Chapter 8

WBNM2000 FOR FLOOD STUDIES ON NATURAL AND URBAN CATCHMENTS

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ABSTRACT

WBNM2000 is a comprehensive flood hydrograph model for natural, urban and part-urban catchments. It calculates recorded storms, and has built-in design storm and probable maximum precipitation storm procedures. It calculates separate hydrographs from the pervious and impervious surfaces in an urban catchment, and allows any combination of these to be sent to a flood detention storage. The flood detention storage has built-in culvert and weir hydraulics procedures which calculate the elevation-discharge relation for the specified outlet type and size. When a storage has multiple outlets, the outflow through each can be directed to a nominated downstream point. Diversion of surcharging flows, when the capacity of the channel or culvert is exceeded, can be directed to nominated downstream points.

WBNM2000 comes with a suite of programs, including full documentation, sample runfiles, a front end file creation editor, and graphics and plotting routines.

8.1. INTRODUCTION

8.1.1. History of the Model

The Watershed Bounded Network Model WBNM arose out of research into the allocation of lag times to the various subcatchments which are contained within the complete catchment, with the objective of developing a geophysically realistic, spatially varying flood hydrograph model. A computer program for the model was published by Boyd, Pilgrim and Cordery (1979a,b) and, it is interesting to note, consisted of just 191 lines of Fortran code. This program took a rainfall hyetograph, subtracted an initial loss and continuing loss rate, and calculated the flood hydrograph for a natural catchment.

While this model had very limited functionality, the core algorithms were found to give consistently good results, and still form the basis for hydrograph calculations in WBNM2000. Continuing development led to major revisions in 1987 [Boyd, Bates, Pilgrim and Cordery, 1987], 1994 [Boyd, Rigby and Van Drie, 1996] and 1999 [Rigby, Boyd and Van Drie, 1999]. With each revision, more features were added, so that WBNM2000 is now a very versatile and comprehensive model for flood studies on natural, urban and part-urban catchments.

WBNM is an event model, taking a rainfall hyetograph and calculating the resulting flood hydrograph. It is not a continuous model, rather it concentrates on detailed modelling of the flood process.

The model uses runoff routing, or hydrologic routing procedures to calculate flood hydrographs. Spatial variations in rainfall, rainfall losses, and land use are handled by dividing the catchment into a set of smaller subcatchments. This also allows hydrographs to be calculated at various points within the catchment, and allows for engineering structures, such as storage reservoirs, to be placed at various points within the catchment.

8.1.2. Current Philosophy of the Model

Whereas the original model concentrated on modelling the flood response of natural catchments, in later versions there has been a considerable shift of emphasis so that WBNM2000 is now a comprehensive tool for engineering flood studies. It is applicable to natural and urban catchments with a variety of hydraulic structures and

and consequently all runoff from the subcatchment flows to its outlet. Hydrographs formed at the outlet of all subcatchments are added consecutively in moving down the catchment to its outlet, with flood routing occurring on the catchment surface and within the stream channel at every stage.

Geomorphological similarity in catchments has been observed by many workers, starting with Horton (1932, 1945), and also by Strahler (1964), and Leopold et al. (1964). The relations apply both to complete catchments, and to subcatchments within the larger catchment, as long as the division is based on the stream network and surface contours. This similarity can be expressed in terms of stream order laws between the subcatchments of a larger catchment, and in terms of power relations between the various physical properties of different catchments. These approaches are consistent with one another and in fact the power laws can be derived from the stream order laws. The power laws are typically between stream length and catchment area, and between catchment slope and either stream length or catchment area (Fig. 8.2)

Based on 47 natural catchments, Gray(1961) derived the following relations, which are similar to other published results [Hack, 1957; Mueller, 1973]:

$$L = 1.30.\ A^{0.57} \qquad r^2 = 0.915 \qquad (8.1)$$

$$S = 20.7.\ L^{-0.66} \qquad r^2 = 0.923 \qquad (8.2)$$

$$S = 15.9.\ A^{-0.38} \qquad r^2 = 0.858 \qquad (8.3)$$

where A is catchment area (km^2), L is main stream length (km) and S is equal area main stream slope (m/km). Whereas the relation between L and A applies over the complete range of catchments, the relations involving S have similar powers but different coefficients for different regions.

quite complex flow paths. Considerable effort has gone into adding features which allow engineers to quantify flooding problems, using the program to handle a great many of the calculations necessary for a flood study, and providing good records of results for quality assurance purposes.

When a flood study is being carried out, many options will be considered. For example, should a flood detention basin be placed at location A or at location B, should the stream channel be modified at location C, should onsite detention be provided at location D ? It is very desirable that these features be able to be added or deleted easily, without requiring a major restructuring of the model. With this in mind, WBNM2000 uses a modular format. Every subcatchment within the total catchment can contain pervious and impervious surfaces, onsite detention storage, mainstream detention basin storage, and a stream channel, all of which can be easily switched on or off. It is also a simple matter to add or delete the subcatchments themselves if this becomes necessary, without restructuring the model.

During large floods, the normal pattern of flow paths in streams and channels will often be replaced by overflow paths, with the diverted flow going to adjacent streams or even being diverted out of the catchment. It is also possible that flow from an adjacent catchment can be diverted into the catchment. WBNM2000 allows considerable flexibility for the user to model these diversion flow paths.

In engineering flood studies, record keeping is essential for quality assurance. WBNM writes detailed results of all calculations to an output file. This file contains a record of the date, user name and organisation, and includes the rainfall hyetographs and runoff hydrographs for flows from pervious and impervious surfaces, flows into and out of detention storages, and diverted flows. These are kept for every subcatchment.

WBNM2000 has been developed to transfer research carried out by the authors and other workers to the engineering profession, and for this reason it is provided free of charge.

8.2. HYDROLOGICAL ASPECTS

8.2.1. Overview

This section covers calculation of the flood hydrograph resulting from a storm rainfall. This requires subtraction of rainfall losses to obtain an excess rainfall hyetograph, and the selection of an appropriate lag time to transform the excess rainfall into the runoff hydrograph.

To model spatial variability of land use and spatial variability of rainfall, and to provide hydrographs at various points within the catchment, the catchment is divided into smaller subcatchments. These are selected as geomorphologically similar units of the main catchment, and consequently the same lag relation can be used for each subcatchment as for the main catchment itself. This leads to internal consistency in the model, and allows considerable flexibility in deciding on the actual division into subcatchments.

8.3. NATURAL CATCHMENTS

8.3.1. Catchment geomorphology and hydrology

A catchment is modelled by dividing it into smaller subatchments. This division is based on the stream network and the surface contours. Each subcatchment is bounded by its ridge line or watershed divide (Fig. 8.1),

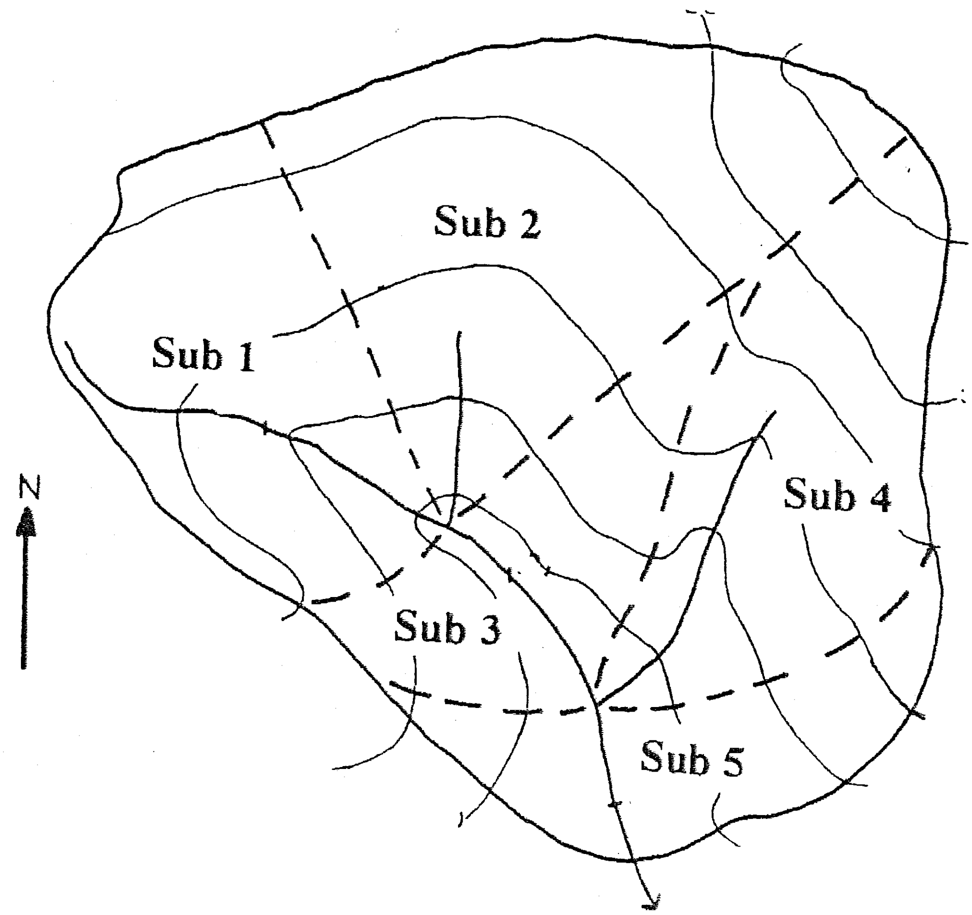


Fig. 8.1. Division of catchment into subcatchments for modelling.

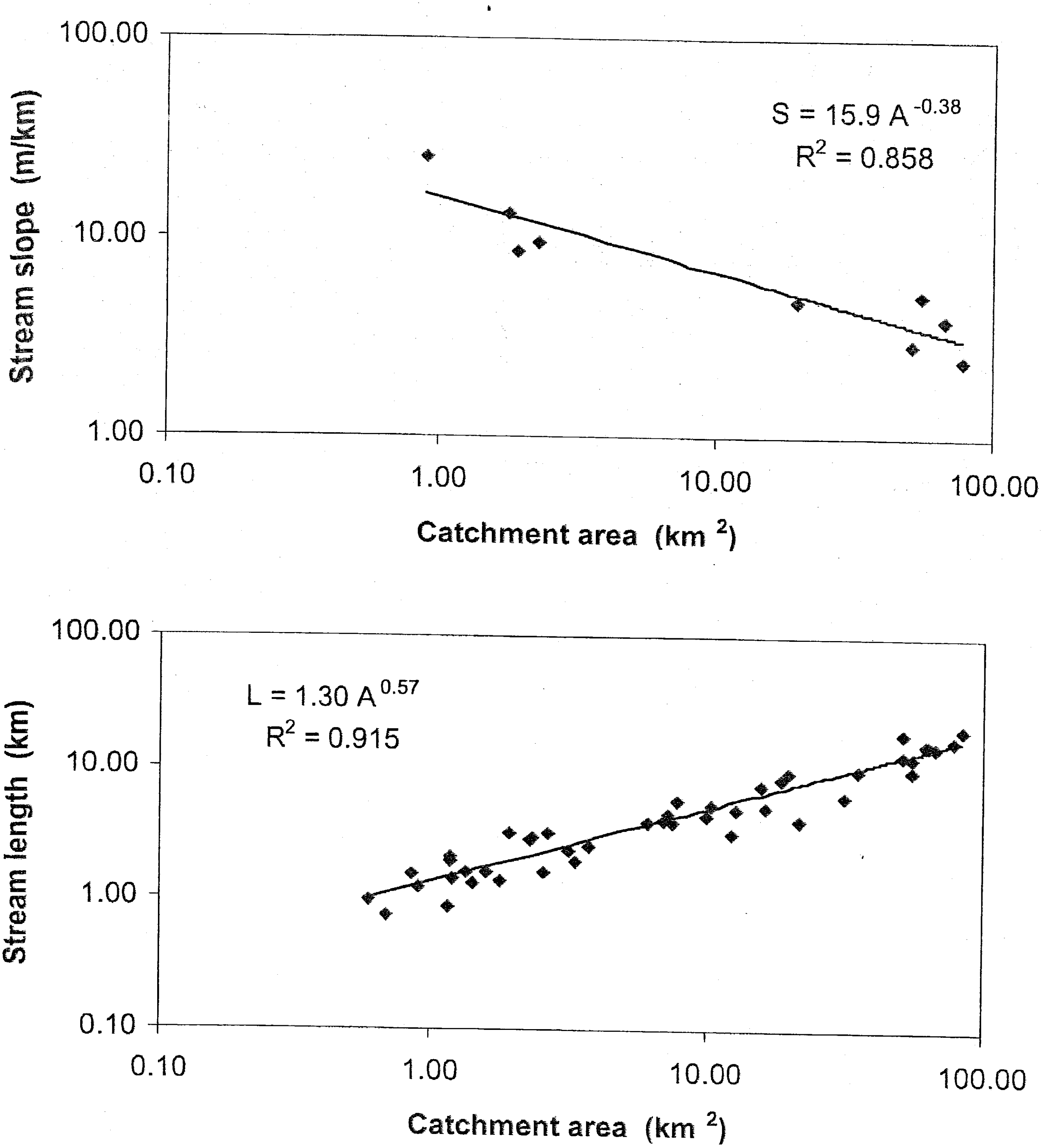


Fig. 8.2. Relations between catchment physical properties (after Gray, 1961).

8.3.2. Lag relations for natural catchments

Since geomorphological similarity exists between catchments, it is not surprising that hydrological similarity also exists [Boyd, 1978; Rodriguez-Iturbe and Valdez, 1979; Gupta et al, 1980]. This hydrological similarity can be expressed as relations between the lag time and stream order, and between lag time and catchment properties (Fig. 8.3).

Lag time is here defined as the time between centroids of an excess rainfall hyetograph and the resulting flood hydrograph. Lag time can be viewed as an average travel time for runoff from all parts of the catchment surface to reach the outlet. Lag time can be related to various physical characteristics, but the most significant relation is with catchment area. For 10 catchments in NSW Australia [Boyd, 1978]:

$$Lag = 2.52.\,A^{0.38} \qquad r^2 = 0.941 \qquad (8.4)$$

$$Lag = 4.09.\,A^{0.33}.\,S^{-0.14} \qquad r^2 = 0.965 \qquad (8.5)$$

where Lag is in hours, A in km^2 and equal area stream slope in m/km.

Table 8.1 contains several published relations for lag time. Some include slope, while others do not. Stream lengths L and L_c are closely

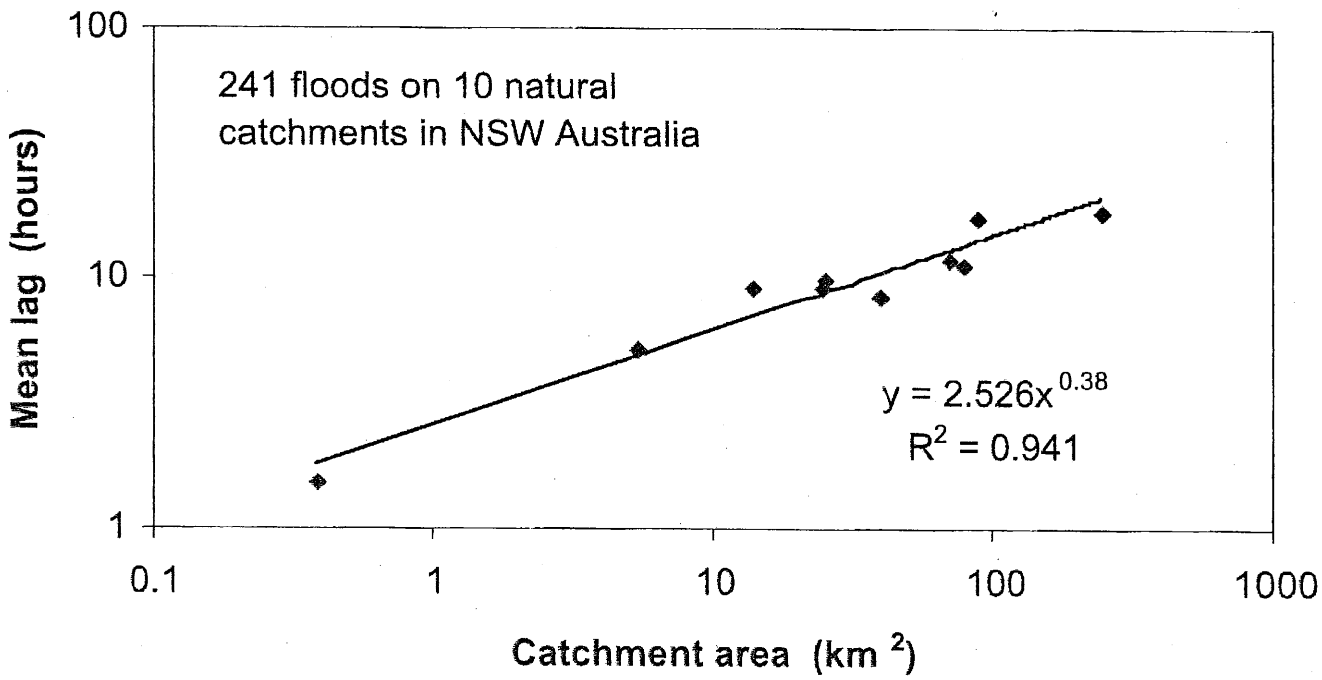


Fig. 8.3. Relation between lag time and catchment area.

related to A (Eq. (8.1)) and those equations could be re-written in terms of A. Catchment area A contains most of the information needed to determine the lag time, with only minor improvement in r^2 when S is included. It is likely that, within a geographical region, the inter-relation between S and A allows reasonable estimates of lag time from A alone.

Table 8.1. Lag relations for natural catchments.

Reference	Number of catchments	Catchment size (Hectare)	Lag relation
Linsley et al (Snyder)			$L^{0.3}\ L_c^{0.3}$
Linsley et al (USCE)			$L^{0.38}\ L_c^{0.38}\ S^{-0.19}$
Present study	10	40-25000	$A^{0.38}$
Present study	10	40-25000	$A^{0.33}\ S^{-0.14}$
Nash(1960)	31	1240-223000	$A^{0.3}\ OLS^{-0.3}$
Askew(1970)	5	40-9000	$A^{0.57}\ Q^{-0.23}$
Cordery & Webb(1974)	33	5-64200	$L^{0.57}$
Cordery et al(1981)	52	5-1500000	$L^{0.57}$

8.3.3. Incorporating Lag Relations into WBNM

In WBNM each subcatchment of the main catchment is represented by a storage routing element. The equations for the element are:

Continuity $$I - Q = dS / dt \qquad (8.6)$$

Storage discharge relation $$S = 3600\, K.\, Q \qquad (8.7)$$

where I = inflow to subcatchment (m^3/s), Q = outflow from subcatchment (m^3/s), S = volume of water stored on catchment surface (m^3), and K = lag time between excess rainfall and flood runoff for the subcatchment (hours). I can be inflow in the form of runoff from upstream subcatchments, or from excess rainfall P (mm/hour), where I = P.A / 3.6.

Equations 8.6 and 8.7 can be combined and solved numerically:

$$Q_{i+1} = \frac{Q_i.(2K - \Delta t) + (I_i + I_{i+1}).\Delta t}{2K + \Delta t} \qquad (8.8)$$

When several subcatchments are connected in a branched network, the lag time for the resulting hydrograph can be calculated by considering the appropriate first moments (Nash, 1960). Considering the simple catchment in Fig. 8.1,

$$Lag = \frac{V_1(K_1 + K_3 + K_5) + V_2(K_2 + K_3 + K_5) + V_3(K_3 + K_5) + V_4(K_4 + K_5) + V_5 K_5}{V_1 + V_2 + V_3 + V_4 + V_5} \tag{8.9}$$

where V is the runoff volume from the subcatchment.

Equation (8.9) indicates an important consequence of defining subcatchments to be hydrologically similar and allocating the lag time to each subcatchment depending on its size. This is that the number of subcatchments into which the total catchment is divided is not crucial. Division of the catchment into many small subcatchments, each with a small lag time, will produce a similar total lag time as dividing the catchment into fewer, larger subcatchments, each with a larger lag time. As long as the power of A in the adopted lag relation is near to 0.5, similar results will occur for a wide range of divisions (Boyd, 1985).

Each subcatchment of the main catchment will have its own lag time K. WBNM is flexible and allows the user to allocate any lag time to any subcatchment. However, it is more efficient to make use of the catchment geomporphologic and hydrologic relations, and allocate the lag times using an equation such as those in Table 8.1.

To complete this discussion of lag allocation in the model, two additional features must be considered.

In Fig. 8.1, each of the 5 subcatchments receives excess rainfall and transforms it to a flood hydrograph at the subcatchment outlet. The flow path consists of a combination of overland flow and flow in small and large stream channels as it makes its way to the subcatchment outlet. Subcatchments 3, and 5 however, as well as transforming local rainfall into runoff, transmit runoff from the upstream subcatchments through them. This upstream runoff is restricted to the main stream channel, and could be expected to have faster flow velocities and therefore shorter travel or lag times compared to the overland flow. WBNM is flexible and has several options for flood routing through stream channels (section 8.5.2). The simplest approach is to adopt the same lag relation for transforming rainfall to runoff, but modify it for the smaller lag times in the stream channel. Boyd et al (1979b) calculated the ratio of lag times for transmission in stream channels to transformation of rainfall to runoff. For 10 natural catchments, this was found to be 0.60, and this is adopted as a default value in the model.

The second feature, is to introduce nonlinearity into the model. If the lag time remains constant for all size floods on a catchment, the catchment response is said to be linear and superposition applies. However, many researchers consider that catchments respond nonlinearly during flood events. This is supported by hydraulic relations such as Manning's equation and the kinematic wave equation for overland flow [Ragan and Duru, 1972], which show that flow velocities increase as the flowrate increases. Consequently, we would expect lag times to decrease as flowrates increase. Nonlinear lag relations involving the flowrate Q include those of Askew (1970) and Aitken (1975). Other nonlinear lag relations are based on the rainfall intensity [Rao et al, 1972; Desbordes (1978)]. The relations using Q are more convenient for modelling because they allow for continually varying flow velocities and hence lag times at all stages of the flood. Figure 8.4 shows lag times and flood discharges for a natural catchment.

When results from several catchments are combined, the lag time can be related to the subcatchment area A and the instantaneous flood discharge Q. The equations adopted in WBNM2000 are based on those of Askew (1970):

Transformation of excess rainfall to runoff

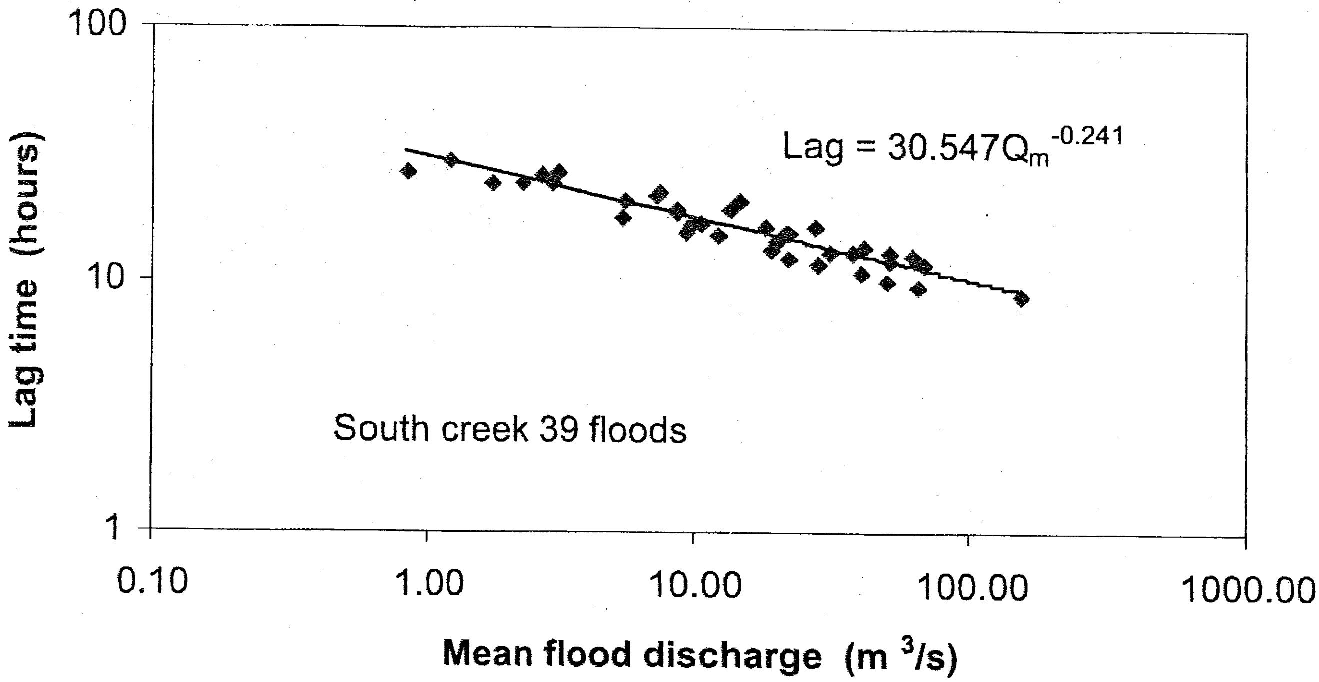
$$K = LagParam.\, A^{0.57}.\, Q^{-0.23} \tag{8.10}$$

Transmission of upstream runoff through stream channel

$$K = 0.6\, LagParam.\, A^{0.57}.\, Q^{-0.23} \tag{8.11}$$

where A is km^2, Q m^3/s, K hours and LagParam is a fitting parameter for the model.

Equations (8.10) and (8.11) are built into the model, and together with Eq. (8.8) used to calculate runoff hydrographs in WBNM. An iterative solution is required, with K_{i+1} and Q_{i+1} adjusted at each time step until convergence.



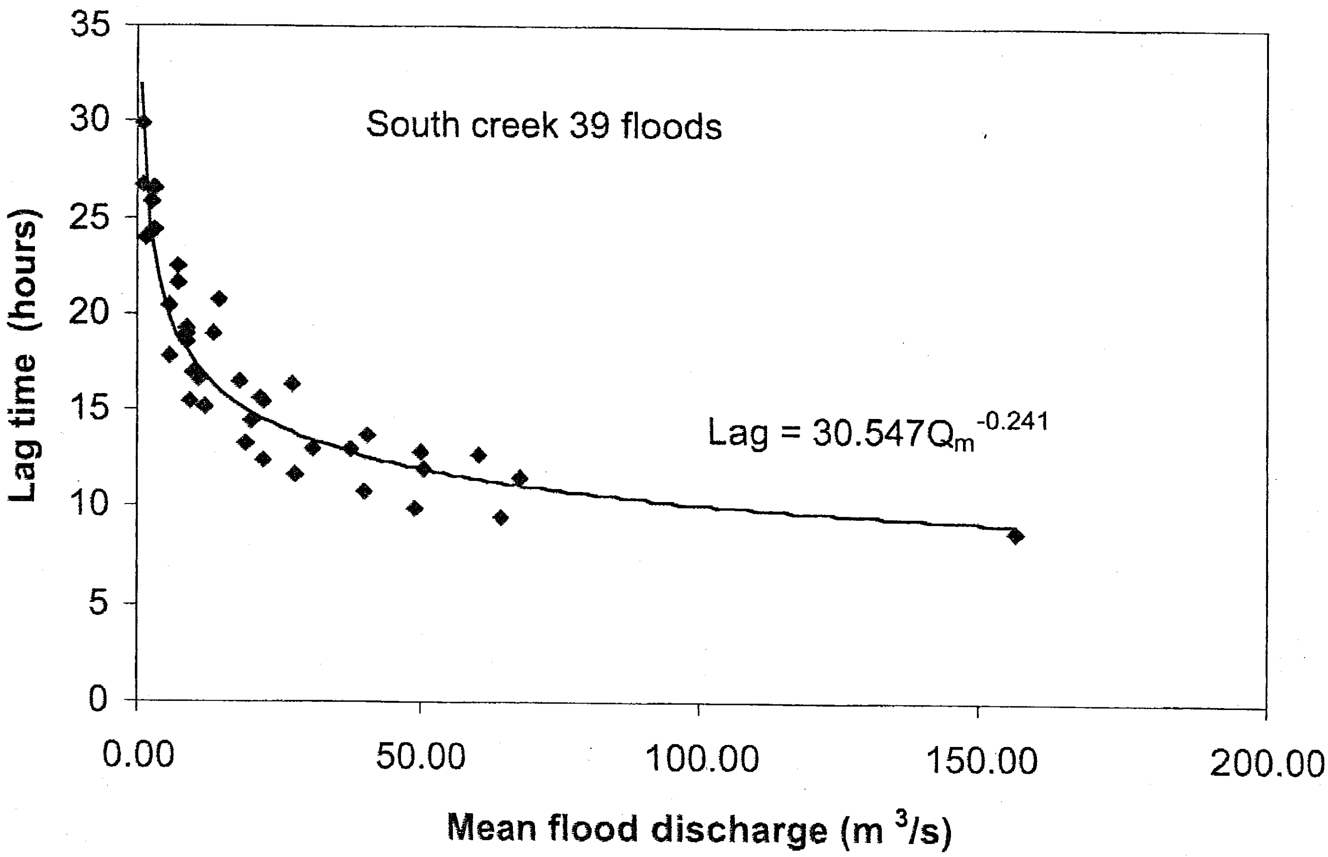


Fig. 8.4. Variation of lag time with flood discharge (after Askew, 1970).

It should be noted that there are differences of opinion regarding nonlinearity of flood response. Figure 8.4 shows that, although a power relation fits the data, when plotted on a linear scale the lag could be interpreted as approaching a constant value, and thus linearity at high flowrates. Additionally, as overbank floodplain flow commences, Manning's roughness increases significantly, leading to reduced and possibly constant velocities [Wong and Laurenson, 1983; Bates and Pilgrim, 1986].

The use of Eqs. (8.10) and (8.11) in WBNM greatly simplifies the model, since the only information needed is the number and size of the subcatchments. There is only one parameter (LagParam) to be evaluated. While this procedure makes WBNM very easy to apply, we recognise that there may be special cases in which these features may need to be varied. WBNM optionally allows the user to change the lag time of any subcatchment, to change the degree of nonlinearity, and even allows a switch from nonlinear to linear flood response as the channel breaks its banks and floodplain flow commences.

8.3.4. Rainfall and rainfall losses

Up to 15 rain gauges can be used in WBNM. Two approaches are available to select the rainfall for each subcatchment. In the first method, specified Thiessen weights are used to select the appropriate rainfall hyetograph. This can be the nearest rain gauge, weighted up or down as necessary, or it can be a Thiessen weighted average of several gauges.

In the second approach, the coordinates of all rain gauges and the coordinates of the centres of all subcatchments can be specified. WBNM will then locate the nearest rain gauge for each subcatchment, adopt its rainfall hyetograph, and weight it up or down according to the total rainfall depth recorded at all surrounding gauges. This weighting is done using the inverse squares of the distances of the rain gauges from the subcatchment centre. This procedure is convenient as rain gauges can be easily added or subtracted without having to specify new Thiessen weights.

Four options are available to simulate rainfall losses:

- Initial loss-continuing loss rate
- Initial loss-runoff proportion
- Horton time varying infiltration rate
- Time varying losses, as specified by the user

8.3.5. Applying WBNM to natural catchments

With built-in relations for allocating lag time to each subcatchment, and for specifying the nonlinearity, WBNM requires only one parameter to apply it to natural catchments. LagParam controls the magnitude of the lag time calculated for each subcatchment. Because Eqs. (8.10) and (8.11) incorporate both A and Q, a single value of LagParam should apply across a wide range of catchment sizes, and also across a wide range of event sizes. Figure 8.5 shows values of LagParam determined by fitting calculated and recorded flood hydrographs in NSW Australia. Although there is some scatter about the central line, there is no trend for LagParam to increase or decrease as the catchment size increases. Similarly, there is no trend when LagParam is plotted against flood size (Fig. 8.6). This indicates that Eqs. (8.10) and (8.11) are fundamentally sound.

Values of LagParam mostly lie in the range 1.0 to 2.0. An earlier study of 10 natural catchments [Boyd et al, 1979 a,b] gave a value of LagParam near to 1.7. Later studies of 33 natural catchments have found that a value of near to 1.3 gives good results across this wider range of catchments. It is recommended however, that whenever recorded rainfall and streamflow data are available, these should be used to check the model calibration.

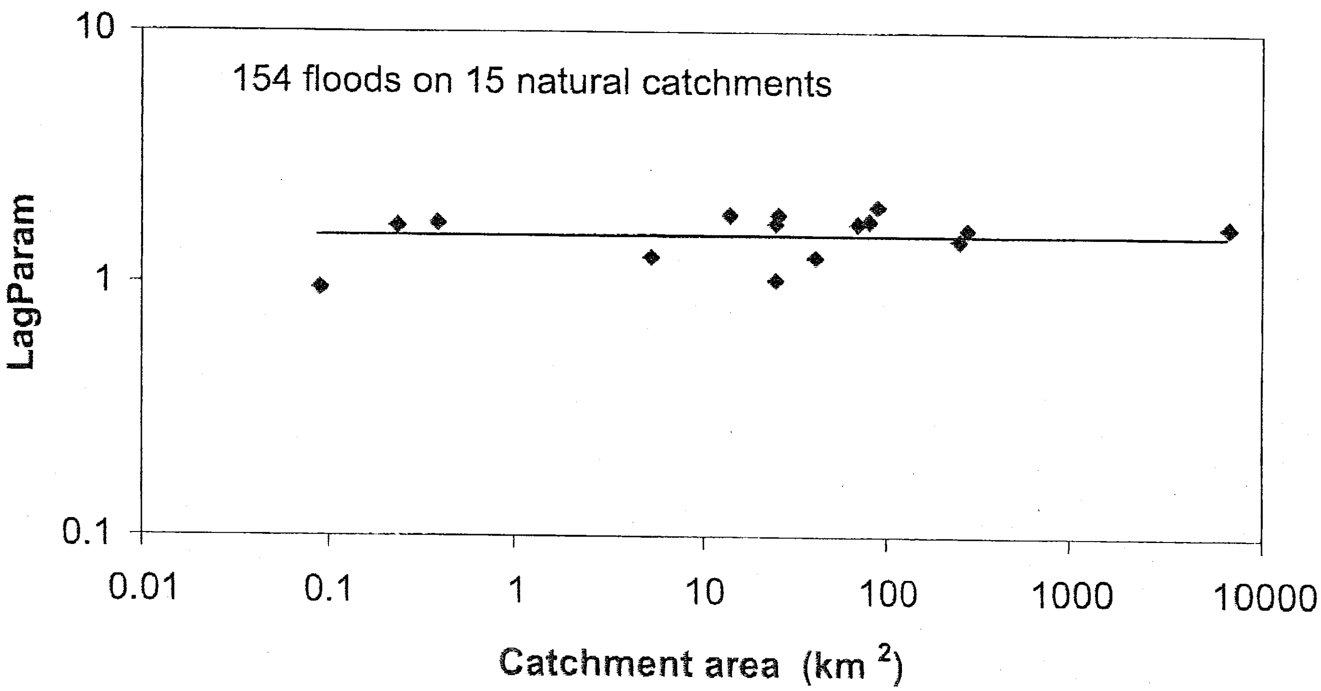


Fig. 8.5. LagParam versus catchment size.

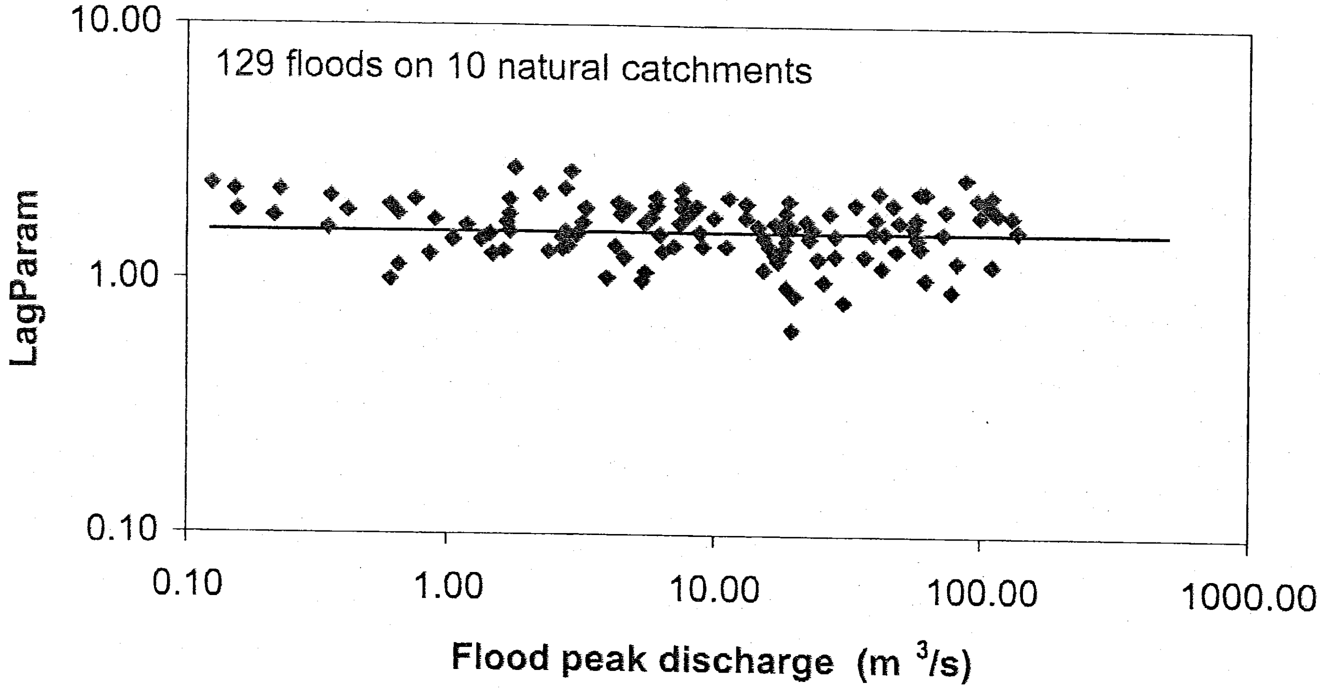


Fig. 8.6. LagParam versus flood size.

8.4. URBAN AND PART-URBAN CATCHMENTS

8.4.1. Rainfall and runoff in urban catchments

It is accepted that as a catchment becomes urbanized, flood discharges increase. The first factor causing this is the increased runoff volume from the impervious paved surfaces. The second factor is the increased flow velocities on paved surfaces, gutters, pipes and lined channels, leading to reduced lag times and so to increased flood peaks.

The urban or part urban catchment consists of pervious and impervious surfaces, each of which may generate runoff. Figure 8.7 shows rainfall and runoff depths from two urban catchments in Australia. Maroubra is 0.57 km^2 , fully urbanized (URB = 1.0) with medium density residential and commercial land use, and 52% impervious surfaces. The soil is highly permeable sand. For this catchment runoff comes almost entirely from the impervious surfaces except in very large storms. Only part of the impervious surfaces are directly connected to the stormwater drainage system, so the effective impervious fraction, given by the slope of the line in Fig. 8.7a, is 0.16.

Curtin is 27.0 km^2, 57% urbanized (URB = 0.57) low density residential, with natural parklands making up the remainder of the

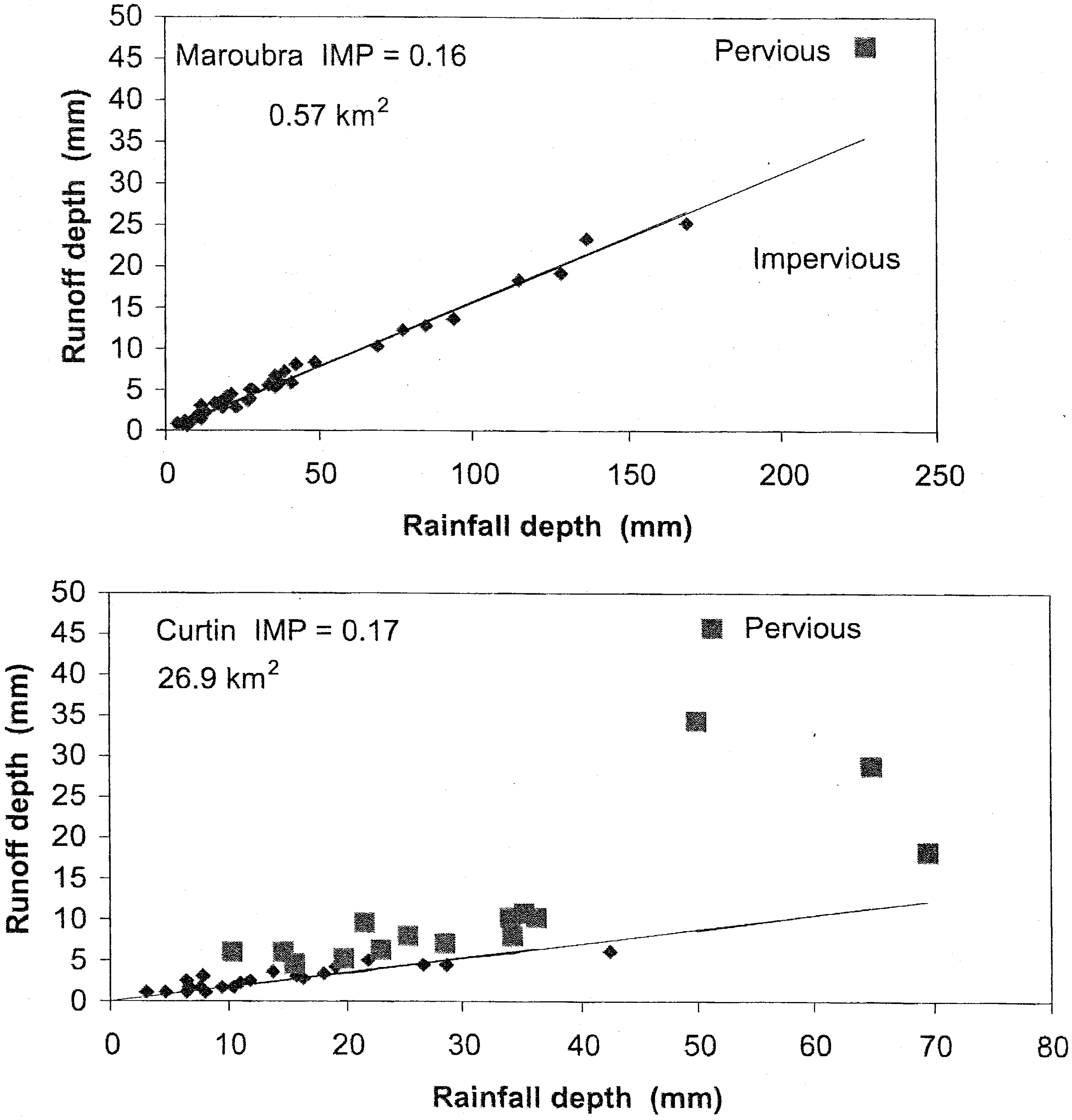


Fig. 8.7. Rainfall and runoff depths on urban catchments.

catchment. From the line fitted through the lower points, the effective impervious fraction is 0.17. On the Curtin catchment, runoff is generated just on the impervious surfaces for smaller storms when the antecedent wetness is low. For large storms, exceeding 40 mm, significant amounts of runoff are generated on pervious as well as impervious surfaces. For rainfall depths between 10 and 40 mm, the points lie just above the limiting line, indicating small amounts of runoff from pervious surfaces. The antecedent wetness for these events has been shown to be higher than for the points on the line, supporting the concept that they consist of both pervious and impervious runoff [Boyd et al, 1993a].

The effective impervious fraction is a lower limiting value, indicating the impervious surfaces which contribute runoff even for small storms. For larger storms, runoff may come from additional impervious surfaces which are not directly connected to the drainage system, and from pervious surfaces. The effective impervious fraction IMP determined from rainfall and runoff plots is less than the urban fraction URB since the latter contains grassed areas and parks as well as impervious surfaces. Figure 8.8 shows results for 38 catchments in 13 countries obtained by Boyd et al (1993b). Fully urbanized catchments (URB = 1.0) show a range of IMP values, but the average of IMP = 0.37 fits well with the data for part-urban catchments. It is also worth noting that the effective impervious fraction obtained by plotting rainfall and runoff depths is less than the impervious fraction estimated from maps. On average:

$$\text{Effective IMP} = 0.37\ \text{URB} \tag{8.12}$$

$$\text{Effective IMP} = 0.75\ \text{Map IMP} \tag{8.13}$$

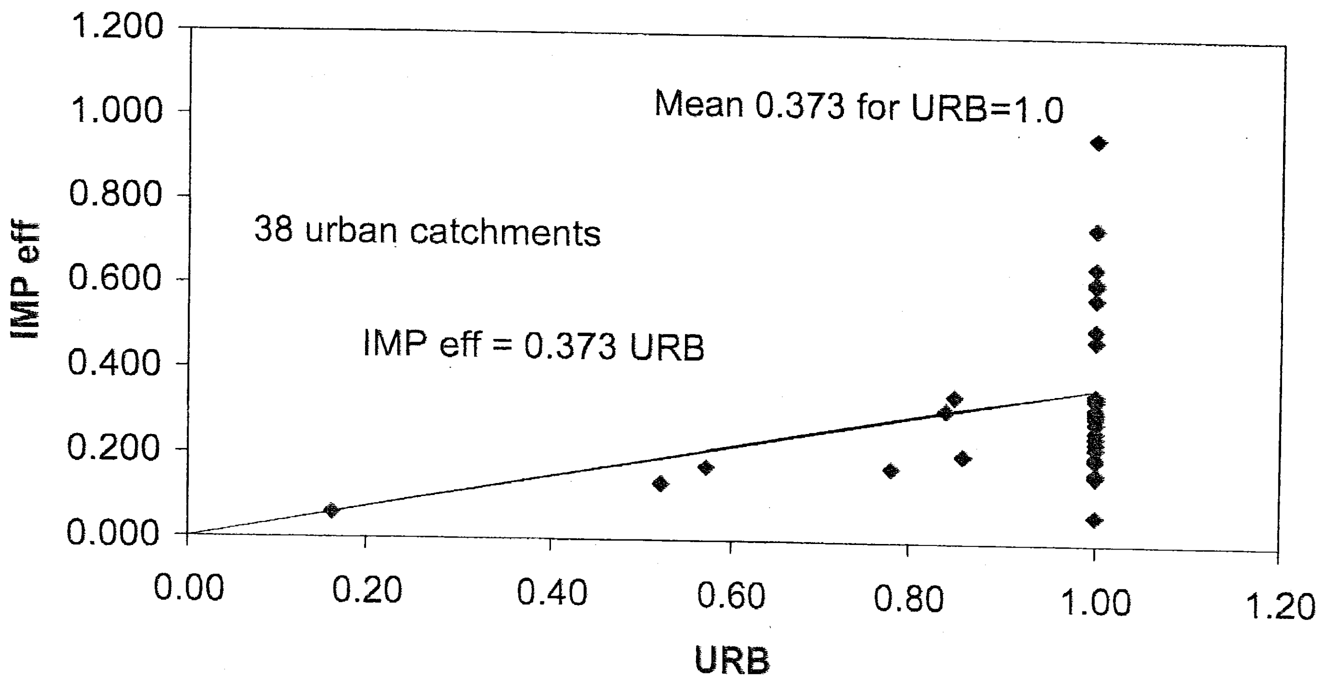


Fig. 8.8. Effective impervious fraction for urban and part-urban catchments.

8.4.2. Approaches to Modelling Urban Catchments

There are various approaches to modelling urban or part urban catchments. The detailed system of gutters, inlets and pipes can be considered, as in models such as MOUSE and SWMM-EXTRAN. Alternatively, the modelling can be broader, looking at the effects with a catchment wide perspective. WBNM uses the broader catchment approach. This is satisfactory if flood hydrographs are only needed at key points, such as the outlet of each subcatchment and the outlet of the catchment as a whole. This approach avoids the need for detailed information on the drainage system, which is very often not available.

Some approaches calculate a single hydrograph from the subcatchment, consisting of combined runoff from the urban and non-urban portions. In this approach a rainfall loss, which is the weighted average of the urban and non-urban losses, is subtracted to obtain an excess rainfall hyetograph which is then routed through storage using a reduced lag parameter. The lag parameter is an average of lag times for runoff from the urban and non-urban parts. An alternative approach is to calculate separate hydrographs from the urban and non-urban portions of the catchment. This is useful if the hydrographs are to be treated separately. For example, runoff from the urban part may have a different pollutant load compared to runoff from the non-urban part. Another case is when the urban runoff is to be directed to a flood detention basin, with the non-urban runoff bypassing the basin.

WBNM can calculate either a single combined hydrograph, or separate hydrographs from the urban and non-urban parts of the subcatchment, as the user chooses.

8.4.3. Lag Relations for Urban Catchments

Table 8.2 shows lag relations for urban and part urban catchments. (P=rainfall depth in storm; D=storm duration; RSMD=residual soil moisture deficit; ϕ=channel improvement factor).

Table 8.2. Lag relations for urban catchments.

Reference	Number catchments	Catchment size (ha)	URB range	IMP range	Lag relation
Aitken(1975)	6	80-5600	0.25-1.0		$A^{0.52}S^{-0.50}(1+URB)^{-1.97}Q^{-0.28}$
Aitken(1975)	11	40-9000	0.0-1.0		$A^{0.44}S^{-0.31}(1+URB)^{-2.74}Q^{-0.28}$
NERC(1975)	138	4-61700	0.0-0.84		$L^{0.14}S^{-0.38}(1+URB)^{-1.99}RSMD^{-0.40}$
Rao(1972)	13	12-5000	0.0-0.38		$A^{0.46}(1+IMP)^{-1.66}P^{-0.27}D^{0.37}$
Desbordes (1978)	21	0.4-5000	0.15-1.0		$A^{0.18}L^{0.15}S^{-0.36}(1+IMP)^{-1.9}P^{-0.07}D^{0.21}$
Schaake(1967)	19	0.09-62		0.09-1.0	$L^{0.24}S^{-0.16}IMP^{-0.26}$
Espey(1977)	41	0.04-39		0.02-1.0	$L^{0.23}S^{-0.25}IMP^{-0.18}\phi^{1.57}$

Unfortunately some of the the studies use different measures of urbanization. Aitken (1975) and NERC (1975) use the urban fraction URB, which includes grassed areas and urban parks. It is not clear whether Rao et al (1972) and Desbordes (1978) used URB or the impervious fraction IMP, since the papers refer to both impervious areas and built up areas. These four studies were for combined pervious and impervious runoff in a single hydrograph. On average, the reduction factor for these studies is:

$$\text{Urban Lag} = \text{Natural Lag.}\ (1+URB)^{-2} \qquad (8.14)$$

Equation (8.14) implies that in fully urban catchment lag times of combined runoff hydrographs are reduced to 0.25 of similar natural catchment values. This is not dissimilar to the results of Carter (1961) for 24 catchments, with a lag ratio 0.17.

Schaake et al (1967) and Espey et al (1977) used IMP rather than 1+ IMP. To calculate the ratio of urban to natural lag time, they adopted a nominal value of IMP=0.05 for the natural catchments. These equations predict a ratio between 0.46 and 0.58 for fully impervious lag time relative to natural catchment lag time. These ratios are higher than the previous studies in Table 8.2. The catchments of Schaake et al (1967) were all small, in most cases fully paved parking lots, and therefore the results apply more to overland flow than to total catchment flows, which include gutter, pipe and lined channels. It may be that urban lag ratios for total catchments, including these gutter, pipe and channel flows, are less than those for impervious overland flow alone. This would support the observation of Carter (1961) and Sauer et al (1983) that changes to the drainage system in urban catchments are more effective in reducing lag times than changes to the amount of impervious surfaces.

8.4.4. Combined Modelling of Pervious and Impervious Runoff

WBNM can model combined urban and non-urban runoff. For each subcatchment, a weighted average rainfall loss is calculated for the two portions, where the weighting depends on the relative area of each type. The LagParam value in section 8.3.5 is adjusted by a lag reduction factor from Eq. (8.14), depending on the urban fraction URB of the subcatchment. A single hydrograph is then calculated at the outlet of each subcatchment.

8.4.5. Separate Modelling of Pervious and Impervious Runoff

As discussed previously, there are some benefits from calculating separate hydrographs from the urban and non-urban parts of the subcatchment. If the urban fraction URB is specified, WBNM2000 splits the subcatchment into two parts. The urban part has reduced rainfall losses appropriate to the increased amount of impervious surfaces and a reduced lag parameter. From Eq. (8.14), the value of LagParam on this part is reduced in the ratio 0.25. The non-urban part of the subcatchment retains the normal value of LagParam from section 8.3.5. The urban and non-urban hydrographs are calculated separately and added at the subcatchment outlet.

Table 8.3 shows flood peak discharges calculated for a 1 in 10 year, 30 minute storm on a 10 hectare subcatchment, adopting various values of URB, and calculating the lag ratio from Eq. (8.14). To allow comparison, the discharges are expressed as a ratio of the natural catchment value (URB = 0). There is an agreeable consistency between discharges when modelled as a combined hydrograph (section 8.4.4) column 3, and the summed separate urban and non-urban hydrographs (section 8.4.5) column 8.

Table 8.3. Variation of flood peak discharge with urbanization – combined and separate modelling.

URB	Combined		Separate				
			Non-urban		Urban		Sum
	Lag ratio	Flood peak	Lag ratio	Flood peak	Lag ratio	Flood peak	Flood peak
1.0	0.250	**2.67**	1.0	0.00	0.25	2.67	**2.67**
0.9	0.277	**2.56**	1.0	0.20	0.25	2.43	**2.63**
0.75	0.326	**2.38**	1.0	0.39	0.25	2.07	**2.45**
0.5	0.444	**1.99**	1.0	0.63	0.25	1.43	**2.06**
0.25	0.640	**1.51**	1.0	0.83	0.25	0.75	**1.58**
0.1	0.826	**1.20**	1.0	0.93	0.25	0.31	**1.24**
0	1.0	**1.00**	1.0	1.00	0.25	0.00	**1.00**

By taking a broad catchment approach, WBNM is easy to apply to urban or part urban catchments. Note that the urbanization factor URB in equation 14 includes an allowance for the reduced travel times for flow in gutters, pipes and channels. As for natural catchments, these lag parameters are default values and calibration to recorded rainfall and runoff data is recommended whenever possible.

8.5. HYDRAULIC STRUCTURES

8.5.1. Overview

WBNM2000 has a modular structure, in which every subcatchment contains pervious and impervious surfaces, a stream channel to carry runoff from upstream subcatchments, an onsite detention storage for local runoff from the subcatchment, and a mainstream flood detention storage at the outlet of the subcatchment. Each of these components can be switched on or off, as needed. This modular structure is very convenient when various alternatives are being considered in a flood study, since the components can be easily added or deleted, without re-structuring the model.

8.5.2. Stream Channels

Stream channels carry runoff from upstream subcatchments through the main stream of the subcatchment being considered. In Fig. 8.1 for example, the stream channel in subcatchment 3 carries runoff from subcatchments 1 and 2, while the stream in subcatchment 5 carries runoff from subcatchments 1, 2, 3 and 4.

Three options are available for flood routing in stream channels (Fig. 8.9). The default is nonlinear routing using Eqs. (8.8) and (8.11).

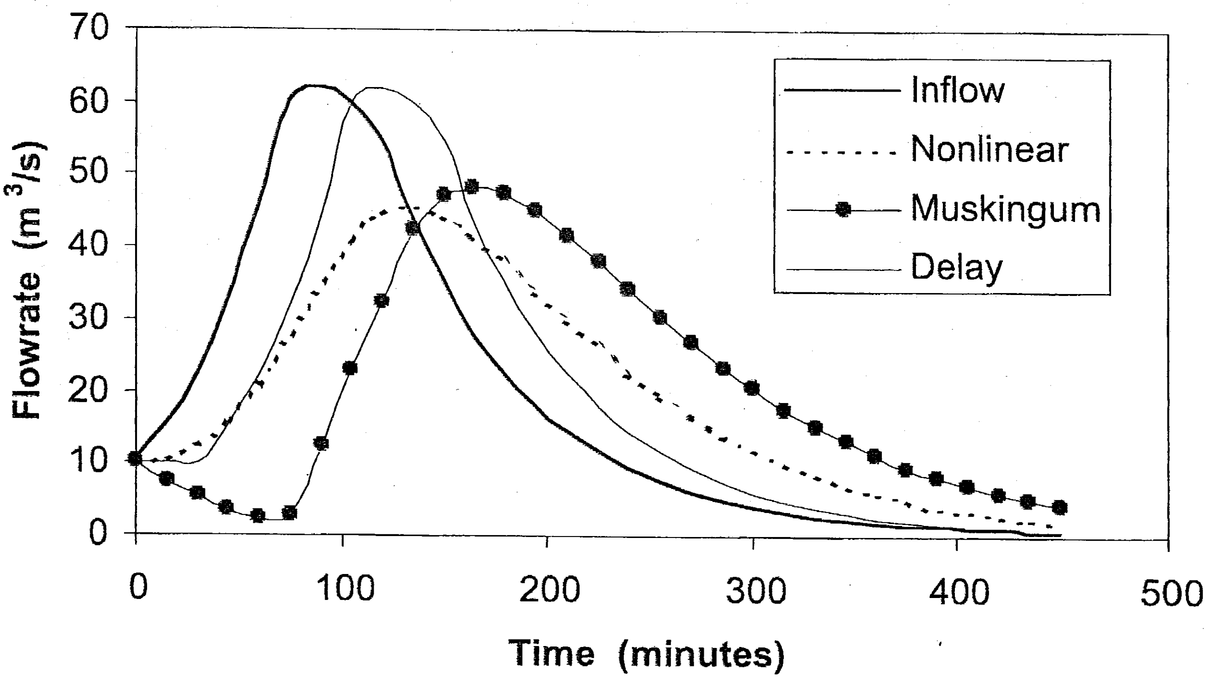


Fig. 8.9. Flood routing in stream channels.

Equation (8.11) already contains a reduced lag time for the faster velocity flow in the stream channel. This value applies to an unmodified stream in a natural catchment, and would have a Manning's n value near to 0.035. If the channel is modified, the lag time can be adjusted appropriately. For example, if the channel was concrete lined, Manning's n would reduce to 0.011, flow velocities would increase approximately three fold, and consequently the lag time should be reduced in the ratio 0.33. Suggested reductions in lag time for other configurations are:

Natural channel	1.0
Gravel bed with rip-rap	0.67
Excavated earth	0.5
Concrete lined	0.33

The second option applies when the stream channel is short and the hydrograph passes through it without significant routing effect. In this case a simple delay can be specified.

Thirdly, if the stream channel is long and significant channel storage routing occurs, Muskingum flood routing can be used. Muskingum flood routing uses 2 parameters, the lag time for the flood hydrograph to pass through the reach K, and a weighting parameter X. K is approximately equal to the reach length divided by the flood wave velocity. Parameter X is typically in the range 0 to 0.5 and allows the peak of the hydrograph at the downstream end of the reach to be delayed beyond the recession of the hydrograph at the top end of the reach. The effect of these parameters on the downstream hydrograph is shown in Fig. 8.10. The value of K principally controls the time of the downstream hydrograph peak. For X=0, the downstream hydrograph

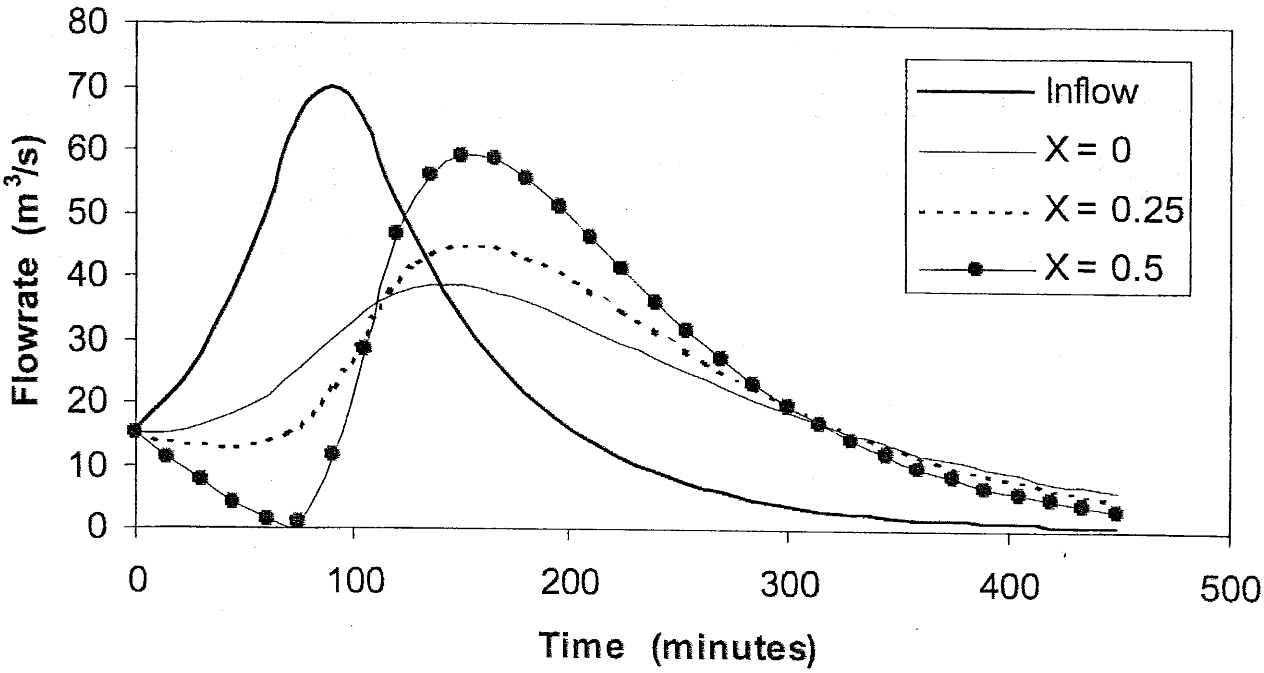


Fig. 8.10. Effect of Muskingum parameters on flood hydrographs.

peak intersects the recession of the upstream hydrograph. As X increases from 0 to 0.5, the peak discharge of the downstream hydrograph increases. When X=0.5 the hydrograph is approaching the case of flood wave translation with minimal attenuation.

8.5.3. Onsite Detention Storages

An onsite detention storage (OSD) can be provided on each subcatchment to provide flood routing for the local runoff from the pervious and impervious surfaces of the subcatchment. The inflow to the OSD can consist of the pervious runoff alone, or the impervious runoff alone, or any specified combination of the two. The storage can be initially filled to any specified elevation at the start of the storm.

Flood routing in the storage uses a Puls type procedure and requires a table of water elevations, storage volumes, and discharges from the storage. If the number and size of the outlets are specified, WBNM has built in hydraulic relations to calculate the elevation-discharge relation, based on the US Federal Highway Administration charts (1965). Equations have been fitted to these charts by Boyd (1987). The outlets can be circular pipes, rectangular box outlets, or weirs.

Onsite detention storages sometimes use a High Early Discharge (HED) type outlet. These storages consist of a small chamber which rapidly fills to its design water level, after which water overflows into the larger main storage chamber. Since the small chamber rapidly fills to its design level, discharges out of the storage rapidly reach their design value. The resulting hydrographs for these storages are shown in Fig. 8.11. When HED storages are used, the outflow from the storage rapidly increases to its design value. The discharge then remains at this constant value while the main storage chamber fills. As a consequence, HED storages maintain good control of the design outflow discharge, and the required storage volume is minimised. WBNM2000 allows HED storages to be modelled.

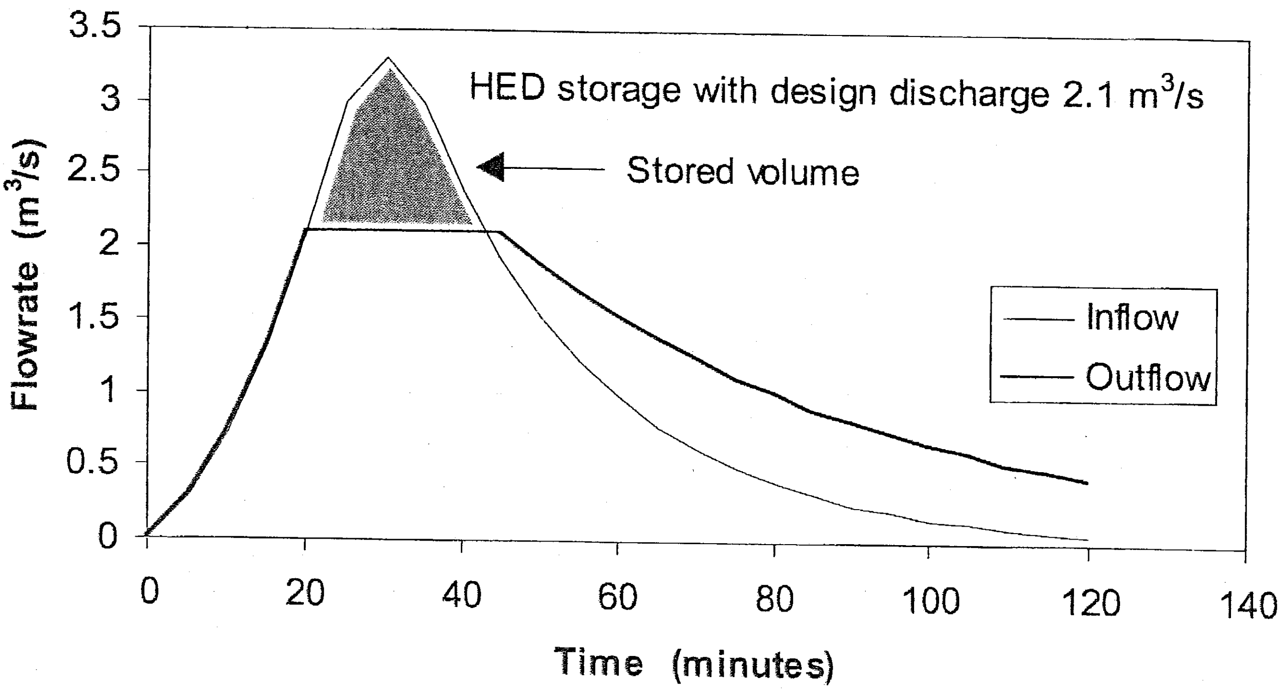


Fig. 8.11. Hydrographs from High Early Discharge type Onsite Detention Storages.

8.5.4. Mainstream Detention Storages

WBNM also allows a storage reservoir to be placed at the outlet of each subcatchment. In this case the inflow to the storage is the local runoff from the subcatchment, including flow from an onsite detention storage, plus runoff in the stream channel which comes from upstream subcatchments. Flood routing procedures are identical to those for onsite detention, with three additional features, outlet control for culverts, downstream diversions and erodible fuseplug spillways.

The culvert hydraulics handle both inlet control and outlet control. If inlet control is specified, only the number, size, and invert elevation of the culverts is needed. If outlet control is specified, the tailwater depth in the downstream channel is needed for each discharge. WBNM allows the tailwater depth to be fixed, or to be specified as a rating table of tailwater depth versus discharge, or the user can supply the dimensions of the downstream channel, and WBNM will apply Manning's equation to calculate the tailwater depths. When outlet control is specified, WBNM compares the inlet and outlet results for each discharge and selects the controlling case. Culvert hydraulics are again based on the US Federal Highway Administration (1965) charts.

In most cases, outflow from the storage reservoir will go to the immediately downstream subcatchment. However there are some important cases when this may not occur. In particular, in urban or part urban catchments, the storage may be formed by a road or rail embankment with the flows carried under the embankment by a set of culverts. When a major flood occurs and the culvert capacity is exceeded (or if the culvert is blocked by debris) the stream channel will break its banks, and runoff will flow parallel to embankment until it reaches a point where it can bypass the embankment. This point will often be an adjacent stream, with the result that the flow is diverted into this adjacent subcatchment. In this circumstance, flow leaving the storage through its lower level outlets will move to the immediately downstream subcatchment, while flow through the higher level outlets (including overbank flow) will move to a different subcatchment. WBNM allows this to be modelled by directing the flow through each of the various outlets to a nominated downstream subcatchment. In some cases these diverted flows will go to the top of the destination subcatchment, while in others it will go to the bottom of the subcatchment. Typically, if the flow breaks the stream's banks and flows along the embankment, it will go to the bottom of the adjacent subcatchment. WBNM allows the user to nominate whether this diverted flow goes to the top or bottom of the destination subcatchment.

In some cases the embankment can overtop and scour out, increasing the flow cross-section [MacDonald and Langridge-Monopolis, 1984]. A section of the embankment can also be designed as a fuseplug to deliberately scour out [Vermeyen and Mares, 1992]. WBNM2000 can model the scour of fuseplug spillways. The dimensions of the embankment, and of the scourable fuseplug section are specified. The scour rate in m^3 of water required per m^3 of scoured embankment material is also specified. At each time step, WBNM calculates the volume of water passing over the fuseplug section and the scoured volume. Next, the increased fuseplug dimensions are determined and a revised elevation-discharge relation is calculated. These calculations are repeated at each time step.

The fuseplug routines in WBNM2000 can be used to model erosion and washout of sandbars in the lower reach of the catchment, and to model erosion and unblocking of previously blocked culverts. To assist in modelling, the time at which scour commences can be specified.

WBNM displays full details of the scouring process. The progressive water volume and scoured embankment volume, and the changing fuseplug dimensions are given at each time step. The water elevation and discharge are also given at each time step.

8.6. STORM DETAILS

8.6.1. Recorded Storms

Rainfall from up to 15 rain gauges can be used with WBNM. The rainfall can be entered as mm/hour or mm/time period. Any rainfall hyetograph can be assigned to a particular subcatchment, or a weighted average of several gauges can be used (section 8.3.4).

Different time periods can be used for the rainfall hyetograph, the recorded hydrograph, the calculation period, and for results written to the output file. A smaller time period for calculation allows better definition of the calculated hydrograph. A longer time period for output reduces the size of the output file.

8.6.2. Design Storms

WBNM has built-in design storms for Australia. The Institution of Engineers Australia (1998) has calculated rainfall intensity-frequency-duration data, based on recorded storms for all of Australia. Storm durations from 5 minutes to 72 hours, and frequencies from 1 in 1 year to 1 in 500 years can be calculated. The method uses Log Pearson type III distribution for frequencies and interpolation for the durations. The rainfall intensity for a specified frequency and duration is then distributed into a design storm temporal pattern, based on average temporal patterns of recorded storms.

Calculation of design storms in WBNM is simple. The user specifies the location, the design frequency and duration, and WBNM produces the resulting design rainfall hyetograph. If multiple design storms are used, WBNM tabulates results and selects the critical design storm.

Design storms for regions outside Australia could be run, using a standard template for the temporal pattern, and adjusting it to the appropriate design storm depth using the rainfall weighting factors (section 8.3.4).

8.6.3. Probable Maximum Precipitation Storms

Probable maximum precipitation storms can also be calculated. The method is based on procedures of the US National Weather Service (1988), modified by the Australian Bureau of Meteorology (1994). The method applies to catchments less than 1000 km^2 and durations less than 6 hours. The user specifies the location, terrain roughness, elevation and moisture adjustment factor. WBNM automatically calculates the PMP rainfall depth and distributes it into a PMP temporal pattern.

8.6.4. Recorded and Imported Hydrographs

Recorded hydrographs can be entered at any location in the catchment for comparison with hydrographs calculated at the same locations. When the hydrograph is recorded at the catchment outlet, WBNM calculates the recorded runoff volume and depth and compares it with the calculated excess rainfall depth, then warns that rainfall losses may have to be adjusted.

Hydrographs can be imported to any location in the catchment. This allows flows diverted from adjacent catchments during major floods to be imported into the model (section 8.5.4). It also allows WBNM to be set up to model only the lower part of a catchment, with flows from the upper part entering as imported hydrographs at the top of the model.

Importing hydrographs introduces considerable flexibility into WBNM. For example, WBNM can be used just for flood routing in a detention basin (section 8.5.4) or it can be used just for Muskingum flood routing in channels (section 8.5.2). In these cases, WBNM would be set up with one subcatchment, with the mainstream detention basin switched on for the first case, and the stream channel switched on for the second.

8.7. WBNM2000 SOFTWARE PACKAGE

8.7.1. Overview

The software package contains the main program, plus several supplementary programs, detailed documentation, and sample runfiles. The software has been developed to be an efficient tool for flood studies in engineering offices. Various flags may be set by the user to produce summary tables and reports, and to add details of the organization name and contact details. For quality assurance, a record of the run time and date, runfile used, and output files is maintained. Very detailed results are written to an output file. The software is fully Windows based, and is written in LF90 Fortran with RealWin for Windowing. There are 35,000 lines of program code in total. The current size of the software package is 1.6 MB. It is available, free of charge, as a zipped set of executable programs, sample runfiles, and documentation at our website:

www.uow.edu.au/eng/research/wbnm.html

8.7.2. WBNM2000 Main Program

The main program consists of three parts: a front end graphical user interface (GUI), the calculation engine, and the plotting and graphics routines.

8.7.2.1. Front end GUI

All details of the catchment and storms being modelled are contained in an ASCII text runfile. The filename is of type RUNFILE.WBN. The front end GUI provides a means of creating and editing these runfiles. It contains smart editing features to check on data values as they are entered. After the runfile is first built, by adding successive subcatchments and their details, the editor automatically re-sequences the subcatchment order, so that calculations can proceed from the uppermost one downstream to the catchment outlet. If more subcatchments are added, the editor automatically updates this order. In this way subcatchments can be easily added or deleted without any major restructuring of the runfile. Figure 8.12 shows a typical screen of the front end GUI.

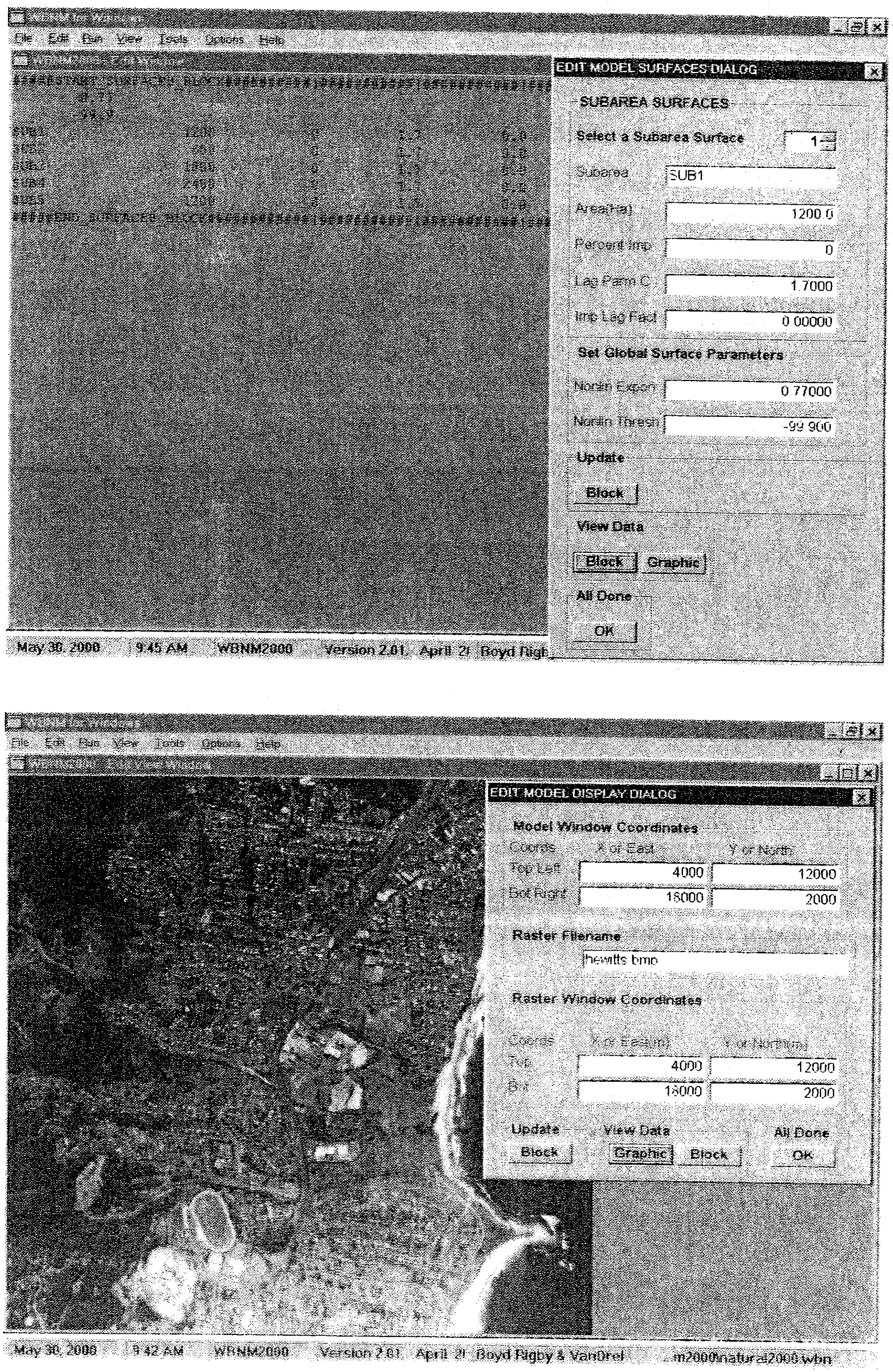


Fig. 8.12. WBNM2000 Graphical User Interface screen.

The GUI front end is also used to access the other parts of the software.

8.7.2.2. Calculation Engine

The calculation engine takes the completed runfile and runs the model. Several flags control output to the screen. A running summary of the stage of calculation is scrolled to the screen. This contains several optional summary tables, giving rainfall, excess rainfall, and runoff depths. For every subcatchment, a summary table of inflow and outflow volumes plus a volume balance is given. Additionally, the peak discharges and times to peak for all hydrographs calculated in each subcatchment are given. If a detention storage is used, a summary table gives inflow and outflow volumes, inflow and outflow peaks, initial and final water levels and volumes, and the maximum water level in the basin.

The runfile can be echoed to a scroll window by setting an echo flag. If the debug flag is set, very detailed information is scrolled to a debug window as it is calculated. These two features are very useful in identifying errors in the runfile, since they indicate the exact point at which the erroneous data value occurs in the runfile.

Detailed results for the run can be optionally written to an output file. This takes the RUNFILE.WBN name and changes it to RUNFILE.OUT. The output file contains an echo of the runfile plus the summary tables. For each subcatchment, the adopted rainfall and excess rainfall hyetographs, plus all hydrographs are written to the output file. These include the hydrographs at the top and bottom of the main stream channel, from the pervious and impervious surfaces, into and out of the detention storages, and any diverted hydrographs. The output is an ASCII text file, with all hyetographs and hydrographs written in columns, allowing easy cutting and pasting to other applications.

A summary report, containing the date and time of run, the organisation details, and the main results can be optionally written to a file RUNFILE.SUM.

In addition, details of the culvert hydraulic calculations, and the fuseplug spillway calculations, can be optionally written to files CULVERTS.OUT and FUSEPLUGS.OUT. The fuseplug file contains a time history of the scouring process. At each time step the cumulative volume of water and scoured embankment material, plus the enlarging fuseplug spillway dimensions are given. The water elevation and flowrate over the spillway are also given.

8.7.2.3. Plotting routines

Plotting routines take the information contained in the output file and produce a wide range of graphical outputs. These include a schematic of the model structure, which can overlay a GIS image of the catchment. Rainfall hyetographs, plus any selected hydrographs for the subcatchment can be plotted. Figure 8.13 gives a sample of the plots available.

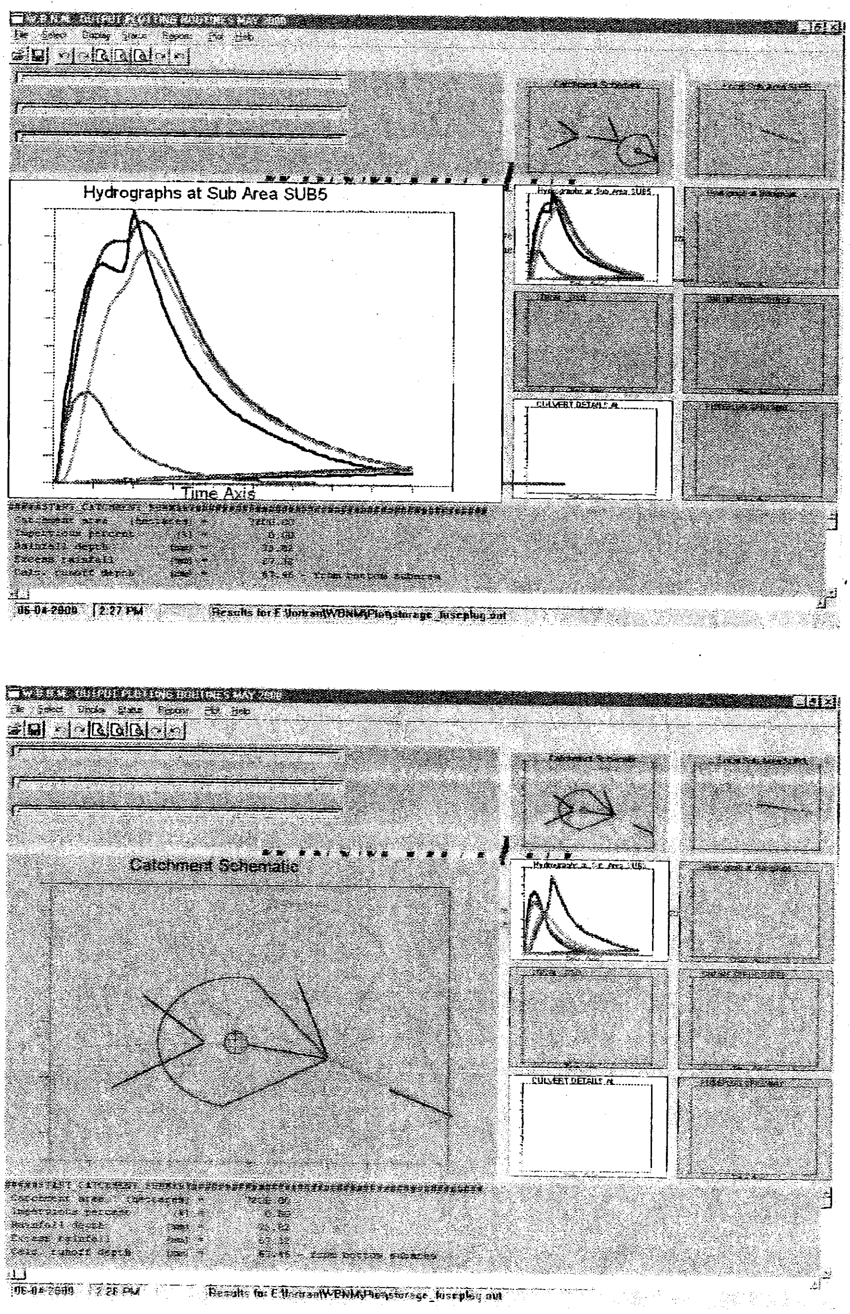


Fig. 8.13. WBNM2000 plotting output.

8.7.3. Supplementary Programs

A program WBNMCHCK can be used to check the runfile, after it is first created, for any major errors and incompatabilities. WBNMCONV can be used to convert runfiles from the previous versions into WBNM2000 format.

8.7.4. Documentation and Sample Runfiles

Detailed documentation is included as a User Guide, in Microsoft WORD. This gives a complete description of all processes in the model, with recommendations for various applications. References to all research publications incorporated into the model are included. Another WORD document gives the layout and format of the runfile.

Sample runfiles for 10 examples, demonstrating the main capabilities of the model, are included.

CONCLUSIONS

From its beginnings as a simple model for calculating flood hydrographs in natural catchments, WBNM2000 has evolved into a comprehensive suite of programs for flood studies in natural, urban and part-urban catchments. It requires a minimum of catchment data, and models quite complex catchments, including flood detention storage, diversion of surcharging flows out of the normal stream system, stream channel routing, and allows hydrographs to be imported and exported from the catchment. Built-in culvert and weir hydraulics subroutines automatically calculate elevation-discharge relations. WBNM2000 models recorded storms and design storms, including probable maximum precipitation storms.

WBNM2000 is a very flexible model, giving the user considerable choice in the type of flood routing, and routing parameters to be used. Its use is greatly simplified by the use of default relations. These make use of built-in lag relations, developed by calibrating the model with recorded rainfall and streamflow data. These default relations simply require values for three parameters, the basic lag parameter (section

8.3.5), a lag reduction factor for stream channels (section 8.5.2), and a lag reduction factor for runoff from impervious surfaces (section 8.4.5).

The WBNM2000 software package is designed to assist engineering flood studies, and includes a front end editor, plotting and graphical output, as well as detailed record keeping for quality assurance requirements.

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WBNM2000 –

Runoff Routing Model for Floods on Natural, Urban and Part Urban Catchments
Beta Version 1.06 of WBNM2000 August 1999

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Previous versions : 1.00 1979 Michael Boyd, David Pilgrim and Ian Cordery
1.10 1987 Michael Boyd, Bryson Bates, David Pilgrim and Ian Cordery
2.10 1994 Michael Boyd, Ted Rigby and Rudy VanDrie

Consult our web page for news on WBNM, and for news and upgrades as they become available: http://www.uow.edu.au/eng/research/water.html

A free download of WBNM2000 is available at the above website

What WBNM2000 Can Do

WBNM2000 is an event based hydrologic model and calculates flood hydrographs from storm rainfall hyetographs. It can be used for modelling natural, part urban and fully urban catchments. For urban catchments, it calculates runoff from pervious and impervious surfaces and routes it through the major system of open watercourses. WBNM does not model piped drainage systems. While the original concept was for a simple, yet physically realistic model, over the years WBNM has added many features to make it more useful for engineering investigations. WBNM was the first model to have built in culvert hydraulics, based on the US Department of Transportation charts, and among the first to have built in design storms.

The current version, WBNM2000 has many features which make it a versatile and useful tool for flood studies. WBNM2000 :

- is fully WINDOWS compatible
- has a WINDOWS template for easy runfile creation
- has comprehensive graphics displays of output
- allows GIS overlays of the model on an image of the catchment
- saves all hydrographs and summary tables of results in an output metafile
- all hydrographs and hyetographs in the output metafile are in ASCII text and in columns, allowing easy cut and paste to other applications such as EXCEL
- the output metafile is designed to serve QA requirements
- you can select from 11 summary tables to write results to the screen and output file
- can convert old WBNM v2.10 runfiles to new WBNM2000 format
- has a separate checking program to detect errors in your runfile
- can be run in three DEBUG modes, allowing examination of all results as they are calculated
- can model 120 subareas
- can model a mainstream storage reservoir on each subarea
- can model onsite detention storage on each subarea

- can have 10 rain gauges
- can calculate 432 time steps (equivalent to a 72 hour flood at 10 minute time steps)
- can easily add or delete subareas without restructuring the model
- can easily add or delete onsite detention basins and storage reservoirs without restructuring the model
- can be calibrated on recorded rainfall and flood data
- allows rainfall to be entered as mm/hour or mm/period
- allows recorded hydrographs at any point in the catchment
- allows hydrographs to be imported to any point in the catchment
- recorded hydrographs, imported hydrographs, rainfall hyetographs and output results can have different time periods
- can calculate design storms, with durations from 5 minutes to 72 hours, and average recurrence intervals from 1 to 500 years
- can calculate probable maximum precipitation using the Generalised Short Duration Method Bulletin 53
- for extreme flood estimates, can switch from nonlinear to linear above a specified discharge
- can calculate embedded design storms, where the critical duration burst is embedded within a longer duration event
- rainfall losses can be initial loss-continuing loss rate, or initial loss-runoff proportion, or Horton infiltration, or continuously time varying loss rate
- routes hydrographs in stream channels separately from overland flow hydrographs
- stream channel routing can be nonlinear, time delay, or Muskingum
- can model natural, urban and part urban catchments
- calculates separate runoff hydrographs from pervious and impervious surfaces
- allows modification (eg urbanisation) to catchment surfaces separately from modification to stream channels
- can model onsite detention storage for pervious and/ or impervious runoff from a subarea
- can have rating curves at any point in the catchment
- can model storage reservoirs/ flood detention basins at any point in the catchment
- has built in culvert and weir hydraulics (inlet and outlet control)
- surcharging flows from the various outlets in a storage reservoir can be diverted to various downstream points
- surcharging flows can be calculated from the hydraulic relation of the appropriate outlet (ie a weir)
- storage reservoirs can have a dead volume to be filled before outflow commences
- storage reservoirs can be part full at the start of the storm
- can have fuse plug spillway, where the cross section is designed to scour as it is overtopped

WBNM2000 SOFTWARE PACKAGE

WBNM2000 contains several computer programs:

- WBNMRUN.EXE
- WBNMCONV.EXE
- WBNMCHCK.EXE

two initialisation files

- GLOBAL.INI
- PROJECT.INI

and the WORD documents :

- WBNM_details.DOC
- WBNM_runfile.doc

Additionally, several sample runfiles:

Natural.WBN is a simple file for a natural catchment, using a recorded storm
Urban.WBN is a simple file for a part urban catchment using a recorded storm
Embedded.WBN uses a design burst embedded within a longer design storm event
Storage_inlet_control.WBN has a storage reservoir with inlet control assumed for the culverts
Storage_outlet_chnl.WBN has a storage reservoir with outlet control to be considered for the culverts, and tailwater depth in the downstream channel controlled by a trapezoidal channel
Storage_outlet_rating.WBN has a storage reservoir with outlet control to be considered for the culverts, and tailwater depth in the downstream channel controlled by a rating table
Storage_fuseplug.WBN has a storage reservoir with an erodible fuseplug spillway
Design_extnl.WBN has a design storm, with design rainfall IFD coefficients located in the external IFD file WBNM2000.IFD (note, all other example runfiles have the coefficients located in the runfile itself)

Basic Concept of WBNM2000

WBNM was originally developed to be a physically realistic representation of the catchment as it transforms storm rainfall into a flood hydrograph. It has built in lag relations, based on recorded rainfall and flood data. Because of this, it requires a minimum of parameters to be evaluated in its basic form, yet still gives good hydrograph reproduction.

A catchment is divided into smaller subareas, based on the stream network. Each subarea is bounded by its ridge line (or watershed) and forms a catchment within the larger catchment. This explains the origin of the model's name : **Watershed Bounded Network Model.**

What each Subarea Contains

Each subarea can contain the following components

- a stream channel from top to bottom
- pervious surfaces
- impervious surfaces
- onsite detention storage for local runoff from the subarea (local structure)
- storage reservoir/ flood detention basin on the main stream channel (outlet structure)
- outflows directed to nominated downstream subareas
- surcharging flows diverted to nominated downstream subareas

For each subarea, the top of the stream channel takes all hydrographs directed to this subarea from upstream subareas, and all hydrographs imported into this subarea. These hydrographs are summed and routed through the stream channel to give a hydrograph at the bottom of the stream channel.

Pervious surfaces take the rainfall hyetograph for this subarea, subtract rainfall losses, and route the excess rainfall to give a hydrograph from the pervious surfaces.

Impervious surfaces take the rainfall hyetograph for this subarea, subtract an initial loss for the impervious surface, and route the excess rainfall to give a hydrograph from the impervious surfaces. A reduced lag parameter is automatically calculated for impervious runoff.

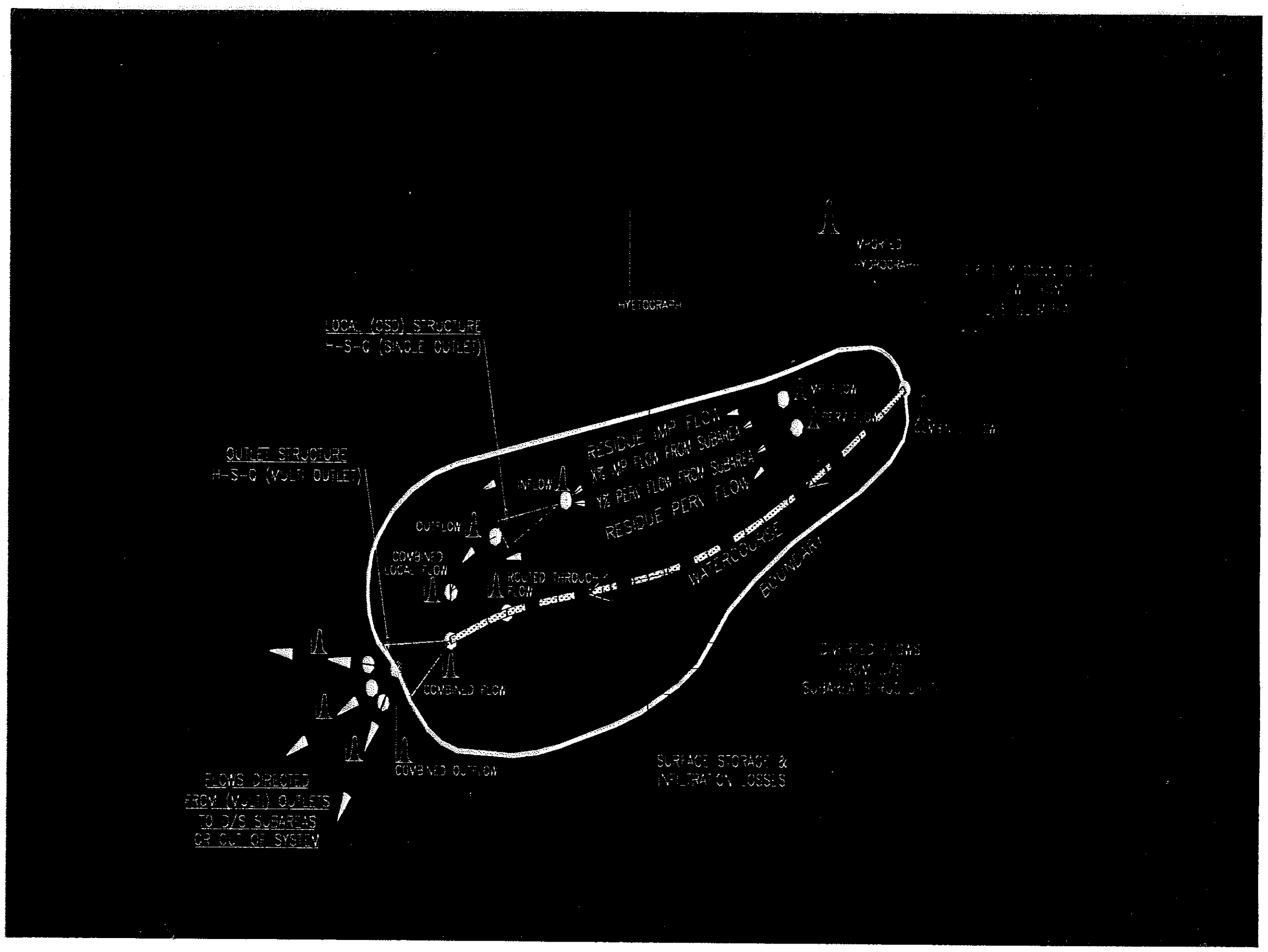
The hydrographs from pervious and impervious surfaces are added to the hydrograph at the bottom of the stream channel to give the combined hydrograph at the bottom of the subarea

Portions of the pervious hydrograph and impervious hydrograph can be directed into an onsite detention storage and routed through the storage. This routed hydrograph is added to other hydrographs at the bottom of the subarea.

A storage reservoir (or flood detention basin) can be placed at the bottom of the subarea. If this storage is present, the summed hydrograph from the stream channel, pervious and impervious surfaces, and from the onsite detention storage is routed through the storage to give an outflow hydrograph from the storage.

Finally, the hydrograph at the outlet of the subarea is directed to a nominated downstream subarea.

Within the storage reservoir/ flood detention basin routing, outflows from the various outlets eg culverts and weirs, can be **diverted** to various nominated downstream subareas. This allows for surcharging flows, which may take different flow paths to the normal one, to be redirected within the catchment.



HYETOGRAPH
LOCAL (OSD) STRUCTURE
H-S-Q (SINGLE OUTLET)
OUTLET STRUCTURE
H-S-Q (MULTI OUTLET)
RESIDUE IMP FLOW
X% IMP FLOW FROM SUBAREA
Y% PERV FLOW FROM SUBAREA
RESIDUE PERV FLOW
INFLOW
OUTFLOW
COMBINED LOCAL FLOW
ROUTED THROUGH FLOW
WATERCOURSE
BOUNDARY
COMBINED FLOW
COMBINED OUTFLOW
FLOWS DIRECTED FROM (MULTI) OUTLETS TO D/S SUBAREAS OR OUT OF SYSTEM
SURFACE STORAGE & INFILTRATION LOSSES