WBNM2000 – computer software for flood studies on natural and urban catchments

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Abstract

A computer model for calculating flood hydrographs from storm rainfall on natural and urban catchments is described. The computer program is specifically designed for engineering flood studies, and includes data checking and verification procedures. All results are written to an output file for QA records. Features of the model include separate calculations for hydrographs from pervious and impervious surfaces, and separate calculation of overland flow hydrographs and stream channel hydrographs. Flood routing in mainstream and onsite detention flood storages is included. Built-in relations allow elevation-discharge relations to be calculated for culverts with inlet and outlet control. Design storms for Australian conditions are built-in to the model. Full documentation plus sample runfiles are included in the software.

The model has a simple but realistic structure and requires only a minimum amount of data to run in its basic form. However the many options available make it a flexible model which is applicable to a wide range of cases.

1 Introduction

The Watershed Bounded Network Model WBNM was originally developed to calculate flood hydrographs resulting from storm rainfall on natural catchments [1]. It does this by routing excess rainfall through catchment storage. The model was simple to use, requiring a minimum of input data, yet gave good hydrograph reproduction. As the model became adopted by the engineering profession, the need to apply it to more complex situations became apparent.

The latest release, WBNM2000, continues this development path, with particular emphasis on making it a useful tool for engineering flood studies. It is fully WINDOWS compatible, and all results are logged and saved for QA. The model itself has additional features, including more detailed culvert hydraulics, hydraulically based flow diversions when channel capacities are exceeded, and erodible fuseplug spillways.

The objective in developing WBNM2000 has been to retain the simplicity and physical realism of the original model, while allowing many of these additional features as options. This has been achieved by allowing the user to simply switch on or off these features as required.

2 Details of the WBNM2000 model

2.1 Modelling natural catchments

The original model made use of geomorphological similarity between the different sized subcatchments which are nested within and make up the larger catchment, as expressed in the various stream order laws [4]. Just as geomorphological properties, such as stream length and subcatchment (or basin) area are related to the subcatchment order, so the lag time for the transformation of rainfall into runoff is also related to stream order, and hence to the size of the subcatchment [5]. This provides a mechanism for accurately allocating lag times to the subcatchments of the model. This lag time can then be used in flood routing calculations.

A catchment is modelled by dividing it into subcatchments based on the stream network. Each subcatchment is bounded by its watershed divide, hence the name Watershed Bounded Network Model. The model therefore consists of a set of subcatchments connected in a branched network structure which reflects the structure and subcatchment sizes on the actual catchment. Due to the geomorphological and hydrological similarity between the subcatchments, lag times are related to their physical properties. Thus only one parameter, representing the lag time of the total catchment, is needed to model a catchment. Once this is selected, the lag time for each of the subcatchments is automatically calculated depending on its physical properties.

Studies of lag times between centroids of excess rainfall and surface runoff for natural catchments, summarised in [6], indicate that the dominant physical property is the catchment size, with slope and shape having a minor or even negligible effect. However catchments may respond nonlinearly, particularly for the smaller events. The nonlinearity appears as a trend for the lag time to decrease as the discharge decreases. Based on the studies of Askew [6], WBNM adopts the following equation to calculate the lag time of each subcatchment: 

\[ \text{Lag time} = \frac{1}{A} \text{(catchment area)} \]

where \( A \) is the area of the catchment in square kilometers.
Lag = Lag Parameter. $A^{0.57} Q^{0.23}$

where Lag = lag time for the subcatchment (hrs), $A =$ subcatchment area ($\text{km}^2$), $Q =$ instantaneous discharge ($\text{m}^3/\text{s}$), and the Lag Parameter is a single value for the catchment which is determined by fitting calculated and recorded hydrographs.

Because the structure of WBNM is based on the geomorphology of the catchment and lag time is allocated according to the size of the subcatchment, the fineness or coarseness of division into subcatchments is not critical. The summation of many small subcatchments, each with a small lag time, gives a similar lag time for the total catchment as does the summation of a smaller number of large subcatchments with large lag times.

Additionally, because the lag time is calculated for each subcatchment depending on its size, the same lag parameter applies over a wide range of catchment sizes. Figure 1 shows values of the Lag Parameter determined by fitting calculated and recorded hydrographs to 89 events on 10 catchments. A value of Lag Parameter = 1.7 was found to apply over a wide range of catchment sizes.

Because individual subcatchments are modelled, hydrographs are calculated at many points within the catchment, and changes to the catchment at particular locations can be modelled. These include construction of storages at nominated points, and modifications to stream channels. Similarly, spatial variations in land use and in rainfall can be modelled.

2.2 Modelling urban catchments

Flood generation in urban catchments is dramatically different from natural catchments. The increased amount of paved or impervious surfaces increase runoff volumes, while the more hydraulically efficient flow paths lead to faster runoff velocities and shorter lag times. WBNM2000 calculates separate runoff hydrographs from grassed (or pervious) surfaces and from paved (or impervious) surfaces.

Several options are available to calculate rainfall losses on pervious surfaces. These are: initial loss-continuing loss rate, initial loss-runoff proportion, and Horton continually time varying. On impervious surfaces, an initial loss is subtracted from the rainfall to represent the initial wetting of the surface, with all subsequent rainfall becoming runoff.

A comparison of lag times on paved surfaces and on grassed surfaces [7] indicated that paved surface lag times were approximately 10% of grassed surface values. WBNM2000 allows the user to specify a paved surface lag reduction factor, with a default value of 0.10.

WBNM2000 models urban catchments at the large scale and does not consider the detailed layout of gutters, pit inlets and pipes. Other models, such as MOUSE or SWMM would be better in these cases. However, WBNM2000 does allow the user to model the effect of urbanisation using a minimum of catchment data. WBNM2000 only requires the directly connected impervious
area of each subcatchment to calculate hydrographs. Details of the drainage system, which are often not available, are not required.

The directly connected impervious area of a catchment can be determined from plots of rainfall and runoff depths [8]. In the absence of rainfall and runoff data, the directly connected impervious area can be estimated from maps. This value is often found to be less than the value estimated from maps. In a study of 38 urban catchments [8], the effective directly connected area was found to be on average 87% of the directly connected, and 75% of the total impervious areas estimated from maps.

Despite its simple data requirements, WBNM2000 can model urbanisation quite satisfactorily. Figure 2 shows calculated and recorded hydrographs for a 57 hectare urban catchment in Sydney which has 52 % impervious surfaces and 16 % directly connected impervious surfaces.

2.3 Stream channel routing

On each subcatchment the streamflow comes from two sources, the local overland flow from paved or grassed surfaces on the particular subcatchment, and the runoff in the stream channel which comes from upstream subcatchments. Flow velocities in the streams are greater than overland flow velocities, and lag times for stream segments are therefore lower than overland flow times.

WBNM2000 calculates hydrographs in streams separately from overland flow. Three options are available for stream channel routing:

(a) Nonlinear routing using a Channel Factor selected to reflect the increased flow velocities in the stream channel.

(b) Muskingum routing, with parameters K and x selected depending on the translation and attenuation properties of the channel segment.

(c) Delay, in which the hydrograph is delayed through the stream segment by a specified time, but without attenuation.

2.4 Mainstream storages

Storage reservoirs or flood detention basins can be placed at the outlet of any subcatchment. Flood routing through these storages uses a Puls level pool procedure. Details of the storage elevation-storage volume relation, and the elevation-discharge relation must be supplied by the user.

Outlets from the storage will generally consist of weirs, spillways and culverts. These can be set at any elevation. The storages can be partly full at the start of the storm.

The elevation-discharge relation for culverts is based on their hydraulics, and WBNM2000 has built-in procedures to calculate them.
2.5 Culvert hydraulics

The most commonly used culvert hydraulics procedures are those of the US Department of Transportation [9]. These are presented as a set of nomograms and so cannot be directly used in a computer program. However equations have been fitted to these charts [10] and they are used in WBNM2000.

The culvert relations handle rectangular box and circular pipe culverts, for both inlet and outlet control. For outlet control, the tailwater depth in the downstream channel is needed, and this can be supplied either as a fixed value, or as varying tailwater depending on the discharge in the downstream channel. The tailwater depth-discharge relation can be either a rating curve, or can be calculated from the downstream channel cross section, bed slope and Manning roughness.

2.6 Fuseplug spillway

Fuseplug spillways, which are designed to scour out when they are overtopped, may be used as emergency structures to release extreme flows. WBNM2000 models these. The user specifies the elevation at which the embankment starts to scour, and the final dimensions of the scoured spillway cross section, plus the scour rate. At each time step, WBNM2000 calculates the volume of water passing through the scouring section, the embankment volume scoured, adjusts the cross section dimensions, and calculates a new elevation-discharge relation.

2.7 Flow diversions

The flow paths in large floods may be substantially different to those in smaller floods. When the stream channel capacity is exceeded, flow may leave the stream and divert to some downstream point. This will often occur at road embankments when the culvert capacity is exceeded, resulting in stream bank overtopping. The diverted flow will move parallel to the road embankment into an adjacent stream. In some cases the flow will be diverted completely out of the catchment.

WBNM2000 allows up to five flowpaths for diversion flows from each subcatchment. These occur at the outlet of the mainstream storages (section 2.4). For each diversion flow, an elevation-diverted discharge relation is required, plus the destination of the diverted flow. These elevation-discharge relations are calculated hydraulically, using the culvert relations in section 2.5.

2.8 Onsite detention storage

The mainstream storages in section 2.4 take all flow in the stream channel at that point, including flow from all upstream subcatchments. WBNM2000 also allows smaller storages to be placed on each subcatchment, to provide flood routing storage for local runoff from the subcatchment alone. This local runoff
will consist of the pervious surface hydrograph plus the impervious surface hydrograph. Nominated proportions of these two hydrographs can be directed to the onsite storage, with the remainder bypassing the storage.

Flood routing in onsite detention storages uses the same procedures as for mainstream storages. Elevation-storage volume and elevation-discharge relations are needed, and the same culvert hydraulic relations are used.

2.9 Design storms

WBNM2000 can be run for two classes of storms. It calculates the flood hydrograph resulting from a supplied storm rainfall, and it calculates design floods from design rainfalls. The built-in design storms allow rapid calculation of design floods, but only for Australian conditions. For other regions, design storms can be entered as supplied storms.

Design storm data for all of Australia has been assembled by the Institution of Engineers [11]. The data covers durations from 5 minutes to 72 hours, and average recurrence intervals from 1 to 100 years. Log Pearson type 3 frequency distributions are used. For each location in Australia, 9 design coefficients are supplied, from which rainfall intensities over these ranges of duration and frequency can be calculated. The rainfall intensities are converted into design storms using design storm temporal patterns. WBNM2000 has all of this information built-in, making design storm calculations simple and rapid.

WBNM2000 also contains built-in probable maximum precipitation design storms. These were developed by the Australian Bureau of Meterorology [12], and use depth-duration-area data plus PMP temporal patterns.

3 WBNM2000 computer software package

3.1 WBNM2000 software package

The software package consists of three computer programs, a design rainfall data bank, initiation files to allow the user to control the output, documentation, and eight sample runfiles. These are zipped onto a single floppy disk, and are also available on the University of Wollongong website.

3.2 WBNM2000 computer programs

The programs are written in FORTRAN, using REALWIN for Windowing. The source code totals 30,000 lines. Details of the catchment being modelled, including impervious surfaces, stream channels, mainstream and onsite detention storages, plus the storm rainfall is contained in a runfile.

The main program WBNMRUN consists of three parts. A Windows front end allows an existing runfile to be selected for calculation, or provides a template to create a new runfile. Automatic checking that values lie in
appropriate ranges, and checking for incompatibilities, occurs as the data are entered.

The calculation engine of this program also has built-in checks, and writes all results to an output file. This output file contains a copy of the runfile, all calculated rainfall hyetographs, and all calculated hydrographs. Hydrographs at the top and bottom of stream segments, from pervious and impervious surfaces, into and out of mainstream storages and onsite detention storages are calculated. These hyetographs and hydrographs are calculated and written to the output file for every subcatchment. The output file therefore contains a complete record of the run, to satisfy QA requirements.

The third part of the main program accesses the details in the output file and creates a series of plots of results. These can be rainfall hyetographs, any of the hydrographs mentioned above, elevation-discharge-storage curves for the storages, and a schematic of the catchment and its stream network. The catchment schematic can overlay a GIS image of the catchment.

The second program, WBNMCHCK, takes the runfile and checks for errors and incompatibilities in the data. These are logged and written to a screen window. This program can be used for screening a new runfile for errors before running the main program. The authors' experience is that problems in running the WBNM2000 program arise almost entirely from errors when the user created the runfile, so this checking program is useful.

Because WBNM2000 is a substantial revision of previous versions, the structure of the runfile has changed. The third program, WBNMCONV, takes runfiles from the previous version and converts them to WBNM2000 format.

3.3 WBNM2000 program controls

WBNM2000 has various flags to control the writing of results to output files, to control writing of summary tables to the screen, to control debugging, and to add details of the user's organisation.

The three flags for output allow the user to write full details of hyetographs and hydrographs to the output file, to write details of culvert calculations to a second output file, and to write details of the erodible fuseplug calculations to a third output file.

The nine flags for summary tables allow screen writes of:

- peak discharges and excess rainfall and runoff depths for the total catchment and for every subcatchment
- the inflow volume from all sources into each subcatchment, all outflow volumes, plus a volume balance for the subcatchment
- for mainstream storages and for onsite detention storages, the inflow and outflow volumes, peak discharges of the inflow and outflow hydrographs, and maximum water level in the storage
- peak discharges and times to the peak discharge at the top and bottom of stream segments, and for the hydrographs from pervious and impervious surfaces
• when a range of design storms is run, a summary to allow the critical storm to be identified.

The three flags for debugging echo the runfile to the screen as it is read; write values to the screen as they are calculated, plus error messages, allowing step by step checking of program operation; and write values and error messages to the screen as the design rainfall data is calculated.

Details of your organisation which can be entered are its name, function, address, phone, fax and email, plus the current user’s name.

Additionally, the user can assemble a batch file for multiple runs. Also, because a very large amount of data is written to the output file, the user can specify a cut-off discharge to limit writing of hydrographs to the output file.

3.4 WBNM2000 documentation

Two Microsoft Word documents are included, one giving the structure of the runfile, and the other giving full details of the background and theory of the model. Eight sample runfiles are provided to demonstrate applications of WBNM2000.

4 Conclusions

WBNM2000 is a simple yet realistic model for calculating flood hydrographs from storm rainfall. It models catchments at the larger scale rather than the detailed scale of gutters and pipes, and therefore does not require detailed input data for the drainage system. For natural catchments, the only data requirements are the structure and size of the subcatchments making up the catchment, and a single lag parameter. For urban catchments, additional requirements are the area of impervious surfaces on each subcatchment, and changes to flow velocities in any modified stream channel segments.

The model allows mainstream storages and onsite detention storages to be placed at any point in the catchment. Erodible fuseplug spillways can be used for the storages. Built-in equations for culverts and weirs allow the elevation-discharge relation of these mainstream and onsite detention storages to be readily calculated.

Major flows which exceed the capacity of the stream channel or culverts can be diverted to downstream points, or completely out of the catchment.

Design storms, including probable maximum precipitation storms are built-in to the software.

The emphasis in developing WBNM2000 has been to provide a tool which can be used for flood studies in engineering offices. All calculations are written to an output file for QA record keeping. Because of the numerous features described in this paper, WBNM2000 has been applied to many catchments with good results.

5 References


Figure 1. Lag Parameter values for natural catchments.

Figure 2. Maroubra urban catchment. 57 ha, 52% impervious