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WBNM — a computer software package for flood hydrograph studies

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Abstract

The flood hydrograph model WBNM calculates flood runoff from rainfall hyetographs. It divides the catchment into subcatchments, thus allowing hydrographs to be calculated at various points within the catchment, and spatial variability of rainfall and rainfall losses to be modelled. It separates overland flow routing from channel routing, thus allowing changes to either or both of these processes, for example in urbanising catchments. The computer program for WBNM contains many useful features for flood studies, including built in design storms, runoff from impervious and pervious catchment surfaces, flood routing through storage reservoirs, built in culvert and weir hydraulics, and diversion of surcharging flows. The program is menu driven and designed to satisfy quality assurance requirements. Full graphics displays are included. Copyright © 1996 Elsevier Science Ltd

Keywords: Flood hydrograph; natural catchment; urban catchment; design flood; storage reservoir routing; detention basin; computer model; graphics

Software availability

Program title:	WBNM (Watershed Bounded Network Model)
Developers:	M. J. Boyd, E. H. Rigby, R. VanDrie
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First available:	1994
Hardware requirements:	PC286 and above
Software requirements:	Runs under DOS
Program language:	FORTRAN 77/90 for computation PASCAL for graphics
Program size:	1.5 Mb
Availability and cost:	Freely available, no charge

1. Introduction

Many environmental studies require the calculation of flood hydrographs. One common case is predicting increases in the magnitude and frequency of flooding as natural catchments are developed for urban land use. When this problem occurs, it is desirable to know flood discharges and maximum water levels at selected points throughout the catchment and to be able to model the effects of various flood mitigation measures on catchment flooding. WBNM was developed to model both natural catchments and catchments which are becoming urbanised. Additionally, effects of changes to stream channels and the flood mitigation effects of detention basins can be modelled.

The Watershed Bounded Network Model WBNM was developed by Boyd *et al.* (1979) and revised by

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Boyd *et al.* (1987). It is included in *Australian Rainfall and Runoff* (Institute of Engineers, 1987), the guide to flood estimation in Australia. The model calculates the flood hydrograph resulting from storm rainfall using a runoff routing approach where the catchment is divided into subcatchments using the stream network, and each subcatchment is allocated a lag time depending on its size, based on studies of the nonlinear variation of lag time on real catchments. The model has recently been built into a comprehensive computer program that includes the following features:

- Spatial variation of rainfall and rainfall losses
- Range of rainfall loss models
- Multiple rain gauges
- Design storms, including short duration probable maximum precipitation
- Natural and urban catchments
- Modifications to stream channels, such as renaturalizing, clearing or lining
- Calculates runoff from impervious and pervious surfaces separately
- Diversion of flows exceeding the channel capacity
- Rating tables to give maximum water levels at selected locations
- Flood routing through storage reservoirs and detention basins
- Culvert and weir hydraulics
- Recorded hydrographs

A menu system allows easy organisation, copying and editing of input data files. All results, plus the input data and model parameters are written to an output file as a permanent record for quality assurance purposes. Additionally, built in graphics allow viewing of the schematic catchment layout, hydrographs from all subcatchments, rainfall hyetographs, rating curves, and storage reservoir elevation-discharge-storage curves.

The following sections describe the background to the model, and the structure of the computer program WBNM.

2. Modelling catchments with WBNM

The catchment to be modelled is divided into subcatchments based on the stream channel network. Each subcatchment or watershed drainage area is bounded by its divide, hence the name Watershed Bounded Network Model. Guidelines for the division into subcatchments are given in Boyd *et al.* (1987). Generally, small catchments are divided into only a few subcatchments while large catchments may be divided into 100 or more. Fig. 1 shows a schematic stream channel network.

Subcatchments are of two types. The first is a headwater at the upper end of the channel network which recieves rain falling on the subcatchment surface and

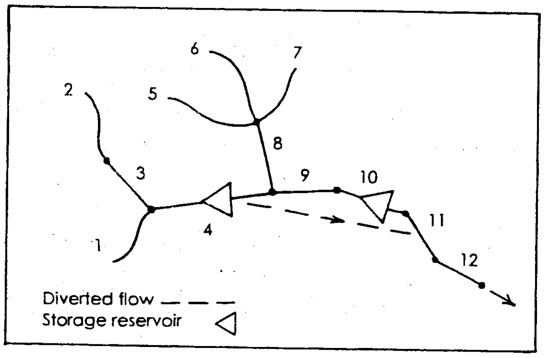

Fig. 1. Schematic catchment structure.

transforms it, via overland flow and its minor drainage network, into a runoff hydrograph at the subcatchment outlet (subcatchments 1, 2, 5, 6, 7 in Fig. 1). The second type receives runoff from upstream subcatchments and routes it through the main stream channel, and in addition transforms rain falling on its associated subcatchment area into a local runoff hydrograph (subcatchments 3, 8, 9, 11, 12 in Fig. 1). As an example, subcatchment 8 receives runoff from the upstream subcatchments 5, 6 and 7. This is routed through its stream channel. Overland flow from rain falling on subcatchment 8 is then added to the routed channel flow to give the total outflow from the subcatchment. Each subcatchment is represented in WBNM by a non-linear storage which is used in the runoff routing calculations. Equations for transforming the excess rainfall hyetograph into a runoff hydrograph on each subcatchment are:

$$\text{Continuity } I(t) - Q(t) = \mathrm{d}S(t)/\mathrm{d}t \tag{1}$$

where

$I(t)$ = $A.R(t)/3.6$ = inflow from excess rainfall on the subcatchment ($m^3\ s^{-1}$)
$R(t)$ = excess rainfall ($mm\ h^{-1}$)
A = subcatchment area (km^2)
$Q(t)$ = outflow from subcatchment ($m^3\ s^{-1}$)
$S(t)$ = volume of water stored on subcatchment surface (m^3)
t = time (s)

$$\text{Storage-Discharge} \quad S = kQ^m \tag{2}$$

which relates the volume of water on the subcatchment surface at any time to the corresponding discharge from the subcatchment; k is a scaling parameter and m indicates the nonlinearity of the relation ($m = 1$ for linear catchment response, $0 < m < 1$ for nonlinear response in which flow velocities increase and hydrograph lag times decrease as the discharge Q increases).

Solving Eqs (1) and (2) gives the routing equation for the subcatchment

$$I(t) - Q(t) = \mathrm{d}S/\mathrm{d}Q.\mathrm{d}Q/\mathrm{d}t = kmQ^{m-1}\ \mathrm{d}Q/\mathrm{d}t \tag{3}$$

The term dS/dQ represents the lag time of the subcatchment. If $0 < m < 1$ the catchment response is nonlinear and the lag time varies with the discharge from the subcatchment. Detailed studies of lag times in natural catchments (Askew, 1970) show that the lag time depends on the size of the subcatchment A, as well as on the discharge Q. The relation derived from that study is:

$$LAG = c.A^{0.57}\,Q^{-0.23} \tag{4}$$

which indicates that $m = 0.77$ and that the LAG (hours) is larger for large subcatchments, and decreases as the flood discharge Q increases. Eq. (4) is built into the model WBNM so that only the subcatchment sizes are needed to calculate their lag times and the resulting flood hydrographs. The model has one parameter, c, which controls the magnitude of the catchment lag time, and can be adjusted for calibration on recorded events.

In WBNM Eq. (3) is solved numerically:

$$Q_2 = ((I_1 + I_2)\,0.5\,\Delta t + Q_1\,(K_1 - 0.5\,\Delta t))\,/(K_2 + 0.5\,\Delta t) \tag{5}$$

where subscripts 1 and 2 indicate values at the start and end of the time step, Δt is the time step in hours, and K is the lag time from Eq. (4) in hours.

Routing of upstream runoff through the main stream channel in the second type of subcatchment uses similar continuity and storage-discharge equations. However flow velocities are greater and consequently the lag times are smaller. Studies of channel routing in gauged natural catchments (Boyd *et al*, 1987) found that a reduction factor of 0.6 should be applied to the lag time calculated from Eq. (4), and this is used in WBNM. The model has been applied to a wide range of catchments, from 0.1 to 8000 km^2, and these relations have been found to give good results (Boyd *et al*, 1987; Boyd and Cordery, 1989).

3. Storm rainfall

Flood hydrographs can be calculated both for recorded storms and for design storms. Recorded storms can be used either for model calibration using the recorded flood, or for predicting the effects of catchment changes or flood mitigation works with real events.

A principal use of flood hydrograph models is to calculate design floods resulting from design storms. WBNM does this according to procedures set out in *Australian Rainfall and Runoff* (Institution of Engineers, Australia, 1987), the guide for design flood estimation in Australia. The procedure is to select a design storm frequency and duration. WBNM automatically calculates the design rainfall intensity (mm h^{-1}) for this storm, using built in relations for all regions of Australia. The procedure uses Log Pearson type III frequency distributions for recurrence intervals of 1, 2, 5, 10, 20, 50, 100, 200 and 500 years, with interpolation for storm durations between 5 min and 72 h. Next, WBNM distributes this rainfall into a design storm temporal pattern, using a built in library of data for all regions of Australia. Naturally, these design storms apply only to Australian conditions, however users in other countries can build in their own design storm procedures by modifying the design rainfall sub-program.

Probable Maximum Precipitation estimates use the generalised short duration methods of the Australian Bureau of Meteorology (1994), which in turn are based on US National Weather Service (1988) procedures. WBNM automatically calculates the total storm depth (mm) from the Depth-Duration-Area data for the region, and distributes it into the appropriate PMP storm temporal pattern. This applies to storm durations up to 6 h and catchment sizes up to 1000 km^2.

Spatially varying rainfall can be modelled using up to 10 rain gauges. The rainfall hyetograph for each subcatchment can be calculated using Thiessen weights for each rain gauge. Alternatively, by specifying grid coordinates for all subcatchments and rain gauges, WBNM automatically calculates weighting factors depending on the inverse square of the distance of each gauge from the subcatchment.

Four rainfall loss models are available: Initial loss–continuing loss rate; Initial loss runoff proportion; Horton exponential; and Initial loss–stepped loss rate. Spatially varying losses can be modelled by specifying different values for the different subcatchments.

4. Modelling urban catchments

It is well known that urbanisation of a catchment increases both flood volumes and flood peaks. The increased volumes result from replacement of naturally vegetated surfaces by impervious surfaces such as roofs, roads and pavements. The increased flood peaks result from faster flow velocities and consequently shorter travel times and lag times, both for overland flow on impervious surfaces, and for flow in the more hydraulically efficient pipes and channels.

WBNM models urbanisation in two ways. For overland flow, each subcatchment is split into a directly connected impervious part and the remaining pervious and semi-pervious part. Runoff from the impervious surfaces has a user-specified initial loss and zero continuing loss, and a significantly reduced lag time. Recommended values of impervious surface rainfall losses are taken from the survey by Boyd *et al.* (1993). The impervious surface lag parameter is based on studies of Rao *et al.* (1974), Aitken (1975) and NERC (1974), plus testing of nine urban catchments in Australia. This resulted in the following equation to determine the lag time for runoff from impervious surfaces:

$$LAG = 0.1c.A_{imp}^{0.25} \tag{6}$$

where A_{imp} is the size of the directly connected impervious area (km^2).

The second urbanisation effect which WBNM models is the decreased lag time in stream channels due to the increased flow velocities in the hydraulically more efficient channels of the urban catchment. Three options are available for flood routing in these channels: nonlinear routing using Eq. (4) but with a reduction factor to allow for the smaller lag times; Muskingum routing with lag parameter K and distributed routing parameter x; or a simple time delay applied to the hydrograph as it passes through the reach.

5. Storage reservoirs and flood detention basins

Storage reservoirs consisting of dams with spillways or detention basins with culvert and weir outlets can be placed at any point in the catchment (locations 4,10 in Fig. 1), and WBNM performs level pool reservoir flood routing. This requires a table of elevation H, discharge Q, and storage volume S values for the storage, which are obtained from the hydraulics of the outlet and the contours of the storage site. WBNM has built in culvert and weir hydraulic relations (Boyd, 1987) and calculates the H–Q relation given the number, type, size and invert elevations of the culverts and weir.

The invert level of the outlet can be above the floor of the storage, in which case the 'dead' volume between the floor and outlet must be filled by the inflowing flood before outflow commences. The initial water level at the start of the flood can be at any elevation and WBNM commences flood routing from this point. These two features allow the storage to be designed as a standard detention basin whose primary purpose is to temporarily store water and thereby reduce downstream flooding; or for longer residence times to allow settling of sediments and the associated nutrients; or as a water pollution control pond holding a permanent body of water.

6. Flow diversions

In large floods on real catchments, the capacity of the channel may be exceeded, and in this case the overflowing or excess flow leaves the channel and travels down a floodway to rejoin the channel at some downstream point (diversion from 4 to 11 in Fig. 1). In some cases the diverted flow leaves the catchment altogether, and overflows into the adjacent catchment. WBNM models this by diverting a specified percentage of the excess flows to a nominated downstream point.

7. Computer software package

The computer program WBNM is structured around three blocks, a MENU block, a COMPUTATION block, and a GRAPHICS block. The MENU block organises files under a Catchment directory and various Project sub-directories, for different projects on the same catchment. Within each of these, pull down menus allow the user to:

Change the catchment (or project)
Add a new catchment (or project)
Delete a catchment (or project)
List all catchments (or projects)

This allows efficient organisation of data files in a directory tree which corresponds to the organisation of jobs in the design office.

For each project there will be several input Runfiles, for example some will contain recorded rainfall and flood data for use in calibration runs, while others will contain details of design storms. The Runfile pull down menu allows the user to:

Change the runfile
Browse the runfile
Copy the runfile to another file
Add a new runfile
Delete a runfile
Edit the runfile
Compare two runfiles
List all runfiles
Print a runfile

The WBNM pull down menu allows the user to:

Build a new data file
Check an existing data file for errors
Run the WBNM model
Prepare a summary report
Show the graphic display
Set the echo flag
Set the debug flag
Nominate the plotter port
Nominate the plotter type
Set the impervious area lag factor
Set the impervious area initial loss

The summary report summarises important results of the run, including: total rain depth; excess rain depth; peak discharge and time of peak discharge for all subcatchments; volumes flowing into and out of all subcatchments plus a volume balance check; and runoff volumes and peak discharges from the impervious and pervious surfaces of all subcatchments.

The echo flag writes the summary report to the screen on each run, otherwise skip this. The debug flag, when turned on, writes the results of computations to the screen as they are calculated, and therefore can be used to track down errors in the runfile which are causing problems in the run.

The COMPUTATION block performs all numerical calculations. These include design storm rainfall intensities using the Log Pearson type III distribution and a library of standard temporal patterns; subtraction of rainfall losses; routing excess rainfall on subcatchments using Eqs (4) and (5), channel routing, either non-linear, Muskingum, or time delay; flood routing through storage reservoirs; and flow diversions. The computation block also calculates the summary statistics.

All calculated values are written to an output file which is automatically overwritten on each run. Copying and renaming this file allows a permanent record of all input data, settings and results for the run to be kept for quality assurance purposes. The output file is also accessed by the graphics routines.

The GRAPHICS block first displays a master screen containing all graphics displays (Fig. 2). Graphics can be maximised or minimised by mouse clicks.

The graphics displays available are:

Catchment schematic showing location of all subcatchments and rain gauges
Rainfall hyetographs at all rain gauges
Rating curves
Storage reservoir elevation-discharge-storage volume curves (Fig. 3)
Summary table
Rainfall hyetograph and flood hydrographs for all subcatchments

For each subcatchment, hydrographs can be viewed for runoff from impervious surfaces, from pervious surfaces, at the top end of the steam channel, at the bottom end after channel routing, diverted flows, and finally, the outflow hydrograph from the subcatchment

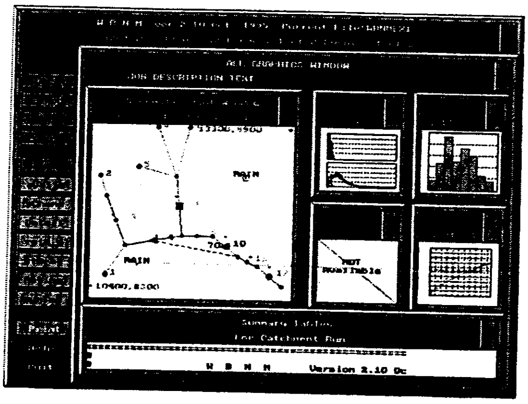

Fig. 2. Main graphics screen.

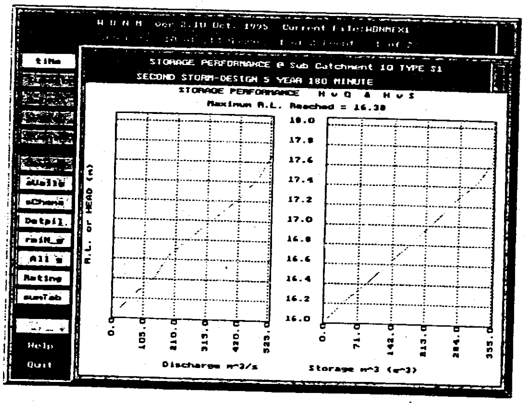

Fig. 3. Storage reservoir elevation curves.

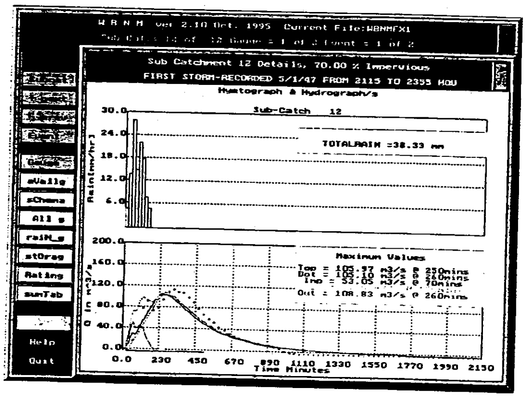

Fig. 4. Rainfall and hydrograph graphics.

(Fig. 4). If recorded hydrographs are available, these can also be viewed.

8. Conclusions

The Watershed Bounded Network Model for flood hydrograph estimation has been built into a comprehensive computer software package which is menu driven, allows efficient data file handling, satisfies quality assurance requirements, and has built in graphics. The computational part of the model allows for spatially varying rainfall and catchment conditions, urban and natural catchments, modifications to watercourses, flow diversions, storage reservoir routing, and detention basins. The computer program has built in culvert and weir hydraulic relations, and built in design storm rainfall. The program contains the README file which gives detailed information on the background and application of the model, including examples.

WBNM is a general flood hydrograph model which can be applied in all countries. In the current version, design storm rainfall is calculated using Australian data and procedures. However, this can be modified for other countries.

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