A COMPREHENSIVE FLOOD MODEL FOR NATURAL AND URBAN CATCHMENTS

Michael Boyd, Associate Professor
Dept Civil and Mining Engineering, University of Wollongong, AUSTRALIA 2522

Ted Rigby
Forbes Rigby Consulting Engineers, PO Box 5125, Wollongong AUSTRALIA 2500

Rudy VanDrie, Drainage Design Engineer
Wollongong City Council, PO Box 21, Wollongong East AUSTRALIA 2520

KEYWORDS: Flood hydrograph, Urban catchment, Design flood, Storage reservoir routing, Detention basin, Computer model, Graphics.

INTRODUCTION

The Watershed Bounded Network Model WBNM was developed by Boyd, Pilgrim and Cordery (1979) and revised by Boyd, Bates, Pilgrim and Cordery (1987). It is included in Australian Rainfall and Runoff (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 which 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 clearing or lining
Separate runoff from impervious and pervious surfaces
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 full menu system allows easy organisation, copying and editing of input data files. All results are written to a metafile 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. FORTRAN is used for computations and PASCAL for graphics. The program runs under DOS on IBM compatibles.

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

MODELLING CATCHMENTS with WBNM

The catchment to be modelled is divided into subcatchments based on the stream network. Each subcatchment or watershed drainage area is bounded by its ridge line, 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 subcatchments.

Subcatchments are of two types. The first is a Headwater or Overland flow type at the upper end of the stream, which receives rain falling on the subcatchment surface and transforms it, via overland flow, into a runoff hydrograph at the subcatchment outlet. The second type, Watercourse, 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.

Equations for transforming the excess rainfall hyetograph into a runoff hydrograph on each subcatchment are :

Continuity $\quad I(t) - Q(t) = dS(t)/dt \qquad (1)$

where $I(t)$ = $A.R(t)/3.6$ = inflow from excess rainfall on the subcatchment (m^3/s)
$R(t)$ = excess rainfall (mm/hour)
A = subcatchment area (km^2)
$Q(t)$ = outflow from subcatchment (m^3/s)
$S(t)$ = volume of water stored on subcatchment surface (m^3)
t = time (seconds)

Storage-Discharge $\quad S = kQ^m \qquad (2)$

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

$$I(t) - Q(t) = dS/dQ.dQ/dt = kmQ^{m-1}\, dQ/dt \qquad (3)$$

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 :

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

which indicates that $m = 0.77$ and that the LAG (hours) is larger for large subcatchments, and decreases as the flood discharge Q increases. Equation (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.

Routing of upstream runoff through the stream channels in watercourse type subcatchments uses similar continuity and storage-discharge equations. However the faster flow velocities produce shorter lag times. Studies of channel routing in real catchments (Boyd et al, 1987) found that a reduction factor of 0.6 should be applied to the lag time calculated from equation (4), and this is built into the model 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 1979, 1987; Boyd and Cordery, 1989).

Equation 3 is solved numerically

$$Q_2 = ((I_1 + I_2)\ 0.5\ \Delta t + Q_1\ (K_1 - 0.5\ \Delta t))/(K_2 + 0.5\ \Delta t) \qquad (5)$$

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 equation (4) (hours).

RAINFALL HYETOGRAPHS and RAINFALL LOSSES

Up to 10 rain gauges can be used. The rainfall hyetograph for each subcatchment is calculated using Thiessen weights applied to the each rain gauge. Alternatively, by specifying grid coordinates for 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 can be used: 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.

DESIGN STORMS

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, 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/hour) 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 minutes and 72 hours. Next, WBNM distributes this rainfall into a 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 procedures (1988). These apply to storm durations up to 6 hours and catchment sizes up to 1000 km^2.

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 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. Values of impervious surface rainfall losses were selected from the survey by Boyd et al (1993). The impervious surface lag parameter is based on studies of Rao et al (1972), Aitken (1975) and NERC (1975), plus testing on 9 urban catchments in Australia. This resulted in the following equation to determine the lag time for runoff from impervious surfaces :

$$LAG = 0.1c.Aimp^{0.25} \qquad (6)$$

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. Two options are available for flood routing in these channels, either Muskingum routing with lag parameter K and distributed routing parameter x, or a time delay of the hydrograph as it passes through the reach.

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, and WBNM performs level pool reservoir flood routing. This requires a table of elevation H- discharge Q- storage volume S values for the storage, from the hydraulics of the outlet and the contours of the storage site. WBNM has built culvert and weir hydraulic relations (Boyd, 1987) and calculates the H-Q relation given the number, type, size and invert elevations of the culvert 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. This allows for the occurrence of a second flood before the first flood has drained from the storage.

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. 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.

COMPUTER PROGRAM

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, Add a new catchment, Delete a catchment, List all catchments.

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 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 datafile, Check an existing datafile for errors, Run the WBNM model, Prepare a Summary report, Show the Graphic Display, Set the Debug flag, 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 debug flag, when turned on, writes the results of computations to the screen as they 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 log Pearson type III distribution and a library of standard temporal patterns; subtraction of rainfall losses; routing excess rainfall on subcatchments using equations (4) and (5), channel routing, either nonlinear, 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 a metafile which is automatically overwritten on each run. Copying and re-naming the metafile allows a permanent record of all input data, settings and results for the run to be kept for quality assurance purposes. The metafile is also accessed by the graphics routines.

The GRAPHICS block first displays a master screen containing all graphics displays. 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
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 watercourse, at the bottom end of the watercourse after channel routing, diverted flows, and finally, the outflow hydrograph from the subcatchment. If recorded hydrographs are available, these can also be viewed.

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 a 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.

Copies of the computer program are available, without charge, from the first author, Dept. of Civil and Mining Engineering, University of Wollongong, Australia 2522, fax +61 42 213238, email m.boyd@uow.edu.au

REFERENCES

Boyd, M.J., Pilgrim, D.H. and Cordery, I. (1979):A storage routing model based on catchment geomorphology. J. Hydrology. 42, pp. 209-230.

Boyd, M.J., Bates, B.C., Pilgrim, D.H. and Cordery, I. (1987):WBNM-a general runoff routing model. University New South Wales Water Research Laboratory Report 170. ISBN 0 85824 379 2.

Institution of Engineers Australia. Australian Rainfall and Runoff- A Guide to Flood estimation. (1987): 2 volumes. ISBN 085825 434 4.

Askew, A.J. (1970):Derivation of formulae for variable lag time. J. Hydrology. 10, pp. 225-242.

Boyd, M.J. and Cordery, I. (1989):A study of design parameters for flood hydrograph models. Instn. Engrs. Australia, Hydrology and Water Resources Symposium. National Conference Publication 89/19, pp. 119-123.

Bureau of Meteorology (1994): The Estimation of Probable Maximum Precipitation in Australia. Generalised Short-Duration Method. Australian Govt. Publ. Service, Canberra. ISBN 0 644 33419 3.

United States National Weather Service (1988): Probable Maximum Precipitation Estimates - US between the Continental Divide and the 103 rd Meridian. Report No. 55A.

Boyd, M.J., Bufill, M.C. and Knee, R.M. (1993): Pervious and impervious runoff in urban catchments. Hydrological Sciences Journal. 38, 6, pp. 463-478.

Rao, A.R., Delleur, J.W. and Sarma, P.B.S. (1972): Conceptual hydrologic models for urbanising basins. Proc. ASCE. 1974, 98, HY7, pp. 1205-1220.

Aitken, A.P. (1975): Hydrologic investigation and design in urban stormwater drainage systems. Australian Water Resources Council Technical Paper 10. Australian Govt. Publishing Service. ISBN 0 642 501 343.

Natural Environment Research Council (1975): Flood Studies Report Vol. 1 Hydrological Studies.

Boyd, M.J. (1987): Head-discharge relations for culverts. Proc. 21st Congress International Association for Hydraulic Research, Vol. 6. Keynote Addresses, pp 118-122. ISBN 0858252805.