The 13th World Water Congress 2008

AN EVALUATION OF THREE LUMPED CONCEPTUAL RAINFALL-RUNOFF MODELS AT CATCHMENT SCALE

N.T. Lan Anh [1], P. Willems[2], J.B. Boxall[1] & A.J. Saul[1]

[1] Department of Civil and Structural Engineering, University of Sheffield, Sir Frederick Mappin Building, Mappin Street, Sheffield, S1 3JD. UK.

[2] Department of Civil Engineering - Hydraulics Laboratory, Katholieke Universiteit Leuven, Kasteelpark Arenberg 40, B-3001 Leuven, Belgium.

Keywords: Rainfall-runoff, calibration, modelling

ABSTRACT

Lumped conceptual rainfall runoff models have been widely used in hydrology for many years. These models are usually able to describe most important processes in a catchment through a set of solvable equations. Thus, in many cases they are preferably over full physically-based models since they have such advantages: basic physically-based and simplicity. However, many parameters of these models can not always be directly measured due to the fact that the conceptual models are lumped on catchment scales. Even though the model structure can be very detailed, the modelled results are possibly meaningless if the model parameters are poorly specified. The usefulness of the hydrological model relies on how well the model is calibrated.

Three lumped conceptual rainfall-runoff models were presented and compared in this paper: NAM (DHI), FEH (UK), and TVM (a simplified model was developed by the author). If the NAM and TVM models are representative for continuous modelling, then the FEH model is event-based type. These three different models were applied to the Bradford catchment (UK) on a seasonal basis (summer and winter) with a time step of hourly or quarter hourly. The procedure of model calibration was presented. Model validation was performed together with statistical analysis.

It has been shown in the study that overall the hydrological models represented in the paper give reasonable results in terms of accuracy. However, the selection of models for particular catchments should be based on data availability, project objective and model structure.

1. INTRODUCTION

Flood risk management and impacts of climate change have become an increasing area of concerned for researchers over the last decades. As with a number of cities around the world, Bradford city faces increasingly serious flooding problems. In 2003, the City of Bradford Metropolitan District Council set up an independent inquiry to investigate all aspects of flooding and its relevance within Bradford. In the mean time, the City Council has participated in an EU funded project called Urban Water Cycle (UWC) as part of the Interreg IIIb North Sea Programme. This project aims to improve the water bodies of the Bradford catchment by sustainable urban regeneration. In order to set realistic objectives, many approaches are required to give a full understanding of water flow, flood risk, and public amenity. Watercourse management requires a holistic, catchment-wide view of human impacts on water resources. Hence, a modelling framework for integrated catchment management was developed for the Bradford catchment [Lan-Anh et al. 2006].

This paper presents a piece of work in the entire catchment modelling for the Bradford catchment. Three conceptual rainfall-runoff models were applied to the study catchment; the calibration procedure was presented; and model evaluation was performed.

2. OVERVIEW OF THE STUDY CATCHMENT

The Bradford catchment is located in West Yorkshire, UK. The city of Bradford has developed in a natural basin on the lower eastern slopes of the Pennine range of hills. The natural drainage of about 58.4 km^2 catchment is via the Bradford Beck which flows steeply eastwards into the city centre before turning sharply northwards to join the River Aire at Shipley (Figure 1). The catchment is a mix of rural area and urban area. The Bradford Beck and its tributaries comprise a total stream length of 35 km, of which 19 km is located in the urban area. A large proportion of the urban river reaches on both the main channel and the tributaries are fully enclosed as culverts. The main watercourse, Bradford Beck, has a length of 14 km. Before reaching the city centre, the Bradford Beck collects a number of important tributaries, such as Pitty Beck, Clayton Beck, Chellow Dean Beck and Bull Greave Beck. Coming through Bradford, it is joined by other three tributaries, Westbrook, Bowling Beck and Eastbrook, which drain steeply in a radial pattern to the city centre [City of Bradford Metropolitan Council, 1987a].

The character of the Bradford Beck course changes significantly along its length. The upper reaches, extending for 6 km, are steeper than the lower sections, with a main channel average bed slope of 22 m km^{-1}. For 5 km through central Bradford the watercourse is mostly culverted. The remaining 3 km to the River Aire consists of mostly lined, semi-lined open channels with occasional culverted sections and crossing bridges. In general, the bed slope of the total of 8 km length is hydraulically steep and there is a marked variation of bed slope. Out of 28 catchments used in a UK national flood study, and classified as either very heavily or extremely heavily urbanised, only one was steeper than the Bradford catchment [Old et al., 2003]. The Bradford Beck has a overall average steep gradient of greater than 13 m km^{-1} (from 1:50 000 map and survey).

The catchment, particularly in the city reaches, comprise a mixture of various types, shapes and sizes of culverts and channels. Changes in form of construction, cross-sectional area and gradient often occur over very short lengths which result in wide variations in hydraulic capacity. Extensive sections, often located inaccessibly underneath buildings, or major utilities in streets, fall far short of the capacity necessary to afford adequate flood protection standards for the city centre.

Significant features are the radical pattern of steep tributary watercourses joining the main Bradford Beck in the city centre and the extensive urbanisation of the majority of their contributing catchments. In combination these features produce watercourse flows which respond very rapidly to rainfall, producing fast rising flood flows in the low lying city centre. Additionally during intense rainstorms, CSOs within the Bradford catchment have a significant influence on both the water quantity and quality of the watercourse.

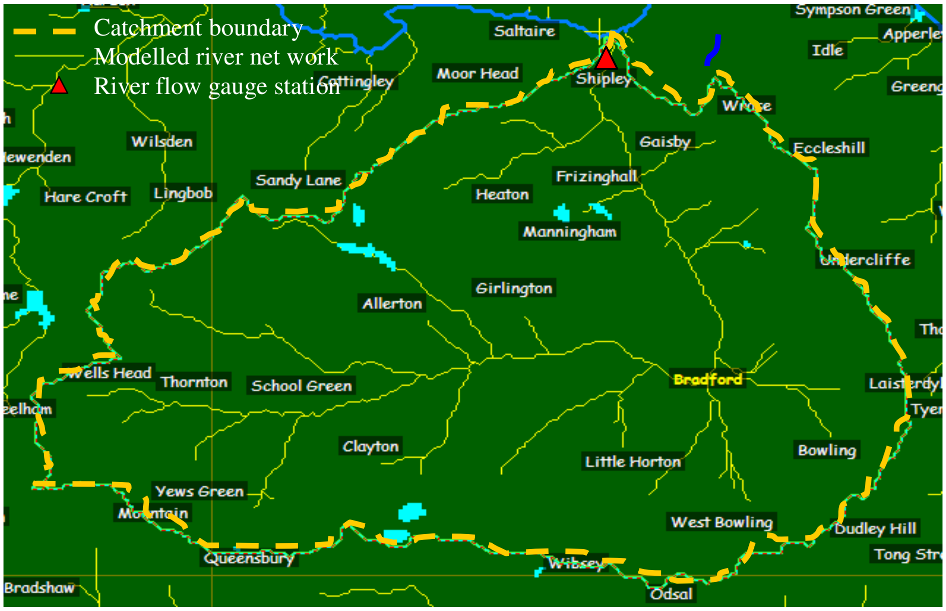

Figure 1. Planview of the Bradford catchment

3. METHODOLOGY

3.1 *Modelling approach*

The hydrology of the Bradford catchment was performed using the lumped conceptual models. The lumped conceptual models have been widely used in hydrology for years. The models are usually able to describe the most important processes in a catchment through a set of solvable equations. In many cases, they are preferably because they have such advantages: basic physically-based and simplicity. However, the parameters of these models can not always be measured directly due to the fact that the conceptual models are lumped on a catchment scale and the catchment is treated as a single unit. Model variable and parameter sets are values averaged for the entire catchment. In such lumped system models, flows are calculated as a function of time at a particular location [Chow et al., 1988].

Three lumped conceptual model were evaluated for the study catchment: NAM (DHI), FEH (UK), and TVM (a simplified model was developed by the author). MIKE-FEH and NAM modules that are part of MIKE11 modelling package (DHI) selected for the study, combined with the hydrodynamic module for further study. If the NAM model is a representative for continuous modelling, then the FEH model is an event-based modelling approach. For this particular catchment, another lumped conceptual model called TVM was developed by the author. The TVM model is also continuous modelling type. In general, data requirements for the rainfall-runoff models are meteorological data (rainfall and potential evapotranspiration), model parameters, initial conditions, and river flow data. Those basic inputs provide information about the catchment being modelled. Short descriptions for each model used are given below.

The FEH model (FEH, 1999)

MIKE-FEH has been developed as a comprehensive modelling tool for analysing catchment runoff and carrying out flood risk assessments using the methods of Flood Estimation Handbook (FEH), Volume 4 (CEH, Wallingford, 1999). The FEH is a standard method for UK catchments. On the basic it is a unit hydrograph method that is linear response to rainfall and event-based. The hydrograph is distribution of the runoff in time. The centre of rainfall-runoff modelling in the FEH method is the FSR unit hydrograph and losses model. The model is based on the analysis of individually record flood events. For each event, the total flow hydrograph is separated into runoffs (1) which is a direct response to the storm rainfall and (2) which is not, so-called baseflow. The difference between the rainfall volume and the direct response runoff volume is loss. There are three model parameters required: baseflow, percentage runoff, and unit hydrograph in which percentage runoff is the most influential parameter because it has a direct scaling influence on the magnitude of the rapid response runoff flood peak while the shape of the rapid response runoff hydrograph is influenced by the unit hydrograph time-to-peak. Baseflow in the FEH model is assumed constant throughout events.

The NAM model (DHI, 2004)

It forms part of rainfall-runoff modules in MIKE 11 river modelling system which can be either applied independently or used to represent one or more contributing catchments that generate lateral inflows to a river network. The NAM model can be characterised as a deterministic, lumped, conceptual model with moderate input data requirements.

The NAM model is a set of linked mathematical statements describing behaviours of the land phase of the hydrological cycle in a simplified way. It represents various components of the rainfall-runoff process by continuously accounting for the water content in four different and mutually interrelated storages: snow storage, surface storage, root zone storage (subsurface) and groundwater storage that represent different physical elements of the catchment. In NAM, total flow is a sum of the overland flow, interflow and baseflow. The overflow and interflow are routed based on the linear reservoir concept through two linear reservoirs in series with their time constant while the baseflow is calculated as the outflow from a linear reservoir with baseflow time constant. The NAM model can be used either for continuous hydrological modelling over a range of flows or for simulating single events.

The TVM model

This model was developed adopted the downward approach that was first introduced into hydrological modelling by Klemes (1983). The approach is a data-based approach learning and interpreting behaviour of a catchment from patterns of data that are obtained at catchment scales. The downward approach has the advantage of having a minimum initial data requirement, then the refinement processes keep going until either a model of sufficient accuracy obtained at the study scale, or the availability/quality of data met lower limits that are not qualified enough to justify further model refinement. The approach implies that models should decrease in complexity with increase of scale.

In general, the TVM model was developed at catchment scales based on the water balance with soil moisture as a central theme, i.e. it uses soil moisture accounting to simulate water balance within catchment. The TVM consists of subroutines for evapotranspiration estimation, soil moisture calculation, and runoff generation. The model is represented by storage elements and transport units. Three storage elements are included: surface storage (overland flow and interflow), subsurface storage (soil moisture storage) and groundwater storage (baseflow); flow routing is described by linear reservoir models; and infiltration rate is represented by linear or exponential equations.

In the TVM, rainfall input is thus partitioned into different subflows (1) surface runoff (overland flow and interflow), (2) soil moisture storage, and (3) groundwater (baseflow). Taking advantage of separation of hydrographs, rainfall portions that distribute into each storage can be estimated. The corresponding fractions of the subflows are thus the fraction of subsurface (soil moisture content), the fraction of surface storage (quick flow), and the fraction of groundwater storage (slow flow). Then the quick flow can be separated into the overland flow and interflow.

3.2. ***Model calibration and validation***

On the basis of data required by the models being used, data available for the study catchments have been collected, processed, and made use of. Data processing is the most important task in modelling. The models need to be ensured to have the best possible data set to use. This is not only to ensure that the modelled results are reliable but also to speed up the calibration process.

Two periods of time series data are used for model calibration (06/2000 – 06/2001) and model validation (01/1999 – 01/2004) with time resolution of 15-minute and hourly.

All the models are calibrated based on the recorded rainfall data and the river flow data. While model parameters in the FEH are estimated based on actual storm events and soil moisture deficit (thus it is assumed to be accurate and not require calibration), in the NAM and TVM, model parameters have to be calibrated in a more complicated way because they can not be directly measured or they were not empirically specified in a prior study of UK catchments as done in the FEH approach.

A procedure of model calibration was done in combination between manual and automated calibration to give a good insight in the hydrology of the study catchment. For instance, recession times of flow components that are separated from the total flow were estimated using a numerical digital filter. These model parameters thus do not tune when calibrating other parameters. Model calibration and validation are mutually beneficial process, checking on agreements between simulated and measured results by hydrograph shape, hydrograph maxima and minima, water balance by cumulative volume, and extreme values distribution. These comparisons can be made using statistical measures, for example the hydrograph shape can be checked by the overall Root Mean Squared Error (*RMSE*), flow maxima and minima by the Mean Squared Error (*MSE*), etc. [Madsen, 2000a, 2000b; Willems, 2000].

In order to unify the presentation and comparison of the different models, in this study the modelled results were evaluated based on the same statistical measures as following: (1) water balance error (W_R), (2) model efficiency (E_Q) by using the method of Nash & Sutcliffe (1970), and (3) peak flows (quick flow) and low flows (slow flow) statistics including MSE, RMSE and the coefficient of determination (R^2). The Nash–Sutcliffe model efficiency is a measure of how well the observed and simulated values match whereas R^2 is an indicator of the strength of the relationship between the observation and simulation. Values of E_Q and R^2 towards 1 indicate better performances.

Time series of peak flow maxima and low flow minima were constructed using the Peak-Over-Threshold approach. The discharge series was split for this purpose in "nearly independent" quick flow and slow flow events. Quick flow maxima were selected as the highest discharge values during the quick flow periods and the slow flow minima as the lowest values during the slow flow periods. To eliminate effects of errors that tend to increase with extreme values, Box-Cox transformation is applied to equally weights given to all flow magnitudes. After transformation, the results become normally distributed and independent.

4. MODEL RESULT AND DISCUSSION

Firstly, the FEH was carried out with big selected storm events in the study years and synthesis storms in order to verify the model. The NAM model was then undertaken. The modelled results of two models were compared since the NAM can be used to simulate single events. At last, the TVM was performed. Owning its nature that is designed for continuous modelling, the TVM was compared to the NAM only. Finally, model evaluation was undertaken by comparing between the modelled results and the observations, and the goodness-of-fit were quantified.

Comparison between the FEH model and the model NAM

Examination of the model performances show that overall the NAM has given better results in comparison with the FEH (see Table 2). The reason is due to limitations of the FEH method. As stated earlier, the FEH assumes that the baseflow is constant throughout events and is added into the quick response runoff hydrograph. This is not true in reality since the baseflow varies depending on soil moisture state, ground water level and rainfall. Thus, in MIKE FEH, the computed runoff hydrograph has a constant lower limit which is the assumed value of the baseflow (Figure 3). Nature of the FEH method is event-based; therefore it can not simulate long term simulations, such as a few years' time series of rainfall since the model parameters might be lumped in a wrong way. For example, in the Bradford catchment the runoff percentage appeared greater than one hundred if the time period of the simulation was for the period of validation, i.e. the model parameters become unrealistic. However, the FEH model worked well for single events/short periods. Figure 2 shown the results for the synthetic storms while Figure 3 presents for the actual selected storm events. For the actual storms during the calibration period, two biggest storm events (event 1: 19/9/2000 – 26/09/2000, and event 2: 28/10/2000 – 10/11/2000) were selected to simulate using the NAM and FEH models.

The modelled results showed that although no big discrepancy was found between the NAM and FEH results for synthetic storms ($RMSE = 0.0016$), the modelled actual event results clearly showed the limitation of the FEH method for the baseflow ($RMSE = 3.528$).

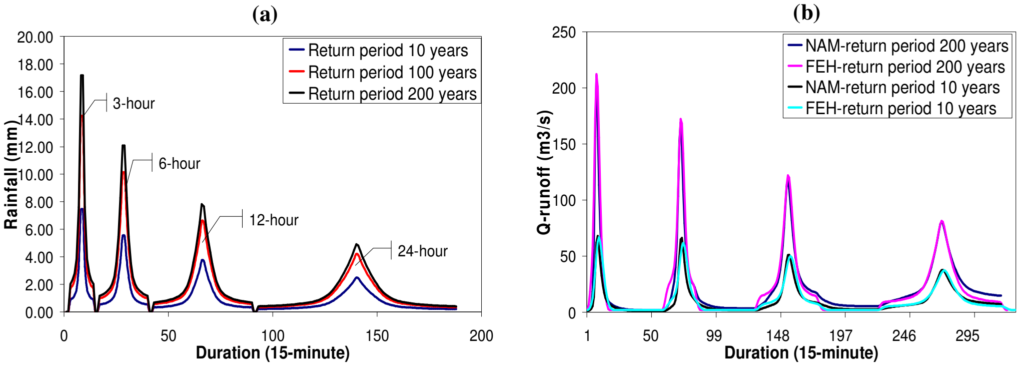

Figure 2. (a) Synthetic storms for the Bradford catchment with different durations and return periods; (b) Comparison of the NAM and FEH simulations for synthesis storms

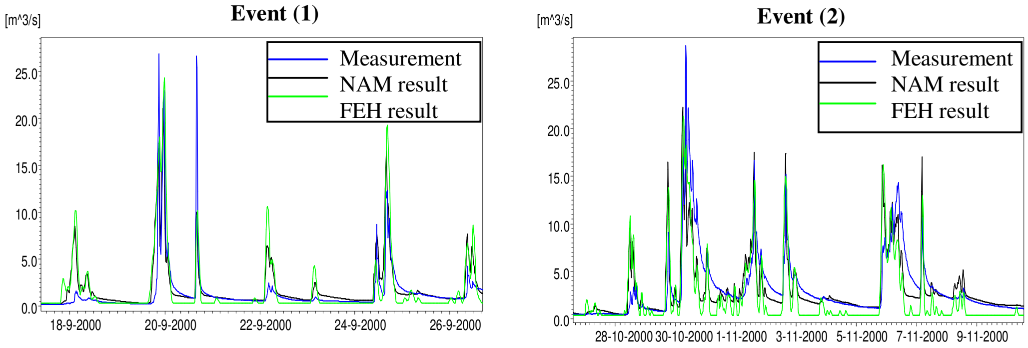

Figure 3. Comparison of the NAM and FEH modelled and observed result for the selected events

Table 1. Statistical measures of the NAM and FEH models for the selected rainfall events

Events	NAM	FEH
Synthetic storms		
RMSE (m^3/s)	1.4801	3.136
ME (BIAS) (m^3/s)	0.576	1.0185
Actual rainfall events		
Water balance error W_R (%)	-6.031	-17.40
Model efficiency E_Q	0.561	0.421
RMSE (m^3/s)	2.691	6.760
ME (BIAS) (m^3/s)	0.937	1.897

Comparison between the NAM model and the TVM model

Graphical plots and the goodness-of-fits for two models were represented after simulations. In general, two models performed well the runoffs of the study catchment representing by high values of model efficiency (E_Q) and R^2 (Table 3). Figure 4 and 5 show the scatter plots of the flow maxima and minima after Box-Cox transformation of the observed and modelled flows. They indicate good matches between the simulations and observations.

It can be seen that the volume of water balance in the NAM model is higher than in the observation (see Table 2, W_R = -6.5 %. This can be explained by overestimation of intermediate flows. Statistical analyses revealed that for the NAM model results overestimation is apparent to the flows smaller than 6.7 m^3/s and underestimation is observed for the flows above that threshold. Although the NAM model tends to underestimate the peaks, there are more of the intermediate flows than the peaks, thus, the amount of water from overestimation of the intermediate flows compensated for underestimation of the peaks is larger than required. This can also be clearly seen in the statistical analyses for the flow extreme values shown in Figure 6 and 7.

The analysis of extreme flows (discharge maxima and minima) is represented in Figure 4, Figure 5 and Figure 6. A comparison between calibration and validation periods for the independent high and low flows after the Box-Cox transformation shows an acceptably good match as shown in Figure 5. However, the underestimation of the peaks can be seen in Figure 6 where the flow maxima and minima were compared. Although both models, the NAM and TVM, underestimated the peaks but the TVM modelled results were much closer to the observation. This is confirmed by the flow duration curve in Figure 7(a), time series of total flows in Figure 8, and statistical measures in Table 2. *RMSE* values of the TVM model are smaller than those of the NAM model, for instance, the value of 0.9672 for flow maxima from the TVM model is compared to 5.200 from the NAM model. The high peaks occurred in the Bradford catchment can be explained by effects of the urban component which contribute a significant amount of water into the river though the CSO network. The flow minima, however, was well simulated for both models.

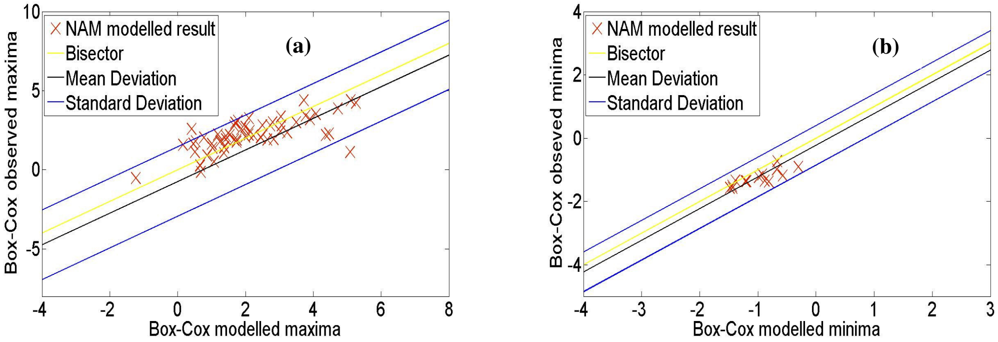

Figure 4. Comparison between the modelled and measured flows for extreme values after Box-Cox transformation, the NAM model

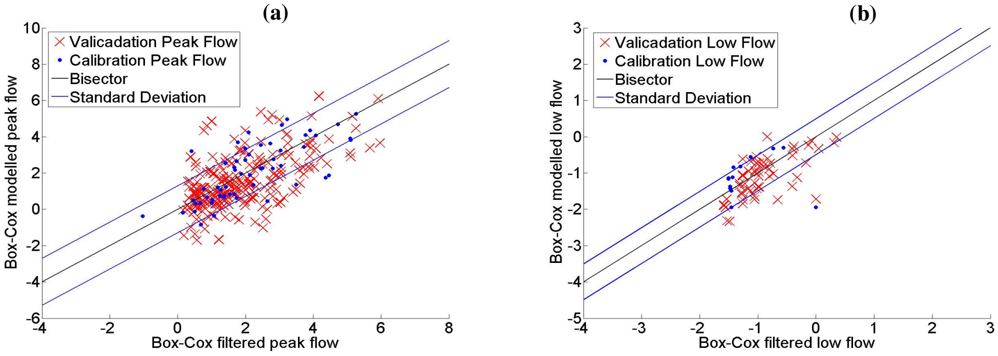

Figure 5. Comparison between the modelled and measured flows for extreme values after Box-Cox transformation, the TVM model

The flow duration curve characterises the ability of the catchment to provide flows at various magnitudes. It is very useful for designing purposes since it gives information about the relative amount of time that the flows past a site are likely to equal or exceed a specified value. The shape of the flow-duration curve, especially upper and lower parts, is particularly significant in evaluating model results. The shape of the curve in the high-flow region indicates the type of flood regime the basin is likely to have, whereas, the shape of the low-flow region characterises the ability of the basin to sustain the low flows during dry seasons. A very steep curve (high flows for short periods) of the Bradford catchment indicates the catchment is sensitive with rainfall events causing floods and periods of very small flow exhibit in the low-flow region Figure 7(a)). It also means that the study catchment is very flashy with short time response to storm events. The tails at the high-flow region indicate the TVM model slightly underestimated some peaks while the low flow was well predicted. Again, it has been clearly shown in the flow duration curve that the NAM model overestimated the intermediate flows and underestimated peaks while the TVM modelled result matches the observation very well. Figure 7(b) also indicates that water balance in the NAM was over predicted whilst the TVM gave a fairly good result.

A general conclusion can be made that the TVM performs well for the Bradford catchment in comparison with the NAM model.

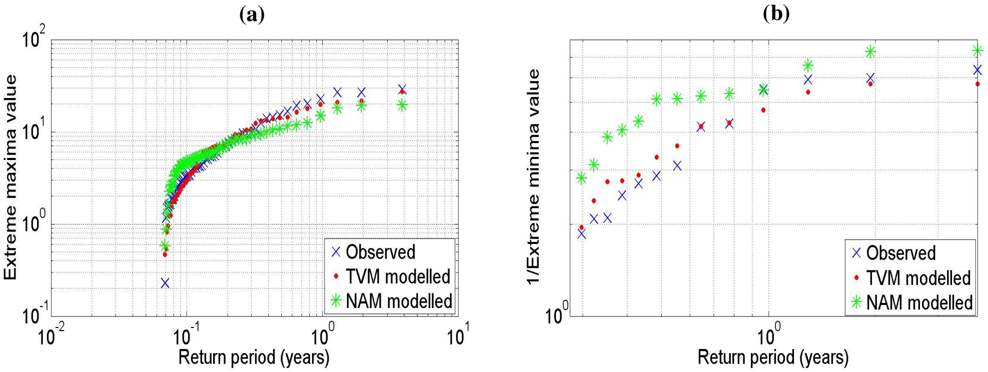

Figure 6. Validation of (a) extreme maxima and (b) low flows at time interval 15-minute

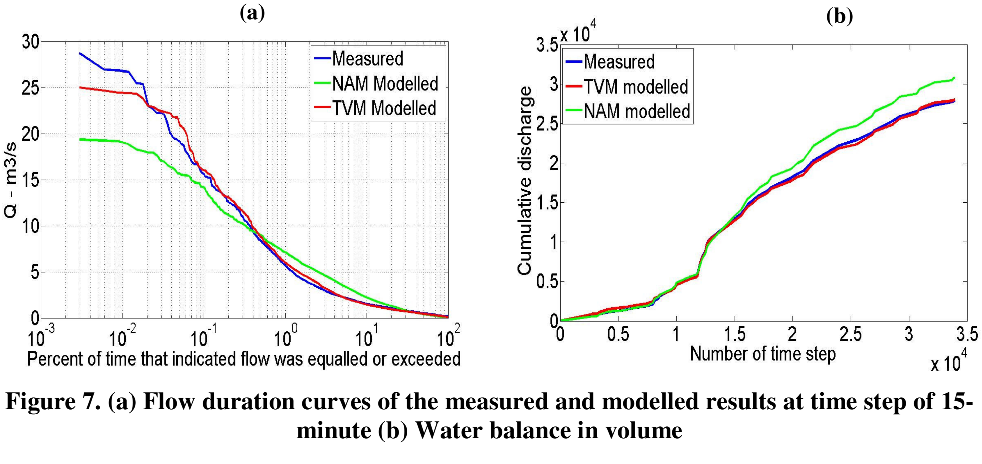

Figure 7. (a) Flow duration curves of the measured and modelled results at time step of 15-minute (b) Water balance in volume

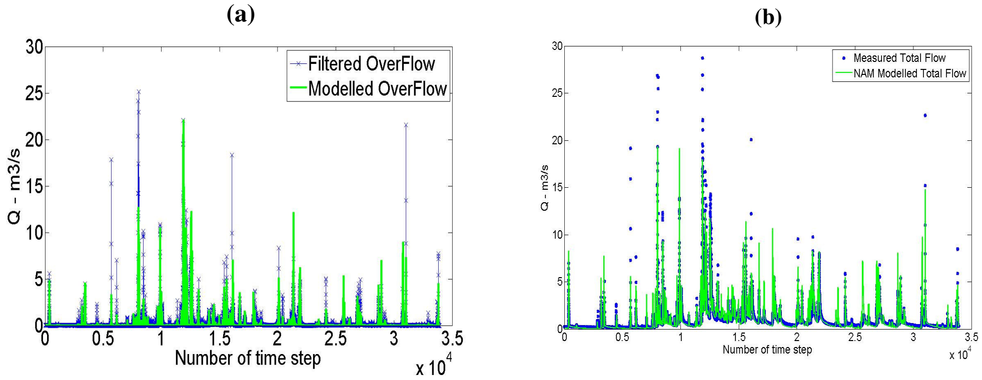

Figure 8. Time series discharge compared between the measured and modelled results (a) the TVM model (b) NAM model

Table 3. Comparison of statistical performance between the NAM and TVM model

Goodness-of-fit statistic	**NAM**		**TVM**	
	Calibration	**Validation**	**Calibration**	**Validation**
Overall				
Water balance error W_R (%)	-6.527	10.426	-0.3158	2.3741
Model efficiency E_Q	0.532	0.450	0.7942	0.5367
Flow maxima				
RMSE	5.200	5.395	0.9672	1.1473
ME (BIAS) (m^3/s)	-0.750	-1.150	0.9358	-0.1718
Flow minima				
RMSE (m^3/s)	0.159	0.210	0.1725	0.3180
ME (BIAS) (m^3/s)	-0.113	-0.0295	0.0736	-0.0734

5. CONCLUSION

Three rainfall-runoff models were tested for the Bradford catchment. The FEH model is event-based modelling while the NAM and TVM models are continuous modelling. These three models were implemented and calibrated for the study catchment, and then model performances were evaluated based on the graphical visual plots and means of statistics used to quantify the goodness-of-fit.

It has been shown in this study that these rainfall-runoff models, regardless of their different advantages and disadvantages, have performed acceptable results in terms of accuracy. However, the selection of the models is highly dependent on the purpose of studies. Continuous modelling is of interest to this study as it aims towards a holistic approach of river catchment modelling. The FEH model cannot be used to simulate long term time series rainfall data due to its nature. However, it is workable for single storms that would be useful for flood analysis. A short period of continuous time series may be undertaken with the FEH provided that model parameters are still in an acceptable range. The NAM model has an advantage over the FEH model by being able to simulate data continuously although in case of the Bradford catchment it does not handle the intermediate flows well which makes the volume of water balance increases significantly due to overestimation of these intermediate flows.

Taking into account limitations in the modelled results produced by the FEH and NAM models, a conceptual rainfall-runoff model, the TVM model, was developed for the Bradford catchment to tackle these shortcomings. The TVM model has a flexible structure through various relationships in each module that can be changed/modified depending on characteristics of the study catchments. As a general rule, the model is specified with the idea of selecting the smallest and simplest model structure that adequately describes data availability in order to make it easier to estimate, to predict, and to analyze, the so-called simplicity and parsimony. The TVM model structure selected was based on the downward approach, i.e. the first trial was to find simple relationships, and go on to more complicated relations if the simple one did not match the real system. The approach aims to compromise between parsimonious and complex alternatives in model development. In addition, it allows, at a certain level, to penalise their complexity. The TVM model takes full advantage of useful information from data availability for the catchment, thus highly reflects the characteristics of the catchment. Usage of the river flow data to determine the recession constants and to extract the POT values, i.e. physical-based data, gives a reliable approach. The model also makes a good combination of numerical and trial-and-error calibration methods. In this way, modellers' knowledge about the catchments is efficiently used. During the calibration process, the model structure was adjusted to explore the best relationship to represent the catchment.

ACKNOWLEDGEMENTS

The study was conducted at Department of Civil and Structural Engineering, the University of Sheffield (UK) in collaboration with Hydraulics Laboratory, Department of Civil Engineering, Katholieke Universiteit Leuven. Supports, granted the first author by the Vietnamese Government and the City of Bradford Metropolitan District Council, United Kingdom, are gratefully acknowledged.

REFERENCES

Chapman, T. (1991). "Comment on 'Evaluation of automated techniques for base flow and recession analyses'" by R. J. Nathan and T. A. McMahon, Water Resources Research, vol. 27, No. 7, 1783-1784.

Chow V. T., Maidment D.R., & Mays L.W., 1988. "Applied hydrology". *New York: McGraw-Hill.*

City of Bradford Metropolitan council, 1987a. "Report in support of Land Drainage Grant Application to Ministry of Agriculture, Fisheries and Food (Vol.1)". *Bradford Beck Flood Alleviation Scheme, Directorate of Community Environmental Services.*

DHI, 2004. "MIKE11 – A modelling system for rivers and channels – Reference Manual". *DHI software 2003.*

Institute of Hydrology, 1999. "Flood Estimation Handbook". IH 1999, 5 volumes, ISBN 0 948540 94 X

Lan-Anh N.T., Boxall J., Saul A., and Willems P., 2006 “Development of a holistic approach to river modelling in the Bradford catchment (UK). Proceedings of the 7th International Conference on Hydroscience and Engineering (ICHE 2006), Philadelphia, PA, September 2006.

Madsen H., 2000a. “Automatic calibration of the MIKE11/NAM rainfall-runoff model”. *Nordic Hydrological Conference, 26-30 June, 2000, Uppsala, Sweden*. Nordic Hydrological programme, NHP-Report No.46 (ed. Torbjorn Nilsson), Vol.1, pp. 276-283.

Madsen H., 2000b. “Automatic calibration of a conceptual rainfall-runoff model using multiple objectives”. *Journal of Hydrology,* 235 (2000), pp. 276-288.

Nash J. E. & Sutcliffe J. V., 1970. River flow forecasting through conceptual models. I. A discussion of principles. *Journal of Hydrology*, Vol. 10, pp. 282-290.

Old G.H, Leeks G.J.L., Packman J.C.P, Smith B.P.G, Lewis S., Hewitt E., Holmes M. and Young A. (2003). “The impact of a convectional summer rainfall event on river flow and fine sediment transport in a highly urbanised catchment: Bradford, West Yorkshire”, The Science of the Total Environment, 314 –316 (2003), pp. 495–512.

Nathan, R. J., and McMahon, T. A. (1990). “Evaluation of automated techniques for base flow and recession analysis”, Water Resources Research, Vol. 26, No. 7, pp. 1465-1473.

Singh V. and Frevert D.K. (2003). “Watershed Modelling”, Proceeding of the Word Water and Environmental Resources Congress 2003 and Related Symposia, June 23-26, 2003, Philadelphia, Pennsylvania.

Willems, P. (2000). “Probabilistic immission modelling of receiving surface waters”, PhD thesis, K.U.Leuven, Belgium.