parallel weir units, immediately downstream of the Great Corby gauging weir. The purpose of this weir is to create a stilling basin to allow the fish to migrate further upstream. Again the two side weirs were identical and were merged into one unit.

2.4. Hydraulic Feature Summary

The key hydraulic feature in the improved flood forecasting model can be compared with the original strategy model and the cut-down version of the strategy model covering the required model extent, as shown in Table 1.

It should be noted that all of the floodplains in the strategy model, represented by 61 ISIS reservoir units and a large number of floodplain units and lateral spill units, have been retained within the required model extents in the improved flood forecasting model. Yet the improved flood forecasting model is robust and stable and runs fast.

Unit \ Model	Original Strategy Model	Cut-down Strategy Model (within the required model extent)	Improved Flood Forecasting Model
Number Count of Model Nodes	1798	1269	1138
Number of River Cross-Sections	573	401	315
Number of Interpolated Cross-Sections	232	122	91
Number of Floodplain Reserveroirs	68	61	61
Number of Floodplain Units	55	58	63
Number of Spill Units Used	386	288	283
Number of Hydraulic Structures	78	24	17
Number of Benoulli Loss Units	50	14	12

TABLE 1. Hydraulic feature summary

3. Hydraulic Model Performance

As a result of the model conversion and improvement, the improved flood forecasting model can now run stably and quickly. The model has been tested for various historical flood events, including February 1990, February 1995, January 1999 and January 2005 events. In addition, the model has also been tested for standard design event, i.e. the 1% annual flood probability (100 year return frequency), and its scaled up variations with 20% and 30% extra flows being added respectively. The model runtime statistics for these tests can be shown in Table 2 for model simulations on a 3.2 GHz PC.

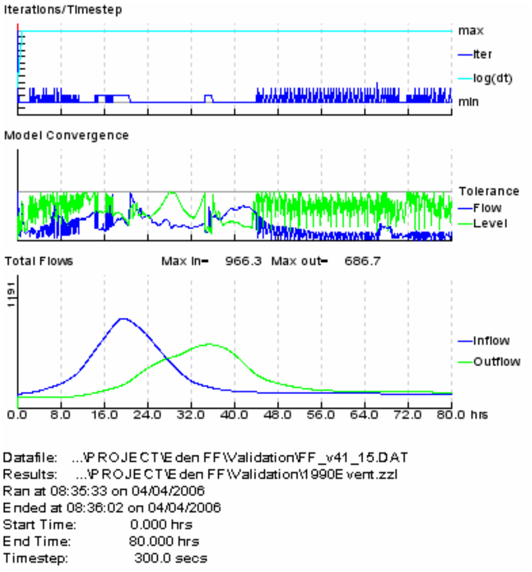
Flood Events (Simulation Duration)	**Maximum Outflow (m^3/s)**	**Total Model Runtime (second)**	**Number Used for Each Timestep**			
			300s	**150s**	**75s**	**<37.5s**
Feb 1990 (80 hr)	687	31	951	4	3	3
Feb 1995 (80 hr)	915	31	947	5	4	5
Jan 1999 (80 hr)	686	32	946	5	4	6
Jan 2005 (150 hr) *	1319	47	1791	4	3	3
100 year design (80 hr)	1443	36	455	500	3	3
100 year +20% (80 hr)	1791	64	614	39	259	49
100 year +30% (80 hr)	1954	88	565	15	294	87

* January 2005 inflows were estimated based on FEH units

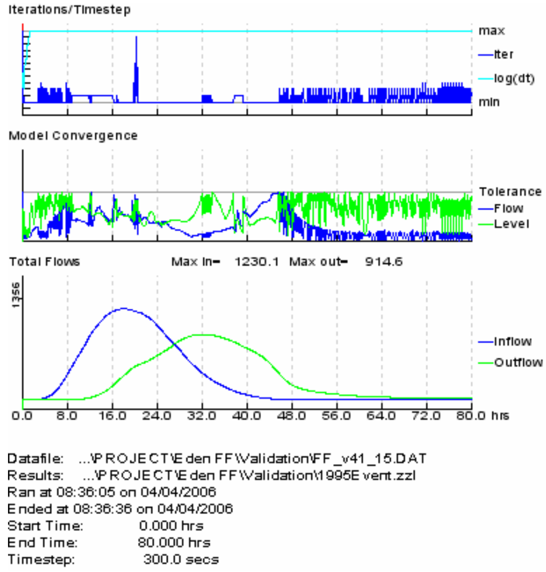
TABLE 2. Model Runtime Statistics (Model Save Interval = 300sec)

It can be seen that the improved flood forecast model runs very fast for smaller flood events (representing ordinary conditions for most of the time), with slightly increased model runtimes for higher flows and for extreme flood events. The model runs stably with very good stability/convergence performance, as shown in Figures 2 and 3 for historical events and extreme design events respectively. Furthermore, the improved flood forecast model has also been tested for all of the above events using a save interval of 900 second. The model runs even faster due to a longer save interval and still maintains very good stability/convergence performance consistently.

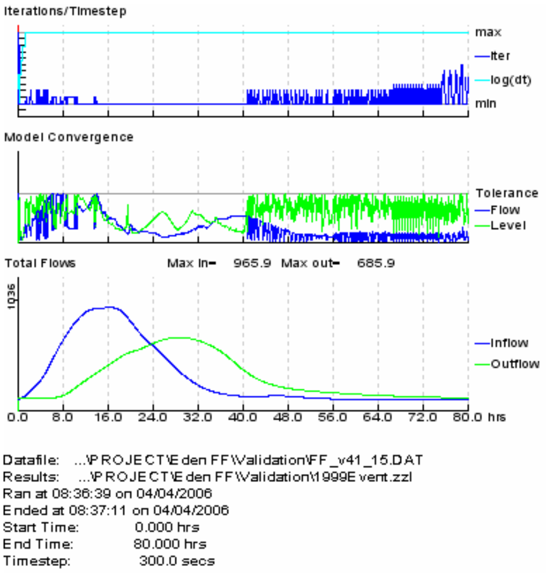
Typical runtimes are in the range of 0.5 to 1.5 minutes (on a 3.2 GHz PC) for an 80 hour simulation.



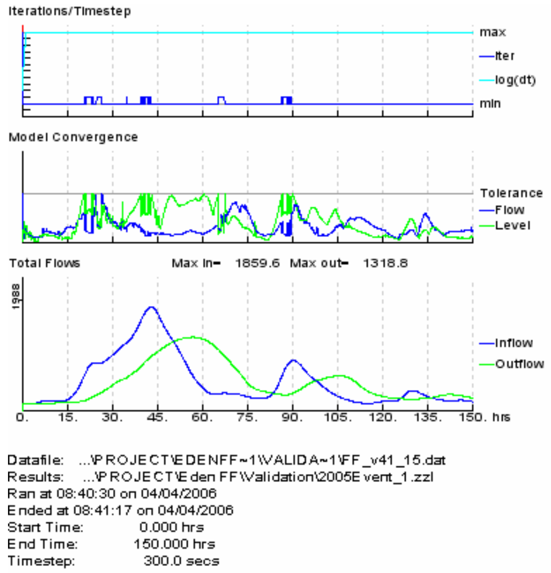
(a) Feb 1990 Event



(b) Feb 1995 Event

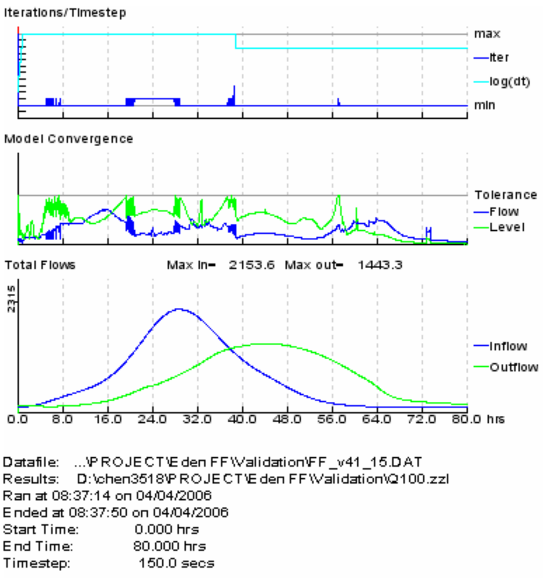


(c) Jan 1999 Event

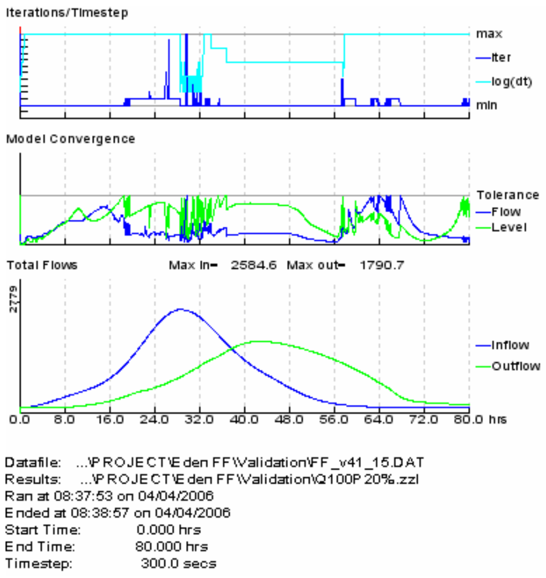


(d) Jan 2005 Event

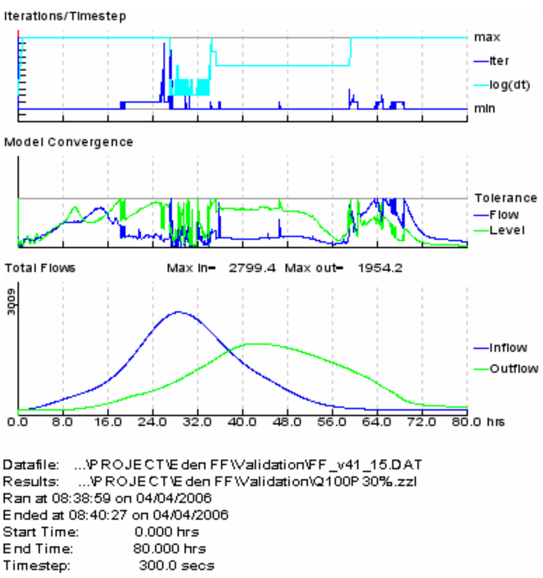
FIGURE 2. Improved River Eden flood forecast model stability/convergence/runtime performance for historical flood events



(a) 100 Year Design Event



(b) 100 Year plus 20% extra flow



(c) 100 Year plus 30% extra flow

FIGURE 3. Improved River Eden flood forecast model stability/convergence/runtime performance for extreme design flood events

4. Hydraulic Model Validation

Once the strategy model had been converted into the improved flood forecasting model, the improved flood forecast model was validated to ensure the model accuracy for flood forecasting purposes.

Model validation was based on four historic events:

- February 1990
- February 1995

- January 1999
- January 2005

Two validation approaches were adopted:

- like-for-like comparisons of the modelled results between the improved flood forecasting and the strategy models – using FEH based inflows
- comparisons of the modelled results of the improved flood forecasting model with the recorded data – using the gauged inflows from the Rivers Eden, Eamont, Irthing, Petteril and Caldew, supplemented by FEH based inflows for other ungauged or lateral inflows

However, it should be noted that the second validation approach relies on two aspects: (1) the main flow gauge ratings must be accurate and reliable (i.e. not bypassed and/or drowned as these will affect the gauge ratings); and (2) the estimates of the ungauged or lateral inflows from other sub-catchments must be accurate.

The validation model run results at key gauging sites were collated and compared against the corresponding results from the strategy model for the above mentioned two validation approaches.

For the purposes of model validation, so that relative comparisons of the modelled results between the improved flood forecasting and the strategy models could be made, the FEH based inflow boundaries, previously derived during the development of the strategy model for each of the 25 sub-catchments, were used. These sub-catchments can be shown in Figure 4.

In general the improved flood forecasting model results at the key gauge locations either match, or are better than, the equivalent results of the original strategy model. An example comparison at Sheepmount gauge can be shown in Figure 5 for the January 1999 event. It can be seen that the shape of the hydrograph, the timing and the magnitude of the flood peak were very well modelled for the event.

5. Conclusions

The River Eden/Carlisle strategy model has been successfully converted into a robust and stable flood forecasting hydrodynamic model for real time use. The improved flood forecasting model incorporates the key hydraulic features of the strategy model and retains all of the originally modelled floodplains within the required model extent. The improved flood forecasting model runs very fast, with a typical model runtime being in the range of 0.5 to 1.5 minutes for an 80 hour simulation of various flow conditions on a 3.2 GHz PC. The accuracy of the model has been demonstrated by two types of model validations for the historic events – using the same FEH based inflows as used during the development of the original strategy model and replacing the inflows from Rivers Eden, Eamont, Irthing, Petteril and Caldew by the available recorded flow data. The shape of the flood hydrograph, the timing and the magnitude of the flood peak were very well modelled for the historical events.

References

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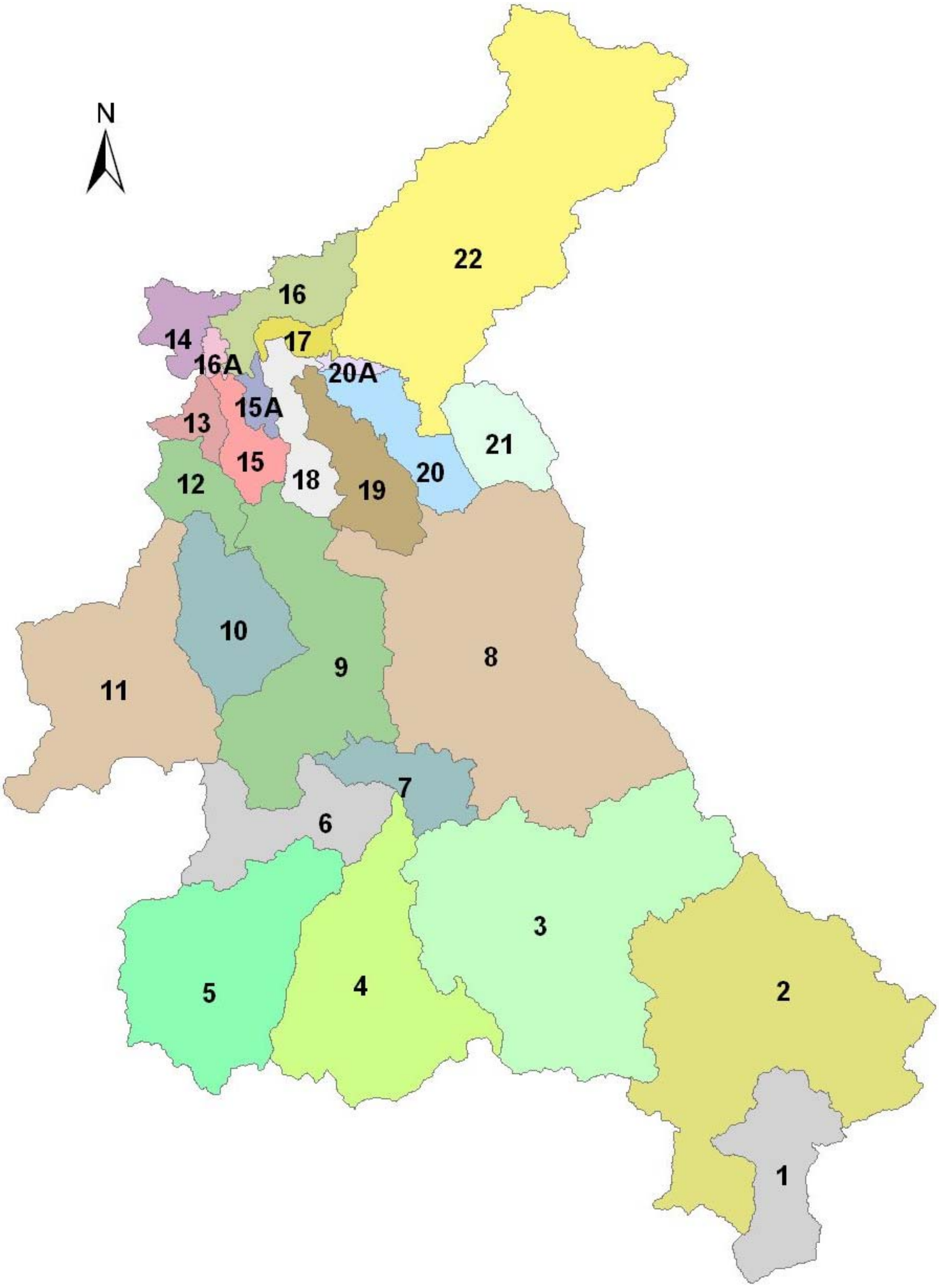

FIGURE 4. Eden sub-catchment delineation

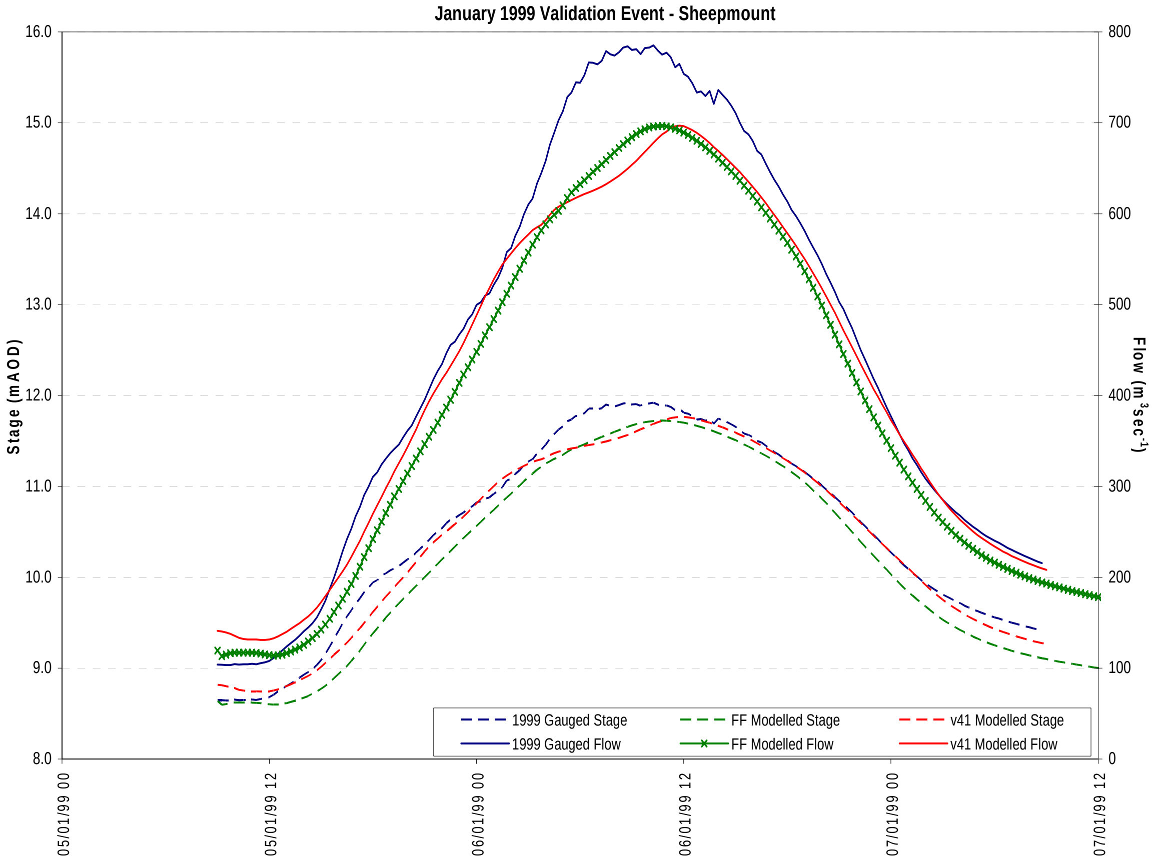

FIGURE 5. Model validation at Sheepmount, January 1999 event