Integration of WBNM into A Continuous Simulation System for Design Flood Estimation

O.P. Droop[a] **and W.C. Boughton**[b]

[a]Gilbert & Associates Pty. Ltd., Brisbane, Australia (gaconslt@bigpond.net.au)

[b]Honorary Senior Fellow, Griffith University, Brisbane, Australia.

Abstract: The main approach to design flood estimation in Australia is event-based with the use of flood hydrograph models such as RORB, WBNM and URBS the most common practice for estimating design floods via rainfall based approaches. A characteristic of these models is that the routing of rainfall excess is distributed within the catchment, the amount of routing depending on the amount of sub-division of the catchment. Continuous simulation of losses is now established as an alternative to event-based design. The Continuous Simulation System for Design Flood Estimation (CSS) is currently the main continuous simulation system in use in. The CSS uses the WBMOD flood hydrograph model which routes rainfall excess at a concentrated storage at the outlet of the catchment instead of distributed through the catchment. This paper describes a comparison of the different methods of runoff routing when used in a continuous simulation system. Using the same data and loss system calibration used in a benchmark study for the CSS, the WBMOD was replaced with the Watershed Bounded Network Model (WBNM) and the benchmarking study was repeated. The results show comparisons of the two runoff routing models as well as comparisons of design flood estimates by flood frequency analysis, conventional event-based methods, and by the two routing models. Overall, calibration results for the CSS/WBNM were of a similar accuracy as for the original CSS/WBMOD with calibration of a single parameter (lag k) and simulation via a more realistic routing of flows through catchment subdivision based on drainage patterns. The most obvious differences between systems were the timing of flows and consistently lower design flood estimates for the CSS/WBMN.

Keywords: *Design flood estimation; Continuous simulation; WBNM; Modelling*

1. INTRODUCTION

The main approach to design flood estimation in Australia is event-based, with floods treated as isolated events. The main guide to design practice is Australian Rainfall and Runoff (Institution of Engineers, Australia 1987) which contains generalised rainfall intensity data, recommended values for initial/continuing losses, temporal patterns to distribute the rainfall excess, and flood hydrograph models to convert rainfall excess to streamflow at the outlet of the catchment. Flood hydrograph models most used in practice with this approach are RORB (Laurenson and Mein, 1997), WBNM (Boyd et al., 2002) and URBS (Carroll, 1994). A characteristic of these models is that the routing of rainfall excess is distributed within the catchment, the amount of routing depending on the amount of sub-division of the catchment for modeling.

Continuous simulation of losses is now established as an alternative to event-based design and is increasing is use in Australia, with systems also in operational use in UK/Europe, USA and South Africa (Boughton and Droop, 2003). The Continuous Simulation System for Design Flood Estimation (CSS) (Boughton et al., 2002) is the main continuous simulation system in use in Australia at the time of writing. Boughton and Droop (2003) give an overview of continuous simulation systems used for design flood estimation and describe the models used in Australia and elsewhere in the world.

This study compares the different methods of runoff routing when used in a continuous simulation system. Using the same data and calibration of the loss system as in the CSS benchmarking study (Boughton et al., 2002)., the WBMOD was replaced with the Watershed Bounded Network Model (WBNM) and the benchmarking study repeated. Results show comparison of the two runoff routing models as well as comparison of design flood estimates by flood frequency analysis, conventional event-based methods and by the two routing models.

2. BACKGROUND

2.1. Continuous Simulation System (CSS)

The CSS combines stochastic generation of daily rainfalls, disaggregation of daily rainfalls into hourly temporal patterns, a catchment water balance model (AWBM) for continuous simulation of losses and calculation of rainfall excess at hourly intervals and a flood hydrograph model (WBMOD) for converting hourly rainfall excess to streamflow at the catchment outlet.

The operating manual available with the software (CRCCH web site www.catchment.crc.org.au) is the main reference material, unless an alternative citation is given.

2.2. WBMOD

The WBMOD flood hydrograph model uses a distribution of travel times (in the form of a time-area contributing diagram) to spread the arrival of each mm of rainfall excess at the catchment outlet. The rainfall excess becomes input into a concentrated storage with a non-linear storage-discharge relationship. The discharge from the storage is the generated streamflow. WBMOD was developed with the CSS and has not been used as a flood hydrograph model independently of the CSS.

2.3. Watershed Bounded Network Model

The WBNM is a conceptual, event-based, model developed for simulation of flood hydrographs and estimation of design floods. The catchment to be studied is defined by sub-catchments on the basis of drainage lines and catchment boundaries with the capacity for distribution of rainfall inputs, main modelling catchment characteristics and generated excess.

The model consists of two sub-area types representing ordered basins where rainfall excess is transformed into runoff, and interbasin areas where there is the additional component of transmission of upstream runoff. A separate storage function is specified for both the rainfall-runoff from the interbasin area and the upstream throughflow, with different lags applied to each separate component of flow.

Full background of the most recent version of the WBNM can be found in Boyd et al. (2002).

2.4. Combined CSS/WBNM

The combined CSS-WBNM system has been developed with the WBNM in place of WBMOD as the flood hydrograph model. Continuous estimation of surface excess (and thus losses) is undertaken via the AWBM on a daily or hourly basis with the generated excess during periods of significant rainfall routed through the catchment on an hourly basis using WBNM. A significant point to note is that the WBNM generates excess on a distributed basis (ie. for each individual sub-area) and routes as overland flow through each sub-area, followed by channel routing through all subsequent downstream sub-areas.

The combined CSS/WBNM system simulates the timing of baseflow contribution to total streamflow via the use of a baseflow recession constant applied to each sub-area. The recession constant determines the rate of discharge from the baseflow store of each sub-area reproducing baseflow at the outlet of the sub-area. Baseflow contribution is estimated individually for each sub-area. Routed sub-area overland flow and baseflow is then summed at the sub-area outlet and routed as channel flow through downstream interbasin areas as a combined flow.

3. DATA

Three catchments in Victoria were used to benchmark the original CSS and these same three data sets have been utilized for the assessment of the combined system described in this paper. The three catchments comprise the Avon River (259 km^2), Boggy Creek (108 km^2) and Spring Creek (62 km^2) and the characteristics of each are summarized in Table 1 below. Catchments were subdivided based on guidelines for minimum and maximum numbers of subareas (Boyd, 1985) following the drainage pattern of each catchment.

Table 1. Hydrological characteristics of the benchmark catchments (from Boughton et al., 2002).

Station Number	415224	403226	405261
Catchment	Avon River	Boggy Creek	Spring Creek
Gauging Station	Beazley's Bridge	Angleside	Fawcett
Catchment Area (km^2)	259	108	62
Average annual rainfall (mm)	539	1039	735
Average annual evaporation (mm)	1070	1132	1041
Average annual runoff (mm)	52	290	145

4. RESULTS

4.1. Calibration

Calibration of the combined CSS/WBNM is undertaken via a staged approach in which first the loss model (AWBM) is calibrated following a methodology developed for the original CSS. The same calibration of the loss model used in the benchmarking study (Boughton, et al., 2000) was used here. The flood hydrograph model (WBNM) was calibrated using trial and error assessment of variations in the lag parameter (k) using minimization of the sum of squared differences of observed and simulated peak flows for all events as the objective function.

Table 2 below summarises the simulated peak flows for the CSS/WBMOD and CSS/WBNM system, with comparison against both recorded peak flows as well as against each other. Using the sum of square differences of the peak flows as an objective function for assessing comparative performance, the reproduction of peak flows via the CSS/WBNM is of similar accuracy to that using CSS/WBMOD. Based on the sum of squared differences, the results for Avon River and Boggy Creek show some improvement. An important point to note however is the relative simplicity of adopting the SSD as the defining criterion for model performance. The adoption of a single objective function as the sole means for comparing model accuracy is likely to be flawed in most cases and this is apparent in the case of the Avon River results.

The apparent improvement in Avon calibration is due almost entirely to a single event (65.4 m^3/s actual peak flow) which accounts for approximately 75% of the squared difference for the CSS/WBMOD objective function. Ignoring this event, the SSD's for the WBMOD and WBNM models are 433 and 1093 respectively, indicating a significantly different outcome when comparing the performance of the two models in reproducing peak flows.

In the original benchmarking study Boughton et al. (2002) state that if the calculated values of peak flow for each catchment were ranked in order of magnitude the comparison between the sets of ranked values (i.e. simulated versus recorded) could be likened to a comparison of frequency distributions. The ranked results are included below in Table 3 for both the CSS/WBMOD system reported within the original paper and the CSS/WBNM system being discussed here. The comparison between the ranked sets of actual and simulated peak flows for the CSS/WBMOD showed an improvement over the comparison of non-ranked results (Table 2) for all three catchments. The improvement in comparison between ranked sets for the CSS/WBNM system is more marked than for the CSS/WBMOD, in particular for the Avon River.

Figures 1 to 3 below show the recorded hydrographs compared with simulated hydrographs using both the CSS/WBMOD and CSS/WBNM systems for the largest calibration event on each of the three catchments.

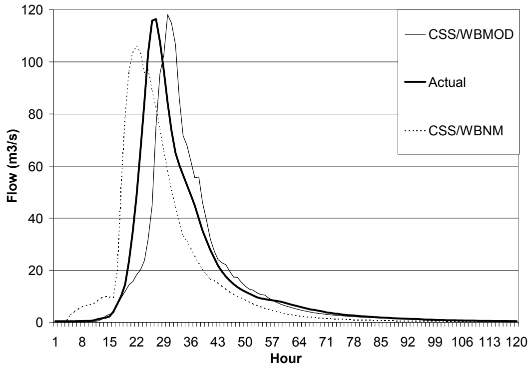

Figure 1. Avon River - Comparison of actual and modelled largest hydrograph.

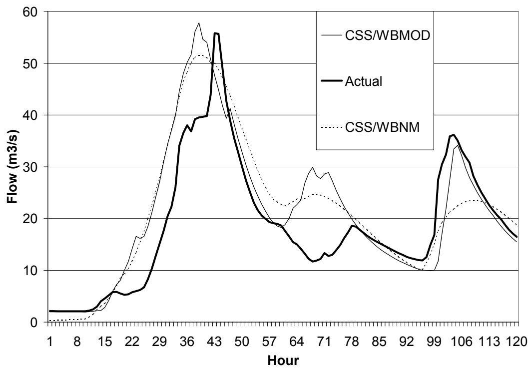

Figure 2. Boggy Creek - Comparison of actual and modelled largest hydrograph.

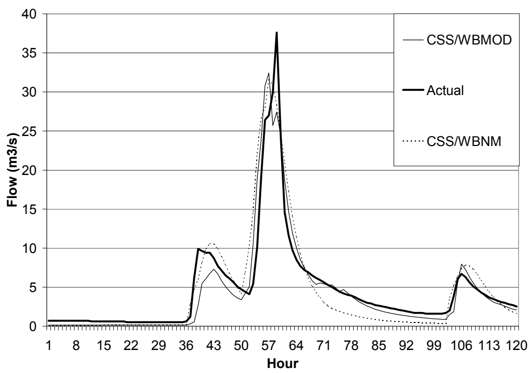

Figure 3. Spring Creek - Comparison of actual and modelled largest hydrograph.

Table 2. Calibration of flood hydrographs – Peak flows in m^3/sec.

Avon River			Boggy Creek			Spring Creek		
Obs	**WBMOD**	**WBNM**	**Obs**	**WBMOD**	**WBNM**	**Obs**	**WBMOD**	**WBNM**
116.4	118.9	106.0	55.8	59.4	51.6	37.6	32.6	31.6
110.9	111.3	116.8	33.1	38.2	33.0	25.7	22.1	18.2
92.2	84.2	66.7	24.7	23.4	17.8	22.8	26.2	21.2
65.4	102.9	92.0	23.3	38.0	33.7	22.2	19.0	17.3
63.7	64.0	54.9	14.1	20.3	17.2	20.1	10.4	10.1
59.6	56.5	52.4	8.0	2.8	2.9	19.3	16.0	21.3
49.1	67.8*	59.2	5.4	1.6	1.5	14.9	22.2	29.0
-	-	-	0.2	1.0	2.0	-	-	-
SSD	**1839**	**1732**		**337**	**227**		**218**	**421**

* The calculated peak flow for Avon River 49.1 m^3/s actual event is 67.8 m^3/s, not 56.5 m^3/s as reported in benchmarking study (Boughton et al., 2000).

Table 3. Ranked peak flows

Avon River			Boggy Creek			Spring Creek		
Obs	**WBMOD**	**WBNM**	**Obs**	**WBMOD**	**WBNM**	**Obs**	**WBMOD**	**WBNM**
116.4	118.9	116.8	55.8	59.4	51.6	37.6	32.6	31.6
110.9	111.3	106.0	33.1	38.2	33.7	25.7	26.2	29.0
92.2	102.9	92.0	24.7	38.0	33.0	22.8	22.2	21.3
65.4	84.2	66.7	23.3	23.4	17.8	22.2	22.1	21.2
63.7	67.8	59.2	14.1	20.3	17.2	20.1	19.0	18.2
59.6	64.0	54.9	8.0	2.8	2.9	19.3	16.0	17.3
49.1	56.5	52.4	5.4	1.6	2.0	14.9	10.4	10.1
SSD	**565**	**79**		**296**	**166**		**58**	**81**

4.2. Effect of BFI on Results for CSS/WBNM

An important outcome of the original CSS benchmarking study was that the methods used for calibration of a loss model for water yield study are not necessarily adequate for calibration of the same model to calculate losses for design flood estimation. Calibration of the flood hydrographs can be sensitive to changes in the BFI as shown in Table 4 below, with a change in BFI from 0.5 to 0.7 leading to an approximate halving in simulated peak flows. The range of peak flows obtained using WBNM is similar to the range of values using WBMOD in the original benchmarking study, indicating that both models are equally sensitive to errors in the calculation of losses and the split of runoff into surface runoff and baseflow.

Table 4. Comparison of Actual v. Calculated Peaks (m^3/s) for a range of values of BFI – Boggy Creek Catchment

Actual	**Value of BFI**				
	0.50	**0.55**	**0.60**	**0.65**	**0.70**
55.8	63.8	57.3	50.8	37.3	29.4
33.1	39.4	35.8	31.9	24.6	21.5
24.7	20.5	18.5	16.7	14.8	12.7
23.3	42.5	37.7	33.0	25.8	17.3
14.1	20.3	18.8	16.4	15.7	14.2
8.0	2.8	2.9	3.0	3.4	3.2
5.4	1.4	1.5	1.5	1.5	1.5
0.2	2.0	2.0	2.0	2.0	2.0

4.3. Design Flood estimate results - FFA, CSS/WBMOD, ARR[RORB], CSS/WBNM

Following calibration of the loss model and flood hydrograph model components of the system, calibration of the rainfall generation program incorporated into the CSS would normally be undertaken. In this case, the rainfall generation model has already been calibrated for the study catchments during the original benchmarking study and resultant parameters have been adopted for the purposes of this study. Table 5 summarises the comparative results of four methods of design flood estimation: the original continuous simulation system with WBMOD as the flood hydrograph model (MOD), Flood Frequency Analysis (FFA), use of ARR87 and CRC-FORGE rainfall estimates with RORB (ARR) and the combined CSS/WBNM system as described in this paper (WBN).

Results for FFA and RORB(ARR) estimation methods have been shown here for completeness sake and comparison with the CSS/WBMN is not explicitly included within this assessment. Assessment of and comparison with FFA and RORB(ARR) results (i.e. between estimation methods) has been undertaken more fully within Boughton et al. (2002).

Table 5. Design Flood Estimates from 4 Methods (values in m^3/s).

ARI (yrs)	MOD	FFA	ARR	WBN
Avon River				
100	335	172	335	290
50	275	159	266	230
20	198	137	176	166
10	145	117	119	125
5	93	92		85
2	28	46		30
Boggy Creek				
100	90	179	137	60
50	70	135	114	51
20	55	90	91	41
10	44	65	73	33
5	32	45		26
2	16	23		14
Spring Creek				
100	176		114	136
50	141		97	113
20	104	60	79	88
10	81	48	60	71
5	60	37	47	53
2	32	24	29	32

5. DISCUSSION

5.1. Comparison of Flood Hydrographs

Avon River: CSS/WBNM estimated peaks occur 8 to 11 hours earlier than the recorded peaks and also significantly earlier than those estimated by the CSS/WBMOD system. This could represent a systematic inconsistency between the timing of the hourly rainfall and streamflow data (e.g. rainfall data corresponds to 9 hours earlier than streamflow data). It may also indicate justification for a translation of the hydrograph as described in AR&R for when the shape of the hydrograph can be reproduced but not the timing.

In contrast, the characteristics of the WBMOD routing model are such that timing inconsistencies between rainfall and flow data would be overcome by the 20 hourly lag values simulating lag from various parts of the catchment. As these lag values are determined purely on the basis of matching the simulated and recorded hydrographs by maximising a numerical optimisation function, timing errors or the need for hydrograph translation would be overcome automatically.

Boggy Creek: Calibration of the CSS/WBMN lead to a relatively high lag parameter required to match peaks (k = 2.2) compared with a range of 1.3 to 1.8 quoted in Boyd et al. (2002) as being applicable to a wide range of catchments. Higher lag values tend to lead to the simulation of smoother and smaller intermediate peaks (e.g. Figure 2). Comparison with recorded hydrographs indicates that a lower lag parameter value would be required to more closely reproduce the characteristics of the entire hydrograph (most notably sharper peaks) of the recorded events.

Spring Creek: The use of the CSS/WBNM shows less accuracy in reproducing peak flows than for the CSS/WBMOD (Tables 2 & 3) on the basis of sum of squared differences, although in general results are good and of a similar order of magnitude to original results.

5.2. Comparison of design flood estimates

Direct comparison of overall design flood estimation results from the CSS/WBMOD and the combined CSS/WBNM system indicates a systematic difference in design flood estimates across the three benchmark catchments with consistently lower design flood estimates obtained using CSS/WBNM as opposed to CSS/WBMOD. Estimates for the Avon River are some 10% lower, Boggy Creek values some 35% lower and Spring Creek approximately 20% lower using WBNM as the flood hydrograph model than using WBMOD.

There was no apparent systematic difference between design flood estimates obtained using the two continuous simulation systems (CSS/WBMOD and CSS/WBNM) and either flood frequency analysis (FFA) or event based method (ARR-RORB).

6. CONCLUSIONS

For any model the method of calibration can be a significant factor in the overall accuracy of results. As indicated by results for the Boggy Creek catchment, calibration of the WBNM against recorded peak flows alone can lead to deficiencies in reproduction of hydrograph characteristics. This would tend to suggest that a more complex, or at least less focussed, calibration methodology would be required to more accurately reproduce the entire hydrograph.

Calibration results for the CSS/WBNM with calibration of a single parameter (lag k) and simulation via a more realistic routing of flows through catchment subdivision based on drainage patterns were of a similar accuracy as for the original CSS/WBMOD. The most obvious difference between systems was the timing of flows with significant differences shown up for the Avon River calibration events.

However, the overall difference between flood hydrograph models was comparatively small compared with the difference in results between loss estimation methods. The results for the CSS/WBNM were comparable although consistently lower across the three catchments than for the CSS/WBMOD, whereas significant and inconsistent differences exist between ARR(RORB) results and those of the two tested continuous systems. Comparison of results from the continuous systems with event based rainfall based method (ARR-RORB) showed no consistent relationship across the three catchments, with reasonable agreement for the Avon, lower values for Boggy Creek and higher values for Spring Creek. The results for Avon River and Boggy Creek illustrate the differences between loss estimation methods for continuous and event-based approaches, in particular the explicit simulation of baseflow and thus loss estimation during flood events. For catchments with a high baseflow component of overall flow loss estimation for current event based methods of design flood estimation have the potential to significantly underestimate losses during flood flows and so over-estimate peak flows. This is indicated by the Boggy Creek results although the effect of the high lag parameter for the calibration of the CSS/WBNM may also be a factor in the reduced peaks estimated via this method.

The results for Spring Creek require further scrutiny to provide explanation of the significant differences in design peak flows between continuous and event based approaches. Given the low baseflow component of total streamflow (Spring Creek has a BFI of some 15%) the differences in design peak flows are more likely due to differences in the rainfall input used to generate these design events, i.e. differences between the stochastically generated rainfall data utilised in the continuous systems and the Intensity-Frequency-Duration and especially the design temporal pattern information used in the ARR(RORB) methodology.

7. ACKNOWLEDGEMENTS

The authors thank Associate Professor Mike Boyd and Dr John Macintosh for their advice in the formative stages of this study and Mr Erwin Weinmann for the supply of data for Spring Creek RORB analysis.

8. REFERENCES

Boughton, W. C., Srikanthan, S. and Weinmann, P. E., Benchmarking a new design flood estimation system. *Australian Journal of Water Resources*, 6 (1), 45-52, 2002.

Boughton, W.C. and O.P. Droop, Continuous Simulation for Design Flood Estimation – a review. *Environmental Modelling and Software*, 18 (4), 309-318, 2003.

Boyd, M. J., Effect of catchment sub-division on runoff routing models. *Civil Engineering Transactions*, I.E. Aust CE27(4), 403-410. 1985.

Boyd, M. J., E.H. Rigby, R. VanDrie, and I. Schymitzek, WBNM 2002: Details of the theory used in WBNM. University of Wollongong, 38, 2002.

Carroll, D., URBS: The BCC catchment management runoff routing model - Version 3.3, Design Branch, Department of Works, Brisbane City Council, 1994.

Institution of Engineers, Australia, *Australian Rainfall and Runoff,* Institution of Engineers, Australia, 1987.

Laurenson, E. M. and R.G. Mein, RORB - Version 4 Runoff Routing Program User Manual, Monash University Department of Civil Engineering, 1997.