Distributed Modelling of Catchment Surface Hydrology

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

[a] *Gilbert & Associates Pty Ltd, Brisbane, Australia (gsbrisbane@bigpond.com)*

[b] *Honorary Senior Fellow, Griffith University, Brisbane (walterboughton@bigpond.com)*

Abstract: Distributed models of catchment surface hydrology differ from lumped parameter models by allowing for different inputs distributed over the catchment and simulation of the hydrological processes within the catchment as well as at the outlet of the catchment. The modelling of distributed hydrology varies with the type of application, such as flood studies, water yield studies, water management studies, low flow studies and water quality studies. This analysis concentrates on the different mechanisms used to distribute inputs and processes, such as sub-areas based on stream channels, grid cell division of the catchment, surface flow paths, idealized planes and channels, and finite elements. While wide variation exists in the models for each type of application, the results of the study show some common themes such as the trend for general purpose models to be common for flood studies and water management studies while transmission loss models are almost always location specific. The paper describes the main distributed models and the major characteristics by which the models are defined and delineated.

Keywords: Distributed catchment modelling, surface hydrology, spatial discretisation

1. INTRODUCTION

1.1 Distributed Vs Lumped Models

Hydrological modelling can be undertaken as distributed or lumped-parameter simulation, differentiated by whether or not spatial variation of hydrological parameters is accounted for. Lumped parameter modelling assumes that hydrological parameters and input, such as topography, soil type, vegetation and rainfall, do not vary over the catchment. Distributed modelling relaxes this assumption and attempts to incorporate the variability of the significant hydrological parameters, processes and input across the catchment, as well as provide for output of hydrological information from potentially anywhere within the catchment. The term "distributed model" means any hydrological model that has spatial differentiation of hydrological parameters, input or processes.

The first catchment scale distributed models became available towards the late 1970's and the approach has become more viable with the improvement in computing capability and data measurement and recording techniques. Distributed models attempt to represent the spatial variability within the catchment and as such offer a means of evaluating hydrological response under influences that may vary across the catchment.

1.2 Sub-Groups of Distributed Models

(i) "Semi-distributed" models, include some form of allowance for spatial variability without explicit simulation thereof. Examples of semi-distributed models include the AWBM [Boughton, 1993] and the Probability Distributed Model [Moore, 1985].

(ii) Four main surface hydrological applications for distributed models are:

- Flood studies – assessment of the size and timing of peak flows.
- Yield studies – assessment of the total flow resulting from rainfall within a catchment.
- Low flow studies – assessment of low flow characteristics.
- Water management studies – assessment of performance and impact of man-made water management infrastructure and/or systems.

A further area that has taken on significance from a distributed modelling perspective is the field of water quality modelling. Water quality modelling consists of the simulation of processes relevant to the generation, transport and/or dispersion of contaminants. As water movement represents a major transport source for contaminants, these models often incorporate, or are linked to, surface and/or subsurface hydrological models. These models have not been included within the scope of this study, however Droop [2001] includes review of distributed hydrological models with water quality applications.

(iii) Characterisation of models may also be made on the basis of the intended range of applicability of the model, either generalised models or specific purpose models. A generalised model is applicable to a range of catchment types and sizes, with model parameters that adequately represent the hydrological effects of a range of catchment characteristics. A specific purpose model is one that has been developed to simulate a single, specific catchment for a specific study.

(iv) Hydrologic models can also be differentiated as event based or continuous models. Event based models deal with the simulation of discrete runoff events and generally operate on an hourly (or shorter) time-step for periods of several hours up to several days. Continuous models operate over longer periods, incorporating simulation of hydrologic conditions during periods of low or no flow in addition to during runoff events. Depending upon the purpose of the modelling, continuous modelling can be undertaken for a range of time-steps, from hourly to monthly.

2. DISTRIBUTED MODELS OF SURFACE HYDROLOGY

Droop [2001] has reviewed 58 distributed hydrological models. Table 1 summarises these models into the groups of application and distribution type. Models applicable to more than one application have been included in all relevant categories.

Table 1. Model Summary by Application and Method of Spatial Discretisation.

Application	Number of models		
	Total	Distributed	Semi-distributed
Flood	33	27	6
Yield	32	26	6
Low flow	2	1	1
Water management	8	8	0

Some models are applicable to more than one application (eg. for both flood and yield studies), as such, the total number of models in Table 2 adds up to more than 58.

The major methods for distribution of catchment characteristics and input/output data are:

- Sub-area: The catchment is sub-divided along the lines of topography with sub-catchments delineated within the overall catchment.
- Grid Cell: The catchment area is divided into a series of regular grid blocks, generally of square dimensions.
- Flow Strips/Flow Paths: Formed by two consecutive lines perpendicular to the elevation contours such that flow can be assumed to be one-dimensional within the strip.
- Hydrological response units[1]: Grouping of all areas defined as having a similar hydrological response.

Table 2 summarises the models on the basis of method of spatial discretisation (semi-distributed models have not been included). Although the above represent four of the main methods of discretisation, others exist and are described in Droop [2001].

Table 2. Model Summary by method of spatial discretisation.

Application	Number of models			
	Sub-area	Grid based	Flow path	HRU's
Flood	15	7	1	4
Yield	10	8	1	7
Low flow	1	0	0	0
Water management	7	0	0	1

Location specific models are developed for a single project/application and are not readily adaptable for use in other catchments or studies. General use models have been developed with flexibility within the model parameters allowing the model to be utilised for a wide range of studies and catchments. Table 3 summarises the models on the basis of generality of application.

[1] Taken to include all methods/terminology dealing with the grouping of non-contiguous areas of a catchment on the basis of similarity of hydrologic response (eg. TOPMODEL uses the "Topographical Index" to group hydrologically similar areas).

Table 3. Summary of models by application generality.

Application	Number of models	
	General purpose	Location specific
Flood	30	3
Yield	30	2
Low flow	1	1
Water management	5	3

Event-based models simulate discrete events (generally flood flows) while continuous models simulate long sequences of flows including periods of receding and low flow. Table 4 summarises the models on this basis.

Table 4. Summary of models by period/method of simulation.

Application	Number of models	
	Event-based	Continuous
Flood	20	13
Yield	9	23
Low flow	1	1
Water management	0	8

The field of distributed modelling is a dynamic field with the ongoing development of new models. The above represents a summary of those available at this point in time.

3. THE CURRENT SITUATION

3.1 Profusion of Models

A significant feature of the approach to distributed modelling over the past 20 years is the large number of models developed, with no single model or modelling approach adopted as an industry standard. There are models that have been adopted within specific organizations, such as the British Institute of Hydrology Distributed Model (IHDM) [Beven et al, 1987], as well as models that have achieved widespread use such as the Runoff Analysis and Flow training System (RAFTS) [Goyen and Aitken, 1976] shown in Figure 1 and RORB [Laurenson and Mein, 1997] in Australia and the Systeme Hydrologique Europeen (SHE) [Abbott et al, 1986] in Europe (Figure 2). However many alternative models, exhibiting a wide range of characteristics, exist to these more widely known models.

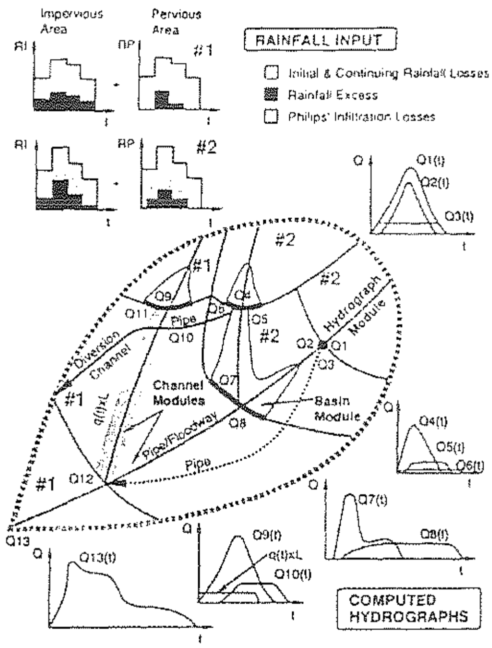

Figure 1. Diagrammatic representation of RAFTS [From Goyen at al, 1991].

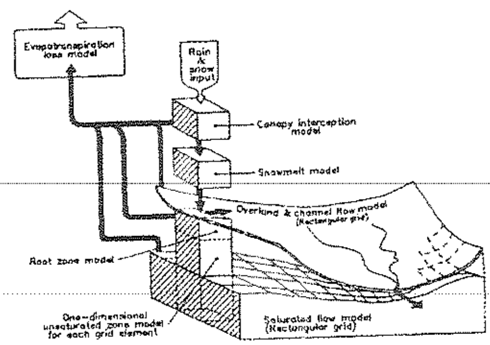

Figure 2. Schematic diagram of the SHE Hydrological Modelling System [From Bathurst and O'Connell, 1992].

For all the profusion of models available, some identifiable trends exist. Often the development of a model has been influenced by the dominant hydrological regimes. Figure 3 is reproduced from Boughton [1988] and illustrates how climates, soils and topography can influence the type of runoff processes likely to have the most effect on the hydrology of a catchment. For example, models developed for application to arid and semi-arid regions simulate Hortonian runoff generation (ie. infiltration excess) as the dominant runoff generation process, with little or no baseflow component. In temperate regions, runoff generation is dominated by saturated area runoff or subsurface stormflow, with the major process dependent upon catchment soils and topography.

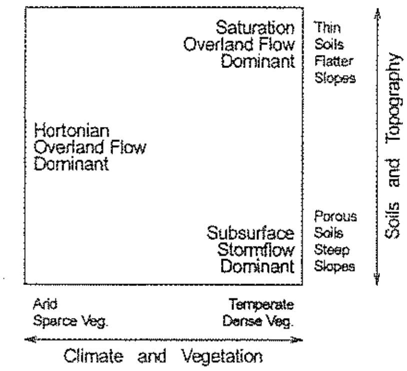

Figure 3. Proposed influences of climate, soils, vegetation and topography on runoff generating processes [From Boughton, 1988].

3.2 Transmission Loss Modelling

Another trend in distributed modelling is the lack of transmission loss components in the overall simulation of catchment hydrology in the majority of models. Models developed for water management application, such as the Integrated Quantity-Quality Model (IQQM) [DLWC, 1999] and WARAS [Lie et al, 1986], include consideration of transmission losses as an input parameter, however very few catchment scale models simulate transmission loss as a discrete process. Of the 58 distributed catchment models summarised in this paper, four include a transmission loss simulation component with only two of these explicitly simulating the process.

In addition, the majority of transmission loss models and methods are location specific and not useful for areas or applications other than those for which they were developed. Stewart and Boughton [1983] reviewed 17 transmission loss models (both distributed and lumped parameter), with a further 7 reviewed in Droop and Boughton [2001]. Of these, 17 were location and/or application specific.

In direct contrast, distributed models for the simulation of flood flows are both numerous and general purpose in nature. Of the 33 flood hydrograph models reviewed, 30 have been developed as general purpose models (Table 3).

3.3 Catchment Sub-division

An issue regarding the widespread use of distributed catchment models is the relative lack of studies into the effect of varying spatial discretisation of the catchment on simulation results. The majority of distributed models sub-divide the catchment into a series of discrete sub-areas with the selection of scale of this discretisation dependent upon varying factors related to the model being used. For example, models such the SHE and ANSWERS [Beasley et al, 1979], shown in Figure 4, require grid-based input data most often provided by GIS/DTM applications. In these cases the scale of discretisation is dependent upon the size of the grid of the input data application. Models such as RORB and WBNM [Boyd, 1980] sub-divide the catchment on the basis of drainage patterns defining discrete sub-catchments, often at the discretion of the modeller.

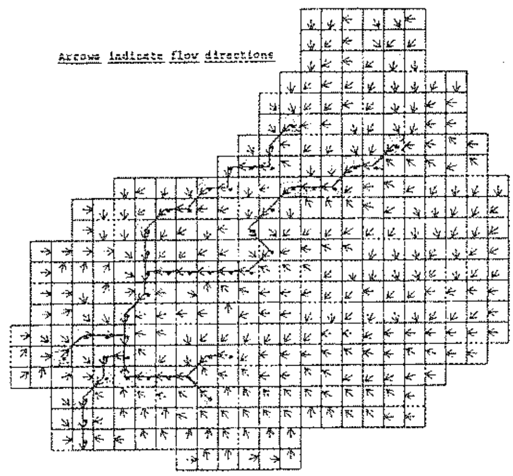

Figure 4. Element map for Middleton Watershed [From Beasley et al, 1979].

The underlying assumption behind distributed modelling is that each discrete sub-area is assumed to be hydrologically homogenous. The smaller the sub-areas, the more accurate the assumption of homogeneity is likely to be. However, smaller scales of discretisation also leads to greater complexity of the model and greater data requirements, leading to a trade off between accuracy and practicality of application. Few studies have been undertaken specifically into the effect of discretisation with a view to assessing the importance of the selection of an appropriate scale. Three available studies are Weeks [1980], Adams [1991], who assessed the effects of catchment subdivision on models such as RORB, and Yuge and Yu [1998] who, as a component of the overall study, assessed the effects of scale of discretisation of a grid-based distributed model. The results of Weeks and Adams are significant in that the studies appear to offer opposing conclusions. Weeks illustrated that the different sub-division of catchments in the RORB model can have a significant effect on modelling results, whilst Adams concluded that fineness of catchment subdivision had little effect on results from RORB, RAFTS and WBNM.

The relative lack of conclusive information on these effects appears to be a significant weakness in the knowledge base required for justification of the distributed modelling approach as an improvement over more simplified methods.

4. THE AUSTRALIAN SITUATION

4.1 General

The increased accessibility of computers in the 1970's lead to the development of flood, yield and water management models which were useful applications for the development of water resources. More recently, a shift in emphasis away from development and towards water management (discussed below) has seen more importance placed on the development of low flow modelling techniques for management of water allocations and environmental flows.

4.2 Flood Hydrograph Modelling

The most well known and widely used distributed models in Australia are generally flood simulation models such as RORB, RAFTS and WBNM. These models have been in use for up to 25 years and are widely accepted within Australia as the industry standard for flood hydrograph modelling. The Australian approach to flood hydrograph modelling has thus far been dominated by event-based models that do not simulate periods of low and receding flow between flood events. The development of continuous simulation models for flood hydrograph modelling has been a more recent development in Australia, for example TOPOG [Vertessy et al, 1994] and the Continuous Simulation System described in Boughton et al [1999].

4.3 Yield Modelling

Yield modelling in Australia has been dominated by relatively few models. Models developed overseas, such as Sacramento and the SCS Curve Number Method have been utilised within Australia as the basis for yield simulation. IQQM generally uses the Sacramento model for major water management studies. The Curve Number Method is still widely used in agricultural hydrology studies. Models developed within Australia include the AWBM, which is semi-distributed in nature with the simulation of three partial area stores. The AWBM was developed for application to the fields of both yield and flood modelling and has become very widely used within Australia for yield applications. The use of the AWBM for flood study applications has developed more slowly and has recently been incorporated into the Continuous Simulation System mentioned above.

4.4 Water Management Modelling

Early distributed water management models were mainly concerned with the assessment of water supply system performance under differing climatic conditions and demand scenarios. Models such as the Monthly Simulation Model (MSM) [Blainey, 1970], developed for the Murray/Darling Basin, were focussed on managing basin water resources from a supply-demand perspective, without assessment of low flows and water quality from an environmental perspective. More recently, Australia has undergone significant changes in the approach to the management of the nations water resources. A consequence of the Council of Australian Governments (COAG) Water Reform Framework has been the shift in emphasis away from water resource development and towards water management. As a result, all states have moved to implement catchment based management strategies, leading to the increased interest in and use of models with both distributed hydrological capabilities and water management procedures such as catchment-wide allocation assessment from government owned water infrastructure[2]. Of the models available, the IQQM, developed from the WARAS model by the NSW Department of Land and Water Conservation, has been adopted in NSW and Queensland as the basis for assessing water management and allocation plans and strategies.

An example of the impact of the COAG reforms on the use of distributed hydrological modelling is the recent water reforms in Queensland. Queensland is in the process of developing Water Allocation and Management Plans (WAMP)[3] for the major catchments around the state. The IQQM has been adopted as the basis for all hydrological and water management modelling upon which the development of the catchment plans has been based. Future planning and decision making regarding water resource management, allocation and potential development will be undertaken on the basis of simulation via the IQQM or similar distributed model.

[2] Recent moves have seen corporatisation of major water resource suppliers which were previously state government departments.

[3] Although a recent name change has seen final documents released as Water Resource Plans (WRP's).

4.5 Transmission Loss Modelling

Transmission loss studies within Australia have tended to be few and far between, and those that have been undertaken have exhibited very location specific results. Given the large proportion of the Australian landmass comprising arid or semi-arid catchments, transmission losses are likely to represent a significant factor in Australian hydrology. It is therefore surprising that greater effort has not been expended in the development of general purpose transmission loss models. It is possible that with the increasing focus on and importance of environmental flows, that the significance of estimating transmission losses will lead to an increase in research effort within this area of hydrology.

5. REFERENCES

Abbott, M.B., J.C. Bathurst, J.A. Cunge, P.E. O'Connell and J. Rasmussen, Introduction to the European Hydrological System - Systeme Hydrologique Europeen, 'SHE', 1: History and Philosophy of a physically based, distributed modelling system. *Journal of Hydrology*, 87 (1-2), 45-59, 1986.

Adams, A., Application and comparison of RORB, WBNM and RAFTS runoff routing model. International Hydrology and Water Resources Symposium, Perth, 1991.

Bathurst, J.C. and P.E. O'Connell, The Future of Distributed Modelling: The Systeme Hydrologique Europeen. Hydrological *Processes*, 6 (3), 265-277, 1992.

Beasley, D.B., L.F. Huggins and E.J. Monke, Planning for water quality using the ANSWERS approach, Proceedings of the Hydrologic Transport Modeling Symposium, ASAE Publication 4-80, 21-30, 1979.

Beven, K.J., A. Calver and E.M. Morris, The Institute of Hydrology Distributed Model, UK Institute of Hydrology Rpt No 98, 1987.

Blainey, J.B., Description of computer programme for River Murray system behaviour studies, River Murray Commission Report, 1970.

Boughton, W.C., Modelling the rainfall-runoff process at the catchment scale, Transactions of the Institution of Engineers, Australia (Civil Engineering), Vol CE30, No 4, 153-162, 1988.

Boughton, W.C., A hydrograph-based model for estimating the water yield of ungauged catchments, Hydrology and Water Resources Symposium, Newcastle, 317-324, 1993.

Boughton, W.C., S.H. Muncaster, R. Srikanthan, P.E. Weinmann, R.G and Mein, Continuous Simulation for Design Flood Estimation – A workable approach, WATER99 Joint Congress, 178-183, 1999.

Boyd, M.J., A storage routing model relating drainage basin hydrology and geomorphology, *Water Resources Research*, 14, 921-928, 1978.

DLWC, Integrated Quantity-Quality Model (IQQM) Reference Manual, NSW Dept of Land and Water Conservation, 1999.

Droop, O.P., Literature Review of Distributed Modelling, Gilbert & Associates, Unpublished Report No 1/01, 2001.

Droop, O.P. and W.C. Boughton, Transmission Losses, Gilbert & Associates, Unpublished Report No. 2/01, 2001.

Goyen, A.G. and A.P. Aitken, A regional stormwater drainage model, Hydrology Symposium, Sydney, 40-44, 1976.

Goyen, A.G., B.C. Phillips and D.C. Black, Recent advances in flood estimation using RAFTS-XP, Hydrology and Water Resources Symposium, 1991, Perth, 66-71, 1991.

Laurenson, E.M. and R.G. Mein, RORB - Version 4 Runoff Routing Program User Manual, Monash Uni. Dept. of Civil Eng, 1997.

Lie, J.S., K.G. Macoun, B.M. Fitzgerald and P.C. Knights, P.C., WARAS: Water Resources Allocation Simulator - A new planning tool for water resources management, Hydrology and Water Resources Symposium, Brisbane, 1-5, 1986.

Moore, R.J., The probability distributed principle and runoff production at point and basin scales, *Hydrological Sciences*, 30 (2), 273-297, 1985.

Stewart, B. and W.C. Boughton, Transmission losses in natural streambeds – A review, Hydrology and Water Resources Symposium, Hobart, I.E. Aust., Nat. Conf. Publ. 83/13, 226-230, 1983.

Vertessy, R., E.M. O'Loughlin, E. Beverley and T. Butt, Australian experiences with the CSIRO Topog model in land and water resources management, Proceedings of UNESCO International Symposium on Water Resources Planning in a Changing World, Karlsruhe, Germany, III-135-144, 1994.

Weeks, W.D., Using the Laurenson model: Traps for young players, Hydrology and Water Resources Symposium, Adelaide, 1980.

Yuge, Y and B. Yu, Predicting flood hydrograph using a stream network model for Oxley Creek, Queensland. *Aust. Journal of Water Resources*, 2 (2), 89-96, 1998.